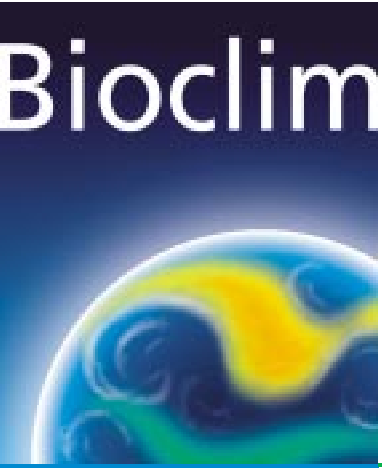

2004

Deliverable D10 - 12 :

Development and Application of a Methodology for Taking Climate-Driven Environmental Change into Account in Performance Assessments

Modelling Sequential
Biosphere Systems
under Climate Change
for Radioactive
Waste Disposal

EC-CONTRACT : FIKW-CT-2000-00024

Work package 4: Biosphere System Description

Foreword

The BIOCLIM project on modelling sequential BIOsphere systems under CLIMate change for radioactive waste disposal is part of the EURATOM fifth European framework programme. The project was launched in October 2000 for a three-year period. The project aims at providing a scientific basis and practical methodology for assessing the possible long term impacts on the safety of radioactive waste repositories in deep formations due to climate and environmental change. Five work packages have been identified to fulfil the project objectives:

Work package 1	will consolidate the needs of the European agencies of the consortium and summarise how environmental change has been treated to date in performance assessments.
Work packages 2 and 3	will develop two innovative and complementary strategies for representing time series of long term climate change using different methods to analyse extreme climate conditions (the hierarchical strategy) and a continuous climate simulation over more than the next glacial-interglacial cycle (the integrated strategy).
Work package 4	will explore and evaluate the potential effects of climate change on the nature of the biosphere systems.
Work package 5	will disseminate information on the results obtained from the three year project among the international community for further use.

The project brings together a number of representatives from both European radioactive waste management organisations which have national responsibilities for the safe disposal of radioactive waste, either as disposers or regulators, and several highly experienced climate research teams, which are listed below.

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- ENVIROS, UK

For this specific deliverable the main contributors were the waste management agencies (Andra, CIEMAT, NIREX, GRS, ENRESA, NRI), the regulator (EA) and the consultant company (ENVIROS). In addition, Mike Thorne and Associates Limited contributed to this document as subcontractor to NIREX.

Content List

1. Introduction

1.1. - Overall Aims of BIOCLIM

The aim of the BIOCLIM project has been to provide a scientific basis and practical methodology for assessing the potential impacts of long-term climate change on biosphere characteristics in the context of radiological performance assessments (PA) of radioactive waste repositories in deep geological formations. The project brought together twelve different European organisations plus associated sub-contractors with responsibilities for either the safe disposal of radioactive waste or the development of climate models. Through this scientific and technical collaboration, climate models that can simulate future climate changes in Europe over very long timescales have been developed. The climate modelling results have been linked to an understanding of the pattern of biosphere changes for selected European regions in order to address the issue of how to represent future biosphere systems in long term radiological performance assessments.

The project was implemented through five work packages (WP).

WP1 ('Consolidation of the needs of the waste management agencies') was to summarise information on the issues that have to be addressed by the waste management agencies represented in the consortium when considering climate change impacts on repository safety, and the current methods used to represent environmental change in repository safety assessments. This was achieved in two reports (BIOCLIM, 2001a; BIOCLIM, 2002).

WP2 ('Hierarchical strategy for climate modelling') has used a hierarchy of three types of climate model to derive the climatic changes for selected discrete time periods of interest to radioactive waste management (i.e. selected time slices during glacial and interglacial periods). These three types of model comprise an Earth-system Model of Intermediate Complexity (EMIC), a General Circulation Model (GCM) and a regional climate model. The outputs from these models consist of climate and vegetation cover scenarios for selected time periods in the future. Statistical downscaling approaches have been developed and evaluated to enable climate model output for large areas to be downscaled to more appropriate scales for the regions of interest. A report has been produced that summarises the different long-term climate simulations that have been undertaken using an EMIC and the recommendations for the six time slices to be studied using the GCM and regional climate models (BIOCLIM, 2001b). Simulations with these models have also been reported (BIOCLIM, 2003a).

WP3 ('Integrated strategy for climate modelling') involved the development and application of an integrated, dynamic climate model, representing the main mechanisms important for long-term climatic variations such as atmospheric forcing, ice sheet development and ocean changes. The time-dependent results from this model have been interpreted in terms of regional climate using a rule-based downscaling approach (BIOCLIM, 2003d). A second integrated, dynamic climate model that is structurally very different from the first has also been developed and applied. Results from these two models have been compared to determine whether the use of different climate models for the same future forcing of climate by variations in insolation and atmospheric greenhouse-gas concentrations gives rise to substantially different patterns of long-term climate change (BIOCLIM, 2003c).

The output from the climate models developed and applied in WP2 and WP3 has been interpreted in WP4 ('Biosphere system description') in terms of model requirements for the post-closure radiological performance assessment of deep geological repositories for radioactive wastes, in order to develop a methodology to demonstrate how biosphere systems can be represented in the long-term. The work undertaken in WP4 is described in this report.

The objective of WP5 ('Final Seminar') is to disseminate information on the methodologies and results obtained in BIOCLIM to the international scientific/technical and waste management community. As each deliverable is finalised, it is made publicly available on the project web site maintained by ANDRA. A final seminar on the project was held jointly with the EC BioMoSA project.

1.2. - Specific Aims of WP4

The overall objective of BIOCLIM Work Package 4 (WP4) is:

The identification and description of the potential effects of environmental evolution on key elements of long-term PAs, and, in particular, the description of biosphere systems appropriate for use in such assessments.

Inputs from WP1, WP2 and WP3 provide a climatological context for describing the likely environmental evolution of the hypothetical repository sites or regions of interest in primary study areas of the United Kingdom, France and Spain, as well as for secondary study areas in Germany and the Czech Republic. However, additional information has to be provided to complete the environmental descriptions for assessment purposes. The BIOMASS methodology (see Sections 1.3 and 4, and Appendix A) has been adopted and enhanced to develop the descriptions of the biosphere systems appropriate for use in long-term performance assessments. Application of this methodology has facilitated a well-structured synthesis of climatological results from the other work packages within BIOCLIM with supplementary data from other sources. In the main, these supplementary data have been provided by the waste management participants in the BIOCLIM consortium (see Appendix C).

The more detailed aims of WP4 were defined as being to:

- Provide a context for the synthesis of data from other work packages that will be useful in PAs;
- Show how those data are used to inform the development of biosphere system descriptions appropriate to PA;
- Investigate the potential radiological significance of transitions between different climatic states;
- Develop biosphere descriptions appropriate to selected climate states and transitions, and recommend how to derive conceptual models for radiological impact assessment;
- Develop recommendations on how the effects of climate change on the biosphere can be taken into account in PAs.

This report describes the methodology used for identification and characterisation of specific climate states and transitions between those climate states. It also covers the application of those methods in the context of the climate modelling results produced in WP2 and WP3.

Within the context of BIOCLIM, WP4 included methodology development and extended the development of illustrative conceptual models of biosphere systems and the transitions between them based on results from WP2 and WP3. This provided an appropriate basis for developing recommendations on how the effects of climate change on the biosphere can be taken into account in PAs, including the advantages/disadvantages and likely viability of potential alternative strategies. However, in order to go beyond this and evaluate which of the alternative methods of taking climate change into account should be preferred in a specific context would require application of the methodology developed under WP4 to proposed facilities at specific sites. It could also require the conceptual models of biosphere system states and transitions to be translated into mathematical models. These matters are outside the formal remit of BIOCLIM.

1.3. - Relationship to Previous Work Undertaken in VAMP, BIOMOVS II and BIOMASS

It is generally recognised that to assess the radiological impact of practices and interventions relating to the nuclear fuel cycle it is necessary to be able to analyse and quantify the behaviour of radionuclides in the biosphere. In the early 1990s, there were two principal international programmes aimed at the improvement of methods for assessing the impact of radionuclides in the environment. These were the IAEA-sponsored VAMP (VAlidation of environmental Model Predictions) programme and the BIOMOVS II (BIOspheric Model Validation Study) programme supported by organisations from Canada, Spain and Sweden. These programmes had some common elements and themes, but each had its main focus on different biospheric issues.

The VAMP programme was established to take advantage of the opportunity offered by the fallout from the Chernobyl accident for testing the predictions of environmental models, whereas the emphasis in BIOMOVS II was on issues related to the disposal of radioactive wastes.

When the VAMP and BIOMOVS II programmes ended, a need was identified for a new programme addressing the broad areas covered by these earlier programmes. Thus, in 1996, the IAEA-sponsored BIOMASS (BIOsphere Modelling and ASSessment) programme was established.

The general goals of BIOMASS were described as being:

- To provide an international focal point in the area of biospheric assessment modelling for the exchange of information and in order to respond to biospheric assessment needs expressed by other international groups;
- To develop methods (including models, computer codes and measurement techniques) for the analysis of radionuclide transfer in the biosphere for use in radiological assessments;
- To improve models and modelling methods by model testing, comparison and other approaches;
- To develop international consensus, where appropriate, on biospheric modelling philosophies, approaches and parameter values.

Theme 1 of BIOMASS related to solid radioactive waste disposal. In the preceding BIOMOVS II programme, the concept of defining ‘Reference Biospheres’ for assessment purposes had been developed. The objective of BIOMASS Theme 1 was to develop the concept of ‘Reference Biospheres’ into a practical system for application to the assessment of the long-term radiological safety of repositories for radioactive waste. Various Task Groups were set up to address different aspects of this issue. These related to:

- Definition of the various contexts within which assessments are conducted and the implications of those contexts for biosphere characterisation;
- Principles of biosphere system identification and justification;
- Principles of biosphere system description;
- Principles for the definition of potentially exposed groups;
- Principles for the application of data in assessment models;
- Development of models.

As a result of this work, not only was a comprehensive methodology developed (see Appendix A), but the methodology was applied in a sequence of examples of increasing complexity through to the stage of formulating and parameterising assessment models, and carrying out illustrative assessment calculations.

Although the BIOMASS methodology can be used to characterise biosphere systems subject to environmental change, in practice, the examples explored in detail and subject to mathematical modelling related only to time-invariant biosphere states. A further example discussed how environmental change could be represented in two site-specific contexts and one generic context, but did not fully characterise the associated environmental states and transitions between them. Thus, these issues are being explored in BIOCLIM for the first time. More details of the BIOMASS programme are provided in Section 3 and details of the BIOMASS methodology for biosphere system identification and description are given in Appendix A.

1.4. - Relationship to Work Undertaken in WP2 and WP3

WP2 and WP3 were structured to provide climatic information at global, regional and local scales relevant to the sites and regions of interest in the United Kingdom, France, Spain, Germany and the Czech Republic. However, the approach adopted in the two work packages was very different and this influences the information that is available to WP4.

In WP2, a hierarchical strategy was used for representing future climate change. First, the climate of the next million years was simulated using the UCL model LLN-2D-NH with different scenarios for combined natural and anthropogenic greenhouse-gas forcing (BIOCLIM, 2001b). On the basis of these simulations, six potential future situations were selected for detailed study using both a GCM and a regional climate model.

These six potential future situations, and a 'baseline' case representing present day conditions, were studied using a GCM that comprised the LMDz model for atmosphere/vegetation coupled to an ocean model. These simulations provided climatic characteristics for the various situations at approximately a 400 km resolution. GCM results were produced for a period of 30 years for each situation, so inter-annual climatic variability could be characterised as well as mean climate characteristics (BIOCLIM, 2003a).

Using the GCM results as a starting point, a regional climate model (MAR) was used to produce estimates of local climate conditions at the sites and regions of interest. This model allows the spatial resolution to be improved to about 50 km. Only a single year was simulated for each situation, so information on inter-annual variability was not generated. However, comparison of results from the LMDz and MAR models for that year permitted an evaluation of the degree to which downscaling using a regional climate model can systematically modify results obtained from a GCM with coarser spatial resolution (BIOCLIM, 2003b).

In addition, statistical downscaling techniques were used to derive local/regional information from the GCM results for comparison with the dynamical downscaling achieved using MAR and with the rule-based downscaling developed in WP3 (see below).

In WP3, long-term simulations of future climate were obtained using EMICs. Effectively, LLN-2D-NH is an EMIC, so one set of relevant results could be obtained from WP2. However, for the purposes of WP3, two other EMICs were developed and applied. These were MoBidiC and CLIMBER-GREMLINS.

These EMICs either provide climatological output by surface type and latitude band (LLN-2D-NH and MoBidiC) or on a very coarse geographical grid (CLIMBER-GREMLINS). Thus, only limited spatially distributed information was available for downscaling the results to a regional or local scale. In WP3, such downscaling was achieved by using a rule-based methodology (BIOCLIM, 2003d). Potential future climate states were identified using the Køppen-Trewartha classification scheme and the climatic characteristics of those states were defined by using data for present day analogue stations selected taking into account the geographical contexts of the regions or sites to which the downscaled results were to be applied. In addition, by an analysis of simulations of the past performed using the EMICs in conjunction with palaeoclimatic data and by consideration of short-term future simulations of greenhouse-gas warmed conditions obtained using GCMs, thresholds were established in EMIC output variables that define transitions between the various potential future climate states (see Section 3). With this information on thresholds and climate state characteristics, it was possible to interpret the EMIC results for long-term future climate simulations in terms of a sequence of climate states for a particular region or site, and hence in terms of the evolving climate for that region or site.

Further information on the climate scenarios used and the downscaling techniques adopted are given in Section 3. A comparison of the downscaling techniques used is provided in Appendix B.

WP2 and WP3 have provided primarily climatic outputs, together with information on global sea level and ice-sheet characteristics. However, the information from WP2 and WP3 is not sufficient to characterise environmental evolution in a region or at a site in the degree of detail required for PA. Thus, an important component of WP4 has been to take the information from WP1, WP2 and WP3 and combine it with knowledge of environmental processes to provide narratives of environmental change for the regions and sites of interest. In order to focus on the implications of climate change for PA, these narratives excluded from consideration environmental changes arising from causes not directly related to climate (e.g. those due to Earth processes or human factors). Furthermore, in common with the general practice in PA, patterns of human behaviour were based on those observed at the present day, i.e. no account was taken of potential technological or socio-economic developments. The development of narratives is discussed further in Section 5 and the narratives for the various regions and sites of interest are presented in Appendix C.

1.5. - Structure of the Report

Following this general introduction, Section 2 discusses the nature of environmental change. Because our understanding of relationships between climatic and more general environmental change in specific areas is informed through an examination of the palaeoenvironmental record, this matter is the main topic of Section 2. Individual subsections detail past environmental change in the five study areas. However, the discussion for each study area has been edited to avoid repetition of aspects of past environmental change that are common to more than one of the study areas.

Both past and future climate change can be simulated using computer models of different degrees of complexity. Furthermore, these models can provide a wide range of climate-related outputs. In the context of PA, it may be appropriate to undertake a variety of different types of calculations using the available models and to select or post-process subsets of results to provide an input to the associated environmental change analysis. Section 3 provides a route map for the generation and application of climate data for use in PA. This embeds the process of generation and application of such data within the overall BIOMASS assessment methodology. In this report, discussion of generation and application of climatological data is tied into the specific models and techniques used in BIOCLIM. Section 3 also addresses the specific scenarios for climate forcing developed in BIOCLIM and the climatological implications of those scenarios. In particular, consideration is given to the outputs from the climate models that are of direct applicability in PA and to the computation of derived quantities, such as soil moisture deficit and irrigation requirement, that are also required for PA purposes.

Various types of climate model were used in BIOCLIM singly or in combination. This is because only EMICs currently have the capability to simulate climate change on a continuous basis over the very long timescales that are relevant to the deep geological disposal of solid radioactive wastes. However, these EMICs have only coarse spatial and temporal resolution. Thus, other climate models are used as intermediaries to downscale the results from EMICs to the spatial and temporal scales of interest. This hierarchical approach to downscaling effectively combines long-term overall patterns of change obtained directly from the EMIC results, with snapshots of climate at specific times (but with a higher spatial resolution) obtained from GCM and regional climate models. The boundary conditions of the GCM model are taken from the associated EMIC at the specified snapshot time. Similarly, the regional model is nested within the GCM by matching its boundary conditions to the characteristics of the GCM on those boundaries.

The use of a hierarchical, model-based approach is not the only way that downscaling can be addressed. An alternative approach is rule-based downscaling in which palaeoenvironmental data and other considerations are used to identify thresholds in selected outputs from EMICs that allow the partitioning of past and future climates into sequences of states. Only a few distinct states are recognised, so information on the temporal variability of climate within each state is lost as a consequence of the rule-based downscaling procedure. This loss of information is partly compensated for by selecting several different analogue meteorological stations to span the anticipated range of variability within each state. Thus, temporal variability is replaced by stochastic uncertainty as to the climatological characteristics of each state. However, because the state is now represented by actual meteorological stations, it is characterised at the point scale and at all temporal scales likely to be of relevance in PA. Furthermore, environmental characteristics, e.g. patterns of vegetation and agricultural practice, in the vicinity of the analogue stations may provide a useful input to the development of narratives of environmental change in the areas of interest, as discussed below.

The issue of downscaling is addressed in rather more detail in subsection 3.4. However, because of the substantial amount of work on this topic that has been undertaken in BIOCLIM, a more detailed account of the approaches used and a comparison of the results obtained are presented in other BIOCLIM reports.

Although climatic and environmental changes are continuous in nature, it is not necessarily advantageous to attempt to represent continuous change explicitly in the context of PA. Indeed, the practice has developed of representing future biosphere characteristics for PA purposes in terms of one or more time-invariant states. Even, if this simplification is adopted, there are further choices that have to be made before PA calculations can be defined and undertaken. For example, states can be considered independently of each other (the non-sequential approach) or in succession (the sequential approach). If the sequential approach is adopted, either instantaneous changes between states can be assumed, or aspects of the transitions between them can be investigated explicitly. Alternative approaches to representing potential future climatic and environmental change are described in Section 4. The general methodological approach is based closely on the work of BIOMASS. However, some extensions to that approach are required, as the effects of climatic and environmental change were not investigated extensively in BIOMASS and no techniques were proposed for formally characterising transitions between climate states to demonstrate comprehensiveness of the assessment process.

In order to provide a context for defining future biosphere states and transitions, the extended BIOMASS methodology developed for BIOCLIM involves the development of narratives of potential future climatic and environmental change. The nature of a narrative is determined by the scenario for climate forcing adopted, the climatic implications of that scenario as determined through climate modelling studies, and the consequences of the inferred pattern of future climate and climate change in terms of evolution of the landscape. The development of such narratives for the three principal and two supplementary areas studied as part of the BIOCLIM project is described in Section 5. This section also includes examples drawn from the narratives and shows how these examples provide a context for the identification and characterisation of environmental states and transitions for PA purposes. The complete narratives developed as part of the project are quite lengthy and are reproduced in full in Appendix C, together with their decomposition into states and transitions, and the analyses of each of those states and transitions for PA purposes through application of the extended BIOMASS methodology.

A discussion and conclusions from the study are presented in Section 6. Implications from the study are presented in Section 7. This covers both requirements for further methodological developments and implications for the role and scope of climate studies in support of PA.

2. The observed Nature of Past Climatic and Landscape Change in the Regions of Interest

The nature of past climate and landscape change in the regions of interest is of relevance for several reasons. First, the palaeoclimatic record from those regions is used directly to develop some of the thresholds adopted for rule-based downscaling, and also to determine the climate and climate classification of those potential future climate states that have identifiable analogues in the palaeoclimatic record. The ability to relate potential future climate states to palaeoclimatic analogues helps guide the selection of present-day meteorological stations for the characterisation of those potential future climate states in a specific regional context.

Where downscaling is undertaken using a hierarchical modelling approach rather than through rule-based downscaling, the application of palaeoclimatic data is more indirect. The hierarchical modelling approach may be used to reconstruct snapshots of past climate at the regional or local scale and these reconstructions may be compared with palaeoclimatic data as one aspect of validation. Indeed, the hierarchical modelling approach can be carried through to the reconstruction of patterns of vegetation and these patterns can be compared directly with the pollen diagrams generated from analyses of sediment cores, as such pollen diagrams are often the basis upon which palaeoclimatic reconstructions are undertaken. The use of palaeoclimatic and palaeovegetation data in the validation of hierarchical modelling of climate and climate change is of considerable potential interest, but it was beyond the scope of the BIOCLIM project and was not addressed.

In addition to its relevance to palaeoclimatic reconstruction, palaeoenvironmental information is relevant to the more general issue of characterisation of the landscape under different climatic conditions, and of the pattern and tempo of landscape evolution over time and under changing climatic conditions. It should be noted that the landscape evolves even under constant climatic conditions, but that both the pattern and tempo of evolution will be influenced by changes in climate. It should also be recognised that the landscape at any time will seldom be in equilibrium with the current climate and, consequently, that the characteristics of the landscape at any time are determined, in part, by the local antecedent history of climate.

In this section, a brief account is provided of what is known of climate and landscape evolution in the five areas of interest through interpretation of available palaeoenvironmental data. A more extensive account is given elsewhere (BIOCLIM, 2002). For conciseness, where particular aspects of evolution are relevant to more than one of the areas of interest, they are discussed only in the context of one of the areas. Thus, all five of the summaries given in the following subsections should be considered together in evaluating the factors that may be relevant to the future environmental evolution of local areas and broader regions of Western and Central Europe.

2.1. - United Kingdom

In BIOCLIM, the region of the United Kingdom that is considered is termed 'Central England'. The defined region lies almost entirely within Lowland Britain. This is a undulating lowland with deep rich soils and few steep slopes to interrupt cultivation. Human settlement is essentially continuous, with villages and towns closely and evenly scattered. The greater part of the area is occupied by farmland, which includes both cultivated land for agriculture and grass land for grazing livestock. Such moorlands, heaths, 'wastes' and other unimproved lands as occur do so as remnants of previously more widespread environments interrupting the otherwise continuous farmland and coinciding with patches of poorer soils. A more detailed characterisation of central England has been provided elsewhere (BIOCLIM, 2002), along with a location map.

It is well established that the Quaternary has been characterised by a sequence of glacial-interglacial cycles. Over the period since the Brunhes/Matuyama magnetic reversal at about 780 ka Before Present (BP) there have been about eight cold (glacial) stages. Although these eight cold stages were coeval with large global ice volumes, this does not necessarily mean that the British Isles were extensively glaciated in all of them. However, Clayton (1994) has concluded that it seems highly probable that upland glaciers extending at least into the adjacent lowlands occurred in all eight cold stages. He further commented that field evidence suggests that glaciations extended across much of Wales and perhaps all of Scotland and northern England in at least six cold periods during the last 700 ka. The evidence for several of these episodes is limited and the majority of British authors describe the glacial record in terms of only two ice advances. The first of these is the Anglian (usually correlated with Oxygen Isotope Stage (OIS) 12 at around 440 ka BP. The second is the Devensian (OIS 4 to 2) with its maximum during OIS 2, about 20 ka BP.

The effects of ice-sheet advances over the British Isles can be characterised in broad terms as erosion of bedrock, deposition of various unconsolidated deposits, collectively often referred to as 'drift' and the diversion of rivers.

In the uplands of Britain, landforms characteristic of glacial erosion are readily recognised. However, the effects of glacial erosion on Lowland Britain are less easily identified. Nevertheless, as Clayton (1994) commented, a consensus has developed that The Wash and The Fens are the result of erosion during the Anglian advance, and similar arguments have been advanced for the Vale of Belvoir. It seems likely that the Vale of York was lowered by the action of ice. Also, the Dee and Mersey estuaries have been described as lying within intrusive troughs formed as the ice rode up southwards from the Irish Sea basin. Much of the Cheshire plain is thought to have been reduced in level in the same way. Of particular relevance to central England, the low elevation of the crest of the Chalk outcrop east of The Fens and the absence of a normal escarpment is regarded as the work of ice. The degree to which other outcrops of more resistant rocks in lowland Britain have been modified by the passage of ice is not yet clear (Clayton, 1994).

Based on various lines of evidence and notably the large volumes of sediment present on the continental shelf and slope around the British Isles, Clayton (1994) has argued that there is good evidence that each major ice advance sweeps away the drift cover remaining from the previous advance and moves the bulk of it to the edge of the continental shelf. It also erodes sufficient bedrock (on average about 20 m) to create a new layer of glacial drift with an average depth of about 27 m. This glacial drift typically has a subdued topography that is subsequently incised by streams and rivers. Good examples of such incised palaeosurfaces are found in Suffolk (developed in Anglian deposits) and Northumbria (developed in Late Devensian deposits). Comparison of the patterns of incision, suggests that much of the development of stream and river channels occurs in the first few tens of thousands of years after deposition. Sagging of the palaeosurface over buried valleys is thought to have been caused by subglacial drainage under a considerable isostatic head and has often influenced the alignment of modern rivers.

The southward advance of successive ice sheets has also brought about major changes in the river network of the British Isles through direct action (Clayton, 1994). In particular, the Anglian ice interacted with the River Thames and eventually diverted it from its earlier route along the Vale of St. Albans and then north-eastwards to its present valley through London. Diversions of other major rivers, e.g. the Trent, also occurred at the time of the Anglian glaciation. Although most of the major diversions were accomplished by earlier glaciations, it was the Late Devensian advance that diverted the upper River Severn south to join the Avon.

Patterns of flow in river systems and the associated incision would also have been influenced by changing base level, i.e. the height at which the river discharges to another water body, such as the sea. For the major rivers, base level would have been defined by alterations in sea level. The pattern of spatial and temporal variation in sea level around the British Isles following a glacial episode is known to be complex. This is because global (eustatic) sea-level rise has to compete with isostatic adjustments following from changes in loading by ice and water (see Thorne et al., 1997). In the period leading up to a glaciation, a simpler pattern of falling sea level may have occurred, as significant build-up of ice in the British Isles is likely to have taken place only during the latter part of each glacial episode.

As illustrated by the period after the Late Devensian glaciation, immediately following a glacial episode, immature, unstable, base-rich soils support an open herb and dwarf shrub vegetation with arctic-alpine flora. This period is typically followed by an interval of rising temperatures and increasing shade, as tree taxa immigrate and shade out plants of arctic-alpine meadows. Soil maturation occurs over this period and, as conditions ameliorate, trees increase in height and the composition of the forest changes. Thus, by the end of this stage, forests of birch, hazel and pine already contain elements of the mixed oak forest characteristic of the Mesocratic (or interglacial) stage (BIOCLIM, 2002).

The natural vegetation of the interglacial stage is characterised by a mixed oak forest, with co-dominants of elm, alder, lime and ash. Such forests are also rich in shrubs, herbs and climbers. Soils are typically base-rich brown forest soils, though leaching of bases and sesquioxides could lead to incipient podzols in some contexts (BIOCLIM, 2002).

As temperatures decline subsequent to an interglacial, the forest canopy tends to open and retrogressive plant succession occurs. Late emigrating trees such as beech and hornbeam replace the dominants and co-dominants of the mixed oak forest, conifers reappear, heathlands of Ericales are of some significance and blanket bogs, dominated by Sphagnum, develop at both high and low altitudes.

As temperatures decline further, interglacial conditions are replaced by boreal and then periglacial conditions. Seasonal ground freezing becomes of significance in boreal conditions, as does snowpack development in winter. High spring meltwater discharges of rivers would be expected to occur in these conditions. In periglacial conditions, first discontinuous permafrost starts to develop and eventually continuous permafrost forms. Structural features such as patterned ground and ice wedges also form under these conditions. A detailed account of evidence for permafrost in the British Isles is provided by Harris (2002). He demonstrates that there is evidence of ground disturbance by permafrost to depths of at least a few tens of metres throughout Britain. Only in the far south-west is permafrost thought to have been largely absent. This is attributed to the high geothermal heat flux in that area.

2.2. - France

In BIOCLIM, the French region of interest is Andra's Meuse/Haute-Marne (MHM) site located in the Meuse department in the eastern part of the Paris basin, within 250 m of the border with the Haute-Marne department. This site was chosen in 1999 by the French government for the establishment of an underground laboratory in a clay formation. Located at an average elevation of 370 m above sea level (Andra 1996a), on a limestone plateau that slowly falls towards the north-east, the site is characterised by a temperate oceanic type of climate with an annual mean temperature of 10°C and an annual precipitation in the range of 0.7 to 1.0 m (Andra 1996a). The greatest part of the area is occupied by farmland. Farming practices include the growing of crops and rearing of cattle. The soil of the region is primarily chalky and drainage is mostly from south to north (Andra 1996b). The Andra site is drained by a stream (la Bureau) that discharges into a local river (l'Orge) and hence to the river Saulx. To more than 1000 m in depth, the local geology comprises a succession of Cretaceous, Jurassic and Triassic sediments (limestones, marls and clays) dated from 245 to 96 million years BP. An average erosion rate of 10 m in 1 10^5 years has been estimated (Andra 1996a). The uppermost (Tithonian) limestone formation is used as a source of domestic, agricultural and industrial water.

During the Quaternary, the region has experienced the effects of global climate change associated with glacial-interglacial cycling. The reference climatic record is the Grande Pile sequence in the Vosges, situated 120 km southeast of the MHM site at an altitude of 330 m. This peat bog is some 17 m thick and palynological analyses of its characteristics have been of great importance in reconstructing the evolution of both vegetation and climate for the last 140 ka. However, analyses of other sequences have also been used for estimation of the regional variability.

Schematically, thirteen climate intervals can be identified during the last climatic cycle (see BIOCLIM deliverable D3, Table 3-1), the shortest lasting 1 ka (Younger Dryas) and the longest 20 ka. The first interval corresponds to the earliest part of the last interglacial (i.e. the Eemian from 126 ka to 116 ka BP). This was 1-2°C warmer than today, as an annual average. Then an oscillatory cooling tendency started, including two 6 ka long cold episodes (Melisey I and II). This was followed by a period of generally stationary cold conditions (the Middle Pleniglacial, which occupied the interval from 70 ka to 30 ka BP). This cooling tendency eventually ended in the coldest stade of the last climatic cycle: the Recent Pleniglacial, from 25 ka to 15 ka BP. The Last Glacial Maximum (which reached its most intense at about 18 ka BP) was associated with annual average temperatures about 15°C lower than today. A rapid deglaciation followed. This lasted about 5 ka and was interrupted at 11-10 ka BP by an intense cold spell (the Younger Dryas) when periglacial conditions were re-established. The thermal optimum of the Holocene was reached at about 8 ka BP, with annual average temperatures 1-3°C warmer than today.

As annual temperatures declined, subsequent to the last interglacial, the regional MHM climate passed through boreal conditions to tundra and eventually to a cold steppe state characteristic of periglacial conditions. Woody species progressively disappeared in favour of grasslands. As temperature declined, the type of soils at the site MHM went from a combination of Vertic Cambisols/Luvisols/Vertisols (under temperate conditions) to Gelic Gleysols (under tundra conditions) and then to Chernozems (under cold steppe conditions). More details for these three types of climate can be inferred from present-day analogue conditions at high northern latitudes (Watkins et al. 2000a, 2000b, 2000c). In particular:

- Boreal (taiga) climates are classified EO Subarctic Oceanic/EC Subarctic Continental in the Køppen-Trewartha classification (Goodess et al., 1991). Typical annual average temperature and precipitation values for boreal conditions range from -2°C to 5°C and from 500 mm a^{-1} to 1800 mm a^{-1}, respectively, with long cold winters (mean monthly temperature being around -25°C) and cool summers (~15°C). Most of the precipitation falls in late Summer/early Autumn and around 25-30% as snow. Under such climatic conditions coniferous species (pine), birch, poplar and alder dominate. Some deciduous species can also be found. The taiga understorey comprises low shrubs, mosses and lichens, plus various grasses, ferns and fungi.
- Tundra climates are classified as FT Tundra in the Køppen-Trewartha classification (Goodess et al., 1991). Typical annual average temperature and precipitation values range from -13°C to 2°C and from 150 mm a^{-1} to 1170 mm a^{-1}, respectively, with long severely cold winters (minimum mean monthly temperatures are ~ -40°C) and cool summers (maximum mean monthly temperatures ~15°C). Most of the precipitation falls as snow, and about 50% falls between August and November. Rivers can be seasonally frozen and there can be high discharge volumes over frozen ground at the time of snowmelt. Under such climatic conditions, woody plants are of limited significance. Overall, a grass/herb/shrub vegetation with significant contributions from mosses/lichens/sedges and dwarf heath dominates.

- Cold steppe climates are classified as EC Subarctic continental in the Køppen-Threwartha classification (Goodess et al., 1991). Typical annual average temperature and precipitation values range from -14°C to -3°C and from 220 mm a^{-1} to 1300 mm a^{-1}, respectively, with at least 6 months below freezing. Most of precipitation falls during Spring and Summer and around 30% falls as snow during the 6 months of Winter. Under such climatic conditions, a steppe vegetation of grasses/sedges/low shrubs/ lichens and mushrooms develops. Trees are rare and scattered.

The landscape of the MHM site area result from a generalised erosional process that started a few million years ago, during the Pliocene epoch. The processes of valley incision, retreat of the line of cuestas and plateaux erosion were all components of this erosion. The main effects of erosion were expressed in valley areas. Typically, during glacial periods, the alluvial plains are eroded and rivers incised the substratum (to a depth of 10 to 12 m for the Marne valley during the last glacial period). The alluvial plains of the valleys (which are currently used for agriculture) are, therefore, expected to disappear at the beginning of the cold periods, to be later on reconstructed during interglacial episodes.

At the location of the MHM site, there is no evidence of cover by ice sheets during cold periods. At their closest, during the Last Glacial Maximum (LGM), the land-based UK and Fennoscandian ice sheets were some 500 km to the north of the Andra site, whereas the principal mountain glaciers remained about 150km to the south-east (Alps, Massif Central and Jura). However, periglacial conditions, characterized by annual average temperatures some 15°C lower than present-day values, were able to generate the development of relatively thick permafrost (Courbouleix 1994, Van Vliet Lanoë and Hallegouët 2001). Some model results indicate that, during the last 120 ka, continuous permafrost (in other words at least 50 metres deep) may have been of frequent occurrence and could have reached a considerable depth during the LGM: between 125 m and 315 m depending on the scenario (Couberleix 1998).

2.3. - Spain

The Spanish region of interest for the BIOCLIM Project is a 400x400 km area in central Spain, termed the Toledo area. However, for this aspect of the study, a smaller region of 200x200 km centred in the south-western part of the larger area has been considered (CIEMAT, 2003). A large part of the Toledo area is characterised as the Tajo depression, also known as the southern Submeseta, which is a wide interior intracratonic depression of the Iberian Meseta with an average altitude of 600-700 m above sea level. The Tajo river basin is interesting from a palaeoenvironmental point of view, because of the evolutionary similarity between this valley and other major valleys in Spain.

In the Toledo area, all five Mediterranean bioclimate stages defined by Rivas-Martínez (1987) for the Iberian Peninsula are represented. The mesomediterranean stage (annual average temperature values ranging from 13 to 17°C) is the most extensive and dominant one in both the central and southern parts of the region. The crioromediterranean stage (annual average temperature values below 4°C) is also present in the central and southern part of the region, but occupies only very restricted zones in the Sistema Central range above 2100 m of altitude (CIEMAT, 2002).

The soils in the Tajo valley alluvial sequence are mainly alfisols, except for those in the Holocene alluvial plain. The most recent argillic horizon surface in this area is from the Upper Pleistocene and the most evolved soil in the sequence is the Ultic Paleoxeralf of the La Raña piedmont, the most characteristic geomorphological formation in the area. Carbonate crusts are found in some soils corresponding to the Lower Pleistocene, and there was a generalised calcification and a redistribution of carbonates during the Middle Pleistocene and the Upper Pleistocene, but not during the Holocene (Pérez-González et al., 1995). The main soil groups developed on the area considered herein are cambisols, lithosols and fluvisols (FAO classification, CIEMAT, 2003). The area is covered mainly by natural vegetation of sclerophylic forests, typical of climate types with a clearly defined 'dry' period. The current climax vegetation is represented by Quercetum ilicis, but it has been extensively modified by human action and has today been partially substituted by bush and steppe-like vegetation. In higher topographic areas, arboreal vegetation is composed of Q. pyrenaica, and Pinus sylvestris. A more detailed characterisation of the area of interest can be found in BIOCLIM (2002) and CIEMAT (2003).

Practically all the Quaternary deposits in Spain are continental, with a predominance of fluvial, glacis, piedmont and alluvial fan deposits. The Quaternary began with the deposition of piedmont deposits, followed by fluvial dissection that created a complex system of terraces, glacis and alluvial fans in the major river valleys. The clastic piedmont of La Raña and the limestone plateau known as the Páramo are the Pliocene geomorphological and chronological indicators of subsequent Quaternary evolution. This evolution has been subject to processes more of erosion (initiated during the Upper Neogene) than of accumulation. These processes of erosion have structured the landscape as a system of geomorphological surfaces, with or without deposits, during the Pliocene, Pleistocene and Holocene. These systems are relatively well known (in terms of geomorphology, geometry, lithology, soils and spatial and temporal geometric relationships), but important gaps still exist in our knowledge of their origins and associated deposits, chronology and palaeoenvironmental significance (Bajos et al., 1996). For instance, it is not fully known if all or some of these forms correspond to certain climatic or other geodynamic processes, such as tectonic processes. Good evidence of the erosive processes that have operated in the central area of Spain is the almost complete sequence of terraces that has been found in the Talavera de la Reina area, where the piedmont of La Raña is located at an elevation of more than +200 m with respect to the Tajo River average water-surface level (Pérez-González et al., 1995).

Both, the Raña piedmont and the river terraces are the most typical sedimentary deposits of the Tajo River Depression. Other characteristic formations are alluvial fans, glacis, aeolian accumulations of sand and clay, travertines and tuffs, and limestone crusts.

Given the scarcity of paleoclimatic data in the area of interest for the Quaternary period as a whole and for the last 104 ka, in particular, a paleoclimatic reconstruction of the southern part of Spain has been synthesised. The synthesis is based on palaeoenvironmental results obtained from the Padul peat bog and the Cúllar-Baza basin, both of them situated in the Granada province, around 60-100 km south of the area of interest. The Padul pollen sequence is the reference climatic record used for the Toledo area, although fluvial terrace analyses and the study of continental carbonate deposits have also contributed to determining the evolution of the Quaternary climate for the central zone of Spain.

In the Iberian Peninsula, the development of vegetation typical of the Quaternary had already started in the Upper Pliocene (3.2 - 1.6 Ma BP), first during a warm and humid climate of subtropical type, but primarily during a climatic deterioration that started around 2.4 Ma BP bringing about an increase in aridity and the subsequent expansion of Mediterranean species. The first glacial-interglacial cycles in the Iberian Peninsula were characterised by an increase in aridity during the glacial episodes and an increase in humidity during the interglacial stages. From the Middle Pleistocene (780-125 ka BP), the rhythm of the climate oscillations became faster, pleniglacial stages being colder and less humid the interglacial ones (Badal and Roiron, 1993).

During the Quaternary, the climate in the Tajo valley area was temperate with variations in humidity. Thus, towards the end of the Pliocene and Lower Pleistocene (1.6 Ma -780 ka BP), the climate in this zone was moister and warmer than at present time, as the intense illuviation of clay minerals in the soils of the Talavera de la Reina chronosequence indicate (Pérez González et al., 1995). Towards the limit of the Lower-Middle Pleistocene (780 ka BP), a sudden climate change resulted in a dryer period with relative deficits of water and with intermediate episodes of climatic amelioration. Overall, the faunal and floristic associations of the Middle and Upper Pleistocene

(780 - 10 ka BP) indicate net Mediterranean climatic conditions, both during the aggradation and incision of the terraces of the Tajo river. Climate conditions were fairly similar to these of the present time, although there was some variability of temperature and rainfall rates between deposition and fluvial incision periods. The genesis of alluvial fans overlying these terraces indicates a tendency towards dryness during the periods of incision. Thus, two important factors that drove landscape evolution in the Iberian Peninsula during the Quaternary were variations in rainfall and the dynamics of incision-sedimentation processes in the fluvial systems. Rainfall variations have exercised a more substantial control on environmental evolution than temperature variations and have also been primary in governing variations in the availability of water in the lithosphere.

In a general way, when the Upper Pleistocene began with the Riss-Würm Interglacial (120 ka BP), the climatic conditions in the Iberian Peninsula were warmer and more humid than in the north and centre of Europe. Nevertheless, over this period, the temperature was slightly lower than during the interglacial periods of the Lower and Middle Pleistocene. The prevailing characteristic of the climate of the Iberian Peninsula during the Würm glaciation was aridity. During the Pleniwürm (23 to 15 ka BP), thermophilous species disappeared and steppe species began to prevail. During the Late Glacial (15 to 10 ka BP), the climate was generally cold and dry, albeit less severe and arid than in the Pleniglacial. During the Pleniglacial period, well-defined bioclimatic differences between the Eurosiberian and Mediterranean regions of the Iberian Peninsula appear to have existed. The Late Glacial began with a cold period (Oldest Dryas) and ended with another cold period (Younger Dryas), but more humid than the former. Although temperatures were cooler than today, interstadial periods of the Late Glacial (Bölling-Alleröd interstadial) show evidence of a climate similar to or slightly more humid than that of the present. From the beginning of the Holocene, at about 10 ka BP, there has been an ongoing climatic amelioration until the current climate of the Iberian Peninsula was reached.

Almost the whole last glacial-interglacial cycle can be identified in the upper 25 m of the Padul peat bog core, corresponding to 104 - 4.4 ka BP (Pons and Reille, 1988). A detailed climatic interpretation of this pollen sequence has been provided in BIOCLIM (2001) and synthesised in Table 4.5 of that report.

In that core, the beginning of the Würm glaciation (Eowürm period, about 63 ka BP) was characterised by a very low arboreal pollen percentage and thermophyllous species such as Olea, Helianthemun halimifolium and Pistacia disappeared, indicating a marked cooling. The predominant vegetation indicates very arid or xeric conditions, with annual average temperatures between 4 and 8°C, and annual average precipitation below 200 mm. The Middle Würm (60 to 24 ka BP) shows climatic fluctuations that are poorly defined, compatible with steppe vegetation and steppe with trees, under semiarid to dry conditions. The annual average temperature would have been in the range from 8 to 4°C and the annual average precipitation from 200 to 600 mm. During the Final Würm (24 to 15 ka BP), expansion of non-arboreal local vegetation was promoted by the change in climate that occurred. In the period from 23.6 to 19.8 ka BP, cold and arid conditions occurred, with annual average temperatures about 4°C and arid or semiarid conditions (annual average precipitation between 350 and 200 mm or less). The Last Glacial Maximum, at about 18 ka BP, was associated with annual average temperatures below 4°C and minimum average temperatures of the coldest month below -7°C, with 350 to 200 mm as annual average precipitation. After this time, a succession of climatic phases occurred. These were quite similar to the classic succession established in central Europe, but with notable peculiarities, e.g. a greater expansion of semiarid vegetation. Towards 15 ka BP, a great expansion of a regional steppe cover took place. This event marks the beginning of the Oldest Dryas. The climatic amelioration of ca. 13.000 calibrated ^{14}C years BP is far more pronounced at Padul than anywhere else in Europe, and represents a distinctive characteristic of Padul sequence in relation to other European palynological records, maybe because Padul is located far to the south and close to pleniglacial arboreal refuges. In contrast, the amelioration that took place about 10 ka BP is not so clearly defined. During the Late Glacial and in the Holocene, a new vegetation period appeared, characterised by the early appearance and prevalence of Quercus ilex forests and by the early occurrence of Quercus suber and Olea. This is the first evidence of an extensive postglacial reforestation history in a region with current semiarid Mediterranean climate. Both the Oldest Dryas and Younger Dryas are identified by respective climatic shifts towards dryness, the first dated at around 15000 years BP and the second dated between 9930 (±130) and 12080 (±180) years BP.

The environmental peculiarities of the Iberian Peninsula with respect to other regions of Europe are a result of its southern latitude, its location between the Atlantic Ocean and the Mediterranean Sea, the morphology of its continental shelf and its orography. As a result, the climates that have occurred throughout the Quaternary over most of the Iberian Peninsula are of Mediterranean type with varying degrees of aridness. During glacial periods the temperatures dropped considerably, but not to the extent that generalised permafrost could be developed. This phenomenon occurred only in specific areas and at great altitudes. Glacial periods did cause an important increase in aridness in peninsular environmental conditions, although the induced continentality due to glacial-eustatic fluctuations throughout the Quaternary was relatively slight (Bajos et al., 1996).

2.4. - Germany

The four sites that have been or are of interest (Asse, Konrad, Morsleben and Gorleben) are located inland on the North German Plain. During the Quaternary period, the climate underwent various changes between ice ages and intermediate periods. The average annual temperatures oscillated between -2 and +10 degrees (Küster, 1995). The average July temperatures lay between +5 and +19 degrees Celsius, whereas in January the average temperatures ranged from very low values to up to +3 degrees Celsius. The cold periods were generally characterised by little precipitation, but precipitation in the warmer periods did not differ much from today (Hendl and Liedke, 1997).

During the cold Elster period 320 ka BP, the area of the sites was covered by an ice sheet (Küster, 1995); the soil layer above the Gorleben salt dome was eroded and a deep trough formed. This trough was later filled with sands and clays. During the Saale period (200 ka BP) melt water ran off into the North Sea forming wide glacial valleys with large outwash plains, in or near which Gorleben and Morsleben are located. In later ice ages, the glaciers did not reach the area of the sites.

During the last ice age, tundra climate (FT) prevailed. The low temperatures and the short, cool summers only allowed sparse tundra vegetation (lichens, fungi, herbs and several types of berry bearing bushes) to grow on the active layer over permafrost soil. Typical soils were regosols and gelic gleysols. In lowlands without run-off, gelic histosols and cryic histosols were frequent (Hendl and Liedke, 1997). Melt water from the ice-covered areas north of the sites ran off into the North Sea via the pre-existing glacial valleys. The impact of water and wind caused general erosion of the preglacial soil. Only pebbles and stones remained in place; sands were blown away over short distances forming dunes; such sand is an important constituent of the soil at the present day. The finer and more lightweight dust was deposited as loess in areas lying further away.

Approximately 18 ka BP warming set in. The glaciers melted, the glacial valleys grew wider due to the larger amounts of water flowing through them, and they filled up with sediments from the upper reaches of the rivers. Sand and dust from the moraines north-east of the sites was carried away with the wind, and deposited and retained on grassland at the sites (Küster, 1995).

The trees were initially birches and pines, but these were subsequently supplemented and displaced by firs and deciduous trees. However, the biodiversity characteristic of the time prior to the cold period was never again reached, because of intermittent cooler spells. The forests affected the soil profile and also caused an enhanced loss of water. The result of this was a reduced frequency of flooding (Küster, 1995).

Different soil types were formed depending on the prevailing temperature and precipitation regime, vegetation and underlying rock. The tundra soils changed steadily into podzols. During warmer climatic conditions and under deciduous trees, browning set in. The resultant soils were chromic cambisols and luvisols. In times of a more continental climate, chernozems were formed and degraded again during subsequent humid periods into phaeozems (Hendl and Liedke, 1997).

The formation and degradation of soils are long-term processes that were often not fully completed within a period of relatively constant climatic conditions. Therefore, soil characteristics typically reflect the climatic history of a region and not just its current climate.

The nutrition of human beings depends on climate and technological development. During cold periods, humans mainly lived on the meat of the large animals they hunted. As the latter migrated over long distances in the search for feed, humans also lived a nomadic life. Following the warming of the climate, the importance of vegetable foodstuffs grew, especially with the introduction of farming, which allowed humans to settle down.

Today's technology makes it possible to use the warmer parts of tundra regions for agricultural purposes as pasture. The open farming of potatoes, barley and similar plants is to a limited extent also possible on tundra soil, albeit not in the long run as the soil will be damaged (Hendl and Liedke, 1997). The longer the vegetation period, the more extensive is the agricultural use. Any possible precipitation deficits are compensated by irrigation. In some circumstances of excess precipitation, bogs and swamps can be drained to permit agriculture.

Man-made changes to the landscape exercise an influence on soil characteristics and on the water regime even without a change of climate. When forests are replaced by fields and pastures, the capacity of the soil to retain water is impaired. This leads not only to a higher frequency of flooding events, but also to increased erosion in the upper reaches of rivers. The material washed down from the upper reaches deposits in the river bed of the lower reaches, in the vicinity of the sites of recent and current interest, and leads to the formation of alluvial clay. Due to the rise of the river beds, long-term relocation of the rivers cannot be precluded. Since the terrain around the sites is almost level (except at the Asse site), increased erosion by water is not expected. If there is further warming, however, increased wind erosion may be possible, especially following harvest (Hendl and Liedke, 1997, Küster, 1995). On the other hand, farming has an improving effect on the soil. The resultant anthrosols are characterised by a higher net production rate, a deeper rooting layer and a reduced acidity compared with a forest soil in the same area (Zech, 2002). Reforestation with coniferous trees strengthens the tendency to form podzols, but reforestation with deciduous trees does not.

2.5. - Czech Republic

The south of the Czech Republic (49.8N - 14.8E, 48.8N - 16.0E) was selected for climatic and biospheric modelling, as it includes some potentially suitable sites for the construction of a deep geological repository. Currently, six sites are subject to geophysical and geological surveys (though some of them are outside this area).

The southern Czech Republic is composed mainly of hard rocks - Proterozoic highly metamorphosed rocks and various granitic massifs of Hercynian (Variscian) age. Granitic rocks represent the preferred host rock for repository siting. This area can be characterised as highlands with various altitudes between 400 and 800 m. Forests, meadows and pastures are frequent and represent a relatively pristine and unpolluted part of the Czech Republic. Agriculture is mostly oriented to cultivation of less demanding crops, mainly potatoes. Towns and villages are less frequent than is typical of the rest of the Republic.

The Quaternary period has been characterised by cyclical changes of climate and environment. Several Pleistocene phases can be distinguished:

- Lower Pleistocene glacial periods were probably warmer and more humid (according to the characteristics of loess development) than later glacial periods of the last 1 Ma. The bright red deeply weathered interglacial soils are characteristic for the period prior to Brunhes-Matuyama palaeomagnetic boundary (as documented at the Beroun highway outcrop near Prague). The fossil content of Lower Pleistocene sediments reflects the presence of thermophilic elements and species (e.g. outcrops of red breccia – see Horacek and Lozek (1982); Lozek (1982)). However, generally the evidence is scarce and limited to a small number of sites. The general pattern of the Lower Pleistocene was of mild glacial periods and warmer and, in some phases, even more arid interglacial periods (resembling current Mediterranean conditions; documented by the presence of 2 kinds of apes). The frequency of climatic changes was probably higher and the differences between glacial and interglacial lesser than during the Middle-Late Pleistocene.
- Middle and Late Pleistocene strata of the Brunhes palaeomagnetic period as recorded in loess series and calcareous sediments display an alternating sequence of more or less well-defined glacial and interglacial sediments. The mean annual temperatures can be estimated in range –2 to –3 °C during pleniglacials (approx. 10 °C colder than in interglacial periods), but with relatively mild summers, even with similar conditions to those existing currently (overall, somewhat resembling current Siberian conditions). The glacial periods were drier with approx. 300 - 400 mm of mean annual precipitation in areas below 400 m a.s.l. (during the LGM only 100 - 200 mm). The glacial ecosystems were composed of cold steppe or grassland, but forest refugia (with spruce, birch, juniper) were present as “islands”. Pollen analyses and even some macrofossils indicate a rather enigmatic presence of more demanding tree species such as elm and oak during warm phases of the last glacial. The malacofauna is represented for most of the glacial periods by a monotonous assemblage of several species such as Pupilla. Although the glacial periods of the last 1 Ma seem to have had similar character, the interglacial periods were more individual as documented by fossil fauna (Horacek and Lozek, 1982). This may have been caused by random migration from either western Atlantic direction or along the Donau River from the south-east, or even along the outer limits of Carpathian range from the area of current Poland.

Central Europe has been continuously uplifted during last one million years and the central part of the Czech Republic has possibly been uplifted faster than average. This process influenced development of the landscape to the current forms. The rivers incised current typical valleys in many sites as is documented by the development of the Vltava river terraces near Prague (where Tertiary fluviatile sediments occur approx. 120 - 150 m above the current terrain).

The extent of past glaciations can be estimated from geomorphological studies, although new glaciations nearly wipe out the evidence of past glaciations. Glacial landforms can be found only as small and rare forms in Krkonose (Giant Mountains), Sumava and Hruby Jesenik Mountains (Silesia) at heights approximately 700 m a.s.l. or higher. The existence of several small (1.5 km or less) mountain glaciers during the Pleistocene can be supposed from field evidence. No glacial bedrock striation caused by thick continental glaciers has ever been reported from the area of the Czech Republic. Glacial sediments including erratics of Scandinavian red granites (rapakivi), rare amber and other Nordic rocks including abundant Cretaceous flintstone can be found in two areas in the northern part of the Czech Republic.

Various periglacial phenomena are documented from the area of Czech Republic – sorted soils, stone glaciers, nivation cirques, solifluction tongues etc. The extent and thickness of permafrost during the glacial periods is uncertain. It is supposed that permafrost in the interior of Bohemia could have been developed as a discontinuous layer some 50 to 100 m thick (or less). Neither the crystalline complexes of the Variscan Bohemian Massif nor even the Upper Cretaceous sandstones display any enhanced microfracturing that can be attributed to permafrost action.

The loess deposits have been documented from many sites. The fact that loess-transporting winds came from the north-west, west and south-west directions was established decades ago on the basis of loess dune orientation and the presence of particles from neighbouring rocks (Demek and Kukla, 1969). The inferred wind directions are similar in most of the Central European loess deposits, but some authors (Vasicek, 1951) have observed evidence of episodes with dominant easterly winds. Such a wind field corresponds to the contemporary North Atlantic Oscillation pattern. The palaesol-loess stratigraphy can be correlated to OIS by the thermoluminiscence dating (summarised in Frechen et al., 2000) or amino-acid racemisation (Oches and McCoy, 1995). Unfortunately, such correlation is reliable for only the last few glacial cycles. Mass accumulation rates (in g m^2 a^{-1}) for many European sites for the last glacial are summarised in Frechen (2003); south-east Czech lands have sites with higher mass accumulation rates (750 - 1 100 in the 18 - 28 ka BP period; 2 600 - 3 700 in the 13 - 18 ka BP period).

Generally, two different modes of loess deposition are documented:

- Series of individual loess laminae some 2 - 5 cm thick can be observed as episodic strata occurring throughout the last glacial cycle (Dolni Vestonice, Zemechy). The relatively coarse sandy grains in the lowermost part of the laminae and gradual decline in particle size indicate a regime with repeated dust storms with each storm corresponding to one lamina. As a consequence, very variable rates of dust sedimentation especially in small deposits and dunes in the lee of hills and within the valleys occurred.
- Relatively homogenous, massive loess without visible stratification probably corresponds to a steady, uniform westerlies regime. The palaeoclimatic data for the last glacial cycle (Tziperman 1997) demonstrates unstable changes of wind direction and a general variability in the climatic oscillations, which is more clearly demonstrated by the macroscopic features of loess sedimentation than by, for example, magnetic susceptibility.

Detailed research on the Holocene deposits conducted during the last few decades on numerous profiles has led to the collection of a large set of climatic and environmental proxies. Precipitation and temperature curves were constructed for the whole Holocene, based on information from about one hundred sites scattered over the region of the Czech and Slovak Republics (Lozek 1973; Lozek and Cilek 1995). Palaeoenvironmental, malacostratigraphic and sedimentological information along with palynological data and archaeological findings were taken into account. The following intervals were recognised.

- A preboreal period is documented from approximately 10 300 year BP that directly followed colder conditions, but is evidenced by occurrence of pines, birches, willows with rare oaks or hazels. Surprisingly rapid extension of relatively thermophilic tree species (pollen of elm, hazel and spruce are found by 9 800 year BP) is documented from a defunct lake in the south part of the Czech Republic. Such rapid migration was probably connected with the floodplain of the local river surrounded by the usual pine-willow forests.
- The following boreal period (9 000 - 8 000 years BP) was characterised by a rapid increase in temperature (mean annual temperature reached 10^{o}C) along with precipitation. Pine-birch forests were continually replaced by mixed oak forests. Birch and pine were vanishing to relict sites with spreading of more demanding species like ash, elm, maple or lime. Characteristic is the absence of beech and fir.
- The Atlantic period (8 000 - 6 000 year BP) represents the climatic optimum with a mean annual temperature of approximately 11 °C and mean annual precipitation approx. 1 000 mm (the highest in the Holocene period). The moist character of the Atlantic period is documented by calcareous sediments, peat and various cave sediments. Beech and fir occurred in formations and later also hornbeam. Typical altitude zonality formed during the Atlantic period composed of mixed oak forests, beech-fir forests and spruce formations. The peak of the Atlantic period somewhat resembled previous interglacials. The younger Atlantic period is characterised by the first permanent settlements and visible human interventions in the character of the landscape.

- In the following Epiatlantic period (6 000 - 4 500 years BP) the mean annual temperature decreased to the current value and precipitation varied substantially.

The following periods oscillated around current conditions, with mean annual temperature stabilised at ± 1 °C of the present-day value. Mean annual precipitation varied approximately ± 30% in comparison with current conditions. Soil development was interrupted by the extensive deforestation and agriculture and therefore did not reach stages typical of previous interglacials.

3. The Use of Climate data in Performance Assessments

3.1. - A Route Map for the Generation and Application of Climate Data

The overall decision tree for determining whether and how climate change should be included in biosphere characterisation for PA has been developed by BIOMASS and is reproduced as Figure A.1 in Appendix A of this report. Step 1 requires that the assessment context should be reviewed to determine whether biosphere systems are pre-defined by explicit legislation or guidance. As the aim of BIOCLIM is to explore the influence of climate change on the evolution of biosphere systems and hence on their characterisation for the purposes of PA, prescriptive definition of the biosphere systems of interest would be inappropriate. Therefore, following the BIOMASS methodology through to Step 2, it is next necessary to address the identification and justification of components of biosphere systems of interest. Here, the first question to be addressed is whether biosphere system change has to be considered. In the context of the aim of BIOCLIM, such change does have to be considered. Under the BIOMASS methodology, this then leads to the following three requirements:

- Identify and justify selection of mechanisms causing change;
- Identify potential impacts on the biosphere system;
- Identify qualitatively different possible 'futures'.

BIOMASS provides detailed guidance on each of these steps, as discussed in Section A1.2.2 and illustrated in Figure A2. In the full BIOMASS methodology, several primary drivers of environmental change are identified. These comprise:

- Social/institutional developments;
- Human influence on global climate;
- Global climate change;
- Vulcanism;
- Orogeny;
- Meteorite impact;
- Large seismic events.

However, for the purpose of BIOCLIM consideration was limited to two of the above, i.e. human influence on global climate and global climate change. This meant that consideration had to be given to the natural factors that influence global climate and the way that they interact with human influences. Detailed discussion in BIOCLIM (2001a) concluded that, over the timescales of interest for PA, the characteristics of the orbit of the Earth, ocean circulation patterns together with air-sea-ice-land feedbacks, and the gas composition of the atmosphere are important mechanisms that need to be included in climate models. Both ocean circulation patterns and air-sea-ice-land feedbacks are internal to the operation of the models. Therefore, in the development of scenarios for future global climate evolution it was only necessary to consider as forcing factors the characteristics of the orbit of the Earth and the gas composition of the atmosphere.

The characteristics of the orbit of the Earth enter into consideration because they affect the spatial and temporal pattern of short-wave radiation delivered to the top of the atmosphere. On timescales of up to a few million years into the future, accurate calculations of these variations in insolation have been made using well-justified models of celestial mechanics. Thus, this forcing factor can be considered as a well-defined input that is not subject to significant uncertainty on the timescales of interest.

In contrast, the future variations in greenhouse-gas concentrations in the atmosphere are subject to considerable uncertainty. One cause of this is that emissions of carbon dioxide from the burning of fossil fuels are difficult to quantify, as they depend on a complex mix of socio-economic and political considerations. Similar uncertainties apply to emissions of other greenhouse gases, such as methane, and to factors affecting aerosol and cloud formation and properties, such as sulphate emission. Furthermore, even for precisely specified carbon dioxide emissions scenarios, considerable uncertainties exist concerning the persistence of the released carbon dioxide in the atmosphere. Compounding this are uncertainties as to how natural carbon dioxide concentrations would vary in the future in the absence of additional anthropogenic inputs and uncertainties as to how anthropogenic emissions of carbon dioxide will influence the processes that give rise to variations in natural carbon dioxide concentrations.

In BIOCLIM, it was thought adequate, for illustrative purposes, to consider only scenarios for potential future variations in atmospheric carbon dioxide concentrations. Thus, the effects of future variations in the concentrations of other radiatively active gases and aerosols were assumed to be subsumed within the envelope of scenarios for future variations in carbon dioxide concentrations. It is not considered that inclusion of the effects of future variations in the concentrations of other radiatively active gases and aerosols would have substantially altered the conclusions reached.

Detailed data on past variations on carbon dioxide concentrations in the atmosphere have been obtained from analyses of the gas trapped as inclusions in ice cores, notably the Vostok ice core from Antarctica. These data show that considerable natural variations in carbon dioxide concentrations have occurred and that these variations are strongly correlated with overall global climate, being low during glacial periods and high during interglacials. In principle, a comprehensive climate model could be developed that calculated such variations by incorporation of a carbon cycle model that was closely coupled to associated atmospheric, oceanic, vegetation and biogeochemical models. However, no such model is currently available, so future variations in natural carbon dioxide concentrations in the atmosphere were estimated using statistical regression techniques or a simple threshold model (BIOCLIM, 2001b).

Imposed upon this natural variation are the changes in carbon dioxide concentrations that arise from human activities, primarily the burning of fossil fuels. Between 1850 and 1950, the concentration of atmospheric carbon dioxide rose from a pre-industrial value of 280 ppmv to 300 ppmv and by 1999 the concentration was approximately 370 ppmv. Future increases were estimated for two emissions scenarios (low and high), based on different projections of future fossil fuel use, combined with a model-based relationship between the amount of carbon introduced into the atmosphere as carbon dioxide and the time-dependent concentration of carbon dioxide in the atmosphere arising in consequence. The relationship used has components with atmospheric mean residence times of $3.65\ 10^2$, $5.5\ 10^3$, $8.2\ 10^3$ and $2.0\ 10^5$ years, so the long-term effects of fossil fuel combustion on atmospheric carbon dioxide concentrations are projected to persist for timescales corresponding to several glacial-interglacial cycles.

Finally, to define overall scenarios for future variations in concentrations of atmospheric carbon dioxide, the contribution from fossil fuel combustion had to be combined with the projected natural variations. As it is unclear whether the fossil fuel component would be subject to temporal modulation in the same way as the natural component, two different approaches to combination were used. However, comparison of the results obtained showed no strong distinction between the two approaches. Furthermore, there was also no strong distinction between the scenarios generated using the statistical regression and threshold models for variations in natural carbon dioxide concentrations (BIOCLIM, 2001b). Therefore, only three scenarios were carried forward for detailed consideration. These all used the threshold model for variations in natural carbon dioxide concentrations and did not modulate the fossil fuel contribution according to variations in the natural concentration. These three scenarios were:

- Scenario A4: Natural variations only with no post-industrial contribution from fossil fuel combustion;
- Scenario B3: Natural variations plus a contribution from the fossil fuel scenario with low future utilisation of fossil fuels;
- Scenario B4: Natural variations plus a contribution from the fossil fuel scenario with high future utilisation of fossil fuels.

The implications of these scenarios were initially studied in WP2. The EMIC LLN 2D NH was run over the period to 1 10^6 years After Present (AP) for these three scenarios. Based on results from those model simulations and on selection criteria developed in the light of the results obtained (see Section 4 of BIOCLIM, 2001b), six specific situations were identified for further study through application of the LMDz GCM and the MAR regional model in the later stages of WP2. Details are given in Section 3.3.

Results from the model simulations of those six situations are discussed elsewhere (BIOCLIM, 2003a) and later in this report (Sections 3.4 and 5, and Appendix B).

The three emissions scenarios described above also provided the basis for the climate modelling that was undertaken in WP3. A second EMIC, MoBidiC, was used to obtain simulations of global climate out to 2 10^5 years AP. In addition, a third EMIC, CLIMBER-GREMLINS, was also used to simulate each of the scenarios out to 2 10^5 years AP. However, the simulations using CLIMBER-GREMLINS were only undertaken at a relatively late stage of the project, so they were not used directly in downscaling studies. Instead, results from MoBidiC and CLIMBER-GREMLINS were compared (BIOCLIM, 2003b) to illustrate the degree to which results obtained from EMICs developed on different conceptual and structural bases can differ when forced by the same orbital and greenhouse-gas scenarios.

Whereas the downscaling undertaken in WP2 was based on a hierarchical modelling approach, in WP3 a rule-based approach was adopted (BIOCLIM, 2003d). The approach can be summarised briefly as follows:

- Using the reviews of palaeodata for the three main regions of interest (Central England, Northeast France and Central Spain) produced at an earlier stage of the project (BIOCLIM, 2002), regional sequences of Køppen-Trewartha climate classes were determined for the last glacial-interglacial cycle;
- Appropriate analogue meteorological stations were identified for each climate class in each region;
- The analogue station data were manipulated into an appropriate format for presentation of results and input to PA;
- For both LLN 2D NH and MoBidiC, the most suitable variables for use in downscaling were identified and objective thresholds in these variables were determined by reference to regional sequences of climate classes for the last glacial-interglacial cycle and from various GCM model simulations for future climatic conditions with no analogue in the palaeoenvironmental record for the region under consideration;
- The adequacy of the procedure for identifying suitable variables and objective thresholds, and of the capability of the EMICs to capture the temporal pattern of climatic change, was evaluated by applying the downscaling technique to EMIC output for the last glacial-interglacial cycle (recognising a degree of circularity in the argument, as data for this interval were used in setting the objective thresholds);
- The rules for identifying climate classes by application of the objective thresholds to the associated variables were applied over the next 1 10^6 years in the case of LLN 2D NH output and over the next 2 10^5 years in the case of MoBidiC output.

The resulting sequences of climate classes were interpreted in the context of narratives of future environmental change in the three regions, as discussed in Section 5 and illustrated for the various regions in Appendix C.

The rule-based downscaling technique was not applied in full to the two supplementary regions (Germany and the Czech Republic). However, the sequences of climate classes determined for the other regions were used, together with climate data from analogue meteorological stations appropriate to these supplementary regions, to construct limited narratives and identify aspects of environmental evolution for these regions that were deserving of specific consideration.

Thus, by reference to modelled and downscaled climate characteristics obtained in WP2 and WP3, it was possible to develop narratives of potential future environmental change for the various regions of interest. These narratives are discussed in Section 5 and Appendix C. Here, it is sufficient to note that the narratives for Scenarios B3 and B4 were qualitatively similar and could be merged to give a single 'future' for each region. However, the narrative for Scenario A4 was qualitatively different from that for Scenario B3/4, so it provided the basis for a second, qualitatively different 'future' for each region.

The narratives developed as described above provide the context in which to practice Step 3 of the BIOMASS methodology (Figure A.1). This requires the selection of an approach to the representation of biosphere system change. Such an approach may be either sequential or non-sequential, as discussed more fully in Section 4. In the non-sequential approach, a small set of time-invariant biosphere system states is identified for each 'future'. It is assumed that each of these states can be considered and modelled separately, and that the sequence in which such states occur is not of importance in determining the radiological impact of radionuclide discharges to the biosphere. Effectively, the assumption is made that the accumulation of radionuclides in the biosphere in one state has only a minor effect on radiological impacts in the next state compared with the effect of radionuclide discharges during that next state. This approach also makes the assumption that there are no special characteristics of the transitions between states that substantially enhance radiological impacts.

The sequential approach is of more relevance in the context of BIOCLIM, as it does not assume a priori the legitimacy of the above assumptions. Rather, the continuous narrative is partitioned into a sequence of biosphere states and transitions of finite duration between them. There is little loss of generality in this approach. In narratives in which the biosphere is stable for long periods, but is subject to a few episodes of rapid evolution, biosphere states will dominate the partitioning and transitions will be of short duration. In contrast, for narratives in which the biosphere evolves continuously at a rate of potential relevance to radiological impact assessments, biosphere states may be of short duration and transitions may be both individually long and the dominant component of the partitioned future. Indeed, the biosphere states may be defined mainly for the purpose of having well-defined end members for use in conceptualising the changes that occur between them during transitions.

Once a sequence of biosphere states and transitions has been defined, the biosphere systems associated with each of those states and transitions can be identified and characterised. The BIOMASS methodology (Appendix A) provides a detailed approach to the identification of biosphere systems associated with specified biosphere states. This is done by describing the biosphere system associated with such a state in terms of the following principal components (see Section A1.1.2 for further details):

- Climate and atmosphere;
- Topography;
- Human community;
- Near-surface lithostratigraphy;
- Water bodies;
- Biota.

The following two items are additionally considered at the stage of system identification, if they have not been adequately specified in the assessment context:

- Geographical extent;
- Location.

Following this stage of system identification, a more detailed biosphere system description can be developed using the methodology set out in Section A2. This comprises three main parts:

- Identification of significant characteristics of each principal component of the biosphere utilising standard tables developed for this purpose within the BIOMASS methodology (BIOMASS, 2003);
- Establishment of inter-relationships between the components through the use of interaction matrices;
- Development of a description of the configuration of, and connectivity between, different parts of the biosphere system, taking account of the part that they would play in the migration and accumulation of contaminants.

The generation of descriptions of transitions between biosphere states was not addressed in detail in BIOMASS. However, a methodology for the generation of such descriptions has been developed and applied in BIOCLIM (see Section 5.4). Such descriptions are generated after the descriptions of the biosphere states existing before and after the transition have been produced. The methodology comprises three steps:

- Production of a summary table detailing how each principal component is modified and the processes associated with that modification in moving from one biosphere state to the next;
- Production of an interaction matrix showing how changes in each principal component affect all the other principal components during the transition;
- Utilisation of the summary table, interaction matrix and other information to produce a transition diagram showing the temporal patterns of change to the principal components and the temporal structures of the interactions between those components during the transition.

In principal, once the descriptions of biosphere states and transitions were completed, there was a basis for the development and application of mathematical models for representing those states and transitions. However, this topic was outside the scope of BIOCLIM. Instead, the descriptions of the states and transitions were examined to determine, for the regions and scenarios under consideration, whether:

- Future climate and environmental change can be adequately represented for PA purposes in terms of biosphere states and transitions;
- Transitions need to be studied in their own right;
- The sequence of states and transitions is important to PA.

A schematic overview of the route map is shown in Figure 3.1. This has been generalized so that it is applicable generally for biosphere characterization and not only in the more restricted context of the BIOCLIM project.

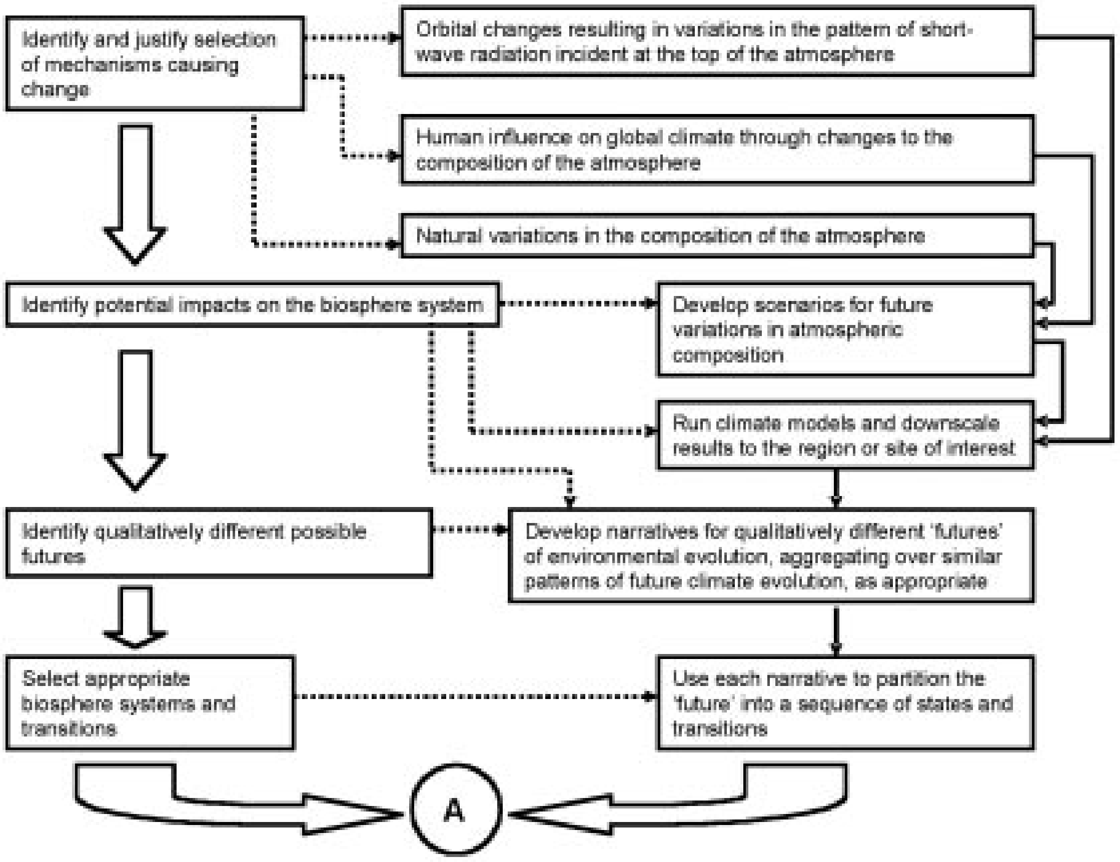


Figure 3.1a: *Initial Stages of the Route Map for Including the Effects of Climate Change in the Representation of Biosphere Systems and Transitions for Performance Assessment*

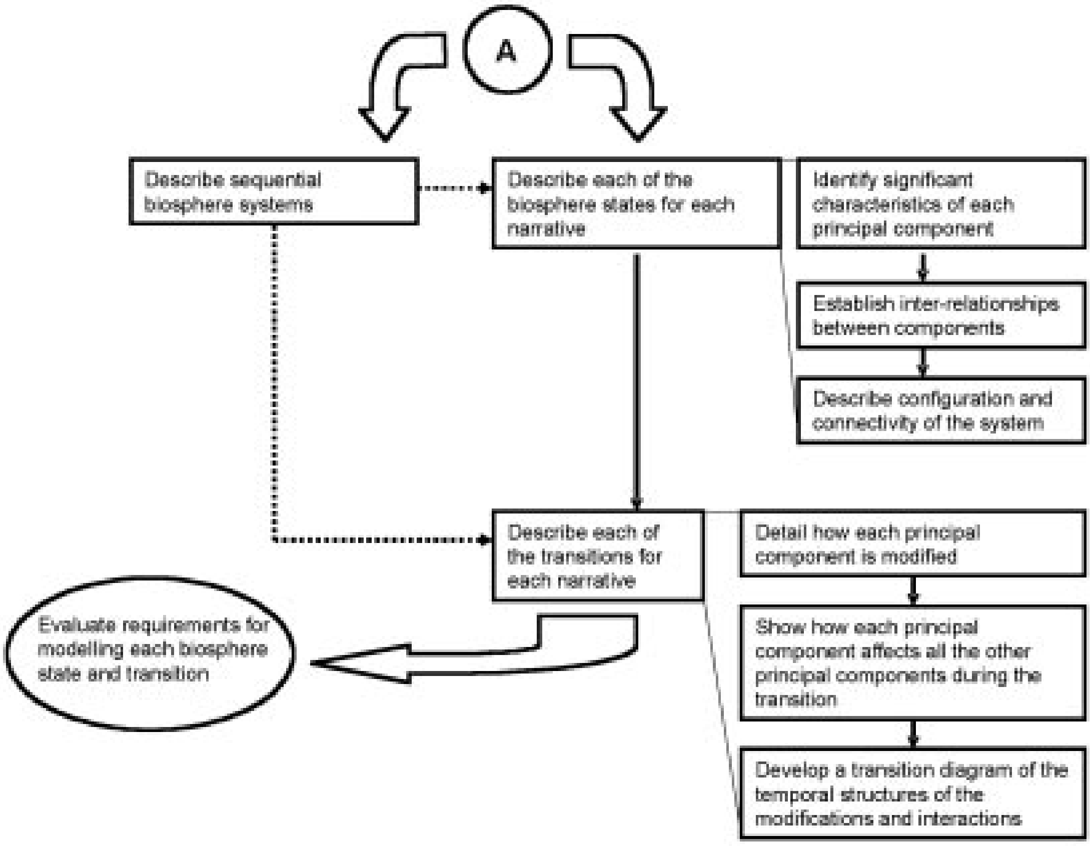


Figure 3.1b: *Later Stages of the Route Map for Including the Effects of Climate Change in the Representation of Biosphere Systems and Transitions for Performance Assessment*

In this figure, the BIOMASS steps are shown on the left and the expansion of those steps identified in BIOCLIM for addressing climate change and associated environmental evolution are shown on the right. Relationships between the two components are shown by dotted arrows and procedural flows are shown by either block or solid arrows. The main difference in the latter part of the procedure from the original BIOMASS methodology (Figure A.1) is that no decision is made on whether the biosphere system should be modelled in sequential or non-sequential fashion until the biosphere states and transitions between them that are of potential interest in PA have been identified and characterized. It is considered that it would be premature to decide between the sequential and non-sequential approaches before the biosphere states and transitions had been characterized and evaluated as to their potential significance in PA.

3.2. - Selection and Manipulation of Climate Data for use in Performance Assessments

In principle, both modelling studies and meteorological data from analogue stations can provide a wide variety of types of climatic data at different temporal scales. However, for the purposes of biosphere modelling in PA, it is generally adequate to use time-averaged data for temperature and precipitation. On the basis of such data, key factors such as the length of the growing season, water availability, irrigation requirements and potential for frozen ground effects can be evaluated. Use of more detailed climatological data would imply an undue degree of confidence in the modelling approaches adopted. In particular, it is emphasized that PA calculations should be robust under uncertainties in future climatic characteristics and that this requirement militates against reliance on very detailed climatic data.

In this context, it is relevant to note that the climatic data that are readily available from the analogue stations of interest are monthly values of temperature and precipitation. Furthermore, mean monthly values of temperature and precipitation are the variables that are conventionally used to assign locations to specific bioclimatic zones, as in the case of the Køppen-Trewartha classification scheme (see also Section 3.4 and Appendix B).

In view of these considerations, it was agreed within BIOCLIM that monthly values of temperature and precipitation should be the principal climatological variables carried forward for assessment purposes. Thus, it is projected future time-series of these variables that are used to develop the narratives of future environmental evolution described in Section 5 and presented in detail in Appendix C. Consideration was given to other variables such as snowpack thickness and windspeed. However, it was considered that these are of secondary interest for PA purposes and are less robustly estimated than temperature and precipitation.

In practice, the nature and parameterization of PA biosphere calculations are often strongly determined not only by the primary climatological variables of temperature and precipitation, but also by derived variables that relate more directly to the surface and near-surface hydrology of the environment of interest. In particular, seasonal variability in water availability determines factors such as the depth of the phreatic surface and flow rates in streams and rivers. It also determines quantities such as soil moisture deficit and associated requirements for irrigation. In view of these considerations it seemed appropriate to identify an acceptable, standardised procedure that could be used to relate values of temperature and precipitation to relevant hydrological variables. Two approaches were used. One was an empirical relationship that allowed potential evapotranspiration to be computed on a month-by-month basis and compared with precipitation. The second was an empirical relationship that allowed irrigation requirements to be estimated directly from climatological variables without the intermediate step of computing soil moisture deficit. In the following subsections, these two approaches are described in detail and compared.

3.2.1 - Estimation of Potential Evapotranspiration and Water Balance

An approach was required that would be robust across a wide range of climatic conditions. As determined in BIOMASS (2003), this is satisfied by the technique originated by Thornthwaite (1948) and detailed by Shaw (1983). In this approach, potential evapotranspiration (PE, units mm) is calculated using:

$$PE_m = 16N_m(10T_m/I)^a$$

Where the subscript m denotes month

T_m (°C) is mean monthly temperature

$I = \Sigma\, i_m$

$i_m = (T_m/5)^{1.5}$

$a = 6.7\ 10^{-7}I^3 - 7.7\ 10^{-5}I^2 + 1.8\ 10^{-2}I + 0.49$

N_m = monthly adjustment factor, related to hours of daylight.

The adjustment was made of only calculating i_m for months in which $T_m>0$ and setting PE_m to zero for months in which $T_m \leq 0$.

Although this is only an approximate approach and neglects distinctions between actual and potential evapotranspiration, it can be used together with precipitation to give an indication of monthly, seasonal and annual water balances.

For Central England, values of N_m for Keele, UK (Shaw, 1983.) were used. These values, by month, are 0.68, 0.82, 0.98, 1.15, 1.31, 1.39, 1.36, 1.23, 1.06, 0.88, 0.72, 0.63. For the other regions of interest, values of N_m were selected appropriate to the latitude of the region of interest.

For each month the calculated potential evapotranspiration was subtracted from the precipitation to give a measure of moisture excess. Negative values of moisture excess correspond to a moisture deficit. However, whereas the moisture excess values are considered realistic, the calculated moisture deficit values will generally be over estimates, as actual evapotranspiration is generally less than potential evapotranspiration when surface soils are unsaturated.

Detailed data for values of moisture excess and deficit are given for the various regions of interest in Appendix C.

It should be noted that the results presented in Appendix C are calculated using data for mean monthly temperature and precipitation values averaged over the thirty years from 1961 to 1990 in the analogue station record. Use of such long-term averages is adequate for many purposes. However, it neglects inter-annual variability. This can be of importance in some contexts, e.g. the determination of irrigation requirements. The issue of inter-annual variability is discussed further in subsection 3.2.4.

3.2.2 - Direct Estimation of Irrigation Requirements

A direct approach to the estimation of irrigation requirements was available from Germany (A Becker, personal communication) and was used in BIOCLIM. The basis of the estimate is:

$$Q_{irr} = K_m T - P$$

where
Q_{irr} is the monthly irrigation requirement in mm;
T is the mean monthly temperature in °C;
P is the monthly precipitation in mm.

K_m is a coefficient that depends both on the mean monthly temperature and the month:

$T<5°C$: $K_m = 0$
$T\geq5°C$: $K_m = 2$ (October to March), 3 (April and September), 4 (August), 5 (May and July), 6 (June)

3.2.3 - Comparison of the Direct Estimate of Irrigation Requirements with Moisture Deficit

Irrigation is generally used to restore soil moisture deficit during the growing season. However, except for the most valuable crops, irrigation does not begin until a soil moisture deficit of 50 mm or more has been established. Furthermore, irrigation is often used to reduce the soil moisture deficit by some degree, rather than restoring the soil to field capacity. Furthermore, it will be recalled that the method set out in subsection 3.2.1 is expected to overestimate soil moisture deficit to some degree.

To compare the two methods, the total soil moisture deficit in the four months of May to August (here termed summer) was compared with the annual irrigation requirement calculated directly for a large number of climate analogue stations appropriate to a wide range of climatic conditions (FT, EC, EO, DC, DO, Cr and Cs in the Køppen-Trewartha classification). Results of this comparison are shown in Figure 3.2.

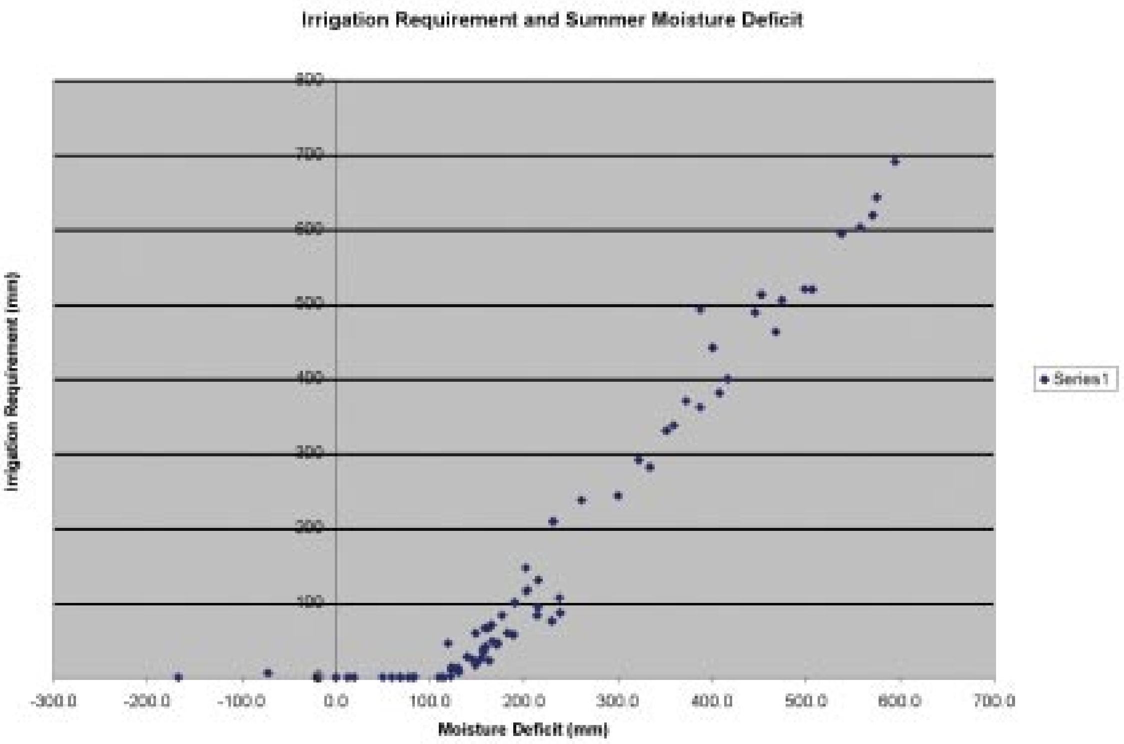


Figure 3.2: *Relationship between Irrigation Requirement and Summer Moisture Deficit*

As expected, there is no irrigation requirement until the overall summer moisture deficit exceeds about 100 mm. At moisture deficits of 100 to 300 mm, the soil is restored to a soil moisture deficit of about 100 mm. At larger soil moisture deficits, there seems to be an indication of restoration of the soil to field capacity. However, this may be a consequence of the empirical formulae being used beyond the limits of their applicable ranges. Overall, it seems reasonable to use the approach set out in subsection 3.2.1 to calculate the summer soil moisture deficit and to assume that all but 100 mm of this deficit is restored by irrigation in circumstances where irrigation is consistent with the agricultural practice. Where high value crops, e.g. salad vegetables and soft fruits, are being cultivated, it may be more appropriate to assume restoration to field capacity rather than a deficit of 100 mm.

3.2.4 - Effects of Inter-annual Variability

In practice, irrigation requirements are determined on a year-by-year basis. Therefore, inter-annual variability is an important consideration. Conveniently, in BIOCLIM, access was available to annual climatic data for selected climate analogue stations, as well as long-term mean values. Thus, the potential significance of inter-annual variability could be evaluated. This is illustrated in Figure 3.3, which shows summer moisture deficits for Goeteborg (DC), Birmingham (DO), Bordeaux (Cr) and Perpignan (Cs) over the period 1951 to 1988, a period for which complete records exist for all these stations.

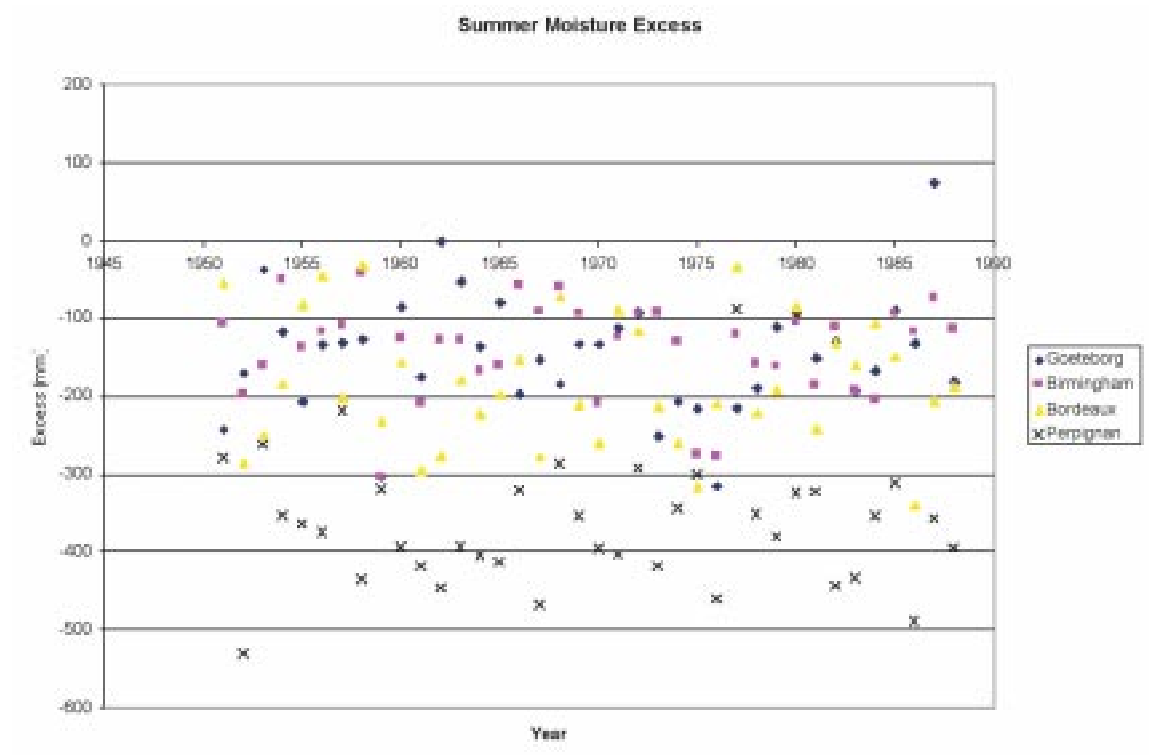


Figure 3.3: *Summer (May, June, July, August) Moisture Excess at Four Analogue Stations over the Period 1951 to 1988*

For the cooler stations (Goeteborg, Birmingham and Bordeaux) irrigation is required in some, but not all, years. In contrast, at Perpignan, irrigation is required in almost every year. In the context of PA, the intensity and frequency of irrigation are likely to exert significant, and possibly non-linear, effects on radionuclide concentrations in both soils and crops.

3.3. - The BIOCLIM Scenarios

As discussed in Section 3.1, WP2 and WP3 were dedicated to the numerical modelling of potential future climate states and transitions. Two different and complementary strategies were developed: a hierarchical strategy (WP2) and an integrated strategy (WP3). The hierarchical strategy used global general circulation models (GCMs) and regional models to produce snapshots of specific future climate states. The integrated strategy used EMICs, simplified versions of global circulation models that require less computing time and are therefore able to simulate not only snapshots but the climate evolution for scenarios of past and/or future forcing. An EMIC was also used in WP2 to identify the situations for which snapshot simulations should be undertaken. The models used in WP2 and WP3, irrespective of their degree of complexity, are all based on fluid dynamic equations. All the models aim to calculate the exchange of energy and momentum, as well as the conservation of mass and water vapour, between the different components of the climate system (atmosphere, ocean, biosphere and cryosphere). They use different spatial resolutions, ranging from 5° wide latitudinal bands (EMICs), to 400 km grid cells (GCMs), down to

50 km grid cells (regional models). Whereas EMICs provide the global general tendency of potential long-term climate change, GCMs simulate the particular climatic patterns of some future climate states over Europe, and regional models illustrate in more detail how these climatic patterns are expressed at the scale of the BIOCLIM regions of interest.

Models used in WP2 were LLN 2D NH (an EMIC), the general circulation model IPSL_CM4_D, the dynamical global vegetation model ORCHIDEE, the regional model MAR (Modèle d'Atmosphère Regional). The models used in WP3 were MoBidiC and CLIMBER-GREMLINS (EMICs). The ORCHIDEE vegetation model was also used in WP3. Statistical and rule-based downscaling methods were used both in WP2 and in WP3. Detailed descriptions of these models are provided in:

- BIOCLIM (2001b) for LLN 2D NH;
- BIOCLIM (2003a) for IPSL_CM4_D and ORCHIDEE;
- BIOCLIM (2003b) for MAR;
- BIOCLIM (2003c) for MoBidiC and CLIMBER-GREMLINS; and
- BIOCLIM (2003d; 2003e) for downscaling methods.

In WP2 as in WP3, the models were used in the sequence shown in Figure 3.4.

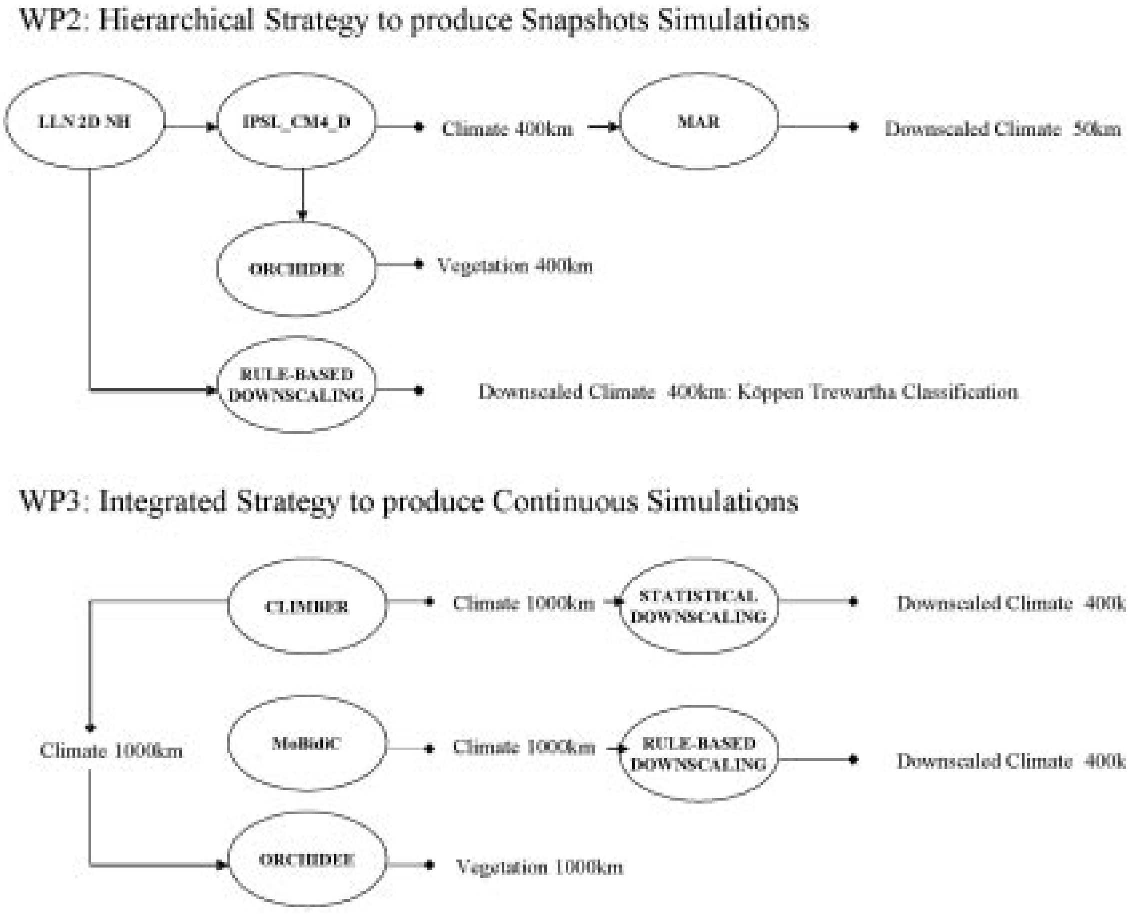


Figure 3.4: *Sequence of Model Applications in BIOCLIM*

In WP2, IPSL_CM4_D simulated the climatic patterns of a small number of future climate states selected on the basis of examination of results from a set of one million year long simulations undertaken with LLN 2D NH. IPSL_CM4_D results were produced for a period of thirty years for each situation, so inter-annual climatic variability could be characterised as well as mean climate characteristics. The IPSL_CM4_D outputs were provided to the MAR model. MAR was used to downscale the IPSL_CM4_D atmospheric patterns to a 50km spatial scale. However, only a single year was simulated for each situation, so information on inter-annual variability was not generated. The global distributions of biomes in equilibrium with the IPSL_CM4_D atmospheric patterns were simulated using the ORCHIDEE vegetation model. In addition, a rule-based downscaling technique was applied in order to identify the sequence of potential future climate states implied in the LLN 2D NH calculations, as characterized using the Køppen-Trewartha classification.

In WP3, the two EMICs MoBidiC and CLIMBER-GREMLINS simulated a set of scenarios for future long-term global climate evolution over the next 2 10^5 years. Their outputs were downscaled at a 400km spatial scale, using either statistical or rule-based downscaling methods. In addition, the global climate tendencies simulated by CLIMBER-GREMLINS were provided to ORCHIDEE, for the latter to simulate the long-term evolution of the global vegetation.

The future discrete climate states and the climate sequences to focus on were all selected from an initial set of long-term simulations done, at the start of WP2, with the LLN 2D NH EMIC. These simulations were forced with different scenarios for combined natural and anthropogenic greenhouse-gas concentrations in the atmosphere, as discussed in Section 3.1. On the basis of these simulations, six situations were selected for detailed study within WP2 and were simulated using the following boundary conditions:

- A: Orbital parameters as at the present day, but with an atmospheric CO_2 concentration of 1100 ppmv;
- B: Orbital parameters as at the present day, but with an atmospheric CO_2 concentration of 550 ppmv and no Greenland ice sheet present;
- C: Orbital parameters for 67 ka After Present (AP), with an atmospheric CO_2 concentration of 345 ppmv and the Greenland ice sheet at its current size;
- D: Orbital parameters for 67 ka AP, with an atmospheric CO_2 concentration of 345 ppmv and no Greenland ice sheet present;
- E: Orbital parameters for 67 ka AP, with an atmospheric CO_2 concentration of 550 ppmv and no Greenland ice sheet present;
- F: Orbital parameters for 178 ka AP, with an atmospheric CO_2 concentration of 280 ppmv and a moderately extensive glacial episode (northern hemisphere ice volume of 1.74 10^7 km^3 compared with the present day value of 3.2 10^6 km^3).

A baseline simulation of the present-day climate completed this set. Situation A can be considered as applicable to the very near future (the next few hundred years) characterised by very high concentration of atmospheric CO_2. Situation B may result from the relatively short term evolution of situation A: as a consequence of the CO_2-induced warming, the northern hemisphere ice has melted, while the CO_2 concentration has decreased down to somewhat above its present-day value. Situations C to E relate to alternative possibilities at 67ky AP, when various atmospheric CO_2 concentrations and northern hemisphere (Greenland) ice volumes may coincide with a relative peak in June insolation at 65°N. The impacts of two different atmospheric CO_2 concentration values are tested, as well as the presence or absence of a Greenland ice sheet. Finally, Situation F represents the potential next major glacial event, at 178ky AP, characterised by an atmospheric CO_2 concentration that is the same as its pre-industrial value and by a northern hemisphere ice volume increased to up to five times its present-day value and implying nucleation of both the Fennoscandian and Laurentide ice sheets.

3.4. - Climatic Implications of the BIOCLIM Scenarios at the Global, Regional and Local Scales

Figure 3.5 outlines the sequence of model applications used in BIOCLIM. The EMICs used in BIOCLIM have a coarse spatial resolution compared with the BIOCLIM study regions and the needs of performance assessment. Each grid box in the CLIMBER2.3 climate model is 51° longitude by 10° latitude, although the GREMLINS ice-sheet model to which it is coupled has a resolution of 45 km by 45 km. LLN 2D NH and MoBidiC have a resolution of 5° latitude, with each latitude band divided into up to seven and 13 sectors respectively. Thus there is a need for downscaling, which can be defined as 'sensibly projecting the large-scale information on the regional scale' (von Storch et al., 1993).

Most of the developmental work on downscaling methodologies undertaken by the international research community has focused on downscaling from the general circulation model (GCM) scale (with a typical spatial resolution of 400 km by 400 km over Europe in the current generation of models) using dynamical downscaling (i.e., regional climate models (RCMs), which typically have a spatial resolution of 50 km by 50 km for models whose domain covers the European region). Downscaling using statistical methods (which can provide information at the point or station scale) has also been investigated in order to construct scenarios of anthropogenic climate change up to 2100 (Hewitson and Crane, 1996; Schubert and Henderson-Sellers, 1997; Wilby and Wigley, 1997; Wilby et al., 1998, Zorita and von Storch, 1999; Giorgi et al., 2001). Dynamical downscaling (with the MAR RCM) is used in BIOCLIM to downscale from the GCM (i.e., IPSL_CM4_D) scale. However, in the context of BIOCLIM, the IPSL_CM4_D GCM can itself be considered as a dynamical downscaling model as the snapshot simulations are performed using boundary conditions prescribed from the LLN 2D NH simulations.

Two different approaches to downscaling from EMICs have been developed in WP3 specifically for BIOCLIM. CLIMBER-GREMLINS is essentially a grid-box model, although the grid boxes are very large. Hence a statistical method using physically-based predictors (continentality and topography) has been developed. The sectorally-averaged nature of MoBidiC means that conventional downscaling methods cannot be applied. Hence a rule-based downscaling methodology has been developed. This assigns climate states or classes to a point on the time continuum of a region according to a combination of simple threshold values which can be determined from the EMIC. The use of climate classes and states makes this methodology particularly appropriate for use with the BIOMASS methodology (see Section 4). It has also been possible to apply this rule-based downscaling methodology to LLN 2D NH output derived from WP2.

The four downscaling methods that have been used to construct the BIOCLIM climate scenarios are summarised in Table 3.1.

Method	**Summary of method**	**Input variables**	**Output variables**
Dynamical downscaling with IPSL_CM4_D Described in detail in BIOCLIM (2003a).	Global coupled ocean-atmosphere model. The atmospheric model has a grid-box resolution of 4° latitude by 5° longitude (about 400 km x 400 km over Europe).	Global mean CO_2 concentration, orbital forcing, orography and the fraction of land covered by ice sheets can be prescribed by the user.	For BIOCLIM, the following gridded variables were archived at the monthly time scale for the BIOCLIM study regions: 2m temperature, precipitation, snow fall and wind strength.
Dynamical downscaling with MAR Described in detail in BIOCLIM (2003b).	Regional climate model with a 4200 x 3400 km domain centred on Western Europe and a grid-box resolution of 50 km x 50 km.	Boundary conditions are taken from the IPSL_CM4_D simulations.	For BIOCLIM, the following gridded variables were archived at the monthly time scale for the BIOCLIM study regions: 2m temperature, precipitation, snow fall and wind speed
Statistical downscaling applied to CLIMBER-GREMLINS output Described in detail in BIOCLIM (2003e).	Generalized Additive Model, i.e., a regression model. A number of the predictors are expressed as smooth (spline) functions in order to allow non-linearity without overfitting.	Observed gridded 10' climatology from the Climatic Research Unit. Predictors: advective and diffusive continentality; mountain masking, lapse-rate and upslope effects; surface height and subgrid standard deviation in height; sea level pressure and large-scale temperature and precipitation fields - defined using EMIC output.	For BIOCLIM, the following gridded variables were archived at the monthly time scale for the BIOCLIM study regions: 2m temperature, precipitation, snow fall and wind speed
Rule-based downscaling applied to MoBidiC and LLN NH 2D output Described in detail in BIOCLIM (2003d).	Climate classes are assigned to a point on the time continuum of a region according to a combination of simple threshold values determined from EMIC output.	Latitundal sector averages (50-55° for Central England and Northeast France and 35-45°N for Central Spain) of mean annual oceanic/continental temperature and Northern Hemisphere ice volume.	Køppen-Trewartha climate class (at the two letter level) for Central England, Northeast France and Central Spain. Monthly temperature and precipitation are described using analogue stations identified from a data base of present-day climate observations.

Table 3.1: *Summary of the Four BIOCLIM Downscaling Methodologies.*

Recent work on the construction of scenarios of greenhouse gas-induced warming over the 21st century reflects the growing recognition of the need to take into account the full range of uncertainties in scenario construction and, at the same time, to distinguish between climate model deficiencies and the inherent unpredictability of climate (Hulme and Brown, 1998; Hulme and Carter, 1999; Hulme et al., 1999; Katz, 1999; Mitchell and Hulme, 1999; Giorgi and Francisco, 2000a,b; Jones, 2000a,b; New and Hulme, 2000; Visser et al., 2000; Räisänen and Palmer, 2001). The IPCC Third Assessment Report (TAR) (Houghton et al., 2001) and many of the references cited above, refer to a cascade of uncertainty related to:

- the emissions or radiative forcing scenarios, i.e., inter-scenario variability;
- the use of different climate models, i.e., inter-model variability;
- different realizations under a given emissions scenario with a given climate model, i.e., internal model variability (which is, in part, a reflection of natural climate variability); and,
- sub-grid scale forcings and processes.

Appropriate techniques for handling the first three sources of uncertainty are widely recognised (see references above, also Andronova and Schlesinger, 2001; Wigley and Raper, 2001; Katz, 2002; Stott and Kettleborough, 2002), although they are not yet routinely or comprehensively applied in impacts assessments:

- uncertainties due to inter-scenario variability can be handled by using more than one emissions scenario;
- uncertainties due to inter-model variability can be handled by using output from more than one climate model; and,
- uncertainties due to internal model variability and thus, in part, natural variability, can be handled by using ensembles of simulations with each model (i.e., simulations performed with the same climate models and forcing, but starting from different initial conditions).

Comparative studies of the first three sources of uncertainty (the fourth has been less-widely addressed) indicate that, for mean climate, inter-model variability tends to be greater than inter-scenario or internal model variability, particularly over the earlier part of the 21st century (Dutton and Barron, 2000; Giorgi and Francisco, 2000a,b; Bergstrom et al., 2001).

Although the above approaches have been developed for the construction of scenarios of greenhouse gas-induced warming over the 21st century based on GCM and RCM output, the principles are equally relevant to the construction of the BIOCLIM climate scenarios.

Two anthropogenic CO_2 scenarios - the 'high' B4 scenario, which peaks at 1600 ppmv, and the 'low' A4 scenario, which peaks at 1100 ppmv, were constructed for BIOCLIM (2001b). These emissions scenarios are broadly consistent with current estimates of economic resources and with the IPCC TAR (Houghton et al., 2001). However, they are based on a single instantaneous response function (Archer et al., 1997). Two methods were initially proposed for the construction of natural CO_2 scenarios: a regression model and a threshold model. Based on the two anthropogenic and two natural CO_2 scenarios, together with two constant CO_2 scenarios (210 and 280 ppmv) and two different methods of combining the natural and anthropogenic emissions, 15 possible emissions scenarios were identified for the WP2 LLN 2D NH simulations (see Table 1, BIOCLIM, 2001b). However, due to time and computing restraints, it was only practical to run nine scenarios for the next one million years. One of these scenarios, B3 (i.e., the 'low' anthropogenic scenario combined with a natural scenario) was used to define the six snapshot situations for the WP2 GCM/RCM simulations, whereas two anthropogenic plus natural scenarios (B3 and B4) and one natural (A4) scenario were used for the WP3 EMIC simulations (see Section 3.1 for a summary of these situations/scenarios).

In contrast to the two anthropogenic scenarios studied in detail in BIOCLIM, the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000) identifies 40 emissions scenarios for the period up to 2100, all of which are considered equally plausible. Thirty-five of these scenarios have sufficient data to drive climate models and were used in the IPCC TAR (Houghton et al., 2001). The TAR concluded that globally averaged surface temperature is projected to increase by 1.4 to 5.8°C over the period 1990 to 2100 (based on the full range of 35 SRES scenarios and output from a number of GCMs and a simple climate model (SCM)). Since publication of the TAR, attempts have been made to explore this warming range in probabilistic terms. Wigley and Raper (2001) use the SCM from the TAR to explore uncertainties in emissions, climate sensitivity, the carbon cycle, ocean mixing and aerosol forcing. They concluded that, in the absence of climate mitigation policies, the 90% probability interval for 1990 to 2100 warming is 1.7°C to 4.9°C, i.e., towards the centre of the IPCC TAR range. The median is 3°C, with a 0.6% probability of warming exceeding 5.8°C, i.e., the upper end of the IPCC TAR range. More recently, Andronova and Schlesinger (2001) used another simple climate/ocean model, the observed temperature record and a bootstrapping technique to estimate the probability distribution of climate sensitivity (i.e., the warming in response to a doubling of the CO_2 concentration). Uncertainties in radiative forcing models were also considered, together with natural variability. In this case, it was concluded that the 90% probability interval for 1990 to 2100 warming is 1.9°C to 6.02°C, i.e., shifted towards the upper end of the IPCC range.

With respect to inter-model uncertainty, the only direct and internally-consistent comparisons that can be made in BIOCLIM are between the global MoBidiC and CLIMBER-GREMLINS simulations carried out in WP3, because these use exactly the same emissions scenarios (B3, B4 and A4). Thus, output from these models is presented side-by-side in BIOCLIM (2003c) and can be considered as an inter-model ensemble. Differences between the two models are highlighted in BIOCLIM (2003c) (in the case of the B3 scenario, for example, the Greenland ice sheet melts more slowly in CLIMBER-GREMLINS – about 40,000 years – than in MoBidiC – a few thousand years) and are taken into account in developing the regional narratives (see Section 5 and Appendix C). The LLN 2D NH WP2 simulations could also be considered part of this inter-model ensemble, although only the Northern Hemisphere is modelled. It should be noted, however, that the structure and parameterisation of the BIOCLIM EMICs are likely to have less in common than different GCMs or RCMs developed by different modelling centres.

Although they are based on the same six situations, the IPSL_CM4_D and MAR WP2 simulations can not really be considered as inter-model ensembles because of their different spatial scales and domains and because MAR is forced with boundary conditions taken from IPSL_CM4_D rather than LLN 2D NH.

The various emissions and forcing scenarios used in BIOCLIM have only been run once for each model. Thus no account is taken of internal model variability and hence, natural variability.

The fourth source of uncertainty identified above, sub-grid-scale forcings and processes, has not yet been adequately addressed in the literature with respect to the construction of scenarios of greenhouse gas-induced warming over the 21st century, but could be explored using statistical and dynamical downscaling (Goodess et al., 2003). In the BIOCLIM context, this means inter-comparing results from the four downscaling methods employed here (Table 3.1).

First, however, it must be stressed that the performance of any downscaling method is limited by the reliability of the larger-scale model providing the boundary conditions or predictors:
- LLN 2D NH in the case of IPSL_CM4_D;
- IPSL_CM4_D in the case of MAR;
- CLIMBER-GREMLINS in the case of the WP3 statistical downscaling method; and
- MoBidiC and LLN 2D NH in the case of the rule-based downscaling method.

Although this is a common disadvantage of all BIOCLIM downscaling methods, each of the four methods has specific advantages and disadvantages inherent to the approach taken which are summarised in Table 3.2.

Dynamical downscaling with IPSL_CM4_D

+ Provides physically and internally consistent multi-variate empirical information
+ Wide experience of GCM use, e.g., palaeoclimate and greenhouse warming simulations

- Spatial-scale problems arise, i.e. grid box rather than point values
- Grid-box values may not be reliably simulated
- Spatial scale is relatively coarse (400 x 400 km)
- Computationally expensive

Dynamical downscaling with MAR

+ Provides physically and internally-consistent multi-variate empirical information
+ Higher spatial resolution than GCM (50 km x 50 km)

- Spatial-scale problems may still arise, i.e. grid box rather than point values
- Grid-box values may not be reliably simulated
- Computationally expensive
- Relatively short (one year) runs

Statistical downscaling applied to CLIMBER-GREMLINS output

+ Provides high-resolution (10’) information
+ Predictors reflect underlying physical mechanisms and processes

- Assumes that predictor/predictand relationships will be unchanged in the future (the stationarity issue)
- Dependent on the reliability of the gridded climatology

? Sensitive to specific methodology, choice of predictor variables, etc.
? Less computationally demanding than dynamical downscaling, but more demanding than rule-based downscaling

Rule-based downscaling applied to MoBidiC and LLN NH 2D output

+ Computationally undemanding
+ Use of climate states/classes is consistent with BIOMASS methodology

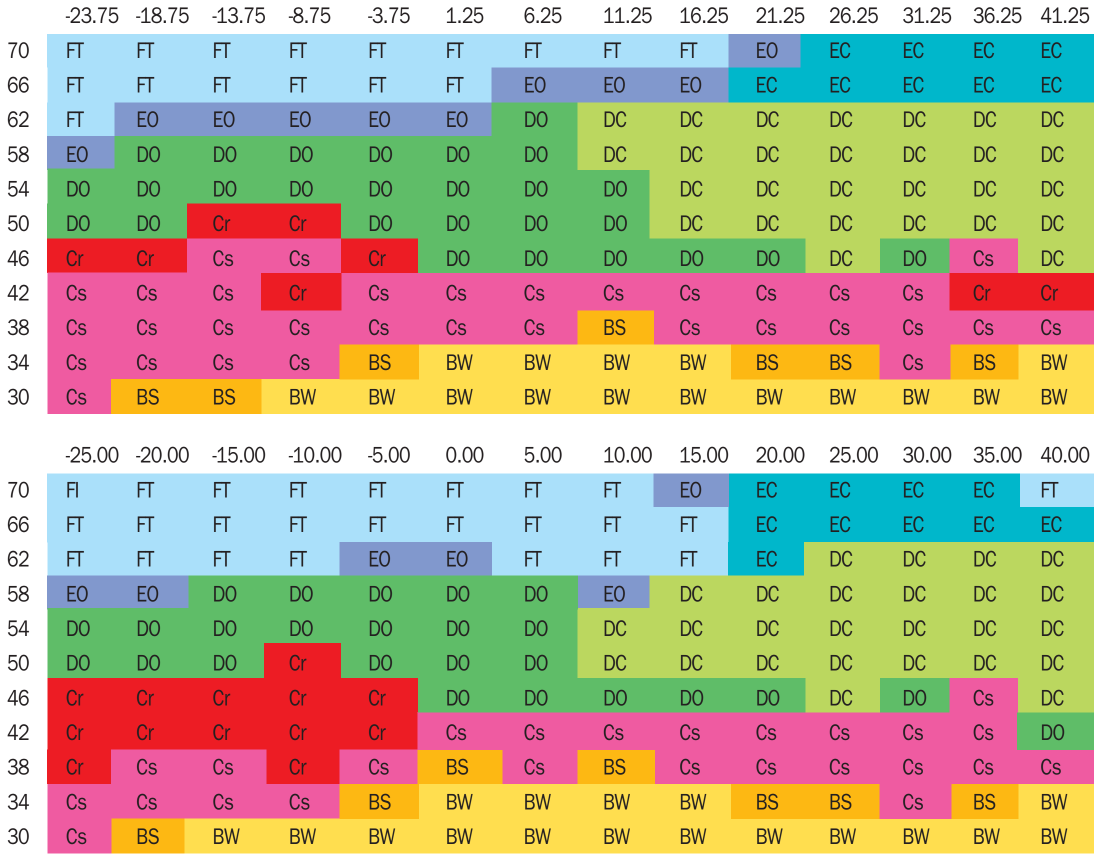
- Assumes that the rules and thresholds identified for the last climate cycle are applicable to the future (the stationarity issue)
- Identification of appropriate rules/thresholds and analogue stations involves subjective judgement
- Independent validation is difficult

? Does not involve large volumes of input/output data

Table 3.2: *Summary of the General Advantages (+) and Disadvantages (-) Inherent to Each of the BIOCLIM Downscaling Methodologies. (?) indicates that the advantage or disadvantage is uncertain.*

Køppen-Trewartha climate classes (see Appendix B) represent a lowest common denominator by which all BIOCLIM downscaling methods may be compared. From WP2, long-term continuous output for LLN 2D NH is available, and from WP3 for MoBidiC (and also from CLIMBER-GREMLINS). It was originally proposed to apply rule-based downscaling only in WP3. However, towards the end of the BIOCLIM project, it was agreed that the ruled-based downscaling method would also be applied to LLN 2D NH results from WP2. There are several reasons for this. First, it is straightforward to do and provides added value to the project. Second, it allows a comparison to be made on the degree to which results from rule-based downscaling are influenced by the nature of, and quantitative results from, the long-term climate model that is used. Effectively, this replaces the comparison that might have been made by comparing rule-based downscaled results from MoBidiC and CLIMBER-GREMLINS. A further consideration is whether the global MoBidiC model provides a better representation of past climate than does the LLN 2D NH model of the Northern Hemisphere – an issue that was not explicitly explored in WP3.

When the snapshot simulations from WP2 are considered, results from IPSL_CM4_D are available at the 400 km scale. These results can be expressed in terms of climatological variables, notably values of mean monthly temperature and precipitation. Using this information, not only can a two-letter Køppen-Trewartha climate class be assigned to grid squares (see examples in Figure 3.6) or area-averages associated with the regions of interest, it can also be used to determine where each grid square or area-average lies within that climate class, i.e., with respect to the third and fourth letters of the classification (see below) and hence potentially to investigate consistency with the criteria used in selecting analogue stations for the rule-based downscaling. Furthermore, the snapshots used in WP2, e.g. at 67 ka AP, include not only a ‘best’ representation of the scenario, but also variants (different CO_2 concentrations; presence or absence of a Greenland ice sheet). The degree of difference between the reference case and variants can therefore be examined both in terms of changes to climatological variables (BIOCLIM, 2003a) and in terms of changes to the implied climate class (see below). Climate classes can in turn be compared with those identified for the snapshot times from application of rule-based downscaling to outputs of LLN 2D NH and MoBidiC (see below).



	-23.75	-18.75	-13.75	-8.75	-3.75	1.25	6.25	11.25	16.25	21.25	26.25	31.25	36.25	41.25
70	FT	FT	FT	FT	FT	FT	FT	FT	FT	EO	EC	EC	EC	EC
66	FT	FT	FT	FT	FT	FT	EO	EO	EO	EC	EC	EC	EC	EC
62	FT	EO	EO	EO	EO	EO	DO	DC	DC	DC	DC	DC	DC	DC
58	EO	DO	DO	DO	DO	DO	DO	DC	DC	DC	DC	DC	DC	DC
54	DO	DO	DO	DO	DO	DO	DO	DO	DC	DC	DC	DC	DC	DC
50	DO	DO	Cr	Cr	DO	DO	DO	DO	DC	DC	DC	DC	DC	DC
46	Cr	Cr	Cs	Cs	Cr	DO	DO	DO	DO	DO	DC	DO	Cs	DC
42	Cs	Cs	Cs	Cr	Cs	Cs	Cs	Cs	Cs	Cs	Cs	Cs	Cr	Cr
38	Cs	Cs	Cs	Cs	Cs	Cs	Cs	BS	Cs	Cs	Cs	Cs	Cs	Cs
34	Cs	Cs	Cs	Cs	BS	BW	BW	BW	BW	BS	BS	Cs	BS	BW
30	Cs	BS	BS	BW	BW	BW	BW	BW	BW	BW	BW	BW	BW	BW

	-25.00	-20.00	-15.00	-10.00	-5.00	0.00	5.00	10.00	15.00	20.00	25.00	30.00	35.00	40.00
70	FI	FT	FT	FT	FT	FT	FT	FT	EO	EC	EC	EC	EC	FT
66	FT	FT	FT	FT	FT	FT	FT	FT	FT	EC	EC	EC	EC	EC
62	FT	FT	FT	FT	EO	EO	FT	FT	FT	EC	DC	DC	DC	DC
58	EO	EO	DO	DO	DO	DO	DO	EO	DC	DC	DC	DC	DC	DC
54	DO	DO	DO	DO	DO	DO	DO	DC	DC	DC	DC	DC	DC	DC
50	DO	DO	DO	Cr	DO	DO	DO	DC	DC	DC	DC	DC	DC	DC
46	Cr	Cr	Cr	Cr	Cr	DO	DO	DO	DO	DO	DC	DO	Cs	DC
42	Cr	Cr	Cr	Cr	Cr	Cs	Cs	Cs	Cs	Cs	Cs	Cs	Cs	DO
38	Cr	Cs	Cs	Cr	Cs	BS	Cs	BS	Cs	Cs	Cs	Cs	Cs	Cs
34	Cs	Cs	Cs	Cs	BS	BW	BW	BW	BW	BS	BS	Cs	BS	BW
30	Cs	BS	BW	BW	BW	BW	BW	BW	BW	BW	BW	BW	BW	BW

Figure 3.6: *Køppen-Trewartha two-letter classification (see Appendix B) applied to IPSL_CM4_D grid square temperature and precipitation output for the control simulation (upper panel) and simulation F (lower panel) which represents a moderately extensive glacial episode at 178 ka AP (see Section 3.3 for a summary of these scenarios). Results are shown for a European window extending from 30 to 70N and from 23.75W to 41.25E for the control simulation and from 25W to 40E for simulation F.*

Four-letter classifications for the control and six snapshot simulations (see Section 3.3) calculated using area-averaged IPSL_CM4_D and MAR mean monthly temperature and total precipitation are shown in Table 3.3 for the BIOCLIM study regions. It should be noted that these regions are defined slightly differently in IPSL_CM4_D (see Figure 1 of BIOCLIM, 2003a) and MAR (see Figure 2 of BIOCLIM, 2003b) output. In the case of the IPSL_CM4_D control-run results for Central England (Table 3.3a), the assigned climate class, DOlk, is consistent with the set of analogue stations selected for this class/region (BIOCLIM, 2003d). This is reflected in the close agreement between mean monthly temperatures for these stations and the Central England region in IPSL_CM4_D (Figure 3.7). The control-run classifications are also broadly consistent with the present-day analogue stations selected for Northeast France and Central Spain (not shown).

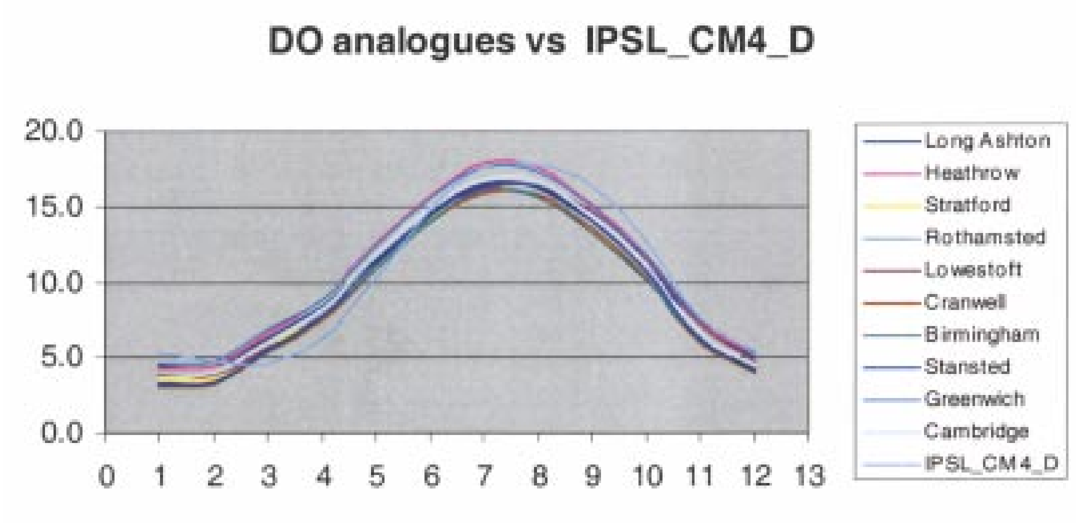


Figure 3.7: *Comparison of Mean Monthly DO Analogue Station Temperatures for Central England with IPSL_CM4_D Results.*

The main feature of the IPSL_CM4_D-based classifications for 67 ka AP and 178 ka AP is the very small differences in climate class (Table 3.3a). Only two climate classes occur for Central England: DOlk and DObk. Northeast France is classified as DOak, i.e., the same as the control run, in four out of the six snapshot simulations, whereas Central Spain oscillates between Csal, Cshl and Cshk conditions. With the exception of the A - high CO_2 - scenario for North-east France, the classification at the two-letter level does not change from that of the present-day in any region, emphasising the relative insensitivity of IPSL_CM4_D despite fairly major differences in forcing. Thus, the presence or absence of the Greenland ice sheet, for example, appears to make relatively little difference. However, it should be noted that the method of interpolating ice sheet volume between the LLN 2D NH model simulations used to define the boundary conditions for the snapshot simulations and IPSL_CM4_D means that the IPSL_CM4_D ice volume is 66% of the LLN 2D NH model value in the control simulation and only 58% in simulation F (see Section 4.1 of BIOCLIM 2003a). In particular, the volume of the Eurasian ice sheet is underestimated in IPSL_CM4_D compared to LLN 2D NH.

Comparison with the classifications based on MAR output (Table 3.3b) is complicated by two factors. First, MAR has a cold bias (BIOCLIM, 2003b) – thus Central England and North-east France are classified as DC in the MAR control simulation rather than DO, and Central Spain as DO in the MAR control simulation rather than Cs. Second, MAR results are for a single year, whereas the IPSL_CM4_D results in Table 3.3a are derived from a 30-year average. Ideally, IPSL_CM4_D classifications for the same single year would be calculated – but these data are not available. Even if they were, comparison would be difficult because of the MAR cold bias. In general, however, it appears that the range of climate classifications encountered is somewhat greater for MAR than for IPSL_CM4_D. Combined with the cold bias, this causes a potential problem, in that 'no-analogue' climate classes occur, i.e. classes (such as Csao for Scenario A in Northeast France) for which no analogue stations occur in the Climatic Research Unit archives.

(a) *calculated from IPSL_CM4_D 30-year averages*

Simulation Region	0	A	B	C	D	E	F
Central Spain	Csal	Cshl	Cshl	Cshl	Cshl	Cshk	Csal
Central England	DOlk	DObk	DOlk	DObk	DObk	DObk	DOlk
Northeast France	DOak	Cshk	DOak	DOak	DOak	DOak	DObk
Central Europe	DObk	DOak	DObk	DOak	DOak	DOak	DObk

Central Spain = 36N to 43N, 1W to 8W
Central England = 50N to 58N, 7W to 2E
Northeast France = 43N to 50N, 2W to 5E
Central Europe = 46N to 53N, 5E to 13E

(b) *calculated from MAR single-year output*

Simulation Region	0	A	B	C	D	E	F
Central Spain	DObk	Csak	DCbo	DOak	DOak	DCak	DObk
Central England	DClo	DObk	DClo	DCbo	DCbo	DCbo	DClo
Northeast France	DCbo	Csao	DCbc	DCbo	DCbo	DCbo	EObo
Germany	DCbo	DCao	DCbc	DCbc	DCbc	DCac	ECbo
Czech Republic	DCbc	DCbo	DCbc	DCbc	DCbc	DCac	EClc

Central Spain = 38.6N to 41.0N, 1.6W to 6.5W
Central England = 51.7N to 54.7N, 3.2W to 0.1E
Northeast France = 48.1N to 49.0N, 5.1E to 6.4E
Germany = 51.9N to 52.9N, 9.7E to 11.0E
Czech Republic = 48.8N to 49.8N, 14.8E to 16.0E

Table 3.3: *Results of the Rule-based Downscaling Methodology applied to IPSL_CM4_D and MAR Output for the BIOCLIM Study Regions.*

The climate analogue stations can be used to evaluate the representativness of MAR outputs which relate only to a single year. One option would be to use results from IPSL_CM4_D to identify one or more appropriate climate analogue stations. MAR output could then be compared with data from those stations to determine whether they lie within the envelope of interannual variability. However, interannual variability is likely to be higher for individual stations than for area averages. A high-quality area-average temperature record, the Central England Temperature (CET) record (Manley, 1974; Parker et al., 1992) was used to define the geographical extent of the Central England study region. Thus, the CET record can be used to determine whether the single year of MAR temperature output for Central England lies within the observed interannual variability.

Figure 3.8 indicates that the single-year MAR temperature only exceeds the CET mean in September and October. MAR is colder than the observed 10% percentile for eight months of the year and colder than the minimum observed value in half of all months. Thus, it is concluded that the cold bias evident in MAR output is not due to interannual variability (i.e., sampling error), but reflects a systematic error. Figure 3.8 suggests that the seasonal cycle is too strong and that the maximum is shifted rather late in the year (i.e., August/September rather than July/August as observed). Comparable observed area averages are not available for Central Spain or North-east France (although they could be constructed, from the gridded data sets held in the Climatic Research Unit, for example). However, Table 3.3, together with the results presented in BIOCLIM (2003b), indicates that the cold bias is likely to be a problem in all BIOCLIM study regions.

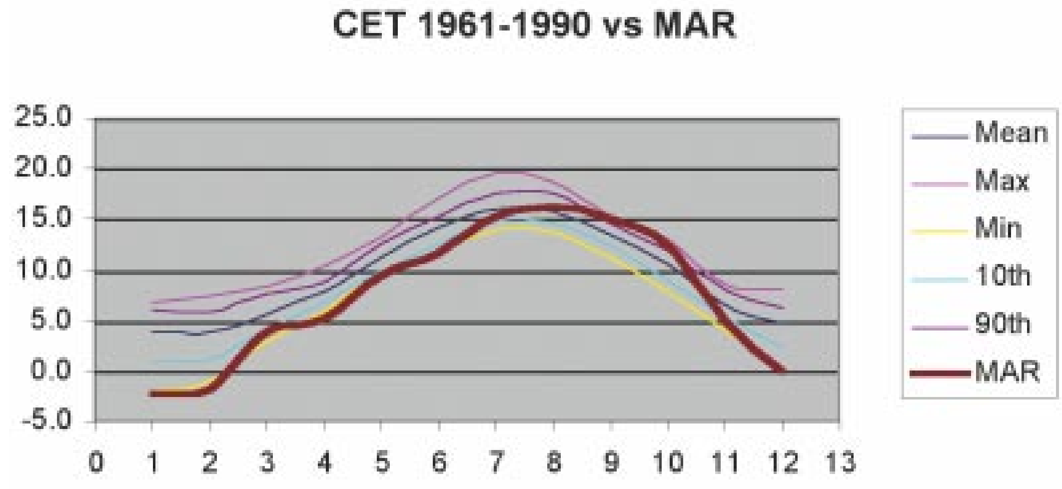


Figure 3.8: *Comparison of Mean Monthly Temperatures for Central England between the CET Record and MAR Results for a Single Year*

This cold bias complicates other comparisons that could be made. For example, it would be useful to look at the spatial pattern of MAR results (not shown) relative to IPSL_CM4_D results (e.g., Figure 3.6) to determine whether the downscaling had resulted in systematic shifts in climate, e.g. changes in regional patterns of precipitation. It might then be possible to consider whether the causes of such shifts could be identified by reference to the model structures and the nature of the downscaling techniques used.

As Figure 3.8 indicates a systematic cold bias in the single year MAR output, the question arises as to what extent is this due to MAR itself and/or due to biases in IPSL_CM4_D? This question is explored in Figure 3.9 for Central England temperature. This figure compares observed temperature (CET and for the 10 DO analogue stations selected for Central England) with IPSL_CM4_D output averaged over the 30-year control simulation and MAR output for the same single year. The IPSL_CM4_D output agrees reasonably well with the observed data, although the shape of the seasonal cycle is somewhat anomalous, with the coldest month occurring in March rather than in January/February as observed. Ideally, IPSL_CM4_D output for the MAR single year would also be shown in Figure 3.9. Although this is not available, it seems likely that the problems are more related to the MAR cold bias than to selection of an unusually cold year to provide the MAR boundary conditions.

Although the IPSL_CM4_D temperature output for Central England is considered reasonably reliable (Figure 3.9), this is not the case for precipitation (Figure 3.10). The observations indicate a weak precipitation cycle with a tendency towards maxima in winter/late autumn months. In contrast, both IPSL_CM4_D and MAR have a very strong seasonal cycle, with pronounced summer minima of about 20 mm or less. The Køppen-Trewartha classification system is primarily temperature based, but precipitation output is also used, hence these large precipitation biases are of concern.

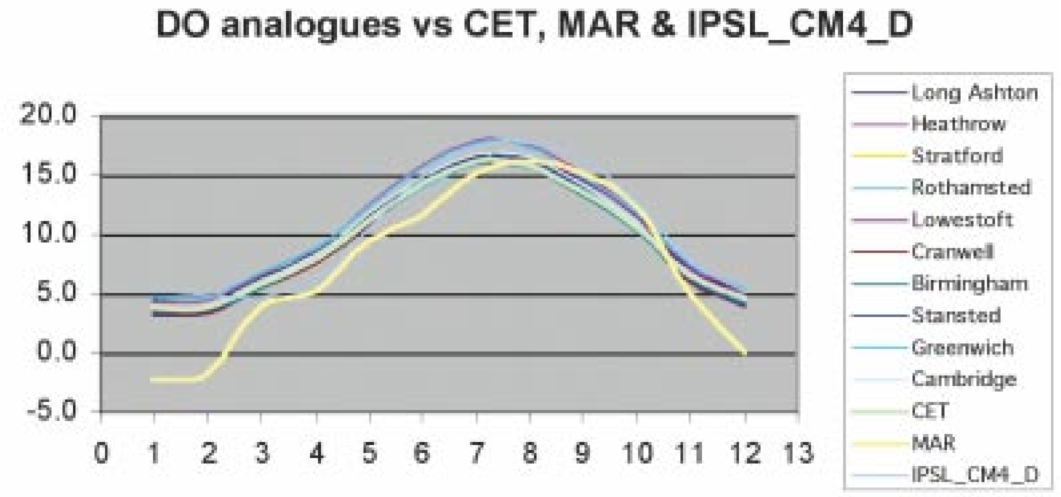


Figure 3.9: *Comparison of Mean Monthly DO Analogue Station Temperatures for Central England with CET Values and MAR and IPSL_CM4_D Results*

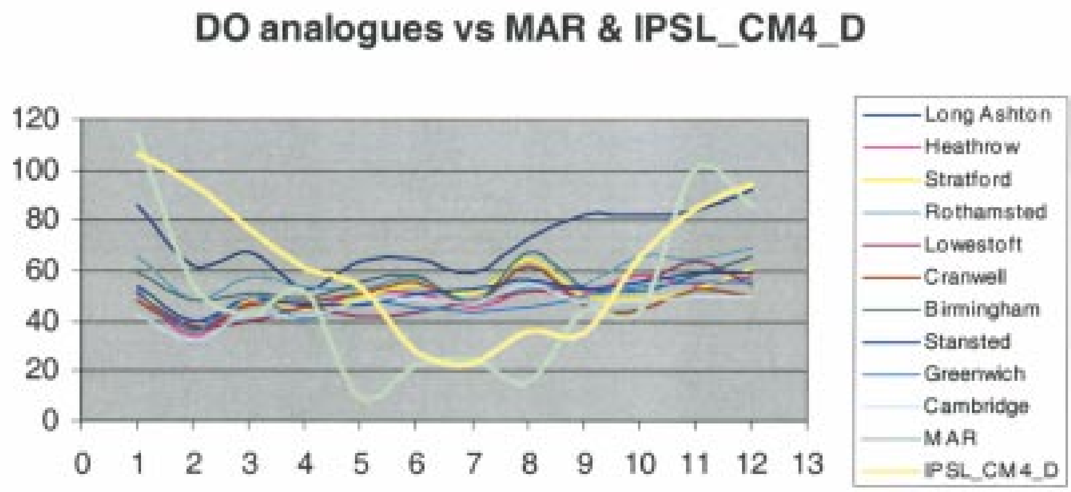


Figure 3.10: *Comparison of Mean Monthly DO Analogue Station Precipitation for Central England with MAR and IPSL_CM4_D Results*

Faced with such biases in GCM and RCM output, a recommended and widely-used strategy for constructing scenarios of greenhouse gas-induced warming over the 21st century is to add the perturbed minus control-run difference (i.e., the climate-change signal) to an observed baseline climatology, on the assumption that the errors will be unchanged in the future (Giorgi et al., 2001; Goodess et al., 2003). This approach was used, for example, to construct datasets supporting the UKCIP02 scenarios (Hulme et al., 2002). The UKCIP02 scientific report presents scenario changes based on output from the UK Hadley Centre HadRM3H RCM (which has a grid-box resolution of 50 km by 50 km). For selected variables (see Appendix 4 of Hulme et al., 2002) these changes were interpolated to match the 5 km spatial scale of a new gridded climatology for the UK and then added to the latter baseline. A similar approach could have been used in BIOCLIM. However, considerable work would be required in the construction and evaluation of appropriate baseline climatologies for all BIOCLIM study regions. In order to demonstrate the potential of this approach, therefore, an example is shown below using readily-available Central England area averages.

CET could have been used for the purposes of this example. However, that leaves the question of what precipitation baseline to use. The widely-used England and Wales Rainfall (EWR) record, for example, is not directly comparable with CET. However, Figure 3.11 indicates very close agreement between CET and the average class temperature for the set of DO (i.e., present-day climate class) analogue stations selected for Central England. On the assumption that similar agreement would exist between an area-averaged Central England precipitation record and the DO average class precipitation, it was decided to use the DO class averages as an observed baseline. For each of the six snapshot simulations, the perturbed minus control run difference was calculated and added to the class average. The climate classes for each simulation/region were then re-calculated (Table 3.4).

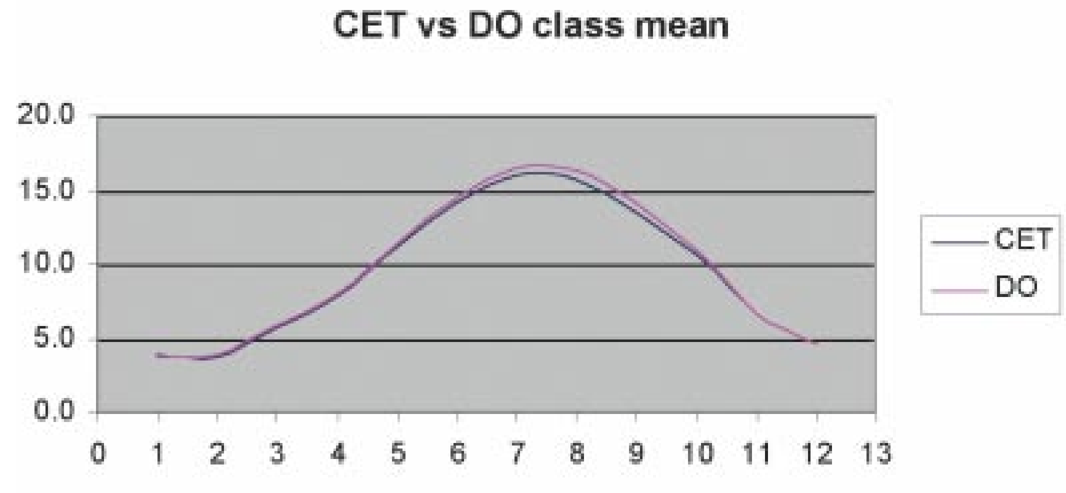


Figure 3.11: Comparison between CET and the Mean Monthly Temperatures of the DO Analogue Stations for Central England

The climate class given in Table 3.4 for the control run is now correct, because it is calculated from the baseline climatology. The 'corrected' results for IPSL_CM4_D are identical to the 'uncorrected' results shown in Table 3.3a for all snapshot simulations, reflecting the relatively good performance of IPSL_CM4_D with respect to temperature (Figure 3.9). For MAR, with the exception of simulation F, consistently warmer classes occur in Table 3.4 compared with Table 3.3b: Crbk rather than DObk for the A – high CO_2 – simulation, for example. In the case of simulation F for 178 ka AP, Table 3.4 gives a classification of EO, rather than DC, although the third and fourth letters indicate mild summers and cold winters in each case. Comparison of the 'corrected' results in Table 3.4 confirms the greater sensitivity of MAR, with DO, Cr, DC and EO conditions experienced in the snapshot simulations, compared with DO only for IPSL_CM4_D.

Simulation Model	0	A	B	C	D	E	F
IPSL_CM4_D	DOlk	DObk	DOlk	DObk	DObk	DObk	DOlk
MAR	DOlk	Crbk	DOlk	DCbk	DCbk	DCbk	EOlo

Table 3.4: *Results of the Rule-based Downscaling Methodology applied to 'Corrrected' IPSL_CM4_D and MAR Output for the Central England Study Region.*

Given the problems with model biases, particularly with respect to MAR, together with the difficulty of using output for a single year in the case of MAR and the low sensitivity of IPSL_CM4_D, considerable care is needed in using these dynamical downscaling results. However, it is reasonable to ask how they compare with the rule-based downscaling results and can the latter be considered any more reliable?

The first question is addressed by Table 3.5 which shows the climate class obtained by applying the rule-based downscaling method to MoBidiC and LLN 2D NH output from the B3, B4 and A4 simulations for the present day and the times of the WP2 snapshots, i.e., 67 ka AP and 178 ka AP. It should be noted that the rule-based method only provides a classification at the two-letter level and that LLN 2D NH output was not downscaled for Central Spain (because the methodology performs less well than for Northeast France and Central England (BIOCLIM, 2003d)). Table 3.5 indicates relatively little difference in results for the B3 and B4 scenarios. However, there are substantial differences between these two anthropogenic scenarios and the natural A4 scenario. There is broad agreement between results based on MoBidiC and LLN 2D NH output, although agreement is less good for North-east France than for Central England, and for 178 ka AP than for 0 ka AP and 67 ka AP. Compared with the WP2 snapshots, the rule-based results indicate larger changes in climate classes, for example, a range of Cs to EC for Central England, compared with a range of Cr to EO for the 'corrected' MAR results and stable DO conditions for IPSL_CM4_D (Table 3.4). The low sensitivity of the latter model has already been commented on and is discussed in more detail in BIOCLIM (2003a). However, without extracting the LLN 2D NH and MoBidiC forcing conditions at the snapshot times and comparing them with those used for the snapshot simulations, it is not possible to determine to what extent the differences reflect different model sensitivities and/or differences in forcing.

	Scenario	0 ka AP	67 ka AP	178 ka AP
Central England				
MoBidiC	B3	Cs	Cs	DC
	B4	Cs	Cs	Cr
	A4	DO	EO	EC
LLN 2D NH	B3	DO/Cs	Cr	EC
	B4	DO/Cs	Cr	DO
	A4	DO	EO	EC
Northeast France				
MoBidiC	B3	Cs	Cs	DC
	B4	Cs	Cs	Cr
	A4	DO	EO	EC
LLN 2D NH	B3	DO/Cr	Cr	EC
	B4	DO/Cs	Cr	DC
	A4	DO	EO	EC
Central Spain				
MoBidiC	B3	BWh	BSh	Csa
	B4	BWh	BSh	Csa
	A4	Csa	Csa	BSk

Table 3.5: *Results of the Rule-based Downscaling Methodology applied to MoBidiC and LLN 2D NH output for 0, 67 and 178 ka AP for the Central England, Northeast France and Central Spain Study Regions. Note that the first MoBidiC time step is at 0.5 not 0 ka AP, whereas the first LLN 2D NH time step is at 0 ka AP, thus LLN 2D NH results are given for both 0 and 1 ka AP, where these are different.*

The second question posed above, i.e., can rule-based downscaling results be considered more reliable than the dynamical downscaling results, is somewhat more difficult to address. The very different nature of GCMs/RCMs and EMICs means, for example, that common statistical diagnostics cannot be used to directly compare the relative performance of the two groups of models. Biases have been identified in the EMICs used in BIOCLIM. MoBidiC, for example, tends to underestimate ice volume and extent during the last glacial and overestimates ice during the Holocene. The implications of these biases for development and evaluation of the rule-based downscaling methodology are discussed in BIOCLIM (2003d). BIOCLIM (2003d) also discusses the particular difficulties that were encountered in identifying appropriate rules and thresholds for Central Spain compared with Northeast France and Central England. The use of simulated temperature to define moisture-related thresholds is considered to be the major cause of the relatively poor performance of the rule-based downscaling methodology in Central Spain.

The intercomparisons described above focus on three of the four BIOCLIM downscaling methods (Table 3.1). The general advantages and disadvantages of the fourth method, statistical downscaling applied to CLIMBER-GREMLINS output are summarised in Table 3.2. The developers of this methodology stress that it is the first version of a rather new method which requires further validation and improvement (BIOCLIM, 2003e). In particular, they conclude that the downscaling results for precipitation, which indicate much larger changes than CLIMBER-GREMLINS, should be used cautiously. Nonetheless, Table 3.2 indicates that this statistical downscaling method has a number of potential advantages. However, direct comparison with the other methods presented here is not straightforward for two main reasons. First, the statistical method is applied to CLIMBER-GREMLINS output, whereas the other methods are applied to LLN 2H 2D and MoBidiC output. Although the same forcing scenarios are used for the MoBidiC and CLIMBER-GREMLINS simulations, there are differences in the response of the two models (BIOCLIM, 2003c). This makes it difficult to determine whether any differences in downscaled results are due to differences in the EMIC response and/or the particular downscaling methodology used. Second, the statistical downscaling methodology outputs temperature and precipitation for January and July only. Thus, it is not possible to calculate Køppen-Trewartha classes which provide a useful basis for comparing the other downscaling methods.

Table 3.2 also summarises the general advantages and disadvantages of the dynamical and rule-based downscaling methods used in BIOCLIM. The two major advantages of the rule-based downscaling approach are its minimal computing requirements and consistency with the BIOMASS methodology. The Excel spreadsheets for calculating, applying and evaluating the rules and thresholds are available for use and further development by the country assessment teams, for example. Thus it is considered most appropriate for the construction of narratives of environmental change and the characterisation of such change for performance assessments (see Section 5 and Appendix C). However, its disadvantages, in particular, the number of subjective decisions that must be made, should not be forgotten. Ideally, dynamical downscaling for snapshot periods would be used to add confidence to the rule-based results, but the problems identified above limit the extent to which this can currently be done. Although the relative performance of LLN 2D NH and MoBidiC over the last glacial-interglacial cycle requires further evaluation, the broad agreement of rule-based downscaling results for the two models, indicates that it is reasonable to base narratives for the next 200 ka on MoBidiC output alone.

4. The Identification and Characterisation of Biosphere states as developed in BIOMASS

4.1. - The Use of Non-Sequential and Sequential Approaches to Biosphere System Characterization

Choices about the way biosphere system change is represented within an assessment should reflect the underlying assessment context, in particular the purpose of the assessment and the endpoints to be evaluated. Selection of a preferred approach will depend on understanding inter-relationships between various timescales for change, not only in terms of the dynamics of change to the system itself, but also in respect of radionuclide dispersion and accumulation within the dynamic system. For example, if the emphasis is on providing indicators of the lifetime-average annual individual exposure, explicit representation of changes leading to fluctuations in radionuclide concentration on timescales of less than a lifetime are not necessarily appropriate, unless those changes lead to short duration exposures that dominate the lifetime average.

Two general approaches have been adopted for representing climate change:

a. Discrete, non-sequential system states

It may be possible to identify a finite number of discrete, quasi-equilibrium biosphere system states that are judged to be adequately representative of key stages (e.g. climate states) in the evolution narrative. Time-invariant assessment biospheres corresponding to these quasi-equilibrium conditions may then be identified and simulated in such a way that they are independent from one another, with their projected sequence disregarded. A non-sequential approach will be appropriate in situations where radiological impacts associated with the assumed quasi-equilibrium state are not significantly affected by possible previous concentrations of radionuclides in environmental media.

An example of the discrete system state approach is the assumption that contamination enters the accessible environment via a well. To determine potential radiological exposures, it is assumed that land use and water use are broadly consistent with assumed climate conditions at a given time in the future. In this case, it is unlikely that significant benefit would be gained from considering the sequence of climate and landscape change before (and after) the well has been constructed.

b. Sequential approach

The aim of adopting a sequential approach is to provide for explicit representation of biosphere system change, either through simulating a sequence of discrete states (with sharp transitions from one to the next) or via quasi-continuous variation of the properties and characteristics of biosphere system components. Such an approach is particularly appropriate in situations where the judgement is made that accumulation of radionuclides at an earlier stage in the evolution narrative may have implications for the radiological consequences at subsequent times during or after change has taken place. The sequential approach provides for assessment biospheres to have a “memory” of the distribution of contamination prior to and during the particular transition(s) they are intended to simulate. However, in dealing with sequences of change to biosphere characteristics, it is also necessary to ensure that appropriate consideration is given to corresponding sequences of change in the location and pattern of radionuclide release from the geosphere to the biosphere.

Whichever approach is taken, the development of an adequate representation of change for the purposes of the safety assessment should not necessarily depend on attempting to provide a complete simulation of biosphere system evolution throughout the overall time frame of interest. Rather, the aim is to work from narrative descriptions of landscape evolution over that period in order to identify assessment biospheres that are sufficiently representative to provide an adequate measure of projected overall safety performance of the disposal system. This involves the use of scientific understanding and judgement to highlight periods of time that are expected to be of particular interest or concern. For example, the identification of particular transitions or sequences of change, that are projected to occur within a specific time period as being of interest or potential importance, does not imply a need to represent the complete future evolution of the biosphere using a sequential approach. In such situations, it may be sufficient to consider the dynamics associated with a specific transition, or series of changes, in a separate calculation, the results of which could then be considered alongside results from identified, non-sequential 'system state' models.

It is not easy to draw an absolute distinction between 'continuous' and 'discrete' (step-wise incremental) representations of sequential change. Indeed, any dynamic representation of a changing system will tend to introduce some discontinuities, effectively collapsing the assumed timescale of system response to zero over the period in which a defined change takes place. The important consideration is to ensure that such discontinuities do not introduce unacceptable artefacts into the results of the assessment. The choice of appropriate time-steps in representing a sequence of system conditions can be considered as the temporal equivalent of grid refinement in spatial representations of flow and contaminant transport.

Change from one state to another may be assessed as if it were instantaneous. This will usually tend to overestimate the likely radiological consequences during the period in which the anticipated change actually takes place. For example, if a projected future fall in sea level is represented as a step-change from a coastal to a terrestrial environment, the erosion of sea bed sediment and remobilisation of contaminants, resulting from coastal processes taking place as sea level fell, might not be properly taken into account. Hence it is likely that the potential radiological implications of reclaiming former bed sediments, contaminated by discharges that occurred under earlier environmental conditions, for use as arable land would be overestimated. Another example relating to the agricultural use of former lake-bed sediments is given in BIOMOVS (1989).

The more complex modelling requirements and judgements associated with representing biosphere change more realistically as a continuous variation may only be justified if the assumption of a sequence of discrete states were judged to give rise to excessively pessimistic estimates of radiological impact. In practice, the extent to which system dynamics may have a significant impact on repository radiological performance over time might only be assessable through sensitivity studies for a particular repository context.

4.2. - Climate States and their Relationship to Biosphere States

Evolution of the climate over timescales relevant to safety assessments brings changes to the biosphere that can have an important influence on the pathways for transfer of contaminants to a receptor such as man. Changes in temperature and precipitation influence the types of flora and fauna that are present in the biosphere and can affect the type of agricultural activities practised by a local population. This, in turn, can affect the drinking water intake and diet of a population and any consequent radiological impact arising from use of contaminated foodstuffs and groundwater. Climate change may have broader impacts on the landscape, for example, on the characteristics of surface water bodies such as rivers and lakes as a result of changes in erosion rates or sediment deposition. More significant changes in landscape could occur if an area were subject to glaciation, for example, significant surface erosion might take place as a result of glacial advance and extensive deposition of till, outwash deposits and lacustrine sediments might occur, mainly during phases of ice stagnation and retreat.

Many safety assessments for radioactive waste repositories focus on the groundwater pathways as the principal routes for transport of contaminants to and within the accessible environment. The groundwater pathways are principally defined by the hydrogeological and geochemical characteristics of formations along the pathways and the regional hydrogeology. Changes in any of these system characteristics may affect radionuclide transport and need to be considered in safety assessment calculations. Over very long timescales, climate change is an important influence on such system characteristics; for example, changes in precipitation will affect regional recharge rates and groundwater flow, potentially affecting the degree of dilution occurring at the interface between deep and near-surface hydrological systems. A further example is the advance and retreat of ice sheets may also affect groundwater flow, through sub-glacial recharge and the growth of permafrost ahead of the ice, and through associated changes in sea level.

In some safety assessments, possible future climate sequences have been generated based on a number of discrete climate states, for example, temperate, boreal, periglacial and glacial. Use of discrete climate states is one of the simplifications adopted to represent long-term biosphere change in safety assessments of radioactive waste disposal facilities. Discrete climate states can be defined based on data from the historical record, from pollen and ice core studies, and from information from existing analogue sites where the climate conditions are considered likely to be similar to a future state at a particular repository site. Use of climate analogues often provides a useful means of gathering relevant information on, for example, vegetation patterns, meteorological data and human activities to fulfil modelling data requirements. Evidence from the past climate record may also be used to define, and possibly justify, selection of future climate change sequences for safety assessments.

The concept of discrete climate states is a convenient simplification that allows development and implementation of models to represent future biosphere evolution at a particular repository site. The simplification may not be realistic since there are generally sharp transitions between climate states whereas climate change is more likely to occur as a continuum. As noted above, representation of the transitions between climate states by simulating dynamic changes more realistically might only be justified if the assumption of a sequence of discrete states were judged to give rise to excessively pessimistic estimates of radiological impact.

A strategy for dealing with the implications of climate and environmental change has been outlined in the BIOMASS project (BIOMASS, 2003). Within the strategy, the principal elements in the definition of assessment biospheres are:

- Identify possible time sequences of climate change and other relevant primary mechanisms of environmental change.
- For each identified time sequence of interest, develop one or more broad-brush descriptions of regional landscape evolution (narratives).
- Review relevant assessment context information relating to the source term and geosphere biosphere interface for each landscape evolution narrative.
- Identify one or more time series of assessment biosphere system states corresponding to each landscape evolution sequence.
- Taking account of the projected behaviour of radionuclides in the evolving biosphere, consider the potential advantages and disadvantages of simulating the effects of transitions from one biosphere system state to another.

In applying the strategy, is important to recognise that the factors involved in defining a representative assessment biosphere are not restricted to consideration of changes to climate and landscape. In particular, the identification and description of the assessment biosphere also involves consideration of the form and location of the geosphere-biosphere interface zone as well as the anticipated time-pattern of release of radionuclides, according to the projected response of the overall disposal system to characteristics and changes at a regional scale. Other relevant guidance provided by the overall assessment context also includes the timeframes of interest and the nature of the assessment end-points that are to be determined.

Rather than attempting to capture all possible futures, the emphasis in defining variant evolution pathways is on using scientific understanding to justify the development of meaningful illustrations that are sufficiently representative of a broad class of futures to assist the decision process. In the BIOMASS methodology, the underlying basis for the treatment of change is a set of narrative descriptions of projected regional landscape evolution in the vicinity of the repository site. Landscape evolution narratives, combined with understanding of the effects of changes caused by geological and geochemical events and processes, act as a common point of reference for dealing with both:

(a) the impact of change on the long-term performance of the repository and geological barriers; and

(b) the implications for radiological impact of potential releases to the accessible environment.

In selecting and justifying the particular choice of narratives to be used, it is important to ensure that consideration is given to the implications for both aspects of the safety assessment. Climate modelling work undertaken within BIOCLIM is directed towards providing the scientific understanding that underpins the definition of such narratives. The approach used for the generation and interpretation of such narratives has been outlined in Section 3.1 and is expanded upon with illustrative examples in Section 5.

4.3. - Characterisation of Individual Biosphere States: The BIOMASS Approach

The BIOMASS methodology provides a systematic process for establishing a logical audit trail to justify the scope, constituents and definition of assessment biospheres. The assessment context provides the starting point for identification and justification of the major components of the biosphere for a particular study. Major components are defined within the BIOMASS methodology as human activities; climate; topography; location and geographical extent; flora and fauna; near-surface lithology; and water bodies such as rivers and lakes. A biosphere system description is then developed based on a detailed, systematic examination of the interactions and characteristics of the major components of the biosphere system under study and their influence on transport, accumulation and loss of contaminants within and from that system.

The biosphere system description should include consideration of the characteristics relevant to each major component and the ways in which they are interrelated, both in terms of system dynamics and their assumed spatial arrangement. The process of developing a biosphere system description includes identification of potential pathways from the contaminant source to a receptor such as a human population or an ecological system. Where possible impact on humans is the assessment end-point, relevant human activities need to be considered as part of the process of defining potential pathways.

The biosphere system description is a ‘word picture’, which provides a starting point for an assessment model simulating radionuclide transport and accumulation in which exposures are assumed to take place, coupled with a description of the assumed geosphere-biosphere interface for radionuclide release into the system. The development and justification of an assessment model will not always be a simple process. An iterative approach to refining the model, coupled to enhancement of the corresponding biosphere system description, may be necessary in order to ensure that a practicable and justifiable approach is achieved. Within the BIOMASS methodology, the following basic steps were identified:

- Identify those components or sub-components of the biosphere system that are to be characterised as separate conceptual model entities (i.e. distinct environmental media) in the representation of radionuclide transport;

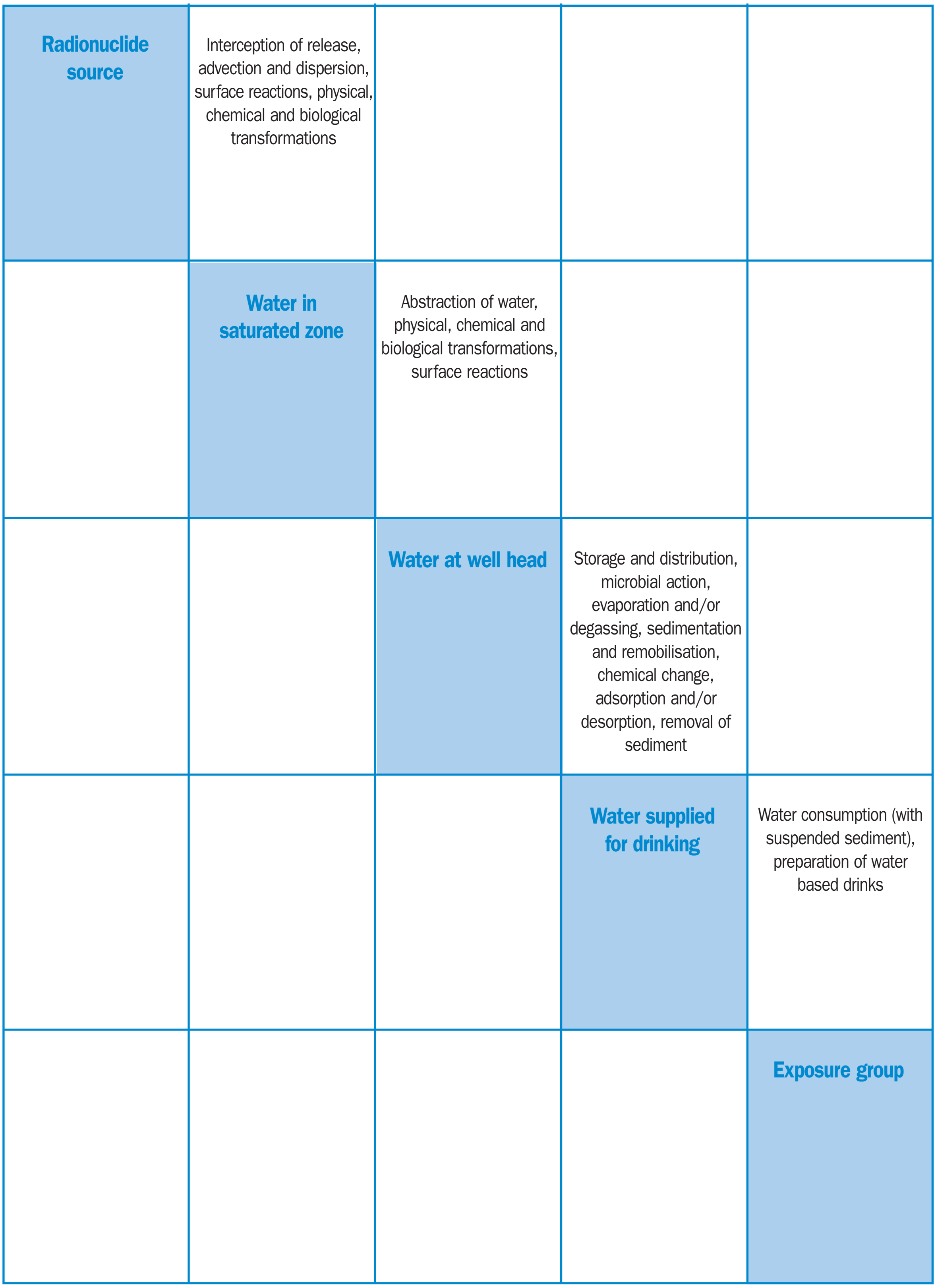
- Taking account of the assumed spatial configuration and intrinsic dynamics of the biosphere system components, devise a conceptual model of radionuclide transport between these conceptual model objects;
- Ensure that all relevant features, events and processes (FEPs) are addressed adequately within this representation of contaminant behaviour in the system, taking account of the phenomena identified in the biosphere system description;
- Define the mathematical model, taking into account available data and scientific understanding related to the phenomena of interest.

The BIOMASS methodology uses the initial description of relevant aspects of the biosphere system and their interrelationships as a basis for developing an interaction matrix description of the biosphere system within the domain of interest to radiological assessment. This involves decomposing the system description to separate those FEPs that are related to bulk mass movements between physical features, or internal elements of the system, from those that can be considered to act as 'external influences'. A further interaction matrix is then developed that explicitly accounts for the release of radionuclides to the biosphere, their transport and accumulation, and relevant radiological exposure pathways. The matrix is then screened against an appropriate biosphere FEP checklist to ensure that all potentially relevant FEPs have been addressed. Examples of the two forms of interaction matrix for BIOMASS Example Reference Biosphere 1B (drinking water well) are given in Figures 3.1 and 3.2. The interaction matrices help define the biosphere system for the region of interest in the safety assessment and provide a conceptual model for development of a mathematical model of that biosphere system.

Mathematical representation of the conceptual model depends on a good understanding of the importance of FEPs to long-term radiological assessment and the best ways in which they can be described mathematically. Modelling constraints, such as the preferred solution method to be adopted within the assessment tool, may restrict the ability to represent particular events or processes and thereby lead to revision of the list of FEPs included. Separate models may need to be developed if FEPs cannot easily be combined into a single model.

Climate		Climate properties in zone of recharge will affect input	Influence on flow boundary conditions in discharge zone	Temperature etc. will affect the volume of water required by the community	May have some influence on water quality but is time invariant	Variability may be relevant factor in determining need for storage	
	Aquifer/ Aqitard	Infiltration rate affected by hydraulic properties of the system	Discharge rate affected by hydraulic properties of the system	Determines quantity and quality of available water at abstraction point	Properties of geological system affect water characteristics		
	Affects flow regime, chemistry etc. in subsurface features	**Water input to aquifer system**					
	Affects flow regime		**Discharge from the aquifer system**	Determines surface water bodies and hence availability of local supplies			
	May perturb natural flow regime			**Abstraction of water from the aquifer for domestic use**	Could cause physical, chemical or biological changes	Cannot store or distribute water until it has been abstracted	Drinking water supply comes from abstraction
	Properties of water affect characteristics of geological system			Physical and chemical changes may affect actual abstraction rate	**Physical and chemical properties of aquifer water**		Water must be potable to be used in drinking water supply
						Water storage and distribution	May affect quality of water supply
							Drinking water supply

Figure 4.1: *Interaction Matrix representation of the biosphere system for Example 1B*



Radionuclide source	Interception of release, advection and dispersion, surface reactions, physical, chemical and biological transformations			
	Water in saturated zone	Abstraction of water, physical, chemical and biological transformations, surface reactions		
		Water at well head	Storage and distribution, microbial action, evaporation and/or degassing, sedimentation and remobilisation, chemical change, adsorption and/or desorption, removal of sediment	
			Water supplied for drinking	Water consumption (with suspended sediment), preparation of water based drinks
				Exposure group

Figure 4.2: *Interaction Matrix representation of the radionuclide transport and exposure pathways for Example 1B including the results of FEP screening*

4.4. - The Representation of Transitions between Biosphere States

Although BIOMASS (2003) addressed the representation of biosphere change in PA, this work was not advanced as far as the work on characterization of individual biosphere states. For this reason, the BIOMASS methodology was extended in BIOCLIM to address this issue. The approach was:

- Develop a narrative of environmental change for the scenario under consideration;
- Use that narrative to partition the scenario into a sequence of biosphere states and transitions each of defined duration;
- Identify from those sequences the transitions between states that were likely to exhibit characteristics of interest for PA purposes;
- Characterise each of the states using the standard BIOMASS (2003) methodology;
- Identify the states occurring before and after each transition of interest;
- Develop interaction matrices setting out the key characteristics of each transition, with the diagonal elements of each matrix comprising the major components of each biosphere state, as defined in the BIOMASS (2003) and modified in this study (topography, soils and lithology, water bodies, biota, human communities);
- Display the information from the interaction matrices on transition diagrams showing the time course of change from one biosphere state to the next.

It is emphasised that the interaction matrices and transition diagrams are not intended to represent all aspects of transitions. Rather, they focus on those aspects that could result in radiological impacts differing substantially from those in the initial and final states.

Examples of interaction matrices and transition diagrams are shown in Section 5. Comprehensive narratives and extensive sets of interaction matrices and transition diagrams for all the five study areas are provided in Appendix C.

5. Narratives of Environmental Change and the Characterisation of such Change for Performance Assessments

As discussed in Section 4.4, the analysis of future environmental change for the purposes of PA begins with the development of narratives of such change. Those narratives provide a coherent and continuous account of the evolution of an area. Results from climate modelling are used in a semi-quantitative sense in the development of such narratives and the flexibility of the narrative form permits uncertainties to be incorporated. In particular, in the context of BIOCLIM, results from several different approaches to climatological modelling can be taken into account in narrative development. Also, it has been found that more than one scenario for climate change can be included within a single, generalised narrative of environmental change. This was found to be the case for Scenarios B3 and B4. However, these two scenarios could not be aggregated with that for A4.

Having developed a narrative, it was inspected to determine how it could be sequenced into climate states and transitions. In practice, this was found to be relatively straightforward for the five areas of interest (Central England, North-east France, Central Spain, Germany and the Czech Republic). Examination of those sequences of states and transitions provided a basis for identifying those states and transitions that should be examined in more detail for PA purposes. At this stage, a set of states and transitions could be identified from all the scenarios of interest, i.e. it was determined that it is not necessary to study each scenario in its entirety. Thus, the outcome of this analysis was a limited set of states and transitions requiring further analysis from all the scenarios considered.

Characterisation of the individual states was undertaken using the standard BIOMASS methodology, as outlined in Appendix A. The standard classificatory tables were used as a framework for providing descriptions of each state. This then provided a basis for characterising the transitions between states. Such an analysis of transitions had not been attempted previously. It was found that the analysis could usefully be split into two steps. In the first step, an interaction matrix was set up with the principal elements of the BIOMASS state description listed along the lead diagonal. These elements were slightly modified within BIOCLIM to comprise topography, soils and lithology, water bodies, biota and human communities. The off-diagonal elements were then completed by entering information on how the driving element changed over a transition and how it affected the driven element. The standard clockwise convention was used in defining driving and driven elements. This approach does not have a specific framework for recording the changes in the lead diagonal elements themselves, but this information had already been captured in the definitions of the environmental transitions of interest.

Although the interaction matrices are useful in recording the processes of change and their interactions, they lack a temporal element. Thus, they were complemented by transition diagrams. In these the principal elements of the BIOMASS description were listed across the top and bottom of the diagram, representing the initial and final states of interest, respectively. Changes between the two states for each principal element were represented by vertical arrows and brief associated captions. Interactions between elements were represented by diagonal arrows connecting the vertical arrows and derived from information on those interactions given in the associated interaction matrix.

Having developed state and transition descriptions, the next step would be to develop conceptual and mathematical models for representing the states and transitions for PA purposes. However, this was outside the remit of BIOCLIM. Nevertheless, a careful examination was made of the narratives, state descriptions, interaction matrices and transition diagrams developed for all five study regions, and no major issues were identified that would have given rise to substantial problems in such model development, had it been undertaken.

Details of the narratives and the associated analyses are presented in Appendix C. In the remainder of this section only illustrative examples are shown. For the purposes of coherence, all these examples relate to Central England, but the information for all five study areas was developed to a similar level of detail, with the caveat that downscaled climatological information was not available for the supplementary study areas of Germany and the Czech Republic.

5.1. - Development of Narratives of Environmental Change for the Specific Regions of Interest

Narratives are extended accounts of the evolution of an area within the context of a specific scenario. In the case of scenarios B3 and B4 for Central England, the relevant material is included in Section C.1.2. A summary of the narrative, without detailed justification, is provided below.

It seems reasonable to assume that, over the next few hundred years, mean annual temperatures in Central England will increase from about 10°C to between 13°C and 16°C. The seasonal variation in temperature (warmest month – coldest month) may remain as it is at the present day (~ 12°C) or may weaken slightly (to ~ 9°C). Winter precipitation could be only marginally higher than it is at the present day, or increase by as much as 1 to 2 mm d^{-1}. In contrast, precipitation in summer is likely to decrease by 0.2 to 1.4 mm d^{-1}.

These changes in climate would apply to a landscape with near-surface lithostratigraphy and topography essentially unchanged from that at the present day. Annual precipitation, runoff and interflow could either increase or decrease relative to the present day. However, it seems highly likely that stream and river flows would decrease in summer, with some smaller streams becoming ephemeral. If winter precipitation increased by 1 to 2 mm d^{-1}, the total increase over the winter half of the year could be up to 0.4 m. This is a substantial increase. In the transitional period over which winter precipitation increased, the frequency of overbank flooding could increase and the magnitude of such floods could be larger. However, in the longer term, the dimensions of stream channels would adapt to the higher flows, unless constrained by human activities, and the frequency of overbank flooding would diminish.

If winter precipitation were to be only slightly more than that at the present day, the combination of higher temperatures throughout the year and somewhat decreased summer precipitation would almost certainly imply a reduction in groundwater resources. Indeed, there might be an extended period of depletion by over-utilisation before a new sustainable water-management regime was established. Various surface-water storage schemes might be undertaken to ensure better capture of winter precipitation for subsequent use in the hotter, somewhat drier, summers.

The hotter, somewhat drier summers would also result in an increased soil moisture deficit during the growing season. This would result in an increased irrigation demand. However, it seems that the overall change would not be as extreme as to result in arid Mediterranean conditions, in which extensive irrigation of pasture occurs. As at the present day, it seems likely that irrigation would be mainly of high value fruit and vegetable crops. With irrigation, a wide range of crops could be grown, as at the present day. Yields would be increased and there could be more than one harvest per year for some crops. There is no reason why animal husbandry practices should be very different from those at the present day. Overall, with a similar pattern of agriculture to that at the present day, there is no climate-driven reason to propose any substantial change in human community characteristics.

Overall, it is considered that, following a peak in mean annual temperature over the next few hundred years, a cooling trend will ensue, such that temperate conditions similar to those of the present day will recur at between 60 ka and 160 ka AP. Thereafter, there is no strong trend in climate through to 200 ka AP, though MoBidiC and LLN 2D NH results for scenario B3 indicate that a brief cold episode in the range of EC to EO conditions would be expected to occur at around 175 ka AP and persist for a few thousand years.

The period from the present day through to 170 ka AP is characterised by a climate that is only moderately warmer than at the present day and that is associated with a similar degree of water availability throughout the year, though with somewhat drier summers. The main factor in landscape evolution over this period is not climate change relative to the present day, but the duration of the period of interglacial conditions that is projected to occur. The last interglacial (OIS 5e; the Eemian) lasted 10 to 15 ka, and this is thought to be characteristic of full interglacial episodes in the Late Quaternary (i.e. since OIS 12 at around 440 ka BP). A period of interglacial conditions lasting 180 ka (from the beginning of the Holocene at around 10 ka BP to 170 ka AP) is unprecedented for Central England during the Quaternary. However, because some parts of the area of interest were beyond the margins of the British ice sheet at the Last Glacial Maximum (OIS 2 at around 18 ka BP) and have not been glaciated since the peak of the Anglian glaciation (attributed to OIS 12 at around 440 ka BP), information exists relevant to long term rates of generalised denudation and incision of such a landscape. However, in using this information, due account has to be taken of the colder conditions that persisted through much of the period.

Subsequent to a glacial episode, the resultant till sheet is subject to a continuing process of erosion. Based on reconstructions of the palaeosurfaces of till sheets formed in Northumbria, in the North-west of England, at the time of the Last Glaciation (with till formation at around 15 ka BP) and in East Anglia at the time of the Anglian Glaciation (around 440 ka BP), it is thought that the lowering of interfluves has been by no more than 1 to 2 m. In contrast, depths of valley incision due to fluvial erosion have been considerable. In the case of the Anglian till, maximum depths of valley downcutting are several tens of metres, though they do not exceed 60 m.

On this interpretation, the additional incision of stream channels that might be expected to occur over the next 170 ka can be bounded by use of data relating to the Anglian till. In that case, the maximum depth of incision that has occurred is 60 m over 440 ka. It seems likely that about 40 m of this probably occurred within 20 ka of deposition of the till. Thus, if a maximum of 20 m of incision has occurred over the last 420 ka, the additional incision over the next 170 ka should be no more than about 8 m. It could be substantially less if streams have already achieved a close to equilibrium profile. On interfluves, the overall depth of denudation over the next 170 ka is unlikely to exceed 1 m, as no intervals of arid conditions are postulated that could substantially enhance aeolean erosion. In terms of the average rate of lowering of the surface, the average depths of incision of the Anglian and Northumbrian tills of 16.91 m and 11.85 m, respectively, imply that once the early active erosion phase is complete, long-term average erosion rates are unlikely to be much in excess of 0.01 m per ka. Thus, the average depth of erosion over the next 170 ka is estimated as 1.7 m. With up to 8 m of additional incision over the next 170 ka and 1.7 m on average, slope angles should not increase by more than about 10%. Thus, topographic changes are assessed as very limited.

In principle, one factor that could affect the above analysis is a change in sea level, as this is the ultimate determinant of base level. However, in scenarios B3 and B4, there is generally a smaller global ice volume throughout the next 170 ka than at the present day. Thus, sea level will be at, or a few metres above, its present level throughout the period.

Outside the river valleys, the degree of surface lowering over the period is expected to be less than 1 m. Therefore, there will be very little increase in the area of land from which till is completely removed exposing the underlying parent material. Generalised aeolian and fluvial erosion will remove existing superficial soil horizons. However, the soil system will remain covered with vegetation, so a new organic A horizon will continually be formed and changes in the soil profile are expected to be very limited. In the river valleys, several metres of erosion could result in removal of the till in some areas and the establishment of new hydraulic connections between surface waters and the underlying rock. It seems unlikely that the nature and extent of alluvial deposits would be substantially altered. However, the spatial pattern of those deposits might alter somewhat, with switching between erosional and depositional regimes being determined by detailed spatial and temporal changes in the flows of surface waters.

Losses of material by solubilisation (chemical erosion) are likely to be very limited compared with fluvial and aeolian erosion, except, possibly, in the case of the outcrop of the Chalk east of The Fens. However, the low elevation of this Chalk outcrop is regarded as mainly due to the effects of the Anglian ice, so it seems unlikely that chemical erosion would result in lowering of that outcrop by more than a few metres over the next 170 ka.

With the limited changes in topography projected over the next 170 ka and the limited changes in either amounts of precipitation or seasonal temperatures, it seems unlikely that there would be substantial changes in the pattern of surface water flows or in groundwater levels. Thus, the overall surface and near-surface hydrological system is likely to be very similar to that at the present day. These remarks reflect the maturity of the landscape. However, it is noted that substantial changes in hydrology could occur as a consequence of human activities. The effects of changes in human activities, except in so far as they determine and are determined by climate change, are outside the remit of BIOCLIM.

However, some consideration must be given to the increased demand for groundwater that would be expected under climatic conditions warmer than those at the present day. By use of the approach discussed in Section 3.2, it has been demonstrated that mean annual irrigation requirement increases from about 80 mm under DO conditions to about 120 mm in Cr conditions and about 460 mm in Cs conditions. Thus, as already discussed, at the peak of greenhouse-gas induced warming over the next few hundred years, there might be a substantially increased demand for irrigation water, which could potentially result in reductions in available groundwater sources, including reductions in the amount of perched water and a lowering of the regional water table. However, in the longer-term, the demand for irrigation water is not likely to be substantially higher than at the present day.

Again as discussed above, under Cs conditions and with irrigation, a wide range of crops could be grown, as at the present day. Furthermore, there is also no reason why animal husbandry practices should be very different from those of the present day, except that pasture might be irrigated and animals would be able to graze such irrigated pasture throughout the year. As the climate cooled, patterns of agriculture would not be expected to change markedly, but there would be some reduction in the demand for irrigation. Also, there is good reason to consider that the landscape would continue to be fully utilised for human activities throughout the warming and cooling phases considered herein, i.e. no increase in the extent of natural and semi-natural biotic communities is taken into account. However, it is emphasised that the pattern of agriculture could change substantially as a result of various social, political and economic factors not directly determined by climate. Evaluation of the implications of such factors for performance assessment is outside the scope of BIOCLIM.

With only limited changes in climate, topography, water bodies and biota over the next 170 ka, there is no requirement in BIOCLIM to assume that different demographic patterns would develop. Therefore, human community structures are assumed to remain as they are at the present day. As with agriculture, it is emphasised that such community structures could change substantially as a result of various social, political and economic factors not directly determined by climate.

Climate state EO would be characterised by cool summers (mean temperature of the warmest month just over 10°C) and winter temperatures in the coldest month of between about -6°C and 0°C. The total precipitation would be very similar to that at the present day and distributed approximately uniformly throughout the year. There would be an annual moisture excess of about 200 mm and a summer moisture deficit similar to that at the present day. However, with an overall annual moisture excess and a very wet spring, it is unlikely that irrigation would be required. Even if irrigation did occasionally occur, it would probably utilise surplus surface water, rather than groundwater.

As discussed above, the topography and near-surface lithostratigraphy would be very little altered from the present day. However, there could be some soil modification to produce gelic histosols. In respect of water bodies, groundwater levels would probably be higher than at the present day. Marshes are likely to develop in depressions and other poorly drained areas, as well as along water courses. Requirements would be mainly for drainage rather than surface water storage.

In terms of vegetation, a largely treeless landscape is likely to develop, either from forested or unforested antecedent conditions. Agriculture would be largely animal husbandry, with land given over to grass for either summer grazing or hay production. Animals would be over-wintered indoors. Arable cultivation would mainly be of vegetables, with barley grown in areas with the least severe climate. Extensive areas of natural vegetation are likely to develop, i.e. the spatial extent of utilisation of the landscape by humans is likely to decrease. This natural vegetation would comprise mainly various types of low-growing shrubs. With a low productivity agricultural system based on livestock husbandry, small villages, hamlets and isolated homesteads widely dispersed over the rural landscape are likely to be the characteristic human communities. However, it would be possible to sustain a mix of urban and rural communities as at the present day.

The EC climate is typically characterised by warmer summers than EO and much colder winters. Overall, this results in a mean annual average temperature about 5°C colder. It is debatable whether this extreme contrast in continentality would apply in Central England, though it might arise as a result of changes to ocean circulation patterns in the northeast Atlantic. Characteristics of the near-surface lithostratigraphy and topography would be similar to those discussed for the EO climate. Substantial changes to water bodies would be expected. Very cold winters would lead to extensive snowpack development and the freezing of rivers. The spring melt would be associated with ice dams in the rivers and very high peak flows. In consequence, there would be considerable remodelling of river channels. Discontinuous permafrost is expected to be present, overlain by a seasonal active layer. Soil structures, such as ice wedges, that are characteristic of cold regions are expected to form.

The natural vegetation would be the low shrub and herb vegetation characteristic of tundra environments. However, agricultural systems and human communities could closely resemble those associated with the EO climate class.

As the cold state described above came to an end, it is anticipated that a mature, farmed landscape similar to that at the present day would be developed. However, as the natural climax vegetation of Central England under temperate conditions is a mixed deciduous woodland, it is also possible that a network of small settlements existing in a mainly forested environment might develop.

It will be noted that the above narrative relates to environmental change and does not imply abrupt changes in characteristics in moving from one climate class to another. This is appropriate, as climate changes continuously and is artificially distinguished into distinct climate states only for purposes of tractability of analysis.

5.2. - Identification of Sequences of Biosphere States and Transitions Based on the Narratives

Having developed a narrative such as that set out in Section 5.1, it is possible to identify the associated states and transitions. For Central England, this is done in Section C.1.4. For scenarios B3 and B4, the following were identified:

a) A biosphere state with a landscape and climate similar to that at the present day persisting for no more than about 100 years;
b) A biosphere transition over a few hundred years to a landscape similar to that at the present day, but with a climate with an annual mean temperature between 3 and 6°C warmer;
c) A biosphere state with a landscape similar to that at the present day, but with a climate with an annual mean temperature between 3 and 6°C warmer, persisting to about 50 ka AP;
d) A biosphere transition over tens of thousands of years to a landscape and climate similar to that at the present day;
e) A biosphere state with a landscape and climate similar to that at the present day persisting to about 170 ka AP;
f) A biosphere transition to a cold (boreal) climate state over 5 ka;
g) A biosphere state with a mean annual temperature of ~ 0°C lasting a few thousand years;
h) A biosphere transition to a biosphere state with a landscape and climate similar to that at the present day occurring over a few thousand years from about 180 ka AP;
i) A biosphere state with a landscape and climate similar to that at the present day persisting to the end of the study period at 200 ka AP.

In the case of Scenario A4, the following states and transitions were identified:

a) A biosphere state with a landscape and climate similar to that at the present day;
b) A biosphere transition over a timescale of several thousand years to a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day;
c) A biosphere state with a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day persisting to 100 ka AP;
d) A biosphere transition to glacial conditions with the development of discontinuous permafrost over a period of about 5 ka;
e) A glacial biosphere state with a mean annual temperature of about -5°C, the existence of discontinuous permafrost and tundra vegetation persisting for a few thousand years;
f) A biosphere transition over a timescale of about 12 ka to a biosphere state with a landscape and climate similar to that at the present day;
g) A biosphere state with a landscape and climate similar to that at the present day persisting until about 140 ka AP;
h) A biosphere transition over a timescale of several thousand years to a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day;
i) A biosphere state with a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day persisting to 170 ka AP;
j) A biosphere transition over a timescale of a few thousand years to a landscape similar in form to that at the present day, but with EC climatic conditions, discontinuous permafrost and tundra-type vegetation;
k) A biosphere state with a landscape similar in form to that at the present day, but with EC climatic conditions, discontinuous permafrost and tundra-type vegetation persisting to the end of the study period at 200 ka AP.

Taking into account the overall commentaries on scenarios B3 and B4, some further simplification was then made. Biosphere state (c) is reached rapidly and may even have been attained by the end of the institutional control period that would be expected to follow repository operations and closure. Therefore, from this scenario biosphere state (c), transition (d) and state (e) are of particular interest. The degree of cooling toward the end of the study period is very much less than in scenario A4, so transitions to colder states and the colder states themselves are more usefully studied in the latter context.

Thus, from scenario A4, it was considerd useful to address biosphere state (a), transition (b) and state (c). The glacial episode encompassing transition (d), state (e) and transition (f) was also considered of interest. However, the cooling episode encompassing state (g), transition (h) and state (i) exhibits only limited differences from the sequence state (a), transition (b) and state (c). It was not, therefore, considered to require detailed analysis. However, the further cooling from state (i) through transition (j) to state (k) was considered to require consideration, particularly because of the relatively long duration of state (k).

Thus, the states requiring consideration were identified as:

1) A biosphere state with a landscape and climate similar to that at the present day;

2) A biosphere state with a landscape similar to that at the present day, but with a climate with an annual mean temperature between 3 and 6°C warmer;

3) A biosphere state with a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day;

4) A glacial biosphere state with a mean annual temperature of about -5°C, the existence of discontinuous permafrost and tundra vegetation persisting for a few thousand years;

5) A biosphere state with a landscape similar in form to that at the present day, but with EC climatic conditions, discontinuous permafrost and tundra-type vegetation.

The transitions between these states that were considered to be of particular interest are:
[2–>1] over a timescale of tens of thousands of years;
[1–>3] over a timescale of a few thousand years;
[3–>4] over a timescale of about 5 ka;
[4–>1] over a timescale of about 12 ka;
[3–>5] over a timescale of a few thousand years.

Characterisation of the identified states is discussed in Section 5.3 and characterisation of identified transitions is discussed in Section 5.4.

5.3. - Characterisation of the Identified States for Performance Assessment Purposes

The characterisation process required the generation of tables of the standard BIOMASS (2003) form in which the generic classificatory material (see Appendix A) was replaced by information specific to the states. The tables required relate to:

- Climate type
- Characteristics of water bodies
- Human community types
- Ecosystems
- Soil types
- Topography

In each case, it was found convenient to provide descriptions relative to the present day, as the tables were later used in characterising transitions between states. Illustrative tables relating to water bodies and human community types for Central England are shown below, to illustrate the approach adopted.

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Characteristics of Water Bodies in Central England compared with Present

State	Characteristics
1	Mainly flowing rivers and streams. Substantial lakes and wetlands are uncommon, but do occur. Estuarine environments are present. Rivers and estuaries discharge to shallow coastal waters.
2	Stream and river flow reduced in summer, with some smaller streams becoming ephemeral. Increases in winter precipitation could result in increased channel sizes. Summer flows might not fill these channels from bank to bank. Groundwater resources would be less than at present. Regional water levels would be lower and spring lines would be shifted downslope. Global sea-level rise of a few metres would result in inundation of estuaries and low-lying farmland and wetland areas, e.g. the fens and Norfolk Broads. Increases in surface-water storage to ensure better capture of winter precipitation for subsequent use in the hotter, somewhat drier, summers.
3	Overall annual moisture excess. Groundwater levels higher than at the present day. Marshes are likely to be extensive in depressions and along water courses and requirements are likely to be for drainage rather than surface water storage. However, the main land use is likely to be for animal husbandry and resource utilization is likely to be reduced relative to the present day, so there will be a limited requirement to drain wetland areas. Sea-level is likely to be a few metres to tens of metres lower than at present, so surface drainage systems will extend across the current offshore continental shelf. Indeed, land bridges may develop between Britain, Ireland and the Continent. Lakes and wetlands could be a major feature of the current offshore areas, as these are likely to exhibit only limited topographic variability.
4	Tundra type environment. Extensive wetlands in lowland areas. Sea-level is likely to be some tens of metres lower than at present, so surface drainage systems will extend across the current offshore continental shelf. Indeed, land bridges may exist between Britain, Ireland and the Continent. Lakes and wetlands could be a major feature of the current offshore areas, as these are likely to exhibit only limited topographic variability. The main distinction from State 3 is due to the very cold winters. These would lead to extensive snowpack development and the freezing of rivers and streams. The spring melt would be associated with ice dams in the rivers and very high peak flows. Stream channel sizes would be adjusted to these high peak flows. Groundwater flow patterns would be affected by discontinuous permafrost and the seasonal freezing of soil water. Ice-sheet formation would be limited to the north-western upland areas, so Central England would not be glaciated.
5	Overall annual moisture excess. Groundwater levels higher than at the present day. Marshes are likely to be extensive in depressions and along water courses and requirements are likely to be for drainage rather than surface water storage. However, the main land use is likely to be for animal husbandry and resource utilization is likely to be reduced relative to the present day, so there will be a limited requirement to drain wetland areas. Sea-level is likely to be some tens of metres lower than at present, so surface drainage systems will extend across the current offshore continental shelf. Indeed, land bridges may exist between Britain, Ireland and the Continent. Lakes and wetlands could be a major feature of the current offshore areas, as these are likely to exhibit only limited topographic variability. The main distinction from State 3 is due to the very cold winters. These would lead to extensive snowpack development and the freezing of rivers and streams. The spring melt would be associated with ice dams in the rivers and very high peak flows. Stream channel sizes would be adjusted to these high peak flows. Groundwater flow patterns would be affected by discontinuous permafrost and the seasonal freezing of soil water. Ice-sheet development in Britain is not considered likely to occur.

Classification of Human Community Types in Central England based on Socio-economic and Environmental Considerations			
State	**Trading**	**Biosphere Control**	**Community Types and Activities**
1	Large-scale	High	Commercial agriculture and horticulture. More limited silviculture (but some deciduous and coniferous woodland management on more marginal land, e.g. heathland). Large-scale mixed farming characteristic with extensive monoproduction of edible and some non-edible crops. Hamlets, villages, market towns and cities in a trading network. Fish farming not extensive. Some water plants (watercress) from streams. Glasshouse horticulture for specialist purposes only (e.g. early fruit, decorative plants for cut flowers and gardens). Range of small scale commercial agricultural practices in market towns, but only a small percentage of the population engaged directly or indirectly in agricultural activities. However, garden cultivation of fruit and vegetables common. Extensive use of groundwater and surface water resources for agricultural and domestic irrigation in some drier areas, e.g. East Anglia.
2	Large-scale	High	Agriculture as at the present day, but with a greater degree of irrigation of high value fruit and vegetable crops. Probably not sufficiently dry in summer to justify irrigation of pasture. Increased yields of most crops (particularly with irrigation) and possibly more than one harvest per year for some crop types. No substantial difference in human community characteristics and infrastructure relative to the present day.
3	Large-scale or small scale	High	Largely treeless landscape. Agriculture dominated by animal husbandry, with land given over to summer grass for either summer grazing or hay production. Animals over-wintered indoors. Some arable cultivation of vegetables and barley in areas of least severe climate. Extensive areas of semi-natural vegetation comprising low-growing shrubs. Small scale trading would occur with widely dispersed small villages, hamlets and isolated homesteads. However, it would be possible to sustain a mix of urban and rural communities, as at the present day.
4	None	None	Natural vegetation of the tundra type. Land use primarily herding and hunting. Communities mainly located close to the coastline with a substantial reliance on marine organisms in their diet. However, the coastline would have retreated considerably due to eustatic sea-level fall.
5	Small scale	High	The natural vegetation would be low shrub and herb vegetation characteristic of tundra environments. However, agricultural systems and human communities could closely resemble those under State 3. The more extreme conditions would tend to favour small scale trading with few market or urban centres.

Development of conceptual models based on these descriptive tables was not taken further. However, this process is well illustrated for Example Reference Biosphere 2B in BIOMASS (2003).

5.4. - Characterisation of the Identified Transitions for Performance Assessment Purposes

As described in Section 4.4 and the introduction to this section, the characterisation of transitions began with the development of transition diagrams. The generation of such diagrams is essentially an expert elicitation. If undertaken in the context of a PA underlying a safety case, it would properly be conducted using a well-defined formal procedure. However, within the scope of BIOCLIM, only a more informal elicitation could be conducted and substantial parts of the interaction diagrams were drawn up by individuals and only subsequently scrutinised by other members of the team. Thus, the interaction matrices that have been developed should be considered as illustrative rather than definitive.

The interaction matrices for Central England are provided in Section C.1.6 and that for the transition State 2 to State 1 (States as defined in Section 5.3) is shown below.

State 2 to State 1 over tens of thousands of years.				
TOPOGRAPHY	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	**SOILS AND LITHOLOGY**	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
Limited coastal retreat with sea-level fall of a few metres due to thermal contraction.	No substantial influences identified. However, the long period of interglacial conditions may lead to soils developing to a no analogue codition with continued irrigation.	**WATER BODIES**	No substantial influences identified.	Limited coastal retreat of little influence on human communities due to the long period involved.
No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	**BIOTA**	No substantial influences identified.
No substantial influences identified.	No substantial influences identified.	Reducing demand for irrigation water coupled to increasing supply is likely to lead to decreasing demand for surface water storage, but the trend will be very slow.	Changes in crop types and reduced yields.	**HUMAN COMMUNITIES**

This is a particularly simple example. However, it should be noted that the matrix is fully completed and that where no substantial influences are identified this is specifically recorded.

This interaction matrix is complemented by an associated transition diagram, as reproduced in Figure 5.1.

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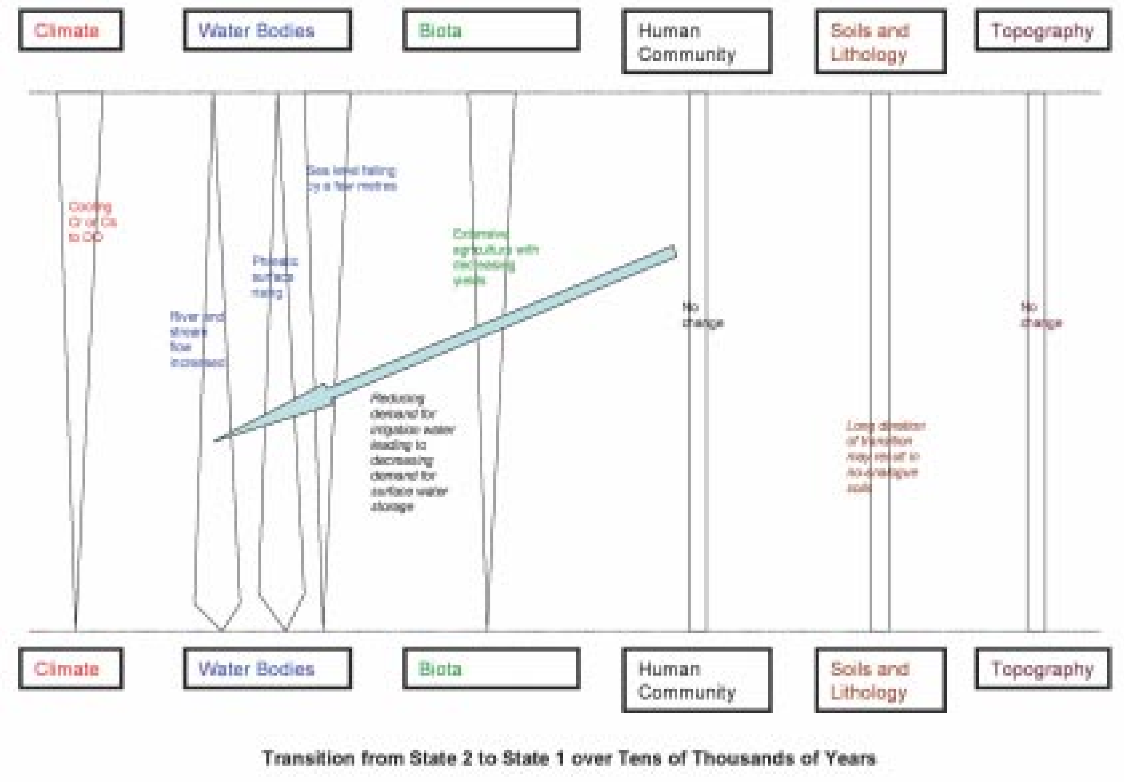

***Figure 5.1:** Transition Diagram for State 2 to State 1 for Central England*

Vertical arrows are used to indicate increasing, decreasing or stationary trends in the principal components. In this case, the main interaction is that an unchanging human community makes different demands on water resources because of changes in the surface hydrological regime.

More complex interaction matrices and associated transition diagrams are illustrated for the five study areas in Appendix C.

6. Discussion and Conclusions

6.1. - Overall Results of BIOCLIM

Overall, BIOCLIM can be considered to have made six major achievements.

1. A substantial synopsis has been provided of mechanisms of climate change and the methods used by the waste management agencies at the start of the project to represent such changes in radiological assessments. A coherent compilation of palaeological data for the last glacial-interglacial cycle for the regions of interest in England, France, Spain, Germany and the Czech Republic has been made. This involved a novel interpretation of those data for subsequent use in the downscaling analyses.
2. A demonstration has been made of how a hierarchy of climate models can be used in a cascade mode to obtain global and regional data on climate and vegetation changes for various time slices over very long timescales. Further developments to refine and extend the methods used should be possible in the future, as required.
3. Considerable developments have been made to state-of-the-art EMICs. These EMICs are now capable of continuous simulation of climate change over future timescales of 200 ka or more, forced by coherent scenarios of variations in insolation and atmospheric carbon dioxide concentrations.
4. Various downscaling methodologies have been developed to allow climate model output to be incorporated in PA. In particular, these downscaling methodologies have been developed through close consultations between climatologists and PA specialists. They are, therefore, conditioned both by what can legitimately be asked of climate models and what information is useful for performance assessment purposes.
5. The BIOMASS methodology has been successfully augmented such that biosphere system descriptions included in PA can incorporate transitions between different environmental states over long timescales.
6. Both interim and final results from the project have been comprehensively reported and archived in such as way as to provide a substantial resource for future PA activities, including conceptual and mathematical model development.

6.2. - Discussion and Conclusions related to Climate Modelling

BIOCLIM has delivered a comprehensive methodology for incorporating climate-driven environmental change into the biosphere component of PA. Furthermore, the project has provided a substantial body of climatic modelling results for Europe. These results represent an important resource for national organisations wanting to include future climate change in PA.

However, it should be recognised that environmental change is not driven solely by alterations in climate. Earth processes may also have an effect and, probably more importantly, human actions can substantially modify the landscape. In BIOCLIM, human activities modifying the landscape were considered only if they arose directly as a consequence of climate change. Hence, there is room to expand the narratives that have been developed to include an account of the potential effects of human actions.

At a more technical level, although BIOCLIM has included innovative work on EMICs, it should be recognised that this type of model is at an early stage of development. Substantial differences were identified in the results obtained from the various EMICs used in BIOCLIM. These models will undoubtedly be developed further over the next few years and there will be a need to continue to apply them over the long future timescales of interest in solid radioactive waste disposal, to ensure that an appropriate range of scenarios is identified and addressed. Also, in BIOCLIM, only a single GCM was used and this was recognised as having a particularly low sensitivity to increased carbon dioxide concentrations in the atmosphere. Thus, there would be advantages in exploring uncertainties in modelling through the use of a larger ensemble of models. In particular, the models used in BIOCLIM were not very appropriate for exploring issues of abrupt climate change, as might occur for example by rearrangement of the thermohaline circulation. This is a rapidly developing research area (NAS, 2002) that should be kept under review.

Although it is clear that both EMICs and GCMs have an important role to play in the development of scenarios for PA, it is not clear that RCMs have such a role. Within BIOCLIM, RCM results were only available for a single year within each snapshot period and the particular model used exhibited a substantial cold bias. Furthermore, the climate results that were found to be most useful in scenario development were found to be semi-quantative. Given this observation and the high resource requirements of RCMs, it is doubtful whether their deployment provides much added value and limited resources are probably better used to explore uncertainties at the EMIC and GCM scales.

Notwithstanding, the above remarks, it has become clear, from combining output from WP2 and WP3, that multiple models and various downscaling methods can provide a robust picture of potential climate changes for the purposes of scenario development. In particular, the required inputs for PA are best obtained from use of EMICs to characterise long-term trends and GCMs applied in snapshot mode to give more detailed information at specific times. It was also found that the different downscaling techniques applied were complementary and that comparisons of the results obtained were extremely useful in quantifying uncertainties and in conditioning the narratives that were developed.

It should be recalled that the climate modelling was based on a limited number of emissions scenarios. However, these included both low and high anthropogenic emissions and a natural scenario without anthropogenic emissions, so guidance is available on a reasonable range of future possibilities. Although greenhouse-warmed scenarios should be included in PA, natural evolution scenarios can usefully also be included for confidence building, as the environmental conditions described can be more closely related to palaeoenvironmental data. A further important point is that these scenarios are also strongly conditioned by the persistence of enhanced carbon dioxide levels in the atmosphere. A single multi-component model was used to represent this. However, carbon-cycle modelling and incorporation of the global carbon cycle in climate models are active research issues. This matter needs to be kept under review, as changing views on the persistence of atmospheric carbon dioxide could substantially influence the scenarios developed in BIOCLIM.

6.3. - Discussion and Conclusions related to Performance Assessments

At the beginning of BIOCLIM, there was anticipation amongst the climate modellers that detailed quantitative results of their models would be required to inform PA. However, in practice, the development of narratives is an essential element of the methodology to transform climate change scenarios into environmental change scenarios for use in PA. These narratives are dependent on the broad pattern of climate modelling results, rather than quantitative details. Indeed, to prevent proliferation of scenarios that have to be studied in a PA context, it is desirable to subsume various specific climate change scenarios into a smaller number of generalised environmental change scenarios. However, when representative instances of these generalised environmental change scenarios are modelled for PA purposes, it is likely to be useful to select specific quantitative climatic data to ensure internal self-consistency of the model calculations. Thus, results from the climate models are likely to be used both semi-quantitatively in narrative development and more quantitatively as input to the computational PA models developed or used to represent aspects of those narratives.

It was not clear at the outset of BIOCLIM whether representation of environmental change in terms of states and transitions would prove suitable for the biosphere component of PA. However, examination of scenarios for the five study regions included in BIOCLIM demonstrated that a description in terms of states and transitions was appropriate. However, none of the regions was considered to be directly impacted by an ice-sheet advance within the next 200 ka. Direct or ice-marginal effects could result in a revision of this view, but it seems more likely that they could be appropriately represented within an additional type of transition.

Furthermore, it was found that the BIOMASS methodology, with some minor modifications, was suitable both for characterising individual biosphere states and for providing a framework for analysing transitions. It was noted that there was not a one-to-one correspondence between the environmental states and transitions of relevance to PA and the climate states used in developing the narratives of environmental change.

In extending the BIOMASS methodology to characterise transitions, it was found to be useful to develop an interaction-matrix-based approach. Interaction matrices were used within BIOMASS, but not in this role. However, interaction matrices cannot readily be used to represent temporal aspects of succession or influence. Therefore, transition diagrams were developed as a complement to the matrices. Although these tools are simple in principle, they provide a powerful framework for structuring elicitations of information, recording results and demonstrating the comprehensive nature of the assessment process.

Although the development of conceptual and mathematical models of the identified states and transitions was outside the BIOCLIM framework, detailed scrutiny of the narratives, system descriptions, interaction matrices and transition diagrams did not reveal any areas in which this further extension of the work would be likely to pose major difficulties. Again, a caveat on this conclusion is that none of the scenarios involved ice-sheet advance or retreat over a region of interest.

Because of limitations in the scope of climate modelling undertaken in BIOCLIM and the somewhat informal way that narratives were developed and analysed, it is likely that national organisations developing site-specific safety cases would wish to complement the BIOCLIM work with additional climate modelling and formal scenario analyses using the methodology developed and applied in BIOCLIM. However, it is likely that such work would generally refine and confirm the results presented here, rather than leading to radically different conclusions.

One major consideration for PA that should not be overlooked, is that BIOCLIM has demonstrated how scientifically plausible and justified estimates of environmental change can be factored into the more schematic scenarios that are necessarily used in PA. Detailed climatological modelling, using the best available tools, was used to produce quantitative and internally self-consistent results. These results were exported and combined with assessment-related information through the development of narratives. Such narratives can be related to climate model outputs, palaeoenvironmental data that provide guidance on constraints on, or modes of, landscape evolution, and also to regulatory issues, such as the types of potentially exposed groups that should be considered to exist and the nature of their exploitation of the environment. The narrative thus provides a primary interface between scientific knowledge and regulatory judgment.

Although these remarks are made in a biosphere context, they apply more widely to the whole disposal system. In this wider context, issues of spatial scale arise. Whereas climate states can be described at spatial scales ranging from global through regional to

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local, environmental states and transitions are properly described at a regional or local scale, as has been done in Appendix C. It is likely to be useful to obtain agreement between waste management organisations on the climate scenarios to be modelled at the global scale, so that downscaling to local circumstances is based on an agreed set of global climate-change scenarios. The scenarios studied in BIOCLIM represent a first step on that path. Having agreed such scenarios, downscaling to local conditions can be performed using the types of techniques developed in BIOCLIM. Climatological downscaling should be to the regional or local level depending upon the degree to which local factors such as altitude and aspect need to be taken into account. For the biosphere, environmental change will typically need to be described at the local scale only. However, if the disposal system as a whole is considered, then environmental change may have to be addressed at both the regional and local scales, e.g. to capture the effects of changing climate on regional groundwater flow patterns.

Whereas the narratives discussed above include consideration of the timing and duration of the climate states and transitions, the next step of abstraction is the identification of those states and transitions that are of particular relevance to PA. As different scenarios will result in variations in the duration and timing of the states and transitions, additional robustness can be built into the assessment process by assuming that the timing and duration is subject to substantial uncertainty and imposing the relevant states and transitions at a wide variety of times in the future. In this way, key states and transitions could be imposed on the system at those times when fluxes of particular radionuclides from the geosphere to the biosphere are at their maximum values. In addition, the consequences of transitions could be analysed in sensitivity studies in which the duration of the transition is increased or decreased to determine the effects on PA results.

It is interesting to note that the narratives developed in Appendix C lead to only a small number of transitions of interest. In particular, not all the transitions that could, in principle, occur are identified as relevant to the scenarios under consideration. It is likely that the set of transitions requiring detailed study could be further reduced by scoping calculations to demonstrate that their radiological impacts are bounded by those of the immediately preceding or following states. Only those transitions that incorporate characteristic transient accumulation and release mechanisms for radionuclides in environmental media are likely to require detailed specific study.

7. Discussion of Implications for future Applications and development of the Methodology

The NEA (2004) has drawn attention to the need to present results from PAs over different timeframes. Time frames can provide a useful framework for internal discussions among experts within an implementing organisation, between implementers and regulators, and between implementers, regulators and the public. The climate change scenarios and environmental implications analysed in BIOCLIM are of greatest relevance to the longest time periods, typically 1000 years or more (often much more) post-closure when engineered barriers have failed and radionuclides have begun to migrate through the host rock toward the biosphere. Although, as mentioned in Section 6, waste management agencies are likely to wish to conduct studies additional to those reported in BIOCLIM, the climate modelling results already provide a substantial basis for PAs in various regions of Europe. Furthermore, the narratives that have been developed can immediately be used to provide coherent descriptions and linked conceptual models of radionuclide migration from the geosphere to the biosphere, and of radionuclide transport through the biosphere, in the various regional contexts. Additionally, the quantitative climatic data available can be used as input to mathematical models of the geosphere and biosphere based on those underpinning conceptual models. Although the project itself was concerned only with biosphere implications, the scope of work has been such that application of the results to overall disposal system performance is appropriate. Furthermore, although the work was not targeted at specific sites, the narratives and associated analyses can be readily adapted to specific sites. In particular, it is emphasised that there is considerable commonality in environmental processes across Europe in changing climatic conditions and aspects that are not discussed in detail in Appendic C in the context of one of the regions are often elaborated for one of the others. Thus, for example, the deposition and characteristics of loess are discussed in the context of the Czech Republic, fluvial denudation is described in most detail for Central England and soil evolution is emphasised in the discussion relating to Germany.

The main outstanding requirement is now to apply the methodology that has been developed and the underlying database of climatological results in existing models. In particular, the data are directly relevant to modelling groundwater flow and near-surface hydrology, as well as providing information relevant to the configuration and parameterisation of biosphere models. It seems likely that such applications will reveal a need to extend and clarify some aspects of the methodology. However, it is believed that the overall framework is robust and that much of the detail will remain appropriate.

With respect to extension of the methodology, in the biosphere, although human community is one of the principal components in the description, the issue of definition of potentially exposed groups within those communities has not been addressed. A useful extension to the work would be to development of a matrix of descriptions of potentially exposed groups appropriate to the climate states and transitions that have been identified as being of interest.

No major requirements are identified for climate research in direct support of PA. Further development and refinement of climate models will undoubtedly occur as part of the overall rearch programme of the climatological community. Whereas new results from appropriate simulations and, in particular, explorations of uncertainties using ensembles of models will clearly inform scenario development, it is not considered likely that such development and refinement will substantially affect how climate models are used in support of PA. However, one exception to this could be research into abrupt climate change. If further modelling studies and field investigations determine that substantial, abrupt climate change is likely in the next few hundred years, e.g. through complete switching off of the thermohaline circulation, this could have substantial implications for the siting and operational phases of deep geological repositories.

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Appendix A - The BIOMASS Methodology for Biosphere System Identification and Description

A1. Procedure for System Identification and Justification

The approach to biosphere system identification and justification is presented as a decision tree in Figure A1.

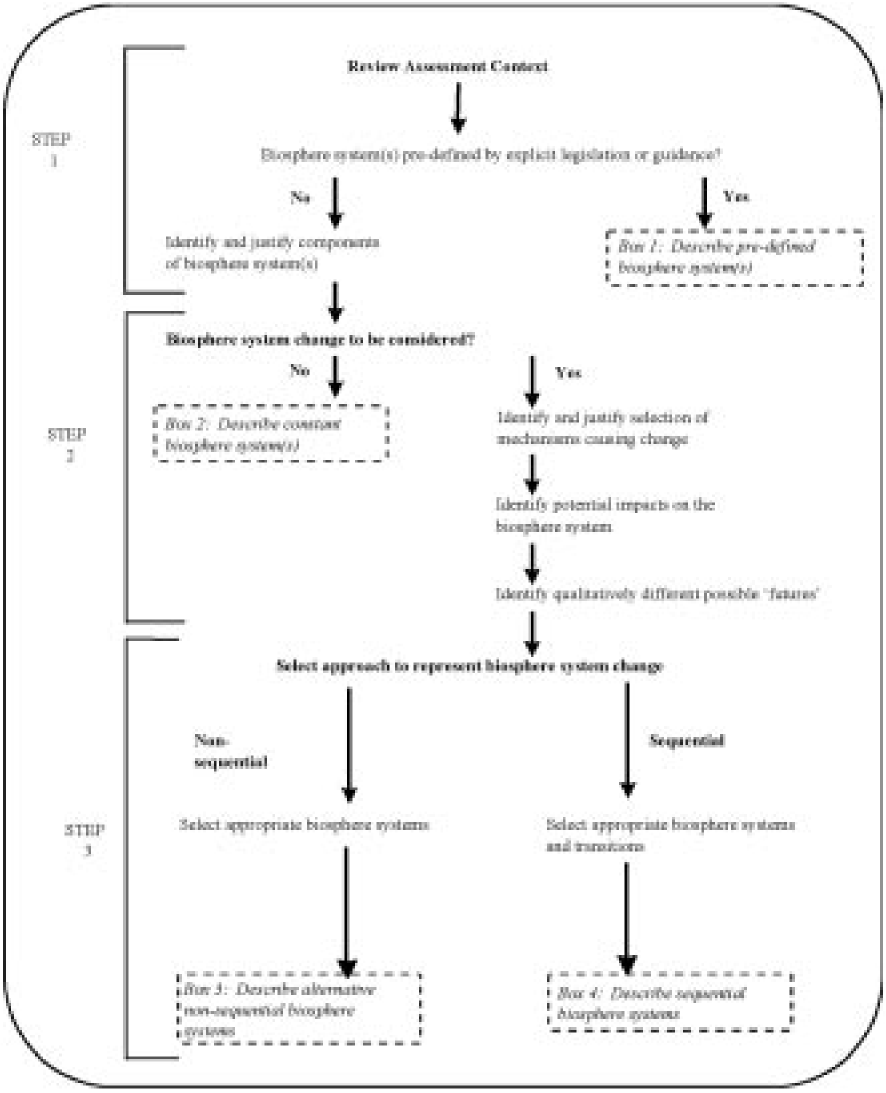

Figure A1: *Decision Tree for Identification and Justification of Biosphere Systems*

In summary, the overall approach consists of up to three steps. In Step 1, the assessment context is reviewed to establish whether or not it pre-defines the biosphere system(s) that are to be considered. If it does not, the components of the biosphere system(s) to be represented are identified and justified according to an interpretation of the assessment requirements, taking account of the site context. In Step 2, with further guidance from the assessment context, a decision is taken as to whether or not biosphere system change is to be considered. If biosphere change needs to be addressed, the mechanisms responsible for change are identified and their associated potential impacts on the biosphere system described. These changes are then linked together as one or more narratives of the anticipated possible future evolution of the biosphere system. Finally, in Step 3, an approach is selected for representing the implications of biosphere system change within the assessment.

A1.1. - Step 1: Review the assessment context

When attempting to identify and justify the biosphere system to be considered, the first step is to review the information provided by the assessment context that is pertinent to the case. (The components of the assessment context are set out in BIOMASS (2003).)

There are basically two main situations, as shown in Figure A1, and these are described in the following sub-sections.

A1.1.1 - Biosphere system pre-defined by explicit legislation or guidance

At one extreme, the assessment context might state that the biosphere system to be assessed is pre-defined by explicit legislation/guidance, or by those commissioning the assessment. For example, it might be stated that the assessment biosphere system should represent the current biosphere system at the disposal site. The system can then be described (see below) from the predefined system. This was the case (for example) in the 1998 assessment of proposed high-level radioactive waste (HLW) disposal at Yucca Mountain undertaken by the United States Department of Energy (USDOE) (Tappen 1997).

A1.1.2 - Biosphere system not pre-defined by explicit legislation or guidance

More commonly, the assessment context only loosely constrains the system to be considered. For example, current French regulations require consideration of typical biospheres representative of the different climate states which might occur in the future at a disposal site, but the biosphere systems to be assessed are not pre-defined. In such cases, it is necessary to consider all potentially relevant components of the assessment context.

Such information should provide a starting point for identifying and justifying the biosphere system to be considered for the given assessment context. Through a review of the assessment context, it should be possible to identify some initial information concerning the biosphere systems that need to be considered in the assessment. To allow for a clear identification and further description, the biosphere system is defined through a set of components that are referred to as “principal components” of the biosphere system.

These principal components are listed below:

- **Climate and atmosphere**. Climate is the expression of meteorological parameters such as temperature, precipitation, evaporation, wind speed and direction over an area. These parameters should be described so that they are consistent with the other principal components of the biosphere system and/or on the basis of the assessment context. At a minimum, information should be provided concerning the broad classification of the assumed climate state(s) e.g. temperate, boreal etc. Climate will often have a profound effect on many of the other biosphere system principal components. Atmosphere is defined in terms of the composition of the air.
- **Topography** is the configuration of the earth's surface including its relief and relative positions of natural and man-made features. Information should be provided concerning the features of the system under consideration and its relief.
- **Human community** describes the nature of communities (e.g. agrarian vs industrial); their habits; their level of technological development; and their degree of subsistence. This principal component of the biosphere system provides an indication of how humans utilise/exploit the environment/resources and the extent to which humans have disturbed or continue to disturb their environment.
- **Near-surface lithostratigraphy** describes the general characteristics of soils and sediments including both their composition and structure. It includes all weathered material above the bedrock and associated life forms (excluding those predefined under biota). It can include bedrocks if they contain aquifers which are considered to be within the biosphere.
- **Water bodies** are the surface and subsurface water masses e.g. lakes, rivers, wetlands, seas, and estuaries. These may include near-surface aquifers and ice-sheets. At a minimum, information should be provided as to whether such features are present in the biosphere system.
- **Biota** are the terrestrial and aquatic plant and animal life in the biosphere system. A distinction should be made between domestic and wild flora and fauna, and between those flora and fauna that are in the human food chain and those which are not but which are used by humans for purposes other than food.

The following two items are additionally considered at this stage of system identification, if they have not been adequately specified in the assessment context.

- **Geographical extent** defines the boundaries/spatial domain of biosphere that is to be described. At a minimum, the area over which direct contamination of the biosphere may occur should be considered. It should be recognised that the extent might change as a function of time. Additional issues to consider when defining the geographical extent include: the end-point(s) of interest; human activities, especially resource area requirements; and the nature of the geosphere-biosphere interface. If the assessment end-points (one of the components of the assessment context) include collective dose to the world population, then the biosphere system will be global in scale. If, however, the sole end-point is individual dose to members of a hypothetical exposure group living in the vicinity of the discharge from the repository, then the biosphere system might be restricted to the area around the discharge location.
- **Location** is the position of the biosphere system on the earth's surface. Information concerning latitude and longitude should be provided for site-specific contexts. For more generic situations less specific information might be available and might be restricted to more general information, for example whether the system is coastal or inland, and information describing its distance from the sea and altitude.

In order to assist with the process of biosphere system identification, BIOMASS created a set of classification schemes (see Annex A) that relate to certain basic categories for each of the biosphere system principal components. Such classification schemes also provide the necessary primary information to guide development of the biosphere system description to the level of detail required for modelling purposes. A summary that relates each of the principal components of the biosphere system, identified above, to the classification tables and characteristics used for the detailed biosphere system description is given in Table A1.

Natural correlations or dependencies between different biosphere system components (principal components and/or principal component types) can be identified, which provide overall coherency and justification for the assumptions that are made. Hence, for example, for a given climate type, the corresponding natural vegetation and soil types can be broadly defined using generally accepted relational schemes. Such an approach allows for completion of biosphere system component identification in situations (assessment contexts) where no other more specific or verifiable information is available. The classification schemes given in Annex A are offered as practical and useful, but alternatives could be used.

Biosphere system components			**Characteristics (System Description)**	
Principal components *(Related Scientific Areas)*	**Classification/Principal component types (System Identification)**			
CLIMATE *(Climatology / Meteorology)*	Climate Classification	Table CI	Climate Characteristics	Table CII
WATER BODIES *(Hydrology / Hydrogeology / Hydrochemistry)*	Water Body Types	Table WI	Water Body Characteristics	Table WII
HUMAN ACTIVITIES *(Anthropology / Sociology)*	Human Community Types/Activities	Table HI	Human Community use of biosphere system components	Table HII
BIOTA *(Ecology)*	Types of Aquatic and Terrestrial Ecosystem	Table BI	Composition of biotic community Patterns of biotic communities	Table BII
NEAR-SURFACE LITHOSTRATIRAPHY *(Geology / Geomorphology / Edaphology)*	• Rock Types • Zonal Soil Types and Sediment Types	Table GI Table SI	• Geological Characteristics • Soils and Sediment Characteristics	Table GII
TOPOGRAPHY *(Geography)*	Topographical Categories	Table TI	Topographic Characteristics	Table TII

Table A1: *Organisation Scheme relating Principal Components of the Biosphere System and corresponding Scientific Areas to Tables listing Classification Schemes and Characteristics (see Annex A)*

The starting point in identifying and justifying representative biosphere systems usually focus on decisions relating to the type of climate and human activities in relation to the environment. Soils, vegetation and certain aspects of human behaviour are all influenced strongly by climate. Therefore, in identifying the ecosystems that are to comprise an assessment biosphere, assumptions relating to climate will usually be a primary concern, which points to the importance of BIOCLIM. Similarly, assumptions related to human activities will also be of major importance. This is because human communities can have a strong influence on the type of environmental system that is present and also because radiological exposures will depend on what people are assumed to do. Such assumptions should be consistent with the context of the assessment. They will represent primary drivers in the biosphere system identification and description process.

Depending on the assumed degree of human control or management over the biosphere system, the decision line for the process of system identification can be driven in one of two ways. If strong control or management by the human community over the biosphere system is assumed, this will be a necessary prior assumption, leading to the identification of other biosphere system components. Alternatively, if only weak control or management over the system is assumed, the system identification process can be driven by assumptions relating to climate.

A1.2. - Step 2: Consideration of biosphere system change

It is recognised that biosphere systems are intrinsically dynamic (for example sedimentation in a water body, or the meandering of a river). In some systems, the combination of processes responsible for dynamic behaviour may (over time) be in balance and the biosphere system can then be considered to be in a state of dynamic quasi-equilibrium. For example, the sedimentation rate in a water body may be equivalent (over a given time period) to a rate at which sediment is removed by erosion or dredging, as assumed in BIOMASS Example Reference Biosphere 2B (BIOMASS, 2003). It is possible to represent biosphere systems, or sub-systems, where dynamic equilibrium is maintained as being time invariant: the dynamic processes operate (and contribute to contaminant migration and accumulation) but no apparent overall change occurs. However, if the processes responsible for mass transport in the biosphere system are assumed to be in dynamic equilibrium, it is important to ensure that the spatial and temporal frame, within which the assumption of equilibrium is valid, is explicitly stated. Often, however, the intrinsic dynamics of the biosphere system are not in any recognisable quasi-equilibrium, or the system may be influenced by agents of change that originate outside the immediate domain of interest. Such mechanisms can then result in fundamental changes to one or more biosphere system components e.g. the configuration and location of the water bodies may change with time.

Changes can occur over different temporal and spatial scales. Some, such as the clearance of woodland and its replacement by farmland, might occur over relatively short timescales. Others, such as the natural in-filling of a water body and associated ecosystem successions, may occur over longer timescales and can be considered to be gradual. There are different alternatives to be considered, which are developed further below, following the scheme represented in Figure A.1.

A1.2.1 - No biosphere system change

The assessment context may sometimes specify whether biosphere system change needs to be considered. If the assessment context states that system change does not need to be considered, then the use of a time invariant (constant) biosphere system, or alternative systems, is appropriate. The biosphere system(s) identified through the review of the assessment context (Step 1) can then be used to represent the unchanging biosphere. The system can then be described according to the approach given in Section A2. This approach has previously been used in biosphere assessment for a number of HLW disposal concepts, for example the Electric Power Research Institute (EPRI) assessment of Yucca Mountain (Smith et al., 1996). It has the advantage of simplicity and provides an illustration of the consequences that might arise at the time of radionuclide release from the geosphere into the biosphere. However, it does not necessarily represent the range of systems that might exist during the time of the release for a particular site, or address issues associated with the sequence in which change may take place.

A1.2.2 - Biosphere system change

If there is no explicit guidance from the assessment context, or if the assessment context expressly requires biosphere system change be considered, the following questions need to be addressed:

— what are the relevant mechanisms causing environmental change?

— what are the potential impacts of the resultant environmental change on the biosphere system?

When considering these questions, relevant information from the assessment context, in particular the timeframes of interest and the nature of the assessment end-points, should be reviewed, alongside basic hypotheses relating to the way in which potential exposure group(s) will be defined. This will help to guide identification of the relevant mechanisms for change and description of their impacts on the biosphere system for the case under consideration. In practice, some biosphere system components may be assumed to evolve with time, whereas others will be taken to remain in dynamic equilibrium. Such 'mixed' approaches are included under the general heading of biosphere system change.

Step 2.1: Identification of mechanisms causing environmental change

Apart from processes, such as erosion and sedimentation, that are internal to the biosphere system, the external driving mechanisms responsible for environmental change can be divided into natural mechanisms (long-term landform and climatically controlled environmental changes) and human actions.

The influence diagram shown in Figure A2 provides a hierarchical illustration of the relationships between different mechanisms that together, over various timescales, may be capable of modifying the features and characteristics of a given biosphere system. Because such sources of change will typically have their origin outside the restricted domain that is of interest in describing an assessment biosphere, they are identified for convenience as External FEPs, or EFEPs. The influence diagram representation is intended to promote identification and analysis of relevant interactions between EFEPs, which is important in developing a coherent picture of their combined impact on the future evolution of the system.

This schematic model provides for clear identification of the primary system drivers, or initiators of change (shown in bold in Figure A2), whose effects are then propagated through the External Environment. A specific point of note in this context is that one potential mechanism of landform change (regional isostacy) can be both an initiator of change (in so far as it may be an element of the present-day regional context) as well as a response to other changes (such as ice-loading).

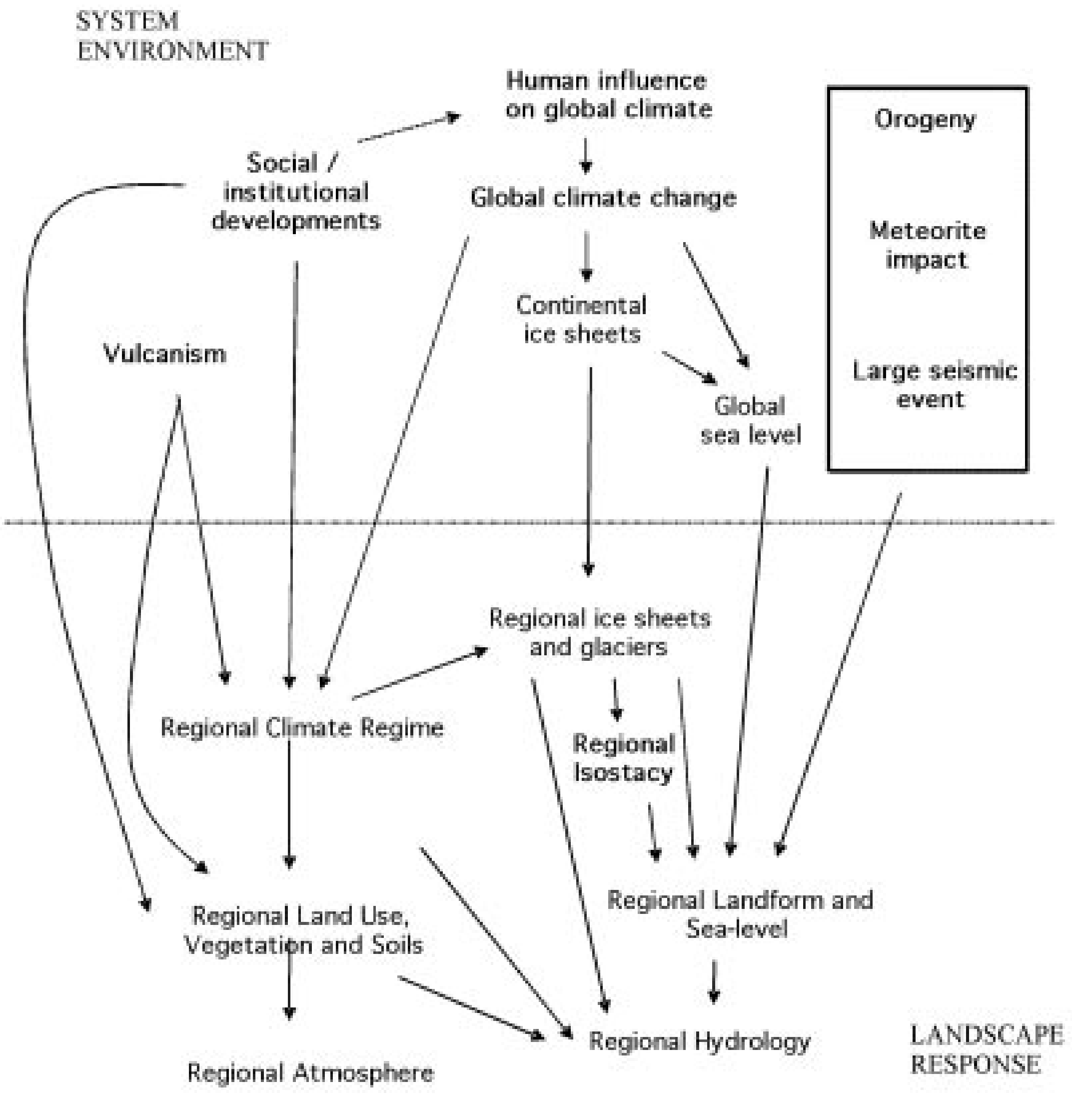

Figure A2: *Influence Diagram Representation of EFEPs and their Relationships*

Consideration of mechanisms of change and their associated impacts on the biosphere system (Step 2 of the procedure summarised in Figure A1) can then be undertaken, first via systematic screening of system drivers and then by evaluating the importance of links between EFEPs according to the particular assessment context under study. This allows an assessment-specific version of the influence diagram to be constructed, as a model of the relationships between EFEPs relevant to that assessment.

Whereas the regional response to changes occurring on a global scale may differ from one location to another, according to specific features and inherited characteristics of the landscape, global changes themselves can be characterised (e.g. through their time sequencing and magnitude) independently of any particular site or region. Hence, in developing practical descriptions of the mechanisms of biosphere system change and their effects, it can be helpful to make a distinction (as shown in Figure A2) between:

- — the main time-dependent drivers of environmental change, typically operating on a global scale (including both continuous change and sudden or intermittent events); and
- — the response to such drivers within the regional landscape.

Step 2.2: Identify potential impacts on the biosphere system

Biosphere system changes of potential relevance to long-term radiological assessment can be defined through consideration of the way in which biosphere system components respond to the changing landscape. Hence, drawing on consideration of changes occurring at a regional scale, it is necessary to consider how such changes influence the identification and description of the assessment biosphere. This requires consideration to be given to the internal dynamics of the process system, taking account of external influences on the system as the landscape evolves. A general mapping of the relationship between principal components and characteristics of the biosphere system and the corresponding properties of the regional landscape is shown in Figure A3.

Because of the strongly-coupled nature of interactions at the temporal and spatial scales relevant to describing the assessment biosphere, a practical approach is to use an interaction matrix (IM) representation of the dynamics of the biosphere system, based on interactions between biosphere system components, as the basis for considering possible changes. Modifications to the characteristics of leading diagonal elements of the IM, as a result of the action of regional-scale EFEPs, may be propagated through the system by tracing pathways of influence via off-diagonal elements of the matrix. A generic IM description of biosphere system dynamics, for use as a tool to investigate the internal dynamics of the assessment biosphere, is provided in Figure A4.

Step 2.3: Identify qualitatively different possible "futures"

In is envisaged that FEPs associated with off-diagonal elements of the IM would be highlighted in accordance with knowledge and understanding of the importance of the phenomena they represent as intrinsic mechanisms for change for a specific biosphere system. These can then be translated into descriptions of the sequence of change within the biosphere system, in response to changing boundary conditions.

It should not be forgotten that the characteristics of biosphere systems can also change as a result of disequilibria associated with their intrinsic dynamics (e.g. as a result of aeolian or fluvial erosion and deposition processes), regardless of any 'external' effects. In describing assumed change and its potential contribution to radiological impact within the assessment biosphere, it may be equally important to account for such intrinsic phenomena (summarised in the interaction matrix, Figure A3) as it is to consider global change and its expression in the regional landscape.

Principal Components of the Biosphere System	**Characteristics**	**Corresponding Regional Landscape Properties**
Local Climate	Rainfall, Temperature, Windspeed, Solar Radiation Atmosphere Characteristics	Regional Climate Regime Regional Landform Regional Land Use Regional Atmosphere
Geology	Unconsolidated Stratigraphy and Stratification	Regional Climate Regime Regional Landform Regional Hydrology
Soils and Sediments	Soil and Sediment Characteristics	Regional Hydrology Regional Land Use, Vegetation and Soils
Topography	Relief, Altitude	Regional Landform
Water Bodies	Flow Rate, Water Level, Suspended Load Ice Sheet Characteristics	Regional Hydrology Regional Landform Regional Ice Sheet and Glaciers
Human Activities	Human Behaviour Characteristics	Regional Climate Regional Land Use, Vegetation and Soils
Biota	Ecosystem Community Characteristics	Regional Land Use, Vegetation and Soils

Figure A3: *Identification of Relationship between the Principal Components of the Biosphere System and Regional Landscape Properties. The 'near-surface lithostratigraphy' has been split into 'geology' and 'soils and sediments'. This allows a clearer explanation of the interactions in Figure A4.*

Narrative descriptions of regional landscape evolution in response to global system drivers thus provide an evolving site context to guide the identification and description of the assessment biosphere. However, the issues involved in defining a representative assessment biosphere are not restricted to consideration of physical changes to the landscape. Just as is the case for time-independent systems, identification and description of the assessment biosphere also involves consideration of the assumed geosphere-biosphere interface and source term (defined – along with the site context – as part of the overall assessment context). Hence it is important that consideration of change within the assessment biosphere should also takes account of the changing regime for radionuclide release, according to the projected response of the overall disposal system to initiators of change at a regional scale.

Climate/	Weathering	Meteoric erosion	Level changes (e.g. evaporation, storm events) Deposition Freezing	Deposition Erosion Conditioning and moisture content (e.g. evaporation, freezing)	Environmental conditioning	Defines natural climax ecosystem, Affects transpiration rate. Storm damage
Contribution to dust load from eroded surface material, radon and other gas release	**Geology**	Definition of relief	Defines groundwater flow system and chemistry	Contribution to mineral composition (by weathering), gas release to soil/sediment	Availability of mineral resources. Type of geology affects construction practices	Nutrient support for microbial populations
Aspect effect on wind and insolation. Altitude effect on wind speed. Relief effect on boundary layer structure	No effect	**Topography**	Defines geometry (e.g. catchment areas, coastline) and hydrology (including mixing of meteoric and ground water)	Defines geographical extent relative to water bodies. Slope affects erosion rate and drainage characteristics	Relief affects size and type of community (e.g. capacity to develop agricultural systems and other land uses)	Relief affects characteristics of natural systems
Large water bodies influence seasonal temperature and humidity variation, local source/sink for heat and moisture	Erosion and dissolution (e.g. to form karst systems, geochemical reactions, freeze/thaw)	Erosion and dissoluton (e.g. downcutting of river bed, meandering, coastal processes)	**Water Bodies**	Sedimentation, erosion, mixing and suspension. Chemical conditioning by exchange with porewater.	Source, quality and quantity affects sustainability of community, recreational activities. Contribution to trace elements in diet	Source, quality and quantity affects type and behaviour of natural communities
Soil gas exchange with atmosphere	Diagenesis	Soil and sediment deposition influence the geometry (e.g. lake infilling, meandering and delta formation)	Contribution to sediment load. Chemical conditioning of meteoric water. Effect on flow field. Permeability of horizons contributes to geometry	**Soil / Sediments**	Soil moisture characteristics, structure and mineralogy affect potential utilisation. Source of fuel (peat)	Soil moisture characteristics, structure and mineralogy affect development of natural communities
Pollution, Creation of microclimates (buildings etc)	Quarrying and mining activities	Ground levelling	Hydrochemical conditioning (e.g. water treatment, waste water disposal). Extraction. Dam building. Augmentation	Agricultural practices, Dredging. Drainage systems	**Human Community**	Agriculture. Genetic manipulation. Population / ecosystem modification
Atmospheric composition (e.g. pollen and gas release). Microclimate development (e.g. wind break, boundary layer)	Biogeochemical conditioning by microbes	Effects assumed to be insignificant	Conditioning of flow, particulate load and hydrochemistry	Bioturbation. Conditioning, stabilisation & development. Control on moisture content (transpiration)	Natural resources. Disease vector	**Biota**

Figure A4: *Generic Interaction Matrix describing 'Intrinsic' Biosphere System Dynamics*

The key elements of Step 2 of the decision tree are therefore:

- Screen primary mechanisms for change based on their relevance to the assessment context, with particular reference to those EFEPs identified on Figure A2 as belonging to the System Environment.
- Identify possible time sequences of change to the System Environment, based on consideration of the attributes and characteristics (type, magnitude and timing of change) for the identified initiators, and propagating their influence through the upper part of the influence diagram.
- For each identified time sequence of interest, develop a coherent description of the regional landscape response by propagating projected changes to the System Environment through the lower part of the influence diagram, giving due consideration to disequilibria (leads and lags) in the response of the regional biosphere. One or more time series of broad-brush descriptions of the projected evolution of the landscape can then be defined.
- For each landscape evolution, relevant assessment context information relating to the source term and geosphere biosphere interface is then reviewed.
- One or more time series of assessment biospheres can then be identified and described, corresponding to each landscape evolution sequence, taking into account the intrinsic dynamics of the biosphere system and changes to its physical boundary conditions as a result of the evolving regional landscape.
- Finally, based on arguments relating to the projected behaviour of radionuclides in the evolving biosphere, consideration is then given to the potential advantages and disadvantages of simulating (within the assessment) the effects of transitions from one biosphere system to another, so that a preferred assessment approach can be defined. This 'sequential approach' is discussed in the next section.

A1.2.3 - *Step 3: Representation of biosphere system change*

Choice of sequential or non-sequential approach

Choices about the way biosphere system change is represented within an assessment (Step 3 in Figure A1) should reflect the underlying assessment context, in particular the purpose of the assessment and the endpoints to be evaluated. Selection of a preferred approach will depend on understanding inter-relationships between various timescales for change, not only within the biosphere system itself (in terms of the dynamics of mass fluxes) but also in respect of radionuclide dispersion and accumulation within the dynamic system. The main choice of modelling approaches is between a non-sequential and a sequential representation. These are defined as follows.

Non-sequential approach

Taking account of the description of projected changes to regional landscape and to the corresponding source term, it may be possible to identify a finite number of discrete, quasi-equilibrium biosphere states, which are judged to be adequately representative of key stages in the evolution narrative. Time-invariant assessment biospheres corresponding to these quasi-equilibrium conditions may then be identified and simulated in such a way that they are independent from one another, with their projected sequence disregarded. A non-sequential approach will be appropriate in situations where radiological impacts associated with the assumed quasi-equilibrium state are not significantly affected by possible previous concentrations of radionuclides in environmental media.

Sequential approach

The aim of such an approach is to provide for explicit representation of biosphere system change, either through simulating a sequence of discrete states or via quasi-continuous variation of the properties and characteristics of biosphere system components. It is particularly appropriate in situations where the judgement is made that accumulation of radionuclides at an earlier stage in the evolution narrative may have implications for the consequences at subsequent times after change has taken place. The sequential approach provides for assessment biospheres to have a "memory" of the distribution of contamination prior to and during the particular transition(s) they are intended to simulate.

Whichever approach is taken, the development of an adequate representation of change should not necessarily depend on trying to provide a complete simulation of biosphere system evolution throughout the overall time frame of interest. Rather, the aim is to work from narrative descriptions of landscape evolution over that period in order to identify assessment biosphere systems that are sufficiently representative to provide an adequate measure of projected overall safety performance of the disposal system. This involves the use of scientific understanding and judgement to highlight periods of time that are expected to be of particular interest or concern. For example, the identification of particular transitions, projected to occur within a specific time period, as being of interest or potential importance does not imply a need to represent the complete future evolution of the biosphere using a sequential approach. In such situations, it may be sufficient to consider the dynamics associated with a specific transition, or series of changes, in a separate calculation, the results of which could then be considered alongside results from identified non-sequential 'system state' models.

It is not easy to draw an absolute distinction between 'continuous' and 'discrete' (step-wise incremental) representations of sequential change. Indeed, any dynamic representation of a changing system will tend to introduce some discontinuities, effectively collapsing the assumed timescale of system response to zero over the period in which a defined change takes place. The important consideration is to ensure that such discontinuities do not introduce unacceptable artefacts into the results of the assessment. The choice of appropriate time-steps in representing a sequence of system conditions might be considered as the temporal equivalent of grid refinement in spatial representations of flow and contaminant transport.

Explicit representation of change as a sequence of discrete biosphere system states will usually tend to overestimate the likely radiological consequences during the period in which the anticipated change actually takes place. For example, if a projected future fall in sea level is simulated as a step-change from a coastal to a terrestrial environment, the erosion of sea bed sediment and remobilisation of contaminants, resulting from coastal processes taking place as sea level fell, might not be properly taken into account. Hence it is likely that the potential radiological implications of reclaiming former bed sediments for use as arable land would be overestimated. Nevertheless, the more complex modelling requirements and judgements associated with representing biosphere change more realistically as a continuous variation may only be justified if the assumption of a sequence of discrete states is found to give rise to excessive overestimates of environmental impact.

A1.3. - Mechanisms of Change and Their Potential Radiological Significance

A1.3.1 - External factors relevant to regional landscape change

Global and regional climate

Figure A2 illustrates the hierarchy of relationships and dependencies between potentially relevant External FEPs (EFEPs) and their influence on the boundary conditions of the biosphere system in which radionuclide transport and radiological impacts are assessed. In general terms, the major drivers of system change are seen to exert influence initially at a global scale. This influence is then propagated down to regional and local scales and it is at these smaller scales that changes to the biosphere system are defined and their radiological significance needs to be considered.

An important intermediate level of the description of change within the EFEPs system relates to the regional landscape in which the assessment biosphere is assumed to be embedded. The present day landscape can be characterised (e.g. in terms of landform, hydrology and land use) from observations within the region of interest or (for a more generic assessment) on the basis of appropriate hypotheses regarding the setting in which the radiological impacts of potential releases will be determined. EFEPs operating at the regional and local level are then assumed to modify this landscape over time, providing a context in which the temporal evolution of the boundary conditions on the biosphere system can be specified.

A significant consideration in the above is that the landscape description is developed on a larger spatial scale than that of the assessment biosphere. This is necessary so that it can include a characterisation of those factors that influence the boundary conditions of the assessment biosphere. For example, the subsurface hydrological conditions that determine radionuclide transport within the assessment biosphere itself may need to be defined on a spatial scale of only a few kilometres. However, in setting those boundary conditions, consideration may need to be given to the geometry, hydraulic properties and recharge/discharge characteristics of the regional aquifer. This means that the area of interest in describing landscape evolution could encompass the wider region in which a disposal facility is situated from the local uplands to either a major river or the coastal zone of discharge.

Changes in the regional climate regime

Once an overall regional climatic regime has been established, consideration can be given to local perturbing factors. For example, social and economic developments may result in an increase in industrialisation of a region. Apart from larger-scale effects, such as the contribution to sulphate aerosol production (mentioned above), there are more localised effects e.g. the production of heat domes over cities, which can be factored in at this stage.

The potential radiological implications of changes to seasonal patterns of temperature and precipitation on a regional scale are various. It is not the intention here to provide an exhaustive list of the types of change that might occur, but selected examples include:

- Warmer climate regimes may provide for a greater diversity of agricultural practice, as well as influencing human diet and behaviour (for example, changes in water consumption);
- Colder climate regimes will tend to restrict the range of possible agricultural practices to crops tolerant of a shorter growing season, with increased emphasis (in communities dependent on local resources) on bringing animals inside during the winter, greenhouse cultivation and reliance on food products from natural and semi-natural ecosystems.

There may also be increased seasonal differences in surface hydrology (snow melt, ice dams etc.) and human behaviour (e.g. diet, time spent indoors or outdoors).

— More arid climate regimes imply a greater soil-moisture deficit and corresponding increased requirement for groundwater and surface water resources to be used in support of irrigation;

— More humid climate regimes may increase the availability of local water resources and rates of erosion, with the potential for increased dilution and dispersion of contamination.

Climate change and associated changes in vegetation are closely coupled to soil development. Vegetational colonisation of a regolith leads to the early stages of soil development, which in turn provides a changing substrate on which ecological succession occurs. Climate-dependent considerations include influences on rates of decay and decomposition of organic matter. For example, in some cooler climate regimes primary productivity may be relatively high, while decomposition rates may be restricted, leading to an accumulation of organic detritus.

Other changes at the regional level might include:

- glaciation and ice sheets
- isostatic effects
- changes in landform and sea level.

Earth processes and meteorites

Global climate change, as influenced by social and institutional developments, is a continuous process that will affect the landscape through the various changes identified above. However, other EFEPs that may, or may not, occur in a particular regional context can also influence the landscape.

Orogeny

Orogeny can be classified as a global process, in so far as it arises on a large spatial scale and its origin is the consequence of global processes such as continental drift, driven by plate tectonics. It is associated with regional uplift, generating a progressively greater erosional instability that results in enhanced denudation, typically on timescales of millions of years or longer. This can lead to the redistribution of eroded materials, potentially resulting in dispersion of environmental contamination. The radiological significance of such effects will depend on regional factors, such as the rate of uplift compared with the overall timescale of interest to the assessment. There may also be a potential for differential effects on topography at a regional scale, which could influence hydrogeology and, thereby, the location of the geosphere-biosphere interface.

Vulcanism

Vulcanism arises from global processes similar to those responsible for orogeny, occurring at plate boundaries or above upwelling mantle plumes. Indeed, vulcanism can be thought of as a component, or result, of fundamental orogenic processes. Hence, evaluation of the possible direct effects of vulcanism on regional landform can be effectively subsumed into the general treatment of orogeny, but the possible effects of volcanic eruptions on the regional climate regime and land use need to be considered separately.

Clearly, in the extreme, the occurrence of vulcanism within the regional landscape itself would be a relevant consideration in describing long-term biosphere change. However, compared with the possible impact of regional magmatic activity on disposal system safety through its effects on engineered system performance and groundwater flow conditions, the radiological implications of associated changes within the biosphere (lava flows onto land or ice sheets) are likely to be of somewhat lower importance.

Large seismic events

Large seismic events are not expected to have more than a limited effect on regional landscape in most site contexts. The main consideration in relation to possible seismic events occurring close to, or within, the regional landscape of interest is more likely to be their possible impact on groundwater flow patterns, through movement of faults and fractures, which might have an influence on the location of the geosphere-biosphere interface.

The occurrence of tsunami can be related to seismic events occurring under the ocean at the continental shelf. It is not necessary for such events to take place close to the region of interest in order to have an impact on a given landscape – tsunami are able to travel over distances of hundreds of kilometres before reaching land. In affected coastal areas, marine transgressions will lead to salinity contamination, with consequent impacts on water resources, in particular. For example, there might be a switch from the exploitation of surface waters (such as lakes) to rivers and deep aquifers.

Social/institutional developments

There is no obvious 'model' for describing social and institutional developments and their effects on regional landscape and biosphere systems. Where the assessment context dictates that future environmental change should be taken into account, an appropriate response is to consider human behaviours based on present-day (or, if available, historical) land-use and resource exploitation practices in analogue regions, selected for the representativeness of their climate and landform characteristics. When describing the biosphere system identified at this stage, Table HIIa (Annex A) can help to select what human influences can be of relevance in terms of system changes.

The main aspects likely to be significant include human effects on:

- land use
- regional hydrology, and
- regional climate.

These changes may occur over an extended period of time. The potential for human actions to cause acute changes to the environment with long lasting consequences (e.g. land reclamation, earthworks, forest clearance) needs to be recognised. In so far as the radiological implications of the change itself (e.g. in terms of redistribution of any pre-existing contamination) are likely only to be transient, it may be possible to justify excluding representation of the transition itself from the biosphere assessment basis.

A1.3.2 - Internal factors relevant to regional landscape change

Background

The development of a coherent description, or set of alternative descriptions, of the possible evolution of the regional landscape involves not only consideration of the possible influence of external, global factors, but also the dynamics associated with processes that are inherent to the biosphere system itself. Changes to the properties and characteristics of the regional landscape, caused by external factors, therefore need to be propagated through the biosphere according to the coupled system of relationships illustrated in Figure 3.4. Moreover, regardless of any 'external' changes, biosphere system characteristics may change as a result of disequilibria generated by the intrinsic dynamics of the system (e.g. as a result of aeolian or fluvial erosion and deposition processes).

Some key issues associated with the propagation of change through the biosphere are highlighted below, taking each biosphere system component in turn. In practice, interpretation of the effects of such processes to provide a self-consistent narrative may involve a range of techniques, from qualitative reasoning to more detailed quantitative understanding of processes and their effects. The aim here is not to provide a detailed analysis of how such processes might be assessed for a given region, but simply to illustrate how the interactions represented in Figure A4 are able to provide for systematic consideration of the coupled relationships between biosphere system components.

Climate/atmosphere

It is necessary to consider whether specific processes related to climate characteristics can affect other elements of the process system. Some dynamic effects associated with 'equilibrium' climate conditions (e.g. seasonal and diurnal change) occur on very short timescales and it would not normally be appropriate to describe their effects explicitly as part of the narrative of biosphere system change. However, the net effect of short-term changes (such as storm events and freeze/thaw processes) may be a gradual change in the characteristics of other biosphere system components such as soil and rock properties, topographic gradients and the geometry of water courses. Moreover, if regional climate characteristics change, then the rate or direction of change of the properties and characteristics of other biosphere system components may also be altered.

It is also relevant to consider how local climate and atmospheric composition may change as a response to changes in other biosphere system components. For example, the construction of buildings or use of greenhouses for cultivation (i.e. change to human community characteristics) can give rise to localised microclimates that are significantly different from prevailing regional climate conditions. Localised microclimates and alterations to atmospheric composition may be associated with ecosystem change (e.g. through the development of forests) or changes to topography and water bodies.

Geology

Properties and characteristics of the near-surface geology are not intrinsically dynamic, except in so far as they may be affected by the continuous processes of weathering and erosion. The stratigraphy and stratification of the near-surface, unconsolidated geology can, however, be affected by changes to the regional climate regime, regional landform and regional hydrology (see Figure A3). Such changes may have implications for topographic relief, the physical and geochemical properties of the groundwater flow system, as well as the mineral composition of soils within the biosphere system.

Topography

The topographic characteristics of a biosphere system are not intrinsically dynamic, except in so far as relief, as well as the geometry of water courses, may change over time in response to wind and water-driven erosion processes within the biosphere. In addition, relief and altitude may also be affected by more widespread, regional changes in landform. Nevertheless, processes such as coastal erosion and river meander can be important considerations in describing the long-term evolution of the configuration of boundaries between the terrestrial and aquatic environments, irrespective of global EFEPs, such as climate and sea level change.

Topography may also change as a response to changes in other biosphere system components. In particular, human actions may be responsible for changes to topography, for example through land reclamation, the development of earthworks and excavations and canalisation of rivers. This could, in principle, be extrapolated to the conclusion that the overall configuration of biosphere system components may be influenced so much by human actions that it ultimately bears no resemblance to that expected to evolve as a result of natural processes. Whether or not the potential for such artificial changes is taken into account in the identification and justification of the biosphere system depends on judgements about their likely relevance to the underlying assessment context.

Water bodies

Water bodies can be an important dynamic part of the biosphere, representing a major contribution to mass flux. The presence of large water bodies may have an influence on the local climate regime. Erosion and sedimentation processes can be important contributors to the long-term evolution of a landscape, irrespective of other (external) sources of change. The rate at which these processes occur is determined both by the nature of the existing landscape e.g. in terms of its topography and lithostratigraphy, and by climatic conditions.

For example, cliff erosion rates at the coast can be as much as a metre per year or more. River meander, generated by a combination of sedimentation and erosion processes, can be an important process for redistribution of sediments in regions of low relief. The same processes govern the dynamics of estuary development, with the added influence of tidal forces on coastal currents and sediment transport.

Describing the evolution of a biosphere system needs to take account of the response of water bodies to external change, and the resulting effects on the dynamics of erosion and deposition within the biosphere system. Properties of the regional landscape that can have a direct effect on the flow rate, level and suspended load of water bodies include changes to the regional hydrological regime and landform (see Figure A3). The hydrological system may respond to external change in many ways. For example, as a result of changing base levels, river incision can take place to a depth of some tens of metres below a predefined palaeosurface on timescales of as little as a few thousand years. Similarly, sea level rise can have a marked influence on projected rates of coastal erosion.

Soil/Sediments

Properties and characteristics of soils and sediments are not intrinsically dynamic, except in so far as they are affected by the continuous processes of weathering and erosion. These processes contribute to the sediment load in surface water bodies. The composition, texture and stratification of soils and sediments can, however, be affected by changes to regional hydrology, land use and vegetation (see FigureA.3). Such changes may, in turn, have implications for land use and the types of flora that may be supported within the biosphere system.

Human Community

Activities and resource exploitation practices undertaken by the local human community can have a major influence on the composition of the biosphere and the configuration of the biosphere system components. Engineering activities may result in changes to water courses and alterations to topography. Ecosystems may be intensively managed by agricultural communities, resulting in the introduction of alien species through animal husbandry and the development of a patchwork of vegetation monocultures. The construction of buildings will give rise to controlled microclimates that differ significantly in terms of atmospheric quality, temperature and humidity from the outside atmosphere. Hunting, fishing and pest control may have a significant influence on the populations of natural species.

The extent to which human activities are assumed to influence the evolution of the biosphere system will depend on fundamental assumptions relating to the type of community that is present and its technological capabilities. However, there may be some conditioning of the type of activities according to the prevailing climate characteristics and their influence on the natural productivity of the biosphere system.

Biota

Ecosystem community characteristics will largely be defined by land use and vegetation characteristics on a regional scale which, in turn, depend on climate conditions and soil type. Ecosystem dynamics dictate that populations will fluctuate naturally with time in response to the natural processes of change, disease, predation and consumption within the foodweb. Individual species and communities will also respond to changes in regional conditions.

Biota may act dynamically within the biosphere, insofar as population migrations cause changes with time of the types of flora and fauna that are present. Some biotic activity (e.g. burrowing) can contribute to the turnover of bulk material (and hence contamination) within soils and sediments.

A2. Description of Biosphere System(s)

A2.1. - Introduction

The development of a conceptualised description of the biosphere system consists of three main parts:

- Identification of significant characteristics of each biosphere system component, taking account of their relevance to the underlying assessment context.
- Determination of phenomena relevant to providing a suitable description of the dynamic behaviour of the biosphere system for the purposes of radiological assessment. These phenomena may be intrinsic to individual biosphere system components or associated with the interactions and relationships between different biosphere system components.
- Description of the configuration of, and connectivity between, different parts of the system, taking account of the part they would play in the migration and accumulation of contaminants within the biosphere system.

Even though some of the biosphere characteristics correspond to dynamic processes, the procedure for development of a biosphere system description relates to a fixed point in time or to a non-evolving biosphere. If the assessment context requires that biosphere change should be addressed, then the system description would need to include a discussion of the rate of change of the individual characteristics for each affected biosphere system component. However, the time scales for change (rate of change, period of change) in different biosphere system components may be significantly different from one another and from those corresponding to the lifetimes of members of exposed groups (for which the radiological impacts are typically evaluated). The type of conceptual models suitable for simulating biosphere system dynamics under conditions of change may therefore be very different from those relevant to assessing radiological impact.

A2.2. - Procedure to describe biosphere systems

The procedure that leads to the biosphere system description must provide definitions for the biosphere system components, characteristics and phenomena that may need to be represented in the assessment model. In practice, a measure of iteration (rather than a simple once-through procedure) will often be necessary in developing an adequate biosphere system description to support long-term radiological assessment. An iterative approach, based on increasingly refined descriptions of the system, will therefore allow coherence to be maintained while providing a level of detail appropriate to the overall assessment context. The following steps explain in more detail the actions to be followed in arriving at a qualitative and quantitative description of the system of interest.

A2.2.1 *- Step 1: Selection of relevant characteristics of identified biosphere system components*

In this step the relevant characteristics of the identified biosphere system components (as determined by the 'System Identification' in Section A1) are selected, based on screening of information in Tables Type 'II' from Annex A. Such screening needs to take into account the underlying assessment context, including the geosphere-biosphere interface and endpoints of the assessment, but could also invoke modelling judgements regarding the likely significance of particular characteristics. It is recognised that there may be situations where it is unclear whether or not particular characteristics are relevant to the biosphere system description, and these will need to be retained for review later in the procedure.

Activities of the identified human community leading to potential radiation exposure (Table HIIb of Annex A) are also considered in this step. The combination of these potential exposures with additional judgements and knowledge will allow for the definition of potential exposure groups.

In documenting the screening decisions, a record should be kept of which items are considered relevant or not (or 'possibly relevant') to the overall biosphere system description and the reasoning behind the decision. The output of this step will therefore be a record of: (i) those biosphere system characteristics that are considered relevant, or potentially relevant, as a basis for developing a model that meets the overall assessment objective; and (ii) those characteristics that can be justified as not relevant to the scope of the assessment.

A2.2.2 - Step 2: Establish interrelations between biosphere system components

Given the biosphere system characteristics that have been identified as being relevant (or potentially relevant) to the assessment calculation, Step 2 involves establishing the ways in which they are interrelated, thereby providing a phenomenological description of the intrinsic dynamics of the biosphere system. This can be achieved by constructing an interaction matrix (IM) to identify important phenomena based on analysis of the interactions (i.e. relationships and dependencies) between the biosphere system components.

The interaction matrix approach also provides a clear way of ensuring that each of the identified system characteristics can be 'mapped' into the assessment model (BIOMASS, 2003). Moreover, the systematic process of examining how the biosphere system components relate to one another may help to identify new, previously unrecognised relevant characteristics of the biosphere system.

A2.2.3 - Step 3: Basic description of the biosphere system

In Step 3 the information derived through Steps 1 and 2 is used to provide a qualitative description of the biosphere system. This description should include consideration of the characteristics relevant to each biosphere system component and the way in which they are interrelated, both in terms of system dynamics and their assumed spatial arrangement. The result can be considered a 'word picture' of the biosphere system; in practice, a combination of verbal and pictorial description of the biosphere may be helpful, depending on the circumstances of the assessment.

Descriptive parameters are also desirable at this stage in order to provide a more substantive account of (for example) the spatial scale of the particular features that may be identified within the local environment to be represented in the model and the magnitude of the system dynamics. When no site-specific information is available to guide such decisions, other generic information needs to be used. Annex E provides a guide to typical natural correlations and relationships (both qualitative and quantitative) between biosphere system components and characteristics.

A3. References to Appendix A

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Annex to Appendix A:

Definition and generic Classification Schemes for Biosphere System Components

This Annex sets out Type I Tables of biosphere system components (principal components and principal component types), and Type II Tables which define the characteristics of these components. These tables are offered as part of the BIOMASS Methodology. However variants of these Tables could be employed without altering the methodological approach.

Type I - Tables of Biosphere System Components

Climate and atmosphere

Climate is determined by planetary air currents in the atmosphere. Although the atmosphere is a basic physical component of the biosphere system, where relevant transport processes or meteorological conditions can take place, its description is usually assumed jointly with the description of local climate.

At a global scale, meteorologists distinguish seven climate belts [Walter 1984]: (1) the equatorial rain zone, (2) the summer-rain zone on the margins of the tropics, (3) the subtropical dry regions, (4) the subtropical winter-rain regions, (5) the temperate zone with year-round precipitation, (6) the subpolar zone, and (7) the polar zone. These climate belts are related to ecosystem types by providing for a further subdivision of the temperate zone, and combining the subpolar and polar zones. Nine climate zones are then be identified, ecologically designated as zonobiomes (ZB):

ZB I:Equatorial with diurnal climate, humid
ZB II:Tropical with summer rains, humid-arid,
ZB III:Subtropical-arid (desert climate), arid,
ZB IV:Winter rain and summer drought, arid-humid,
ZB V:Warm-temperate (maritime), humid,
ZB VI:Typical temperate with a short period of frost (nemoral),
ZB VII: Arid-temperate with a cold winter (continental),
ZB VIII: Cold-temperate (boreal),
ZB IX:Arctic (including Antarctic), polar.

There are other possible climatological classifications, such as the empirical scheme based on average temperature and precipitation values, developed by Køppen [Strahler 1984]. Table CI provides a summary description of the climate associated with the nine zonobiomes, comparing these with the Køppen classification scheme.

Table CI : Climate type classification

Walter	Køppen	Description
ZB I: Equatorial with diurnal climate, humid	**Af:** tropical climate	The mean monthly temperature is close to 26°C in every month, so the annual variation is very small. The atmospheric mean pressure ranges from 74.5 to 74.7 cm (1009 to 1012 mb). This is a zone of very intensive precipitation, over 200 cm/y in most of the areas (Strahler, 1984).
ZB II: Tropical with summer rains, humid-arid	**Am**: tropical climate, monsoon **Aw**: tropical climate, savanna	Aw is a humid-arid tropical climate, with a humid season that is determined by maritime humid tropical and equatorial masses of air and in the period that the sun is low. The limit between Am and Aw varies according to the total annual precipitation of both the wettest and the driest month. The rain in these climates is not so reliable as in humid equatorial. The alternation of the humid and dry seasons causes the development of a typical vegetation, the tropical savanna. This is characterised by open areas covered by grass, with few trees and shrubs that resist the dryness (Strahler, 1984).
ZB III: Subtropical-arid (desert climate), arid	**BWh**: desert climate **BSh**: steppe climate	A subtropical zone is in general termed desert when the annual rainfall is less than 200 mm and the potential evaporation more than 2000 mm (up to 5000 mm in the central Sahara). A very distinctive feature of all arid regions is the large variability in amount of rain falling in different years. This means that average figures are of little value. In all deserts (except in the fog variety), the air is very dry. Both incoming and outgoing radiation are extremely intense, which means that the daily temperature fluctuations are large. In the rainy season, however, the extremes are greatly reduced (Walter, 1984).
ZB IV: Winter rain and summer drought, arid-humid	**Csa Csb**: Mediterranean climate	Characterised by dry, hot summers with humid, mild winters.
ZB V: Warm-temperate (maritime), humid	**Cfa**: humid subtropical climate	A transitional zone between the tropical-subtropical and the typical temperate regions. In the very humid subzonobioma (with rainfall at all times of year but at a minimum in the cool season), temperatures drop quite severely in the cool season, and there may even be frost, but there is no cold season. A second subzone with rainfall occurring principally in winter and no summer-drought season can be distinguished (Walter, 1984).
ZB VI: Typical temperate with a short period of frost (nemoral)	**Cfb**: warm rainy climate, warm summer **Cfc**: the same, but short and fresh summer	A temperate climate zone with a marked but not too prolonged cold season occurs only in the Northern Hemisphere; apart from certain mountainous districts in the southern Andes and in New Zealand. Warm vegetational season of 4-6 months with adequate rainfall and a mild winter lasting 3-4 months (Walter, 1984).
ZB VII: Arid-temperate with a cold winter (continental)	**BWk - BWk`** fresh to cold desert climate **BSk - BSk`**: steppe fresh to cold climate	The degree of aridity varies considerably, and four subzonobiomes can be distinguished: (1) semi-arid having a short period of drought, with steppe and prairie vegetation; (2) a very arid subzonobiome, with as little rain (falling in winter) as the subtropical desert climate; (3) a subzonobiome similar to 2, but with summer rain; and (4) deserts of the cold mountainous deserts plateaus (Walter, 1984).
ZB VIII: Cold-temperate (boreal)	**Df Dwc Dwd**: forest climate, cold and snowy	The duration of the period with a daily average temperature of more than 10°C drops below 120 days and the cold season lasts longer than 6 months. The northern boundary between the boreal zone and the arctic tundra is where only approximately 30 days with a daily mean temperature above 10ºC and a cold season of 8 months are typical. A distinction should be made between a cold oceanic climate with a relatively small temperature amplitude and a cold continental climate in which, in extreme cases, a yearly temperature span of 100ºC can be registered (from a maximum average monthly temperature of +30ºC to a minimum of -70ºC) (Walter, 1984).
ZB IX: Arctic (including Antarctic), polar	**ET**: tundra climate **EF**: polar climate, perpetual frost	The largest tundra region completely devoid of forest is an area of 3 million km^2 in northern Siberia. At most, there are 188 days in the year with mean temperature above 0°C, and sometimes as few as 55. The low summer temperatures are partially due to the large amount of heat required to melt the snow and thaw out the ground. Winters are rather mild in the oceanic regions but extremely cold in the continental regions. Precipitation is slight, often being less than 200 mm, but since potential evaporation is also very low, the climate is humid. Surplus water is unable to seep into the ground because of the permafrost and thus extensive swamps are formed. Snowfall amounts to 19-50 cm annually.

Near-Surface Lithostratigraphy

Geology

Parent rock and its genesis influence the shape, size and development of erosional relief. A rock classification scheme based on origin is provided in Table GI, under the basic headings of Igneous, Sedimentary and Metamorphic. This allows the general type of rock present at a particular location to be identified.

Table GI: Classification of Rock Types (Strahler, 1984)

Rock Type	Description
IGNEOUS	Rocks that have solidified from a molten state. There are two primary types: Plutonic (rock from magma rising up from deep under the earth's crust, and solidifies as it cools before it reaches the earth's surface, e.g. Granite, Peridotite) and; Volcanic (rock that was originally lava, hot magma that reached the surface of the earth before it hardened, e.g. Obsidian, Basalt, Rhyolite)
SEDIMENTARY	Rock formed by the accumulation of particles on or near the earth's surface, and compacted down, often under extreme pressure, creating rock layers. E.g. Limestone, Gypsum, Sandstone, Dolomite, Quartzite.
METAMORPHIC	Rocks resulting from changes within pre-existing rocks, by extreme pressure, temperature, and chemical activity e.g. Mica, Calcite, Gneiss, Quartz

Edaphology (Soils and sediments)

Climate, topography, parent rock and vegetation together determine whether or not a soil layer is developed and, if so, its specific properties. Soils are formed from a mixture of mineral substances (produced as a result of the weathering of rocks) and organic matter (the product of the activities of organisms and of the decomposition of dead organic matter, mostly plants).

Soils often consist of several layers that may differ in colour and composition. The upper layer (the A-horizon) contains the decomposition products of organic matter as well as mineral matter. The next layer (the B-horizon) includes mostly mineral components. Soluble inorganic material is carried from A horizon to B horizon by the downward flow of soil water. The third layer (the C-horizon) consists of slightly altered debris of the original rock (also known as unconsolidated rock).

Many different soil classifications can be found in the literature, to the extent that many countries have their own classification scheme based on slightly different properties/purposes. Since the 1970s there has been an international effort promoted by FAO–UNESCO to avoid confusion by developing a general classification that can be referenced world-wide.

A zonal soil classification is used here for consistency with the climate zones defined in Table CI (Table RT2 shows the Climate-Soil-Vegetation interrelationships). Table SI provides a summary classification of different soil types that may be present in the biosphere system, including a brief description and comments regarding their natural fertility or other properties. Correspondence with the FAO–UNESCO classification is also indicated.

Table SI: Zonal soil types and descriptions (Strahler, 1984)

Soil type	Description	Comments
Equatorial brown clays (ferralitic soils, latosols	**Latosols**: chemical and mechanical decomposition of the parent rock is complete due to the temperature and humidity conditions. Silica has disappeared almost completely, humus is scarce due to the quick bacterial activity, soils are typically red. The loss of clay-silica minerals make the latosols slightly plastic and notably porous.	Latosols loose fertility quickly after the first few harvests. They can form strata where deposits of great value can be found (aluminium oxide, iron oxide or manganese oxide). ***FAO nomination: e.g: Ferralsols***
Red clays or red earths (savanna soils)	**Red soils**: Areas of this type of soils have in common a notable degree of climatic dryness (winter or summer season). This causes the presence of calcium carbonate in the lower layers. The red colour is the evidence of the presence of iron oxides where there are limited quantities of organic acids.	***FAO nomination: e.g. Vertic Cambisol, Chromic Luvisols and Vertisols.***
Sierozems	**Sierozems**: they are poor in humus due to the disperse distribution of vegetation. Colour goes from light grey to brown-grey. The horizons exist but only slight differences are found. Big quantities of calcic carbonate at depth less than 0.3 m.	Soils are appropriate for cultivation only where the soil texture is fine, for example along the flooding plains. Irrigation is essential. ***FAO nomination: Xerosols***
Mediterranean brown earths	**Brown earths**: the soil profile is similar to the chernozem one but with less humus content.	These soils are fertile in adequate conditions of precipitation or irrigation. ***FAO nomination: e.g. Cromic Cambisols and Luvisols***
Yellow or red podzol soils	**Yellow-red podzols**: Warm summers and soft winters favour bacterial action. Humus content is low. Red and yellow colours are due to iron compounds in hydroxide form. Aluminium hydroxides are also plentiful, caracteristic of tropical soils in warm and humid regions.	***FAO nomination: e.g. Orthic acrisol***
Forest brown-grey soils	**Brown-grey podzols**, the leaching is less intense than in yellow-red podzols and the colour is brown. The B-horizon is thick and brown-yellow to brown-red colour and, as in podzols, there is a concentration of bases and colloids.	These soils treated with lime and fertilizers allow for highly productive farms. ***FAO nomination: e.g. ferric or albic Luvisols***
Chernozems	**Chernozem or black earths**: profile typically consists of two layers: just under the vegetal cover there is a black layer (A horizon) rich in humus and of about 0.6-0.9 m thick. C horizon accumulates colloids and bases from A horizon. They are rich in calcium. This soil type is developed over parent material rich in calcium carbonate. Aridity is another important factor in the development of this soil.	Steppe pasture and meadow are the natural vegetation of this soil in medium latitudes. Geographically, the most important property of chernozems is the productivity of cereals (wheat, oats, barley and rye). ***FAO nomination: Chernozems***
Podzols (raw humus-bleached earths)	**Podzols** require a cold winter and an adequate precipitation range distributed throughout the year. A horizon is formed by three layers where the first stratum is rich in dead or in decomposing vegetation, under this an acid stratum rich in humus can be found, under this a highly leached stratum exists. B horizon has a heavy clay consistency due to the colloids coming from A horizon. Both A and B horizons are less than 1 m thick.	Fertility is limited, which make the soils not appropriate for cultivation, although the addition of lime and fertilisers corrects its acidity and restores the leached bases to the soil. ***FAO nomination: Podzols***
Tundra humus soils with solifluction	**Tundra soils**: the long and intense cold winters freeze the humidity of the soil during a number of months during the year, bulk material then is formed by particles mechanically broken. Peat is abundant due to the slow vegetal decomposition process. These soils do not have clear profiles but they form slight layers of sandy clay and raw humus.	***FAO nomination: e.g. Gelic Gleysols***

Table RT1: Zonobiomes and corresponding zonal soil type and zonal vegetation (Walter, 1984)(2)

Zonobiome	Zonal soil type	Zonal vegetation
ZB I	Equatorial brown clays (ferralitic soils, latosols)	Evergreen tropical rain forest
ZB II	Red clays or red earths (savanna soils)	Tropical deciduous forest or savannas
ZB III	Sierozems	Subtropical desert vegetation
ZB IV	Mediterranean brown earths	Sclerophyllous woody plants
ZB V	Yellow or red podzolic soils	Temperate evergreen forest
ZB VI	Forest brown earths and gray forest soils	Nemoral broadleaf-deciduous forest (bare in winter)
ZB VII	Chernozems to sierozems	Steppe to desert with cold winters
ZB VIII	Podzols (raw humus-bleached earths)	Boreal coniferous forest
ZB IX	Tundra humus soils with solifluction	Tundra vegetation (treeless)

Topography

Topographic relief is an important characteristic that influences the development of soils and vegetation and is therefore of some interest when trying to develop a coherent description of a biosphere system. Primary categories and related general topographic characteristics used to identify a particular region are summarised in Table TI.

Table TI: Topographical categories

Geographical Context	Coastal Inland
Altitude	Lowland Upland High Mountain
Landform	Plain Subdued Marked Slopes
Localised Erosion	Limited Fluvially incised Glacially incised

Water Bodies

Water in its three different states is a major element in all the components of the biosphere and one of the basic factors that permits the existence of living organisms. Water is present in the atmosphere and in the lithosphere (glaciers, surface waters and ground waters). Table WI identifies a variety of water body types that may be present in the biosphere system.

(2) Defined for natural ecosystems and semi-natural systems not yet substantially influenced by man

Table WI: Water Body Types

1	**Surface Water Bodies** • Natural: - Rivers - Lakes - Springs - Streams - Wetlands - Estuaries - Seas - Oceans • Artificial: - Canals - Harbours - Wells - Reservoirs - Distribution/storage water systems
2	**Subsurface Water Bodies** • Variably saturated zone • Saturated zone
3	**Ice Bodies** • Continental • Shelves • Corrie and valley glaciers • Sea Ice

Biota (Fauna and Flora)

A biome describes a set of ecosystems within a geographical region exposed to the same climatic conditions and having dominant species with a similar life cycle, climatic adaptation, and physical structure (Botkin, 1986). The types of organism that are present at a particular location depend on the environment and on certain aspects of the history of our planet. Organisms will have adapted both physically and metabolically to their local environment, and it is possible to categorise the organisms by external shape and internal form. This is called physiognomic classification.

An ecosystem may be defined as the smallest unit of the biosphere that has all the characteristics required to sustain life. It therefore corresponds to an assemblage of populations of biota, grouped into communities and interacting with each other and their local environment. With this in mind, a biome can be defined as a physiognomic class of a set of ecosystems.

A simple basis for classifying ecosystems is according to type of media. Thus, for example, a general distinction can be made between terrestrial and aquatic biomes. **Terrestrial** biomes are often defined by the vegetation types that dominate the community (physiognomy) or, as defined in this Annex, in terms of climate, type of soil/s, and vegetation, see for example (Walter, 1984). **Aquatic** ecosystems fall into two main categories: fresh water and marine. Freshwater ecosystems, such as lakes, rivers, marshes and swamps are typically considered as part of terrestrial biomes. Exceptions to this simple classification, include "estuaries" (unique in that they lie at the interface of the terrestrial and marine biomes) and, "hypersaline" ecosystems (unique in that they are dominated by a complex microbiota, many species of which require exceedingly high concentrations of salt). Herein, both of these are classified under aquatic.

Three main categories are identified here: (a) no-management, referring to “natural systems”; (b) low-management, referring to “semi-natural systems” and; (c) high-management, referring to “managed systems”. The overall classification scheme for identification of ecosystem types is summarised in Table BI.

Table BI : Ecosystem Classification

NATURAL SYSTEMS (Rambler et al. [1989])			
Terrestrial Ecosystems	Tropical rain forest Tropical seasonal forest Temperate evergreen forest Temperate deciduous forest Boreal forest Woodland and shrubland Savannah Temperate grassland Tundra and alpine meadow Desert scrub Rock, ice and sand	**Aquatic Ecosystems**	Open oceans Upwelling zones Algal bed Coral reef Thermal vents Swamp and marsh Lake and Rivers Littoral marine Continental shelf or slope benthic Abyssal benthic Estuaries Brackish
SEMI-NATURAL SYSTEMS (Countryside Commission [1990], DoE, ITE, IFE [1990])			
Terrestrial Ecosystems	Upland heath Upland smooth grass Upland coarse grass Blanket bog Bracken Lowland grass heath Neglected grassland	**Aquatic Ecosystems**	
MANAGED SYSTEMS (Countryside Commission [1990], DoE-ITE-IFE [1990], Cole and Brander, [1986], Michael, [1987])			
Terrestrial Ecosystems	Managed grasslands	• Improved grassland • Rough grassland	
	Field crop ecosystems / Cultivated land		
	Tree crop ecosystems		
	Greenhouse ecosystems		
	Bioindustrial ecosystems [Cole and Brander 1986]	• Intensive dairying • Intensive beef-cattle production • Pig industry • Poultry	
	Continuous Built-up land		
	Suburban development		
	Urban open space		
	Hard cover		
	Transport routes		
Aquatic Ecosystems [Michael 1987]	Fresh water fish ponds		
	Man-made reservoirs		
	Autotrophic mass cultures of micro-algae		
	Managed coastal waters for oysters		

Human Activities

The identification and description of human communities indicates the extent to which human activities and man-made communities have disturbed or replaced natural systems. Throughout the world, natural biomes have been superseded by agriculture and urbanisation. One result of this is that natural hydrological and biogeochemical pathways and processes have been modified significantly by land and water management practices. Hence, the assumed influence of mankind on ecological communities and the transport and cycling of materials clearly needs to be taken into account(3) . In addition, consideration of the assumed relationship of human communities to the biosphere is important in describing the manner in which local (and potentially contaminated) environmental resources are exploited. Such issues are relevant to characterising the behaviour of hypothetical exposed groups as a basis for estimating doses and risks.

A primary consideration is the extent to which it is assumed that the environment is regulated by human activities. If the degree of management is ‘none’ or ‘low’, the biosphere system may be considered to be in a natural or semi-natural state respectively, whereas more intensively managed systems will tend to be artificially controlled and maintained. In addition, the socio-economic basis on which a community operates can be important in determining the extent to which it depends for its survival on locally available resources. This, in turn, will influence the variety of activities undertaken within the biosphere system, thereby, the potential exposures to contaminated environmental media.

Table HI presents a broad classification of human community types, defined according to both their assumed degree of independence/trade and the intensity of environmental modification and maintenance. The development of descriptions of the effect of human behaviour on the biosphere system, as well as the classification of actions relevant to human exposure, should be broadly consistent with fundamental assumptions regarding the type of community that is present.

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(3) It is recognised that temporal variations may be important; all types of biosphere system can be exposed to significant short-term transformation, both naturally (e.g. by fire) or artificially (fallow agricultural land, forest clearance).

Table HI: Classification of human community types based on socio-economic and environmental control considerations

Trading	Biosphere Control	Community Types	Community activities* in relation to the system
None	None	Nomadic / Hunter-gatherer	Hunting, Gathering, Fishing, Nomadic herding, Direct use of surface waters
	Low	Primitive Agricultural	Hunting, Gathering, Fishing, Grazing, Low yield crop production, Selective Forestry, Direct use of water resources
	High	'Subsistence' Agriculture	Crop production, Cattle, Recycling of residues, Use of wood resources, Use of water resources
Small-scale	High	Small farming communities living off local produce	Edible and non-edible crop production, Animal Husbandry/Grazing, Recycling of residues, Use of wood resources, Use of water resources
		Small farming community – external foodstuffs permitted	Edible and non-edible crop production, Animal Husbandry/Grazing, Recycling of residues, Use of wood resources, Use of water resources
Large-scale trading	Low	Urban with Domestic Gardening	Use of water resources, Gardening, Amenity grass management.
		Industrial	Use of water resources for industrial production
	High	Commercial Agriculture	Use of water resources
		• Agriculture/ Horticulture/ Silviculture	Edible and non-edible crop production, Animal Husbandry/Grazing, Deciduous/Coniferous woodland management
		• Aquaculture	Fish farming, Water plant farming
		• Climate controlled farming/ "Zero-land" farming	Hydroponic crop production, Permanently stabled animals, Glasshouse horticulture
		• Large scale monoproduction	Edible and non-edible crop production
		Market Town	Range of small-scale commercial agricultural practices
		Mineral Exploration / Exploitation	Land movement, Use of water resources

* Note: Use of land for residential purposes, and potential exploitation of local water resources, are assumed possible in association with any of the different classes of activities.

Type II - Tables of Biosphere System Components Characteristics

In what follows, a series of checklists is presented, which are intended to provide a self-consistent basis for defining the characteristics of identified biosphere system components. The naming scheme (CII, BII etc.) adopted in presenting the Tables is consistent with that adopted in the procedure for System Identification.

Climate and atmosphere

Climate characteristics are usually described by meteorological data referring to a specific period of time and location. Depending on the time period over which data are collected and the area of the region being identified/described, some characteristics (usually given as average values of one or several "representative" stations) may be of only marginal significance for incorporation in models for radiological impact assessment over long time periods. Nevertheless, it may still be appropriate to account for such characteristics as contributors to the overall uncertainty in the description of climate for the assumed biosphere system. Table CII identifies common climate characteristics, typical time periods over which meteorological data may be obtained, and spatial/aspect variables that could affect those data. As far as possible, some degree of variability should be accepted in choosing representative data for the biosphere system in order to reflect uncertainties that may need to be taken into account in developing the conceptualised representation of the biosphere system.

Table CII : Climate Characteristics

- **Climate Characteristics**
  - - Temperature
  - - Precipitation (Rainfall/Snowfall/Occult)
  - - Pressure
  - - Wind speed and direction
  - - Solar radiation (hours of sunshine)
- **Temporal Variability of Climate**
  - - Diurnal
  - - Seasonal
  - - Interannual
  - - Decadal
- **Spatial Variability of Climate**
  - - Latitudinal
  - - Longitudinal (continentality)
  - - Altitudinal
  - - Aspect-related

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Near-surface lithostratigraphy

Geology

General characteristics of the parent rock within the near-surface environment, including both the consolidated part, and any overlying unconsolidated region, are identified in Table GII.

Table GII: Geology characteristics

- Lithostratigraphy (vertical and horizontal variation)
- Fracture systems (vertical and horizontal variation)
- Weathering (degree of)
- Erodability
- Mineralogy

Edaphology (Soils and Sediments)

The primary common characteristics of soils and sediments are summarised in Table SII.

Table SII: Soil and Sediments characteristics

- Stratification (i.e. horizons)
- Composition (organic content, mineralogy)
- Texture
- Fracture system
- Areal variation
- Weathering (degree of)

Topography

Specific generic characteristics describing topographic features at any specific location are summarised in Table TII.

Table TII : Topography characteristics

- Altitude
- Slope
- Erodability
- Deposition rates

Water Bodies

Table WII summarises generic water body characteristics relevant to providing a comprehensive description of water bodies within the biosphere.

Table WII: Water Body Characteristics

- **Geometry**
  - Level
  - Position
  - Variation (Global, local)
  - Basal characteristics
- **Flow rate**
  - Variation (e.g.: permanent, ephemeral)
- **Suspended Sediments**
  - Composition
  - Load
- **Freeze/Thaw Phenomena**
  - Ground freezing
  - Seasonal
  - Long-term (Permafrost, ice lens etc)
  - Snowpack development
  - Water body freezing
- **Hydrochemistry**

  Composition of:
  - Major anions and cations
  - Minor anions and cations
  - Organic compounds
  - Colloids
  - pH and Eh

Ecosystem Community

Within an identified ecosystem, the individual component communities can be described and characterised. Table BII provides a scheme for describing and characterising plants and animals relevant to providing a comprehensive description of the biota within the biosphere.

Table BII: Ecosystem Community Characteristics
(Terrestrial and Aquatic Components)

- **NET PRIMARY PRODUCTIVITY** (Rate at which energy is bound or organic material created by photosynthesis after accounting for respiration per unit area per unit time)
- **NET SECONDARY PRODUCTIVITY** (Net productivity of heterotrophic organisms – animals and saprobes)
- **BIOMASS/STANDING CROP** (Dry weight per unit area)
    - Plants
    - Animals
    - Other organisms
- **CROPPING** (Rate of removal by humans)
    - Animals and animal products
    - Plants and plant products
    - Other organisms and their products
- **POPULATION DYNAMICS**
    - Plants
    - Animals
    - Other organisms
- **VEGETATION CANOPIES**
    - Physical structure
    - Interception of light, water, aerosols, vapours and gases
- **PLANT ROOTS**
    - Structure and distribution with depth
    - Absorption of nutrients and water with depth
- **ANIMAL DIETS**
    - Composition
    - Quantity
- **BEHAVIOURAL CHARACTERISTICS** (e.g. the part of the ecosystem in which an animal forages and the time it spends foraging in different parts of the ecosystem, including management aspects where applicable)
    - Animals
    - Other mobile organisms
- **CHEMICAL COMPOSITION and CHEMICAL CYCLES** (Including sources and sinks)
    - Major nutrients
    - Minor nutrients
    - Trace elements
- **METABOLISM**
    - Animals
    - Plants
    - Other organisms

Note: VARIATION WITH SPACE is dealt with under Extent and Heterogeneity) and VARIATION WITH TIME (Diurnal, Seasonal, Annual or other) is dealt in the appropriate descriptive characteristics.

Human Activities

The description of human communities and activities is a necessary component of the biosphere system description for two primary reasons. First, it indicates the extent to which human activities and man-made communities have disturbed or replaced natural systems. One result of this is that, over large regions, natural hydrological and biogeochemical pathways and processes have been modified significantly by land and water management practices. Hence, the assumed influence of mankind on ecological communities and the transport and cycling of materials clearly needs to be taken into account in the description and modelling of hypothetical future biosphere systems for long-term radiological impact assessment(4). Second, consideration of the assumed relationship of human communities to the biosphere is important in describing the manner in which local (and potentially contaminated) environmental resources are exploited. Such issues are relevant to characterising the behaviour of hypothetical exposed groups as a basis for estimating doses and risks.

Table HII: Human Community Characteristics

- **Population**
  - Age distribution
  - Density
  - Economical Sectors distribution
  - Diet
- **Human behaviour**
  - Activities in relation to the system:
    Table HIIa identifies relevant activities that may be important in terms of their influence over the different components of the system.
  - Activities in relation to exposure:
    Table HIIb identifies activities in relation to potential exposure modes and pathways. Characteristic parameters associated with quantifying exposure (e.g. exposure duration, rate of intake, shielding factors, location with respect to the source etc.) are also indicated.

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(4) It is recognised that temporal variations may be important; all types of biosphere system can be exposed to significant short-term transformation, both naturally (e.g. by fire) or artificially (fallow agricultural land, forest clearance). The nature of regulatory risk criteria is such that explicit characterisation of the effects of transitions associated with unpredictable, one-off events resulting from human actions tends not to figure centrally in the development of representative indicators for potential long-term radiological impact. Nevertheless, scoping estimates of the potential significance (whether transient or long-term) of such changes may be of some interest.

Table HIIa. Activities in relation to the biosphere system

Biosphere System Components	Human Influence on Biosphere System Components
Climate Atmosphere	Change composition of the atmosphere (local, global scale) Create a local microclimate Controlled ventilation of buildings (Air)
Geological Media	Quarrying Mining
Soils / Sediments	Homogenisation (ploughing / tilling) Change composition (soil improvement and fertilisation, including crop residues and animal waste) Transport/transformation (dredging and disposal of sediment) Impermeable surfaces / artificial drainage
Topography	Alteration of erosion rates
Water Bodies	Change the physical shape and flows (damming) Change the effective volume/level (artificial mixing, water abstraction) Transport of water (pumping and distribution of water) Change the composition (waste water discharge)
Natural and Semi-Natural Ecosystems (Terrestrial/ Aquatic)	Fire control (e.g. periodic burning / firebreaks) Pest / weed control Use for grazing Hunting/fishing
Managed Ecosystems (Terrestrial/ Aquatic)	Planting Irrigation Cropping Husbandry practices (e.g. seasonal relocation) Feeding and watering

The extent to which any of the activities identified in Table HIIa is practised by the local human community, and their detailed characterisation, will depend on fundamental assumptions relating to the type of community and its technological capabilities. The list presented here is not considered exhaustive, but is intended to provide a working basis for developing a comprehensive description of such activities as part of a coherent overall system description.

Table HIIb: Human Activities leading to Potential Radiation Exposure

Biosphere system components[1]	Potential Exposure Mode -> Exposure Routes	Related Activities	Relevant Parameters[2]
Atmosphere	*Inhalation* Breathing	All activities, indoors and outdoors	B
	Ingestion Particulate deposition on foods, surfaces	Eating, recreational activities	B, D, H
	External Submersion	All activities, indoors and outdoors from airborne concentrations	A, C, F, G
Geological media	*Inhalation* Resuspension of dust	Mining, Quarrying	A, B, E, G
	Ingestion Incidental ingestion	Contamination of food / fingers etc. in working environment	B, D, H
	External Exposure to walls, ceiling and floor	Mining, Quarrying	A, C, F, G
Soils	*Inhalation* Gaseous release into air (Volatile radon.)	All activities, indoors and outdoors	A, B, E
	Inhalation Soil/dust resuspension	Soil disturbance activities (e.g. ploughing, walking, outdoor activities, indoor exp. from dirt tracked in)	A, B, E Particle size
	Ingestion Incidental soil ingestion	Gardening, eating, recreational activities	A, B, H
	External External irradiation (including dermal contact)	Activities over/near contaminated soil Living in contaminated buildings	A, C, F, G
Sediments	*Inhalation* Resuspension of dried sediments	Dredging (includes tank cleaning), farming activities after land application	A, B, E
	Inhalation Spray of suspended sediment.	Irrigation spray, showering Drinking water, bathing, swimming, cooking	A, B, E Particle size
	Ingestion Incidental ingestion of suspended sediments		A, B, H
	Ingestion Incidental ingestion of dried sediments	Gardening or eating fresh vegetables from deposition areas downwind of dried sediments, recreational activities on dried sediments	A, C, F, G
	External Gamma exposure from sediments	Activities near water bodies (including tanks), Activities on dried sediments, swimming,	

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Table HIIb: Human Activities leading to Potential Radiation Exposure

Biosphere system components^1	Potential Exposure Mode -> Exposure Routes	Related Activities	Relevant Parameters^2
Water Bodies	*Inhalation* Spray, Aerosols, Volatile	Spray (Irrigation, surface waters), Domestic (showering/sauna/cooking)	A, B, E
	Ingestion Drinking	Drinking	B
	Ingestion Incidental ingestion	During bathing/swimming	A, B
	Ingestion Eating	Cooking practices	B
	External Submersion in water External from water bodies	Bathing, swimming, working near contaminated water bodies (including water tanks and filtration systems)	A, C, F, G
	Dermal Absorption Submersion in water	Swimming, bathing, interception of irrigation spray	B
Fauna	*Inhalation* Animal-derived particulates from incineration or cooking	Incineration of waste products, cooking, occupational use of animal products	A, B, E
	Ingestion Food	Eating (meat, offal, milk products, eggs, gelatin) Drinking milk	B
	External Gamma exposure from animals/animal products	Animal husbandry, processing/storage, wearing clothes	A, C, F, G
Plants	*Inhalation* Particulate from combustion	Fuel burning, ecosystem control by fire	A, B, E, G
	Ingestion Eating food	Eating plant products Drinking plant-based drinks	B
	External Gamma exposure from plants/plant products	Working/Recreation in fields, storage/processing, wearing clothes, living in buildings with material or furniture contaminated	A, C, F, G

Note 1: The generic subset of biosphere system components that are potentially contaminated environmental media

Note 2:Explanation of Parameters (final column) relevant to the Quantitative Description of Pathways

A - Exposure Duration (hrs, yrs etc.)
B - Rate of Intake (kg/yr, g/hr etc.)
C - Shielding of Source (yes/no, effective thickness, shielding factor)
D - Deposition Rate (g/m^2/yr etc.)
E - Resuspension/Release Rate (g(soil)/cu. m air, 1/m, g/hr etc.)
F - Geometry of Source (infinite plane, line, sphere, semi-infinite cloud etc.; source area/volume - sq. m)
G - Relation to Source (Distance - m; Relation to source - beside, above, below, in etc.)
H - Age-specific Information Important (because children may have greater total intake rates than adults [i.e. in situations where children behave fundamentally differently from adults])

References for Annex A to Appendix A

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Appendix B - The KØppen/Trewartha Climate Classification Scheme

• **A tropical climates:**	over 17°C in all months	Ar tropical rain Am tropical monsoonal rain Aw tropical summer rain As tropical winter rain
• **C subtropical climates:**	over 9°C 8-12 months	Cr subtropical rain Cw subtropical summer rain Cs subtropical winter rain
• **D temperate climates:**	over 9°C 4-7 months	DO temperate oceanic DC temperate continental
• **E subarctic climates:**	over 9°C 1-3 months	EO subarctic oceanic EC subarctic continental
• **F polar climates:**	over 9° no month	FT tundra FI ice
• **B dry climates:**	evaporation > precipitation	BS steppe BW desert BM marine desert

The rules for Køppen/Trewartha climate classification shown below are taken from pages 84-85 of Rudloff, W., 1981: World-Climates, Wissenschaftliche Verlagsgesellschaft mbH, Stuttgart, 632pp. Within BIOCLIM, they are applied to long-term averages of monthly temperature and precipitation from potential analogue stations as part of the rule-based downscaling methodology (BIOCLIM, 2003d). They have also been applied to monthly temperature and precipitation averages from the General Circulation Model and Regional Climate Model used in BIOCLIM Work Package 2 in order to inter-compare the various downscaling methods used in BIOCLIM (see Section 3.4).

The following variables must be calculated in order to classify each station or model gridbox:

Tann = mean annual temperature
Rann = mean annual precipitation
Rsum = mean precipitation in summer (April-September)
Rwin = mean precipitation in winter (October to March)
RW = desert limit of precipitation = 10(*Tann*-10) + 300 Rsum/Rann
rmin = mean monthly precipitation of the driest month
R’ = 25(100-rmin)

First of all, one has to ask whether annual precipitation is lower than the desert limit:

- *The climate is BW* if Rann < RW.
- *The climate is BM* if Rann < RW and the place is near the coast and has a high air humidity.
- *The climate is BS* if Rann < 2 RW.
- The class is not B if Rann ≥ 2 RW.

Secondly, one has to ask how many months are > 17°C:

- If all months are, *the climate is A.*

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Then one has to ask how many months have > 59 mm precipitation:

- *The climate is Ar* if more than 9 months do.
- *The climate is Am* if Rann ≥ than R': otherwise
- *The climate is Aw* if Rwin < Rsum, and
- *The climate is As* if Rsum < Rwin.

If not all months, or none, are > 17°C, we have to ask how many months are > 9°C:

- *The climate class is F* is there are no months > 9°C,
- *The climate class is E* if there are 1-3 months > 9°C,
- *The climate class is D* if there are 4-7 months > 9°C, and
- *The climate class is C* if there are more than 7 months > 9°C.
- *The climate is Cr* is the class is C and the driest month of summer has > 29 mm precipitation.
- *The climate is Cs* if rmin is in summer with < 30 mm precipitation and is exceeded at least three times by the wettest month in winter, and Rann < 890 mm; otherwise *the climate is Cr.*
- *The climate is Cw* if rmin is in winter and is exceeded at least ten times by the wettest month in summer; otherwise *the climate is Cr.*

(The foregoing procedure can also be applied to characterise D climates by means of r, s and w. However, s and w can also be applied without restriction to B, E and F climates. This was not done within BIOCLIM)

The next question is how many months there are < 0°C:

- *The climate is Fl* if the class is F and all months < 0°C; otherwise *the climate is FT.*
- *The climate is DO* if the class is D and no month < 0°C; otherwise *the climate is DC.*
- *The climate is EO* if the class is E and no month < –9°C; otherwise *the climate is EC.*

The classifications are prefixed by a G if the height of the place is between 500 m and below 2500 m, by an H if it is 2500 m or more. In addition to this, all classifications can be expanded by two code letters of the thermal standard scale indicating the warmth of summer and the cold of winter corresponding to the maximum and minimum of the mean monthly air temperature.

Universal Thermal Scale:

35°C	to …	severely hot	i
28°C	to 34°C	very hot	h
23°C	to 27°C	hot	a
18°C	to 22°C	warm	b
10°C	to 17°C	mild	l
0°C	to 9°C	cool	k
-9°C	to –1°C	cold	o
-24°C	to –10°C	very cold	c
-39°C	to –25°C	severely cold	d
…	to –40°C	excessively cold	e

Appendix C - Narratives of Environmental Change for the regions of Interest and Characterisation of System states and transitions Arising From the Narratives

C1. The Evolution of Central England

C1.1. - Characteristics of Central England at the Present Day

At the present day, the climate of Central England is temperate oceanic (Køppen-Trewartha Class DO). Mean monthly temperature and precipitation characteristics for various climate analogue stations appropriate to these conditions are shown in Figures C1.1 and C1.5, respectively. The near-surface lithostratigraphy comprises geometrically complex unconsolidated Quaternary deposits overlying mainly the Liassic clays, Oolite sequence, lower Cretaceous rocks and Chalk. The topography is an undulating lowland intersected by fluvially incised river valleys. Generalised erosion and incision of the valleys is now thought to be proceeding only very slowly. Surface water bodies are mainly flowing rivers and streams. Substantial lakes and wetlands are uncommon, but do occur. In respect of biota, the overall characteristics are those of an intensively farmed environment. Cereal crops, root crops and green vegetables are grown. Fruit growing is practiced extensively, with different areas specialising in soft fruits and tree fruits. In the lower areas, arable land extends over the ridges, as well as occurring in valley bottoms. Grasslands are more common on the higher ridges of the chalk downlands, but, even there, arable agricultural activities can be observed. Sheep grazing is characteristic of these higher areas, but the rearing of cattle for milk and meat is more characteristic of the lowland pastures. Small herds of goats are kept. However, most goats are kept in small numbers domestically. Pigs are reared commercially and domestic fowl are reared both commercially and domestically.

In rural areas, hamlets and villages are the characteristic human communities, with inter-settlement distances of a few kilometres. These hamlets and villages relate economically to market towns (separated by distances ~ 20 km), which in turn relate economically to larger towns and cities. The characteristic small-scale demographic unit is the rural parish. This will typically cover the land area associated with a village and surrounding smaller settlements. Rural parish populations are typically a few hundred to a few thousand individuals. Today, only a small percentage of the inhabitants of a rural parish will be involved in agricultural activities. In general, consumption of locally derived foods is limited, as much of the agriculture is of a large-scale commercial nature.

However, vegetable gardening is common, farm shops are popular and pick-your-own fruit options are offered by some farmers. Coarse fishing is a common recreational activity, but very little freshwater fish is caught for human consumption.

C1.2. - Evolution of Central England in Scenarios B3 and B4

Over the next few hundred years, the effects of anthropogenic greenhouse-gas releases are expected to result in a substantial change in the climate of Central England. Results of the rule-based downscaling technique (D8a) imply a rapid transition to Køppen-Trewartha Class Cs conditions. Mean monthly temperature and precipitation characteristics for various climate analogue stations appropriate to these conditions are shown in Figure C1.1 and C1.5, respectively. However, it is also relevant to compare with Simulation A undertaken in WP2. In this simulation, the insolation pattern is as it is at the present day, but the atmospheric CO_2 concentration is 1100 ppmv. In this simulation, the global increase in annual mean air temperature is 2.2°C, reflecting the relatively low sensitivity of the GCM to enhanced greenhouse-gas forcing. However, over the North Atlantic, the temperature increase is less than this, due to deep mixing of oceanic waters. This has implications for the climate of Central England, which is located on the margin between oceanic and continental changes. In this region, temperature changes relative to the present day are estimated to be about 2 to 3°C in both summer and winter. Precipitation in autumn is increased by about 0.2 to 0.5 mm d^{-1} relative to the present day and precipitation in summer is decreased by between 0.2 and 0.4 mm d^{-1}. These results imply that overall annual temperatures would be increased by about 2 to 3°C, without any substantial change in the seasonal cycle and that the total annual precipitation would be very similar to that at the present day, but with a decrease of about 40 mm during the summer months. Inspection of the temperature class averages in Figure C2 suggests that this is more consistent with a change to Class Cr than to Class Cs. Also, inspection of the precipitation class averages in Figure C6 indicate that the analogue stations selected for Classes Cr and Cs are generally too wet in winter (precipitation increases relative to the present day ~ 1 to 2 mm d^{-1}) and too dry in summer (precipitation decreases relative to the present day of 0.7 to 1.4 mm d^{-1}).

It is also relevant to compare results from the one-year MAR calculation for Simulation A with the corresponding LMDz calculation for the same year. This comparison is provided in D6. For Central England, the LMDz calculation gives an increase in winter and summer temperatures of 3.2°C and 3.9°C, respectively. The MAR calculation gives 7.0°C and 4.4°C, respectively. This suggests that the long-term average LMDz temperature increase of 2 to 3°C may be an underestimate and that there may be a weakening of the seasonal cycle, making Central England rather more oceanic. In respect of precipitation, the LMDz calculation gives an increase in winter of 0.65 mm d^{-1} and a decrease in summer of 0.01 mm d^{-1}. The corresponding MAR calculation gives a winter increase of 0.84 mm d^{-1} and a summer decrease of 0.12 mm d^{-1}. These results are very similar, so there is no reason to modify the estimates of changes in precipitation obtained from inspection of the long-term average LMDz results (i.e. unchanged annual precipitation and summer precipitation decreased by 0.2 to 0.4 mm d^{-1}).

Overall, it seems reasonable to assume that, over the next few hundred years, mean annual temperatures in Central England will increase from about 10°C (Figure C3) to between 13°C and 16°C. The seasonal variation in temperature (warmest month – coldest month) may remain as it is at the present day (~ 12°C) or may weaken slightly (to ~ 9°C). Winter precipitation could be only marginally higher than it is at the present day, or increase by as much as 1 to 2 mm d^{-1}. In contrast, precipitation in summer is likely to decrease by 0.2 to 1.4 mm d^{-1}.

These changes in climate would apply to a landscape with near-surface lithostratigraphy and topography essentially unchanged from that at the present day. Annual precipitation, runoff and interflow could either increase or decrease relative to the present day. However, it seems highly likely that stream and river flows would decrease in summer, with some smaller streams becoming ephemeral. If winter precipitation increased by 1 to 2 mm d^{-1}, the total increase over the winter half of the year could be up to 0.4 m. This is a substantial increase. In the transitional period over which winter precipitation increased, the frequency of overbank flooding could increase and the magnitude of such floods could be larger. However, in the longer term, the dimensions of stream channels would adapt to the higher flows, unless constrained by human activities, and the frequency of overbank flooding would diminish.

If winter precipitation were to be only slightly more than that at the present day, the combination of higher temperatures throughout the year and somewhat decreased summer precipitation would almost certainly imply a reduction in groundwater resources. Indeed, there might be an extended period of depletion by over-utilisation before a new sustainable water-management regime was established. Various surface-water storage schemes might be undertaken to ensure better capture of winter precipitation for subsequent use in the hotter, somewhat drier, summers.

The hotter, somewhat drier summers would also result in an increased soil moisture deficit during the growing season. This would result in an increased irrigation demand. However, it seems that the overall change would not be as extreme as to result in arid Mediterranean conditions, in which extensive irrigation of pasture occurs. As at the present day, it seems likely that irrigation would be mainly of high value fruit and vegetable crops. With irrigation, a wide range of crops could be grown, as at the present day. Yields would be increased and there could be more than one harvest per year for some crops. There is no reason why animal husbandry practices should be very different from those at the present day. Overall, with a similar pattern of agriculture to that at the present day, there is no climate-driven reason to propose any substantial change in human community characteristics.

Rule-based downscaling studies for the two greenhouse-gas warmed scenarios B3 and B4 indicate that the warmer climate of Central England described above could persist for several tens of thousands of years (D8a). Best estimate downscaling results based on MoBidiC output for scenario B3 give Cs conditions until about 70 ka After Present (AP), Cr conditions to 90 ka AP and then a return to DO conditions similar to those at the present day persisting until about 105 ka AP. For scenario B4, Cs conditions persist until about 160 ka AP, with short episodes of Cr conditions at around 100 ka AP and 150 ka AP. Sensitivity studies for scenario B3 indicate the robustness of these results against changes in the thresholds that are consistent with the available palaeodata. Downscaling using LLN 2-D NH output for scenario B3 gives a shorter period of Cs conditions, but then an extended period of Cr conditions to 90 ka AP. For B4, Cs conditions occur out to about 60 ka AP, then Cr conditions persist until about 160 ka AP, with two brief periods of DO conditions at about 100 ka AP and 150 ka AP. Thus, overall, the projections of climate based on MoBidiC results are somewhat warmer than those based on LLN 2-D NH results.

Comparisons of these results can be made with various snapshot scenarios studied in WP2 using LMDz. The relevant simulations are those appropriate to 67 ka AP. Three simulations are particularly relevant. These are:

- E: CO_2 concentration as in the baseline study (345 ppmv) and the configuration of the Greenland ice sheet identical to that at the present day;
- D: CO_2 concentration as in the baseline study (345 ppmv) and with no Greenland ice sheet;
- C: CO_2 concentration of 550 ppmv and with no Greenland ice sheet.

In all of these simulations, mean monthly temperatures in the UK from August to May are within about 0.5°C of those in the baseline simulation, i.e. there is essentially no warming in late summer through to spring relative to the present day. However, warmer summers occur in all three simulations, with June and July temperatures about 2°C warmer than those of the baseline simulation. Mean monthly precipitation values from January to March are ~ 0.3 mm d^{-1} larger than in the baseline simulation. From April to July mean monthly precipitation values are very similar to those from the baseline simulation and from August to December there is an increase in precipitation averaging about 0.5 mm d^{-1} and peaking in September at about 1.3 mm d^{-1}. Comparison of the MAR and LMDz one-year simulations (D6) does not reveal any substantial distinctions, though winter temperatures in simulation C are 2 to 3°C higher in the MAR results than in the LMDz results.

However, inspection of Figures C1.1 and C1.2, and also the comparison of mean climate class characteristics shown in Figure C1.3 indicate that in Cr conditions the mean annual temperature of Central England should be about 4.5°C warmer than at the present day and that the seasonal cycle should be almost unaltered. This suggests that the cooling from Cs and Cr conditions to DO conditions may occur more rapidly than is suggested by the rule-based downscaling procedure.

Overall, it is considered that, following a peak in mean annual temperature over the next few hundred years, a cooling trend will ensue, such that temperate conditions similar to those of the present day will recur at between 60 ka and 160 ka AP. Thereafter, there is no strong trend in climate through to 200 ka AP, though MoBidiC and LLN 2D NH results for scenario B3 indicate that a brief cold episode in the range of EC to EO conditions would be expected to occur at around 175 ka AP and persist for a few thousand years.

As discussed above, at the thermal peak in a few hundred years from now mean annual temperatures in Central England will have increased to between 13°C and 16°C. The seasonal variation in temperature may remain as it is at the present day (~ 12°C) or may weaken slightly (to ~ 9°C). Winter precipitation could be only marginally higher than it is at the present day, or increase by as much as 1 to 2 mm d^{-1}. In contrast, precipitation in summer is likely to decrease by 0.2 to 1.4 mm d^{-1}. Thus, the main climatic change associated with the return to temperate conditions at between 60 ka and 160 ka AP, is a general cooling throughout the year of between 3 and 6°, with any changes in seasonality being very limited. Winter precipitation may decrease somewhat and summer precipitation is likely to increase, so that the current pattern of precipitation being reasonably uniformly distributed throughout the year is recovered. There may then be further cooling to a 'boreal' episode lasting a few thousand years around 175 ka AP. This would be associated with mean annual temperatures ~ 0°C, with a maximum mean monthly temperature of 10 to 18°C in July or August, and a minimum mean monthly temperature of -1 to -20°C in January. The total annual precipitation during this colder episode is expected to be very similar to that at the present day (Figure C1.7) and also relatively uniformly distributed throughout the year. However, modest maxima in mean monthly precipitation either in winter or in summer may occur (Figure C1.5).

Overall, the period from the present day through to 170 ka AP is characterised by a climate that is only moderately warmer than at the present day and that is associated with a similar degree of water availability throughout the year, though with somewhat drier summers. The main factor in landscape evolution over this period is not climate change relative to the present day, but the duration of the period of interglacial conditions that is projected to occur. The last interglacial (OIS 5e; the Eemian) lasted 10 to 15 ka, and this is thought to be characteristic of full interglacial episodes in the Late Quaternary (i.e. since OIS 12 at around 440 ka BP). A period of interglacial conditions lasting 180 ka (from the beginning of the Holocene at around 10 ka BP to 170 ka AP) is unprecedented for Central England during the Quaternary. However, because some parts of the area of interest were beyond the margins of the British ice sheet at the Last Glacial Maximum (OIS 2 at around 18 ka BP) and have not been glaciated since the peak of the Anglian glaciation (attributed to OIS 12 at around 440 ka BP), information exists relevant to long term rates of generalised denudation and incision of such a landscape. However, in using this information, due account has to be taken of the colder conditions that persisted through much of the period.

As discussed in D2 (Section 5.4.1), subsequent to a glacial episode, the resultant till sheet is subject to a continuing process of erosion. Based on reconstructions of the palaeosurfaces of till sheets formed in Northumbria, in the North-west of England, at the time of the Last Glaciation (with till formation at around 15 ka BP) and in East Anglia at the time of the Anglian Glaciation (around 440 ka BP), it is thought that the lowering of interfluves has been by no more than 1 to 2 m. In contrast, depths of valley incision due to fluvial erosion have been considerable. In the case of the Anglian till, maximum depths of valley downcutting are several tens of metres, though they do not exceed 60 m. The average depth of erosion across the whole area studied was 16.91 m and the modal depth of erosion was 10.46 m. The average depth of erosion corresponds to a rate of 38 mm ka^{-1}. In the case of the Northumbrian till, some caveats on the available data are appropriate. These are that the till does not fully clothe the solid rocks and that, whereas the rivers of the Anglian till originate within the domain that was studied, those of the Northumbrian till rise beyond the till sheet and cross it to the sea. Nevertheless, it is relevant to note that, for the whole of the Northumbrian till, the maximum depth of incision is 47.1 m, the average depth of incision is 11.85 m and the modal depth of incision is 7.46 m. These results indicate that incision into a till sheet is likely to occur mainly during the first few thousands to tens of thousands of years after it is deposited. This effect occurs for two reasons. First, the post-glacial surface hydrological regime tends to be very active, with copious amounts of available surface water that acts as an efficient agent of fluvial incision. Second, the initial channels that are formed are far from equilibrium, so rapid downcutting occurs as streams develop equilibrium profiles graded to the local base level. Thereafter, there is limited incision and sediment loads are determined mainly by the delivery of sediments from the surface-water catchment area that are transported downstream and either deposited on the floodplain or enter the estuarine/marine environment.

On this interpretation, the additional incision of stream channels that might be expected to occur over the next 170 ka can be bounded by use of data relating to the Anglian till. In that case, the maximum depth of incision that has occurred is 60 m over 440 ka. It seems likely that about 40 m of this probably occurred within 20 ka of deposition of the till. Thus, if a maximum of 20 m of incision has occurred over the last 420 ka, the additional incision over the next 170 ka should be no more than about 8 m. It could be substantially less if streams have already achieved a close to equilibrium profile. On interfluves, the overall depth of denudation over the next 170 ka is unlikely to exceed 1 m, as no intervals of arid conditions are postulated that could substantially enhance aeolean erosion. In terms of the average rate of lowering of the surface, the average depths of incision of the Anglian and Northumbrian tills of 16.91 m and 11.85 m, respectively, imply that once the early active erosion phase is complete, long-term average erosion rates are unlikely to be much in excess of 0.01 m per ka. Thus, the average depth of erosion over the next 170 ka is estimated as 1.7 m. With up to 8 m of additional incision over the next 170 ka and 1.7 m on average, slope angles should not increase by more than about 10%. Thus, topographic changes are assessed as very limited.

In principle, one factor that could affect the above analysis is a change in sea level, as this is the ultimate determinant of base level. However, in scenarios B3 and B4, there is generally a smaller global ice volume throughout the next 170 ka than at the present day. Thus, sea level will be at, or a few metres above, its present level throughout the period.

Outside the river valleys, the degree of surface lowering over the period is expected to be less than 1 m. Therefore, there will be very little increase in the area of land from which till is completely removed exposing the underlying parent material. Generalised aeolian and fluvial erosion will remove existing superficial soil horizons. However, the soil system will remain covered with vegetation, so a new organic A horizon will continually be formed and changes in the soil profile are expected to be very limited. In the river valleys, several metres of erosion could result in removal of the till in some areas and the establishment of new hydraulic connections between surface waters and the underlying rock. It seems unlikely that the nature and extent of alluvial deposits would be substantially altered. However, the spatial pattern of those deposits might alter somewhat, with switching between erosional and depositional regimes being determined by detailed spatial and temporal changes in the flows of surface waters.

Losses of material by solubilisation (chemical erosion) are likely to be very limited compared with fluvial and aeolian erosion, except, possibly, in the case of the outcrop of the Chalk east of The Fens. However, the low elevation of this Chalk outcrop is regarded as mainly due to the effects of the Anglian ice, so it seems unlikely that chemical erosion would result in lowering of that outcrop by more than a few metres over the next 170 ka.

With the limited changes in topography projected over the next 170 ka and the limited changes in either amounts of precipitation or seasonal temperatures, it seems unlikely that there would be substantial changes in the pattern of surface water flows or in groundwater levels. Thus, the overall surface and near-surface hydrological system is likely to be very similar to that at the present day. These remarks reflect the maturity of the landscape. However, it is noted that substantial changes in hydrology could occur as a consequence of human activities. The effects of changes in human activities, except in so far as they determine and are determined by climate change, are outside the remit of BIOCLIM.

However, some consideration must be given to the increased demand for groundwater that would be expected under climatic conditions warmer than those at the present day. By use of the approach discussed in Section 3.2, it has been demonstrated that mean annual irrigation requirement increases from about 80 mm under DO conditions to about 120 mm in Cr conditions and about 460 mm in Cs conditions. Thus, as already discussed, at the peak of greenhouse-gas induced warming over the next few hundred years, there might be a substantially increased demand for irrigation water, which could potentially result in reductions in available groundwater sources, including reductions in the amount of perched water and a lowering of the regional water table. However, in the longer-term, the demand for irrigation water is not likely to be substantially higher than at the present day.

Again as discussed above, under Cs conditions and with irrigation, a wide range of crops could be grown, as at the present day. Furthermore, there is also no reason why animal husbandry practices should be very different from those of the present day, except that pasture might be irrigated and animals would be able to graze such irrigated pasture throughout the year. As the climate cooled, patterns of agriculture would not be expected to change markedly, but there would be some reduction in the demand for irrigation. Also, there is good reason to consider that the landscape would continue to be fully utilised for human activities throughout the warming and cooling phases considered herein, i.e. no increase in the extent of natural and semi-natural biotic communities is taken into account. However, it is emphasised that the pattern of agriculture could change substantially as a result of various social, political and economic factors not directly determined by climate. Evaluation of the implications of such factors for performance assessment is outside the scope of BIOCLIM.

With only limited changes in climate, topography, water bodies and biota over the next 170 ka, there is no requirement in BIOCLIM to assume that different demographic patterns would develop. Therefore, human community structures are assumed to remain as they are at the present day. As with agriculture, it is emphasised that such community structures could change substantially as a result of various social, political and economic factors not directly determined by climate.

The transition to a period of colder climate at around 170 ka AP gives rise to some additional considerations. This climate is projected to fall into either Køppen-Trewartha class EO or EC.

Climate state EO would be characterised by cool summers (mean temperature of the warmest month just over 10°C) and winter temperatures in the coldest month of between about -6°C and 0°C (Figure C1.1). The total precipitation would be very similar to that at the present day and distributed approximately uniformly throughout the year (Figures C1.5 and C1.7). There would be an annual moisture excess of about 200 mm and a summer moisture deficit similar to that at the present day (Figures C1.10 and C1.11). However, with an overall annual moisture excess and a very wet spring, it is unlikely that irrigation would be required. Even if irrigation did occasionally occur, it would probably utilise surplus surface water, rather than groundwater.

As discussed above, the topography and near-surface lithostratigraphy would be very little altered from the present day. However, there could be some soil modification to produce gelic histosols. In respect of water bodies, groundwater levels would probably be higher than at the present day. Marshes are likely to develop in depressions and other poorly drained areas, as well as along water courses. Requirements would be mainly for drainage rather than surface water storage.

In terms of vegetation, a largely treeless landscape is likely to develop, either from forested or unforested antecedent conditions. Agriculture would be largely animal husbandry, with land given over to grass for either summer grazing or hay production. Animals would be over-wintered indoors. Arable cultivation would mainly be of vegetables, with barley grown in areas with the least severe climate. Extensive areas of natural vegetation are likely to develop, i.e. the spatial extent of utilisation of the landscape by humans is likely to decrease. This natural vegetation would comprise mainly various types of low-growing shrubs. With a low productivity agricultural system based on livestock husbandry, small villages, hamlets and isolated homesteads widely dispersed over the rural landscape are likely to be the characteristic human communities. However, it would be possible to sustain a mix of urban and rural communities as at the present day.

The EC climate is typically characterised by warmer summers than EO and much colder winters. Overall, this results in a mean annual average temperature about 5°C colder. It is debatable whether this extreme contrast in continentality would apply in Central England, though it might arise as a result of changes to ocean circulation patterns in the northeast Atlantic. Characteristics of the near-surface lithostratigraphy and topography would be similar to those discussed for the EO climate. Substantial changes to water bodies would be expected. Very cold winters would lead to extensive snowpack development and the freezing of rivers. The spring melt would be associated with ice dams in the rivers and very high peak flows. In consequence, there would be considerable remodelling of river channels. Discontinuous permafrost is expected to be present, overlain by a seasonal active layer. Soil structures, such as ice wedges, that are characteristic of cold regions are expected to form.

The natural vegetation would be the low shrub and herb vegetation characteristic of tundra environments. However, agricultural systems and human communities could closely resemble those associated with the EO climate class.

As the cold state described above came to an end, it is anticipated that a mature, farmed landscape similar to that at the present day would be developed. However, as the natural climax vegetation of Central England under temperate conditions is a mixed deciduous woodland, it is also possible that a network of small settlements existing in settlements in a mainly forested environment might develop.

C1.3. - Evolution of Central England in Scenario A4

The discussion in Section C.1.2 relates entirely to BIOCLIM scenarios B3 and B4. However, a scenario forced only by variations in insolation and natural atmospheric carbon dioxide concentrations has also been studied (scenario A4). Application of rule-based downscaling to that scenario and based on MoBidiC results leads to the projection that temperate conditions similar to those at the present day will persist for the next 50 ka. At that time, a cooling transition to Køppen-Trewartha class EO conditions is projected to occur. These conditions are projected to persist until around 100 ka AP. At that time, a rapid cooling through class EC to full glacial conditions (class FT) is projected to occur. Those glacial conditions are estimated to last for only a few thousand years before amelioration in climate occurs, recovering to temperate conditions by about 120 ka AP. Thereafter, a general cooling trend ensues, with class EO conditions from about 140 to 155 ka AP, a brief amelioration to temperate conditions to 160 ka AP, then a cooling through EO to EC conditions at 200 ka AP. In the corresponding analysis based on LLN 2-D NH results, the cooling at around 100 ka AP results in class EC conditions, rather than full glacial (FT) conditions. Thereafter, a mix of EC and EO conditions persist through to 200 ka AP.

As the MoBidiC results lead to a more extreme projection of future climate changes, posing more issues in biosphere system characterisation, those results are used as a basis for development of an associated narrative below.

During the period of temperate conditions to 50 ka AP, very little change in the landscape is envisaged, with valley incision of no more than about 2 or 3 m, almost no generalised denudation and stable soil, biotic and human community characteristics. As the climate cools at around that time, the changes would be very similar to those described for the B3/B4 scenario at around 170 ka AP. The main distinction in this case is that EO conditions would persist for much longer (50 ka rather than about 5 ka). In this case, consideration has to be given to the annual moisture excess of about 200 mm. This would tend to enhance surface runoff, increasing both generalised denudation rates and, possibly, valley incision. Effects on the latter could also be affected by a fall in sea level causing rivers to regrade to new base levels. However, these effects are likely to be minor compared with the substantial changes expected to occur as a glacial episode is initiated at around 100 ka AP.

The projected glacial episode is substantially different from the Last Glaciation that reached its maximum intensity at around 18 ka BP. That episode was preceded by a long period of very cold conditions that gave rise to substantial build up of both the Fennoscandian and British ice sheets. Specifically, MoBidiC gives an estimated northern hemisphere ice volume that exceeds 2 10^7 km^3 at 65.5 ka BP, increases to 3 10^7 km^3 at 27.5 ka BP and reaches a maximum of 4.1 10^7 km^3 at 18 ka BP. It then decreases rapidly (though not as rapidly as actually occurred). In contrast, for the episode at 100 ka AP, MoBidiC gives an estimated northern hemisphere ice volume that peaks at 1.95 10^7 km^3 at 108 ka AP. This strongly suggests that ice sheet formation in the British Isles would be limited to the north-western upland areas and that Central England would not be glaciated. This view is further supported by the short duration of the projected glacial episode compared with the Last Glaciation, as there would be only a limited interval available for British ice sheets to nucleate, grow and spread south from their postulated nucleation centres in the north-west. Thus, the main cold regions phenomena of interest relate to ground and surface water freezing.

The glacial episode is entered by a rapid (less than 3.5 ka) transition through EC conditions and then persists for about 5 ka or a little longer. EC conditions are described above in the context of scenario B3/B4 and do not require further elaboration. The following FT state is characterised by a mean annual temperature of about -5°C (Figures C1.3 and C1.4), a seasonal range in which the mean temperature of the coldest month is typically -5 to -20°C and the mean temperature of the warmest month is about 7°C (Figure C1.1), and an annual precipitation of about 700 mm distributed reasonably uniformly throughout the year (Figures C1.5 and C1.7). A caveat should be noted on these climate characteristics. Palaeoenvironmental data suggest that Central England experienced intensely cold winters during previous episodes of polar tundra (FT) conditions. This suggests that the temperature of the coldest month should be assessed as about -20°C and that a temperature approaching -5°C is substantially too high. However, set against this, the limited development of northern hemisphere ice associated with this episode will mean that Central England is not in an ice marginal location, as it was at the Last Glacial Maximum.

The mean annual temperature of this state is consistent with the development of discontinuous permafrost in Central England. This is consistent with the palaeoenvironmental record, as relict permafrost features are observed in those areas that were within the margin of the Anglian ice sheet but outside the margin of the Late Devensian (Last Glaciation) ice. Indeed, it is likely that discontinuous permafrost would begin to develop during the latter part of the preceding EC climate state. However, the short duration of that state makes this of only very limited significance. In addition to the permafrost, seasonal freezing and thawing of the overlying soils and sediments would occur. Thus, cryoturbated soils and other frozen ground effects would be induced. Effects on water bodies would be similar to those discussed in relation to EC climatic conditions, i.e. very cold winters would lead to extensive snowpack development and the freezing of rivers. The spring melt would be associated with ice dams in the rivers and very high peak flows. In consequence, there would be considerable remodelling of river channels. The natural vegetation would be of the low shrub and herb tundra type. No agriculture would be practiced. Apart from exploitation of the environment for natural resources such as minerals, the land use is expected to be restricted to herding and hunting activities. The communities involved are likely to have their main permanent settlements close to the coastline, which will be displaced from its current location by a eustatic sea-level fall of around 60 m, uncompensated by any significant isostatic depression of the area because substantial ice-loading of the British Isles does not arise. Communities located close to the coastline would be expected to include a substantial component of marine organisms (fish and shellfish) in their diet, taking their catches from the highly productive polar waters that would be expected to extend south of the British Isles.

Warming from polar tundra conditions is projected to occur somewhat more slowly than at the end of the Last Glaciation. In that episode, the ice sheets were at their greatest extent at around 18 ka BP and fully interglacial conditions were established in Central England by the early Holocene at between 10 and 9 ka BP. Within that period, substantial oscillations in climate occurred, notably the intensely cold but brief (~ 1 ka duration) Younger Dryas. In the projection, the warming to full interglacial conditions is projected to occur in about 12 ka, rather than 8 or 9 ka. However, this distinction in timing is at the limit of the resolution of the models used, so it is considered appropriate to use palaeodata for the Late Glacial to Early Holocene from Central England to characterise this interval. Such data are extremely extensive and a useful summary is the brief description of the first three stages of the model for the evolution of soils and vegetation proposed by Iverson (D2, Section 5.3). The earliest (Cryocratic) stage is characterised by immature, unstable, base-rich soils on which is developed an open herb and dwarf scrub vegetation with arctic-alpine flora. In the following Protocratic stage, rising temperatures and increasing shade are associated with the immigration of tree taxa. Soil maturation occurs and the plant communities comprise heb-rich meadows with juniper scrub and successively tree birches and pine. Poplar or aspen and willow are also elements of the evolving forest. Pedogenesis is likely to be slow in the early part of this stage, but will occur at an increasing rate as temperatures rise. The stature of trees is also likely to increase as the stage progresses. By the end of the Protocratic stage, any natural forests that are present are likely to contain elements of the mixed-oak forest that is characteristic of the following Mesocratic stage. During the Mesocratic stage, the forest is likely to be of oak, with co-dominants of elm, alder, lime and ash. A rich undergrowth of shrubs would be present, with some (e.g. holly, hazel and yew) attaining the stature of small trees. Various herbs and climbers are likely also to be present. The characteristic soils are base rich, with the horizon of mull humus associated with brown forest soils.

In the Mesocratic stage, conditions are similar to those of the Holocene. Human activities could be expected to result in forest clearance, if extensive forests had been allowed to develop during the Protocratic stage, and a mature landscape similar to that existing at the present day, though rather more deeply incised, could develop. Climatic conditions similar to those at the present day are projected to persist until about 140 ka AP. Thereafter, cooling to EO conditions is projected. These conditions would last to about 170 ka AP, with a brief episode of DO conditions at around 160 ka AP. Over this period, only slow evolution of the landscape would be expected to occur. From about 170 ka AP, further cooling would result in EC conditions through to 200 ka AP. The characteristics of the landscape under EC climatic conditions are discussed in Section C.1.2.

C1.4. - Identification of Characteristic Climate States and Transition

From the characteristics of Central England under Scenarios B3 and B4, the following states and transitions are identified as forming the basis for a suitable generalised scenario of environmental change.

a) A biosphere state with a landscape and climate similar to that at the present day persisting for no more than about 100 years;

b) A biosphere transition over a few hundred years to a landscape similar to that at the present day, but with a climate with an annual mean temperature between 3 and 6°C warmer;

c) A biosphere state with a landscape similar to that at the present day, but with a climate with an annual mean temperature between 3 and 6°C warmer, persisting to about 50 ka AP;

d) A biosphere transition over tens of thousands of years to a landscape and climate similar to that at the present day;

e) A biosphere state with a landscape and climate similar to that at the present day persisting to about 170 ka AP;

f) A biosphere transition to a cold (boreal) climate state over 5 ka;

g) A biosphere state with a mean annual temperature of ~ 0°C lasting a few thousand years;

h) A biosphere transition to a biosphere state with a landscape and climate similar to that at the present day occurring over a few thousand years from about 180 ka AP;

i) A biosphere state with a landscape and climate similar to that at the present day persisting to the end of the study period at 200 ka AP.

In the case of Scenario A4, the following states and transitions are identified:

a) A biosphere state with a landscape and climate similar to that at the present day;

b) A biosphere transition over a timescale of several thousand years to a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day;

c) A biosphere state with a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day persisting to 100 ka AP;

d) A biosphere transition to glacial conditions with the development of discontinuous permafrost over a period of about 5 ka;

e) A glacial biosphere state with a mean annual temperature of about -5°C, the existence of discontinuous permafrost and tundra vegetation persisting for a few thousand years;

f) A biosphere transition over a timescale of about 12 ka to a biosphere state with a landscape and climate similar to that at the present day;

g) A biosphere state with a landscape and climate similar to that at the present day persisting until about 140 ka AP;

h) A biosphere transition over a timescale of several thousand years to a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day;

i) A biosphere state with a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day persisting to 170 ka AP;

j) A biosphere transition over a timescale of a few thousand years to a landscape similar in form to that at the present day, but with EC climatic conditions, discontinuous permafrost and tundra-type vegetation;

k) A biosphere state with a landscape similar in form to that at the present day, but with EC climatic conditions, discontinuous permafrost and tundra-type vegetation persisting to the end of the study period at 200 ka AP.

In this case, it should be noted that the duration of transition (d) has been extended to allow for the continuing development of discontinuous permafrost in the following glacial period.

Taking into account the overall commentaries on Scenarios B3 and B4, some further simplification is possible. Biosphere state (c) is reached rapidly and may even have been attained by the end of the institutional control period that would be expected to follow repository operations and closure. Therefore, from this scenario biosphere state (c), transition (d) and state (e) are of particular interest. The degree of cooling toward the end of the study period is very much less than in Scenario A4, so transitions to colder states and the colder states themselves are more usefully studied in the latter context.

Thus, from Scenario A4, it is useful to address biosphere state (a), transition (b) and state (c). The glacial episode encompassing transition (d), state (e) and transition (f) is also of interest. However, the cooling episode encompassing state (g), transition (h) and state (i) exhibits only limited differences from the sequence state (a), transition (b) and state (c). It does not, therefore, require detailed analysis. However, the further cooling from state (i) through transition (j) to state (k) does require consideration, particularly because of the relatively long duration of state (k).

Thus, the states requiring consideration are:

1) A biosphere state with a landscape and climate similar to that at the present day;
2) A biosphere state with a landscape similar to that at the present day, but with a climate with an annual mean temperature between 3 and 6°C warmer;
3) A biosphere state with a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day;
4) A glacial biosphere state with a mean annual temperature of about -5°C, the existence of discontinuous permafrost and tundra vegetation persisting for a few thousand years;
5) A biosphere state with a landscape similar in form to that at the present day, but with EC climatic conditions, discontinuous permafrost and tundra-type vegetation.

The transitions between these states that are of particular interest are:
[2–>1] over a timescale of tens of thousands of years;
[1–>3] over a timescale of a few thousand years;
[3–>4] over a timescale of about 5 ka;
[4–>1] over a timescale of about 12 ka;
[3–>5] over a timescale of a few thousand years.

The individual states are characterised in subsection C.1.5, using the BIOMASS methodology. Transitions are characterised in subsection C.1.6, using the methodology developed in BIOCLIM.

C1.5. - Characterisation of States

Based on the material in the annex to Appendix A, it is appropriate to describe the various states identified as being of interest as shown in the following tables.

Climate Type Classification for Central England

State	Køppen/Trewartha Class	Description
1	DO	Landscape and climate similar to that at the present day.
2	Cr or Cs	Landscape similar to that at the present day, but with a climate with an annual mean temperature between 3 and 6°C warmer.
3	EO	Landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day.
4	FT	Landscape similar in form to that at the present day, but with a mean annual temperature of about -5°C, the existence of discontinuous permafrost and tundra vegetation persisting for a few thousand years.
5	EC	Landscape similar in form to that at the present day, but with EC climatic conditions, discontinuous permafrost and tundra-type vegetation

Characteristics of Water Bodies in Central England compared with Present	
State	**Characteristics**
1	Mainly flowing rivers and streams. Substantial lakes and wetlands are uncommon, but do occur. Estuarine environments are present. Rivers and estuaries discharge to shallow coastal waters.
2	Stream and river flow reduced in summer, with some smaller streams becoming ephemeral. Increases in winter precipitation could result in increased channel sizes. Summer flows might not fill these channels from bank to bank. Groundwater resources would be less than at present. Regional water levels would be lower and spring lines would be shifted downslope. Global sea-level rise of a few metres would result in inundation of estuaries and low-lying farmland and wetland areas, e.g. the fens and Norfolk Broads. Increases in surface-water storage to ensure better capture of winter precipitation for subsequent use in the hotter, somewhat drier, summers.
3	Overall annual moisture excess. Groundwater levels higher than at the present day. Marshes are likely to be extensive in depressions and along water courses and requirements are likely to be for drainage rather than surface water storage. However, the main land use is likely to be for animal husbandry and resource utilization is likely to be reduced relative to the present day, so there will be a limited requirement to drain wetland areas. Sea-level is likely to be a few metres to tens of metres lower than at present, so surface drainage systems will extend across the current offshore continental shelf. Indeed, land bridges may develop between Britain, Ireland and the Continent. Lakes and wetlands could be a major feature of the current offshore areas, as these are likely to exhibit only limited topographic variability.
4	Tundra type environment. Extensive wetlands in lowland areas. Sea-level is likely to be some tens of metres lower than at present, so surface drainage systems will extend across the current offshore continental shelf. Indeed, land bridges may exist between Britain, Ireland and the Continent. Lakes and wetlands could be a major feature of the current offshore areas, as these are likely to exhibit only limited topographic variability. The main distinction from State 3 is due to the very cold winters. These would lead to extensive snowpack development and the freezing of rivers and streams. The spring melt would be associated with ice dams in the rivers and very high peak flows. Stream channel sizes would be adjusted to these high peak flows. Groundwater flow patterns would be affected by discontinuous permafrost and the seasonal freezing of soil water. Ice-sheet formation would be limited to the north-western upland areas, so Central England would not be glaciated.
5	Overall annual moisture excess. Groundwater levels higher than at the present day. Marshes are likely to be extensive in depressions and along water courses and requirements are likely to be for drainage rather than surface water storage. However, the main land use is likely to be for animal husbandry and resource utilization is likely to be reduced relative to the present day, so there will be a limited requirement to drain wetland areas. Sea-level is likely to be some tens of metres lower than at present, so surface drainage systems will extend across the current offshore continental shelf. Indeed, land bridges may exist between Britain, Ireland and the Continent. Lakes and wetlands could be a major feature of the current offshore areas, as these are likely to exhibit only limited topographic variability. The main distinction from State 3 is due to the very cold winters. These would lead to extensive snowpack development and the freezing of rivers and streams. The spring melt would be associated with ice dams in the rivers and very high peak flows. Stream channel sizes would be adjusted to these high peak flows. Groundwater flow patterns would be affected by discontinuous permafrost and the seasonal freezing of soil water. Ice-sheet development in Britain is not considered likely to occur.

Classification of Human Community Types in Central England based on Socio-economic and Environmental Considerations

State	Trading	Biosphere Control	Community Types and Activities
1	Large-scale	High	Commercial agriculture and horticulture. More limited silviculture (but some deciduous and coniferous woodland management on more marginal land, e.g. heathland). Large-scale mixed farming characteristic with extensive monoproduction of edible and some non-edible crops. Hamlets, villages, market towns and cities in a trading network. Fish farming not extensive. Some water plants (watercress) from streams. Glasshouse horticulture for specialist purposes only (e.g. early fruit, decorative plants for cut flowers and gardens). Range of small scale commercial agricultural practices in market towns, but only a small percentage of the population engaged directly or indirectly in agricultural activities. However, garden cultivation of fruit and vegetables common. Extensive use of groundwater and surface water resources for agricultural and domestic irrigation in some drier areas, e.g. East Anglia.
2	Large-scale	High	Agriculture as at the present day, but with a greater degree of irrigation of high value fruit and vegetable crops. Probably not sufficiently dry in summer to justify irrigation of pasture. Increased yields of most crops (particularly with irrigation) and possibly more than one harvest per year for some crop types. No substantial difference in human community characteristics and infrastructure relative to the present day.
3	Large scale or small scale	High	Largely treeless landscape. Agriculture dominated by animal husbandry, with land given over to summer grass for either summer grazing or hay production. Animals over-wintered indoors. Some arable cultivation of vegetables and barley in areas of least severe climate. Extensive areas of semi-natural vegetation comprising low-growing shrubs. Small scale trading would occur with widely dispersed small villages, hamlets and isolated homesteads. However, it would be possible to sustain a mix of urban and rural communities, as at the present day.
4	None	None	Natural vegetation of the tundra type. Land use primarily herding and hunting. Communities mainly located close to the coastline with a substantial reliance on marine organisms in their diet. However, the coastline would have retreated considerably due to eustatic sea-level fall.
5	Small scale	High	The natural vegetation would be low shrub and herb vegetation characteristic of tundra environments. However, agricultural systems and human communities could closely resemble those under State 3. The more extreme conditions would tend to favour small scale trading with few market or urban centres.

Ecosystem Classification for Central England

NATURAL SYSTEMS

	Terrestrial Ecosystems	Aquatic Ecosystems
State	Description	Description
1	Very little extent of natural systems. Woodland and shrubland is the natural climax vegetation.	Mainly rivers and streams. Substantial fish stocks, but fishing mainly for sport not consumption. Some shallow lakes and wetlands. Estuaries and shallow offshore waters.
2	Very little extent of natural systems. Woodland and shrubland is the natural climax vegetation.	Mainly rivers and streams. Substantial fish stocks. Some shallow lakes and wetlands. Estuaries and shallow offshore waters.
3	Limited extent of natural systems. Where agriculture is not practiced, semi-natural systems are likely to dominate.	Mainly rivers and streams. Estuarine and coastal waters of less significance than at the present day. Wetlands more extensive than at the present day, possibly particularly in current offshore areas.
4	Primarily natural systems. Tundra.	Mainly rivers and streams. Extensive wetlands.
5	Possibly extensive tundra vegetation.	Mainly rivers and streams. Extensive wetlands.

SEMI-NATURAL SYSTEMS

	Terrestrial Ecosystems	Aquatic Ecosystems
State	Description	Description
1	Minor areas of neglected grassland, lowland grass heath and bracken.	Not applicable. Discussed under natural systems.
2	Minor areas of neglected grassland, lowland grass heath and bracken.	
3	Extensive areas of low growing shrubs, neglected grassland, lowland grass heath and bracken.	
4	Primarily natural vegetation, as agriculture is not practiced, so agricultural land in succession to natural vegetation is not present.	
5	As for State 3, but with the balance more toward natural (tundra) vegetation.	

MANAGED SYSTEMS

State	Description
1	**Terrestrial Ecosystems :** Mainly field crops. Some tree crops (e.g. fruit orchards). Limited greenhouses. Mainly improved, but some rough, grassland. Intensive dairying, beef-cattle production, sheep rearing (on downland), pig industry and poultry. Extensive urban and suburban areas (high population density) and transport routes.
	Aquatic Ecosystems : Some ponds, but mainly covered under natural ecosystems.
2	**Terrestrial Ecosystems** : Mainly field crops. Some tree crops (e.g. fruit orchards). Limited greenhouses. Mainly improved, but some rough, grassland. Intensive dairying, beef-cattle production, sheep rearing (on downland), pig industry and poultry. Extensive urban and suburban areas (high population density) and transport routes.
	Aquatic Ecosystems : Some ponds, but mainly covered under natural ecosystems.
3	**Terrestrial Ecosystems :** Mainly animal husbandry. Both intensive dairying and beef production are likely to be practiced. Sheep rearing, pig rearing and poultry. Some vegetable production. May be increased use of greenhouses to grow fruits and vegetables. Barley production likely to be used for animal feed. Reduced extent of urban and suburban areas and transport routes relative to the present day.
	Aquatic Ecosystems : Some ponds, but mainly covered under natural ecosystems.
4	**Terrestrial Ecosystems :** No practice of agriculture.
	Aquatic Ecosystems : Covered under natural ecosystems.
5	**Terrestrial Ecosystems :** Mainly animal husbandry. Both intensive dairying and beef production are likely to be practiced. Sheep rearing, pig rearing and poultry. Some vegetable production. May be increased use of greenhouses to grow fruits and vegetables. Conditions too severe for barley production Reduced extent of urban and suburban areas and transport routes relative to the present day. Generally, reduced extent of agriculture, urban and suburban areas relative to State 3.
	Aquatic Ecosystems : Some ponds, but mainly covered under natural ecosystems.

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Zonal Soil Types for Central England			
State	**Soil type**	**Description**	**Comments**
1	Forest Brown Earths/Agricultural	Natural soils are often Brown Earths or Brown Forest podzols. However, these have been substantially modified by long-term agricultural activities. Well-drained, deep soils are characteristic, though some gleyed soils with near-surface impermeable layers also occur.	A detailed account of the soils of Central England, with emphasis on their hydrological characteristics is given in Institute of Hydrology (1995).
2	Forest Brown Earths/Agricultural	As for State 1.	
3	Forest Brown Earths/Agricultural	Increased extent of gleyed soils with raised groundwater levels. Development of more extensive range of organic soils in wetlands.	
4	Tundra humus soils	Extensive organic soils in wetlands. Substantial cryoturbation structures due to seasonal freezing and the development of permafrost.	
5	Tundra humus soils with some areas of agricultural soil.	Agricultural soils as for State 3, but declining in area and quality.	

Topographical Categories for Central England

Stage 1	Geographical Context Altitude Landform Localised Erosion	Inland and Coastal Lowland Plain to Subdued Fluvially incised
Stage 2	Geographical Context Altitude Landform Localised Erosion	Inland and Coastal Lowland Plain to Subdued Fluvially incised
Stage 3	Geographical Context Altitude Landform Localised Erosion	Inland and Coastal Lowland Plain to Subdued Fluvially incised
Stage 4	Geographical Context Altitude Landform Localised Erosion	Inland and Coastal Lowland Plain to Subdued Fluvially incised
Stage 5	Geographical Context Altitude Landform Localised Erosion	Inland and Coastal Lowland Plain to Subdued Fluvially incised

It should be noted that the topography of Central England is currently described as an undulating lowland intersected by fluvially incised river valleys. This topography will change only very slowly and to a limited degree over the next 200 ka. The main distinction is that falling sea levels in periods of cold climate will result in exposure of sea-bed sediments with the subsequent evolution of a fluvially incised drainage system in those sediments. Also, throughout the period, river channel dimensions will adjust to alterations in the hydrological regime.

C1.6. - Characterisation of Transitions

Characteristics of transitions between the various climate states described in Section C.1.5 are set out in the following transition diagrams.

State 2 to State 1 over tens of thousands of years.					
	TOPOGRAPHY	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
	No substantial influences identified.	**SOILS AND LITHOLOGY**	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
	Limited coastal retreat with sea-level fall of a few metres due to thermal contraction.	No substantial influences identified. However, the long period of interglacial conditions may lead to soils developing to a no analogue codition with continued irrigation.	**WATER BODIES**	No substantial influences identified.	Limited coastal retreat of little influence on human communities due to the long period involved.
	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	**BIOTA**	No substantial influences identified.
	No substantial influences identified.	No substantial influences identified.	Reducing demand for irrigation water coupled to increasing supply is likely to lead to decreasing demand for surface water storage, but the trend will be very slow.	Changes in crop types and reduced yields.	**HUMAN COMMUNITIES**

State 1 to State 3 over a few thousand years					
	TOPOGRAPHY	No substantial changes in currently on-shore topography, so no major effects on soils. Offshore, desalination of sediments will occur followed by development of a soil profile. The exposed area will become progressively incised as strem channels develop and bed sediments will be mobilised and transported down gradient.	Adjustments to a lower base level will cause the long profile of streams and rivers to be modified. Thus, the overall flow pattern will be modified, with feedback effects on further incision. Eventually a new equilibrium profile will be developed. Exposure of the continental shelf will provide a context in which shallow lakes can develop. These could largely disappear as the drainage network matures.	No substantial influences identified.	The newly exposed coastal plain would be occupied by communities similar to those of the on-shore area.
	No substantial influences identified.	**SOILS AND LITHOLOGY**	Limited changes in soil texture will occur, modifying the partition of meteoric waters between surface flow, throughflow and infiltration.	Increasing areas will become of marginal use for agriculture, e.g. waterlogged gley soils, and semi-natural vegetation will develop on those areas.	No substantial influences identified.
	Falling sea-level results in exposure of an extensive area of the coastal shelf. Subsequently, a drainage network is established over this area and fluvial incision occurs.	A rising phreatic surface gives rise to an increasing extent of gleyed soils. Marshy areas develop, but may be subsequently drained leading to new areas of organic soils.	**WATER BODIES**	Waterlogging of soils will place constraints on agriculture and also determine the types of semi-natural plant communities that may occur. New types of community develop in lakes and wetlands of areas currently offshore.	Reorganisation of communities around newly formed lakes and rivers, particularly in the region that is currently offshore.
	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	**BIOTA**	Changes in the extent and distribution of land suitable for agriculture will alter the density of human communities. The increasing extent of natural and semi-natural habitats will place greater emphasis on hunting and fishing.
	Minor modifications of stream channel cross-sections and profiles in drainage operations, but no substantial changes to topography.	Fertilisation in association with drainage in the maintenance or reclamation of areas of land.	Artificial drainage will be used to maintain soils for agriculture or to reclaim newly exposed land.	Trend to decreasing arable land use and increasing relative extent of pasture. Abandonment of some land to semi-natural vegetation.	**HUMAN COMMUNITIES**

State 3 to State 4 over about 5000 years					
	TOPOGRAPHY	Sea level fall leads to extended coastal plain. Desalination of sediments will occur followed by development of cryosols.	The long profile of streams and rivers may be modified to a limited degree. However, with low slopes on the expanding offshore plain, this effect is likely to be limited. Shallow lakes would develop on the newly exposed zone. The extending system of lakes and streams would develop naturally, as artificial drainage would not be appropriate in a climate that was rapidly becoming more severe.	No substantial influences identified.	Human communities would tend to migrate with the retreating coastline, as substantial reliance on marine foods is postulated.
	No substantial influences identified.	**SOILS AND LITHOLOGY**	The development of tundra humus and organic soils is thought to be a minor factor influencing the characteristics of water bodies compared with the direct effects of ground and channel freezing.	Soils become unusable for agriculture. Semi-natural vegetation spreads and is subsequently modified to become fully tundra-like. Animal husbandry is replaced by herding and hunting.	No substantial influences identified.
	Falling sea-level results in exposure of an extensive area of the coastal shelf. Subsequently, a drainage network is established over this area and fluvial incision occurs. Seasonal freezing of groundwaters and river channels has a major effect on the flow regime and hence on incision. Channel cross sections are likely to increase to accommodate high peak flows.	Seasonal ground freezing and the development of intermittent permafrost will lead to the development of cryosols and various features of cold regions such as patterned ground.	**WATER BODIES**	Seasonal ground freezing limits both the type and productivity of vegetation.	No substantial influences identified.
	No substantial influences identified.	Decreasing rate of degradation of biotic materials contributes to the development of humic tundra soils.	No substantial influences identified.	**BIOTA**	Progressive abandonment of land leads to development of a hunter/herder economy with a low degree of utilization of the limited primary productivity and hence utilization of terrestrial resources from a very large area. Pre-existing settlements are abandoned and the population drifts to new coastal settlements.
	No substantial influences identified.	No substantial influences identified.	Abandonment of inland communities means that groundwater abstraction is no longer required except at the coast.	Abandonment of land leads to development of natural tundra vegetation.	**HUMAN COMMUNITIES**

State 4 to State 1 over about 12000 years					
	TOPOGRAPHY	No substantial influences identified on the remaining land area. Soils eroded offshore during sea-level rise and eventually replaced by depositional muds when water depths sufficient.	Alterations in channel dimensions change flow patterns as streams adjust to new base levels.	No substantial influences identified.	Human communities forced to migrate by the advancing coastline. With an ameliorating climate they will also tend to spread inland to take advantage of the increasing productivity of the terrestrial environment.
	No substantial influences identified.	**SOILS AND LITHOLOGY**	Development of agricultural soils through natural processes and human actions will affect the partitioning of precipitation between surface flow, throughflow and infiltration towards the end of the transition. However, at an earlier stage, reductions in ground freezing are likely to be more important than changes in soil characteristics.	Development of agricultural soils through a combination of natural processes and human actions leads to the replacement of natural tundra vegetation by agricultural vegetation. However, with continuous human occupation of the environment, a densely wooded landscape may not ever exist.	No substantial influences identified. Rather, humans adapt soils to their requirements as climatic conditions ameliorate.
	Continuous rise in sea level resulting in rapid coastline retreat. Substantial change in the flow regime with loss of large spring flood leads to underfit streams. Change in base level leads to alterations in the erosional/depositional regime along the river profile.	Seasonal ground freezing decreases. Permafrost melts. Relict ice structures, e.g. ice wedges, are formed.	**WATER BODIES**	Reduction in seasonal ground freezing increases the range of plant communities that can develop.	No substantial influences identified. Adequate surface water is likely to be available throughout the transition, so adjustments in human community structures and locations are likely to be mainly determined by other factors.
	No substantial influences identified.	Tundra vegetation will be replaced by temperate region vegetation. If a natural succession occurs, a heavily wooded landscape will contribute to the development of well-drained Brown Earth soils. However, with continuous human occupation, such a well-wooded landscape may not occur and the soils produced may be no-analogue systems.	No substantial influences identified.	**BIOTA**	No substantial influences identified. Rather, humans adapt biota to their requirements as climatic conditions ameliorate.
	No substantial influences identified.	Development of extensive agriculture. Soils may be no analogue systems produced by continuous management.	Increasing exploitation of surface waters and groundwaters.	Development of extensive agriculture.	**HUMAN COMMUNITIES**

State 3 to State 5 over a few thousand years					
	TOPOGRAPHY	Sea level fall leads to extended coastal plain. Desalination of sediments will occur followed by development of cryosols.	The long profile of streams and rivers may be modified to a limited degree. However, with low slopes on the expanding offshore plain, this effect is likely to be limited. Shallow lakes would develop on the newly exposed zone. The extending system of lakes and streams would develop naturally, as artificial drainage would not be appropriate in a climate that was rapidly becoming more severe.	No substantial influences identified.	Human communities might tend to migrate with the retreating coastline. However, this would not necessarily be the case, as a agricultural system supplemented by hunting/herding could be sustained.
	No substantial influences identified.	**SOILS AND LITHOLOGY**	The development of tundra humus and organic soils is thought to be a minor factor influencing the characteristics of water bodies compared with the direct effects of ground and channel freezing.	Soils become less usable for agriculture. Semi-natural vegetation spreads and is subsequently modified to become fully tundra-like. Animal husbandry is replaced, in part, by herding and hunting.	No substantial influences identified.
	Falling sea-level results in exposure of an extensive area of the coastal shelf. Subsequently, a drainage network is established over this area and fluvial incision occurs. Seasonal freezing of groundwaters and river channels has a major effect on the flow regime and hence on incision. Channel cross sections are likely to increase to accommodate high peak flows.	Seasonal ground freezing and the development of intermittent permafrost will lead to the development of cryosols and various features of cold regions such as patterned ground.	**WATER BODIES**	Seasonal ground freezing limits both the type and productivity of vegetation.	No substantial influences identified.
	No substantial influences identified.	Decreasing rate of degradation of biotic materials contributes to the development of humic tundra soils.	No substantial influences identified.	**BIOTA**	Progressive abandonment of land could lead to development of a hunter/herder economy with a low degree of utilization of the limited primary productivity and hence utilization of terrestrial resources from a very large area. However, a mixed agricultural economy supplemented by hunting/herding is also possible.
	No substantial influences identified.	No substantial influences identified.	Abandonment of some inland communities would mean that groundwater abstraction requirements would be reduced inland.	Abandonment of land leads to development of natural tundra vegetation.	**HUMAN COMMUNITIES**

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The transitions between the states can also be represented in the form of diagrams. Illustrative examples for the transition between State 2 and State 1, and the transition between State 1 and State 3 are shown in Figures C1.14 and C1.15. Figure C1.14 illustrates a simple transition with limited changes and only one strong interaction between the principal elements of the biosphere. In contrast Figure C1.15 shows a complex set of interactions between the different components. In this latter case, there are feedbacks throughout the system. Thus, for example, falling sea level changes the topography by increasing the extent of the coastal plain. New soils develop on the exposed area and the characteristics of those soils are then affected by changes in phreatic surface levels and surface water availability. There is also an interaction between the capacity of this newly exposed land to support agriculture and the degree to which human communities find it desirable to export this increasingly marginal land. Transition diagrams such as these can be further developed to illustrate the stages in transitions. Here, all that has been done is to give an indication of sequence and timing by the inclination of the arrows. Close coupling leading to parallel trends, as exist between requirements and capabilities for agriculture, are indicated by horizontal double-headed arrows.

C2. The Evolution of the Meuse/Haute-Marne region of North-east France

C2.1. - Characteristics of Meuse/Haute-Marne Region at the Present Day

At the present day, the climate of the Meuse/Haute-Marne region is temperate oceanic (Køppen-Trewartha Class DO). From local observations, this climate is characterized by long and humid winters with minimum mean monthly temperature of –2°C, frequent freezing days but limited snowfall, and by summers of moderate sunshine, with maximum mean monthly temperatures of 24°C and light storms associated with heavy rainfall. The mean annual temperature is approximately 10°C and annual mean precipitation rates vary from 700mm to 1000mm, depending on location. Based on the analogue stations selected to be representative of DO conditions in the region (Figure C2.1 and Tables C2.1 and C2.2), the annual average temperature is 10.9°C and the annual amount of precipitation is 798.2mm. These analogue stations are in agreement with the local observations cited in various Andra reports. Seasonal mean temperatures of analogue stations are 18.6°C in summer and 4.6°C in winter. The range of the seasonal cycle of temperature experienced at the analogue stations is 17.3°C. For precipitation, there is no marked seasonal cycle.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Annual**
Cs	11.4	12.0	13.3	15.3	18.4	21.9	24.6	25.0	23.1	19.6	15.5	12.5	17.7
Cr	10.2	10.8	11.9	13.1	15.3	18.1	20.2	20.4	19.5	16.6	12.9	10.7	14.9
DO	2.3	3.7	6.6	10.0	13.9	17.3	19.5	19.1	16.3	11.8	6.5	3.2	10.9
DC	-3.8	-3.5	0.0	4.8	10.6	14.8	16.4	15.8	11.8	7.4	2.2	-1.7	6.2
EO	-2.8	-1.9	-1.5	1.8	5.9	9.1	10.8	10.2	6.9	3.2	-0.4	-2.3	3.2
EC	-18.1	-16.9	-10.7	-3.0	4.3	10.3	14.1	13.0	8.1	0.3	-8.3	-15.3	-1.8
FT	-9.9	-11.8	-10.9	-6.7	-0.2	4.1	7.2	7.1	4.3	-0.6	-5.1	-9.1	-2.6
Cs-DO	9.1	8.2	6.7	5.4	4.5	4.6	5.1	5.9	6.8	7.8	9.1	9.3	6.9
Cr-DO	7.9	7.0	5.3	3.1	1.3	0.8	0.6	1.2	3.2	4.8	6.4	7.5	4.1
DC-DO	-6.1	-7.2	-6.6	-5.2	-3.3	-2.4	-3.1	-3.3	-4.6	-4.4	-4.3	-4.9	-4.6
EO-DO	-5.0	-5.7	-8.1	-8.2	-8.1	-8.2	-8.8	-8.9	-9.5	-8.6	-6.8	-5.5	-7.6
EC-DO	-20.4	-20.6	-17.3	-13.0	-9.7	-6.9	-5.4	-6.1	-8.2	-11.5	-14.7	-18.5	-12.7
FT-DO	-12.1	-15.5	-17.5	-16.6	-14.2	-13.2	-12.3	-12.0	-12.0	-12.3	-11.6	-12.3	-13.5

Table C2.1: *Mean Monthly Temperature Data (°C) for the Sets of Analogue Stations taken to be Representative for the Meuse/Haute-Marne Region and Differences relative to the Values for the Current Classification*

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Cs	96.2	76.5	59.5	44.2	25.1	10.4	3.4	8.6	29.8	84.7	93.9	110.9	643,1
Cr	134.7	121.5	87.3	87.0	78.1	49.9	20.3	20.9	54.9	100.7	122.2	128.6	1005,9
DO	57.4	52.7	59.9	64.0	84.0	79.1	64.6	71.7	67.4	67.3	68.3	61.8	798,2
DC	44.8	31.5	37.5	37.8	44.5	55.6	69.7	70.6	69.2	61.8	63.8	53.3	640,1
EO	58.8	53.8	59.0	45.1	33.7	42.6	47.7	54.7	57.3	69.2	63.4	65.8	651,0
EC	33.9	27.1	30.7	34.8	47.0	58.9	73.4	77.5	68.8	61.2	52.2	42.2	607,5
FT	65.9	50.0	50.0	45.0	43.1	40.3	56.2	73.6	73.8	71.4	77.6	63.6	710,5
Cs-DO	38.8	23.8	-0.5	-19.8	-59.0	-68.6	-61.1	-63.1	-37.6	17.4	25.6	49.1	-155,1
Cr-DO	77.3	68.7	27.4	23.0	-6.0	-29.2	-44.3	-50.8	-12.5	33.4	53.8	66.7	207,6
DC-DO	-12.6	-21.3	-22.4	-26.2	-39.5	-23.4	5.1	-1.1	1.8	-5.5	-4.5	-8.6	-158,1
EO-DO	1.4	1.1	-1.0	-18.9	-50.3	-36.5	-16.9	-17.0	-10.1	1.9	-5.0	3.9	-147,2
EC-DO	-23.5	-25.6	-29.2	-29.3	-37.1	-20.1	8.8	5.8	1.4	-6.1	-16.2	-19.6	-190,7
FT-DO	8.5	-2.7	-10.0	-19.0	-40.9	-38.8	-8.4	1.9	6.4	4.1	9.3	1.7	-87,7

Table C2.2: *Mean Monthly Precipitation Data (mm) for the Sets of Analogue Stations taken to be Representative for the Meuse/Haute-Marne Region and Differences relative to theValues for the Current Classification*

The region is overlain by a mainly chalky soil. To over 1000m in depth, the solid geology comprises a succession of Cretaceous, Jurassic and Triassic sediments (limestones, marls and clays) dated from 245 to 96 million years BP. This sequence is characteristic of the eastern part of the Paris Basin, which is where the region is located. The general topography exhibits contrasted relief: valleys cut into cuesta landscapes with limestone scarps and marl depressions conforming to the pattern of outcrops of the large lithological blocks of substrata. The general direction of underground drainage is from the south to the north-west. At the surface, water bodies are flowing rivers and streams: the Andra site is drained by a stream (la Bureau), that discharges into a local river (l'Orge), and thence to the River Saulx. The Saulx discharges into the Seine. Some streams are ephemeral, completely drying out in summer. The uppermost (Tithonian) limestone formation is used as a source of domestic, agricultural and industrial water.

In respect of biota, the overall characteristics are those of an intensively farmed environment. However, some remains of the ancient large forests still exist, such as the forest of Montiers-sur-Saulx, the wood of La Caisse and the forest of Vau. They offer some cover to the local wild life, including hares, deer and boars. Most of the population is involved in agricultural activities. Four villages and hamlets are located within a 2.5km radius of the Andra site. Cereal crops (wheat, barley) are used as cattle feed. Vegetable gardening is common. Animal products are mostly milk and beef from cattle. Some farms raise pigs, poultry and goats. Coarse fishing is a common recreational activity, but very little freshwater fish is caught for human consumption.

C2.2. - Evolution of the Meuse/Haute-Marne Region in Scenarios B3 and B4

The evolution of the Meuse/Haute-Marne region is very similar to the evolution of Central England in scenarios B3 and B4, as shown by the comparison of the Figures 14 and 15 of BIOCLIM 8a (BIOCLIM, 2003a). Over the next few hundred years, the effects of anthropogenic greenhouse-gas releases rapidly drives the climate of Northeast France from the present-day temperate state (DO in the Køppen-Trewartha classification) to warmer Køppen-Trewartha Class Cs condition.

By reference to the data for the Cs analogue stations (Tables C2.1 and C2.2), this climate change correspond to an increase of almost 7°C in mean annual temperature and a decrease of mean annual precipitation by around 155mm. The seasonal cycles of temperature and precipitation characteristics for Cs analogue stations are shown in Figures C2.1 and C2.2. The change from DO to Cs conditions results in a decrease of the magnitude of the seasonal temperature cycle (13.6°C for Cs to be compared with 17.3°C for DO), but a clear increase in the seasonality of the precipitation regime, with low precipitation values in summer and high precipitation values in autumn and winter. Summer precipitation amounts are decreased by about a factor of ten (for Cs 7.5mm per month averaged over June-July-August compared with 71.8mm per month for DO). Winter precipitation is increased by a factor of 1.7 (for Cs 65.7mm per month averaged over December-January-February compared with 38.9mm for DO).

It is relevant to compare values estimated on the basis of data for analogue stations with Simulation A undertaken in WP2 (D4/5) with the LMDz general circulation model forced by insolation patterns as at present, but with an atmospheric CO_2 concentration equal to 1100 ppmv. For Northeast France, temperature changes in simulation A relative to the present day were of the order of 5°C in summer and 3°C in winter. These temperature changes are in good agreement with changes indicated by analogue stations for a DO to Cs transition: an increase of 5.2°C in summer (Cs JJA temperature=23.8°C to be compared with DO JJA temperature=18.6°C), and an increase of 3.5°C in winter (Cs DJF temperature=8.1°C to be compared with DO DJF temperature=4.6°C). Simulated amounts of precipitation are decreased most of the year by between 0.2mm d^{-1} and 0.8mm d^{-1}, except for a slight increase in autumn of 0.2mm d^{-1}, compared with the present day. The LMDz model does not simulate the DO to Cs increase of precipitation in winter and occurrence of a summer drought shown by analogue stations, but does agree on an overall reduction in the annual amount of precipitation in going from DO to Cs.

Taken together, these results imply that overall annual temperatures would be increased by about 4°C, with a seasonal cycle of decreased magnitude, and that the total annual precipitation amount would be decreased, with markedly drier summers, but wetter autumns and, perhaps, wetter winters. As the annual temperature is estimated to change from around 10°C (DO conditions) to 14°C, Figure C2.1 suggests that this is more consistent with a change to Class Cr than to Class Cs.

It is relevant to compare results from the one-year MAR calculation for Simulation A with the corresponding LMDz calculation for the same year. This comparison is provided in D6. For Northeast France, the LMDz calculation gives an increase in summer and winter temperatures of 9.6°C and 3.8°C, respectively for the particular year considered. The MAR calculation gives 7.4°C and 4.6°C, respectively. It is clear that the internal inter-annual variability of the LMDz model is important: the particular year chosen for MAR simulations is warmer than the long-term average, especially during winter. Precipitation is decreased most of the year in MAR, by about 0.2mm d^{-1} in winter and 1.3mm d^{-1} in summer, relative to the present day.

Overall, it seems reasonable to assume that, over the next few hundred years, mean annual temperatures in Northeast France will increase from about 10°C to around 14°C. Also, the seasonal variation in temperature will decrease. The total amount of annual precipitation will decrease, with marked drier summers, but wetter autumns and, perhaps, wetter winters.

Present-day DO mean annual precipitation of 800mm would change, in Cs conditions, to 643mm, based on data for the Cs analogue stations. Results from Simulation A indicate a decrease in mean annual precipitation of the order of 144mm, quite close to the 155mm reduction shown by a comparison of data for the analogue stations for DO and Cs conditions.

These changes in climate would apply to a landscape with near-surface lithostratigraphy and topography essentially unchanged from that at the present day. Annual precipitation, runoff and interflow would decrease during summer relative to the present day, but increase during the autumn and, maybe, the winter. Therefore, it is expected that stream and river flows would decrease in summer, with some smaller streams becoming ephemeral (noting that some streams are already ephemeral at the present day), but groundwater resources would not be substantially depleted over the year relative to the present day, due to some autumn and winter recharge. Nevertheless, in summer, there may be a reduction in groundwater resources due to the combination of higher temperatures, decreased precipitation and higher irrigation demand. Warmer summers would enhance the frequency of forest fires and that would cause vegetation to change: deciduous trees and grass would replace the present-day dominant evergreen trees (BIOCLIM, 2003b).

The hotter and drier summers would also result in an increased soil moisture deficit during the growing season. This would result in an irrigation demand. At present-day, there is no need of irrigation in the Meuse/Haute-Marne region. With irrigation, a wide range of crops could be grown, as at the present day. Yields would be increased and there could be more than one harvest per year for some crops. More intensive farming activities could result in accelerated erosion of soils, unless suitable precautions were taken. This phenomenon of soil erosion is currently observed and, based on present-day observations, it is estimated that only a few hundred years would be sufficient for complete erosion of the soils of the area. There is no reason why animal husbandry practices should be very different from those at the present day. Overall, with a similar pattern of agriculture to that at the present day, there is no climate-driven reason to propose any substantial change in human community characteristics.

Rule-based downscaling studies for the two greenhouse-gas warmed scenarios B3 and B4 indicate that the warmer climate of Northeast France described above could persist for several tens of thousands of years (BIOCLIM, 2003a). As for Central England, best estimate downscaling results based on MoBidiC output for scenario B3 give Cs conditions until about 70 ka After Present (AP), Cr conditions to 90 ka AP and then a return to DO conditions similar to those at the present day persisting until about 105 ka AP. For scenario B4, Cs conditions persist until about 160 ka AP, with short episodes of Cr conditions at around 100 ka AP and 150 ka AP. Downscaling using LLN 2-D NH output for scenario B3 gives a shorter period of Cs conditions, but then an extended period of Cr conditions to 90 ka AP. For B4, Cs conditions occur out to about 60 ka AP, then Cr conditions persist until about 160 ka AP, with two brief periods of DO conditions at about 100 ka AP and 150 ka AP. Thus, overall, the projections of climate based on MoBidiC results are somewhat warmer than those based on LLN 2-D NH results.

Comparisons of these results can be made with various snapshot scenarios studied in WP2 using LMDz. The relevant simulations are those appropriate to 67 ka AP. Three simulations are particularly relevant. These are:

- E: CO_2 concentration as in the baseline study (345 ppmv) and the configuration of the Greenland ice sheet identical to that at the present day;
- D: CO_2 concentration as in the baseline study (345 ppmv) and with no Greenland ice sheet;
- C: CO_2 concentration of 550 ppmv and with no Greenland ice sheet.

These simulations correspond to different hypothesis: warmer climate conditions over the next few hundred years could induce a rapid melting of the Greenland ice sheet, taking place over some thousands of years (Simulations C and D) and the CO_2 concentration could decrease either from 1100ppmv to 550ppmv (Simulation C) or to the a value similar to that of the recent past of 345ppmv (Simulations D and E). The larger the decrease of CO_2 concentration over the next 67ka, the stronger is the impact of insolation changes.

At 67ka AP, insolation is increased during the summer and decreased during the winter, relative to present-day. This change alone induces warmer summers and colder winters. Consequently, in all of these simulations, summers are 3°C warmer than at the present day, but winters are either moderately warmer (+0.5°C) or colder (-0.5°C) than at the present day. Precipitation rates are up to 0.6mm d^{-1} larger than at the present day from the end of the summer until the end of the winter. During spring, precipitation rates are less than at the present day, with the reduction being greatest in May, with a decrease of 0.7mm d^{-1}.

Comparison of the MAR and LMDz one-year simulations (BIOCLIM, 2003c) shows that the MAR model agrees with the amplitude of the summer warming at 67ky AP (between 2.5°C and 3.3°C), but amplifies the winter cooling to up to –4°C in the case of a CO_2 concentration of 345ppmv.

However, inspection of Figure C2.1 indicates that, in Cr conditions, the mean annual temperature of the Meuse/Haute-Marne region should be about 15°C. Thus the snapshot simulation results suggest that, at 67ka AP, the climate of the region would be closer to DO than to Cr conditions.

Overall, it is considered that, following a peak in mean annual temperature at 14°C over the next few hundred years, a cooling trend will ensue, such that temperate conditions similar to those of the present day will recur at between 90 ka AP (B3 scenario) and 170 ka AP (B4 scenario). Thereafter, there is no strong trend in climate through to 200 ka AP, though MoBidiC and LLN 2D NH results for scenario B3 indicate that a brief cold episode in the range of climate class DC (still temperate but more continental conditions) would be expected to occur at around 175 ka AP and persist for a few thousand years. In terms of precipitation, after experiencing a drier climate during the next few hundred years, the Meuse/Haute-Marne region will become wetter, first to a regime with a drier summer but wetter autumn and winter at 67ka AP relative to the present day, and then to a precipitation regime similar to today at between 90ka and 170ka AP.

The B3 and B4 anthropogenic perturbations induce the present-day interglacial period to last throughout the next 200ka at least. Such a length of interglacial is unprecedented for the Meuse/Haute-Marne region during the Quaternary. Nevertheless, the impact of it on the landscape would be limited. The topography would be only moderately modified, due to the low erosion rates that characterize an interglacial period in this area. Dissolution processes would dominate and lower by some metres the limestone plateaus. River systems would be modified to only a limited degree: meandering streams would persist with flows diminished during spring, but increased during autumn and winter, relative to present day. The deepening of the alluvial deposits during times of flood would be only moderate. Soils could be eroded due to more intensive agricultural practice in a warmer world where several crop yields per year would be possible and irrigation would be necessary. Vegetation characteristics would not change drastically. Human communities could remain unchanged. Drier springs and the use of irrigation could induce groundwater levels to decrease during some months of the year, but not to exhibit long-term depletion due to effective recharge in autumn and winter. Human communities might find necessary to use deeper wells than at the present day.

C2.3. - Evolution of the Meuse/Haute-Marne Region in Scenario A4

The discussion in Section C.2.2 relates entirely to BIOCLIM scenarios B3 and B4. However, a scenario forced only by variations in insolation and natural atmospheric carbon dioxide concentrations has also been studied (Scenario A4). Application of rule-based downscaling to that scenario and based on MoBidiC results leads to the projection that temperate conditions similar to those at the present day will persist for the next 50 ka. At that time, a cooling transition to Køppen-Trewartha class EO conditions is projected to occur. These conditions are projected to persist until around 100 ka AP. At that time, a rapid cooling through class EC to full glacial conditions (class FT) is projected to occur. Those glacial conditions are estimated to last for only a few thousand years before amelioration in climate occurs, recovering to temperate conditions by about 120 ka AP. Thereafter, a general cooling trend ensues, with class EO conditions from about 140 to 155 ka AP, a brief amelioration to temperate conditions at 160 ka AP, then a cooling through EO and EC to FT conditions at 178 ka AP, before a return to EC conditions that last until 200ka AP.

During the period of temperate conditions to 50 ka AP, very little change in the landscape is envisaged. As discussed in the case of B3 and B4 scenarios, the topography would be only moderately modified, due to the low erosion rates that characterize an interglacial period in this area. Dissolution processes would dominate and lower, by 1 to 4 metres, the limestone plateaus. Meandering streams would persist with regimes similar to present day and, during times of flood, erode to a very moderate degree the alluvial deposits. Soils could be eroded on timescales of a few hundred years, due to ongoing intensive agricultural practice. Vegetation characteristics would not change drastically. Human communities would remain unchanged.

The transition to EO boreal conditions after 50ka AP would transform the Meuse/Haute-Marne landscape. These boreal conditions would last some 40ka, except for a short return to temperate conditions soon after 60ka AP. Analogue stations show that colder and drier conditions would persist, with a mean annual temperature of the order of 3°C (a decrease of 7.6°C relative to DO) and annual precipitation of about 650mm (a decrease of 147mm relative to DO). Mean monthly temperatures would be around 10°C during summer and –1.5°C during winter. The temperature would remain below 0°C from November until March. The seasonal cycle of temperature would be decreased relative to the present day (13.5°C for EO compared with 17.3°C for DO). Seasonal precipitation would be mainly reduced from March to September. However, there would not be a strongly enhanced seasonal cycle of precipitation.

Change from DO to EO climate conditions would have the following impacts on the Meuse/Haute-Marne landscape. Low winter temperatures would induce some seasonal freezing of rivers and of the top few metres of soils, reducing surface water availability during winter and preventing infiltration. Snow and ice would melt at spring, releasing substantial amounts of water in the river systems, increasing peak flow rates by a factor of four at least, according to reconstructions of past regional situations. This would erode and remove the alluvial deposits and attack the river banks. Valleys would be deepened by about ten metres. Increased surface runoff could induce denudation of soils. Vegetation would change towards a boreal forest dominated by pine trees and epiceas, heathers and moss. Soils would evolve towards podzolic types, characterized by slow decomposition of the organic matter and marked acidity. Potential human communities could be semi-nomadic groups that would spend the winter at a permanent location, but would migrate during the summer in search of pastures for grazing their herds. Such communities could possibly make hay to feed their herds during wintertime. Other potential human communities would be farmers, cultivating cereals, oil-producing plants and vegetables, and raising bovine and ovine animals. Sylviculture and bioindustries could be undertaken, although there are no present-day analogues of such practices in boreal environments.

The next change of climate is simulated around 100ka AP and correspond to a further cooling from EO boreal conditions, through EC periglacial conditions, to FT glacial conditions. These glacial conditions could last some thousands years. Glacial FT conditions correspond to a continental and arid climate with long dry and cold winters and short cool summers. Analogue stations for FT conditions have a mean annual temperature of –2.6°C (to be compared with 3°C for EO conditions) and a mean annual amount of precipitation of 710mm (to be compared with 650mm for EO conditions). These temperature and precipitation values are rather higher than are generally characteristic of tundra. Specifically, the global envelope for tundra climate ranges from –13°C to 2°C for the annual temperature and 200 to 300mm for the annual amount of precipitation. From the analogue station data used here, an EO to FT transition is equivalent to an annual cooling of 5.6°C and a limited change of precipitation. In terms of the seasonal cycle, temperatures would remain below 0°C for a total of eight months of the year, from October to May, with a winter average value of -10.3°C and a summer average value of 6.1°C. Moving from EO to FT conditions, the seasonal cycle of temperature would be increased (20°C for FT to be compared with 13.5°C for EO).

The change from EO to FT climate conditions would have the following impacts on the Meuse/Haute-Marne landscape. Persistent low temperatures would permit the development of discontinuous or continuous permafrost, especially on the limestone plateaus. Rivers and water sources would be frozen most of the year, except for during the short summer. Consequently, from October to April/May, surface water availability would be extremely limited and the soil would be frozen.

During summer, water in the top few metres of soil would melt (mollisol), as would the snow and ice packs, releasing large amounts of water in the river systems to give peak flows a factor of eight larger than at the present day, according to reconstructions of past regional situations. Wetlands could then develop. High river flows would completely erode and remove the alluvial deposits and attack the substratum. Glacial braided river systems would develop. Valleys would be deepened by ten metres or more. However, plateaus would not be eroded to a significant degree.

Increased surface runoff could induce further denudation of soils. Vegetation would change towards a tundra dominated by herbs and low-growing shrubs, but with no trees. Soils would remain only on the limestone plateaus but would disappear from the valleys, which would be covered by a regolith of eroded rocks. Soils on the plateaus would evolve towards tundra types, characterized by a very slow rate of decomposition of the organic matter and a marked acidity.

Potential human communities could be semi-nomadic groups that would migrate during the summer season. They would hunt, fish and collect berries, but would leave the region at the approach of winter. The occurrence of permafrost and the fragility of tundra soils would preclude any agricultural practice, settlement of towns or industries in the long term. Present day analogue regions show that thermal and mechanical perturbations induce damp and unstabilized soils.

After some thousands of years of FT glacial conditions, a rapid transition towards EC periglacial conditions, then EO boreal conditions to reach DO temperate conditions is projected to occur. This FT to DO warming to full interglacial conditions is projected to occur in about 12ka, a time lapse substantially longer than the transition from the end of the Last Glaciation to the early Holocene.

From FT to EC conditions, analogue stations show that annual temperatures would warm by slightly less than a degree to reach a value of –1.8°C. Annual precipitation would decrease by 103mm to reach a value of 607mm y^{-1}. The seasonal cycle of temperature would be moderately enhanced and the seasonal cycle of precipitation unchanged. Monthly temperatures would increase, from FT to EC conditions, from March until October, with a peak increase of 6.9°C in July. The JJA temperature average in EC conditions is 12.5°C, to be compared with a FT summer temperature of 6.1°C. The mean monthly temperature would remain below 0°C for 6 months of the year in EC conditions, but for 8 months of the year in FT conditions.

The warming from FT to EC conditions would not induce large changes in the Meuse/Haute-Marne landscape. The mean annual temperature would remain negative and would allow the permafrost to persist especially on the limestone plateaus. Rivers and water sources would remain frozen for half of the year, from November to April. Surface water would not be available during this period, but would be released during the summer in large amounts, forming wetlands and increasing the discharge of rivers. Braided river systems would remain active and erosion processes in valleys quite efficient. Vegetation and soils would be in transition from tundra type to boreal forests. Potential human communities would remain semi-nomadic groups.

Some few thousands of years later, boreal EO conditions would be re-established. The characteristics of these climatic conditions have been discussed previously. The transition from EC to EO conditions would be associated with an increase in the annual temperature of some 5°C or more, to reach a value of 3.2°C. Winters especially would be much less severe. Thus, a temperature of -2.8°C as the DJF average for EO conditions can be compared with –16.4°C as the DJF average for EC conditions. The unfrozen season would be longer by one month, with positive mean monthly temperatures from April to October in EO conditions, compared with May to October in EC conditions. Major impacts of such climate changes on the Meuse/Haute-Marne region would be the progressive disappearance of permafrost, the return to full boreal forest conditions, a transition from braided to meandering river systems, with decreased river discharges (from eight times reducing to four times the present average value) and, therefore, decreased erosive actions in the valleys. Possibilities for human community types would be widened. Indeed, the return to boreal conditions would allow the re-establishment of semi-permanent settlements and agricultural practices.

Shortly afterwards, a rapid transition to full interglacial conditions would occur. The mean annual temperature would increase by some 7.7°C to reach a value of 10.9°C. Seasonal temperatures would be increased during summer (from 10°C for EO in JJA to 18.6°C in DO) and winter (from -2.3°C for EO in DJF to 3.1°C in DO). The seasonal cycle of temperature would be increased. Annual precipitation rates would be increased by 147mm to reach a value of 1006mm, on the basis of the analogue station data. From March to September, in particular, precipitation would be increased (from 48.6mm in EO conditions to 70.1mm in DO conditions) leading to wetter summers.

These DO interglacial temperate conditions would last some 20ka and would allow the re-establishment of an interglacial type of landscape for the Meuse/Haute-Marne region. Erosion in valleys would be at very limited rates and alluvial deposits would be accumulated in such a way that the valley bottoms would be elevated by about 10m. Erosion by dissolution would increase on limestone plateaus that would be eroded by one to two metres. Soils would be progressively reconstituted in the valleys and meandering river systems would be re-established. The boreal forest would regress in favor of temperate forests. Temperate climate conditions would allow for extensive agricultural practices and predominantly farming communities could develop.

At about 140ka AP, a rapid transition to colder conditions would take place and drive the environment back to EO boreal conditions for 10 to 20ka, then to EC periglacial conditions that would last until the end of the projection at 200ka AP. On this cooling trend, more rapid changes would be superimposed. Thus, at around 160ka AP there would be a short return from EO to DO conditions, and at around 178ka AP a very brief cooling from EO to FT conditions. In terms of valley erosion, the DO to EO warming at 140ka AP would be accompanied by a further deepening of about ten metres, the EO to DO transition around 160ka AP by an approximate change of elevation of 5m, and the brief episode of glacial FT conditions at 178ka AP by a last deepening of about 15 meters. In terms of other environmental changes for these DO to EO to DO to EO to FT to EC transitions, the reader should refer to the text above that describes similar transitions at different times.

C2.4. - Identification of Characteristics Climate States and Transitions

The From the characteristics of the Meuse/Haute-Marne region under Scenarios B3 and B4, the following states and transitions are identified as forming the basis for a suitable generalised scenario of environmental change.

a) A biosphere state with a landscape and climate similar to that at the present day persisting for no more than about 100 years;

b) A biosphere transition over a few hundred years to a landscape similar to that at the present day, but with a climate with an annual mean temperature of 4°C warmer;

c) A biosphere state with a landscape similar to that at the present day, but with a climate with an annual mean temperature of 4°C warmer, persisting to about 50 ka AP;

d) A biosphere transition over tens of thousands of years to a landscape and climate similar to that at the present day;

e) A biosphere state with a landscape and climate similar to that at the present day persisting to about 170 ka AP;

f) A biosphere transition to a more continental temperate climate state over 5 ka;

g) A biosphere state with a mean annual temperature of ~ 6°C lasting a few thousand years;

h) A biosphere transition to a biosphere state with a landscape and climate similar to that at the present day occurring over a few thousand years from about 180 ka AP;

i) A biosphere state with a landscape and climate similar to that at the present day persisting to the end of the study period at 200 ka AP.

In the case of Scenario A4, the following states and transitions are identified:

a) A biosphere state with a landscape and temperate climate similar to that at the present day;

b) A biosphere transition over a timescale of several thousand years to a landscape similar in form to that at the present day, but with EO boreal climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day;

c) A biosphere state with a landscape similar in form to that at the present day, but with EO boreal climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day persisting some 10 ka;

d) A biosphere transition over few hundred years to a landscape similar in form to that at the present day with DO temperate conditions;

e) A biosphere state with a landscape and temperate climate similar to that at the present day lasting some thousands of years;

f) A biosphere transition to EO boreal climatic conditions;

g) A biosphere state with a landscape similar in form to that at the present day, but with EO boreal climatic conditions and an agricultural system based mainly on animal husbandry, with much less arable farming than at the present day persisting some 40 ka;

h) A biosphere transition to glacial conditions with the development of discontinuous permafrost over a period of about 5 ka;

i) A glacial biosphere state with a mean annual temperature of about –2.6°C, the existence of discontinuous permafrost and tundra vegetation persisting for a few thousand years;

j) A biosphere transition over a timescale of about 12 ka to a biosphere state with a landscape and climate similar to that at the present day;

k) A biosphere state with a landscape and climate similar to that at the present day persisting until about 140 ka AP;

l) A biosphere transition over a timescale of several thousand years to a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day;

m) A biosphere state with a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day persisting to 170 ka AP;

n) A rapid biosphere transition to glacial conditions with the development of discontinuous permafrost over a period of some thousands of years;

o) A glacial biosphere state with a mean annual temperature of about –2.6°C, the existence of discontinuous permafrost and tundra vegetation persisting for a few hundred years;

p) A biosphere transition over a timescale of a few thousand years to a landscape similar in form to that at the present day, but with EC climatic conditions, discontinuous permafrost and tundra-type vegetation;

q) A biosphere state with a landscape similar in form to that at the present day, but with EC climatic conditions, discontinuous permafrost and tundra-type vegetation persisting to the end of the study period at 200 ka AP.

In this case, it should be noted that the duration of transition (h) has been extended to allow for the continuing development of discontinuous permafrost in the following glacial period.

Taking into account the overall commentaries on Scenarios B3 and B4, some further simplification is possible. Biosphere state (c) is reached rapidly and may even have been attained by the end of the institutional control period that would be expected to follow repository operations and closure. Therefore, from this scenario biosphere state (c), transition (d) and state (e) are of particular interest. The degree of cooling toward the end of the study period is very much less than in Scenario A4, so transitions to colder states and the colder states themselves are more usefully studied in the latter context.

Thus, from Scenario A4, it is useful to address biosphere state (a), transition (b) and state (c). The glacial episode encompassing transition (d), state (e) and transition (f) is also of interest. However, the cooling episode encompassing state (g), transition (h) and state (i) exhibits only limited differences from the sequence state (a), transition (b) and state (c). It does not, therefore, require detailed analysis. However, the further cooling from state (i) through transition (j) to state (k) does require consideration, particularly because of the relatively long duration of state (k).

Thus, the states requiring consideration are:

1) A biosphere state with a landscape and climate similar to that at the present day;

2) A biosphere state with a landscape similar to that at the present day, but with a climate with an annual mean temperature of 4°C warmer;

3) A biosphere state with a landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day;

4) A glacial biosphere state with a mean annual temperature of about -2.6°C, the existence of discontinuous permafrost and tundra vegetation persisting for a few thousand years;

5) A biosphere state with a landscape similar in form to that at the present day, but with EC climatic conditions, discontinuous permafrost and tundra-type vegetation.

The transitions between these states that are of particular interest are:
[2–>1] over a timescale of tens of thousands of years;
[1–>3] over a timescale of a few thousand years;
[3–>4] over a timescale of about 5 ka;
[4–>1] over a timescale of about 12 ka.

The individual states are characterised in subsection C.2.5, using the BIOMASS methodology. Transitions are characterised in subsection C.2.6, using the methodology developed in BIOCLIM.

C2.5. - Characterisation of States

Based on the material in the annex to Appendix A, it is appropriate to describe the various states identified as being of interest as shown in the following tables.

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Climate Type Classification for Northeast France

State	Køppen/Trewartha Class	Description
1	DO	Landscape and climate similar to that at the present day.
2	Cr or Cs	Landscape similar to that at the present day, but with a climate with an annual mean temperature 4°C warmer.
3	EO	Landscape similar in form to that at the present day, but with EO climatic conditions and an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day.
4	FT	Landscape similar in form to that at the present day, but with a mean annual temperature of about –2.6°C, the existence of discontinuous permafrost and tundra vegetation persisting for a few thousand years.
5	EC	Landscape similar in form to that at the present day, but with EC climatic conditions, discontinuous permafrost and tundra-type vegetation.

Characteristics of Water Bodies Compared with the Present Day for Northeast France

State	Køppen/Trewartha Class	Characteristics
1	DO	Temperate environment. Meandering river systems. Mainly flowing rivers and streams. Some smaller streams may become ephemeral seasonally.
2	Cr or Cs	“Warmer world” environment. Meandering river systems. Stream and river flow reduced in summer, with some smaller streams becoming ephemeral due drier summers. Nevertheless, groundwater resources should not be less than at present, due to some autumn-winter recharge. Regional water levels could be lower and spring lines could be shifted downslope during summer. Increases in surface-water storage to ensure better capture of winter precipitation for subsequent use in the hotter, somewhat drier, summers.
3	EO	Boreal environment. Overall annual moisture excess. Groundwater levels higher than at the present day. Marshes likely to be extensive in depressions and along water courses. However, surface water not available during the winter season, due to river and soil freezing. In springtime substantial release of water in the river systems, with discharges increased by a factor of four. Erosion enhanced and meandering river systems progressively dismantled.
4	FT	Glacial/Tundra environment. Overall annual moisture excess. Extensive wetlands in lowland areas. The main distinction from State 3 is due to the very cold winters and the extensive period of the year with negative temperatures that leads to extensive snow pack development, freezing of rivers and streams, discontinuous to continuous permafrost and seasonal freezing of soil water. Surface water not available for most of the year. The spring melt would be associated with ice dams in the rivers and very high peak flows. Stream channel sizes would be adjusted to these high peak flows and braided river systems would predominate. Groundwater flow patterns would be affected by permafrost and the seasonal freezing of soil water.
5	EC	Periglacial/Tundra environment. Overall annual moisture excess. Groundwater levels higher than at the present day. Marshes extensive in depressions and along water courses. The main distinction from State 3 is due to the colder winters and the long period of the year with negative temperatures that leads to extensive snow pack development, freezing of rivers and streams, discontinuous permafrost and seasonal freezing of soil water. Surface water not available most of the year. The spring melt would be associated with ice dams in the rivers and very high peak flows. Stream channel sizes would be adjusted to these high peak flows and braided river systems would develop. Groundwater flow patterns would be affected by permafrost and the seasonal freezing of soil water.

Classification of Human Community Types for Northeast France Based on Socio-economic and Environmental Considerations

State	Køppen/ Trewartha Class	Trading	Biosphere Control	Community Types and Activities
1	DO	Large-scale	High	Temperate, ntensively farmed environment. Large-scale mixed farming characteristic with extensive production of edible and some non-edible crops. Hamlets, villages, market towns and cities in a trading network. Fish farming not extensive. Glasshouse horticulture for specialist purposes only (e.g. early fruit, decorative plants for cut flowers and gardens). However, garden cultivation of fruit and vegetables common. Extensive use of groundwater and surface water resources for agricultural and domestic irrigation.
2	Cr or Cs	Large-scale	High	"Warmer world" type of environment. Agriculture as at the present day, but irrigation may be more intensively practiced. Increased yields of most crops (particularly with irrigation) and possibly more than one harvest per year for some crop types. No substantial difference in human community characteristics and infrastructure relative to the present day.
3	EO	Large scale or small scale	High	Boreal environment. Natural vegetation of boreal type dominated by pinus trees and epiceas. Agriculture, sylviculture and bioindustry possible. Agriculture dominated by animal husbandry, with land given over to summer grass for either summer grazing or hay production. An alternative would be semi-nomadic groups, settled in permanent locations during winter, but migrating during summer in search of pasture to graze their herds.
4	FT	None	None	Glacial environment. Natural vegetation of the tundra type, mostly treeless. Land use primarily herding and hunting. Communities of semi-nomadic groups migrating during the summer, but leaving the area in winter for better refuges. The permafrost and the fragility of tundra soils preclude any sustainable agricultural practices or permanent settlement.
5	EC	Small scale	High	Periglacial environment. The natural vegetation would be low shrubs and herbs characteristic of tundra environments. Human communities could closely resemble those under State 4.

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Ecosystem Classification for Northeast France

NATURAL SYSTEMS

		Terrestrial Ecosystems	Aquatic Ecosystems
State	**K/T Class**	**Description**	**Description**
1	DO	Limited extent of natural systems. Temperate woodland and shrubland is the natural climax vegetation.	Mainly rivers and streams. Fishing mainly for sport not consumption.
1	Cr or Cs	Limited extent of natural systems. Temperate woodland and shrubland is the natural climax vegetation. May be in transition towards warmer/drier climate ecosystems.	Mainly rivers and streams. Substantial fish stocks. Some shallow lakes and wetlands. Estuaries and shallow offshore waters.
3	EO	Boreal natural systems. Where agriculture is not practiced, semi-natural systems are likely to dominate.	Mainly rivers and streams. Wetlands. Surface water not available during winter due to freezing.
4	FT	Primarily natural systems. Tundra.	Mainly rivers and streams. Extensive wetlands. Surface water not available most of the year due to freezing.
5	EC	Possibly extensive tundra vegetation.	Mainly rivers and streams. Extensive wetlands. Surface water not available most of the year due to freezing temperatures.

SEMI-NATURAL SYSTEMS

Terrestrial Ecosystems		Aquatic Ecosystems	
State	**K/T Class**	**Description**	**Description**
1	DO	Minor areas of neglected grassland.	Not applicable. Discussed under natural systems.
2	Cr or Cs	Minor areas of neglected grassland.	
3	EO	Extensive areas of low growing shrubs, neglected grassland, lowland grass heath and bracken.	
4	FT	Primarily natural vegetation, as agriculture is not practiced, so agricultural land in succession to natural vegetation is not present.	
5	EC	As for State 4.	

MANAGED SYSTEMS

State	K/T Class	Description
1	DO	**Terrestrial Ecosystems :** Intensive farmed environment. Mainly field crops. Some trees. Grassland. Intensive dairying, beef-cattle production, sheep rearing, pig industry and poultry. Hamlets and villages.
		Aquatic Ecosystems : Some ponds, but mainly covered under natural ecosystems.
2	Cr or Cs	**Terrestrial Ecosystems :** Intensive farmed environment. Mainly field crops. Some trees. Grassland. Intensive dairying, beef-cattle production, sheep rearing, pig industry and poultry. Hamlets and villages.
		Aquatic Ecosystems : Some ponds, but mainly covered under natural ecosystems.
3	EO	**Terrestrial Ecosystems :** Sylviculture and bioindustry possible. In farmed environment, mainly animal husbandry. Both intensive dairying and beef production are likely to be practiced. Sheep rearing, pig rearing and poultry. Some vegetable production. May be increased use of greenhouses to grow fruits and vegetables. Barley production likely to be used for animal feed. Reduced extent of urban areas and transport routes relative to the present day.
		Aquatic Ecosystems : Some ponds, but mainly covered under natural ecosystems.
4	FT	**Terrestrial Ecosystems :** No practice of agriculture.
		Aquatic Ecosystems : Covered under natural ecosystems.
5	EC	**Terrestrial Ecosystems :** No practice of agriculture.
		Aquatic Ecosystems : Some ponds, but mainly covered under natural ecosystems.

Zonal Soil Types for Northeast France			
State	**Køppen/ Trewartha Class**	**Soil type**	**Description**
1	DO	Forest Brown Earths/Agricultural	Natural soils are often Brown Earths. However, these have been substantially modified by long-term agricultural activities. Well-drained, deep soils are characteristic.
2	Cr or Cs	Forest Brown Earths/Agricultural	As for State 1. Long-term agricultural activities sustained over the next several hundred years may substantially erode the agricultural soils.
3	EO	Podzolic soils	Soils characterized by slow decomposition rates of the organic matter, marked acidity, depletion of minerals. Development of more extensive range of organic soils in wetlands.
4	FT	Tundra humus soils	Shallow soils characterized by very slow decomposition rates of the organic matter, marked acidity, depletion of minerals. Extensive organic soils in wetlands. Substantial cryoturbation structures due to seasonal freezing and the development of permafrost.
5	EC	Tundra humus soils	As for State 4.

Topographical Categories for Northeast France		
Stage 1 Classe DO	Geographical Context Altitude Landform Localised Erosion	Inland Lowland Cuesta landscapes with limestone scarps and marl depressions Fluvially incised
Stage 2 Classe Cr or Cs	Geographical Context Altitude Landform Localised Erosion	Inland Lowland Cuesta landscapes with limestone scarps and marl depressions Fluvially incised
Stage 3 Classe EO	Geographical Context Altitude Landform Localised Erosion	Inland Lowland Cuesta landscapes with limestone scarps and marl depressions Fluvially incised
Stage 4 Classe FT	Geographical Context Altitude Landform Localised Erosion	Inland Lowland Cuesta landscapes with limestone scarps and marl depressions Fluvially incised
Stage 5 Classe EC	Geographical Context Altitude Landform Localised Erosion	Inland Lowland Cuesta landscapes with limestone scarps and marl depressions Fluvially incised

C2.6. - Characterisation of Transitions

Characteristics of transitions between the various climate states described in Section C.2.5 are set out in the following transition diagrams.

State 2 to State 1 (Class Cr/Cs to Class DO) over tens of thousands of years.				
TOPOGRAPHY	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	**SOILS AND LITHOLOGY**	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	No substantial influences identified. However, the long period of interglacial conditions may lead to soils developing to a no analogue condition with continued irrigation.	**WATER BODIES**	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	**BIOTA**	No substantial influences identified.
No substantial influences identified.	No substantial influences identified.	Reducing demand for irrigation water coupled to increasing supply is likely to lead to decreasing demand for surface water storage, but the trend will be very slow.	Changes in crop types and reduced yields.	**HUMAN COMMUNITIES**

State 1 to State 3 (Class DO to Class EO) over a few thousand years

TOPOGRAPHY	At the inception of State 3, fluvial erosion will be enhanced. This will remove the alluvial deposits and attack river banks. Consequently, valleys will be deepened by some ten metres.	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	**SOILS AND LITHOLOGY**	Seasonal freezing of the top few metres of soil will limit infiltration during winter. In spring, the melting of snow packs and ice will release substantial amounts of water into the river systems and discharges will be increased by at least a factor of four.	Increasing areas will become of marginal use for agriculture and semi-natural vegetation will develop on those areas.	No substantial influences identified.
No substantial influences identified.	A rising phreatic surface gives rise to an increasing extent of gleyed soils. Marshy areas develop, but may be subsequently drained leading to new areas of organic soils.	**WATER BODIES**	Waterlogging of soils will place constraints on agriculture and also determine the types of semi-natural plant communities that may occur. New types of community develop in wetlands.	The seasonal freezing of rivers and lakes will constrain human community development.
No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	**BIOTA**	Changes in the extent and distribution of land suitable for agriculture will alter the density of human communities. The increasing extent of natural and semi-natural habitats will place greater emphasis on hunting and fishing.
Minor modifications of stream channel cross-sections and profiles in drainage operations, but no substantial changes to topography.	Fertilisation in association with drainage in the maintenance or reclamation of areas of land.	Artificial drainage will be used to maintain soils for agriculture or to reclaim newly exposed land.	Trend to decreasing arable land use and increasing relative extent of pasture. Abandonment of some land to semi-natural vegetation.	**HUMAN COMMUNITIES**

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State 3 to State 4 (Classe EO to FT) over about 5000 years				
TOPOGRAPHY	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	**SOILS AND LITHOLOGY**	The development of tundra humus and organic soils is thought to be a minor factor influencing the characteristics of water bodies compared with the direct effects of ground and channel freezing.	Soils become unusable for agriculture. Semi-natural vegetation spreads and is subsequently modified to become fully tundra-like. Animal husbandry is replaced by herding and hunting.	No substantial influences identified.
Seasonal freezing of ground waters and river channels has a major effect on the flow regime and hence on incision. Channel cross sections are likely to increase to accommodate high peak flows (discharges multiplied by a factor of at least eight compared to present-day). Braided river systems replace meandering river systems. Valleys are incised by ten metres at inception of State 4, compared to State 3.	Seasonal ground freezing and the development of permafrost especially on the limestone plateaus will lead to the development of cryosols and various features of cold regions such as patterned ground.	**WATER BODIES**	Seasonal ground freezing limits both the type and productivity of vegetation. Frozen soils enhance surface runoff and this erosive action leads to accelerated soil denudation.	Surface water bodies are frozen most of the year.This constrains human communities and use of the environment.
No substantial influences identified.	Decreasing rate of degradation of biotic materials contributes to the development of humic tundra soils.	No substantial influences identified.	**BIOTA**	Progressive abandonment of land leads to development of a hunter/herder economy with a low degree of utilization of the limited primary productivity and hence utilization of terrestrial resources from a very large area. Pre-existing settlements are abandoned. The population is semi nomadic, migrating from one campsite to another during summer and retiring to permanent settlements in refuge area during winter.
No substantial influences identified.	No substantial influences identified.	Abandonment of inland communities means that groundwater abstraction is no longer required.	Abandonment of land leads to development of natural tundra vegetation.	**HUMAN COMMUNITIES**

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State 4 to State 1 (Class FT to Class DO) over about 12000 years

TOPOGRAPHY	No substantial influences identified.	Alterations in channel dimensions change flow patterns as streams adjust to new base levels.	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	**SOILS AND LITHOLOGY**	Development of agricultural soils through natural processes and human actions will affect the partitioning of precipitation between surface flow, throughflow and infiltration towards the end of the transition. However, at an earlier stage, reductions in ground freezing are likely to be more important than changes in soil characteristics.	Development of agricultural soils through a combination of natural processes and human actions leads to the replacement of natural tundra vegetation by agricultural vegetation. However, with continuous human occupation of the environment, a densely wooded landscape may not ever exist.	Soils fit for agricultural use develop and humans adapt them to their requirements as climatic conditions ameliorate.
As seasonal ground freezing decreases and permafrost melts, river discharges decrease. Alluvial deposits are accumulated in valley bottoms and valleys are elevated by some ten metres during this transition. Meandering river systems progressively replace braided river systems.	Seasonal ground freezing decreases. Permafrost melts. Relict ice structures, e.g. ice wedges, are formed.	**WATER BODIES**	Reduction in seasonal ground freezing increases the range of plant communities that can develop.	Surface water bodies experience shorter freezing periods as climatic conditions ameliorate. Surface water becomes more and more available. Human community structures and locations adapt.
No substantial influences identified.	Tundra vegetation will be replaced by temperate region vegetation. If a natural succession occurs, a heavily wooded landscape will contribute to the development of well-drained Brown Earth soils. However, with continuous human occupation, such a well-wooded landscape may not occur and the soils produced may be no-analogue systems.	No substantial influences identified.	**BIOTA**	As climatic conditions ameliorate, natural woodland develops again. Humans adapt biota to their requirements.
No substantial influences identified.	Development of extensive agriculture. Soils may be no analogue systems produced by continuous management.	Increasing exploitation of surface waters and ground waters.	Development of extensive agriculture	**HUMAN COMMUNITIES**

C3. The Evolution of Central Spain

C3.1. - Characteristics of Central Spain at the Present Day

At the present day, the averaged and general current climate class of Central Spain is Csa (tempered with dry and warm summers and winter rain), known as Mediterranean climate (Lomba et al., 2003). From seven meteorological stations (INM, 2001) located in the selected area (named Pozoblanco, Linares, Montoro, CiudadReal, Toledo (Lorenz), Alcuéscar and Cáceres), precipitation and temperatures have been obtained (Figures C3.1 and C3.2). The number of years present in the data series corresponding to each of the stations are: Cáceres: 1951/1983; Toledo (Lorenz.): 1951/1982; Ciudad Real: 1970/2000; Pozoblanco: 1954/2000; Linares: 1952/2000; Montoro: 1959/2000; Alcuéscar: 1951/2000. Following the Rudloff rules for Køppen-Trewartha classification, two stations (Linares and Montoro) have been classified as Cshk. The other five have been classified as Csak. A climate diagram obtained from the averages of the seven stations is shown in Figure C3.3.

The near-surface lithostratigraphy, from the south of the Sistema Central range to the Campos de Calatrava area, is dominated by Lower Palaeozoic formations, mainly shales and sandstones, but profoundly eroded to the point of constituting a peneplain. However, limestones dominate to the south of Badajoz. Also, intrusive granitic formations are common. The topography has been affected by extensional processes (Agüero et al., 2002). It comprises upland and lowland, with subdued landforms intersected by fluvially incised river valleys on the granitic zones. Surface water bodies are mainly flowing rivers, with some reservoirs located on the main rivers. The main soil groups represented are cambisols, lithosols and fluvisols (FAO, 1993).

The climax vegetation is represented by Quercetum ilicis, but it has been extensively degraded by the long-term effects of human action. Today, it has been substituted by bush and steppe vegetation (Stipa tenacissima, Lygeum starpum, Cistus ladaniferus, Juniperus communis). Four main patterns of soil characteristics and use can be distinguished and these can be further subdivided into irrigated and non-irrigated areas. The classification adopted is agricultural soil (39 % of the total area, with 17 % irrigated), grassland (13 % of the total area, with 3 % irrigated), forest (32 % of total are aand none irrigated), and other (16 % of total area). The faunal analysis has been limited to the vertebrates (mammals, birds, reptiles, amphibians and fish), as distinctions in these are characteristic of the selected ecosystems. The mean human population density is 78 inhabitants per km^2, with 36% living in the capitals of the provinces and the rest in rural areas. The mean population density for the rural areas is 50 inhabitants per km^2.

C3.2. - Evolution of Central Spain in Scenario B3

Several different states and transitions can be identified from the time series of annual mean surface temperature for the B3 scenario shown in Figure 12 of Deliverable D3 (BIOCLIM, 2001) in different segments to characterize the simulated temperature variation for Central Spain in the next 200 ka (Lomba et al., 2003). These are summarised below.

a) A rapid transition (300 y) from current, typically Csa, climate class to a new climate situation (BWh probably) without previous representation in the palaeoclimatic record of the Iberian Peninsula, characterised by a mean annual temperature in the range of 32-33°C and by a CO$_2$ concentration of 1100 ppmv.

b) A moderately rapid cooling transition (over 5 ka) to 27.2 - 28°C (climate state BWh/BSh), also not represented in the palaeoclimatic record from Padul area.

c) A slower (17 ka) cooling transition to a climatic situation at about 22 ka AP with a mean annual temperature of 22.7 to 23°C (climate state BSh), again not represented in the palaeoclimatic record.

d) An extended period (21 ka) with a mean annual temperature of 22.7 to 23°C (climate state BSh).

e) A moderately rapid cooling transition (10.5 ka) to a mean annual temperature of 21°C (climate BSh).

f) A 15ka long period with a mean annual temperature of 21°C, from 52 ka AP to 67 ka AP (climate state BSh).

g) A smooth cooling transition to a relatively warm BSh-Csa climate state with a mean annual temperature of 19.5 to 19.8°C at about 80 to 90 ka AP.

h) A moderately rapid cooling transition (9 ka) to climate state Csb (mean annual temperature of 13.5 to 12.9°C) at around 100 ka AP.

i) A subsequent warming to a mean annual temperature of 20°C (climate state BSh) that is maintained for 6 ka.

j) A brief cooling to Csa (mean annual temperature of 18°C) followed by a rapid warming to a mean annual temperature of 20°C (BSh) and then a rapid cooling to Csb (mean annual temperature of 13.5 to 12.9°C), with the whole sequence complete by 150 ka AP.

k) A moderately rapid warming (8.4 ka) to 20 - 21°C (BSh).

l) A cooling (over 14.7 ka) to DC or BWk/BSk (mean annual temperature of 8.8 to 8°C) at about 175 ka AP.

m) A warming to Csa (mean annual temperature of 16.5°C) over about 14 ka.

n) A cooling to BSk or BWk (mean annual temperature of 11.7 to 11°C) at around 194 ka AP.

o) A warming to a mean annual temperature of 18°C (climate class Csa) that is maintained until 210 ka AP.

It seems that, for almost all of the next 120 ka, the climatic characteristics of Central Spain are likely to lie outside the climatic conditions recorded in the palaeoclimatic record from Padul. For about 67 ka of these, they will be even warmer than the mean annual temperature of 18ºC thought to have been attained in the Atlantic period from 5.4 to 6.6 ka BP. For this reason, it has been necessary to look for climatic analogue stations and environmental analogue locations outside the Iberian Peninsula, including those relating to climate types As (tropical), BSh (warm dry steppe) or BWh (hot desert) depending on the evolution of the atmospheric humidity.

The lowest mean annual temperature to be reached during the next 210 ka is assessed to be 8.8 to 8.0ºC (climate class DC, BWk or BSk), previously experienced during the Younger Dryas, Oldest Dryas, Middle-Final Würm, Eowürm and Mèlisey II (BSk/BWk). That situation is expected at about 175 ka AP.

C3.3. - Identification of Characteristic Climate States and Transitions

In summary, the following main transitions and states (based on Lomba et al., 2003) are considered of relevance for development of the narrative description. Mean annual temperatures are given in parentheses.

Csa –> Situation 1 (32°) (*BWh*) –> Situation 2 (27°) (*BWh/BSh*) –> Situation 3 (22°) –>
300y AP 5ky AP 22-43ky AP

–> Situation 4 (21°C) (*BSh*) –> Csa (19°) (*BSh/Csa*) –> *Csb* (13°) –>
52-67 ky AP 80-90 ky AP 100 ky AP

–> Situation 5 (18º) (*Csa*) –> (*BSh*) (20º) –> (*Csb*) (13º) –> Situation 4 (21º) (*BSh*) –>
oscillatory transition period
106 ka AP 150 ka AP 158 ka AP

–> Situation 6 (8-9º) *DC* or *BWk/BSk* –> Csa (16.5º) –> *BSk* –> *Csa*
175 ky AP 189 ky AP 194 ky 210 ky

Thus, the transitions and states requiring consideration are as described below.

Situation 1: From Csa to BWh

This comprises a rapid transition over about 300 years during which mean annual temperatures in Central Spain will increase from about 14.5°C to between 32 and 33°C. Annual mean precipitation values will decrease to about 200-330 mm per year, and the precipitation will occur mainly in summer (Figure C3.4). Both the high temperatures and limited precipitation imply a markedly arid environment.

These changes in climate would apply to a landscape with soils and sediments, and topography essentially unchanged from that at the present day. Surface runoff and interflow could either increase or decrease relative to the present day. However, it seems highly likely that stream and river flows would decrease, with some smaller streams becoming ephemeral. Due to the aridity, soils would be expected to lose cohesion. Aeolian weathering would be increased, but no substantial changes in topography would be expected in only 300 years. Vegetation may be mostly or entirely absent in some regions, as vegetation is very rare in hot dry deserts, such as those of North Africa. Any plants that are present will almost all be ground-hugging shrubs and short woody trees. Decreased precipitation will probably imply a reduction in groundwater resources. Reservoir construction for surface-water storage might be undertaken by human communities to ensure better capture of summer precipitation for subsequent use. The increased aridity would also result in an increased soil moisture deficit during the growing season (between April and October). On the basis of data from analogue meteorological stations, the mean monthly moisture deficit in June would be more than 400 mm (Figure C3.5); annual mean moisture deficit values could be as large as 2418 mm (Lomba et al., 2003). This would result in a much increased irrigation demand. With irrigation, a wide range of crops could be grown, as at the present day. Human community characteristics would be driven by the limited water availability, with communities being concentrated in the vicinity of sites of exploitation of deep groundwater resources and close to new reservoirs on the main rivers.

Situations 2 and 3: From a BWh to a BWh/BSh state

The main transition is expected to take place between 0.3 and 5 ky AP. The resultant dry climate that then persists for a period of about 75 ka is classified as semiarid (BSh). The cooling transition sees mean annual temperatures fall from about 27.2 to 28°Cto about 21°C during the lengthy BSh period. The analysed BS meteorological stations (Lomba et al., 2003) have mean annual precipitation values of between 144 mm and 879 mm. Averaged over stations, the mean annual precipitation is 521 mm, with a difference in mean monthly values of almost 100 mm between the driest month (February) and the wettest (August).

Over this protracted period, upland zones can be lowered due to prolonged (80 ka) and increased chemical weathering relative to situation 1. Surface runoff will be increased relative to BWh conditions and landscape slopes will be reduced. Intense rainfall with short duration, as is observed under present BWh climates in Spain, will result in more active soil erosion.

Cambisol development will be restricted and leptosols development will be enhanced. Vegetation cover and standing biomass will be increased relative to situation 1, with development of shrub and herb vegetation, and deciduous or evergreen broadleaf trees present only in patches (as there is not enough precipitation for trees to grow except by rivers). Increased precipitation will probably imply an increase in groundwater resources. Reservoirs for surface-water storage might be developed by human communities to ensure better capture of summer precipitation for subsequent use, as in situation 1. The increase in precipitation would also result in a decreased soil moisture deficit during the growing season.

On the basis of data from analogue meteorological stations, the mean monthly moisture deficit would reach a maximum of 290 mm in May (Figure C3.7). This would result in a lower irrigation demand than in situation 1. The cold winter and summer drought reduce the growing season to three or four months (between April and July). Winter cereal crops (77 % of which are not irrigated) and unirrigated pasture grasses are the most common types of agriculture developed under current BS climates in Spain. The steppe climate tends to go in cycles, where there may be ten years or more of good rains followed by as many years of drought (Strahler et al., 1984). In order to be able to cope with this climate, people used to be nomadic. However, now they rely on deep wells and irrigation systems. Nevertheless, the climate is still too harsh for large cities and industries to develop. Overall, human rural communities can be characterised as similar to those at present day, with a low overall density of population.

Situations 4 and 5: From BSh to Cs states

This involves a cooling transition over a period of about 10 ka at the beginning of a total period of 26 ka over which Csa and Csb conditions will occur. Cs states imply climate characteristics corresponding to those currently dominant in Central Spain. The Cs type is typically Mediterranean, being a hybrid between maritime Mediterranean with mild winters (Csa) and continental Mediterranean with cold winters (Csb). The state is often characterised by a dry summer (Figure C3.8). Winter is in general the period with the largest amount of precipitation. The analysed Spanish stations record a mean annual precipitation of 522 mm, with an average range in the mean monthly precipitation of almost 60 mm between the driest month (July) and the wettest (December).

The climate would apply to a landscape with a lower topography than at present due to earlier changes. Surface runoff will be increased relative to the BSh, as it is observed today. Vegetation is likely to be much as at the present day. The holm forest, which develops on any soil type, mainly in plains, and cork trees, which develops easily on silica soils, present various vegetation layers; the most common are evergreen, small leaved bushes, as well as other perennial plants (Polunin et al., 1978). Such bushes are very common under Cs climate conditions. Based on data from analogue meteorological stations, the mean monthly moisture deficit would reach a maximum of 170 mm in July (Figure C3.9). This would result in an irrigation demand similar to that at present. With irrigation, a wide range of crops could be grown, as at the present day. Also, there is no reason why animal husbandry practices and human community characteristics should be very different from those at the present day.

Situation 6: From BSh to DC BWk/BSk

This is a cooling transition to temperate conditions, taking around 20 ka, with expected mean annual temperatures of between 8 and 9ºC. Also, monthly minimum temperatures are expected to be below 0ºC. Precipitation is likely to range between 425 and 525 mm per year, with the minimum monthly precipitation being around 25 mm. The annual moisture deficit/excess, based in the analyzed stations (Lomba et al., 2003), is between a deficit of 99 mm and an excess of 383 mm.

The climate would apply to a landscape with a reduced topography relative to present conditions, due to earlier changes. Surface runoff would be increased relative to BSh conditions, asis currently observed. Vegetation is likely to be grassland and scrub woodland, with some development of forest. Based on data from analyzed meteorological stations, the mean moisture deficit reaches a maximum of only 99 mm in summer. This would result in an irrigation demand much lower than in the current situation. There is no reason why animal husbandry practices should be very different from those at the present day. Overall, with a similar or better pattern of agriculture to that at the present day, there is no climate-driven reason to propose any substantial change in human community characteristics.

The individual states (Cs, BW, BS and DC) and evolution through these are characterised in subsection C.3.4, using the BIOMASS methodology. Transitions are characterised in subsection C.3.5, using the methodology developed in BIOCLIM.

C3.4. - Characterisation of States

Based on Table A1 of Appendix A, relating to Biosphere System components and characteristics (system description), the characterisation of states and changes relative to the current situation is presented in the following tables.

Climate Type Classification for Central Spain		
State	**Køppen/Trewartha Class**	**Description**
Present	**Csa Csb**: Mediterranean climate	Characterized by dry, hot summers with humid, mild winters.
Hot and Arid	**BWh**: desert climate **BSh**: steppe climate	A subtropical zone is in general termed desert when the annual rainfall is less than 200 mm and the potential evaporation more than 2000 mm (up to 5000 mm in the central Sahara). A very distinctive feature of all arid regions is the large variability in amount of rain falling in different years. This means that average figures are of little value. In all deserts (except in the fog variety), the air is very dry. Both incoming and outgoing radiation are extremely intense, which means that the daily temperature fluctuations are large. In the rainy season, however, the extremes are greatly reduced (Walter, 1984).
Colder	**DC**: Temperate continental	

Characteristics of Water Bodies for Central Spain compared with Present		
Present	1	**Surface Water Bodies** • Natural: - Rivers - Springs - Seasonal water courses • Artificial: - Reservoirs/dams - Wells
	2	**Subsurface Water Bodies** • Variably saturated zone • Saturated zone
BWh	1	**Surface Water Bodies (less water available)** • Natural: - Rivers - Spring lines migrate down slope - Seasonal water courses more frequent • Artificial: - Reservoirs/dams increased greatly
	2	**Subsurface Water Bodies** • Variably saturated zone • Saturated zone phreatic surface deeper (with development of wells to extract deeper groundwater)
BSh	1	**Surface Water Bodies (less water available)** • Natural: - Rivers - Spring lines migrate up slope (new springs or reactivation of old springs) - Seasonal water courses less frequent • Artificial: - Reservoirs/dams decreased exploitation (similar to present day)
	2	**Subsurface Water Bodies** • Variably saturated zone • Saturated zone phreatic surface similar to that at present (deep wells similar to present day)
DC	1	**Surface Water Bodies (more water available)** • Natural: - Rivers - Spring lines migrate up slope (new springs) - Seasonal water courses less frequent • Artificial: - Reservoirs/dams decreased exploitation (similar or lower to that at the present day)
	2	**Subsurface Water Bodies** • Variably saturated zone • Saturated zone phreatic surface rises and can form new surface water bodies

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Classification of Human Community Types in Central Spain based on Socio-economic and Environmental Considerations

State	Trading	Biosphere Control	Community Types	Community activities* in relation to the system
Present	Small-scale	High	Small farming community – external foodstuffs permitted Large cities interacting with a network of small communities	Edible and non-edible crop production, animal husbandry/grazing, recycling of residues, use of woodland resources, use of water resources.
BWh	Small-scale	High (resource limited population)	Mix of urban and rural communities is likely to be applicable, with adaptation of resource utilization according to water availability and water usage.	Edible and non-edible crop production, animal husbandry/grazing, fishing, recycling of residues, use of woodland resources, use of water resources more limited or decreased population to match resources. Potential for large-scale discrete abstraction of groundwater from single sites for servicing either crop production or drinking water for urban communities.
BSh	Small-scale	High (possibly resource limited population, but less extreme than BWh)	Mix of urban and rural communities	Edible and non-edible crop production, animal husbandry/grazing, recycling of residues, use of woodland resources, use of water resources. Assumption is that there is extensive resource usage from the local area, but some resource needs may be met by importation from outside the area.

* Note:Use of land for residential purposes and potential exploitation of local water resources are assumed possible in association with any of the different classes of activities. Also, it is recognized that climate may not be the only influence on human communities and their activities.

Ecosystem Classification for Central Spain

NATURAL SYSTEMS

Terrestrial Ecosystems		Aquatic Ecosystems	
Present	Mediterranean oak woodland Mammals, birds, reptiles	Present	Rivers (fish and crabs)
BWh	Desert scrub reptiles	BWh	Rivers (fish)
BSh	Mediterranean forest: pines, grassland and herbs Mammals, birds, reptiles	BSh	Rivers (fish)
DC	Grassland and Scrub woodland	DC	Rivers (fish)

SEMI-NATURAL SYSTEMS

Terrestrial Ecosystems		Aquatic Ecosystems	
Present	Lowland grass heath Upland heath	Present	
BWh	Lowland grass heath Upland heath	BWh	
BSh	Lowland grass heath	BSh	
DC	Grassland and scrub woodland	DC	Rivers (fish)

MANAGED SYSTEMS

Present	**Terrestrial Ecosystems :**	
	Field crop ecosystems / Cultivated land. Some grassland, some wooden areas, mixed crops. Goats, pigs, cattle.	
	Tree crop ecosystems (olive trees)	
	Bioindustrial ecosystems (*)	Intensive dairying and beef-cattle production. Pig industry. Poultry.
	Aquatic Ecosystems :	
	Rivers and man-made reservoirs (fish)	
BWh	**Terrestrial Ecosystems :**	
	Cultivated land with more irrigation (some agricultural crops)	
	Tree crop ecosystems irrigated, mainly fruit	
	Bioindustrial ecosystems, depending on lower water resources availability	• Less intensive dairying • Beef-cattle production
	Aquatic Ecosystems :	
	Man-made reservoirs with lower fish exploitation	
BSh	**Terrestrial Ecosystems :**	
	Field crop ecosystems / Cultivated land. Some grassland, pines, herbs. Goats, pigs, cows.	
	Tree crop ecosystems	
	Bioindustrial ecosystems, depending on water resource availability	• Intensive dairying • Beef-cattle production
	Aquatic Ecosystems : Man-made reservoirs with increased fishing	
DC	**Terrestrial Ecosystems :**	
	Field crop ecosystems / Cultivated land. Grassland, ines, herbs. Goats, pigs, cows.	
	Tree crop ecosystems	
	Bioindustrial ecosystems	• Intensive dairying • Higher Beef-cattle production
	Aquatic Ecosystems : Perennial rivers and man-made reservoirs with increased fishing.	

(*) Although these practices are common, the production is not at industrial level.

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Zonal Soil Types for Central Spain

	Soil type	Description	Comments
Present	Mediterranean brown earths FAO: Cambisols Lithosols and Fluvisols	**Brown earths**: the soil profile is similar to that of chernozem, but with less humus content.	These soils are fertile in adequate conditions of precipitation or irrigation.
BWh			Compared with present day: Cambisols: reduced in extent Leptosols: increased in extent Fluvisols: reduced in extent Bedrock: increased exposure Calcification is the dominant soil-forming process, if indeed soil forming occurs. There is poor development of horizons, with accumulation of calcium carbonate at or near the surface. Sparse vegetative cover and tiny leaves result in little humus production.
BSh			Compared with present day: Cambisols: reduced in extent Leptosols: increased in extent Fluvisols: reduced in extent Calcification is the dominant soil-forming process in semiarid regions. Mild leaching, high organic content and concentration of calcium carbonate in the B horizon typify the dark brown mollisols developed under the temperate grasslands.
DC			Compared with present day: Cambisols: increased in extent Leptosols: reduced in extent Fluvisols: increased in extent

Topographical Categories for Central Spain

Present	Geographical Context	Inland (200 x 200 km)
	Altitude	Lowland and upland (200-800 m)
	Landform	Subdued
	Localised Erosion	Fluvially incised
		Moderate slopes along river valleys
BWh	Geographical Context	Same as present
	Altitude	Lowland and upland
	Landform	Subdued to plain, development of alluvial fans
	Localised Erosion	Fluvially incised
		Aeolian erosion increased
BSh	Geographical Context	Same as present
	Altitude	Lowland probably
	Landform	Subdued or plain
	Localised Erosion	Fluvially incised
DC	Geographical Context	Same as present
	Altitude	Lowland probably
	Landform	Plain
	Localised Erosion	Fluvially incised

C3.5. - Characterization of Transitions

Application of the Interaction Matrix (IM) methodology to characterize and document the influence of climate transitions on the main biosphere system components and the interactions between those components, i.e. how does the change in component A influence the change in component B (through direct effects only).

The main transitions to take into account are the following:

1. From Csa to BWh in the next few hundred years;
2. From BWh to BSh over a period of about 5,000 years;
3. BSh to Cs stages over a period of about 10,000 years;
4. BSh to DC over a period of about 20,000 years.

These transitions are characterized in the following interaction matrices and shown in Figures C3.10 to C3.13.

Climate Class and Transition Period: CSa to BWh (next few hundreds of years for transition)				
TOPOGRAPHY	Aeolian erosion depletes A horizons generating lithosols. Incision in river valleys. It is not clear if Aeolian deposition in valleys will outweigh fluvial outwash of deposits. The above processes affect both lithology and topography.	Incision in channels can change the connectivity of the surface water and groundwater systems, but this is probably of less significance than changes in the height of the regional phreatic surface.	Given timescale of transition no substantial influence identified.	Given timescale of transition no substantial influence identified.
It seems likely that sediments will be cleared from upper reaches of streams and deposited where the channel widens and flow velocities fall.	**SOILS AND LITHOLOGY**	Change of soil type will modify infiltration, but may be secondary to effects of changes in vegetation. Minor dendritic stream development on alluvial fans. Minor change in infiltration due to alteration of pattern of sediments in valley systems.	Changes in organic content and pH. Also hardness and dryness. Original A horizon eroded to leave a lithosol with consequent effects on types of vegetation that can survive.	Natural soil system not readily exploited. Contraction of areas of agricultural crops and livestock farming without intervention.
Changes in depth of phreatic surface.	Increase of sedimentation rates on surface water bodies.	**WATER BODIES**	Development of arid vegetation, xerophilic flora and fauna. Less water available implies population fit of fish and aquatic organisms to available resources.	Concentration of population around surface water bodies.
Nothing of significance on this timescale	Calcification and salinization processes.	No substantial influence identified.	**BIOTA**	Human population adjust to available resources.
Nothing of significance on this timescale	Development of fertilization and irrigation systems.	Increase of deep well and reservoir exploitation.	Adaptation of crops to existing conditions.	**HUMAN COMMUNITIES**

Climate Class and Transition Period: BWh to BSh (five thousand years for transition)				
TOPOGRAPHY	Nothing of significance.	Changes in depth of phreatic surface with upward movement.	Nothing of significance.	Nothing of significance.
Chemical weathering will be increased, so there will be a reduction of landscape slopes.	**SOILS AND LITHOLOGY**	Changes in infiltritation, increasing the volume of subsurface water bodies.	Development of natural vegetation: grasslands on lowlands.	Increases in the extent of cropped areas.
Active surface runoff erosion will reduce landscape slopes on bare ground.	Active leaching.	**WATER BODIES**	Development of natural vegetation: grasslands, pines, herbs. More surface water available implies increase of populations of fish and other freshwater aquatic organisms.	Mix of urban and rural communities.
Increase of natural vegetation cover will reduce degree of aeolian erosion.	Organic matter content and biomass increased.	Increases in evapotranspiration rate.	**BIOTA**	Human population can be increased due to more agricultural and fish resources available.
Decreased development of dams	Natural soil system can be exploited. Non-irrigated crops more important.	Decrease of deep well and reservoir exploitation.	Adaptation of crops to existing conditions.	**HUMAN COMMUNITIES**

Climate Class and Transition Period: BSh to Cs stages (ten thousand years for transition)

TOPOGRAPHY	Nothing of significance.	Changes in depth of phreatic surface with upward movement.	Nothing of significance.	Expansion of population (in flat areas).
Chemical weathering will be increased, so there will be a reduction of landscape slopes.	**SOILS AND LITHOLOGY**	Nothing of significance.	Development of natural vegetation: Holm oak forest.	Natural soil system can be exploited. Non-irrigated crops more important.
Active surface runoff erosion will reduce landscape slopes on bare ground.	Active leaching and development of fluvisols.	**WATER BODIES**	Development of Mediterranean vegetation: pines, grassland and herbs. More water available implies increase of amount of freshwater fish and other aquatic organisms.	Mix of urban and rural communities.
Increase of natural vegetation will reduce erosion.	Increase of organic matter content. Increase of root bioturbation.	Increase of evapotranspiration rate.	**BIOTA**	Human population can be increased due to more terrestrial and aquatic resources available.
Development of dams as in present conditions.	Increase the extent of crops areas.	Increase of surface well explotaition.	Tree crop ecosystems development (olive trees). Intensive dairying and beef cattle production. Fish exploitation.	**HUMAN COMMUNITIES**

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Climate Class and Transition Period: BSh to DC (twenty thousand years for transition)				
TOPOGRAPHY	No substantial influence.	Changes in depth of phreatic surface with upward movement.	Increase in the degree of cover for flat areas.	Increase of population (on flat areas).
Physical weathering will be increased, so there will be a reduction of landscape slopes.	**SOILS AND LITHOLOGY**	Changes in infiltration rates implies increase in amount of subsurface water.	Development of natural vegetation: grassland and scrub woodland.	Natural soil system exploitation is possible. Non-irrigated crops more important.
Active surface runoff erosion will reduce landscape slopes on bare areas.	Development of seasonal permafrost. Development of wetlands.	**WATER BODIES**	Aquatic organisms adapted to cooler conditions.	Mix of urban and rural communities.
Increase of natural vegetation will reduce erosion.	Increase of organic matter content.	Expansion of populations of aquatic organisms due to more surface water availability.	**BIOTA**	Human population can be increased due to more available resources.
Development of dams may occur.	No substantial influence.	Increase of surface well exploitation.	Hunting Wild fruit collection	**HUMAN COMMUNITIES**

C4. The Evolution of North Germany

C4.1. - Characteristics of North Germany at the Present Day

At the present day, the climate of the western part of North Germany is temperate oceanic (Køppen-Trewartha Class DO), whereas the eastern part is more continental (Køppen-Trewartha Class DC). In the region of interest, the mean temperature of the coldest month is around 0°C (Mühr 2001). This is the threshold between DC and DO.

The topography is nearly flat. Rivers do not incise deeply and erosion is proceeding only very slowly. Surface water bodies are flowing rivers, lakes and wetlands. Substantial lakes and wetlands are frequent near one of the sites of interest, but not at all of them.

More than 50 % of the area is arable, but pastures and forests are also substantial in extent. The main crops are cereals, both for human and animal consumption, and root crops. Fruit and vegetables are mainly produced in home gardens (Statistische Ämter des Bundes und der Länder, 2001). Cattle for the production of milk and meat are reared on the basis of pasture and fodder plants grown in the area, whereas pigs are reared partly on the basis of commercially purchased fodder. Sheep grazing is frequent and the main product is meat. Hens are reared both commercially and domestically.

The population density is comparably low. People live mainly in villages, with inter-settlement distances of a few kilometres. The settlements consist typically of a few hundred individuals and only a small percentage of the villagers are involved in agricultural activities. In general, consumption of locally derived food is limited, because only a small range of the necessary foodstuffs is produced. There is especially a lack of fruit and vegetables, which can be relieved to some degree by home garden production and by buying at farm shops. Coarse fishing is a common recreational activity, but little freshwater fish is caught for human consumption. Figure C4.17 shows a typical landscape with forests (various greens), fields (light ochre), pastures and meadows (light green), heaths and mosses (olive), villages (red), manufacturing plants (violet), and rivers and lakes (blue) (Statistisches Bundesamt, 1997).

C4.2. - Evolution of North Germany in Scenario B3

The ecological situation after a climate change can best be visualised by reference to the contemporary situation at analogue stations with temperature and precipitation patterns belonging to the predicted climate class. Analogue stations in flat lowlands were selected for this purpose. The stations were required to be at a reasonable distance from the Gulf Stream, whereas the distance to the Baltic Sea was considered to be of minor importance. Mean monthly temperature and precipitation characteristics for various climate analogue stations appropriate to the various projected future climate conditions are shown in Figures C4.1 and C4.5, respectively. Most of the temperature and precipitation data cited in the figures are taken from Mühr (2001), others are common to other regions described in this appendix, notably Central England and North-east France.

Similarities and differences between the analogue stations for adopted for Central England, North-east France and Northern Germany are shown in Figures C4.14 and C4.15. In general, the graphs show the greater continentality of Northern Germany. Winter temperatures are lower and summer temperatures are higher than in Central England, whereas the differences with the French site are smaller. As to precipitation, the differences between the analogue stations are greater, and it is not clear whether these differences are real or reflect uncertainties in how analogue stations should be selected to characterize future patterns of precipitation. The German analogue stations for climate Class FT show far less precipitation in every month, whereas for Classes EC, EO, DC and DO the precipitation data are similar to those for North-east France. Winter rain at the selected analogue stations is far less than at the analogue stations for North-east France and Central England in these climate classes. There are no substantial differences in precipitation patterns between Central England, North-east France and Northern Germany for Class Cs.

The future climate in North Germany has not been analyzed in WP2 and WP3 as thoroughly as the future climates in the Spanish, French and British regions of interest. Nevertheless, the data given are sufficient to indicate that the future climate will be very similar to the respective climates in Central England and North-east France. Results from MoBidiC show the typical differences between the British, French and German regions. Temperatures in Germany are slightly warmer in summer and slightly colder in winter than in the other two regions, and this is also true today. Nevertheless, the climate class is nearly always the same at the three sites, and the results derived in WP2 and WP3 are also more or less valid for the German region.

Over the next few hundred years, the effects of anthropogenic greenhouse-gas releases are expected to result in a substantial change in the climate. Results of the rule-based downscaling technique imply a rapid transition to Køppen-Trewartha Class Cs conditions in Western Europe.

In WP2, various simulations of steady state climates (snapshots) were undertaken. The simulation relevant for the next few hundred years is Simulation A, where the insolation pattern and the Greenland ice sheet are like the present situation, but the atmospheric CO_2 concentration is 1100 ppmv. The results are given as differences from the simulated present-day situation.

In simulation A, the global increase in annual mean air temperature is 2.2°C, reflecting the relatively low sensitivity of the GCM to enhanced greenhouse-gas forcing. Over the North Atlantic, the temperature increase is less than this, due to deep mixing of oceanic waters. This has implications for the climate of Central Europe. In this region, temperature changes relative to the present day are estimated to be about 3°C in winter and up to 5°C in summer. Precipitation in summer is increased sharply by about 1 mm d^{-1} relative to the present day, whereas precipitation in the other seasons does not differ much from today. Both the differences in temperature and precipitation are somewhat less than the respective differences between Class DO and Cr as shown in Figure C4.2 (temperature) and Figure C4.6 (precipitation). The originators of these simulations state that they have confidence in their results for temperature, whereas they consider their findings in relation to precipitation to be less trustworthy.

It is also relevant to compare results from the one-year MAR calculation for Simulation A with the corresponding LMDz calculation for the same year. For North Germany, the LMDz calculation gives an increase in winter temperature of 4.7°C and in summer temperature of 6.5°C, respectively. The MAR calculation gives 9.0 and 4.4°C. The results for precipitation give a decrease in precipitation both in summer and winter. LMDz gives 0.3 mm d^{-1} (winter) and 0.7 mm d^{-1} (summer) decrease, whereas MAR gives 0.2 and 0.3 mm d^{-1} decreases in winter and summer, respectively. However, the MAR baseline results relate to an extremely cold single year. Such a low mean winter temperature has never been observed over the period for which instrumental records exist. Therefore it is difficult to evaluate the significance of the results obtained.

Overall, it seems reasonable to assume that, over the next few hundred years, mean annual temperatures in North Germany will increase from about 10°C (Figure C4.3) to between 15°C and 17°C. The seasonal variation in temperature (warmest month – coldest month) may remain as it is at the present day (~ 17°C) or may rise slightly (to ~ 18°C). Winter precipitation could increase by up to 1 mm d^{-1}. In contrast, precipitation in summer is assumed to decrease by 0.3 to 1.7 mm d^{-1}.

These changes in climate would apply to a landscape with near-surface lithostratigraphy and topography essentially unchanged from that at the present day. As pointed out above, the distribution of precipitation over the year will change, whereas the total precipitation will not change substantially. Each of the snapshot simulations gives a decrease of precipitation in summer and an increase in autumn. The autumn precipitation will partly replenish the soil water deficit resulting from the dry summer, but part of the autumn precipitation will be lost as runoff to rivers. Overall, whereas river flows are expected to decrease in summer, it seems likely that, in winter, the flows will be greater than those at the present day. Overbank flooding will occur more often than today in autumn and early winter, but less often in late winter and spring, because there is no longer a period of snow melt. After some hundreds of years, the change in river flow patterns and overbank flooding regimes will have an influence on river channel and floodplain characteristics. Farmers will have recognized that fields on the river banks are most appropriately used as pasture where overbank flooding is increased in frequency. Over the centuries, the rivers will broaden. In summer, low flows of water will meander over the entire riverbed. In autumn and winter, the channel will be filled to some level, but overbank flooding will revert to being a rare event.

The combination of higher temperatures throughout the year and somewhat decreased summer precipitation rates would imply a reduction in groundwater resources. Indeed, there might be an extended period of depletion by over-utilisation before a new sustainable water-management regime was established. The reduction in water availability is implied in the data for yearly precipitation and evapotranspiration given in the WP2 simulations. Whereas the current climate provides an annual excess of water that can either run off into the rivers or recharge groundwater resources, in each of the simulations except E (see below) values of precipitation and evapotranspiration are nearly equal. This means, that winter rain is not sufficient to recharge groundwater supplies, because there is always some run-off associated with heavy rain.

The consequences of a climate change for agriculture will be time-dependent. The first consequence is likely to be poor harvests, as farming practice may take some time to adjust to the increased frequency of summer drought. After some years, there would be a switch to other species and varieties of grain that are adapted to the warmer and dryer climate, and irrigation practices in family gardens would be intensified. People would also begin to produce two harvests of leafy vegetables per year and might then try to extend this practice to other irrigated crops in gardens and to field crops. Whereas today the main crops are grain, followed by potato, sugar beet and beetroot, in future the main crops could be fruit and vegetables, which give more profit per acre, but need more warmth and water. Thus, changes in crop types responding to warmer conditions could exacibate water shortages brought about by the alteration in climate. Also, pastures could suffer from summer droughts for some decades until irrigation practices are extended to this land use. Again, the extension of irrigation to pasture would place a greater demand on both surface water and groundwater resources. Irrigation of pasture would lead to a prolonged grazing period and also to a third and fourth harvest of hay or eighth and ninth harvest of silage. However, overall the production of milk and meat is likely to be reduced in favour of fruit and vegetables.

Simulation B is another simulation that is considered to be relevant to the evolution of climate over the next few centuries. In this simulation the concentration of CO_2 is set at 550 ppmv, half of the concentration in Simulation A. Also, the Greenland ice sheet is assumed to have disappeared. The melting of the ice sheet causes slightly lower temperatures and higher precipitation rates than those of the present day.

Rule-based downscaling studies for the two greenhouse-gas warmed scenarios B3 and B4 indicate that the warmer climate described above could persist for several tens of thousands of years. The similarity between the climate in Central England, North-east France and Northern Germany leads to the conclusion that the data given for England and France are also valid for Germany, but with a modification. Because winters tend to be cooler in Germany than in the other regions, some cooler periods of DO in England and France are expected to be DC in Germany. The differences between the monthly temperatures will reflect the different distances to the sea, but it is more difficult to justify the differences between the precipitation rates arising from the analogue stations selected as representative of each of the regions. In general, precipitation is estimated to be less in Northern Germany than in the other two regions, except that in late summer there is projected to be more rain than in Central England.

Based on downscaling of results from LLN 2D NH, the following pattern of long-term climate change is envisaged. Within the next few centuries, temperatures will rise rapidly to give climate Cs. This climate will persist for about 20 ka after Present (AP). Subsequently, temperatures are predicted to fall to give rise to Cr conditions and eventually, at about 90 ka AP, through DO to reach EO at about 100 ka AP. A short time later, temperatures begin to rise and will oscillate between DO and Cr, with a few thousand years of EO at around 145 ka AP. At about 170 ka AP a more severe cooling sets in. Temperatures fall through EO to EC which is then projected to last for some thousands of years. After 182 ka AP, a warming sets in. The alternative B4, with a lower atmospheric concentration of CO_2, gives temperatures that are slightly lower than those of B3. The projections of climate based on MoBidiC results are somewhat warmer than those based on LLN 2D NH results.

A better understanding of the sequence of climate conditions outlined above can be obtained from the snapshots scenarios studied in WP2. Some details of these studies for near-future greenhouse-warmed conditions have already been discussed. Studies were made using the computer models MAR for a single year and LMDz for a longer period. The results from both models include Northern Germany. Snapshots are given for present orbital conditions and elevated concentrations of CO_2, for the orbital conditions in 67 ka with various concentrations of CO_2, with and without a Greenland ice sheet, and for a glacial episode at 178 ka AP. In more detail, the simulations that are available are:

- **A:** Orbital parameters as at the present day, but with an atmospheric CO_2 concentration of 1100 ppmv;
- **B:** Orbital parameters as at the present day, but with an atmospheric CO_2 concentration of 550 ppmv and no Greenland ice sheet present;
- **C:** Orbital parameters for 67 ka After Present (AP), with an atmospheric CO_2 concentration of 345 ppmv and the Greenland ice sheet at its current size;
- **D:** Orbital parameters for 67 ka AP, with an atmospheric CO_2 concentration of 345 ppmv and no Greenland ice sheet present;
- **E:** Orbital parameters for 67 ka AP, with an atmospheric CO_2 concentration of 550 ppmv and no Greenland ice sheet present;
- **F:** Orbital parameters for 178 ka AP, with an atmospheric CO_2 concentration of 280 ppmv and a moderately extensive glacial episode (northern hemisphere ice volume of $1.74\ 10^7$ km^3 compared with the present day value of $3.2\ 10^6$ km^3).

Most of the results of these simulations are given in form of graphs, but some important information is also given in connection with the simulation of the natural vegetation which would grow under the given climate conditions. From the results presented, the following climate classes were deduced as applicable to Northern Germany.

Simulation	Present day	A	B	C	D	E	F
Climate Class	DClo	DObk	DOlk	DObk	DCbo	DObk	DClo
Vegetation period (months)	5	7	5	5	5	5	4

This table shows only minor differences between the simulations. The vegetation period is always between four and seven months long, the mean temperature in the coldest month is over 0°C in the scenarios with high CO_2 concentration, but below this value in the other scenarios. The third character shows the temperature of the warmest month, "b" stands for temperatures between 18 and 22°C, and l for temperatures between 10 and 17°C. The fourth character indicates the temperature of the coldest month, "k" indicates temperatures between 0 and +9°C, and "o" temperatures between -9 and -1°C.

In this table, no snapshots of climate class Cs, Cr, EO and EC are observed. This is in contrast to the results given above for the descriptions of scenario evolution. The distinctions arise in the matching of temperature, precipitation and climate class. A comparison with the temperatures given in Figure C4.1 shows that in climate classes DC, CO, Cr and Cs the mean temperature of the warmest month can lie between 18 and 22°C, and that there are stations of climate class DO with even hotter summers. The difference between the analogue stations of climate classes Cr and Cs and the simulated snapshot conditions is the length of the vegetation period, which is partly influenced by the insolation in spring and autumn. The distinction in climate classes at 178 ka AP (climate class DClo in simulation F in contrast to EC from downscaling results in the continuous simulation of climate evolution) is again associated with a difference in the length of the vegetation period, which would be between 1 and 3 months in EC, but is 4 months in simulation F. Although the climate class DC/DO is maintained, the range of summer temperatures covers the entire interval between the lower and upper bounds of this class.

The same result arises from the EMIC results obtained in WP3. If monthly temperatures for Eurasia, latitude 50° to 55°, are scaled to the actual monthly temperatures at the sites (mean of 1961 to 1990) under the assumption that the natural scenario A4 has unchanged temperatures over the next 500 years, the annual course of temperatures shows that the shortest annual vegetation period is five months and the longest is seven months, both of which belong to Class D. Interestingly, there are some very cold summers with highest July temperatures of only about 14°C at about 175 ka AP, but this period has relatively high January temperatures. This indicates a period of both winter and summer wetness.

There are some differences between the present climate at the analogue stations and the predicted climates. This is because the definition of the climate classes DC and DO is not dependent on precipitation, so the selected analogues were not strongly constrained by this variable (although restrictions on locations provided some constraints). The total amount of precipitation is similar in all the simulations and lies between 450 and 600 mm a^{-1}. The distribution over the year depends on whether or not a Greenland ice sheet is present. When the Greenland ice sheet is absent, most of the rain falls in autumn. However, if a Greenland ice sheet similar to that at the present day is present, the distribution of precipitation is more even throughout the year. In most of the simulations, the driest months are in winter. However, in Simulation A, the winter precipitation is about 1 mm d^{-1} higher than today. The concentration of precipitation in the winter months is not as clear as at the analogue stations of climate class Cr and Cs, but the tendency is visible. Dry winters, as seen in most of the simulations, are characteristic for the continental form of climate D, that is DC, but the January temperature is not always below 0°C, and the predicted climate class would then be DO instead of DC.

The second reason for a difference between present-day analogue stations and predicted climate is the seasonality of temperatures. The number of months with a mean temperature higher than 10°C (the vegetation period) is important for defining the climate as Class D or C. In Class D, the vegetation period is between four and seven months, whereas in Class C it is eight months or more. The temperature in March, April, September and October is strongly influenced by the number of daylight hours. In these months, the daylight hours are shorter at the German sites than at the present-day analogues for Classes Cr and Cs. It is, therefore, likely that the appropriate climate class during the warmer periods is not Cr or Cs, but DO.

Based on the snapshots and the continuous simulation results for B3 the development of climate in the coming 200 ka can be characterized as:

- A warm phase which will last for many thousands of years in which summer and winter temperatures are about 4-5°C warmer than at present, whereas temperatures in spring and autumn remain nearly unchanged; summers will tend to be relatively dry and early winters wet, with overall precipitation increased by about 30 %.
- Then follows a slow cooling over about 50 ka after which temperatures similar to those at the present day are reached, but winters will be warmer and autumns are expected to be wetter. Overall precipitation remains high. (Cr and DO conditions).
- Summers continue to cool, with some oscillations,

but temperatures in spring and autumn remain sufficient for the growth of vegetation. Annual precipitation tends to be less but distributed more evenly over the year (DO and DC conditions).

- At about 170 ka AP, a sudden cooling sets in. Summers are 3 to 4°C colder than at present, whereas the difference in winter is less. The winter, with temperatures near or below 0°C, lasts five months, but temperatures in spring and autumn are still high enough for the growth of vegetation. Late winter and spring tend to be dry, autumn and early winter will be wet.
- Over the period 180 to 200 ka AP, the climate warms and temperatures reach nearly present-day values.

At no time will ice sheets or permafrost develop in the region of interest, not even during the cold episode at around 170 to 180 ka AP.

This development differs rather from the development in the past million years. Such a long period without an ice age has not been observed, and temperatures have never been as high as predicted for the next few thousand years. Instead, in the past, the soil has been regularly degraded after some thousand years, i.e. before it has had time to come into equilibrium with the climate.

Effects on landscape evolution are discussed below.

Ocean level

The warming in the coming centuries is expected to result in partial or complete ablation of the Greenland ice sheet and cause a rise of the ocean level. The German sites will not be influenced directly by this as all of them are inland sites. Nevertheless, the salt dome of Gorleben underlies both banks of the river Elbe, and the river level is only 11 m at the site. Today this site is protected by a barrage 90 km down the river. Without this barrage and under the assumption of an elevated ocean level (WP2 gives a increase of 7 m for Simulations B, C and D), an extreme tidal wave could easily affect the landscape. The effects would be limited to the marshy land north of the river Elbe and result in a deposition of mud from the German Sea. It is not likely that an extreme tidal wave would remove more sediment than it deposits, because of the great distance (200 km) from the German Sea. Effects from coastline movement on the other sites would be negligible.

In the cold period projected to occur at about 175 ka AP, the growing continental ice sheets would cause a eustatic fall in global sea level and make the coastline of the German Sea recede; during the last ice age it was at the Dogger Bank, but the projected cold period will not be as intense and the sea level will only fall about 60 m. The changed coastline will affect the climate, but not the landscape, at the sites.

Soil moisture

Soil moisture status is related to climate conditions, human actions, soil type, vegetation and slope. Under natural conditions, man does not influence the moisture regime, and soil moisture at a given flat site will be a function of climate, soil and natural vegetation. Moisture deficit and excess are given in Figures C4.8 to C4.11 for the analogue stations cited above. The most relevant climate classes are EO, DC and DO, with a moisture deficit from May to August, and Cr and Cs, with a moisture deficit from April to September. The summer deficit is compensated by a moisture excess in winter. Typically, soils under climate class EO have an annual moisture excess. In classes DC and DO, the moisture is approximately in balance over the year, whereas in climate classes Cr and Cs there is an annual moisture deficit.

Hendl and Liedke (1997) describe the consequences of soil moisture status on soil development and plant cultivation. Soil moisture deficit and excess strongly influence the kind of vegetation that can grow. The natural vegetation in regions of climate Class Cs consists of sclerophyllous woodland. Characteristic representatives are the olive (Olea europaea), the evergreen oak (Quercus ilex), the cork oak (Quercus suber) and some species of pine (Pinus halepensis, Pinus maritime). Under the influence of humans, these sclerophyllous woodlands have often been converted to sclerophyllous shrubs.

In climate class Cr, the moisture deficit is only moderate. Therefore, broad-leaved trees are frequent. The natural vegetation in climate classes DO and DC consists of deciduous broad-leaved trees and conifers, the colder the winter is the more abundant are conifers. Birches and willows are especially frequent in climate class DC. In climate class EO, there is an excess of moisture. Where the excess water cannot run off or infiltrate to depth, swamps and mosses develop, as trees are not tolerant of a groundwater within 1 m of the ground surface.

Humans can improve the water balance and make the production of a wide range of crops possible. The nature of these crops will depend on the temperature and on the length of the growing season. The methods are drainage in climate class EO, but irrigation in climate classes Cr and Cs. Climate classes DO and DC have enough natural moisture for the production of many crops, but irrigation is needed to get better harvests of some kinds of plants.

Irrigation water can be rainwater, surface water or groundwater. Groundwater and surface waters may be contaminated by releases from a repository. However, groundwaters have the potential to exhibit higher concentrations of radionuclides. The amount of groundwater use is therefore an important feature and needs a careful examination. Irrigation demand and summer moisture deficit are closely interrelated as shown in Figure C4.16. Here, moisture deficit is calculated according to the rules set out in Section 3.2.1 and irrigation demands according to Section 3.2.2. The calculated irrigation requirements in the Simulations A to F and current conditions are shown with the enlarged symbol of the corresponding climate class. The relationship between summer moisture deficit and irrigation demand is quite clear: a summer moisture deficit of less than about 120 mm will not be compensated. Therefore, a calculated irrigation demand of less than 50 mm will not be met. Irrigation will therefore only take place in the conditions of Simulations A (irrigation requirement 126 mm), C and E (irrigation requirement 90-93 mm in both). The irrigation requirement calculated from the Climatic Research Unit database for the current climate (78 mm) is near the practical threshold. Temperatures in Simulation F are lower than today. Therefore, plants grow slowly the evapotranspiration rate is small and irrigation not necessary. In simulations B and D, summers are wet enough to obviate the need for irrigation. The abstraction of groundwater for irrigation purposes will also depend on the water quality.

If radionuclides have to escape from a salt dome to reach groundwater, that groundwater is likely to be saline, making it unfavourable for irrigation purposes.

Soil and vegetation

Soil characteristics will change in the coming 200 ka to a lesser degree than in the past. This is mainly because of the relatively small changes of climate and, in particular, the absence of very cold climates, the presence of vegetation throughout the period and the situation in lowland plains. These features are closely linked to each other. The effect of only limited and slow changes of climate is that catastrophes in which the soil is suddenly destroyed can be ruled out. The situation on lowland plains ensures that fluvial erosion is limited. River valleys cannot deepen very much because of the small height difference between the sites and base level in the German Sea. The other two features need to be looked at more closely.

Periods of continental cold climates (Climate Classes FT and FI) are characterized by low winter temperatures, short summers and periods of high wind speed. The frozen soil would not thaw completely during the short summer and permafrost would develop. This would cause an increase in groundwater level that would prevent the growth of trees. Only plants with shallow roots could then prosper. These are shrubs and herbs, many of which are annual species. With a more limited plant canopy, the soil would be colder in springtime and autumn, but warmer and dryer in summer. When the soil surface is dry, aeolian erosion can take place. The soil above the permanent frost layer would also undergo cryoturbation. After an ice age the previously existing soil would have partly or totally disappeared. New soil would originate from material that had been eroded in other regions and transported to the site by wind, and from chemical decomposition of underlying rock. Also, the vestiges of effects due to cryoturbation in preserved soils would be present for centuries. In summary, a period of Climate Class F would cause a severe turning point in the life of a soil. The consequences of a glaciation at the site would be even more drastic. However, such cold periods are absent in all of the climate simulations relevant to Scenarios B3 and B4.

Human activity will have an effect on the soil characteristics, as is pointed out below in the context of vegetation.

There are various effects of plants upon soil. A plant canopy protects the soil against heat and frost as well as against wind and heavy rain. The protection provided by above-ground vegetation against fluvial erosion is of minor importance, but plant roots are important in protecting against such erosion.

Mycorrhiza and root hairs have an influence upon soil characteristics (Wild, 1995). Their exudates make trace elements available for plants. This is of significance for both nutrition and radionuclide uptake. Roots excrete carbon dioxide in the course of respiration, thus acidifying the soil. Roots need soil pores to grow quickly to the depth, were water is continuously available; therefore a porous soil structure is favoured. Soil pores are provided by earthworms, which also use pores created and/or widened by plants during root growth. Some roots go very deep into the soil (wheat roots reach more than 2 m, corn roots 3 m and many tree roots even more) and excrete substances that favour the degradation of underlying rock, thus bringing trace elements into the soil, fertilising it and reducing the acidity if the underlying rock is calcareous. In unfertilised soils, the degradation of rock is the most important source of mineral trace elements. On the other hand, rain delivers sulphur and nitrogen.

The vertical transport of stable elements and radionuclides in soil is also influenced by the action of Lumbricus terrestris (Schmidt 1986, Makeschin 1994). This earthworm feeds on soil bacteria and ingests large quantities of soil. It excavates long vertical burrows through the whole soil layer, lining the walls with its excrement. The depth of its residence depends on the conditions in the soil. In particular, Lumbricus terrestris avoids UV. Therefore, it will not come to the surface unless it has to. This occurs when, in rainy periods, the upper parts of its burrows are filled with water, which makes the exchange of the soil atmosphere impossible giving rise to increasing CO_2 concentrations and decreasing O_2 concentrations. Lumbricus then comes up to the surface and produces its excrement, which is rich in soil from the lower layer, onto the soil surface.

The effects of decomposing vegetation are described by Wild (1995) and Hendl (1997). Dead plant material is the nutritional base of many animals, soil bacteria and other micro organisms, together named the edaphone. The decomposition rate depends on temperature and water supply and on the chemical nature of the decomposing plant material. Lignin, a major constituent of wood, is one of the substances that are decomposed especially slowly. Broad leaves with a small lignin concentration therefore decompose more readily than wood or needles.

The products delivered by decomposition depend on the plant material. Conifers deliver more raw humus and fulvic acids, whereas broad-leaved trees and herbs deliver more humic acids. Fulvic and humic acids are important constituents of humus. The half time of humic acid degradation exceeds 500 years and that of fulvic acid exceeds 1000 years. Fulvic acid is more acid and more aggressive than humic acid. Trace elements are dissolved from the clay fraction into the soil solution and from there they can be washed down into deeper soil layers with rain, especially if the soil mainly consists of sand as it is the case at some of the German sites. The acidity makes the life of earthworms impossible, so upward movement of soil components ceases. The result is a podzol.

The other extreme could be a chernozem soil, which is produced when broad-leaved trees and herbs are decomposed and various other conditions apply. These conditions are long and cold winters, warm and dry summers, a rich edaphone, especially with high earthworm content, and calcarous rock as the substrate. These conditions do not prevail at the sites of interest, nor will they do over the next 200 ka, on the basis of the results of climatological analysis reported herein.

The natural vegetation that would develop under the simulated climate was analysed in WP2. Specifically, 80 – 90 % of the vegetation would consist of evergreen needle trees. This holds for each of the simulations. Broad-leaved trees contribute about 10 – 20 %, grassland up to 1 % and bare ground does not occur.

The following information about soil formation is based on Wild (1995), Hendl (1997) and Zech (2002).

Under natural conditions, the soils at the sites would develop into podzols, except in the river valleys, where gleyic soils would be found. The tendency to podzolization would be strongest in the coldest climate, i.e. at around 170 ka AP, but exists also in the warmest climate. All these soils would be acid with a pH of four or even less. A pH of 4.1 forms the threshold for the life of certain earthworms such as Lumbricus terrestris. Without Lumbricus, the movement of soil constituents from deeper to shallower soil layers is nearly impossible. This is macroscopically to be seen by the soil horizons: layers of litter, raw humus and humus are underlain by an acid grey or nearly white eluvial horizon that contains only small concentrations of minerals, radionuclides and clay, because all these substances have been washed down into the illuvial horizon which is less acid and of brown colour because of all the mineral constituents. In podzols, the deep soil layers are, therefore, a sink for many elements and radionuclides.

Podzols are unfertile and need much fertilisation. In former times, people used to cover podzols with turf, plaggen, river sediment or sewage mud; the resultant anthosol is a fertile porous soil with an abundant edaphone. In spring, it warms up early because of its dark colour. On such a soil, plants such as potatoes, oats, barley, fodder plants, vegetables and fruit can be grown. Such anthosols can be created in any of the climates that will occur over the period of interest, but the tendency will be strongest in the first thousands of years with a warm climate, and weakest in the relatively cold episode at 170 ka AP, when agriculture might tend to switch over to animal husbandry. Nevertheless, the temperature will even then allow farming, especially barley, oats, potatoes, kale, and also the production of apples and many species of berries.

A different intervention of humans in soil development can also be observed. In former times, pigs were fed on acorns in the forests. Therefore, the coniferous forest has often been transformed into a mixed forest of oaks, beech trees (beech-nut gives an oil which is slightly poisonous, but people use it in times of famine), hazel-bush (hazel was a main comestible during the climate optimum 6000 years BP) and many other broad-leaved trees together with the autochthon conifers. The presence of broad-leafed trees for thousands of years resulted in the formation of brown and grey forest earths (cambisols and luvisols and, near the rivers, gleysols). Cambisols and luvisols are fertile soils that are normally used for the production of wheat, sugar beet, fodder plants and many other products. This holds for flat sites. On the slope of hills, they are mainly used for pastures and forests.

Today, podzols are frequent at the sites, but there are also other soils. Over loam, fertile luvisols and cambisols have developed indicating a long history of human activity. Soils that indicate the absence of human activity occur at wet sites where the groundwater level is high. These are termed histosols. The frequency of histosols is likely to be increased during the cold period around 170 ka AP.

Rivers

The calculated mean precipitation rates for every snapshot simulation are between 450 and 600 mm a^{-1}, similar to the observed precipitation rate at the present day. Indeed, the observed year-to-year difference at the sites is greater than the difference between the snapshot means. Evapotranspiration varies according to summer temperatures and vegetation characteristics. The difference between evapotranspiration and precipitation on a month-by-month basis is not exactly equivalent to run-off, because much of the excess precipitation of autumn and early winter penetrates into the soil and replenishes the water resources in the soil. Nevertheless it is possible to make a plausible assessment of the effects of changes in precipitation and evapotranspiration on surface water flows and the forms and sizes of river and stream channels.

Most of the rivers in the vicinity of the sites are small and get their water from only a few hundred or thousand km_. The mean water flow is approximately 5.5 l km^{2} s^{-1}. The river Elbe is much larger, with a total catchment of 150000 km_ and a total length of 1091 km, but the mean water flow per unit area of the watershed is the same. These values are also nearly the same as the run-off calculated in WP2 under present conditions (6.5 l km^{2} s^{-1}) and under present climate conditions with natural vegetation (7.3 l km^{2} s^{-1}). In contrast to this, the run-off calculated for each of the simulations A to F lies between 10 and 13 l km^{2} s^{-1}. Only Simulation E gives a value similar to that at the present day. If the natural vegetation were replaced by agriculture, the run-off would be somewhat less.

In total, the rivers will have to carry about twice the water of today. Therefore, inundations will generally occur more often than today, mainly in autumn and early winter, but also in spring in the simulations C to F. Inundations in spring would not occur in the context of Simulations A and B, because winter temperatures are too warm for long-lasting snow cover. In consequence of the higher flow rate, the rivers will become wider. In the first few decades, the inundations will erode the soil near the rivers, later the river channel will have deepened and widened. Then the channel will be filled with water in autumn and winter, but, in summer, rivers carrying small amounts of water will meander through a wide valley that will be used as pasture for cattle and especially for sheep.

Increased river temperature could cause a problem in warmer conditions (as in Simulations A, C and E), because, in some years, river temperatures will be so elevated that in combination with the run-off from fertilised fields this could cause the death of fish. After some decades of problems with fish death in summer, the species will have changed. The new fish species or varieties will tolerate warmer water with lower concentrations of oxygen.

With only limited changes in climate, topography, water bodies and biota over the next 170 ka, there is no requirement in BIOCLIM to assume that different demographic patterns would develop. Therefore, human community structures are assumed to remain as they are at the present day. As with agriculture, it is emphasised that such community structures could change substantially as a result of various social, political and economic factors not directly determined by climate.

C4.3. - Evolution of North Germany in Scenario A4

The discussion in Section C.4.2 entirely relates to BIOCLIM Scenario B3. However, a scenario forced only by variations in insolation and natural atmospheric carbon dioxide concentrations has also been studied (Scenario A4). Application of rule-based downscaling to that scenario and based on CLIMBER results leads to the projection that temperate conditions similar to those at the present day (Køppen-Trewartha DO/DC) would persist for the next 100 ka with little oscillation; the first 30 ka would be climate class DC, the next 70 ka would be DO, but the temperatures of the coldest month would always remain close to the threshold between DC and DO. At 100 ka AP, a cooling transition is projected to occur, but climate class DC would still persist. The cooling would be mainly in summer, with the temperature of the warmest month around 15-16°C; after some thousands of years, summers would become warmer than today, but the climate class remains at DC. From then on, oscillations of summer temperatures occur: 20-22°C at about 120 ka AP, 16°C at 130 ka AP, again over 20°C at 137 ka AP and below 15°C at 147 ka AP, nearly 23°C at 160 ka AP and only 13°C at 170 ka AP. Over the same period, winter temperatures would decrease more or less steadily from 0°C to -3°C.

The threshold between the climate classes D and E is given by the length of the growing season. This is the number of months with a mean temperature over 10°C. This quantity has not been generated, but it seems reasonable to assume that a high summer temperature is linked with a long period of temperatures above 10°C. The German analogue stations with warmest summer months of 16°C or more belong to the climate classes DO and DC, those with less than 16°C to climate class EO. However, the winter at those analogue stations is considerably colder (mean temperatures of the coldest months -7°C and less) than the projected winters at the site (mean temperature of the coldest months 0 to -2°C). Therefore, it is assumed that the winters would not be as long as at they are at the EO analogue stations.

In summary, summer temperatures are projected to oscillate in a range of about 10°C (13 to 23°C), but winter temperatures steadily cool from about 0°C to about -1.5°C after a 30 ka period in which winter temperatures are up to 2°C. The climate class is projected to be DC – DO – DC. Then oscillations between long phases of DC and (perhaps) short phases of EO occur, the first EO is at 100 ka AP, the following are at 150 ka AP, 170 ka AP and from 190 ka onward. The classes EC and FT are not foreseen. According to the results from CLIMBER no glaciations of the sites will occur. This is contrary to the output from MoBidiC.

Precipitation rates remain at the same order of magnitude as today. Corrected CLIMBER estimates for mean monthly precipitation in summer (July) exhibit only limited oscillations, whereas January precipitation rates rise rapidly from 1.6 mm d^{-1} to 1.9 mm d^{-1} at about 30 ka AP, after which time they remain fairly constant.

In contrast to these findings, the downscaling output of CLIMBER shows very high precipitation rates in July which oscillate between 4 and 6 mm d^{-1} in the second half of the period. These results seem to be less trustworthy because high precipitation rates in summer coincide with high summer temperatures. The further analysis is therefore based on the results of the corrected model output.

During the period of temperate conditions to 100 ka AP, very little change in the landscape is envisaged, soil would not be denuded, and biotic and human communities would remain stable. After 100 ka AP, there is some uncertainty about the further development. Precipitation could either remain as it is with little consequences for the landscape, or large oscillations between wet summers and extremely wet summers could occur. These oscillations are not very convincing, but their implications require consideration. The high precipitation rates would make agriculture difficult or impossible, even with a good drainage system. In every case, river valleys would deepen and widen. Erosion at the sites would not be high, because of the local low relief. If agriculture were given up, mosses would grow and the soil would develop into an umbric histosol.

Results from MoBidiC lead to somewhat different conclusions. MoBidiC shows very low winter temperatures in every simulation, in A4 as well as in B3 and B4 and throughout the whole period. This is clearly far from the present condition at the German sites. Obviously the low winter temperatures are influenced by the continental regions of Eurasia. Nevertheless, the vegetation period is never shorter than 2 months. Despite the mean annual temperatures being low, the climate class in the coldest period is EC, and, if corrected for unduly low winter temperatures, it could also be EO, and there is no permafrost. Permafrost in EC regions which are not too continental is a relict from the last glaciation. In summary: MoBidiC does not reveal any glaciation at the German sites. The consequences of a glaciation for the British site are described in Section C.1.3. This description would also be valid for the German sites, with the exception that the change in sea level does not influence the sites because all of them are inland.

C4.4. - Identification of Characteristic Climate States and Transitions

From the characteristics of North Germany under Scenario B3, the following states and transitions are identified as forming the basis for a suitable generalised scenario of environmental change.

a) A biosphere state with a landscape and climate similar to that at the present day persisting for less than 100 years;

b) A biosphere transition over a few hundred years to a landscape similar to that at the present day, in which temperatures rise by 3 to 4°C both in summer and winter and with increasing precipitation in summer, whereas winter precipitation remain constant;

c) A biosphere state with a landscape roughly similar to that at the present day, but with a climate that has warmer winters by 2 to 3 °C and summers warmer by 3 to 4°C, persisting for 45 ka;

d) A short and rapid cooling in which present day summer temperatures are reached but winter temperatures remain elevated;

e) A biosphere state lasting for 3 ka in which summer temperatures are as at present and winter temperatures somewhat warmer;

f) A slow transition over 12 ka to a landscape similar to that at the present day, with summers that are about 5°C warmer and also a bit dryer, whereas winter temperatures and precipitation are not affected;

g) A biosphere state that will last for about 5 ka with a landscape similar to that at the present day, summer temperatures 5°C higher than at present, approximately present-day winter temperatures, and uniform precipitation rates throughout the year;

h) A slow biosphere transition over 15 ka to summer temperatures more or less as at the present day with increasing summer precipitation;

i) A biosphere state lasting 3 ka with mean temperatures in summer and winter as at the present day, but with somewhat higher precipitation in summer.

The succession (f) to (i) is repeated five times. In every repetition, the amplitude of summer temperatures is greater than the time before. The fourth temperature peak rises to 24°C at 160 ka AP, than summer temperatures fall to 15°C at 170 ka AP. Summer precipitation is always somewhat elevated when annual temperatures are low and similar to the present when annual temperatures are higher. Winter temperatures and precipitation rates are almost unaffected. The amplitude of the fifth cycle is smaller.

In the case of Scenario A4, the following states and transitions are identified:

a) A biosphere state with a landscape and climate similar to that at the present day which lasts for about 15 ka;

b) A biosphere transition over a timescale of 15 ka to a landscape similar in form to that at the present day, but with 2 to 3°C warmer summers and slightly warmer winters with slightly elevated precipitation rates;

c) A biosphere state with a landscape similar in form to that at the present day, but with more humid and warmer summers and winters persisting for 10 ka;

d) A slow biosphere transition over 10 ka to cooler conditions, in which the present day temperatures are reached whereas precipitation remains increased;

e) A biosphere state with a landscape and climate similar to the present day which lasts for 2 ka;

f) A biosphere transition over a timescale of about 12 ka to a biosphere state with a landscape similar to that at the present day; but with 3°C warmer summers and winter temperatures as at the present day;

g) A biosphere state with a landscape similar to that at the present day, but with 3°C warmer summers and winter temperatures and precipitation rates as at the present day.

For the early part of A4, the characteristics of scenario B3 hold more or less but with two exceptions. First, that temperatures, both in summer and in winter, are about 1 to 2°C less than in Scenario B3. This implies that the mean January temperature is below 0°C during most of the time. The most extreme oscillation in July temperatures is between 23 and 12°C, this transition occurs within 13 ka. The second exception is that summer precipitation can differ from the B3 scenario by up to 10 mm per month in either direction, whereas winter precipitation is always more or less the same as in B3. A difference of 10 mm per month is regarded as nearly negligible.

In Scenario B3, transition (b) to reach biosphere state (c) has probably already begun, state (c) could exist by the end of the institutional control period that would be expected to follow repository operations and closure, but the adjustment of landscape and soil to new conditions takes time and will not be completed soon after the climate has been transformed to a new state. Therefore, the first transition of interest is the transition from now to biosphere state (c). Also, the further transition (d) from state (c) to state (e) is of particular interest. The degree of cooling toward the end of the study period is very much less than in Scenario A4, so transitions to colder states and the colder states themselves are more usefully studied in the latter context.

In Scenario A4, the transition (b) to reach state (c) is much slower and also much smaller than the first transition in scenario B3, but the direction is the same. More interesting are the transitions in the second part of the period, which go from a cool to a warm climate and vice versa. These transitions are best considered in terms of the largest ones, which take place from 147 ka to 159 ka and from then to 169 ka AP.

Thus, the states requiring consideration are:

1) A biosphere state with a landscape and climate similar to that at the present day;

2) A biosphere state with a landscape similar to that at the present day, but with a climate with a July mean temperature between 3 and 5°C warmer (B3 at 20-40, 67, 90, 115, 140, 160, 180 ka AP) (climate class will rather be DOak than Crak);

3) A biosphere state with a landscape similar in form to that at the present day, but with EOlo climatic conditions and an agricultural system based mainly on animal husbandry, with much less arable farming than at the present day (B3 at 145 and 170 ka AP and A4 at around 147 ka AP and, even more pronounced, at 170 ka AP); in MOBidiC simulations these periods could also be DOlk;

4) A biosphere state with a landscape similar to that at the present day, but with a more continental climate (colder winters, warmer summers, summer rain, A4 at 110-115 ka, 155-160 ka, 180-185 ka AP) (climate class probably DCbo or even DCao).

The transitions between these states that are of particular interest are:

[1–>2] over a timescale of some hundred years;
[2–>1] over a timescale of tens of thousands of years;
[3–>4] over a timescale of ten thousand years;
[4–>3] over a timescale of about ten thousand years.

The individual states are characterised in subsection C.4.5, using the BIOMASS methodology. Transitions are characterised in subsection C.4.6, using the methodology developed in BIOMASS and extended in BIOCLIM.

C4.5. - Characteristics of States

Based on Appendix A, the characterization of states and expected evolution due to climate change is presented in the following tables:

Climate Type Classification and Evolution for Germany		
	Køppen/Trewartha Class	**Description**
Present	**DO** oceanic temperate climate **DC** continental temperate climate	Characterised by 4-7 months in which the mean temperature is higher than 10°C with precipitation throughout the year. The mean temperature of the coldest month can be lower (DC) or higher (DO) than 0°C. Actually, it is close to 0°C. Summer temperatures lie between 16 and 24°C.
Warmer	**Cr** subtropical humid climate **Cs** subtropical summer-dry climate	Characterised by 8-12 months in which the mean annual temperature is higher than 10°C and the mean temperature of the warmest month is higher than 18°C. If the precipitation in the driest summer month is less than 30 mm and the annual precipitation less than 900 mm, the climate is Cs, if either the driest month or the whole year is more humid, the climate is Cr.
Colder	**EO** oceanic boreal climate **EC** continental boreal climate	Characterized by 1-3 months in which the mean temperature is higher than 10°C. The mean temperature of the coldest month can be lower (DC) or higher (DO) than -10°C.
Much colder	**FT** tundra climate	Characterized by the mean temperature of the warmest month between above 0 and +10 °C. The vegetation period is less than 1 month.

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Water Bodies Types Compared with Present for Germany

Present	1	**Surface Water Bodies** • Natural: - Rivers, frozen for up to some weeks per year - Lakes, frozen for up to some weeks per year - Springs • Artificial: - Reservoirs/dams - Wells
	2	**Subsurface Water Bodies** • Variably saturated zone • Saturated zone
Cr	1	**Surface water bodies (water availability generally in summer reduced)** • Natural: - Rivers, seasonality of water flow more accentuated than today - Lakes with varying water table - Springs • Artificial: - Reservoirs/dams: increased necessity for construction and use
	2	**Subsurface water bodies** • Variably saturated zone • Saturated zone deeper in summer, higher in winter
Cs	1	**Surface water bodies (even less water available)** • Natural: - Rivers, seasonality of water flow even more accentuated - Lakes can disappear in summer - Springs - Seasonal water courses more frequent • Artificial: - Reservoirs/dams with increased exploitation
	2	**Subsurface Water Bodies** • Variably saturated zone • Saturated zone deeper, especially in summer (deep wells more useful)
EO	1	**Surface Water Bodies (more water available)** • Natural: - Permanent rivers, frozen during some months - More lakes, frozen during some months - More springs than at present • Artificial: - Reservoirs/dams only used if surface water is of poor quality
	2	**Subsurface Water Bodies** • Variably saturated zone • Saturated zone shallower and can form new water bodies

Water Bodies Types Compared with Present for Germany		
EC	1	**Surface Water Bodies (more water available)** • Natural: - Permanent rivers, frozen for half the year or longer - Lakes frozen during long winters - Springs • Artificial: - Reservoirs/Dams only used if surface water is of poor quality
	2	**Subsurface Water Bodies** • Variably saturated zone • Saturated zone shallower and can form new water bodies
FT	1	**Surface Water Bodies (more water available)** • Natural: - Permanent rivers, frozen unless for a short period - Lakes more frequent but frozen unless for a short period - Springs during summer • Artificial: - Reservoirs/dams only used if surface water is of poor quality
	2	**Subsurface water bodies** • Permafrost • Variably saturated zone • Saturated zone shallower and can form new water bodies

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Classification of Human Community Types for Germany based on Socio-economic and Environmental Considerations				
	Trading	**Biosphere Control**	**Community Types**	**Community activities* in relation to the system**
Present	Small-scale	High	Small farming community – external foodstuffs permitted Large cities interacting with a network of small communities	Edible and non-edible crop production, animal husbandry/grazing, insignificant freshwater fishing, recycling of residues, use of wood resources, use of surface and groundwater resources
Cr	Small-scale	High	Small farming community – external foodstuffs permitted Large cities interacting with a network of small communities	Edible and non-edible crop production, animal husbandry/grazing, insignificant fishing, recycling of residues, use of wood resources, use of surface water resources, enhanced use of groundwater resources
Cs	Small-scale	High	Small farming community – external foodstuffs permitted Large cities interacting with a network of small communities	Edible and non-edible crop production, animal husbandry/grazing, very little fishing at lakes, recycling of residues, low use of wood resources, Use of groundwater resources more enhanced, especially in summer
EO and EC	Small-scale	High	Small farming community – external foodstuffs permitted Large cities interacting with a network of small communities	Less edible and non-edible crop production, edible crop production partly in greenhouses, enhanced animal husbandry/grazing, enhanced fishing, recycling of residues, enhanced use of wood resources, use of surface resources enhanced, use of groundwater resources seldom necessary
FT	Small-scale	Low	Small farming community – external foodstuffs permitted Large cities living mainly on external foodstuff	Edible crop production mainly in greenhouses, enhanced Animal husbandry/grazing, enhanced fishing, recycling of residues, use of surface water resources enhanced, low use of groundwater resources

* Note:Use of land for residential purposes, and potential exploitation of local water resources, are assumed possible in association with any of the different classes of activities.

Ecosystem Classification and Evolution for Germany

NATURAL SYSTEMS			
Terrestrial Ecosystems		**Aquatic Ecosystems**	
Present	Deciduous and needle forests, swamps mammals, birds	Present	Rivers and few lakes: fish. Mussels and crabs possible.
Cr	Deciduous and Mediterranean forests: pines, grassland and herbs Mammals, birds, reptiles	Cr	Rivers: fish. Mussels and crabs possible.
Cs	Mediterranean oak woodland Mammals, birds, reptiles	Cs	Rivers: fish. Mussels and crabs possible.
EO	Boreal forests, grassland, swamps Mammals, birds	EO	Rivers and lakes: fish. Mussels and crabs possible.
EC	Boreal forests, grassland Mammals, birds	EC	Rivers and lakes: fish. Mussels and crabs possible.
FT	Tundra, lichens, swamps, grassland Mammals, birds	FT	Rivers and lakes (fish).

SEMI-NATURAL SYSTEMS			
Terrestrial Ecosystems		**Aquatic Ecosystems**	
Present	Deciduous and needle forests, grasslands, heathers Mammals, birds	Present	Rivers and lakes : fish
Cr	Deciduous and Mediterranean forest: pines, grassland and herbs Mammals, birds, reptiles	Cr	Rivers and reservoirs: fish
Cs	Mediterranean oak woodland Mammals, birds, reptiles	Cs	Rivers and reservoirs: fish
EO	Boreal forests, grassland Mammals, birds	EO	Rivers and lakes : fish
EC	Boreal forests, grassland Mammals, birds	EC	Rivers and lakes : fish
FT	Grassland Mammals, birds	FT	Rivers and lakes : fish

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Ecosystem Classification and Evolution for Germany

MANAGED SYSTEMS

Present	**Terrestrial Ecosystems :**	
	Field crop ecosystems: Crop production, orchards and pastures normally without irrigation. Main crops: cereals, fodder plants, root vegetables. Gardens and vegetable fields with irrigation. Greenhouses for vegetable production.	
	Cows, pigs, horses, sheep, hens	
	Bio industrial ecosystems: *	Intensive dairying, production of beef, pigs and poultry. Fodder plants usually not irrigated.
	Aquatic Ecosystems :	
	Few fishponds	
Cr	**Terrestrial Ecosystems :**	
	Main crops: cereals without irrigation, vegetables and leafy vegetables with irrigation; less root vegetable production than at present, but more green vegetables.	
	Irrigated orchards and gardens	
	Cows, pigs, horses, sheep, goats, hens	
	Bio industrial ecosystems*	Intensive dairying, production of beef, pigs and poultry. Some of the fodder plants is irrigated, also pastures in summer.
	Aquatic Ecosystems :	
	Few Fishponds	
Cs	**Terrestrial Ecosystems :**	
	Main crops: cereals, vegetables and leafy vegetables, fodder plants and fruit are irrigated.	
	Irrigated orchards and gardens. Olive trees not irrigated.	
	Few cows, more sheep and goats; pigs, hens.	
	Bio industrial ecosystems*	Intensive dairying, production of beef, pigs and poultry. Most of the fodder plants are irrigated; pastures are uncommon.
	Aquatic Ecosystems :	
	Few Fishponds	
EO and EC	**Terrestrial Ecosystems :**	
	Field crop ecosystems: Crop production, orchards (apples) and pastures without irrigation. Main crops: cereals, root vegetables, fodder plants, more pastures than fields. Gardens sometimes irrigated, vegetable fields never. Mushrooms and berries, namely cranberries (never irrigated). Greenhouses for vegetable production.	
	Cows, pigs, horses, sheep, hens	
	Bio industrial ecosystems:*	Intensive dairying, production of beef, pigs and poultry. Fodder plants and pastures not irrigated; part of the fodder imported.
	Aquatic Ecosystems :	
	Fishponds	
FT	**Terrestrial Ecosystems :**	
	Field crop ecosystems are not sustainable. Some production of barley, potatoes, cabbage which are never irrigated. Greenhouses for vegetable production.	
	Reindeers, pigs, hens	
	Bio industrial ecosystems:*	Intensive dairying, production of beef, pigs and poultry; feeding on the basis of imported fodder.
	Aquatic Ecosystems :	
	Fishponds frequent	

(*) Although these practices are common, the production is not at industrial level.

Zonal Soil Types for Germany

	Soil type	Description (horizons)	Comments
Present	Podzols	L - O – AE – E – Bh – Bs - C	Sandy acid infertile soils especially under needle forests with negligible bioturbation because of acidity; agriculture with low productivity is only possible after high fertilisation
	Cambisols	Ah – Bw – BwC - C	Young sandy and loamy fertile agricultural soils with high bioturbation, typical soil of this zone
	Luvisols	Ah – E – Bt – BtC - C	Fertile slightly acid sandy and loamy agricultural soils with high bioturbation which originated under deciduous forests, typical soil of this zone
	Albeluvisols	O – Ah – E – Bt - C	Acid humid soils with poor bioturbation, on which agriculture is possible after fertilisation
	Histosols	H1 – H2 – Hf - Crf	Humid organic soils especially over former glacigenic lakes; agriculture is possible after drainage, low productivity
	Gleysols	Ah – Bg - Cr	Semiterrestic soils in river valleys with negligible bioturbation because of humidity, naturally covered with swamps, used for extensive grazing
	Fluvisols	Example: Azh Czg - Czr	Young soil on river deposits with alluvial stratification depending on the material in the upper reaches of the river, typical soil in river plains.
	Phaeosemes	Ah1 – Ah2 – Ah3 – AhBt - C	Slightly acid fertile soils with high bioturbation originating under dense vegetation (grasses, herbs, deciduous trees) on loess in case of sufficient humidity
	Chernozems	Ah1 – Ah2 – Ah3 – AhC - C	Old slightly acid very fertile soils rich in organic matter, with high bioturbation originating under dense vegetation (grasslands) on loess in case of cold and dry winters and short warm and humid summers (in the region of interest today only as a remainder from the climate optimum 6000 a BP)
	Plaggic Anthsol	Ap – AC - C	Relatively fertile acid sandy soil with high biotubation originated by human activity on the basis of podzols
Cr	Luvisols	See above	See above, typical soil of this zone
	Cambisols	See above	See above, typical soil of this zone
	Gleysols	See above	See above

Zonal Soil Types for Central Spain

	Soil type	Description (horizons)	Comments
Cs	Chromic cambisols	Ah – Bw - C	Fertile neutral or slightly acid soil with high content of sandy loam and red iron salts
	Chromic luvisols	A - E – Bt - C	Old fertile slightly acid soils with high organic matter and high bioturbation in the upper layers, containing red iron salts.
EO and EC	Podzols	See above	See above; typical soil at well drained sites, typical soil of this zone
	Histosols	See above	See above; typical soil at poorly drained sites; this soil frequently originates over permafrost after a change of climate from FT or EC to EO, typical soil of this zone
	Albeluvisols	See above	See above – typical soil of this zone
	Gleysols	See above	See above, typical soil of this zone
FT	Cryosols	H – Abg – CBg – Cf - Rf	Typical soil on continuing permafrost; high organic matter because of reduced decomposition in the cold environment; cryoturbation, typical soil in this zone
	Gelic leptosols	A-(B)-R or A-(B)-C	Young cryic soil at the beginning of soil genesis with high content of stones and low content of organic matter, only 10 % fine earth. The A-horizon is thin. Permafrost within 2 m under surface. Used for forests near the edge to climate class EC.
	Cryic histosols	H - Crf	Older cryic soil with high content of organic matter, typical soil in the oceanic part of climate class FT near the edge to climate EO/EC. Covered with swamps and moor-land, upland moors being without contact to groundwater
	Gelic gleysols	See above, but with permafrost	Cryic soil with high groundwater layer over permafrost within 2 m under surface

These descriptions only give a selection of various possible soil types in lowlands. Past climate classes can have an influence on the soil characteristics for some ten thousand years.

The letters characterizing the soil layers are taken from FAO as cited in Hendl (1997).

C4.6. - Characteristics of Transitions

Characteristics of transitions between the various states described in Section C.1.5 are set out in the following transition diagrams.

State 1 to State 2 over some hundred years.				
State 1 : present climate(DCbo, DObk)	**State 2: climate class Crak and DOak**			
TOPOGRAPHY	Heavy storms in the upper reaches of rivers cause erosion there. Settlement of the eroded material in river plains at the site (only in case of long rivers like Elbe) leads to more frequent inundations which widen the valley. Soils at the edge of the valley are transformed to more gleyic soils.	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	**SOILS AND LITHOLOGY**	Limited changes in soil texture will occur, modifying the partition of meteoric waters between surface flow, throughflow and infiltration.	Close to the river Elbe: Rising salinity causes change from crop production to pastures. All sites: Diminishing acidity makes the soil more fertile. Soil worms have better conditions	No substantial influences identified.
Sea level rise of 4 to 7 m could result in sporadic flooding of the plain (only in case of river Elbe which is at a low elevation)	Sporadic flooding driven by the rising sea level causes salinification of the river plain (only Elbe) No substantial influences at other sites identified	**WATER BODIES**	Rising salinity of recent ground water reduces the ability for irrigation. Irrigation with deep groundwater will be preferred (only Elbe) Warming of river water causes problems with oxygen. Less fish or new fish species.	No substantial influences at the sites identified (there are no settlements at the endangered part of the Elbe plain)
No substantial influences identified.	Newly formed soils will be less acid than the old because fulvic acid producing plants are replaced by humic acid producing ones. Soil worms will raise bioturbation and fertility	Tendency to eutrophy in summer	**BIOTA**	Migration of insects could lead to illnesses like malaria, sleeping sickness ... – this could cause people to remove their settlements from the river plains to more elevated sites
No substantial influences identified.	Irrigation of pastures on podzol soils accelerates the downward transport of mineral constituents (only until podzols are replaced by luvisols and cambisols. This is not only probable if pastures are replaced by fields)	Higher irrigation demand can lead to overexploitation of water resources causing the fall of groundwater level and the need to exploit deep groundwater.	Water deficiency leads to the cultivation of other plants (additional to irrigation of existing cultures)	**HUMAN COMMUNITIES**

State 2 to State 1 over some ten thousand years				
State 2: climate class Crak, DOak	**State 1: present climate DCbo, DObk**			
TOPOGRAPHY	No substantial influences identified.	No substantial influences identified	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	**SOILS AND LITHOLOGY**	Limited changes in soil texture will occur, modifying the partition of meteoric waters between surface flow, throughflow and infiltration.	Crops will need more fertilizer	No substantial influences identified.
No substantial influences identified.	No substantial influences identified.	**WATER BODIES**	Decreasing evapotranspiration causes more time until an inundated river plain is dry again; therefore the use of the land along the rivers could be changed from crop production to permanent pastures	Repopulation of river banks probable (because pests decrease)
No substantial influences identified.	Under fields and pastures no substantial influences identified. Under woodland tendency to podzolization	No substantial influences identified.	**BIOTA**	No substantial influences identified.
No substantial influences identified.	Fertilization in association with drainage in the maintenance or reclamation of areas of land.	No substantial influences identified, perhaps drainage to a limited extent	Trend to decreasing arable land use and increasing development of pastures. Abandonment of some land to give semi-natural vegetation.	**HUMAN COMMUNITIES**

State 3 to State 4 over about 10000 years				
State 3: climate class EOlo	**State 4: climate class DCbk**			
TOPOGRAPHY	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	**SOILS AND LITHOLOGY**	Development of agricultural soils through natural processes and human actions will affect the partitioning of precipitation between surface flow, throughflow and infiltration: Inundation will be more frequent in summer	Development of agricultural soils through a combination of natural processes and human actions leads to the replacement of natural boreal vegetation by agricultural vegetation	No substantial influences identified.
No substantial influences identified.	No substantial influences identified.	**WATER BODIES**	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	Boreal vegetation will be replaced by temperate region vegetation. The extent of swamps will be reduced, under forest podzolization will be enhanced, However, with continuous human occupation, the soil will be fertilized to give more favorable anthrosols	Acidification of river water will be reduced because of the reduction of swamps.	**BIOTA**	No substantial influences identified. Rather, humans adapt biota to their requirements as climatic conditions ameliorate.
No substantial influences identified.	Development of extensive agriculture by which anthrosols are formed	Increasing exploitation of surface waters and groundwaters, but without the danger of overexpoiltation	Development of extensive agriculture.	**HUMAN COMMUNITIES**

State 4 to State 3 over about 10000 years				
State 4: climate class DCbk	**State 3: climate class EOlo**			
TOPOGRAPHY	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	**SOILS AND LITHOLOGY**	The development of moist high organic soils leads to the formation of lakes, to the acidification of surface water, and, because of the higher water capacity to the reduction of inundations in summer – in spring inundations are caused by snow melt and will continue to occur.	Soils become less usable for agriculture (unless fertilised). Semi-natural vegetation spreads to give swamps and needle forests. Crop production is reduced to animal husbandry on the basis of pastures.	No substantial influences identified.
No substantial influences identified.	Formation of histosols	**WATER BODIES**	Crop production along the rivers will be impossible because of moisture, but permanent pastures can exist. In swamps only natural vegetation is possible	No substantial influences identified.
No substantial influences identified.	Decreasing rate of degradation of biotic materials contributes to the development of humic boreal soils. Acidity caused by plant degradation products rich in fulvic acid leads to podzolization	Formation of swamps possible	**BIOTA**	Nutrition will get richer in animal products
No substantial influences identified.	Fertilization reduces the tendeny to podzolization, drainage reduces production of histosols to give anthrosols	Groundwater abstraction requirements would be reduced because of limitation of irrigation to glasshouses. Groundwater level would rise	Abandonment of land leads to development of natural boreal vegetation; transformation from arable land into permanent pastures.	**HUMAN COMMUNITIES**

The transition between the states can also be represented in the form of diagrams. Illustrative examples for the five transitions given above are shown in Figures C4.18 to C4.21.

These transition diagrams show that despite climate changes being only limited the biosphere changes substantially.

C5. The Evolution of the Czech Republic

C5.1. - Characteristics of the South of the Czech Republic at the Present Day and in the Past

The south part of the Czech Republic (49.8N-14.8E, 48.8N-16.0E) was selected for climatic and biospheric modelling and assessment of potential environmental evolution, as this area includes several potentially suitable sites for the construction of a deep geological repository. Most of this selected area belongs to the Vysocina administrative region. Thus, climatic and environmental data for the Vysocina region are used in this narrative where appropriate, since the general conditions in the Czech Republic are not characteristic of this region.

This south part of the Czech Republic is composed mainly of hard rocks (metamorphosed rocks, granites) of the Moldanubikum regional geology unit. The landscape is characterised by uplands, with altitudes between 400 and 800 m. Infrequent local rivers are incised and form characteristic valleys. These rivers drain both to the Black Sea (by the Donau River) and North Sea (by the Vltava and Labe/Elbe rivers). The whole study region is characterised by denudation, without any important external supply and deposition of material.

In the main, acid brown soil (Cambisol) prevails, with a minor occurrence of Cambic Podzol (Tomasek, 2000). Forests, meadows and pastures are frequent. The area is mostly of the woodbrush-beech woodland category, with minor occurrence of beech woodland with Dentaria enneaphyllos (in the west) and woodbrush-oak and/or silver fir-oak woodland (in the east) categories, according to the map of potential natural vegetation of the Czech republic (Neuhauslova et al., 1998). Acidophilous beech forests are replaced at many sites by pine and spruce forests; birch mire forests also occur (Chytry et al., 2001).

Agriculture is mostly oriented to cultivation of less demanding crops, mainly potatoes. Consumption of locally derived foods is limited, but vegetable and fruit gardening is common, along with keeping of domestic animals for home consumption (e.g. fowl, rabbits). Mushrooming and picking of forest berries (blueberries, blackberries, etc.) is popular in this area.

Towns and villages are less frequent than in much of the rest of the republic. The average density of population is 50 to 100 inhabitants km^{2}.

The Czech Republic is currently characterised by transient conditions of oceanicity, but with generally prevailing continentality. Specifically, in the Køppen-Trewartha classification, it is DClo according to the 1960-90 temperature normals. Mild winters and cool summers occur when oceanic influences prevail, but cold winters and hot summers are associated with prevailing continental influences.

Local climatic conditions are greatly modified by altitude. The Czech Republic is characterised by considerable variability in altitude (up to 1602 m) and is surrounded by mountains at all cardinal points (with a consequence of preventing humid winds). Interannual variability of temperature is minor in the western parts of the republic. However, in the east it is greater, due to increasing continentality. At higher altitudes, mean annual summer temperatures do not exceed 15 °C and the length of the growing season (with a mean temperature of 5°C or more) is very short.

Absolute measured temperature extremes (CHMI, 2003) are -42.2°C (1929) and 40.2 °C (1983). The 30-year annual temperature normal is 7.5 °C for the Czech Republic and 7.1°C for the Vysocina region. The 30-year annual precipitation normal is 676 mm for the Czech Republic and 638 mm for the Vysocina region, see Figure C5.1. Seasonal variability of precipitation is usually as follows: summer 40%, spring 25%, autumn

20% and winter only 15%. Interannual variability (with respect to the normal) is great, due to variations in oceanity-continentality conditions.

Regional variability in total precipitation is related to altitude, see Figure C5.2.

The main palaeoclimatic features that can be used in the description of future states are summarised below (from Cerveny et al., 1984):

Stage	**Mean annual precipitation (mm)**	**Mean annual temperature (°C)**	**Mean July temperature (°C)**	**Mean January temperature (°C)**
70 - 65 ka BP	355	-3.0	12.5	-16.5
35 - 26 ka BP	355	-2.8	12.1	-14.6
before 35 ka BP and after 26 ka BP	299	-2.8	9.3	-13.0
Current conditions	765	8.0	16.5	0.5

The following table summarises estimates of the characteristics of the past climatic states made in this study.

Climate states	**Climate Class**	**Estimated mean annual temperature (°C)**	**Estimated mean annual precipitation (mm)**
temperate	DC	7.5	676
atlantic (climat. optimum)	DO	11	1 000
boreal	DC to DO	8.5	800
glacial	EClc to FT	-3	150
interstadial	EO to DC	2	200 - 400
(last) interglacials	DO	8-11	800 - 1000

Future climate states for the Czech Republic were not analysed in WP2 and WP3 at the same detailed level as for the Central England, North-east France and Spanish regions. Nevertheless, some qualitative and semi-quantitative interpretation can be made, generally based mainly on 3 sources of information:

- MoBidiC (step 500 year) and LLN-2D-NH (step 1000 year) simulation outputs (B3, B4 and A4 scenarios) that were downscaled by rule-based method to sequences of indexes (climate classes) for North-east France.
- GCM and MAR simulation outputs (baseline + 6 scenarios for time-slices at 67 ka AP and 178 ka AP) for the selected Czech Republic study region (monthly series of temperature and precipitation).
- Physical-statistically downscaled CLIMBER-GREMLINS outputs to 200 ka AP of January and July mean temperatures and January and June daily precipitation for the B3, B4 and A4 scenarios (for the selected Czech Republic study region).

The most comparable area studied in detail is North-east France (with a similar latitude at around 49°N), since Central England is heavily influenced by oceanity and developed ice-sheets during glacials, whereas Spain has currently conditions that were hardly reached in the area of the Czech Republic during very warm previous interglacials. Indeed, conditions that are presumed in B3/B4 scenarios for the region of the Czech Republic more resemble those that occurred in Tertiary warm conditions.

The narratives are based on the assumption of unchanged human population (communities) and the use of only current agricultural practices.

The following criteria were applied to identify analogue stations from the Climatic Research Unit, University of East Anglia database (these data were also checked with information from German database - www.klimadiagramme.de for the presumed range of climate changes for the Czech Republic:

- altitude preferably 350 - 750 m;
- climate normals close to 100% complete;
- tendency to continentality; appropriate distance from the ocean, if possible;
- reasonable intra-year variability (maximum and minimum mean monthly air temperature).

The above mentioned criteria could not be fully satisfied. In particular, the combination of altitude preference with continentality caused problems in station identification.

Characterisation of analogue stations selected for the Czech study region (monthly temperature and precipitation, and differences in comparison with observed values for the Vysocina region - temperature in °C and precipitation in relative difference: % change) is summarized in the following tables and in Figures C5.3 to C5.12. Some classes are not so much used in the narrative (EO, DO, Cr) as other classes - these classes represent "transitional states" or "oscillatory states" (i.e. states that can occur over some hundreds of years during transitions between the main, more stable states) or have low probability of occurrence (Cr).

1) Temperature (°C)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
FT	-27.8	-28.4	-26.5	-18.6	-8.9	-0.3	5.5	3.9	-2.5	-10.2	-18.7	-24.6	-13.1
EO	-8.7	-7.5	-4.1	0.3	6.2	10.9	12.4	11.4	7.2	3.0	-3.0	-6.3	1.8
EC	-23.3	-19.9	-11.8	-2.2	5.6	11.8	14.9	12.9	6.9	-1.8	-12.7	-20.2	-3.3
DO	1.6	3.1	6.1	9.8	14.0	17.7	20.2	19.8	16.8	11.6	6.5	3.4	10.9
DC	-2.7	-0.6	3.9	8.6	13.2	16.3	18.0	17.8	14.5	9.5	3.9	-0.7	8.5
Cs	4.5	5.7	8.9	13.3	17.8	22.3	25.1	24.6	21.0	15.8	10.8	6.5	14.7
Cr	5.7	6.5	8.6	11.5	15.3	19.3	22.2	22.1	19.3	14.6	10.0	6.9	13.5
FT-obs	-24.5	-26.9	-28.6	-25.5	-20.9	-15.5	-11.1	-12.2	-14.9	-17.8	-21.0	-23.1	-20.2
EO-obs	-5.4	-6.0	-6.2	-6.6	-5.8	-4.3	-4.2	-4.8	-5.3	-4.6	-5.3	-4.8	-5.3
EC-obs	-20.0	-18.4	-13.9	-9.1	-6.4	-3.4	-1.7	-3.2	-5.5	-9.4	-15.0	-18.7	-10.4
DO-obs	4.9	4.6	4.0	2.9	2.0	2.5	3.6	3.7	4.4	4.0	4.2	4.9	3.8
DC-obs	0.6	0.9	1.8	1.7	1.2	1.1	1.4	1.7	2.1	1.9	1.6	0.8	1.4
Cs-obs	7.8	7.2	6.8	6.4	5.8	7.1	8.5	8.5	8.6	8.2	8.5	8.0	7.6
Cr-obs	9.0	8.0	6.5	4.6	3.3	4.1	5.6	6.0	6.9	7.0	7.7	8.4	6.4

2) Precipitation (mm)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
FT	15	13	10	17	29	23	35	45	42	46	28	17	319
EO	56	40	41	33	37	54	77	63	73	62	56	65	657
EC	28	21	22	26	38	63	78	68	59	43	38	38	522
DO	60	54	59	64	77	77	61	65	65	70	81	68	801
DC	40	37	40	54	83	96	85	80	55	46	52	47	715
Cs	72	65	62	56	37	20	12	13	22	53	64	78	554
Cr	215	190	134	96	83	49	23	26	63	119	166	236	1399
%													
FT-obs	-64.0	-64.5	-73.9	-59.3	-61.0	-71.7	-52.7	-38.8	-14.7	23.1	-38.1	-62.3	-49.9
EO-obs	29.5	12.2	11.6	-23.4	-50.6	-32.8	3.1	-14.7	49.1	67.2	24.6	48.0	3.2
EC-obs	-35.5	-41.8	-39.8	-39.1	-48.6	-21.5	3.5	-8.6	21.2	16.7	-14.9	-13.1	-18.0
DO-obs	38.8	50.8	60.7	48.2	4.7	-3.6	-18.5	-12.3	32.4	88.2	80.0	55.0	25.8
DC-obs	-7.6	4.0	8.6	24.7	11.7	20.0	13.8	8.3	11.8	24.2	16.3	6.9	12.3
Cs-obs	68.4	81.7	67.5	29.8	-49.4	-75.3	-84.6	-83.1	-55.9	44.3	42.2	78.3	-13.0
Cr-obs	399.0	426.9	262.1	122.4	12.3	-39.0	-69.8	-64.6	28.0	222.3	269.9	437.0	119.7

3) Moisture Excess (mm)

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
FT	15	13	10	17	29	14	-92	-53	42	46	28	17	85
EO	56	40	41	27	-25	-42	-28	-28	18	36	56	65	216
EC	28	21	22	25	-17	-36	-41	-30	8	43	38	38	100
DO	56	46	35	16	-7	-36	-73	-55	-18	22	62	60	107
DC	40	37	22	7	-3	-13	-37	-31	-20	3	39	47	90
Cs	65	55	36	2	-62	-125	-166	-144	-82	-5	38	67	-320
Cr	168	144	88	36	-16	-83	-134	-116	-43	47	115	183	388

Note: A monthly adjustment factor appropriate to 49°N was used (Lorente, 1961).

Comparing the selected analogue stations with French and German stations, relatively good agreement exists for the characteristics of the EC, DO and DC classes, with some small shifts in temperature and larger shifts in precipitation that can be accounted for by the higher latitudes of the analogue stations. On the other hand, two larger discrepancies (Figure C5.13) have been identified. These can probably be attributed to a combination of the effects of both altitudinal position and geographical location:

* **FT** class stations varied markedly in winter temperatures (for example January temperature for France: -9.9°C, Germany: -20.2°C, Czech Republic: -27.8°C) and this led to the differences in the mean annual temperature (France: -2.6°C, Germany: -9.0°C, Czech Republic: -13.1°C).

* **Cs** class stations followed a similar trend to FT stations (January temperatures for France: 11.4°C, Germany: 9.6°C, Czech Republic: 5.7°C).

C5.2. - Evolution of the South of the Czech Republic in the B3 and B4 Scenarios

The B3 scenario simulates a low fossil fuel contribution. This anthropogenic contribution will add 850 ppmv at 325 a AP to the natural concentration. As a consequence, there is still non-natural contribution of 50 ppmv at 200 ka AP. It can be expected that climate would be warmer in comparison with forcing only with natural variations of CO_2 concentrations.

The B4 scenario assumes a high fossil fuel contribution. This anthropogenic contribution will add 1350 ppmv at 325 yr AP to the natural concentration. As a consequence, there is still non-natural contribution of 85 ppmv at 200 ka AP. It can be expected that climate would be warmer in comparison with both B3 and the A4 scenario that represents only natural variations of CO^2 concentrations.

However, as the B3 and B4 scenarios follow the same general trend, they can be described in a single narrative.

Over the next few hundred years, anthropogenic emissions of CO_2 will cause a substantial change of climate. Two main scenarios were evaluated in series of studies focused on regional impacts of CO_2 emissions in the Czech Republic (Kalvova, 2001) - SRESB1 (low or moderate emissions) and SRESB2 (high emissions). The ECHAM4 and HadCM2 climatic models were used. The results of simulation for 2050 AD (for 50°N, 15°E) showed that the mean annual temperature would increase by 0.9°C (low emissions) to 3°C (high emissions). The annual precipitation would decrease by only 0.2% (low emissions) to 0.6% (high emissions), but much larger changes in monthly precipitation compared with the current values were identified (up to 22%), with frequent contradictory results from the two alternative models, indicating much less reliability of precipitation results compared with those for temperature.

Rule-based downscaled results from MoBidiC for Central England and North-east France (in both scenarios) follow the same trend. Therefore, it can be expected that a similar trend will be valid also for the Czech study region. Thus, a relatively rapid transition from the current DC class to Cs conditions can be expected. According to the characteristics of the analogue Cs stations, the annual temperature would increase to 14.7°C (an increase by 7.6°C in comparison with the present) and the annual precipitation would decrease to 554 mm (a 13% decrease). The difference between the lowest (January) and highest (July) mean monthly temperatures were estimated to be around 20°C, as at present. Thus, the general pattern of temperature seasonality will be the same. The precipitation pattern (high precipitation in winter and low during summer) will be the reverse of the current situation (higher precipitation in summer and low in winter). The moisture deficit is estimated to be highest in June, July and August (above 100 mm).

Beneficial insight can bring the results of simulation of A scenario (GCM + MAR) based on the current orbital parameters (insolation) with high CO_2 concentration in atmosphere (1100 ppmv). Due to such huge increase, the increase in global mean temperature would be 2.2°C. Winter temperature will increase approx. by 3°C (comparing with 2°C in the west Europe) and summer at least by 4°C (GCM). Surprisingly, winter precipitation will be the same as today; summer will be decreased approx. by 0.6 mm/d (18 mm / summer month).
Single-year MAR temperature simulation (forced by LMDz results) showed bi-modal distribution with the smaller peak in January (5°C) and larger with July and August mean temperatures above 20°C.

In the overall picture, it is reasonable to assume that annual temperature will be increased from the current annual mean of 7 - 8°C to 10°C - 14°C, with the general pattern of seasonality remaining much as it is at the present day. Winter and early spring precipitation will be similar (as indicated from GCM model runs) or higher (according to analogue station data) in comparison with the situation today, but summer and early autumn precipitation will be profoundly decreased. According to the analogue station data, the difference between mean lowest and highest precipitation is 66 mm. Larger differences between winter and summer precipitation can even lead to the transition from Cs to Cr, but GCM results do not exhibit such a transition.

Landscape conditions will be generally unchanged, due to the predominance of hard rock formations in the study region. An overall decrease in precipitation will result in lower average (annual) flow rates in rivers, increased soil moisture deficit (and therefore a higher demand for irrigation) and general decrease in water availability. New water utilisation schemes would be established to reach sustainability for longer-periods (for overcoming drier and warmer summers). Construction of dams is a possibility, but hot summers will increase evaporation from the free-water surface of the associated lakes and reservoirs. Abstraction wells will be probably deepened. These can partially solve the problem of decreased water availability, due to very long residence time of groundwater in the hard rock formations of the study region. However, an increase of deeper water pollution will be inevitable negative impact. Pumped water will be somewhat saline. This could have some negative effects on soil quality over the longer term. Due to high winter precipitation (mostly in the form of water rather than snow), the flow rate in rivers will be increased during the winter. Such a higher flow rate will be associated with a higher rate of removal of soil and suspended material. Spring flooding will not be of great significance, as there will be no substantial Spring snowmelt in a Cs climate, so flooding will be generally connected with extreme precipitation events. Significant incision of river valleys is not expected, since only a limited volume of water will be transported by streams and rivers (on both an annual and a mean monthly basis).

A large moisture deficit from April to September in Cs conditions is partially compensated by higher winter precipitation. However, overall an annual moisture deficit of around 300 mm is estimated. The soil summer moisture balance (excess or deficit) strongly influences the natural vegetation that can grow and survive (though agricultural lands can be irrigated). Predicted Cs conditions can be compared with some previous warm interglacials when species like Buxus or Ilex were frequent. These now occur mainly in south-western Europe and the Mediterranean area. Migration of plant species that need mild winters, but can grow in a less humid environment (various Mediterranean trees and herbs) is likely to occur. To achieve a sustainable water utilisation scheme over a long period of large summer moisture deficit will be difficult task in central Europe, as the region forms a Europe-wide water divide with no important surface water inflows.

In spite of higher annual temperatures and lower relative humidity, soil-forming processes will continue, since vegetation will cover the land. The moisture deficit will not have impact on the main type of soil forming processes in study area, so the development of various forms of Cambisols will continue.

Rule-based downscaling (for French region; taken also as applicable to the Czech situation) indicates that such warm conditions will prevail to approximately 70 ka AP (B3 scenario) and to 160 ka AP in the B4 scenario with only two cooler episodes around 100 and 150 ka AP.

Such projections can be confronted with snapshot simulations for 67 ky AP (insolation maximum) with various CO_2 concentrations and northern hemisphere ice-sheet volumes:

- **E scenario:** baseline CO_2 concentration, Greenland ice-sheet as today;
- **D scenario:** baseline CO_2 concentration, Greenland ice-sheet absent;
- **C scenario:** higher CO_2 concentration (550 ppmv), Greenland ice-sheet absent.

In all three simulations, no changes in winter and summer precipitation are indicated relative to today. In the case of temperature, the E and D scenarios do not indicate any significant change in winter temperatures (a slight increase in scenario C), but summer temperatures would rise at least by 2.5°C (E), 2-3°C (D) and approx. 3°C (C), in comparison with the baseline simulation. The MAR simulations indicated a similar summer increase in temperature (excluding the D simulation in August, in which there was no change observed).

Contrary of expectation of reaching Cs conditions, the results from both IPSL_CM4_D (30-year averages) and

MAR (single-year output) indicate for the E, D and C scenarios D-type climates, as shown in the following table (for comparison results for other relevant regions are included). If the cold bias of the models is taken into account, the transition to Cs class climate is imaginable, but has not been demonstrated.

Model/Region	**Simulation**		
IPSL_CM4_D	**E**	**D**	**C**
Northeast France	DOak	DOak	DOak
Central Europe	DOak	DOak	DOak
MAR	**E**	**D**	**C**
Northeast France	DCbo	DCbo	DCbo
Germany	DCac	DCbc	DCbc
Czech Republic	DCac	DCbc	DCbc

Valuable information can be potentially obtained from physical-statistical downscaling of CLIMBER-GREMLINS results, since the physical-statistical downscaling technique developed in BIOCLIM accounts for continentality and mountain landscape effects (change of winds and effects on precipitation); both these aspects are particularly applicable to the Czech study region. Calculated temperature and precipitation indices follow the same trend in both the B3 and B4 scenarios, see Figure C5.14. A rapid increase of January temperature around 10 ka AP (by approx. 3°C to around 1°C) is followed by step-like decreases through to 110 ka AP with a subsequent increase over a period of approx. 40 ka. January temperature will approach 0°C some tens of thousands years AP. This is inconsistent with prevailing Cs conditions for a longer period as inferred from the rule-based analysis. July temperature irregularly oscillates around 20°C for approximately the first 100 ky AP followed by more regular oscillations (around 19°C but with higher amplitude than in the earlier period - between 15 and 24°C) from 100 to 200 ka AP. January precipitation sharply increases around 10 ka AP to 60 mm (in agreement with expected Cs conditions), with a subsequent very slow decrease to the end of study period (200 ka AP), but only over the range 60 to 55 mm. July precipitation will be increased above 140 mm also around 10 ky AP with subsequent oscillations around that value. This July precipitation figure is at least a factor of ten higher than the expectation for Cs conditions.

The next 170 ka generally has the character of warm superinterglacial (B3/B4) without any analogy in the Quaternary period concerning length of period and climatic (and environmental) conditions.

Probable diminution of the Greenland ice-sheet (or ice-sheets globally) will cause a change in sea-level of approximately 7 m for the B, C and D scenarios. Such an increase would have devastating impacts on near shore and riverside lands close to seas, but no direct impacts on central Europe. However, some indirect impacts will occur. The lowest geographical point in the Czech Republic is the Labe (Elbe) river valley at the border with Germany (115 a.s.l.), therefore potential increase in sea level and connected ingress of sea water inland will not have any marked influences.

After the period of extended warming, a return to current conditions can be expected (i.e. DC for the Czech study region).

C5.3. - Evolution of South part of the Czech Republic in the A4 Scenario

The scenario based on natural variations of CO_2 concentrations shows, as expected, a totally different picture in comparison with the B3 and B4 scenarios. Rule-based downscaling of the MoBidiC simulation (for the North-east France study area) indicates that conditions similar to those at the present day would last for the next 50 ka. Subsequently, cooling to presumably EC conditions (in the Czech region) is expected. These conditions will then last until approximately 100 ka AP. After that, pronounced cooling is expected to FT conditions, but lasting only some few thousands of years (these EC and FT periods can be characterised as the next glacial). After this, current conditions (DC for the Czech region) will be re-established over approximately 20 ky, with a subsequent cooling (excluding a brief amelioration to temperate conditions at 160 ky AP) to subpolar (EC) and even polar conditions (FT) again.

A different picture emerges from dynamical-statistical downscaling of CLIMBER-GREMLINS simulation results. The current conditions would be preserved for the next 30 ka, followed by a sharp increase in January temperature (to -1.5^{0}C) and precipitation (to 56 mm). An increase in July temperature (to more than 20^{0}C) and precipitation (to approx. 16 mm) also occurs at 30 ka AP. The following general trend in January temperature is decreasing; with minima at 110, 155 and 170 ka AP (the last two minima reach a temperature slightly below -5^{0}C). January precipitation also follows a decreasing trend, but without any pronounced minima. On the other hand, July temperature and precipitation in the period after 30 ka AP exhibit an oscillatory character with the same timing of maxima at approximately 65, 117, 135, 160 and 182 ka AP. At these maxima, the mean temperature is above 20^{0}C and mean precipitation is generally above 200 mm. Comparison of January and July temperature trends in the A4, B3 and B4 scenarios is shown in Figure C5.14.

When evaluating possible colder periods, snapshot F can give some valuable insights, since it is based on orbital parameters at 178 ka AP (insolation minimum), with around 1.7 10^7 km^3 of northern hemisphere ice-sheet volume (Greenland) and a low atmospheric CO_2 concentration simulating the inception of a glacial period (the current Northern Hemisphere ice-sheet volume is 3.2 10^6 km^3 and the volume estimated during the Last Glacial Maximum is around 4.0 10^7 km^3). The GCM simulation indicates no change of winter temperature and precipitation, only a small decrease of summer temperature (by some 1.5^{0}C) and a small decrease of summer precipitation. Simulations of monthly temperatures using MAR revealed cool conditions from December to April (below -5^{0}C), with June/July temperatures above 15^{0}C.

In summary, it is reasonable assume that the current conditions will be preserved for the next few tens of thousands years (for example for the next 50 ky as presumed from rule-based downscaling for France), with little change to landscape, water bodies or biota. Agricultural practices will the same as today (this statement is more robustly valid for the selected study region (prevailing silviculture) than for more agriculturally utilised lowland parts of the Czech Republic).

Change to colder conditions (to boreal forest and then even forest-steppe stage - represented by the EC climatic class) will have large impacts on soil processes, biota and agricultural practices. Such conditions can be characterised by comparing with the selected EC analogue stations and taking account past conditions. Analogue stations indicate that mean annual temperature may slightly exceed 0^{0}C, but with increased seasonality - January and December temperature can reach -20^{0}C, but with five summer months above 5^{0}C (May to September) and with July temperatures similar to those currently observed. Precipitation will be decreased annually (by 18%) with large winter and spring decreases (by 10 to 40%), but with July, September and October increases. These changes are consistent with the expected evolution from current conditions through an interim boreal (vegetational) stage to cold steppe-like conditions close to tundra vegetation with discontinuous permafrost. A decrease in winter precipitation (snow) will be manifested in the diminishing of water reserves and occurrence of only slight summer moisture excess. New schemes of water utilisation will need to be established. The lower volume of winter snow will diminish the risk of spring flooding. Soil-forming processes will also be changed. In the lowlands, chernozem will start to be formed, whereas at the higher altitudes of the Czech study region probably podzolization will prevail. Resulting podzols are infertile and need fertilization to be used for agricultural purposes. Vegetation will comprise less demanding species; at higher altitudes dwarf-like discontinuous forests, shrubs and herbs will prevail (steppe-forest and steppe to tundra vegetation will occur with sporadic permafrost). Agricultural lands will be diminished (in uplands will almost vanish) with simultaneous increase of pastures that can be used for herding of more resistant animals (cattle and sheep).

Landscape forms will be generally unmodified, due to the prevailing hard rocks in the selected study area. Chemical weathering will be diminished as a consequence of replacement of the relatively productive vegetation of temperate conditions - less humic and fulvic substances will be produced and the microbiological content of soil will be reduced and less active. Due to harsh highland conditions in the study area, there is only low probability of occurrence of broad-leaved trees (though birch might occur, possibly with diminished stature); such forms can survive in refugia in lowlands in appropriate local microclimatic conditions.

Further cooling to a short period of FT conditions will profoundly change environmental characteristics. On the basis of the selected FT analogue station data, the mean annual temperature can reach -13^{0}C, with a long and dry winter. Only July and August temperatures will be above 0^{0}C. These conditions represent an extreme that is applicable only to some periods of glacials and to higher altitudes. The selected analogue stations represent probably the worst conditions that can occur - more probable conditions will be somewhere between FT and EC characteristics. Mean annual precipitation can be diminished to 320 mm (based on FT analogue stations). This value is comparable with estimates of precipitation during past glacial episodes - below 300 mm and as low as 150 mm in some periods. Very dry conditions can be prone to forming loess that is a characteristic feature of past glacial periods. Loess formation can occur only at lower altitudes (up to 300 m a.s.l.). In medium to higher altitudes, permafrost could be formed (probably in discontinuous form even in prolonged FT periods). In the closest lowland area (the west part of the study region), discontinuous or mainly sporadic permafrost is presumed, due to long distances from the continental ice-sheet and Alpine glaciers, and also due to an expected short summer with temperatures substantially above 0^{0}C; palaeodata indicate up to around 10^{0}C). At higher altitudes, almost completely unvegetated outcrop and regolith will prevail. Strong winds will prevent the occurrence of trees. Mechanical weathering will be prevailing and transport of rock (blocks, boulders, sediments) on slopes will be frequent. Soil will not be formed and at many places will be rather removed to weathered bedrock (revival will occur connected with occupation of more stable vegetation cover after amelioration of FT conditions).

Agricultural practices are not envisaged in FT conditions in the study area - even hunting will hardly be possible, only fishing in local rivers draining this area is imaginable. In areas where permafrost is created, the specific hydrogeochemical and hydrogeological processes will occur that were recently summarized in Bergab (2003), Ahonen (2001) and Gascoyne (2000).

Warming of climate from FT conditions through EC to DC (with the occurrence DO for a brief period) can be generally similar to the sequence of climatic and environmental stages in the past (rates of change can be different and transition oscillations can also be specific). Disappearance of the permafrost connected with hydraulic activity of the near-surface zone and release of accumulated salty solutes are features that could dramatically affect the migration of radionuclides.

C5.4. - Identification of Characteristic Climate States and Transitions

In summary, the following aspects are crucial for the evaluation of climatic and environmental change in the selected study area:

- Its general position in the Central Europe - Compared with North-east France and Germany, the tendency to increased continentality is clearly identifiable. There are no logical arguments for a longer-term change to oceanic type (excluding frequent transitions shaping the annual meteorological situation) during potential future changes. Therefore, DC and EC conditions will prevail in comparison with DO and EO conditions in North-east France and also in Germany. Increased continentality will generally result in greater differences between summer and winter periods (lower temperatures, dry conditions) than for the other study regions.
- Bedrock composed of (acidic) hard rock determines the formation of only thin soil profiles (Cambisol, Cambic Podzol) and only near-surface aquifers (deeper aquifers are linked with fracture permeability of rocks with long residence times of groundwater). The landscape is therefore also very stable irrespective of warming or cooling of climatic conditions. Incision of valleys is very slow.
- The higher altitudes of the study region (400 - 800 m) implies generally lower mean temperatures and higher mean precipitation values in comparison with related lowlands. The harsher conditions will have profound effects on the characteristic vegetation:

- In cold periods mainly bare land will occur with some herbs (but no refugia of more thermophylic species);
- In boreal conditions coniferous and mixed woodlands prevail;
- In temperate periods broad-leafed trees are the climax vegetation type;
- In extended warmer periods some less water-demanding species can appear.

From the characteristics of the study region in the Czech Republic under Scenario B3/B4, the following states and transitions are identified as forming the basis for a suitable generalised scenario of environmental change.

a) A biosphere state with a landscape and climate the same as that at the present day persisting for some tens of years;
b) A biosphere transition over a few hundred years to a landscape the same as that at the present day, where mean annual temperature will rise from 7 - 8°C to 10 - 14°C with decreasing precipitation in winter;
c) A biosphere state with a landscape similar to that at the present day, but with a climate that has warmer and wetter winters, and dryer and warmer summers (Cs), persisting for a long time (70 or 170 ka);
d) A biosphere transition over tens of thousands of years to a landscape and climate roughly similar to that at the present day;
e) A biosphere state with a landscape and climate similar to that at the present day (DC) persisting to about 170 ka AP;
f) A potential biosphere transition to a colder (boreal) climate state;
g) A (potential) short biosphere state of boreal type (EC - EO);
h) A biosphere transition to a biosphere state with a landscape and climate similar to that at the present day occurring over a few thousand years from about 180 ka AP;
i) A biosphere state with a landscape and climate similar to that at the present day persisting to the end of the study period at 200 ka AP.

In the case of Scenario A4, the following states and transitions are identified:

a) A biosphere state with a landscape and climate similar to that at the present day;
b) A biosphere transition over a timescale of several thousand years to a landscape similar in form to that at the present day, but with cooler summers and longer winters that are not extremely cold;
c) A biosphere state with a landscape similar in form to that at the present day, but with cooler summers and longer, but not extremely cold, winters (EC; retreat of boreal to steppe-forest and steppe conditions and

even to tundra vegetation with sporadic permafrost), persisting to 100 ka AP;

d) A biosphere transition to much cooler conditions, in which boreal characteristics will be transformed to tundra-like vegetation and in which permafrost probably will not occur, persisting over a period of approx. 5 ka;

e) A short cool biosphere state with a low mean annual temperature and harsh conditions (FT);

f) A biosphere transition from harsh conditions through boreal type to finally a biosphere state with a landscape and climate similar to that at the present day;

g) A biosphere state with a landscape and climate similar to that at the present day (DC) lasting approx. 40 ky (next interglacial);

h) A biosphere transition to colder climate (EC);

i) A biosphere state of colder climate (EC) lasting some 18 ka;

j) A biosphere transition of oscillatory character to very cold climatic conditions and back to EC class;

k) A biosphere state of colder type of the last 25 ka of the study period.

The above mentioned sequences of states and transitions are complex for performance assessment purposes. Therefore, as in narratives for the other regions, some further simplifications are made. Biosphere state (c) is reached relatively rapidly and may even have been attained by the end of the institutional control period that would be expected to follow repository operations and closure. Therefore, from this scenario biosphere state (c), transition (d) and state (e) are of particular interest. The degree of cooling toward the end of the study period is very much less than in Scenario A4, so transitions to colder states and the colder states themselves are more usefully studied in the latter context.

From Scenario A4, it is useful to address biosphere state (a), transition (b) and state (c). The glacial period (state (e)) would be also interesting with the proceeding and the following transitions.Other states and transitions occur within this envelope of states and transitions.

Thus, the states requiring consideration are:

1) A biosphere state with a landscape and climate similar to that at the present day (DC);

2) A biosphere state with a landscape similar to that at the present day, but with a climate that has warmer and wetter winters, and dryer and warmer summers (Cs), persisting for a long time (70 or 170 ky);

3) A biosphere state with a landscape similar in form to that at the present day, but with EC climatic conditions (an agricultural system based on mainly on animal husbandry, with much less arable farming than at the present day);

4) A glacial biosphere state (EC to FT) with a low mean annual temperature of much below 0^0C (the existence of discontinuous permafrost and tundra vegetation persisting for a few thousand years).

The transitions between these states that are of particular interest are:

[1–>2] over a timescale of some hundreds of years;

[2–>1] over a timescale of some thousands of years;

[1–>3] over a timescale of some thousands of years (some brief back oscillations are probable);

[3–>4] over a timescale of 10 - 15 ka;

[4–>3–>1] over a timescale of some thousands of years.

The individual states are characterised in subsection C.1.5, using the BIOMASS methodology. Transitions are characterised in subsection C.5.6, using the methodology developed in BIOCLIM (interaction matrices describing transitions).

C5.5. - Characterisation of States

Based on the material in the Annex to Appendix A, it is appropriate to describe the various states identified as being of interest as shown in the following tables.

Climate Type Classification for the Czech Republic		
State	**Køppen/Trewartha Class**	**Description**
1	**DC**	Landscape and climate similar to that at the present day.
2	**Cs**	Landscape similar to that at the present day, but with a warmer climate (annual mean temperature between 10 and 14^{o}C).
3	**EC**	Landscape similar in form to that at the present day, but with EC climatic conditions, sporadic permafrost, dwarfish trees, sporadic vegetation with the transition to tundra-type vegetation.
4	**FT**	Landscape similar in form to that at the present day, but with a mean annual temperature below 0^{o}C, harsh conditions (long and severe winters, brief and relatively warm summers), bare land in uplands, the existence of discontinuous permafrost and tundra vegetation persisting for a few thousand years.

Characteristics of Water Bodies in the Czech Republic compared with Present	
State	**Characteristics**
1	Present day conditions. Mainly flowing rivers and streams. Some ponds in the western part.
2	Stream and river flow reduced in summer, with some smaller streams becoming ephemeral. Reduction of groundwater resources (decrease of groundwater level, minor yields) - relatively quick in Quaternary and sedimentary formations, longer response in crystalline bedrock. Increases in surface-water storage to ensure better capture of winter precipitation for subsequent use in summer.
3	Similar precipitation seasonality picture as today, but with lower monthly values resulting in decrease of water availability (both surface water and groundwater). Marshes can occur in depressions and along watercourses. The main land use is likely to be for animal husbandry and resource utilization is likely to be reduced relative to the present day. Surface waters and groundwaters will be affected by occurring of sporadic permafrost and the seasonal freezing of soil water.
4	Tundra type environment resulting in occurrence of bare land and discontinuous permafrost. Overall dryness of climate, very cold and long winters. Deeper freezing in winter and relatively warm conditions during short summers (flowing water, wetlands).

Classification of Human Community Types for the Czech Republic based on Socio-economic and Environmental Considerations			
State	**Trading**	**Biosphere Control**	**Community Types and Activities**
1	Large-scale	High	Present day conditions. Smaller towns and villages are prevailing. Forest management (silviculture) and utilization of pastures (animal husbandry). Home-organised mushrooming and picking of forest berries is frequent. Limited commercial agriculture (potatoes, rye) and relatively extensive horticulture. Relatively intensive of fish farming in western part (ponds).
2	Large-scale	High	Agriculture similar to the present day, but with a greater degree of irrigation. Intensive silviculture with slightly different tree species (larger representation of leaved species and decline of needle trees). Much better water management schemes applied (expansion of ponding, dams and maybe subsurface storage facilities constructed). No substantial difference in human community characteristics and infrastructure relative to the present day.
3	Small scale	Medium	Decline from continuous forests to dwarfish trees, low shrub and herb vegetation will limit silviculture. More extensive animal husbandry and much less farming. The more extreme conditions can tend to favour small-scale trading with few market or urban centres.
4	None	None	Bare land in uplands and tundra type of vegetation is prevailing. Land use primarily herding and hunting, probably at lower altitudes; in uplands harsh conditions occur. Communities mainly localised to western parts (transition to lowlands).

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Ecosystem Classification for the Czech Republic

NATURAL SYSTEMS

	Terrestrial Ecosystems	Aquatic Ecosystems
State	**Description**	**Description**
1	Limited extent of natural ecosystems.	Mainly rivers and streams (fishing for sport and home-use).
2	Limited extent of natural ecosystems. Similar extention of managed and semi-natural and natural systems as today.	Mainly rivers and streams.
3	Larger extent of natural ecosystems (dwarfish trees, low shrubs).	Mainly rivers and streams. Extensive wetlands at lower altitudes during summer.
4	Natural systems prevailing (bare land, tundra).	Mainly rivers and streams. Wetlands at lower altitudes during summer.

SEMI-NATURAL SYSTEMS

	Terrestrial Ecosystems	Aquatic Ecosystems
State	**Description**	**Description**
1	Semi-natural forests (leaved and mixed forests) and pastures - they can be treated as managed ecosystems.	Not applicable. Discussed under natural systems.
2	Semi-natural forests (leaved forests) and pastures - they can be treated as managed ecosystems.	
3	Decline to natural (tundra) vegetation.	
4	Minimum extent. Primarily natural vegetation, as agriculture is not practiced, so agricultural land in succession to natural vegetation is not present.	

MANAGED SYSTEMS

State	Description
1	**Terrestrial Ecosystems :** Relatively low urbanization and transport routes. Mainly field crops (potatoes, rye) and relatively frequent home-connected lands used for fruit and vegetable gardening along with poultry keeping. Animal husbandry (beef-cattle, pigs).
	Aquatic Ecosystems : Ponds in western part (commercial larger-scale fishing) - they can be treated as partially semi-natural ecosystems.
2	**Terrestrial Ecosystems** : Relatively low urbanization and transport routes. Mainly field crops (potatoes, rye) and relatively frequent home-connected lands used for fruit and vegetable gardening along with poultry keeping. Animal husbandry (beef-cattle, pigs).
	Aquatic Ecosystems : Ponds in western part (commercial larger-scale fishing) - they can be treated as partially semi-natural ecosystems.
3	**Terrestrial Ecosystems :** Relatively low urbanization and transport routes. Larger utilization of animal husbandry (more resistant beef-cattle, pigs, sheep) and decrease of agricultural land use for cultivation of crops. Increased extent of greenhouses.
	Aquatic Ecosystems : Ponds in western part.
4	**Terrestrial Ecosystems :** No practice of agriculture.
	Aquatic Ecosystems : Probably not present.

Zonal Soil Types for the Czech Republic

State	Soil type	Description (horizons)	Comments
1	Forest brown (Cambisol) and agriculturally changed.	Cambisols prevail with a limited extent of Podzolic Cambisols. Some areas are substantially changed by longer-term agricultural practices. Erosion on hillsides occurs.	Detailed description of the current soil types in Tomasek (2000).
2	Forest brown (Cambisol) and agriculturally changed.	Cambisols will prevail with limited extent of Podzolic Cambisols. Some areas will be substantially changed by longer-term agricultural practices as today. Erosion on hillsides occurs, mainly during winter and spring.	
3	Podzols, tundra soils (mainly in lowlands) with limited areas of agricultural soil.	Podzolization will be frequent.	Description of possible soil formation changes in Nemecek et al. (1990).
4	Bare land (uplands) and tundra soils (lowlands). No agricultural soil.	Denudation, rock and soil transport in uplands, occurrence of cryoturbation structures due to seasonal freezing and the development of permafrost.	Description of possible soil formation changes in Nemecek et al. (1990).

Topographical Categories for the Czech Republic

Stage 1	Geographical Context Altitude Landform Localised Erosion	Inland Prevailing uplands Rounded hills (not steep hillsides) Fluvially incised; local erosion on hillslopes
Stage 2	Geographical Context Altitude Landform Localised Erosion	Inland Prevailing uplands Rounded hills (not steep hillsides) Fluvially incised; local erosion on hillslopes
Stage 3	Geographical Context Altitude Landform Localised Erosion	Inland Prevailing uplands Rounded hills (not steep hillsides) Fluvially incised; local erosion on hillslopes
Stage 4	Geographical Context Altitude Landform Localised Erosion	Inland Prevailing uplands Rounded hills (not steep hillsides) Larger transport of rock and soil, solifluction; fluvially incised

C5.6. - Characterisation of Transitions

State 1 to State 2 (DC class to Cs class) over a timescale of some hundreds of years				
TOPOGRAPHY	No substantial influences identified.	Generally drier climatic conditions can cause desiccation of some smaller natural surface water bodies in appropriate topographical contexts.	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	**SOILS AND LITHOLOGY**	Drying of soils - increase of matric potential.	Drying of soils with water stress to vegetation - pressure for natural vegetation changes.	Drying of soil - pressure for better soil (irrigation) schemes.
No substantial influences identified.	Thickening of unsaturated zone - groundwater levels decrease.	**WATER BODIES**	Decreasing water availability - pressure for natural vegetation changes (increase proportion of leaved trees, migration of Mediterranean species, etc.).	Pressure for application of water resources and storage water systems.
No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	**BIOTA**	Some changes in types of agricultural crops - impacts on nutritional composition.
Decreased development of dams	Natural soil system can be exploited. Non-irrigated crops more important.	Decrease of deep well and reservoir exploitation.	Adaptation of crops to existing conditions.	**HUMAN COMMUNITIES**

State 2 to State 1 (Cs class to DC class) over a timescale of some thousands of years				
TOPOGRAPHY	Higher erosion on hillsides and enhancement of fluvial erosion (due to higher precipitation). Removal of deposited material. Slight deepening of valleys.	Due to wetter climatic conditions, new smaller extent water bodies can be formed in predisposed topographical landforms.	No substantial influences identified.	No substantial influences identified.
No substantial changes in topography.	**SOILS AND LITHOLOGY**		Increasing water availability in soils for plants.	Increasing water availability in soils - trend for less frequent irrigation.
No substantial influences identified.	Unsaturated zone will be thinner and phreatic zone shallower.	**WATER BODIES**	Better water availability - change in natural and semi-natural ecosystem vegetation species.	Relative water availability will stimulate development of human communities (agriculture, industry, leisure activities, etc.)
No substantial influences identified.	Large activity of vegetation (decrease of temperature, but substantial increase of precipitation).	No substantial influences identified.	**BIOTA**	Slightly different agricultural practices are allowed with lower irrigation requirements (some different plants, other will be the same with lower irrigation requirements).
No substantial influences identified.	Lower irrigation of fields (managed ecosystems).	Reduced requirements for storing of water - drying of some ponds?	Some change in crops (managed ecosystems) allowing lower irrigation.	**HUMAN COMMUNITIES**

State 1 to State 3 (DC class to EC class) over a timescale of some thousands of years				
TOPOGRAPHY	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	**SOILS AND LITHOLOGY**	Seasonal freezing of surface waters - limitation of winter infiltration. Large denudation events during spring thawing.	Increasing extent of natural and semi-natural ecosystems. Decline of agriculture-usable lands.	Lesser utilisability for agriculture.
Erosion on hillslopes during spring periods.	Freezing of soil. Large denudation events during spring thawing. Marshy areas developing in lowlands and valleys.	**WATER BODIES**	Seasonal freezing of surface waters.	Seasonal freezing of rivers and lakes will constrain of utilisation by human community.
No substantial influences identified.	Minor vegetation activity – more raw humus, decreasing humification.	No substantial influences identified.	**BIOTA**	Changes in the extent and distribution of land suitable for agriculture will alter the density of human communities. The increasing extent of natural and semi-natural habitats will place greater emphasis on hunting and fishing.
No substantial influences identified.	Fertilisation of soils is needed due to large extent of podzolization.	Artificial drainage of the lowland fields that are still used for agriculture.	Decrease of land used for agriculture (substantial increase of greenhousing). Increase of extent of pastures. Abandonment of some land to semi-natural vegetation.	**HUMAN COMMUNITIES**

State 3 to State 4 (EC class to FT class) over a timescale of 10 - 15 ka				
TOPOGRAPHY	Removal of soil, extensive rock and sediment transport from hills and occurrence of bare land.	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
Deposition of material from hills in river valleys and further removal during very late springs. Loess formation development only in lowlands.	**SOILS AND LITHOLOGY**	Seasonal freezing of surface water bodies. Limitation of winter infiltration. Large amount of soils and particulate matter in steam and river water during very late spring melting.	Unfavourable conditions for vegetation (only dwarfish trees, shrubs and herbs that can benefit from brief mild summers will survive).	No possible utilisation of soil for agriculture.
Deposition in valleys with the subsequent removal of material if water flow in rivers is sufficient.	Freeze-thaw effects on soils. In lowlands near water courses some marshy areas can develop with subsequent draining (gleyfication).	**WATER BODIES**	Availability of water for only tundra-type vegetation. No agriculture is possible to due to frozen water for most of the year.	The seasonal freezing of rivers, streams and ponds will constrain use by human communities.
No substantial influences identified.	No substantial influences identified (low biota activity for most of the year).	No substantial influences identified (low biota activity for most of the year).	**BIOTA**	No agriculture is possible. Spreading of hunting and fishing practices. Consequences for human communities - concentration to only some centres in lowlands.
No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	Lower utilization of vegetation - there are no agricultural plants; utilisation of some pastures in lowlands. Abandonment of some land to semi-natural/natural vegetation.	**HUMAN COMMUNITIES**

State 4 through State 3 to State 1 (FT class through EC class to DC class) over a timescale of some thousands of years				
TOPOGRAPHY	Recovery of soil forming processes in uplands (Cambisols, Podzolic Cambisols).	No substantial influences identified.	No substantial influences identified.	No substantial influences identified.
No substantial influences identified.	**SOILS AND LITHOLOGY**		Soil conditions allow spread of more demanding species.	Development of soils for agricultural purposes.
No substantial influences identified.	Decline of freeze-thaw effects on soils (includes creation of relict formations).	**WATER BODIES**	Water availability through the year for biota. Spread of more demanding species.	Availability of surface waters for use by human communities.
No substantial influences identified.	No substantial influences identified.	No substantial influences identified.	**BIOTA**	Development of sequence of boreal forests to leaved forests (as climax vegetation) - potential utilisation by human communities. Decline of hunting and fishing practices.
No substantial influences identified.	Development of agricultural soils. Degradation of soils due to inappropriate soil exploitation.	Increasing utilisation of water bodies.	Development of agriculture - utilisation of former natural ecosystems (deforestation).	**HUMAN COMMUNITIES**

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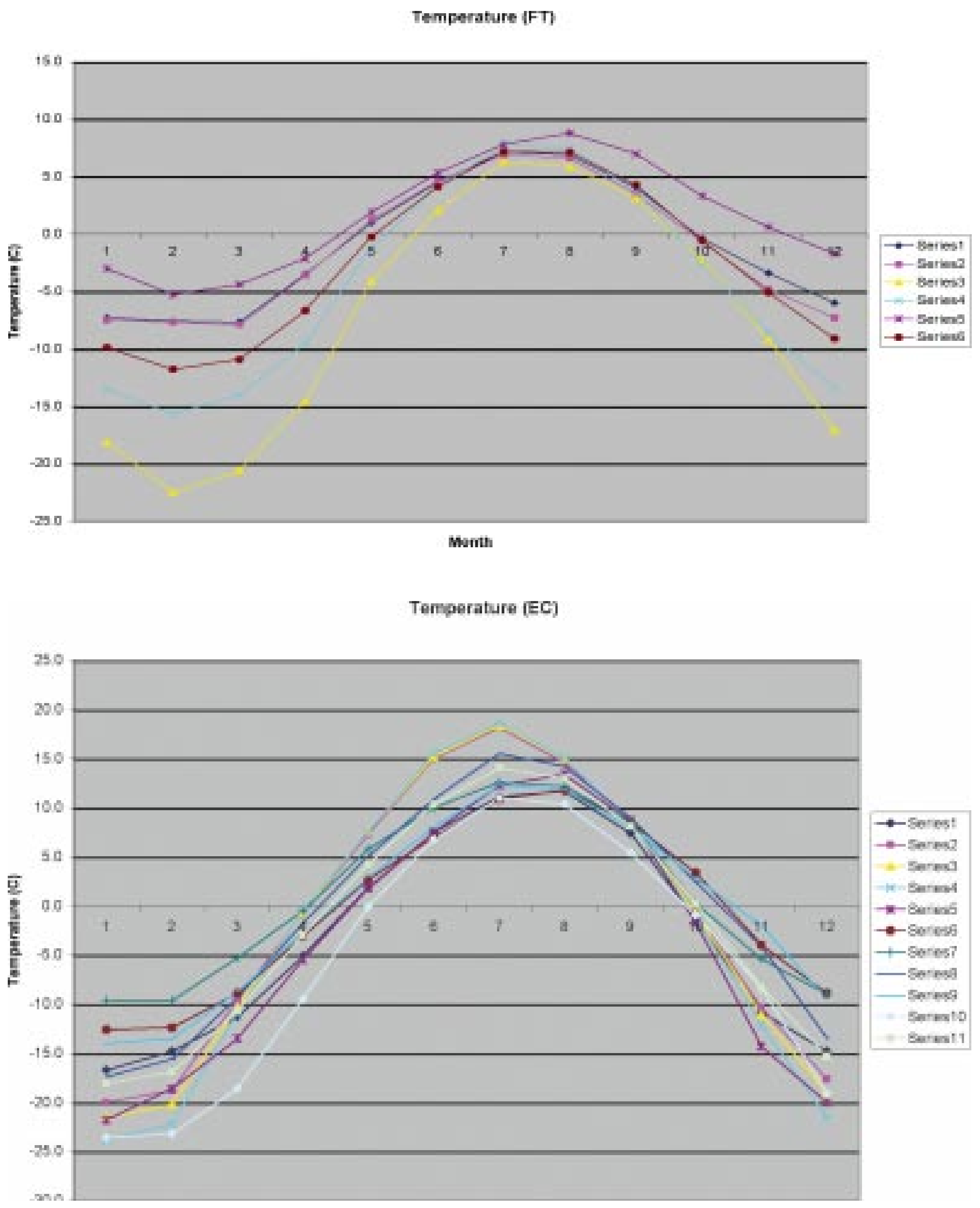
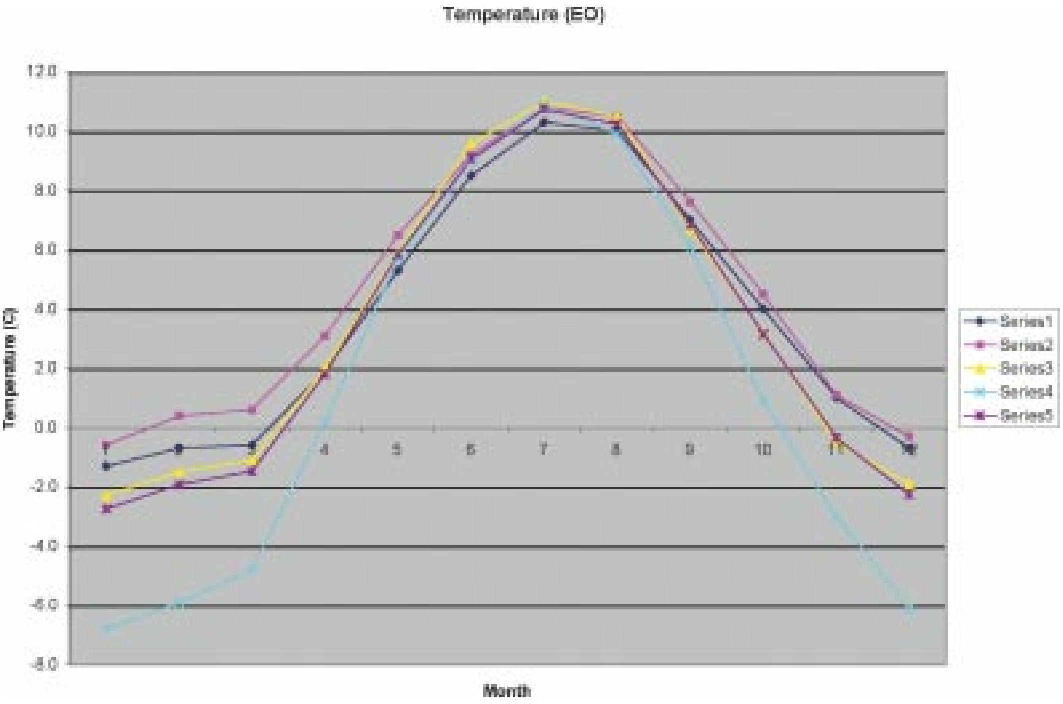
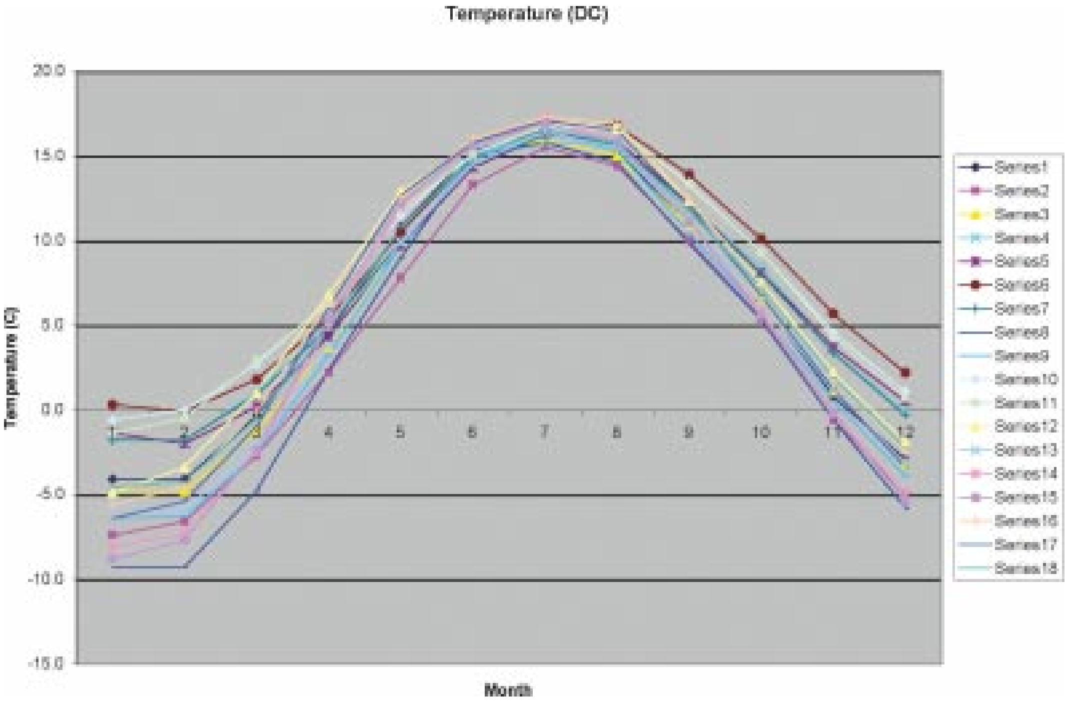
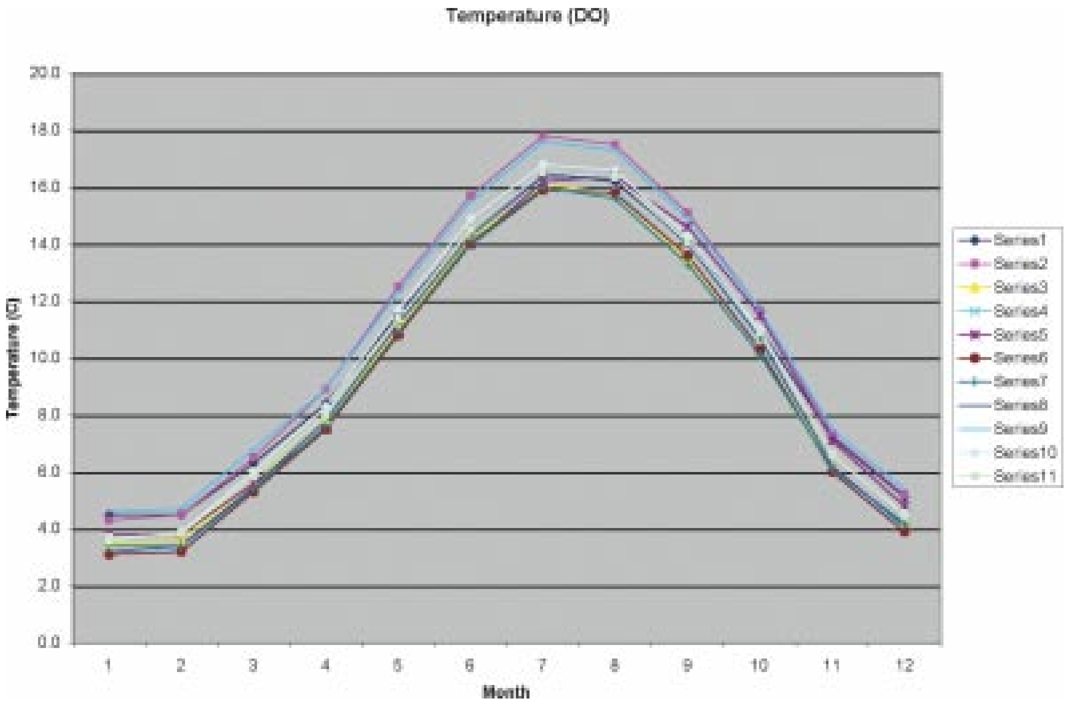
Figure C1.1: *Temperature Data for Analogue Stations for Central England*




Temperature (EO)
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
Temperature (C)
1
2
3
4
5
6
7
8
9
10
11
12
Month
Series1
Series2
Series3
Series4
Series5


Temperature (DC)
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
Temperature (C)
1
2
3
4
5
6
7
8
9
10
11
12
Month
Series1
Series2
Series3
Series4
Series5
Series6
Series7
Series8
Series9
Series10
Series11
Series12
Series13
Series14
Series15
Series16
Series17
Series18


Temperature (DO)
Temperature (C)
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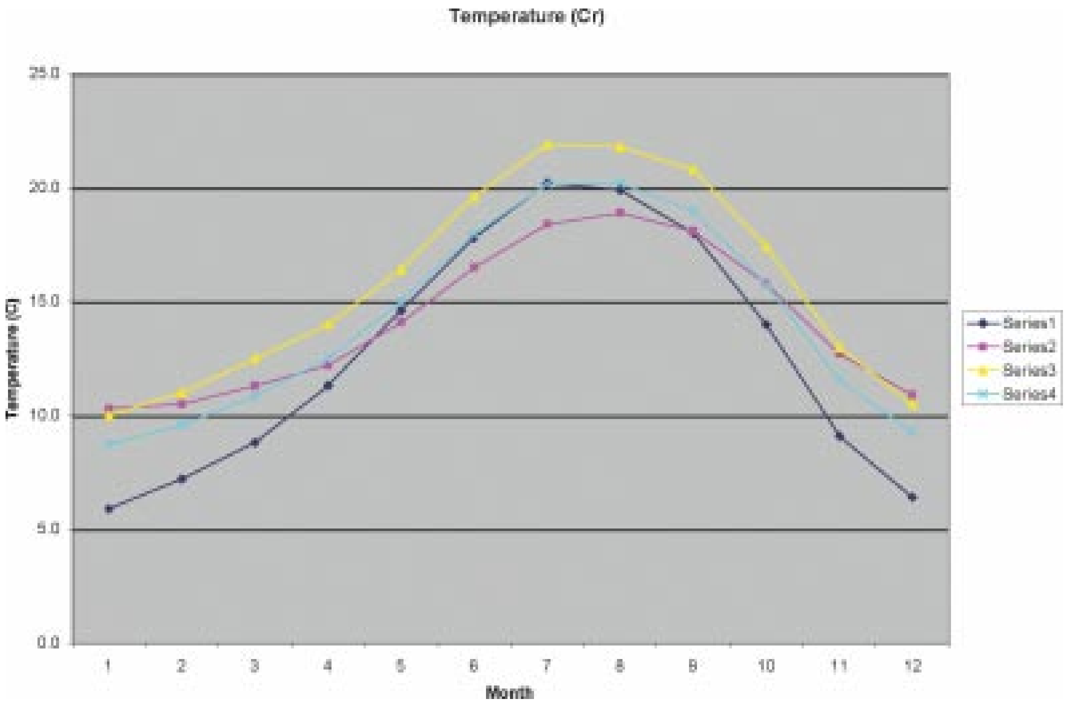
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1
2
3
4
5
6
7
8
9
10
11
12
Month
Series1
Series2
Series3
Series4
Series5
Series6
Series7
Series8
Series9
Series10
Series11


Temperature (Cr)
Temperature (C)
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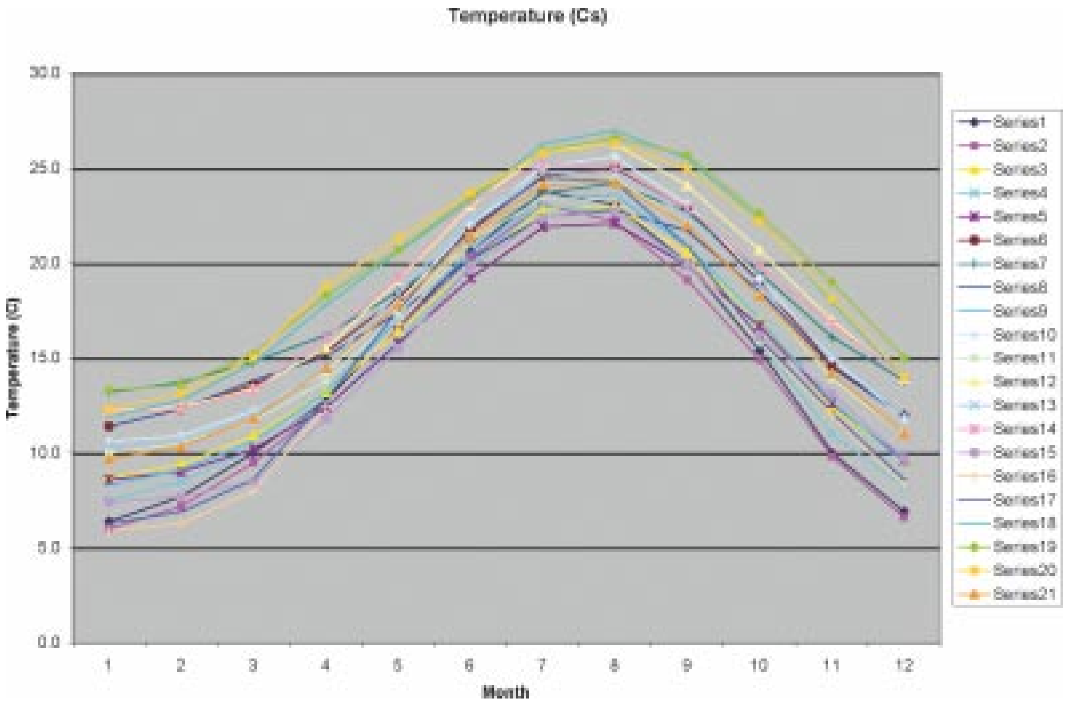
20.0
15.0
10.0
5.0
0.0
1
2
3
4
5
6
7
8
9
10
11
12
Month
Series1
Series2
Series3
Series4


Temperature (Cs)
Temperature (C)
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25.0
20.0
15.0
10.0
5.0
0.0
1
2
3
4
5
6
7
8
9
10
11
12
Month
Series1
Series2
Series3
Series4
Series5
Series6
Series7
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Series17
Series18
Series19
Series20
Series21

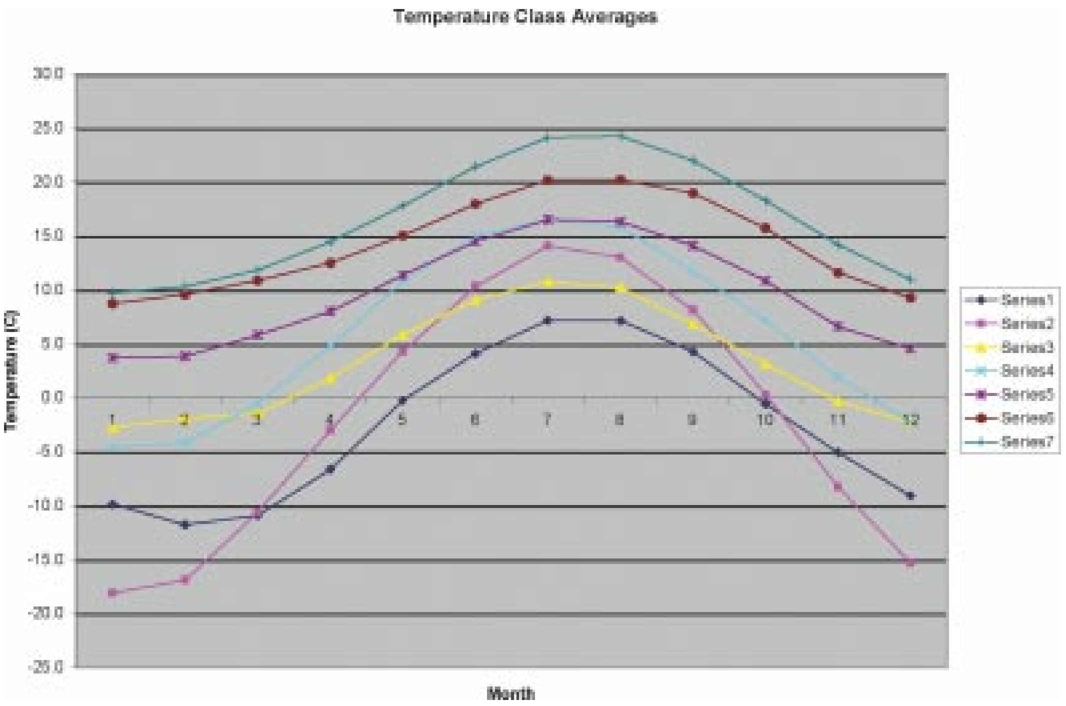


Figure C1.2: *Temperature Class Averages for Analogue Stations for Central England*

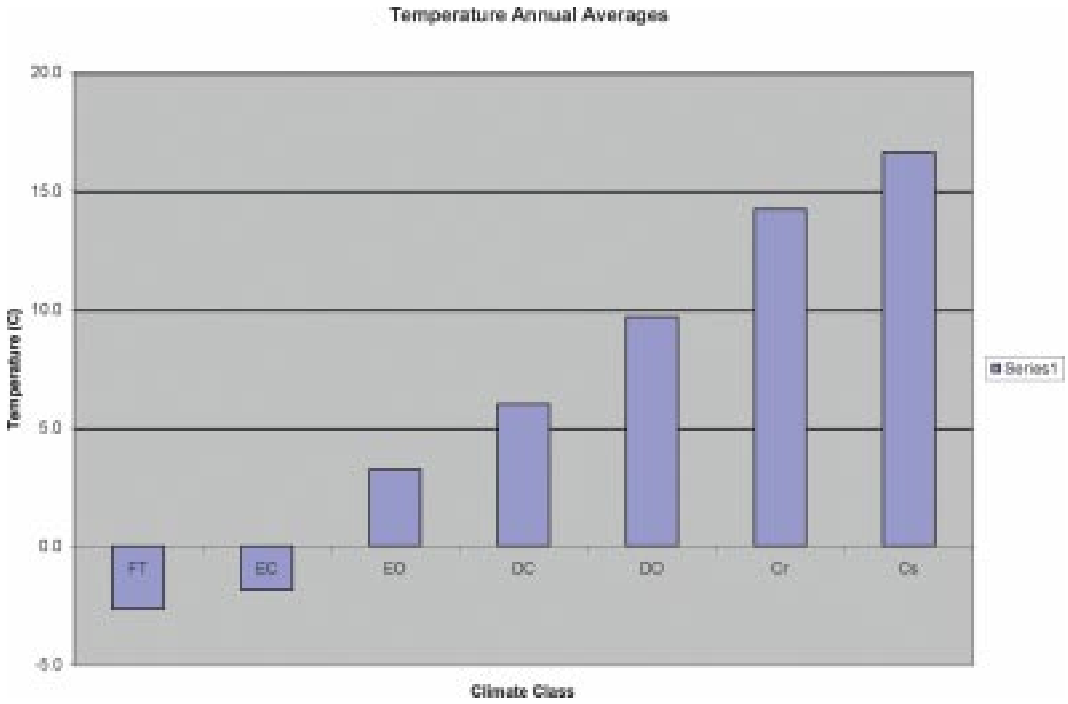


Figure C1.3: *Mean Annual Temperature by Climate Class for Central England*

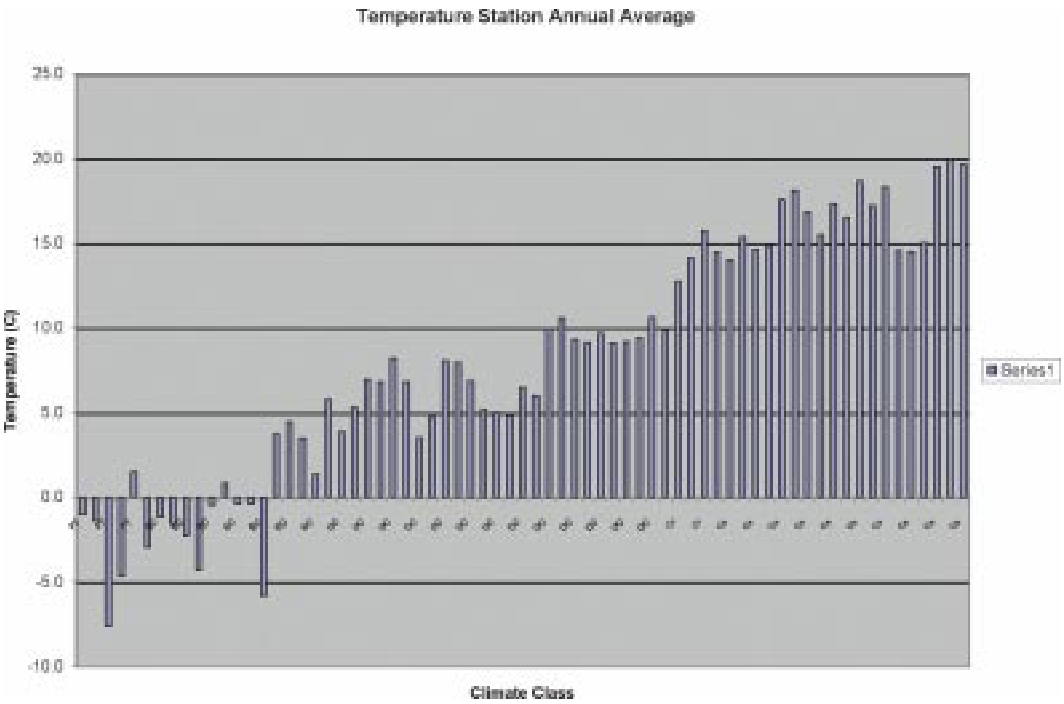
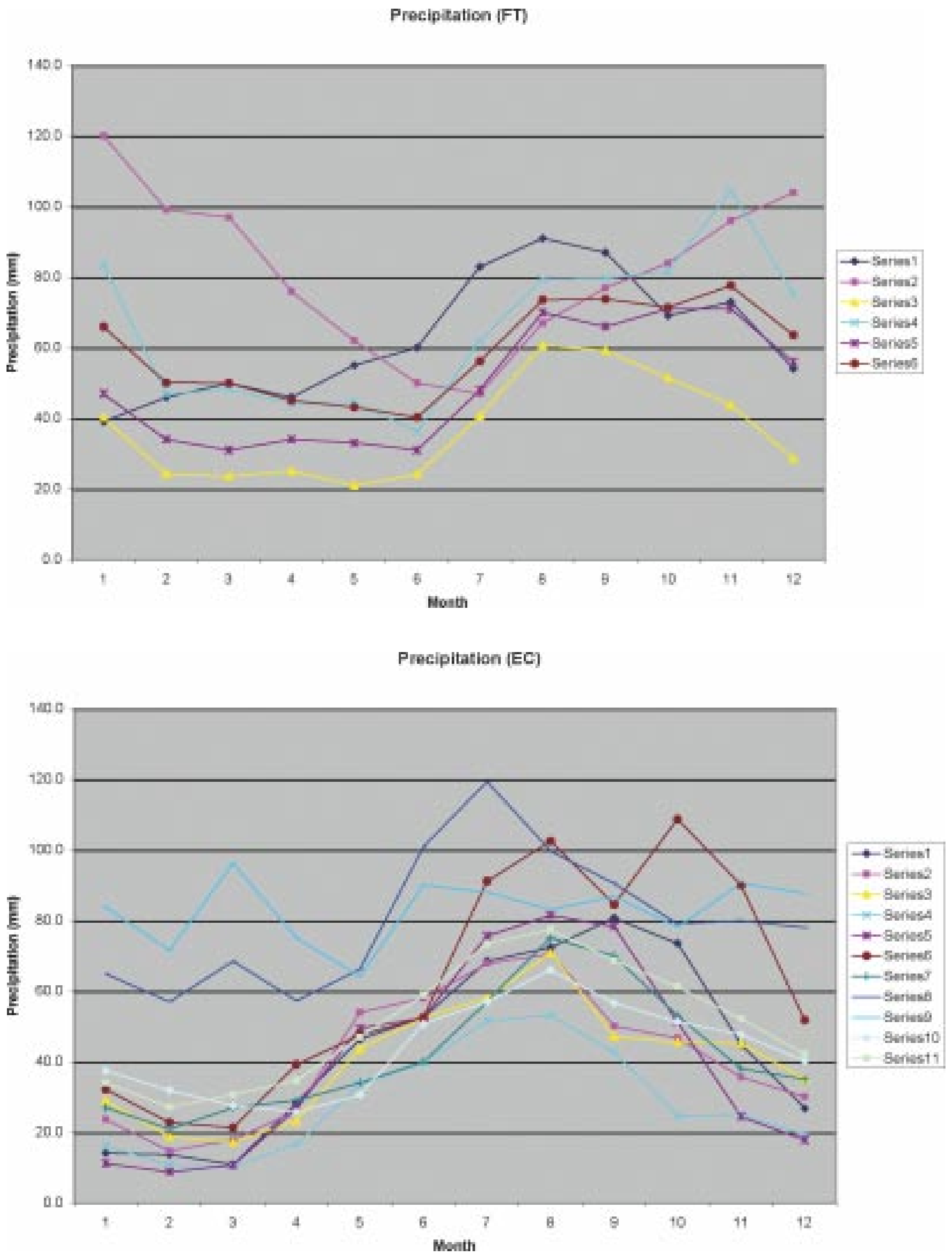
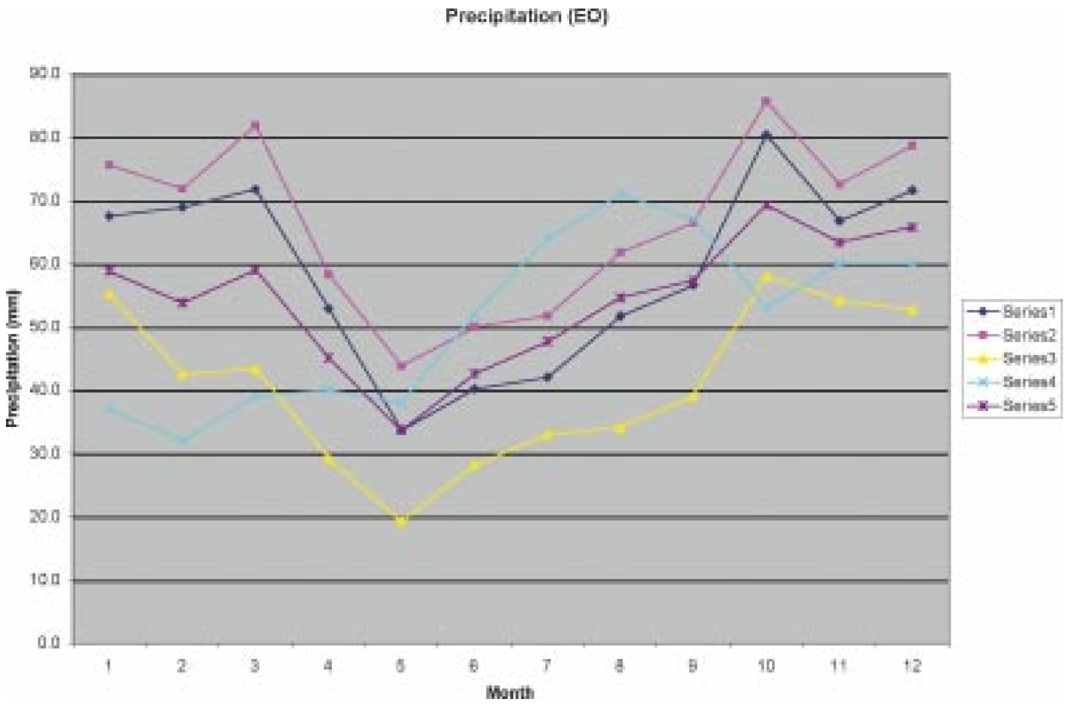
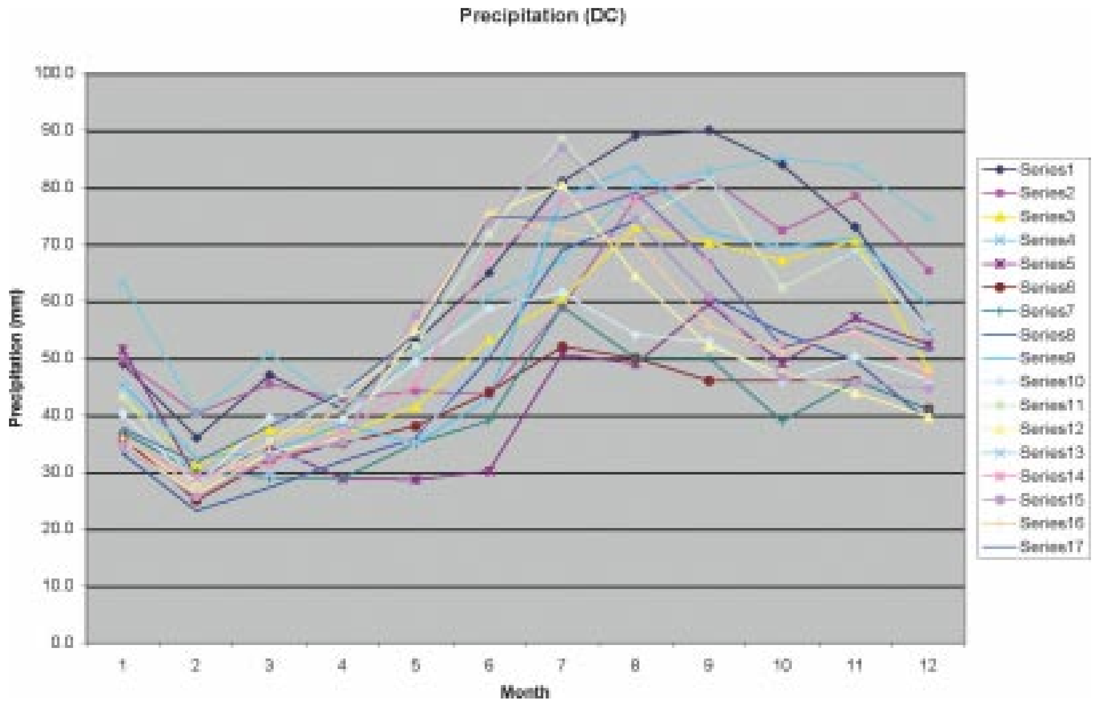


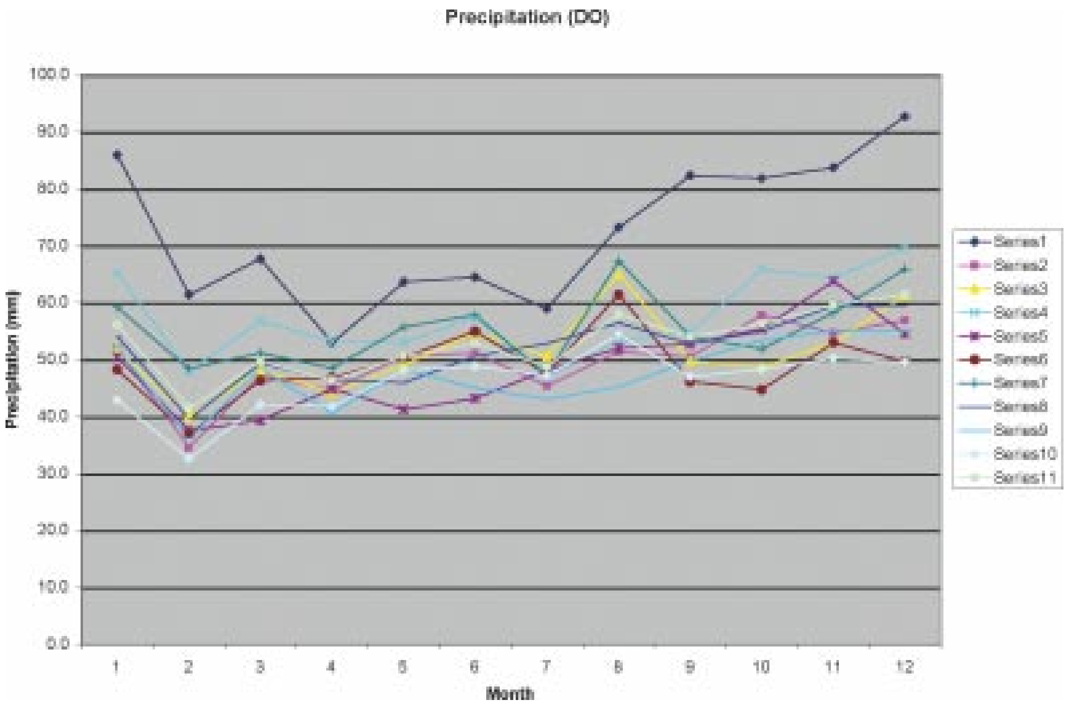
Figure C1.4: Mean Annual Temperatures by Station for Central England

Figure C1.5: *Precipitation Data by Analogue Station for Central England*




Precipitation (EO)
Precipitation (mm)
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
1
2
3
4
5
6
7
8
9
10
11
12
Month
Series1
Series2
Series3
Series4
Series5


Precipitation (DC)
Precipitation (mm)
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
1
2
3
4
5
6
7
8
9
10
11
12
Month
Series1
Series2
Series3
Series4
Series5
Series6
Series7
Series8
Series9
Series10
Series11
Series12
Series13
Series14
Series15
Series16
Series17


Precipitation (DO)
Precipitation (mm)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
1
2
3
4
5
6
7
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Month
Series1
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Series4
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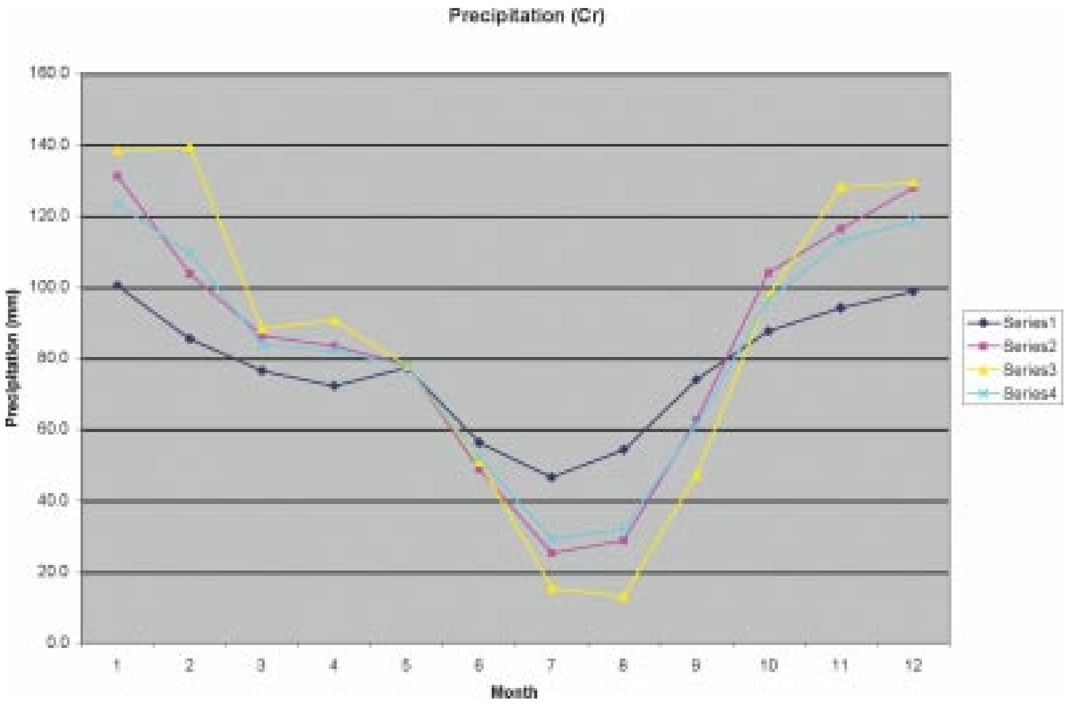
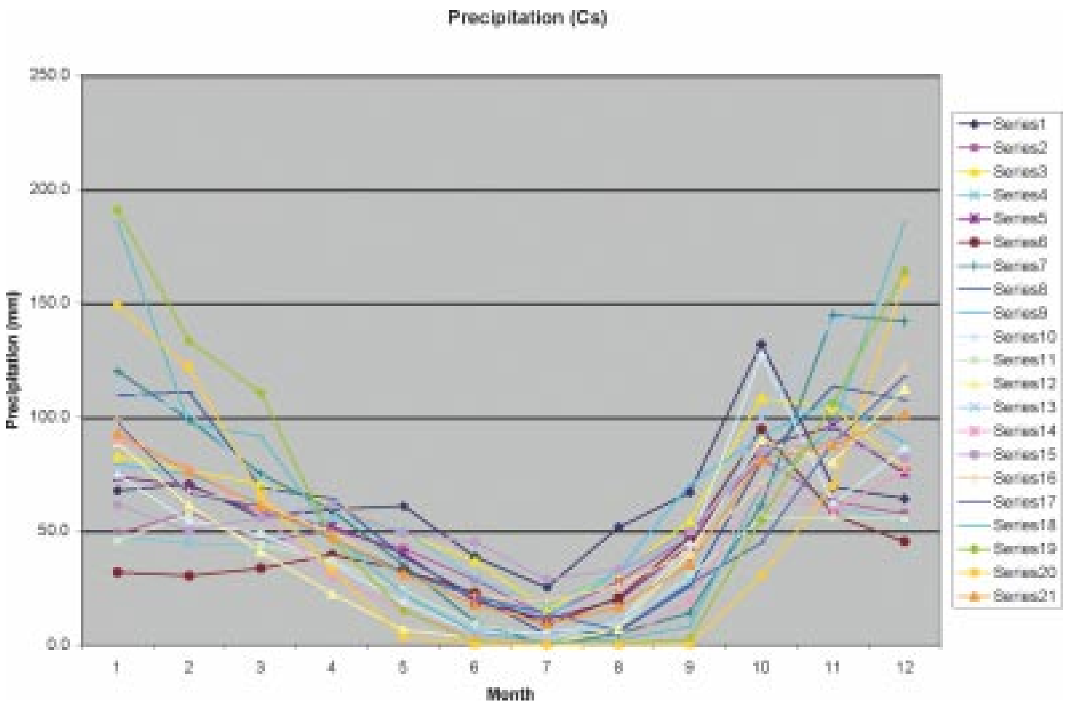
Series6
Series7
Series8
Series9
Series10
Series11


Precipitation (Cr)
Precipitation (mm)
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
1
2
3
4
5
6
7
8
9
10
11
12
Month
Series1
Series2
Series3
Series4


Precipitation (Cs)
Precipitation (mm)
250.0
200.0
150.0
100.0
50.0
0.0
1
2
3
4
5
6
7
8
9
10
11
12
Month
Series1
Series2
Series3
Series4
Series5
Series6
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Series17
Series18
Series19
Series20
Series21

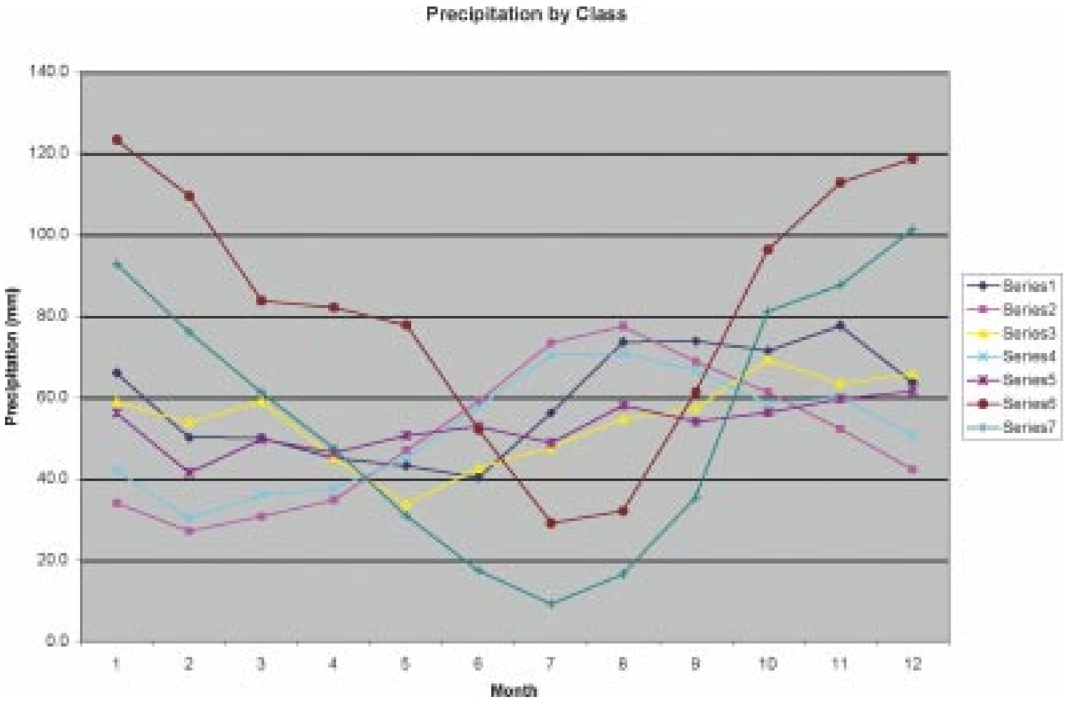


Figure C1.6: *Mean Precipitation Values by Climate Class*

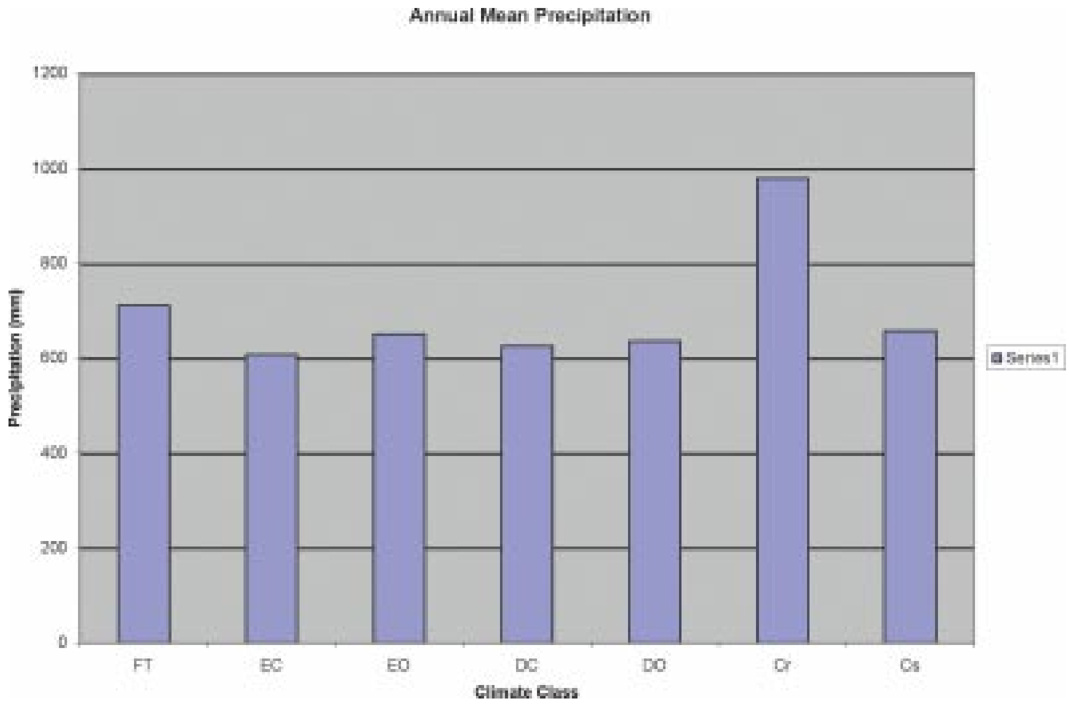
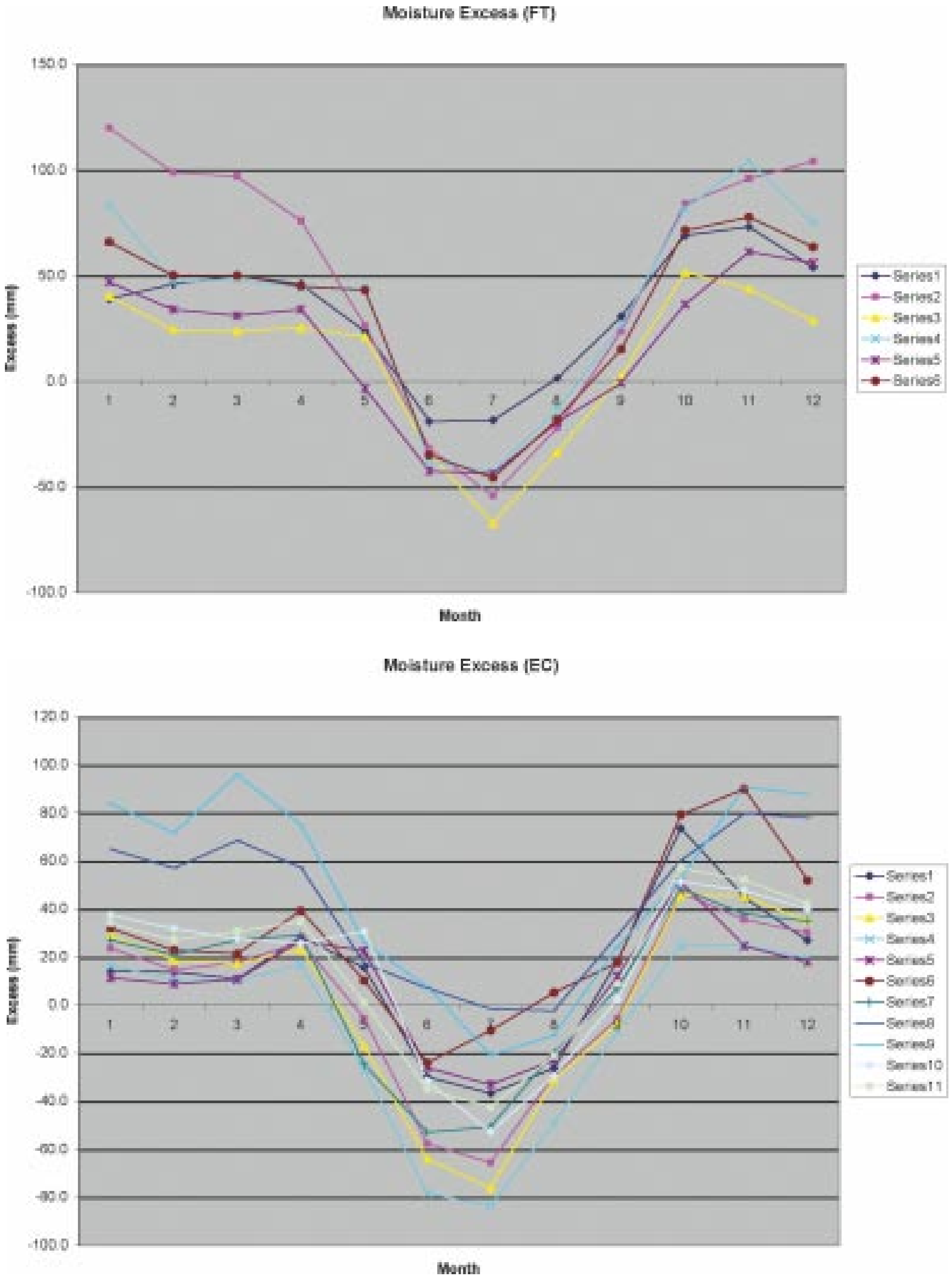
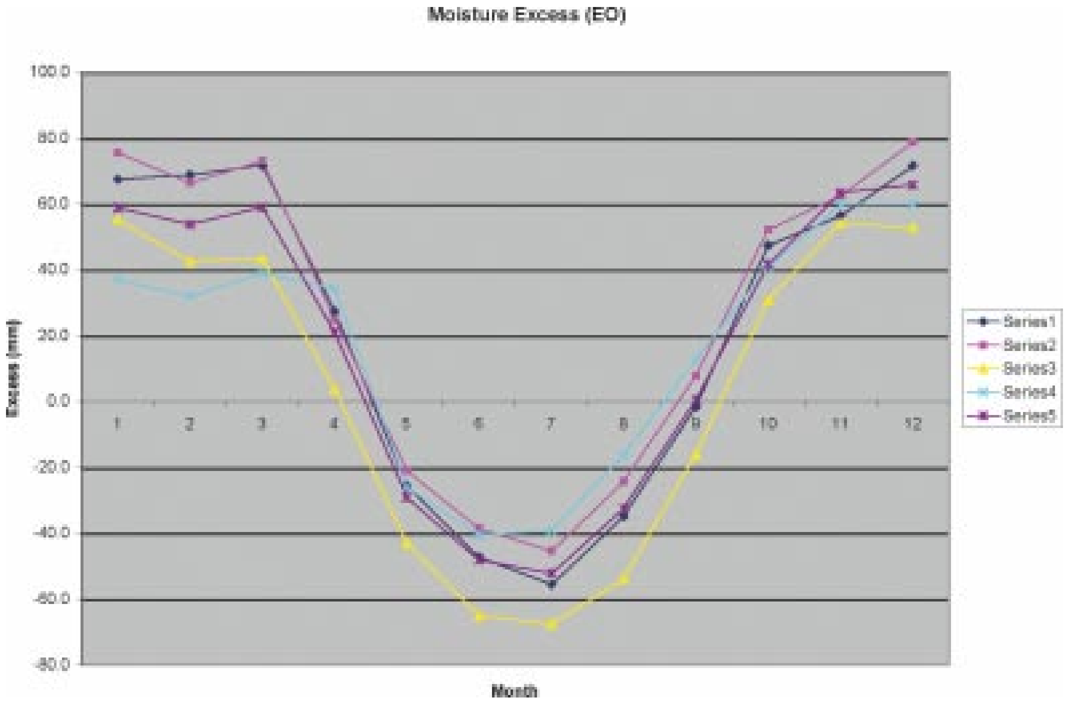
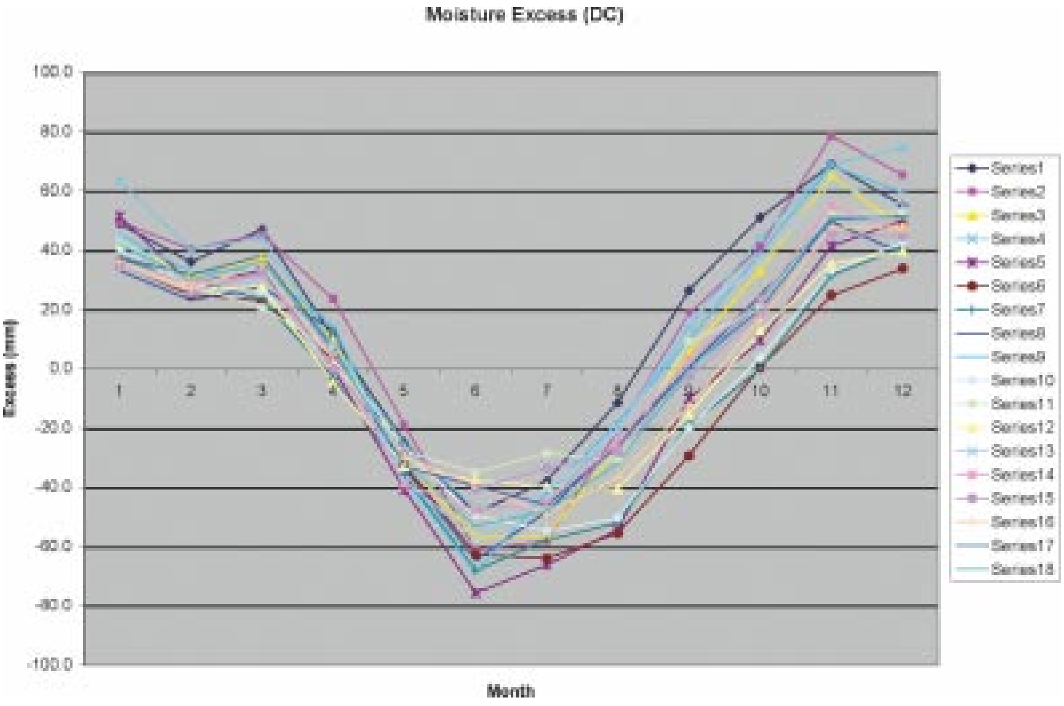


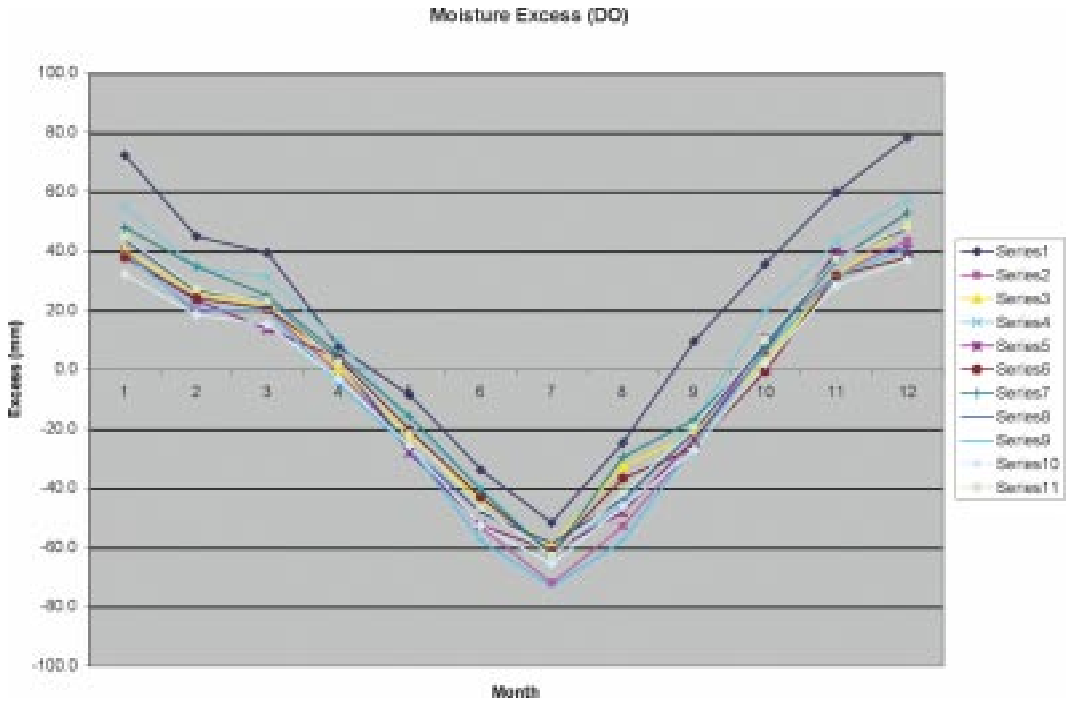
Figure C1.7: *Annual Mean Precipitation by Climate Class*

Figure C1.8: *Moisture Excess for by Analogue Station for Central England*




Moisture Excess (EO)


Moisture Excess (DC)


Moisture Excess (DO)
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
Excess (mm)
1
2
3
4
5
6
7
8
9
10
11
12
Month
Series1
Series2
Series3
Series4
Series5
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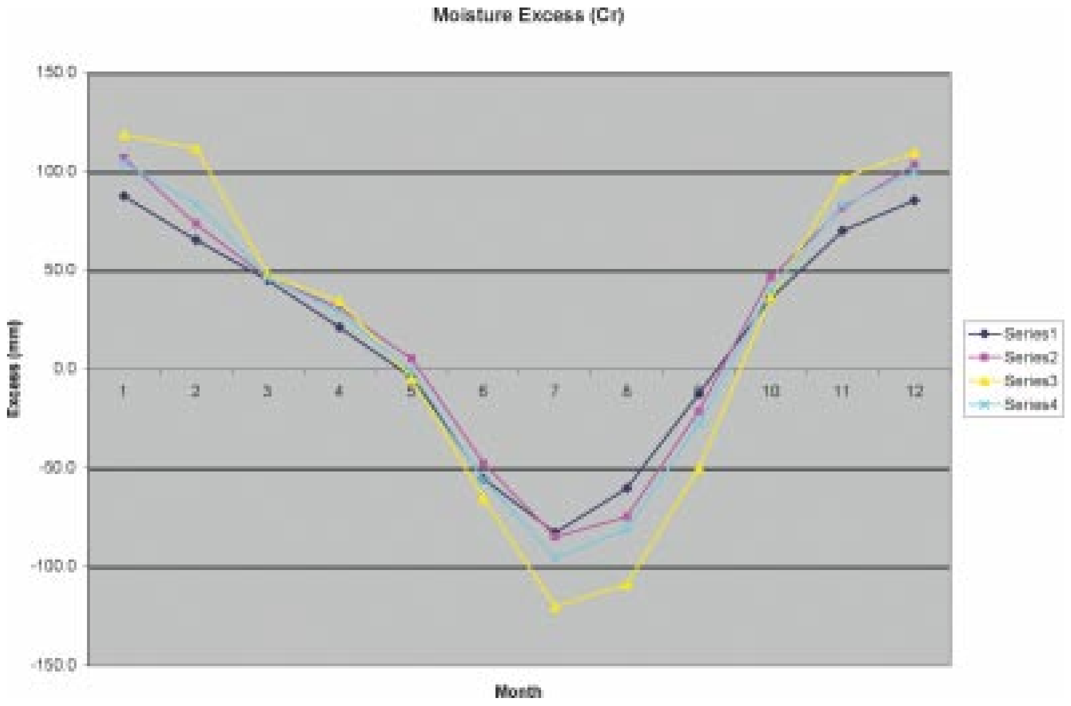
Series7
Series8
Series9
Series10
Series11


Moisture Excess (Cr)
150.0
100.0
50.0
0.0
-50.0
-100.0
-150.0
Excess (mm)
1
2
3
4
5
6
7
8
9
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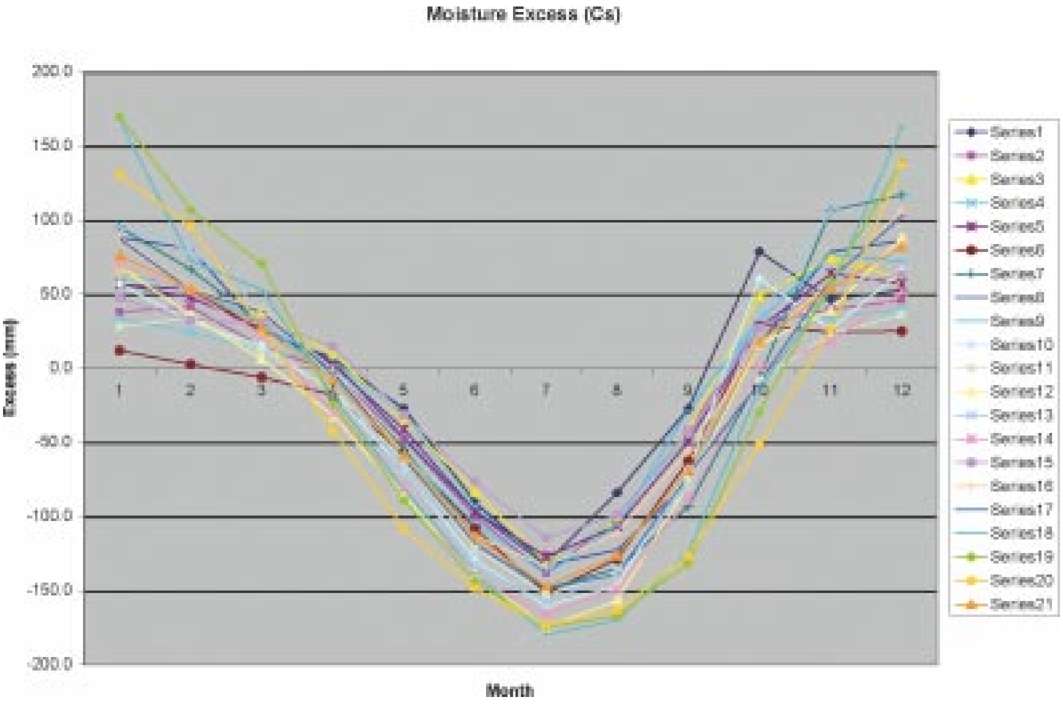
11
12
Month
Series1
Series2
Series3
Series4



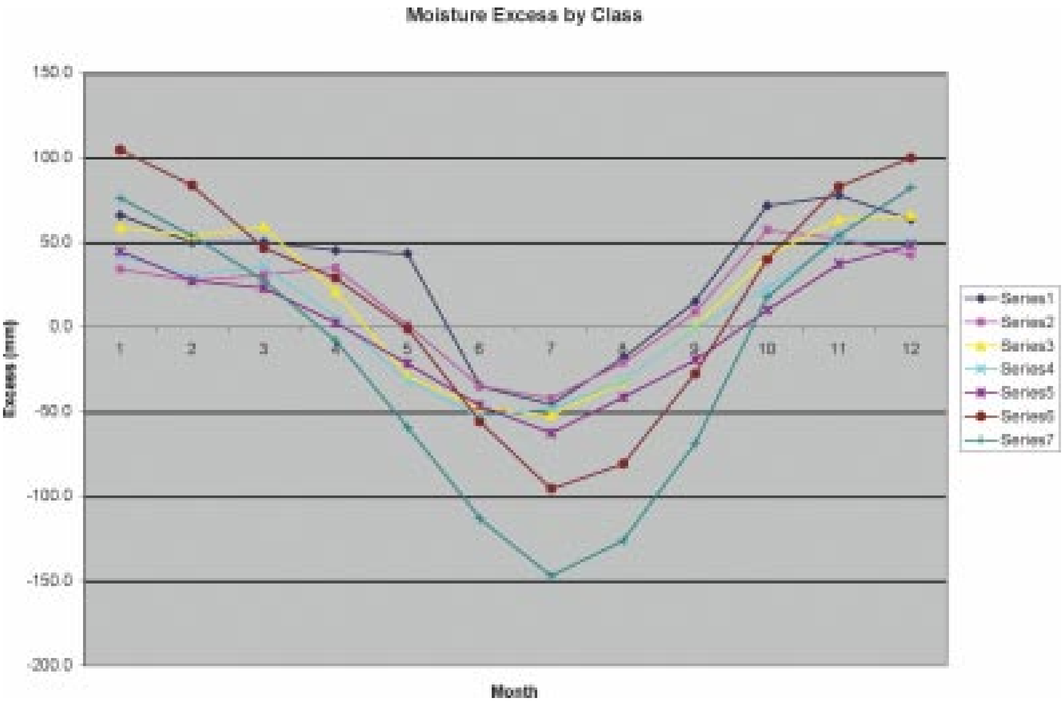


Figure C1.9: *Arithmetic Mean Monthly Moisture Excess by Climate Class*

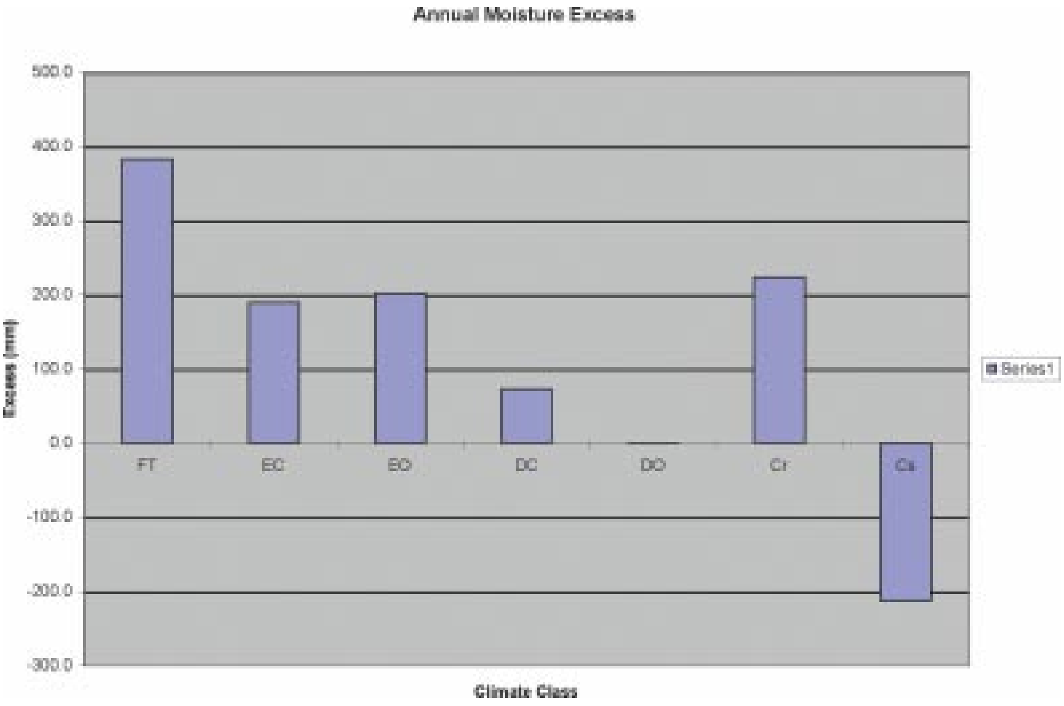


Figure C1.10: *Annual Arithmetic Mean Moisture Excess by Climate Class*

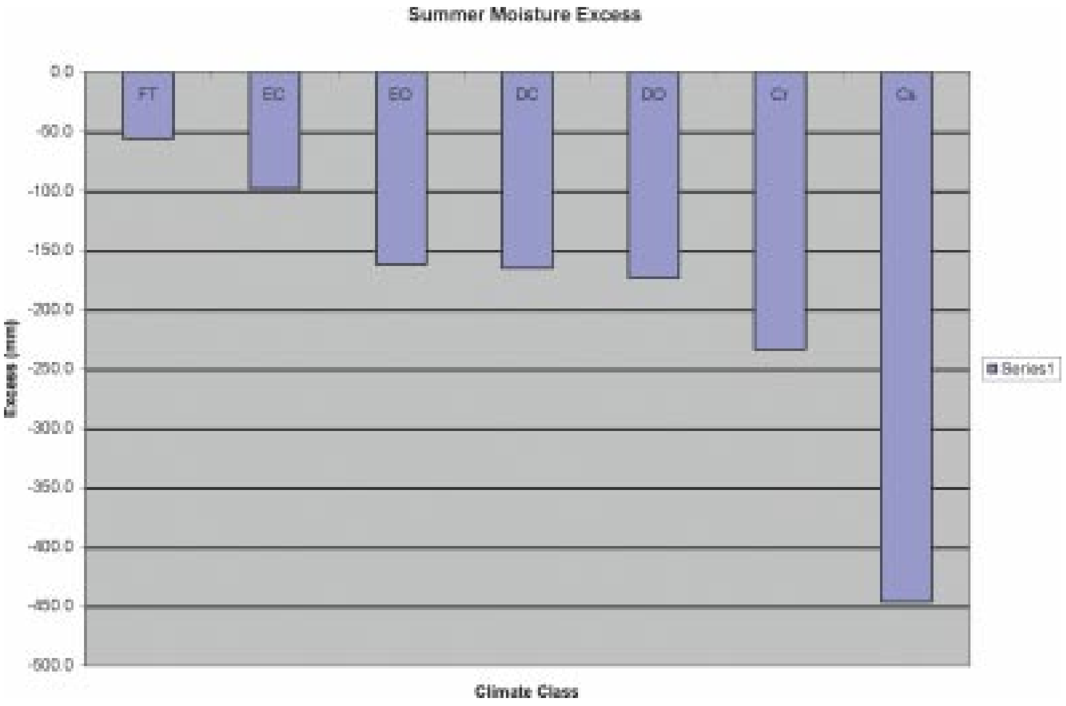


Figure C1.11: *Extended Summer Moisture Deficits by Climate Class*

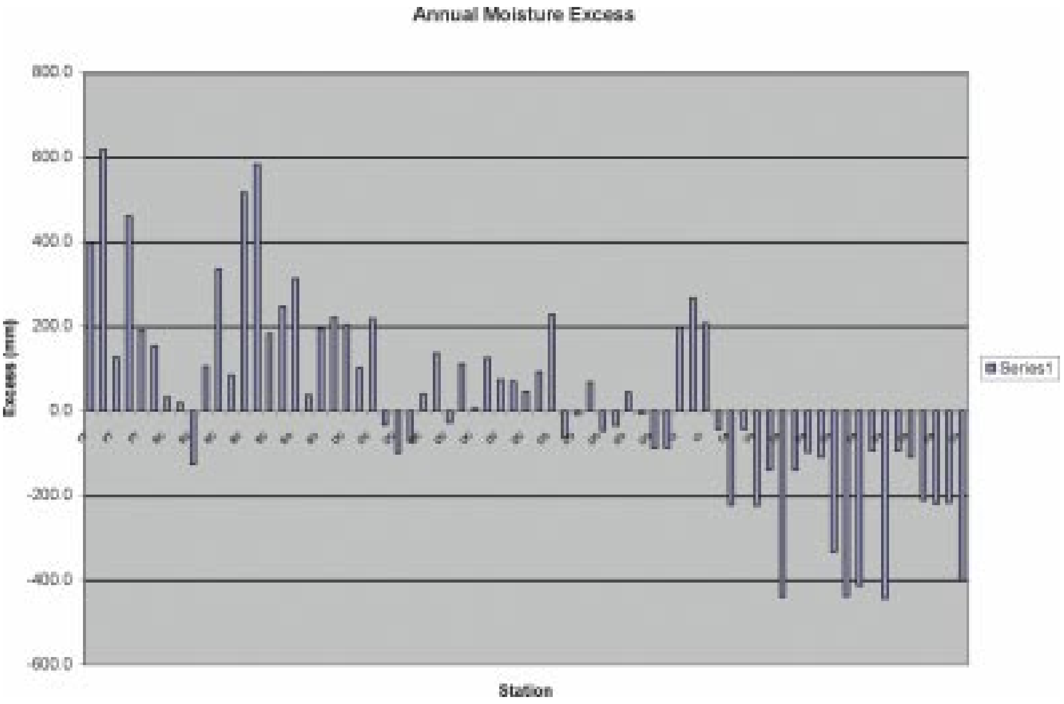


Figure C1.12: Annual Moisture Excess or Deficit by Station

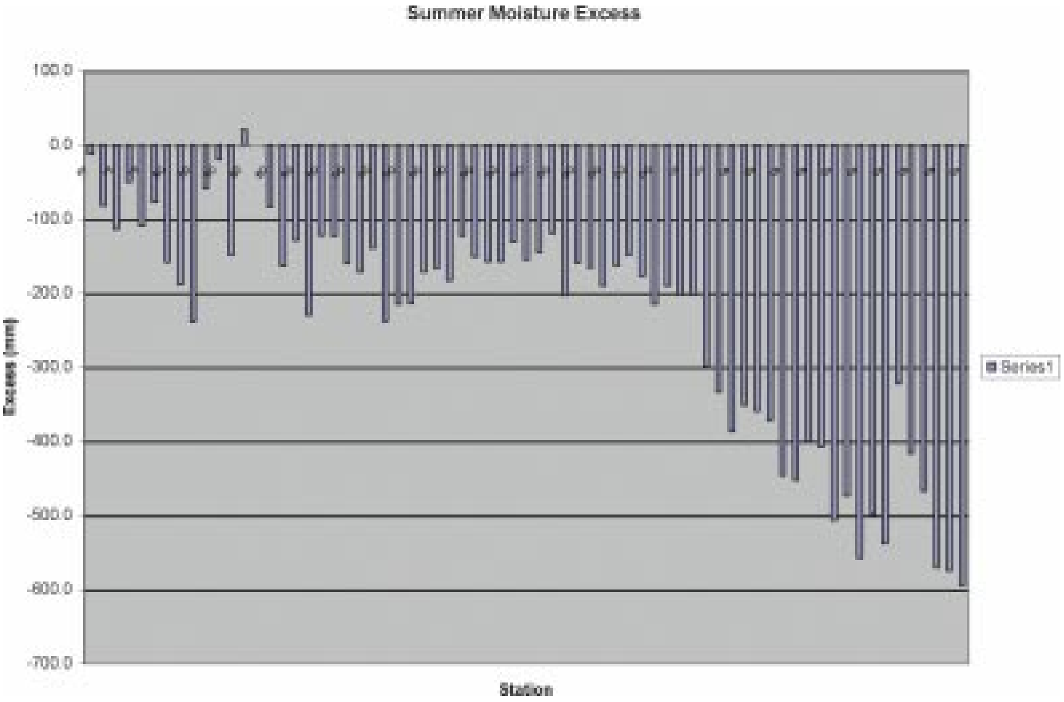
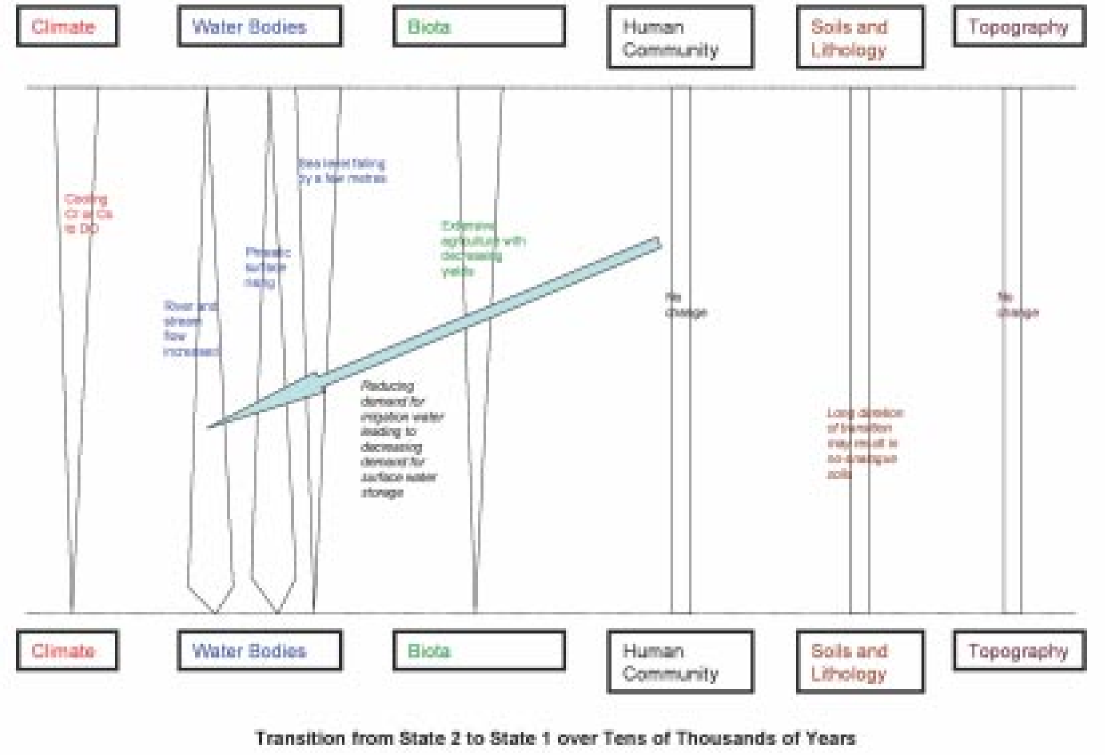
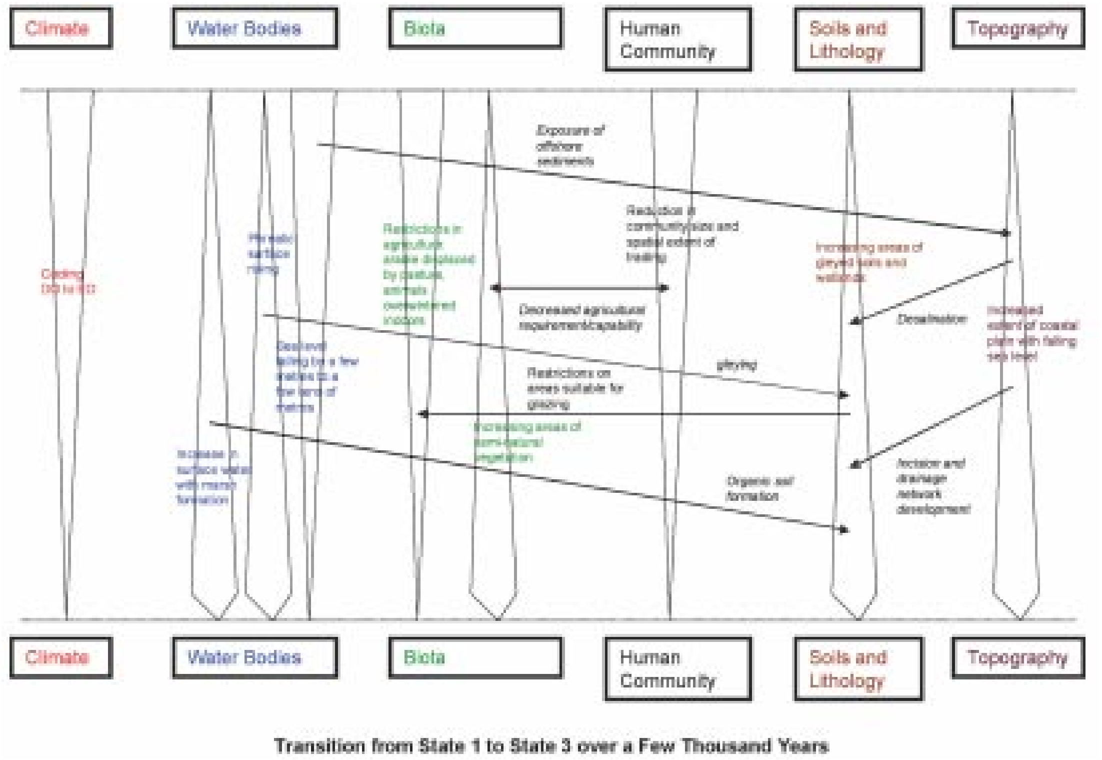


Figure C1.13: Summer Moisture Excess or Deficit by Station



Transition from State 2 to State 1 over Tens of Thousands of Years

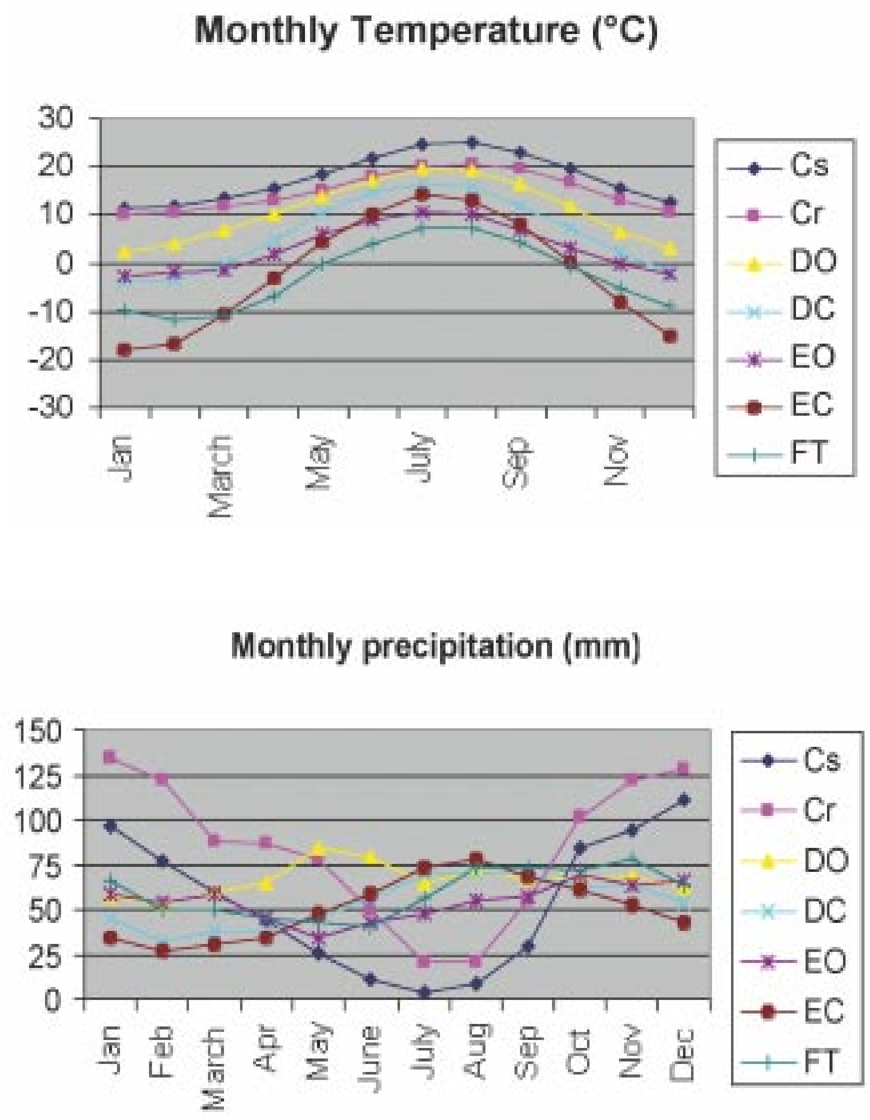
Figure C1.14: *Transition Diagram between State 2 and State 1*



Transition from State 1 to State 3 over a Few Thousand Years

Figure C1.15: *Transition Diagram between State 1 and State 3*

Figure C2.1: *Climate Data for Analogue Stations for the Meuse/Haute-Marne Region of Northeast France*



Monthly Temperature (°C)

Monthly precipitation (mm)

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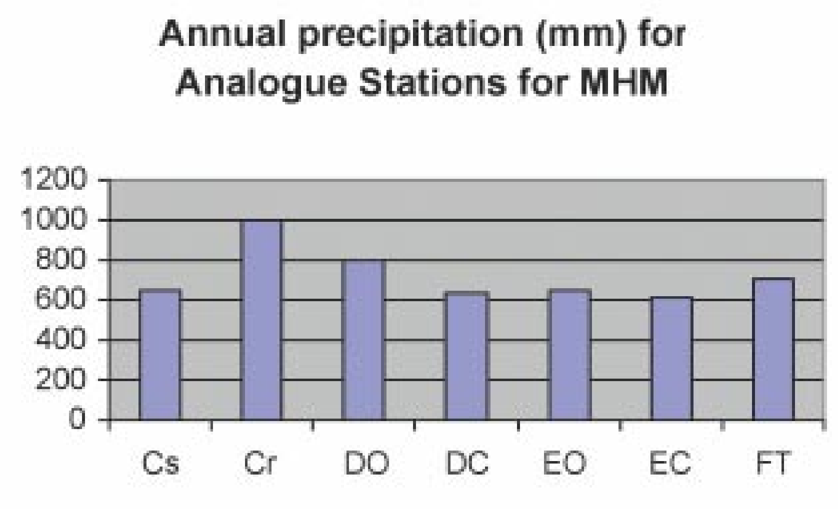
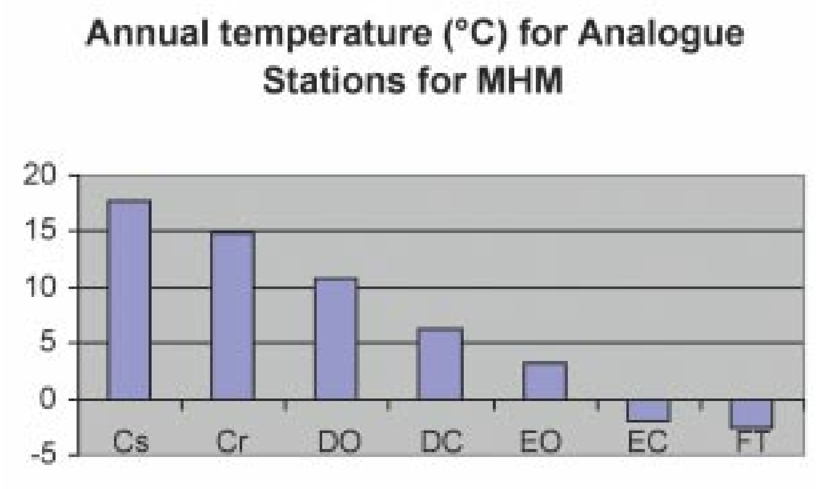

Annual precipitation (mm) for Analogue Stations for MHM
1200
1000
800
600
400
200
0
Cs
Cr
DO
DC
EO
EC
FT


Annual temperature (°C) for Analogue Stations for MHM
20
15
10
5
0
-5
Cs
Cr
DO
DC
EO
EC
FT

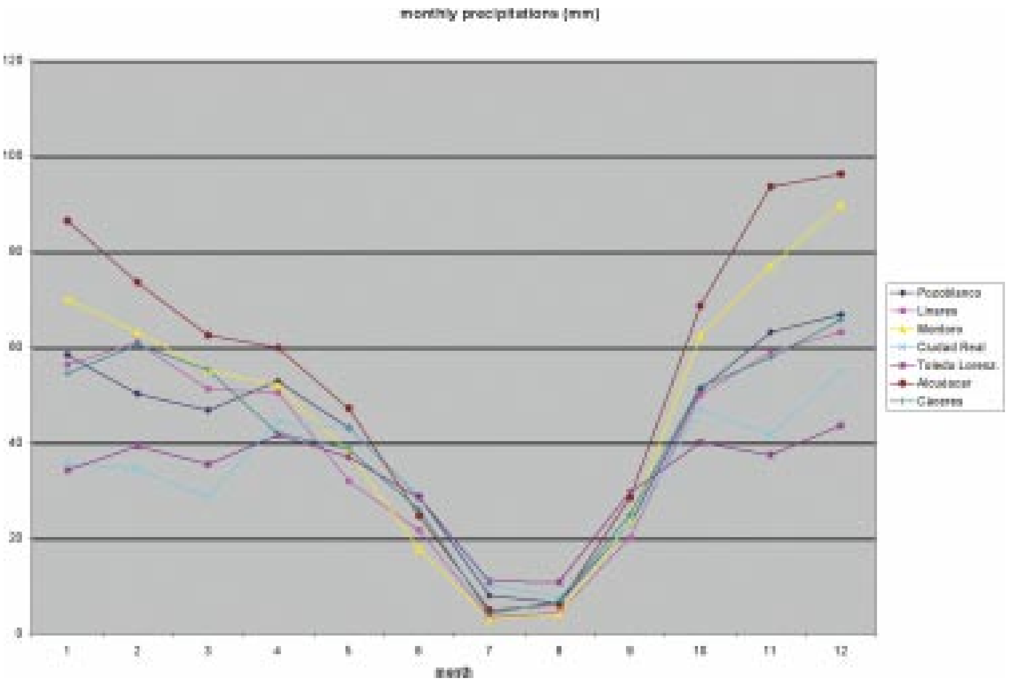


Figure C3.1: *Monthly Values of Precipitation at the Seven Stations located in the Central Spanish Domain*

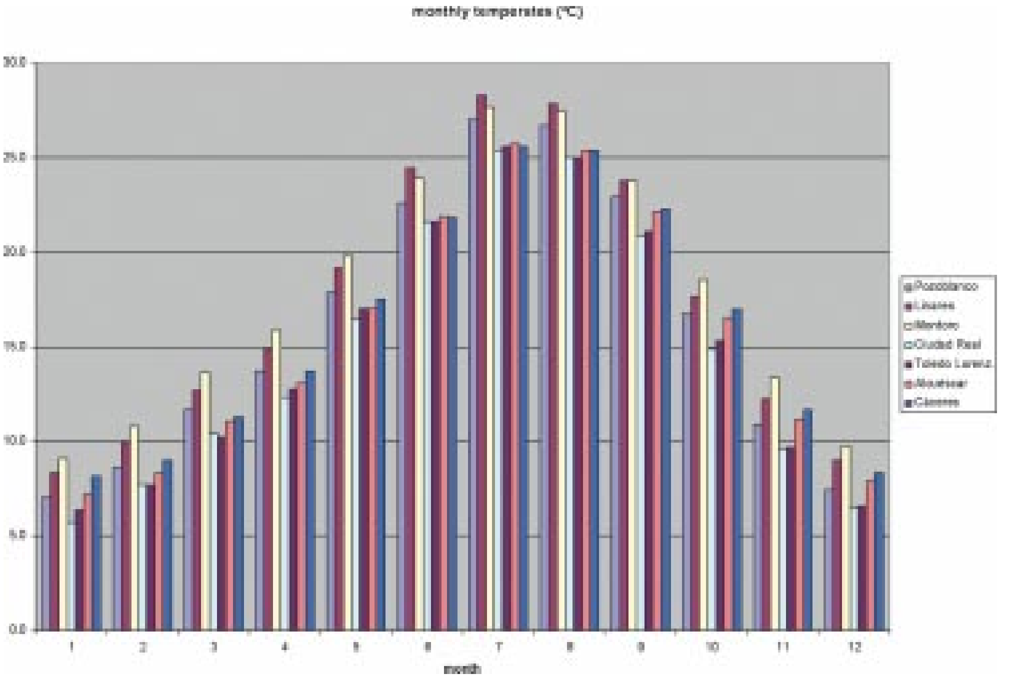


Figure C3.2: *Mean Monthly Temperatures for the Seven Stations located in the Central Spanish Domain*

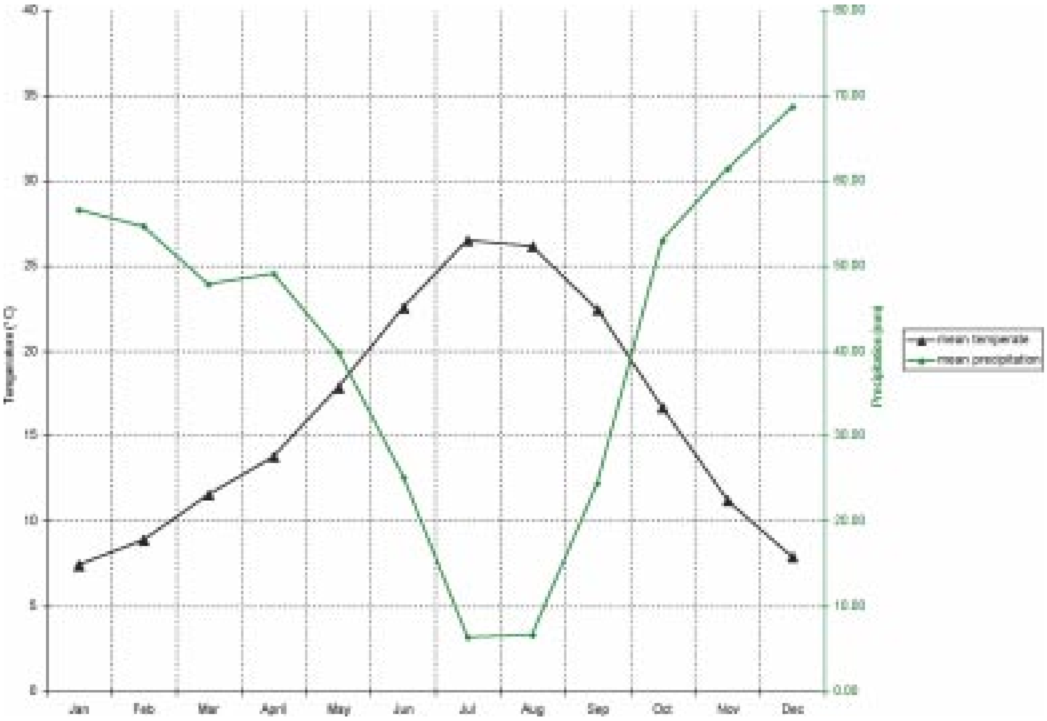


Figure C3.3: *Climate Diagram of Average Monthly Temperature and Precipitation for the Seven Meteorological Stations located in the Central Spanish Domain*

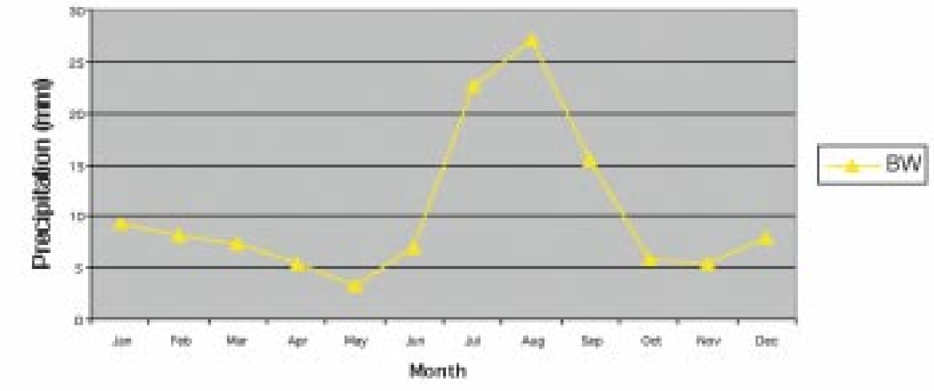


Figure C3.4: *Mean Monthly Precipitation of Analyzed Meteorological Stations of Climate Class BW (Lomba et al., 2003)*

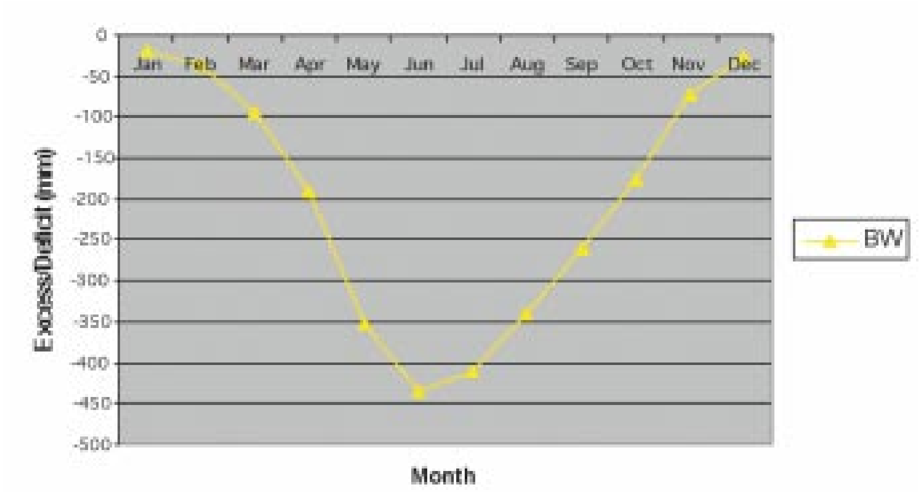


Figure C3.5: *Mean Monthly Moisture Deficit/Excess of Analyzed Meteorological Stations of Climate Class BW (Lomba et al., 2003)*

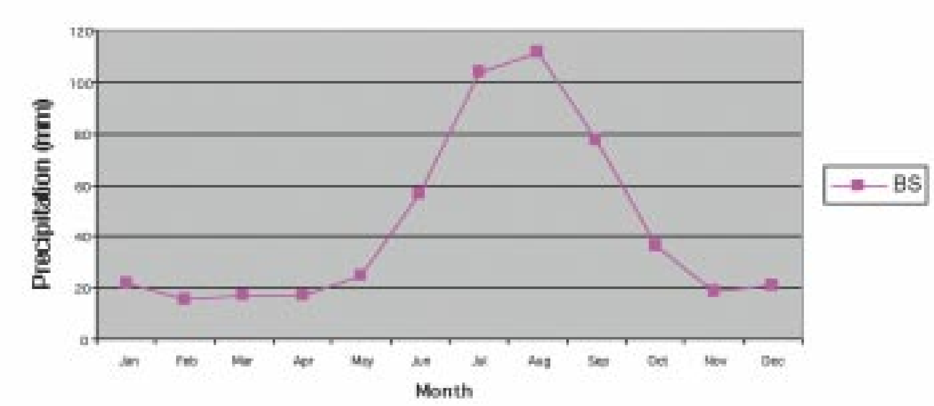


Figure C3.6: *Mean Monthly Precipitation of Analyzed Meteorological Stations of Climate Class BS (Lomba et al., 2003)*

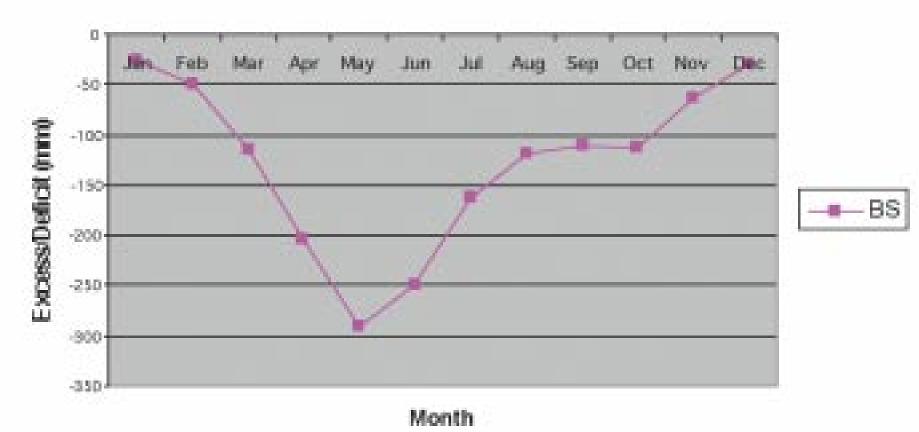


Figure C3.7: *Mean Monthly Moisture Deficit/Excess of Analyzed Meteorological Stations of Climate Class BS (Lomba et al., 2003)*

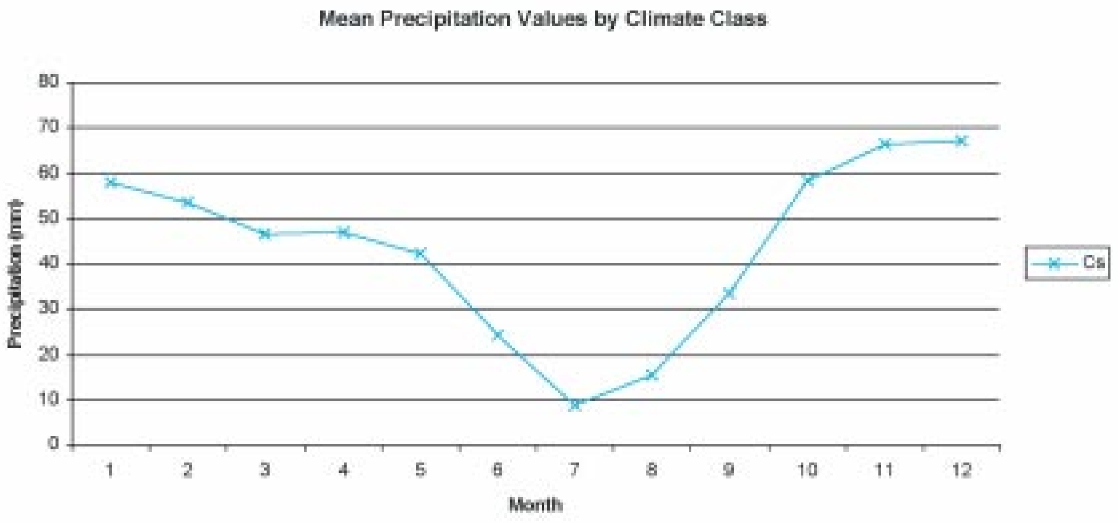


Figure C3.8: *Mean Monthly Precipitation of Analyzed Meteorological Stations from Spain of Climate Class Cs (Lomba et al., 2002)*

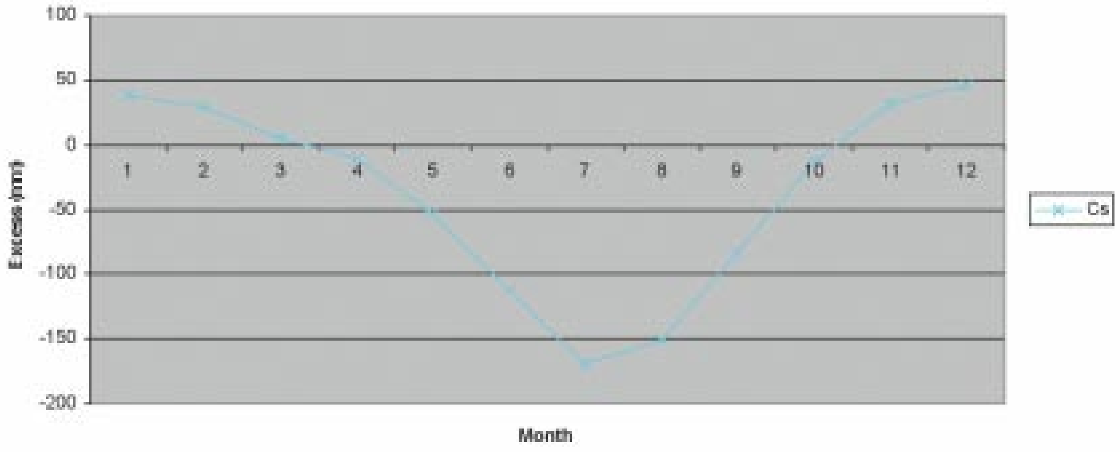


__Figure C3.9:__ Mean Monthly Moisture Deficit/Excess of Analyzed Meteorological Stations of Climate Class Cs (Lomba et al., 2002)

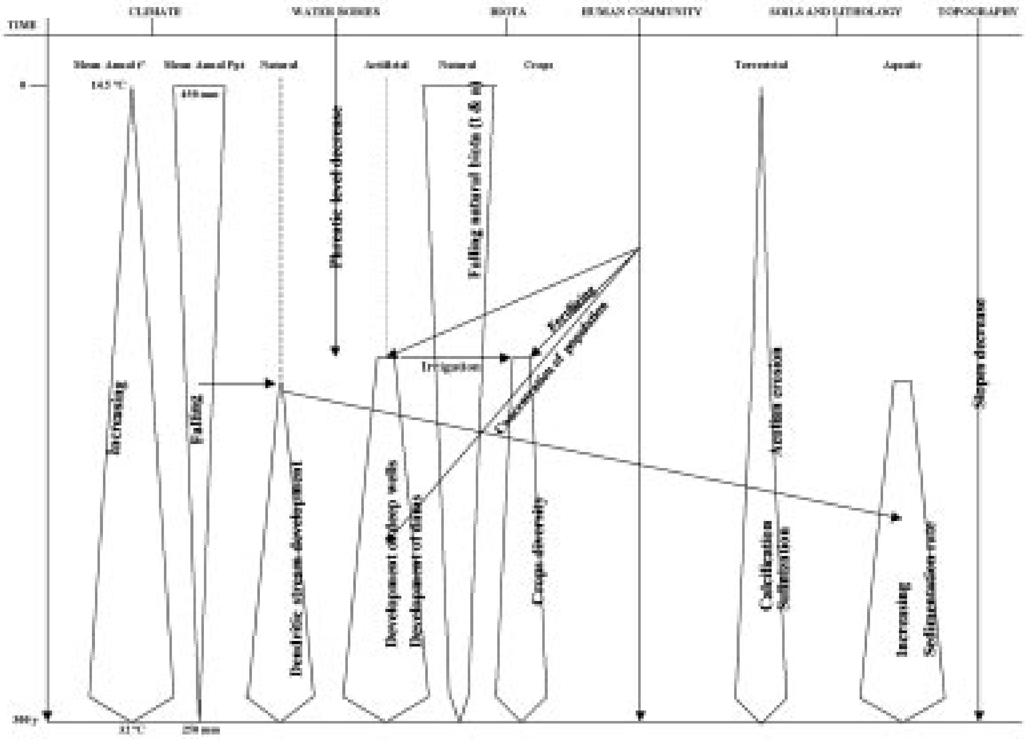


__Figure C3.10:__ Transition Diagram for Central Spain from State CSa to BWh over a Few Hundred Years

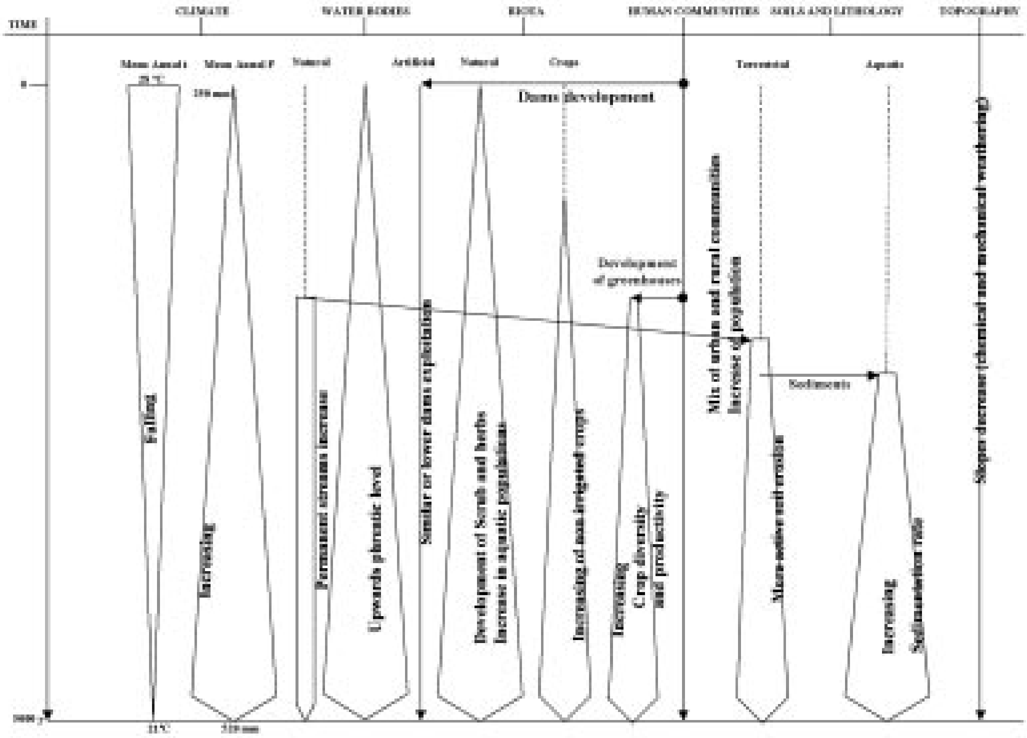


Figure C3.11: *Transition Diagram for Central Spain from State BWh to BSh over Five Thousand Years*

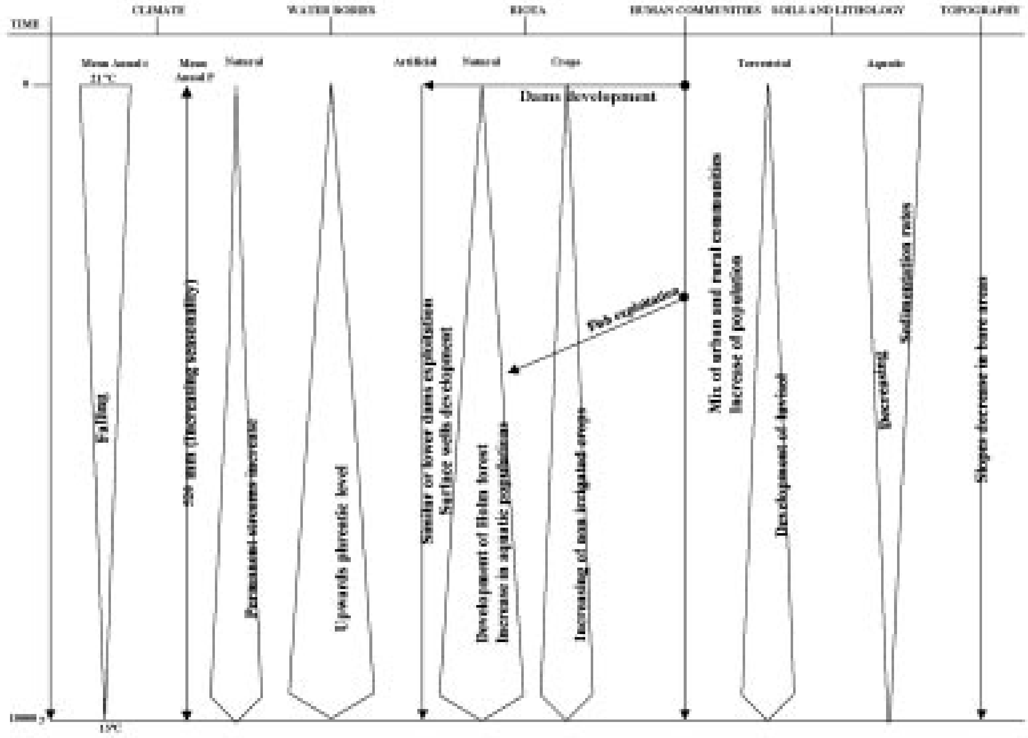


Figure C3.12: *Transition Diagram for Central Spain from State BSh to Cs over Ten Thousand Years*

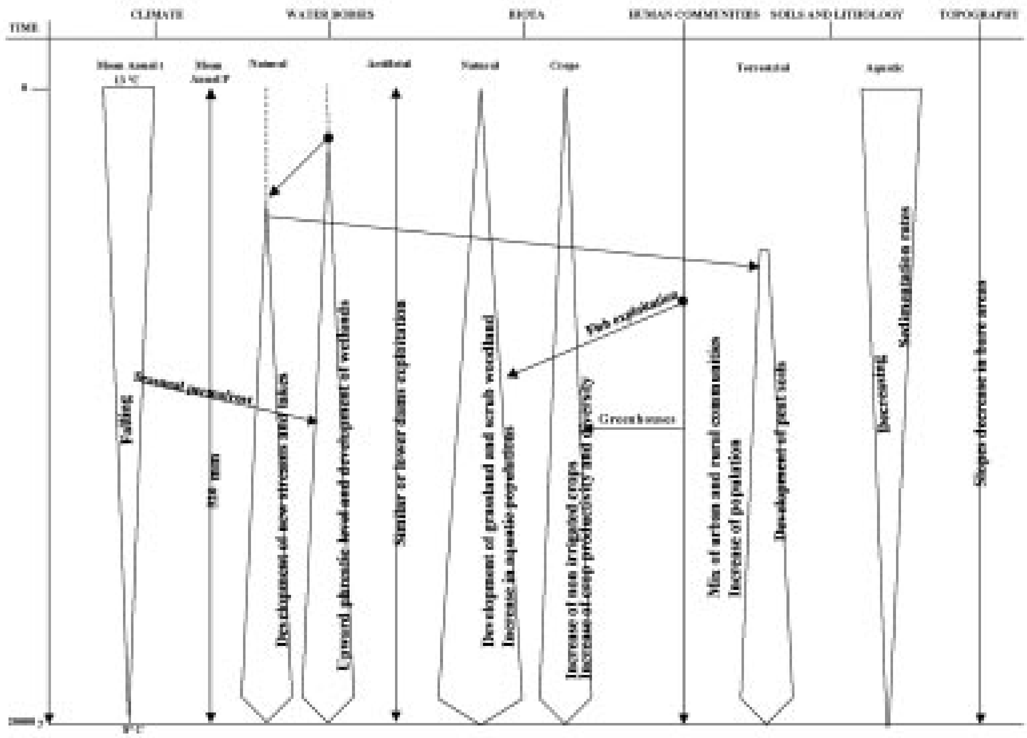


Figure C3.13: Transition Diagram for Central Spain from State BSh to DC over Twenty Thousand Years

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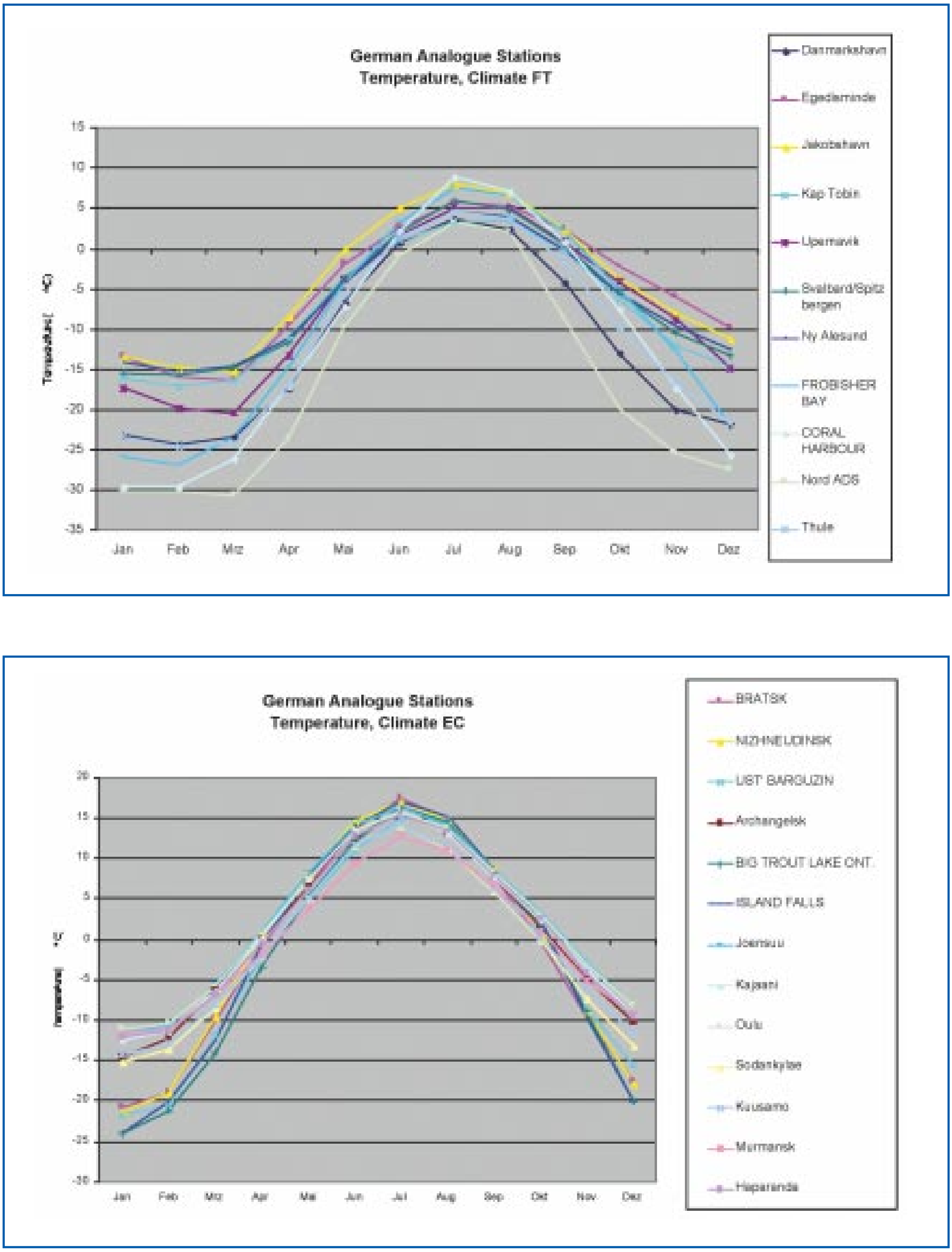
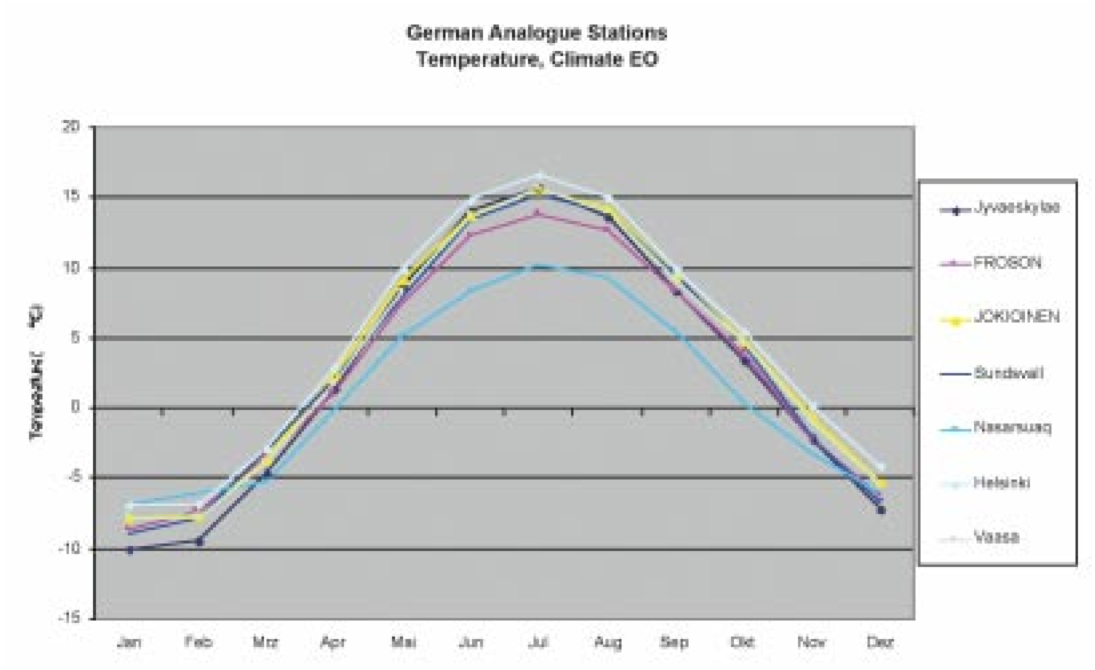
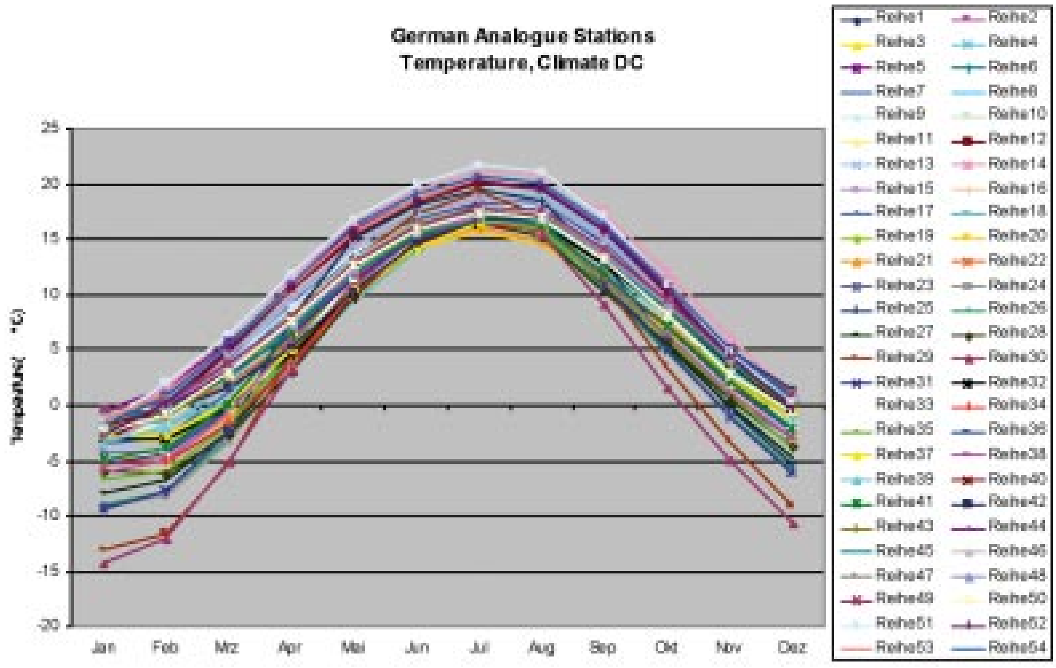
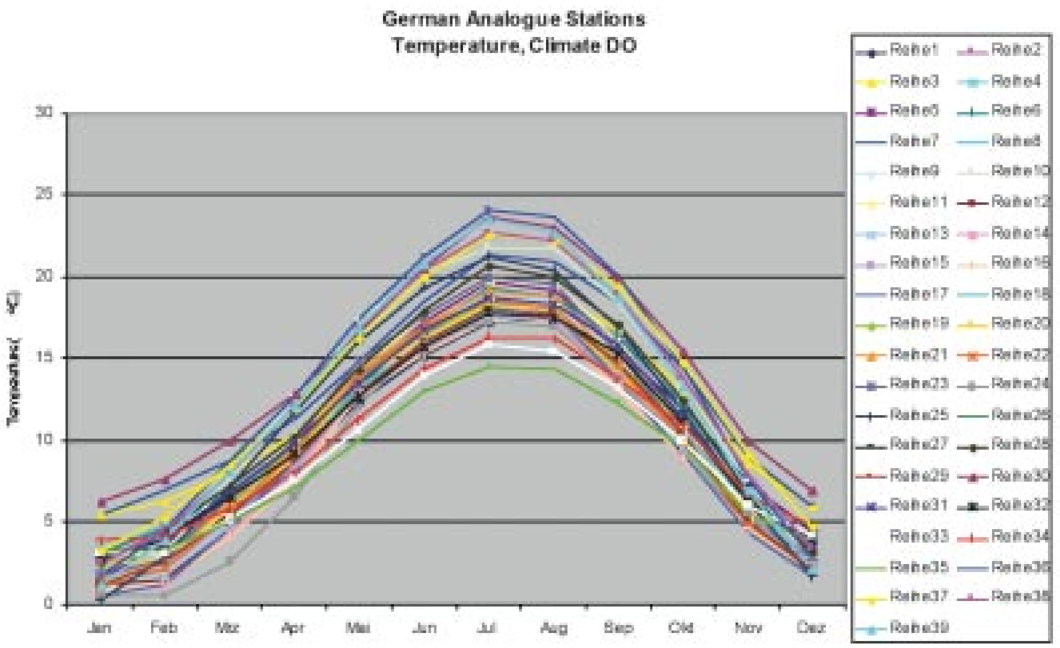
Figure C4.1: *Temperature Data for Analogue Stations for North Germany*




German Analogue Stations
Temperature, Climate EO
Temperature(°C)
20
15
10
5
0
-5
-10
-15
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
Jyvaeskylae
FROSON
JOKIOINEN
Sundsvall
Narsarsuaq
Helsinki
Vaasa


German Analogue Stations
Temperature, Climate DC
Temperature(°C)
25
20
15
10
5
0
-5
-10
-15
-20
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
Reihe1
Reihe2
Reihe3
Reihe4
Reihe5
Reihe6
Reihe7
Reihe8
Reihe9
Reihe10
Reihe11
Reihe12
Reihe13
Reihe14
Reihe15
Reihe16
Reihe17
Reihe18
Reihe19
Reihe20
Reihe21
Reihe22
Reihe23
Reihe24
Reihe25
Reihe26
Reihe27
Reihe28
Reihe29
Reihe30
Reihe31
Reihe32
Reihe33
Reihe34
Reihe35
Reihe36
Reihe37
Reihe38
Reihe39
Reihe40
Reihe41
Reihe42
Reihe43
Reihe44
Reihe45
Reihe46
Reihe47
Reihe48
Reihe49
Reihe50
Reihe51
Reihe52
Reihe53
Reihe54

p.252/253


German Analogue Stations
Temperature, Climate DO
Temperatur (°C)
30
25
20
15
10
5
0
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
Reihe1
Reihe2
Reihe3
Reihe4
Reihe5
Reihe6
Reihe7
Reihe8
Reihe9
Reihe10
Reihe11
Reihe12
Reihe13
Reihe14
Reihe15
Reihe16
Reihe17
Reihe18
Reihe19
Reihe20
Reihe21
Reihe22
Reihe23
Reihe24
Reihe25
Reihe26
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Reihe29
Reihe30
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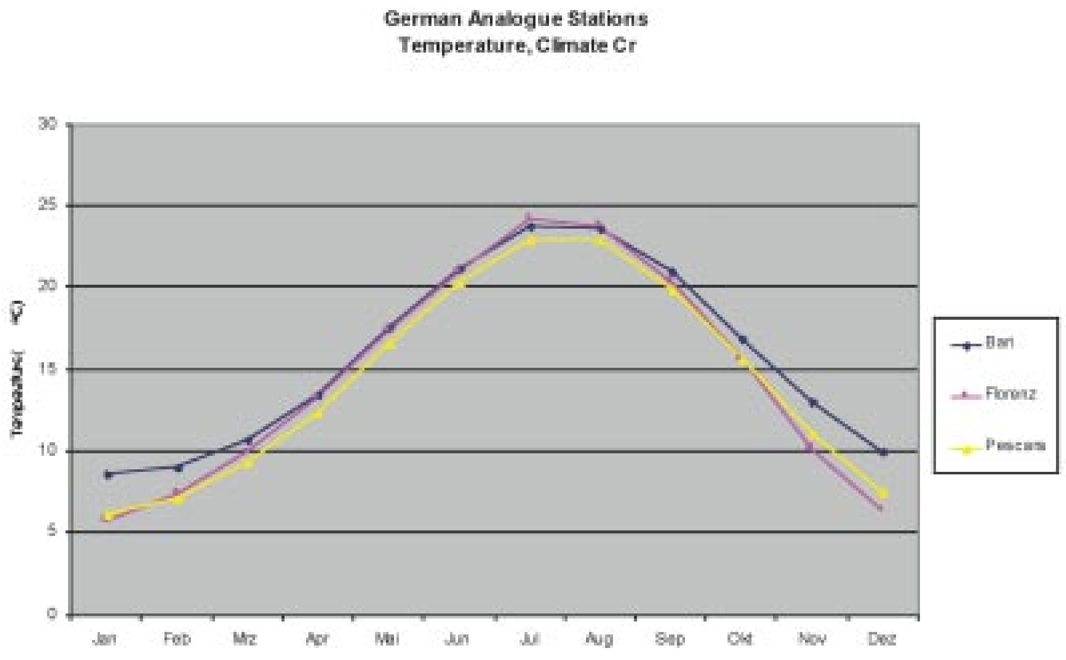
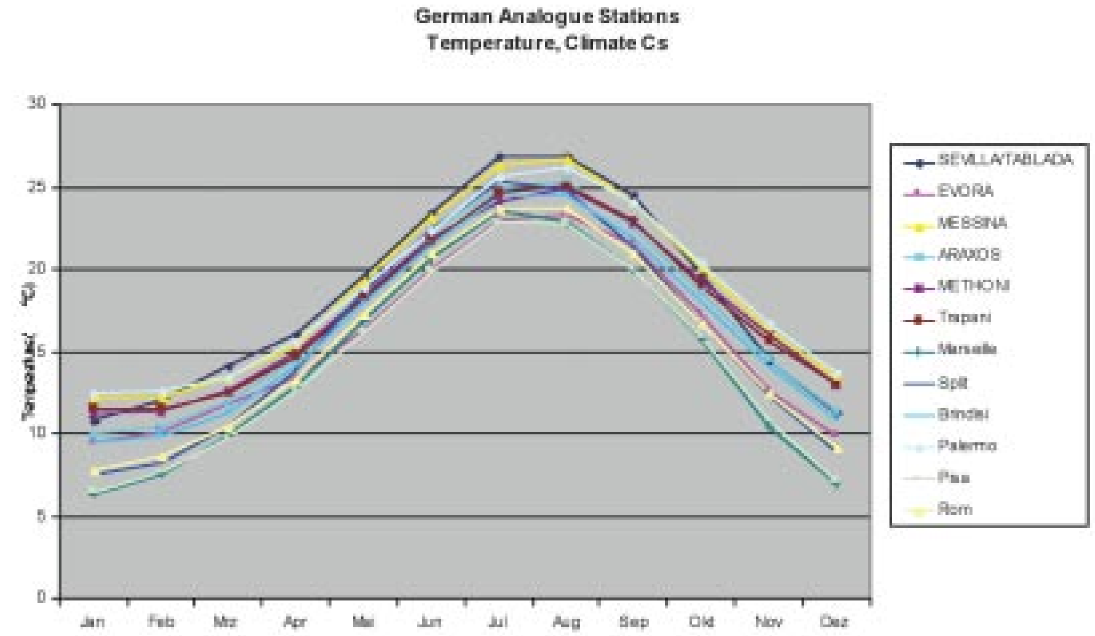
Reihe32
Reihe33
Reihe34
Reihe35
Reihe36
Reihe37
Reihe38
Reihe39


German Analogue Stations
Temperature, Climate Cr
Temperatur (°C)
30
25
20
15
10
5
0
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
Bari
Florenz
Pescara



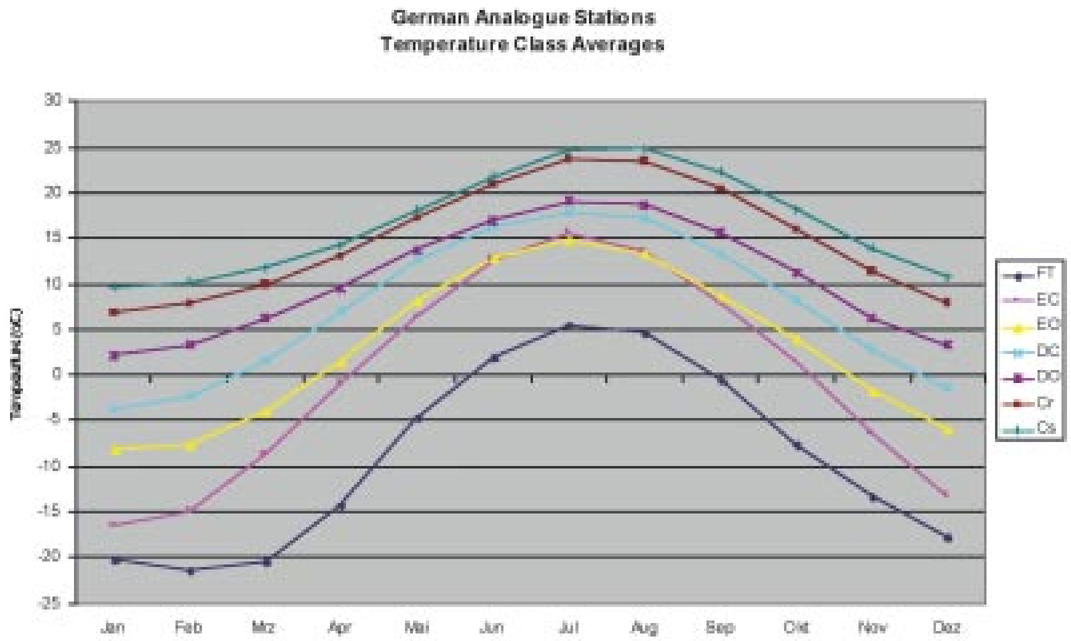


Figure C4.2: *Temperature Class Averages for Analogue Stations for North Germany*

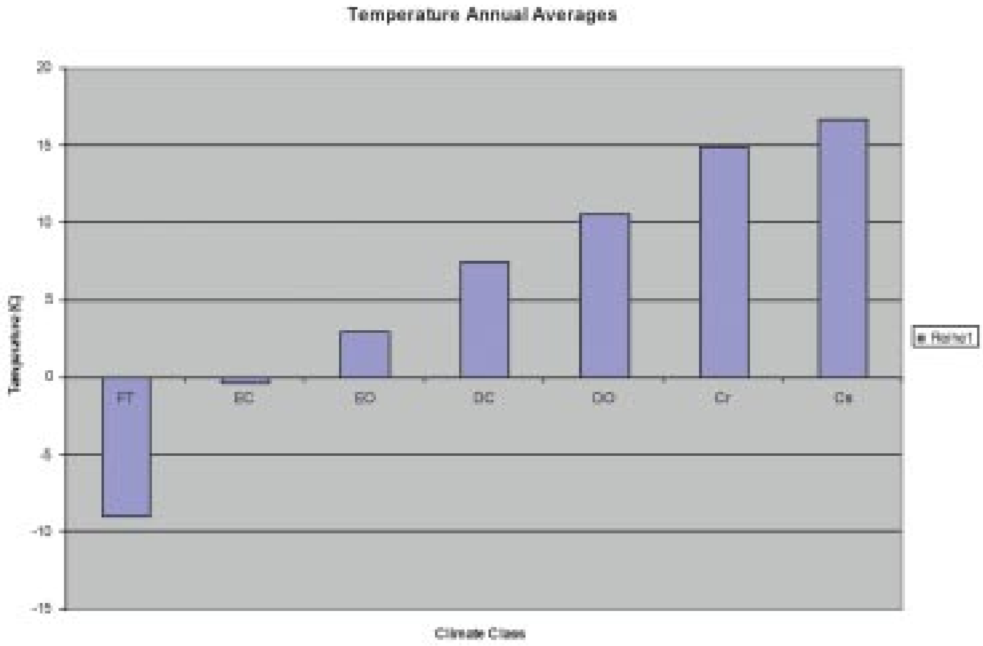


Figure C4.3: *Mean Annual Temperature by Climate Class for North Germany*

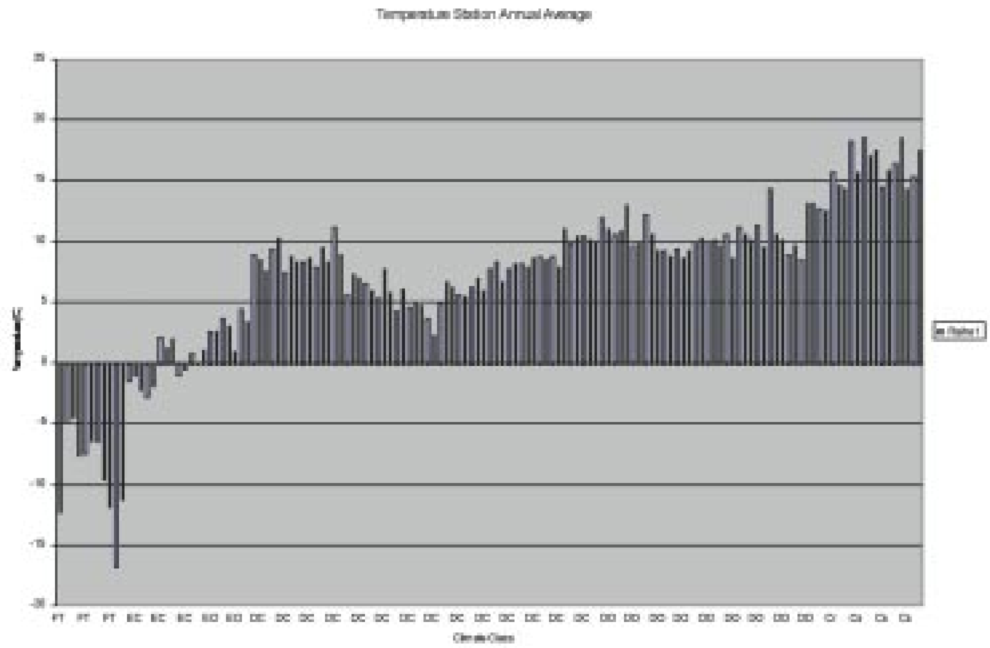
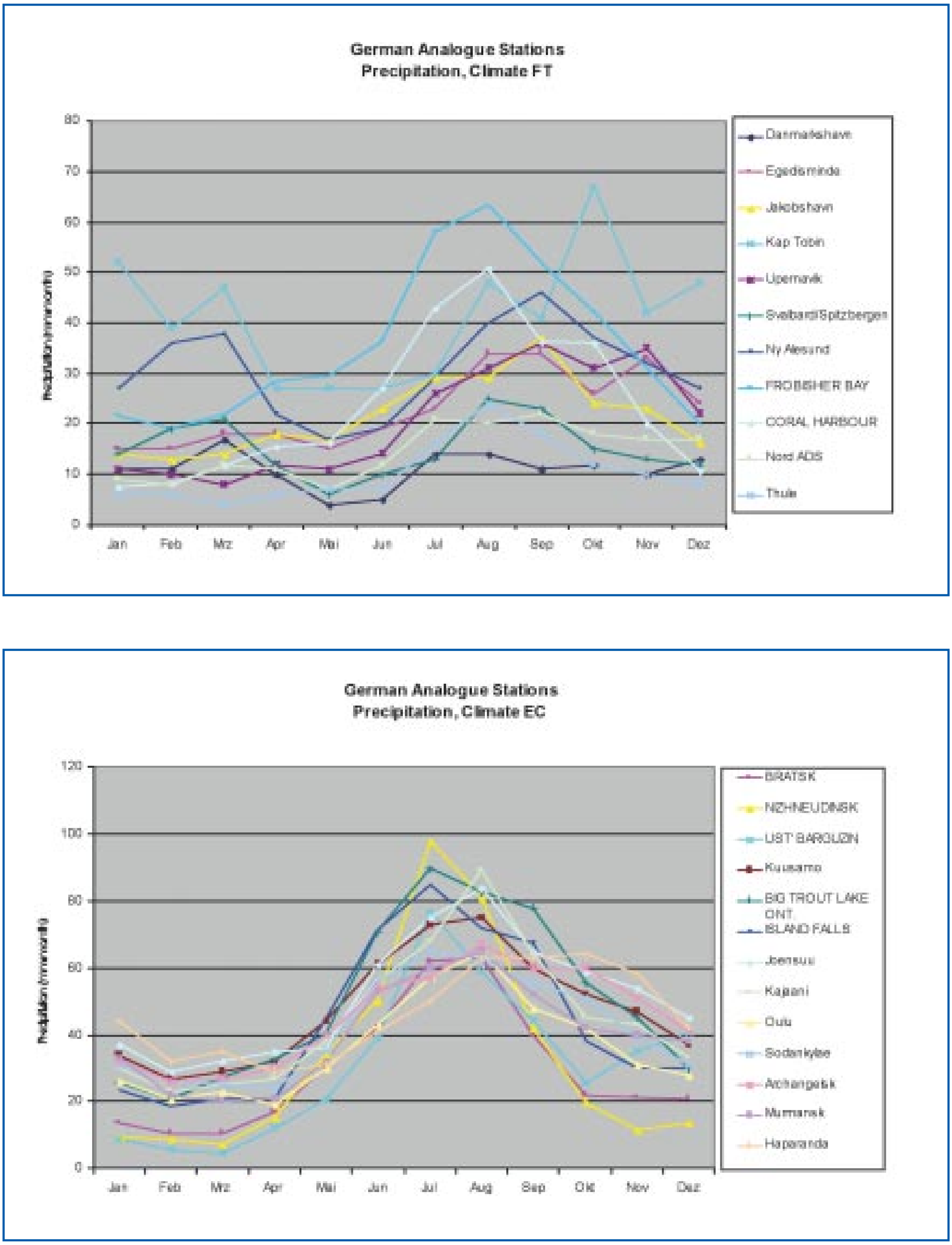


Figure C4.4: *Mean Annual Temperatures by Station for North Germany*

Figure C4.5: *Precipitation Data by Analogue Station for North Germany*



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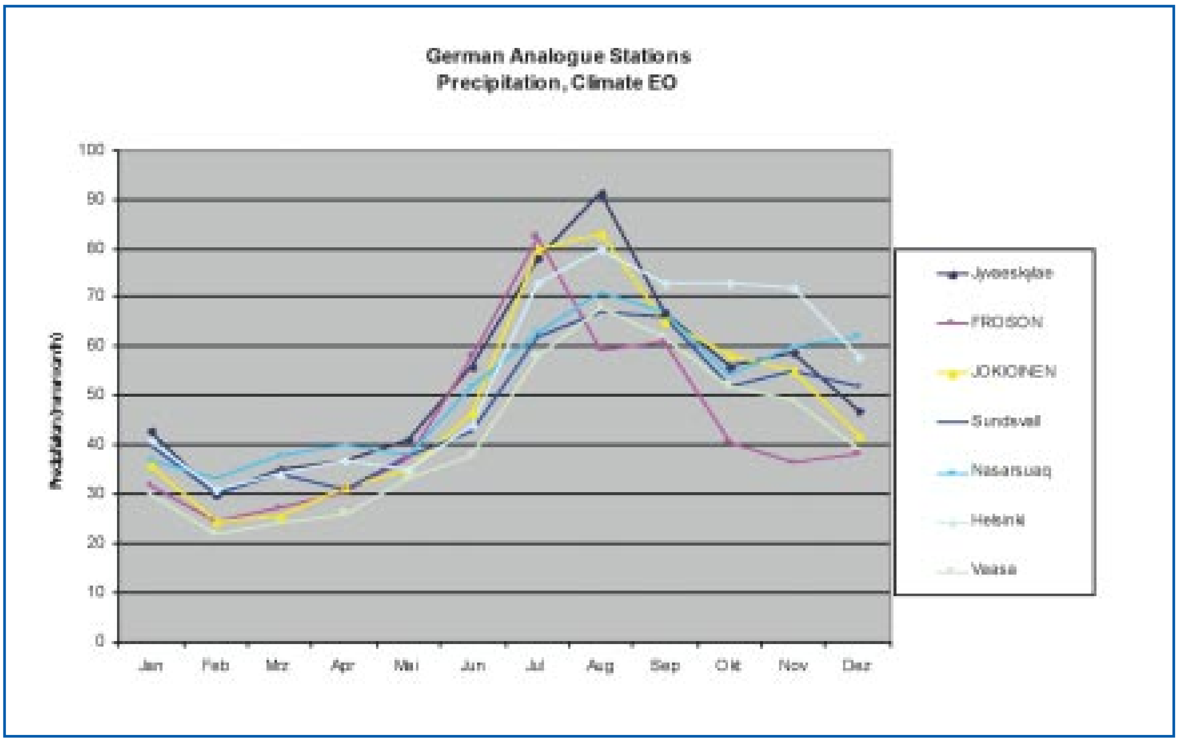
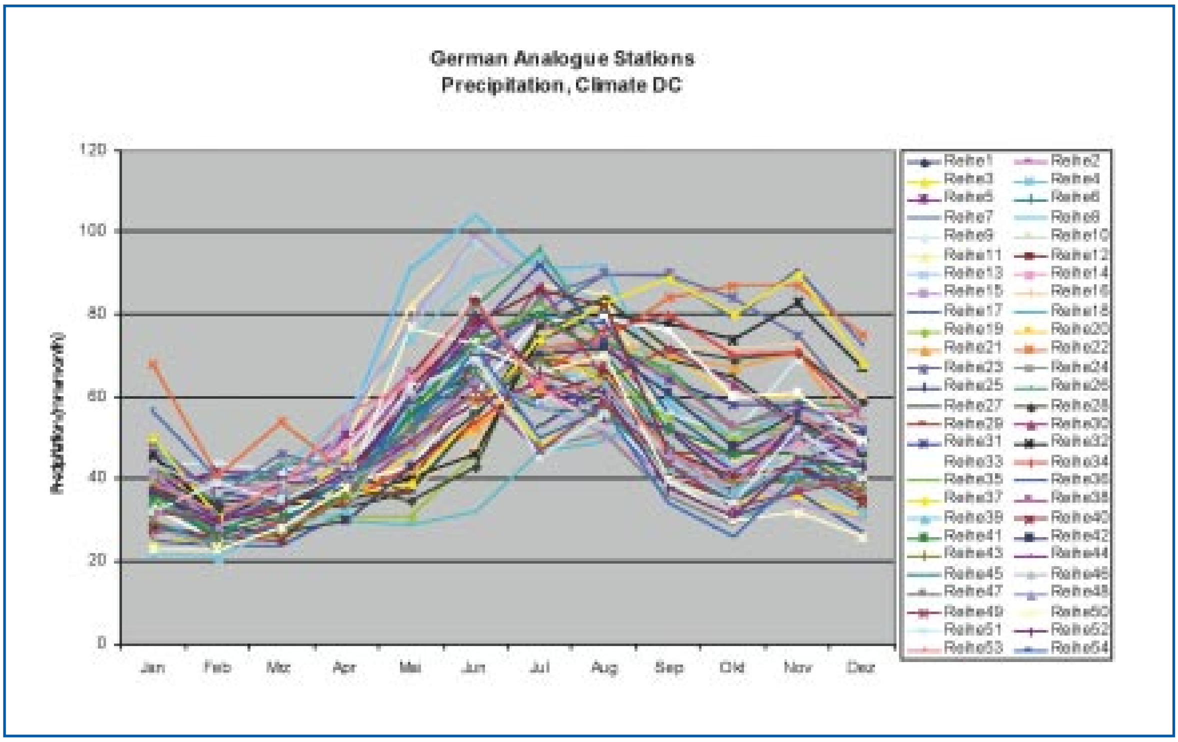

German Analogue Stations
Precipitation, Climate EO
Precipitation (mm/month)
100
90
80
70
60
50
40
30
20
10
0
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
Jyvaeskylae
FROSON
JOKIOINEN
Sundsvall
Nasarsuaq
Helsinki
Vaasa


German Analogue Stations
Precipitation, Climate DC
Precipitation (mm/month)
120
100
80
60
40
20
0
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
Reihe1
Reihe2
Reihe3
Reihe4
Reihe5
Reihe6
Reihe7
Reihe8
Reihe9
Reihe10
Reihe11
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Reihe15
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Reihe44
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Reihe51
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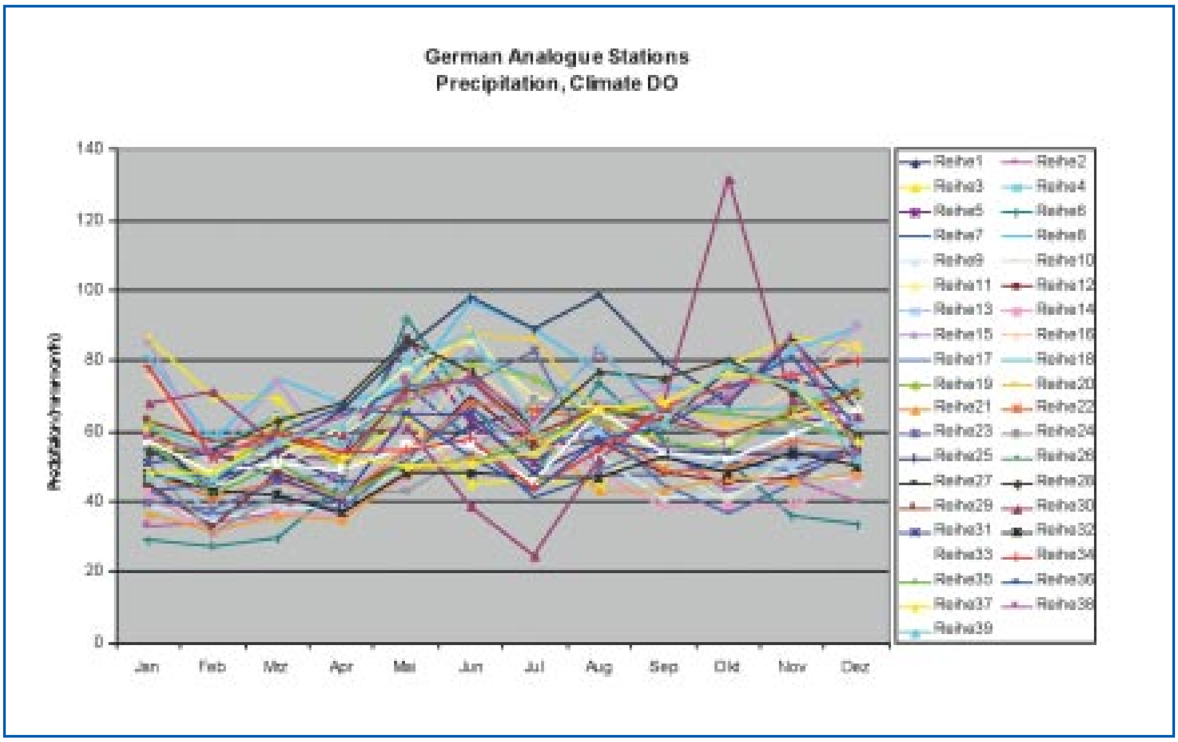
Reihe53
Reihe54


German Analogue Stations
Precipitation, Climate DO
Precipitation (mm/month)
0
20
40
60
80
100
120
140
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
Reihe1
Reihe2
Reihe3
Reihe4
Reihe5
Reihe6
Reihe7
Reihe8
Reihe9
Reihe10
Reihe11
Reihe12
Reihe13
Reihe14
Reihe15
Reihe16
Reihe17
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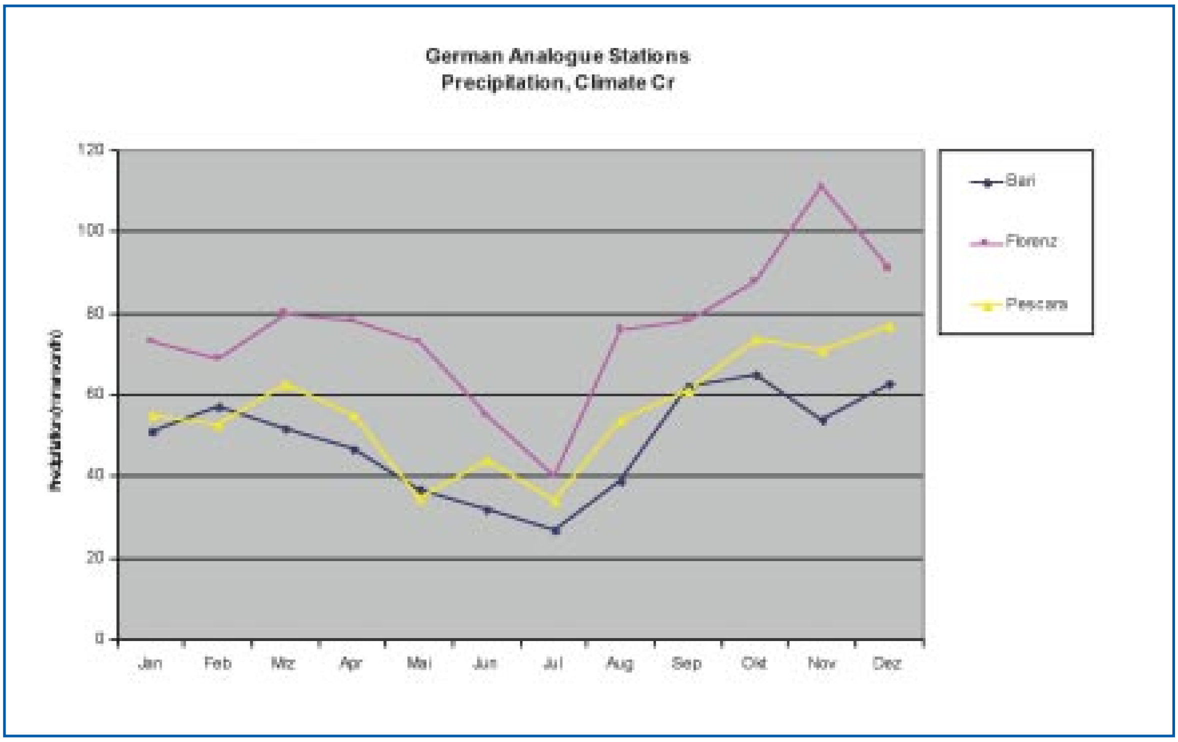
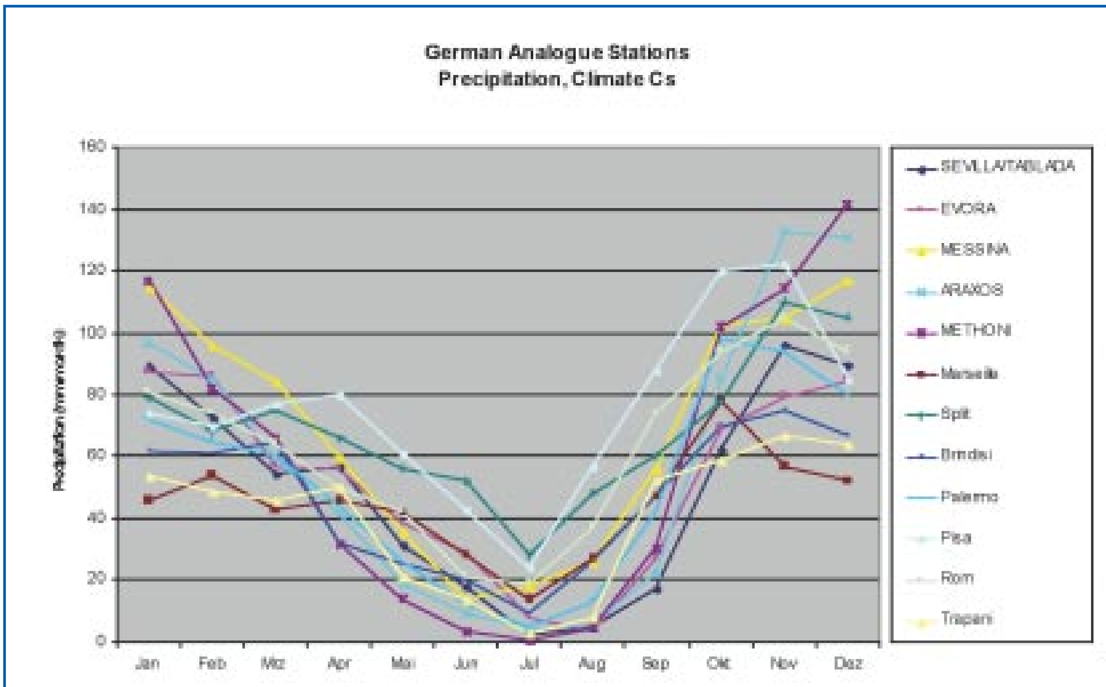
Reihe36
Reihe37
Reihe38
Reihe39


German Analogue Stations
Precipitation, Climate Cr
Precipitation (mm/month)
0
20
40
60
80
100
120
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
Bari
Florenz
Pescara



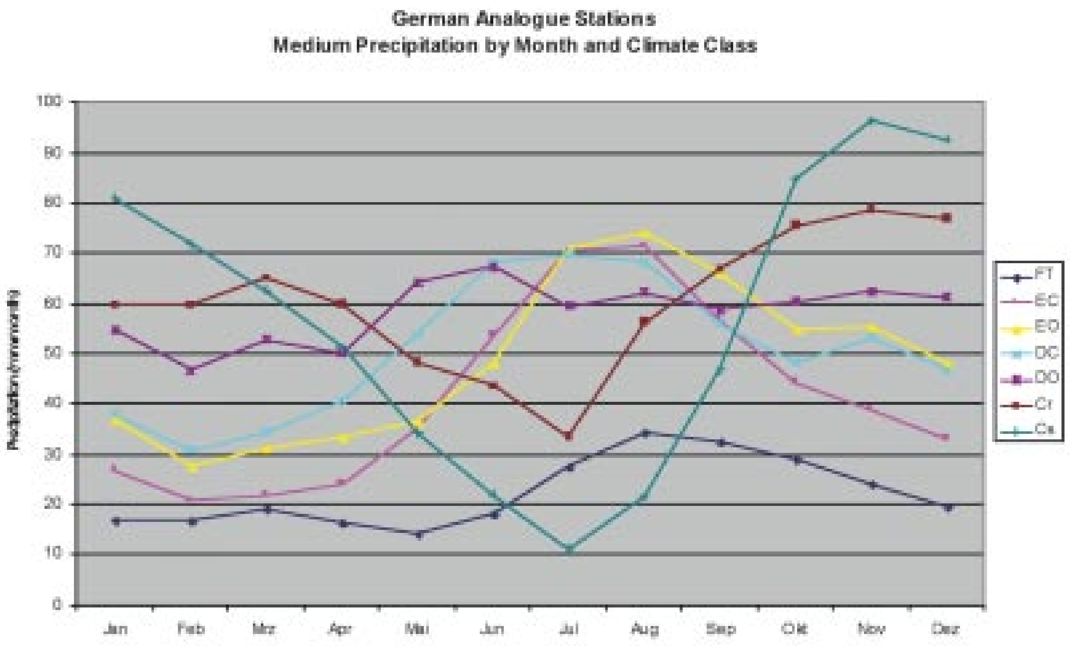


Figure C4.6: *Mean Precipitation Values by Climate Class*

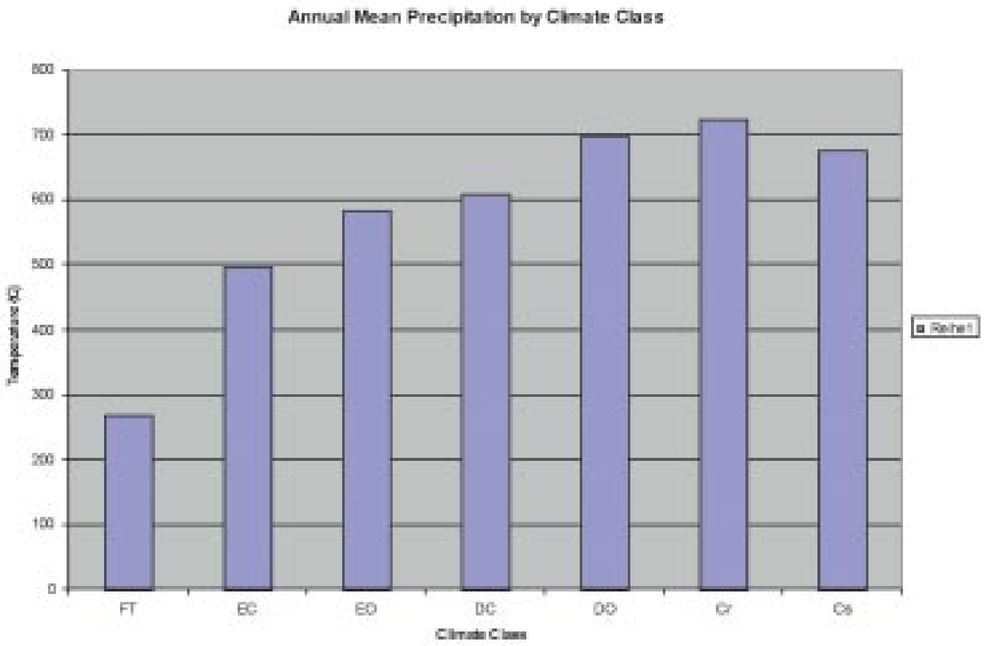


__Figure C4.7:__ Annual Mean Precipitation by Climate Class

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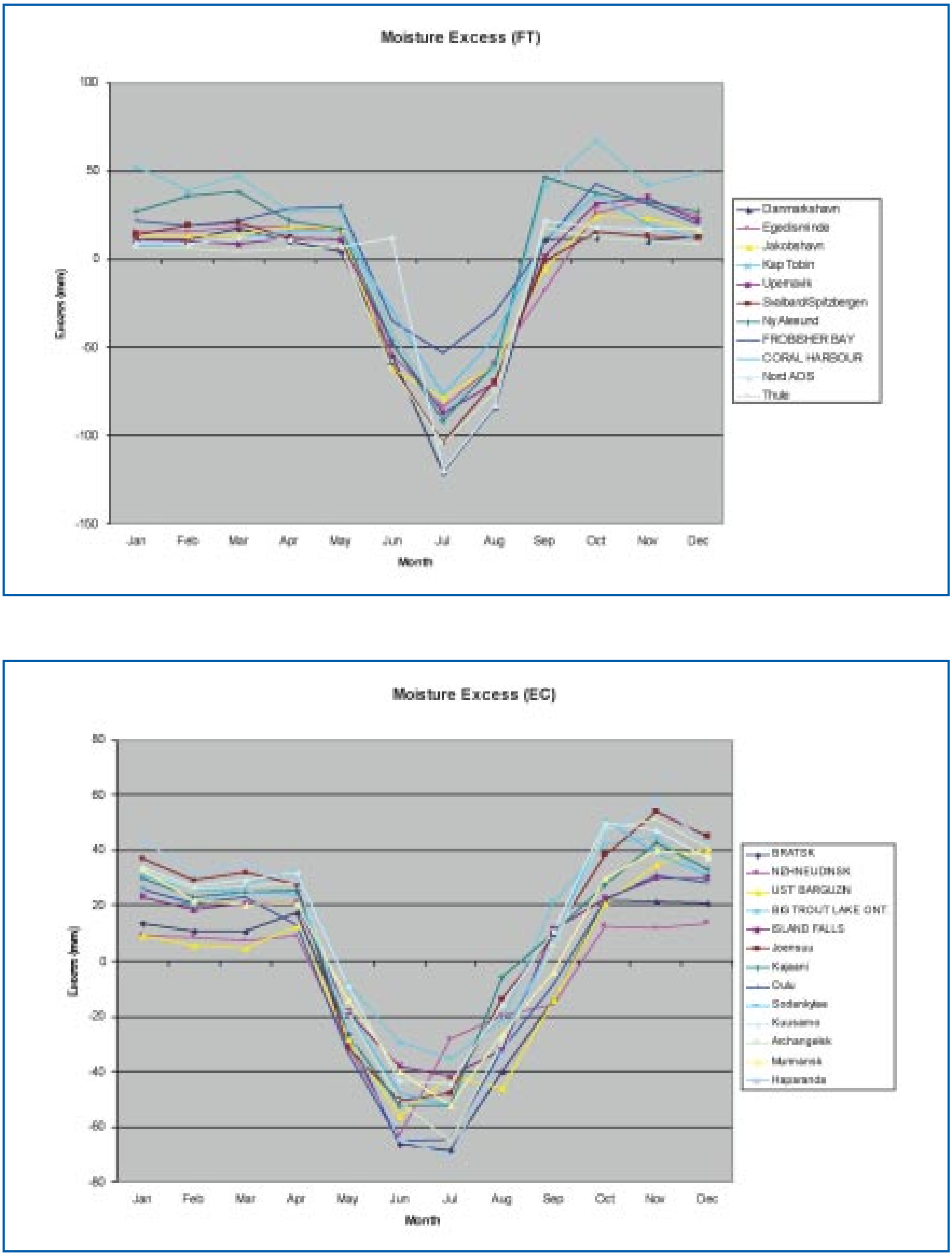
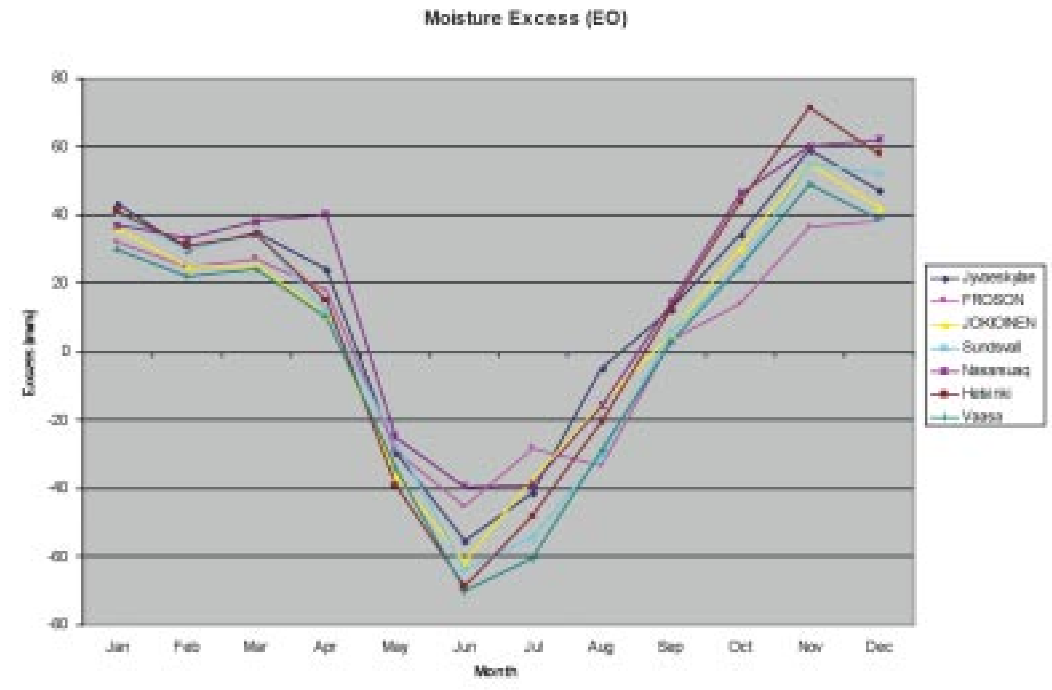
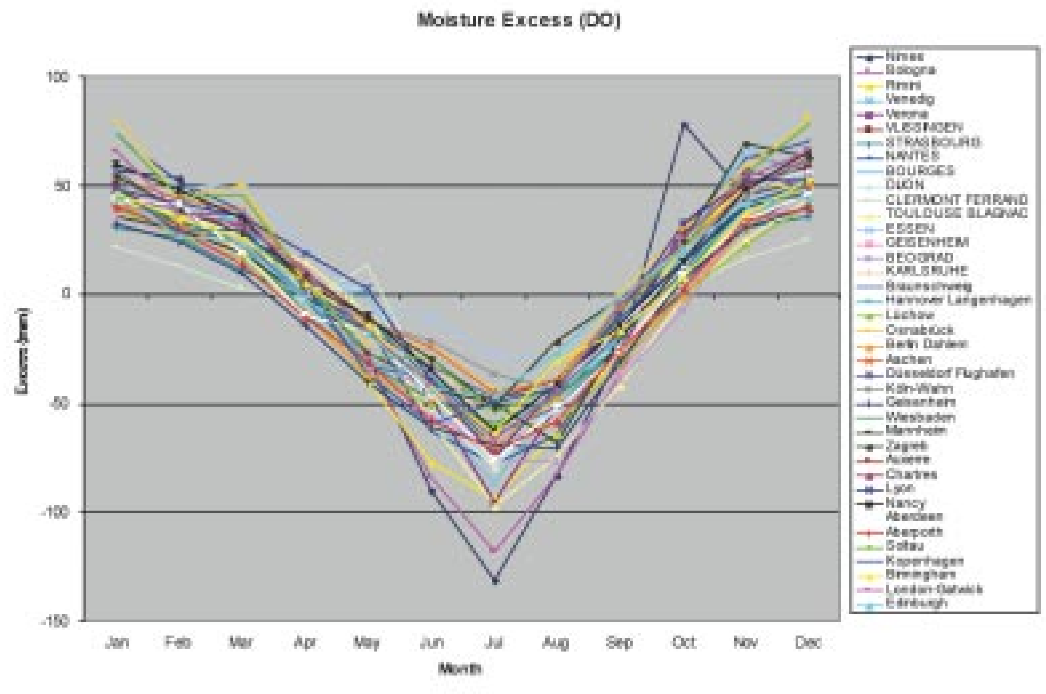
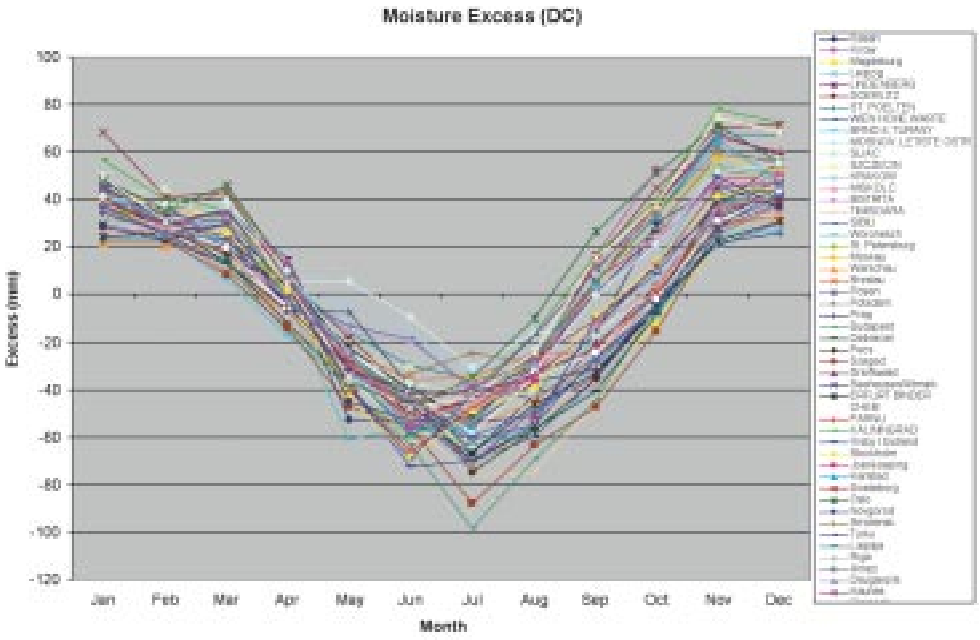
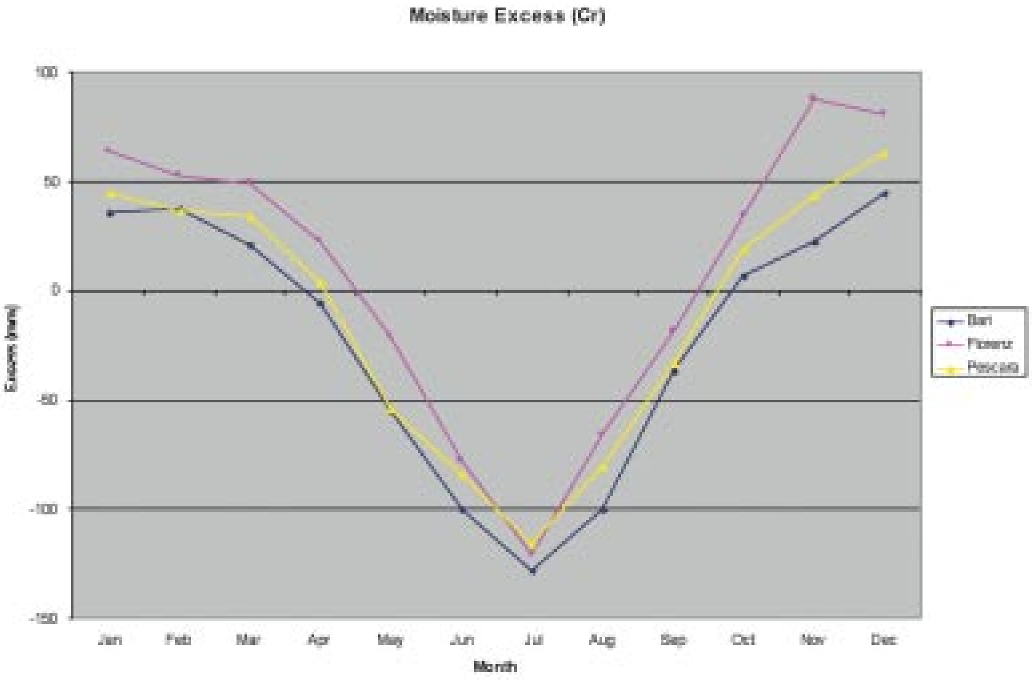
Figure C4.8: *Moisture Excess for by Analogue Station for North Germany*




Moisture Excess (EO)


Moisture Excess (DO)


Moisture Excess (DC)
Excess (mm)
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Magdeburg
LINDENBERG
GOERLITZ
ST. POELTEN
WIEN HOHE WARTE
BRNO-L.TURANY
MOSNOV LETISTE-OSTR
SLIAC
KRAKOW
BISTRITA
TIMISOARA
SIBIU
St. Petersburg
Moskau
Warschau
Breslau
Posen
Potsdam
Prag
Budapest
Debrecen
Pecs
Szeged
ERFURT BINDER
CHEB
KALININGRAD
Stockholm
Oslo
Riga


Moisture Excess (Cr)
Excess (mm)
100
50
0
-50
-100
-150
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Bari
Florenz
Pescara

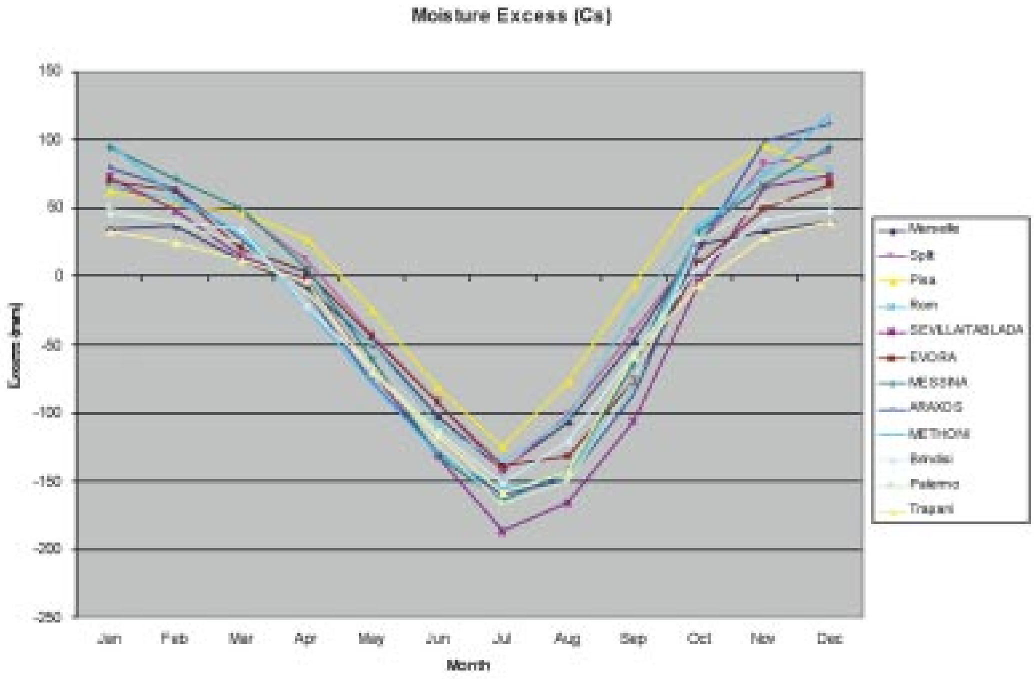


Figure C4.9: *Arithmetic Mean Monthly Moisture Excess by Climate Class*

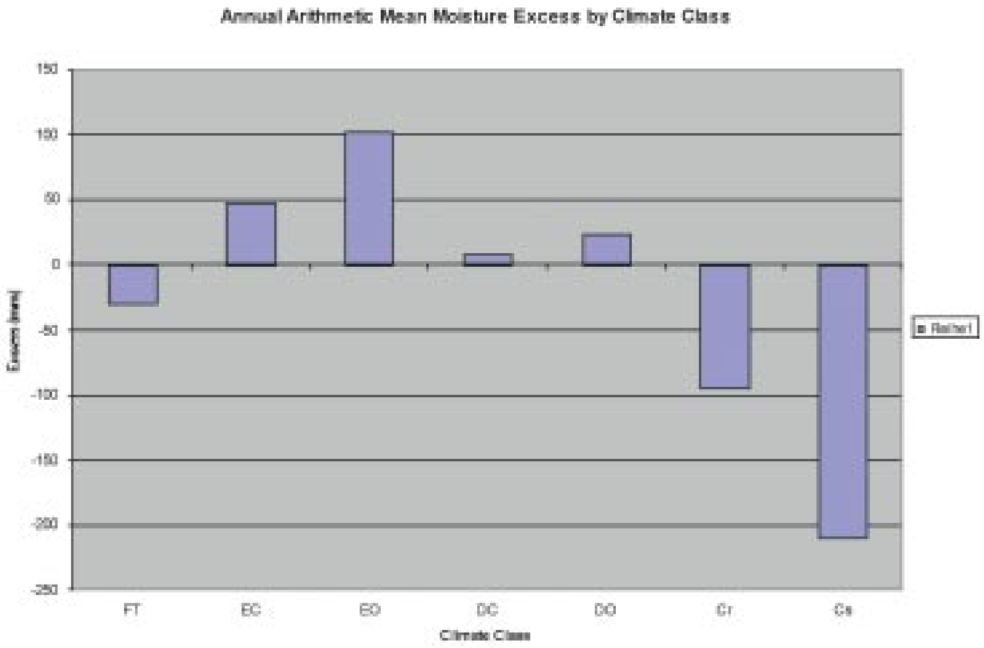


Figure C4.10: *Annual Arithmetic Mean Moisture Excess by Climate Class*

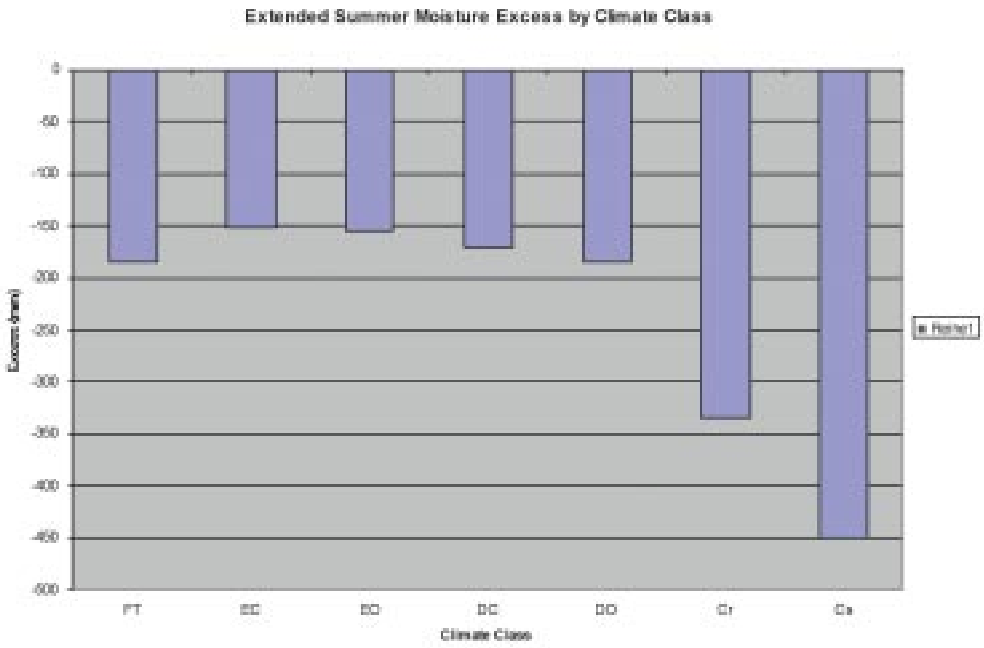


Figure C4.11: *Extended Summer Moisture Deficits by Climate Class*

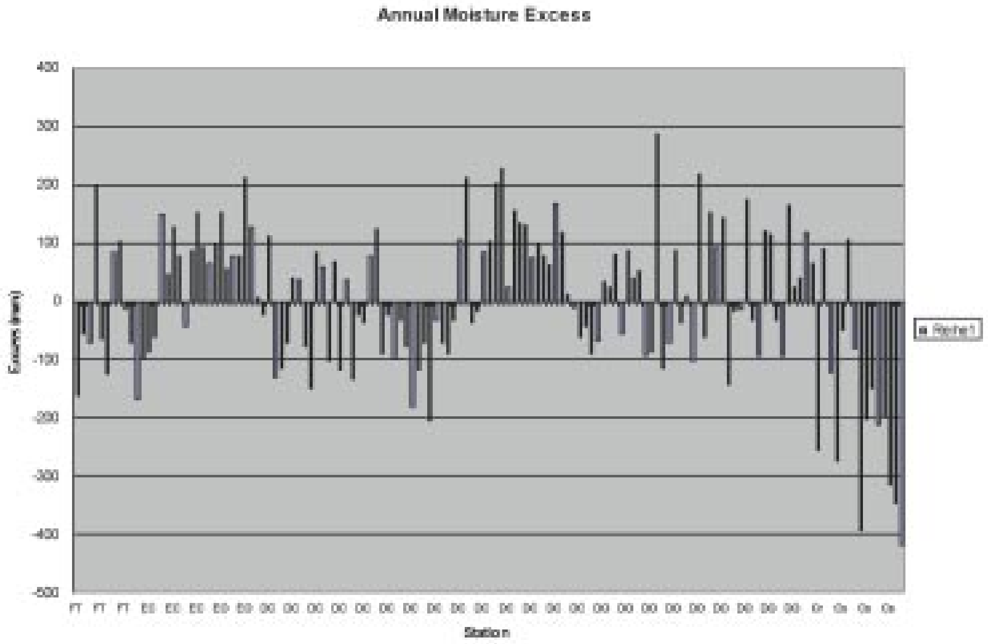


Figure C4.12: *Annual Moisture Excess or Deficit by Station*

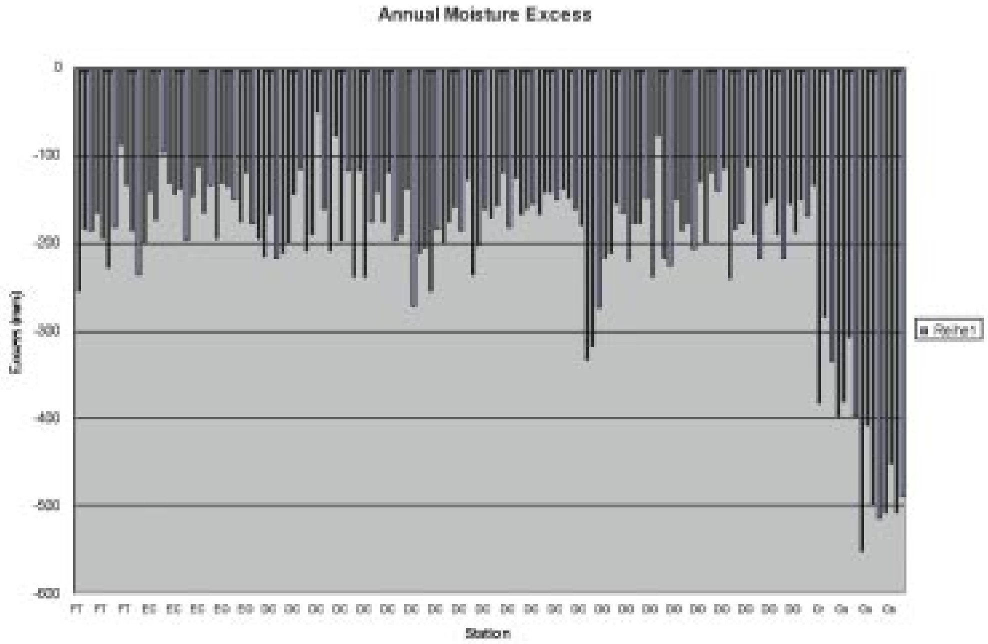


Figure C4.13: *Summer Moisture Excess by Station*

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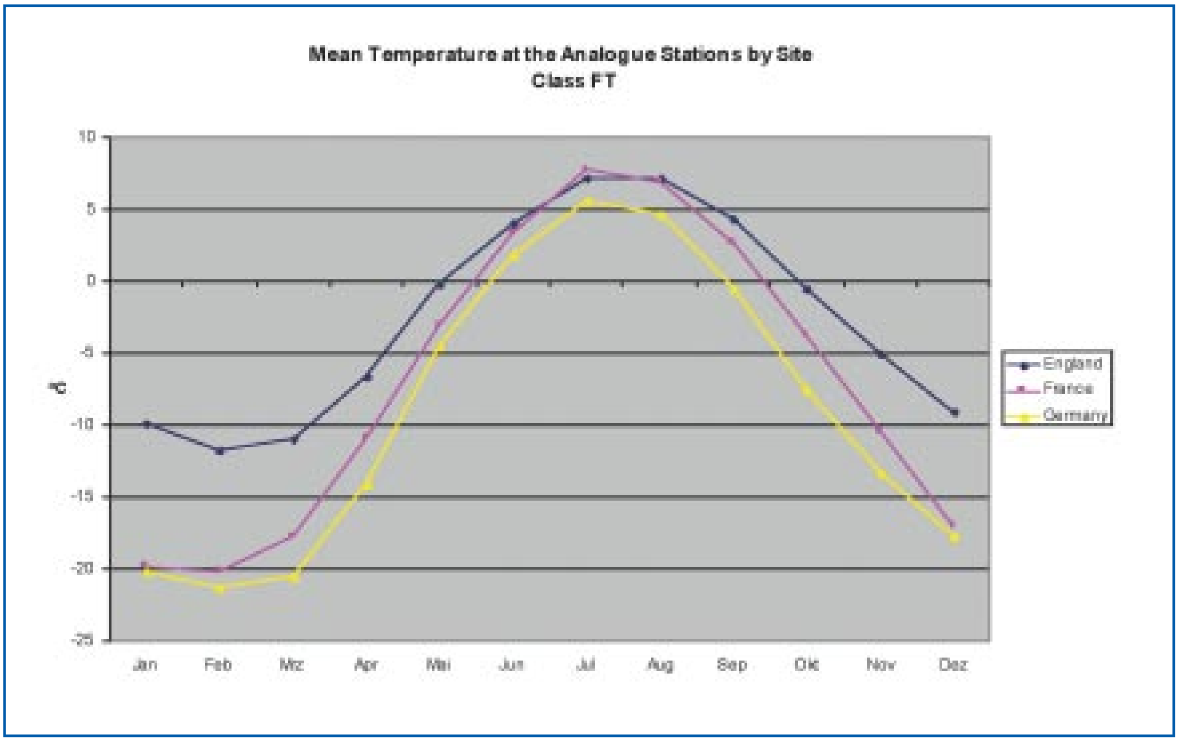
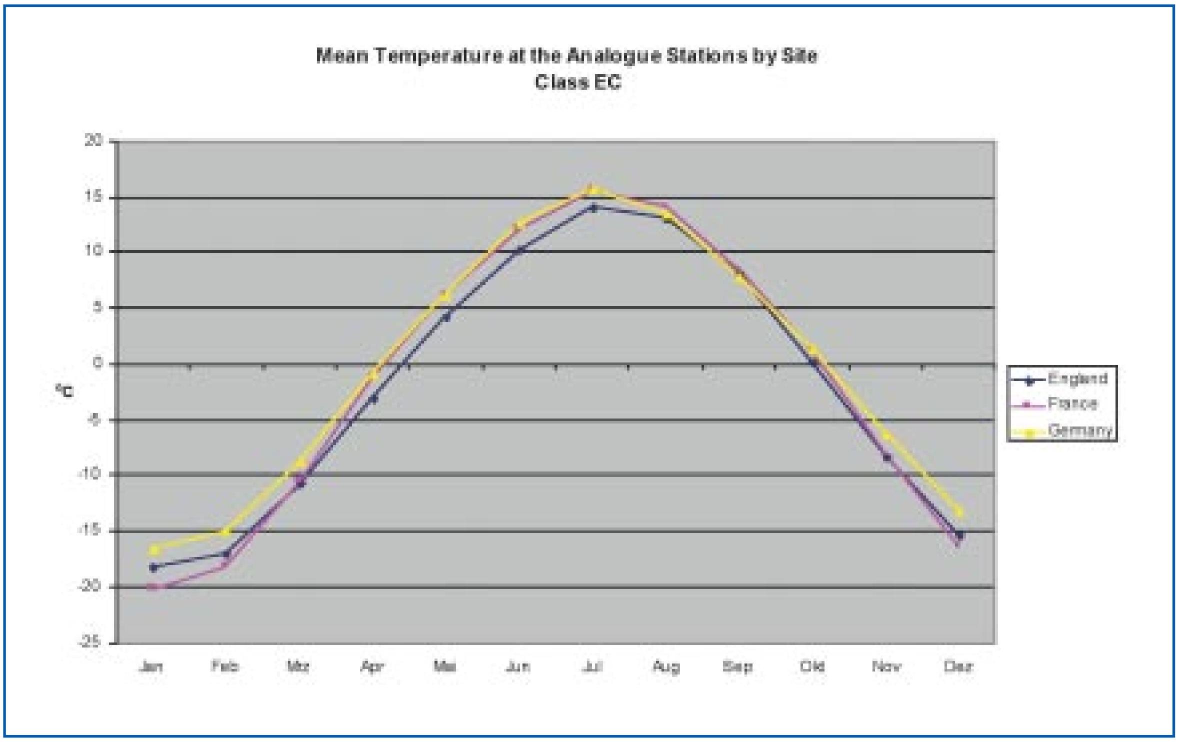
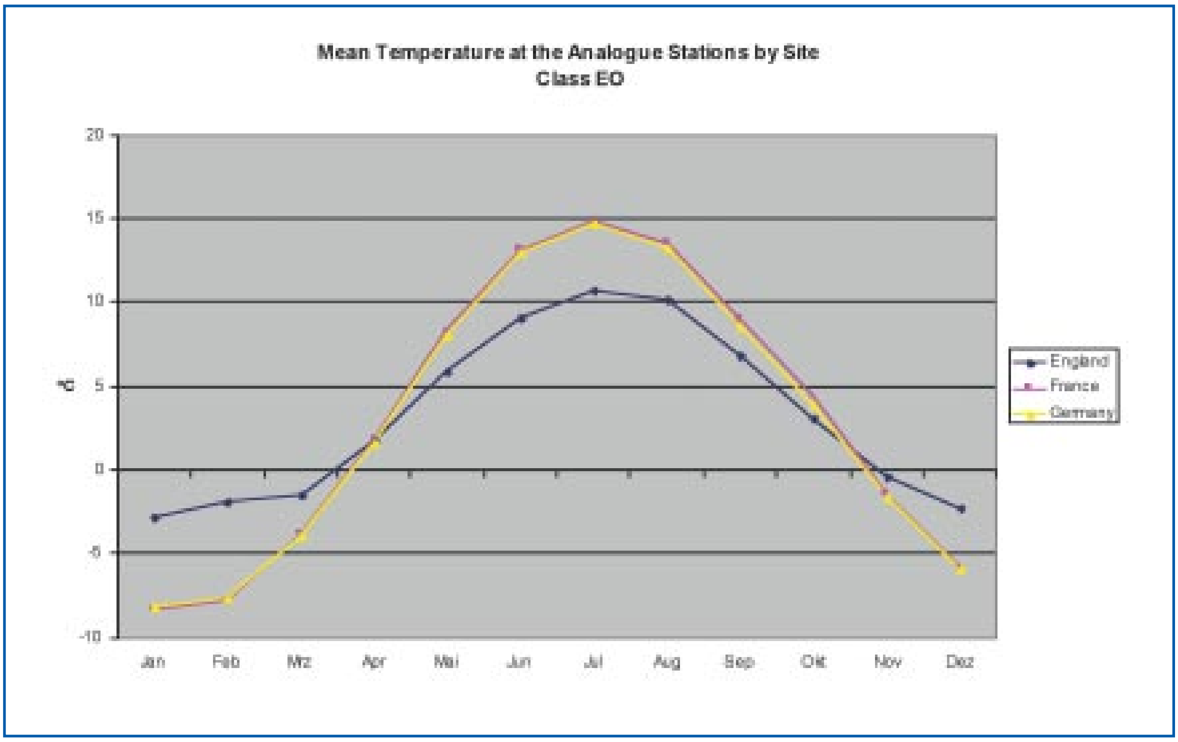
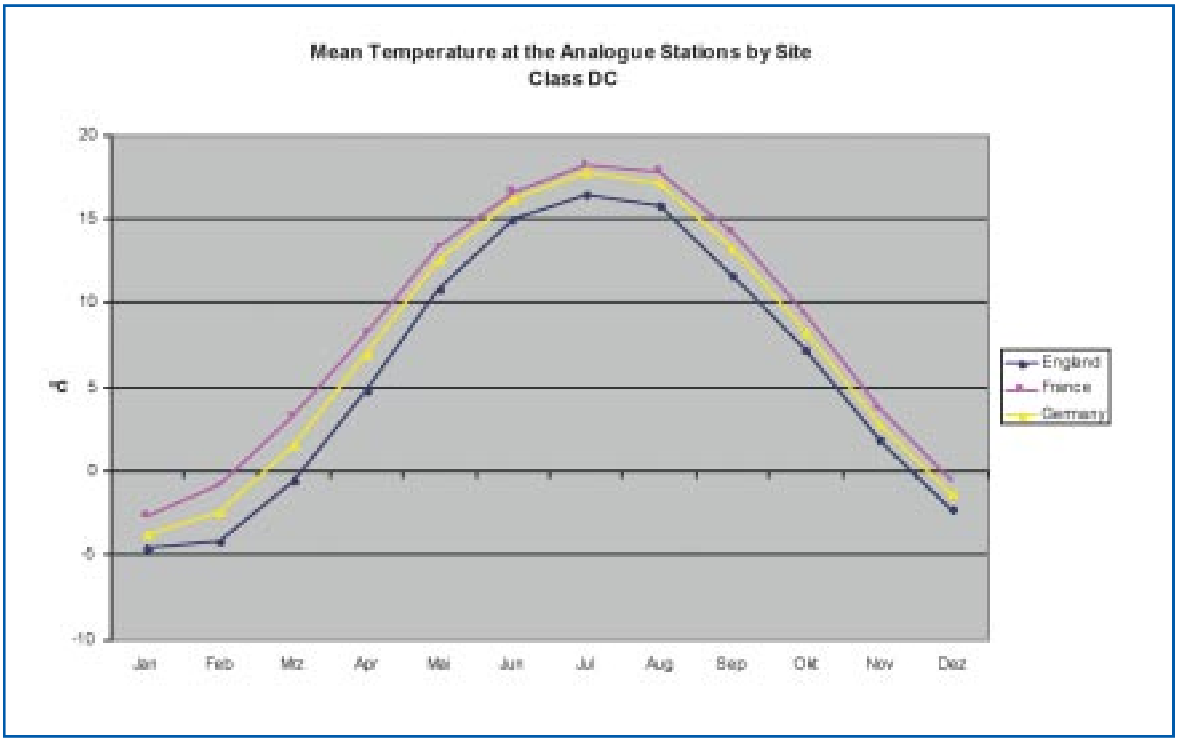
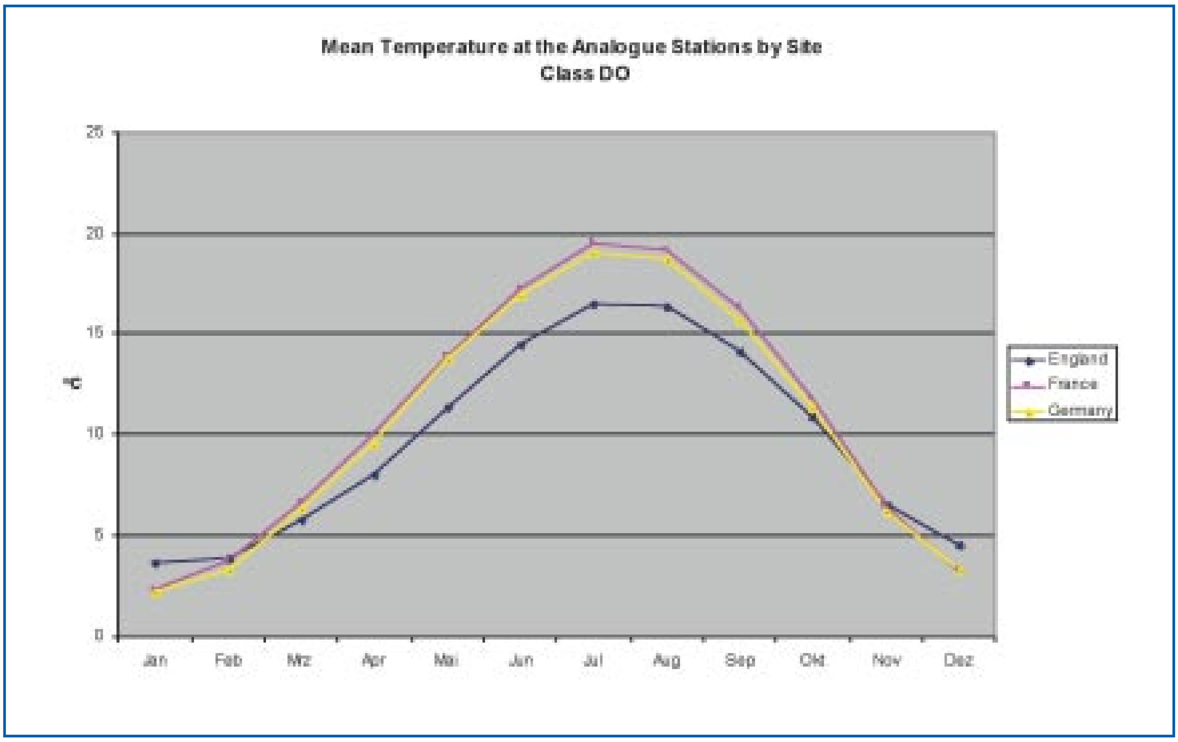
Figure C4.14: *Temperature Data for Analogue Stations of the British, French and German Sites*

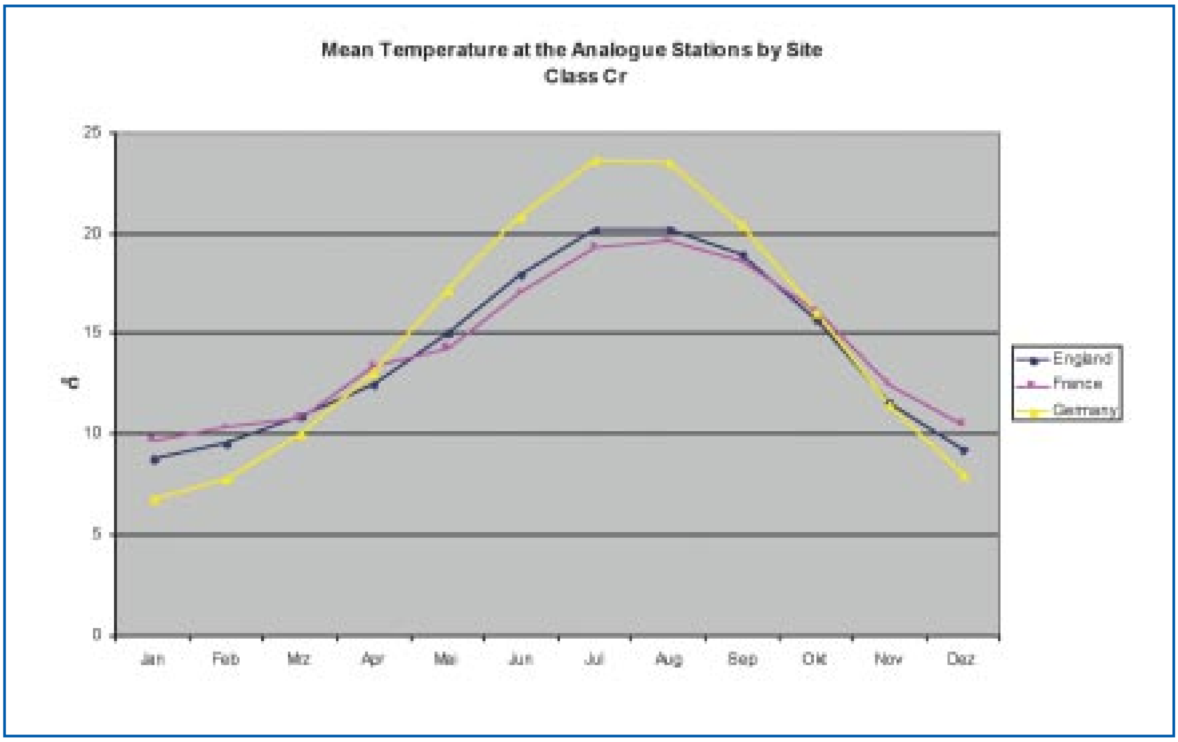





Mean Temperature at the Analogue Stations by Site
Class EO
20
15
10
5
0
-5
-10
°C
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
England
France
Germany


Mean Temperature at the Analogue Stations by Site
Class DC
20
15
10
5
0
-5
-10
°C
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
England
France
Germany


Mean Temperature at the Analogue Stations by Site
Class DO
°C
0
5
10
15
20
25
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
England
France
Germany


Mean Temperature at the Analogue Stations by Site
Class Cr
°C
0
5
10
15
20
25
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
England
France
Germany

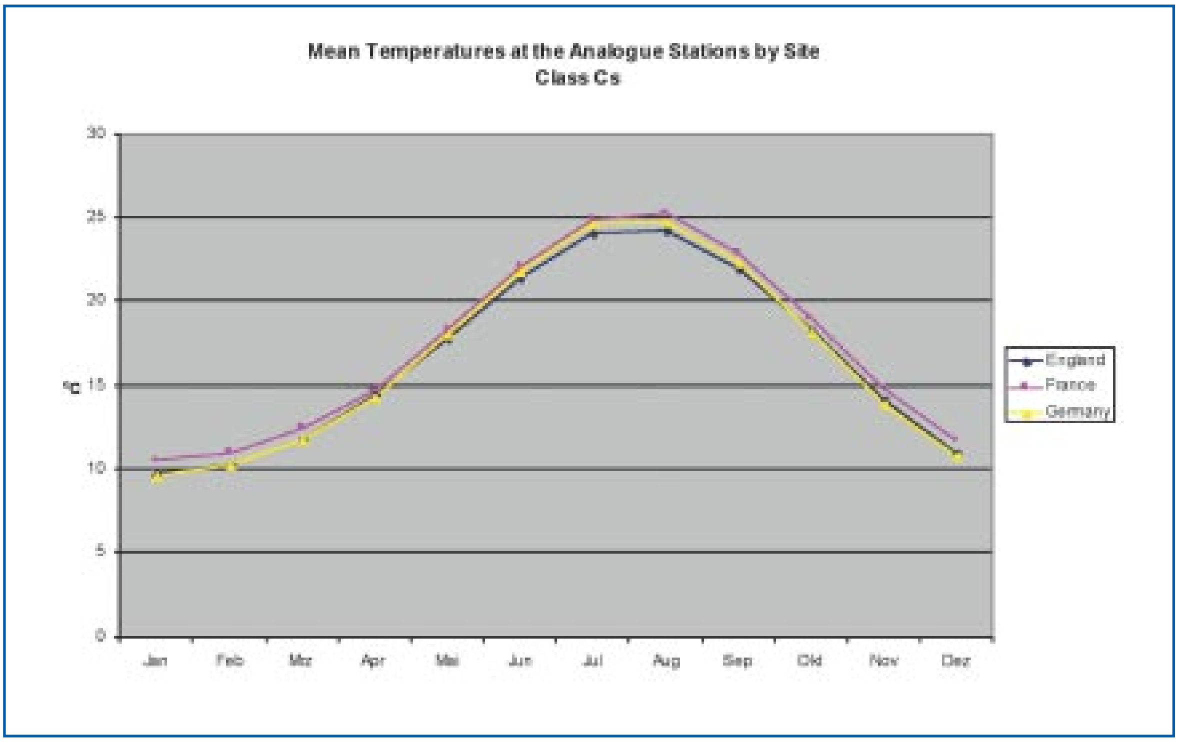

Mean Temperatures at the Analogue Stations by Site
Class Cs
°C
30
25
20
15
10
5
0
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
England
France
Germany

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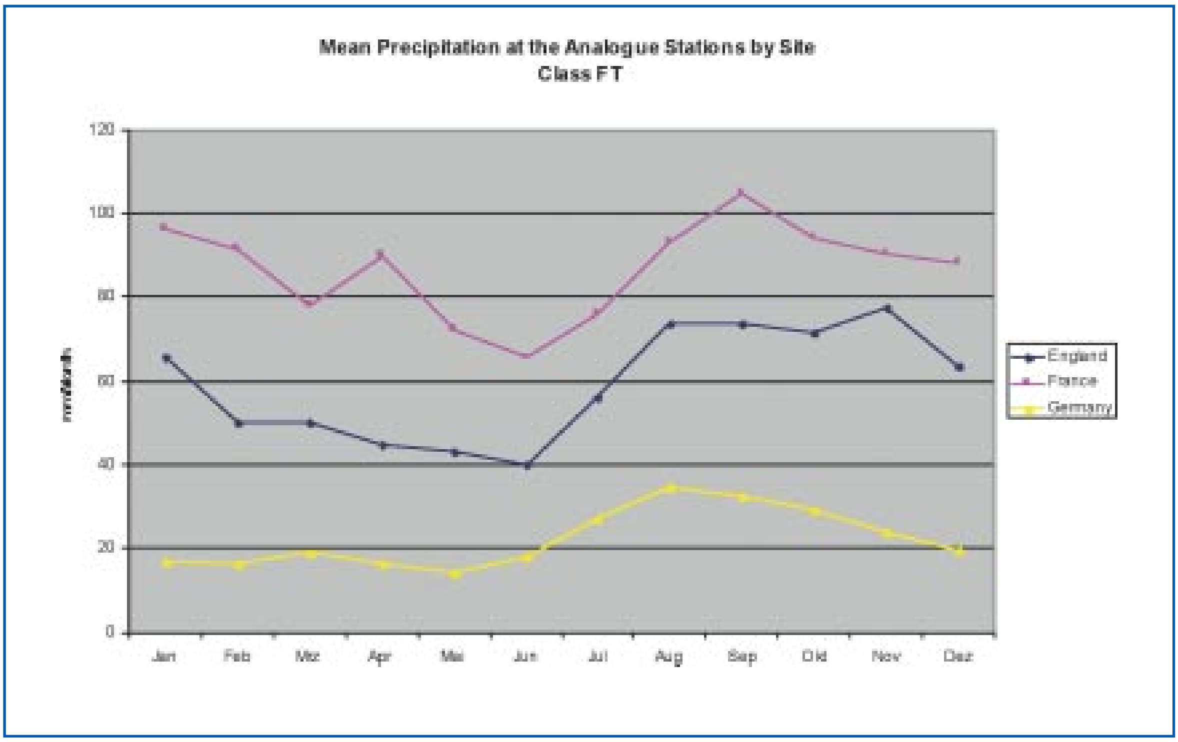
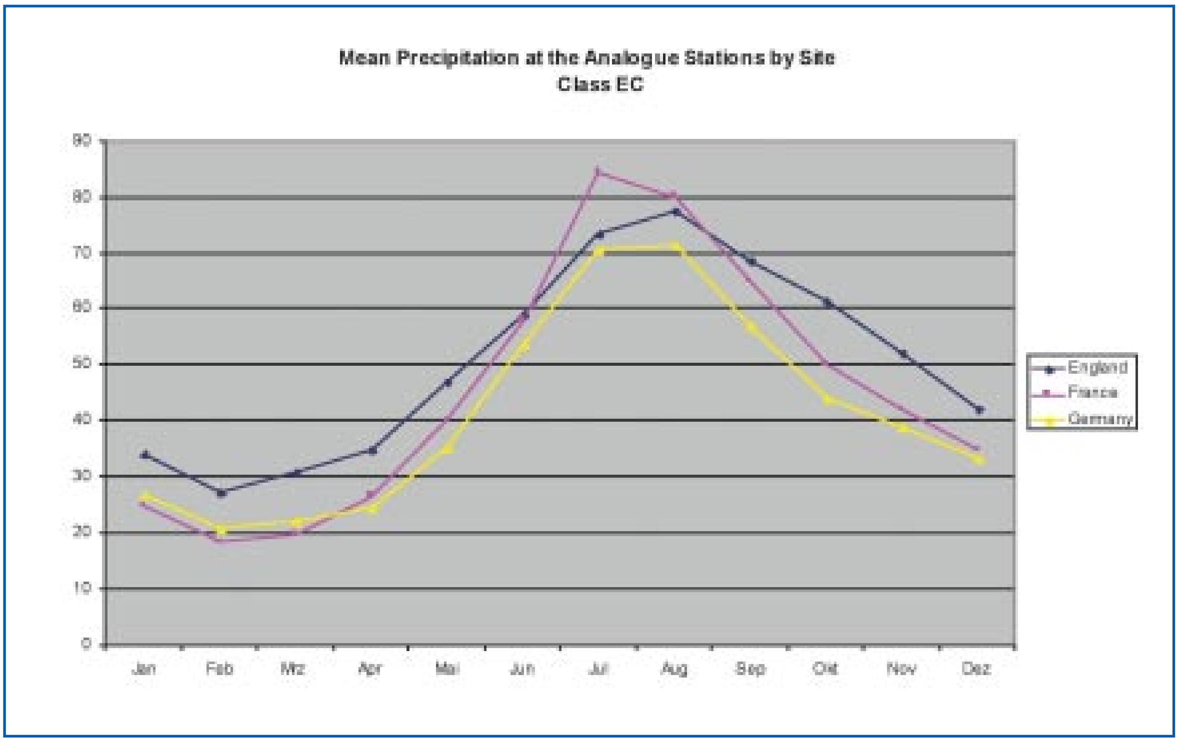
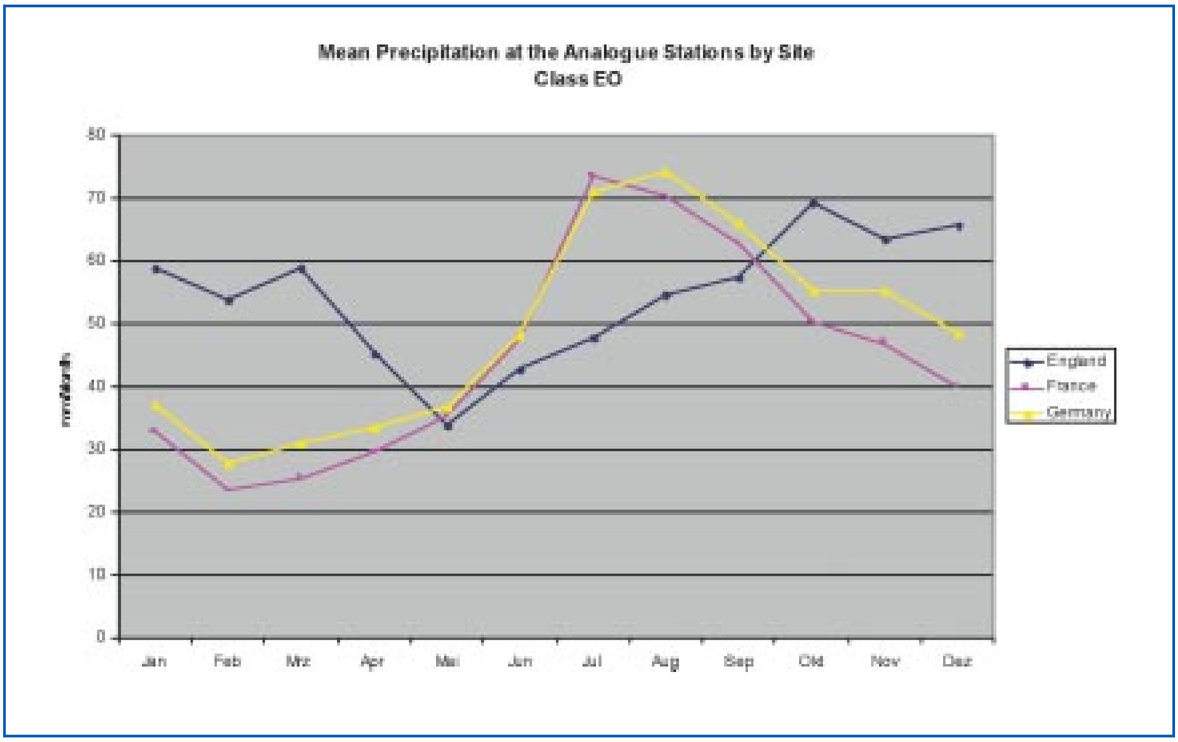
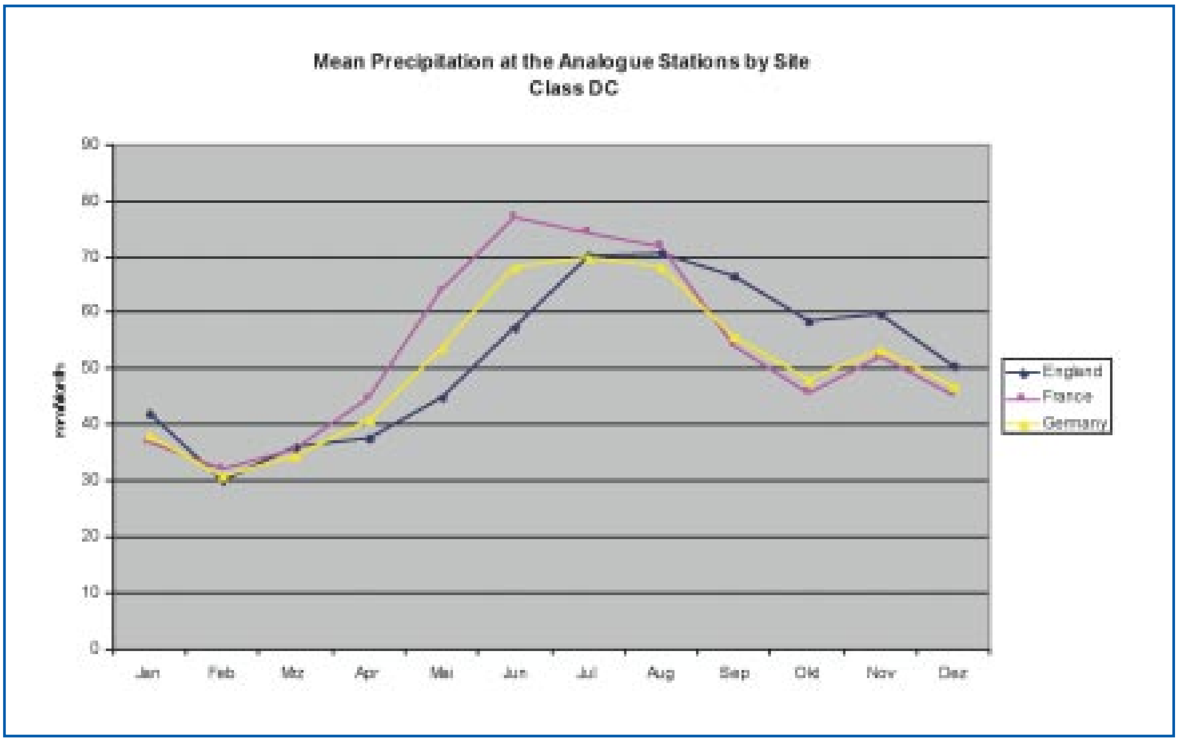
Figure C4.15: *Precipitation Data for Analogue Stations of the British, French and German Sites*






Mean Precipitation at the Analogue Stations by Site
Class EO
80
70
60
50
40
30
20
10
0
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
England
France
Germany


Mean Precipitation at the Analogue Stations by Site
Class DC
90
80
70
60
50
40
30
20
10
0
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
England
France
Germany

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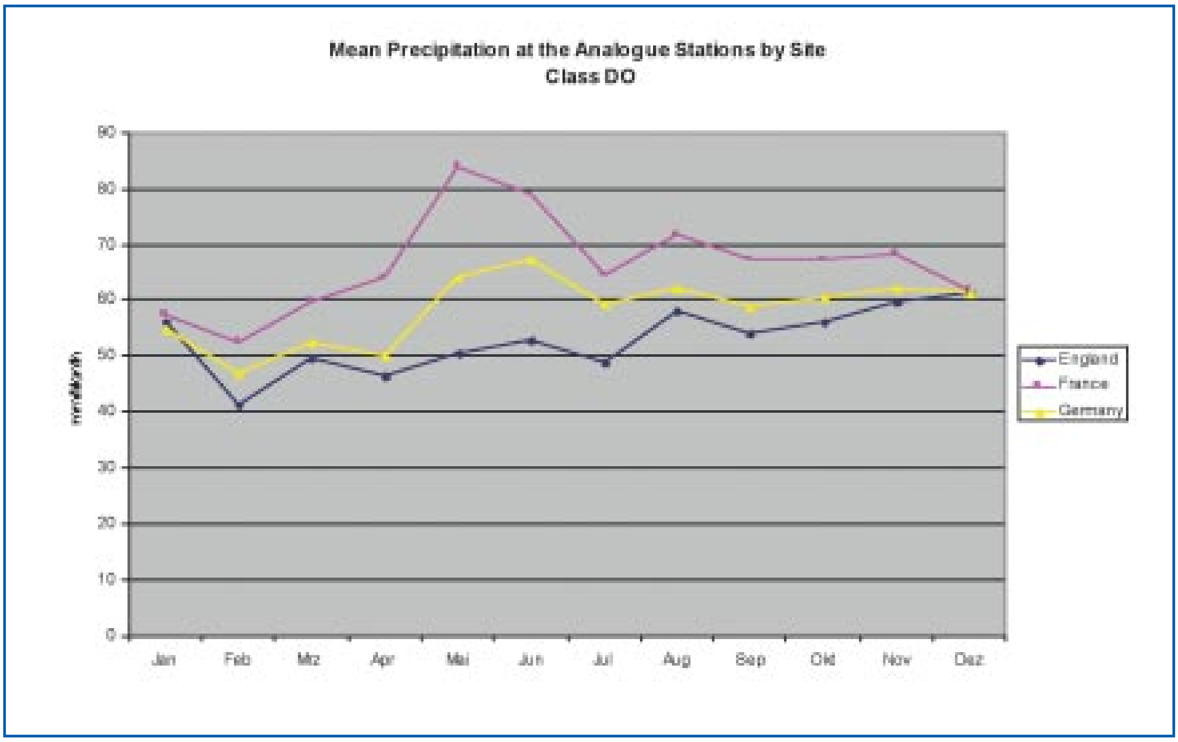
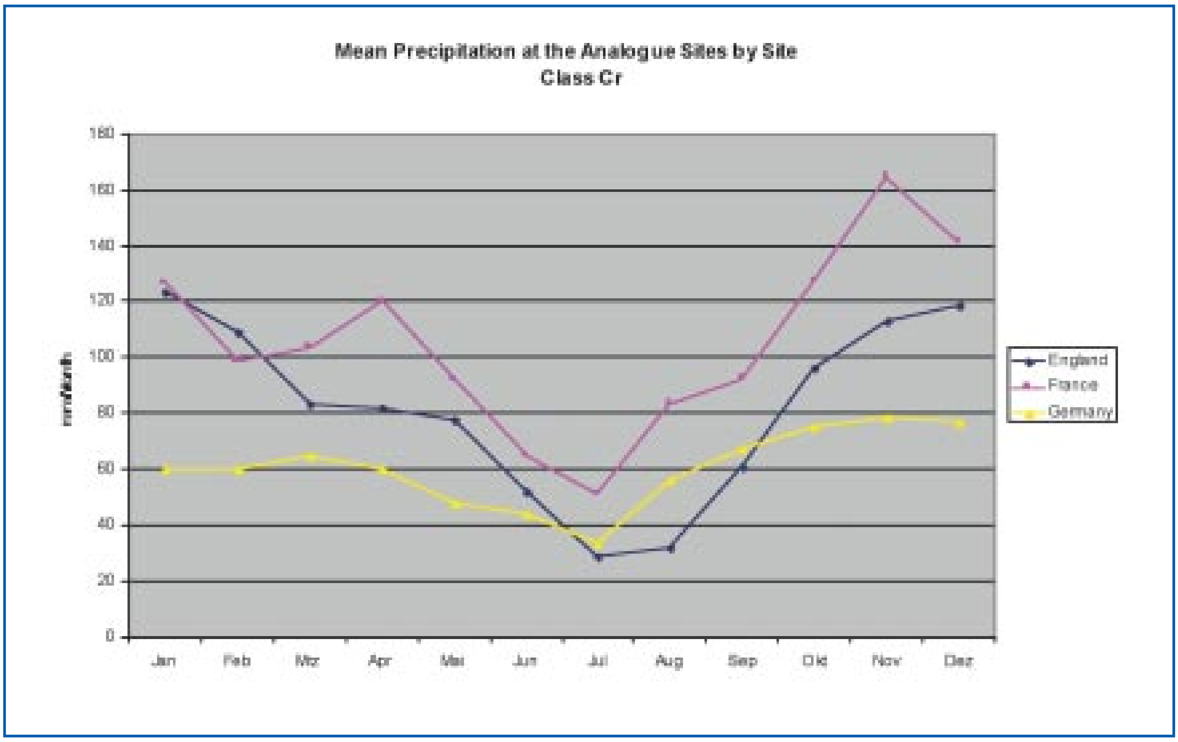
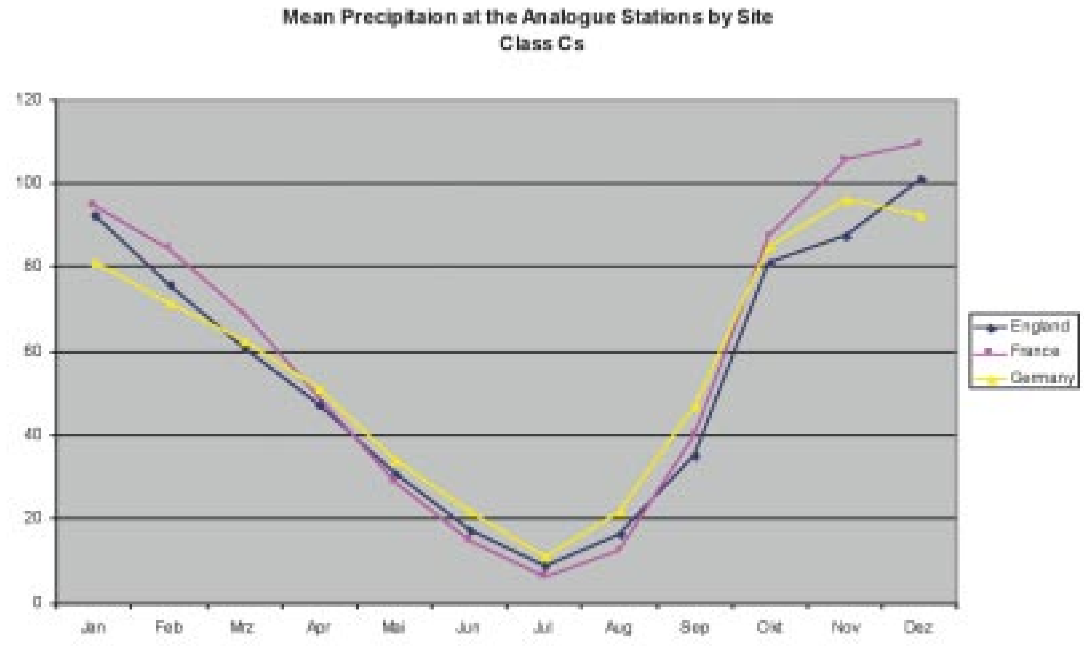

Mean Precipitation at the Analogue Stations by Site
Class DO
mm/Month
0
10
20
30
40
50
60
70
80
90
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
England
France
Germany


Mean Precipitation at the Analogue Sites by Site
Class Cr
mm/Month
0
20
40
60
80
100
120
140
160
180
Jan
Feb
Mrz
Apr
Mai
Jun
Jul
Aug
Sep
Okt
Nov
Dez
England
France
Germany



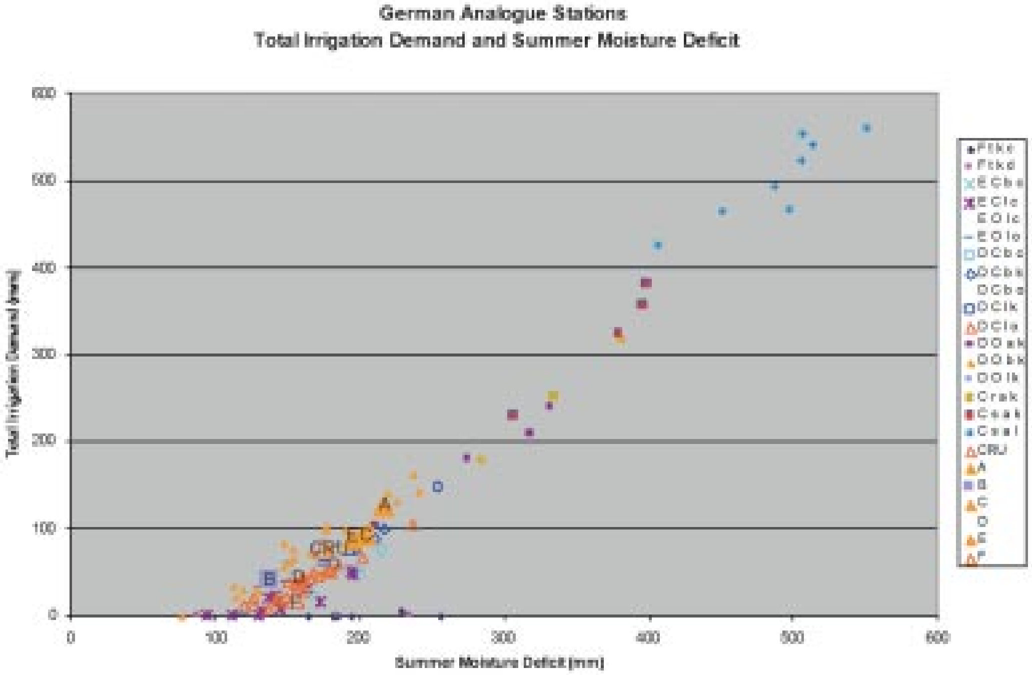


Figure C4.16: *Relation between Summer Moisture Deficit and Total Irrigation Demand*

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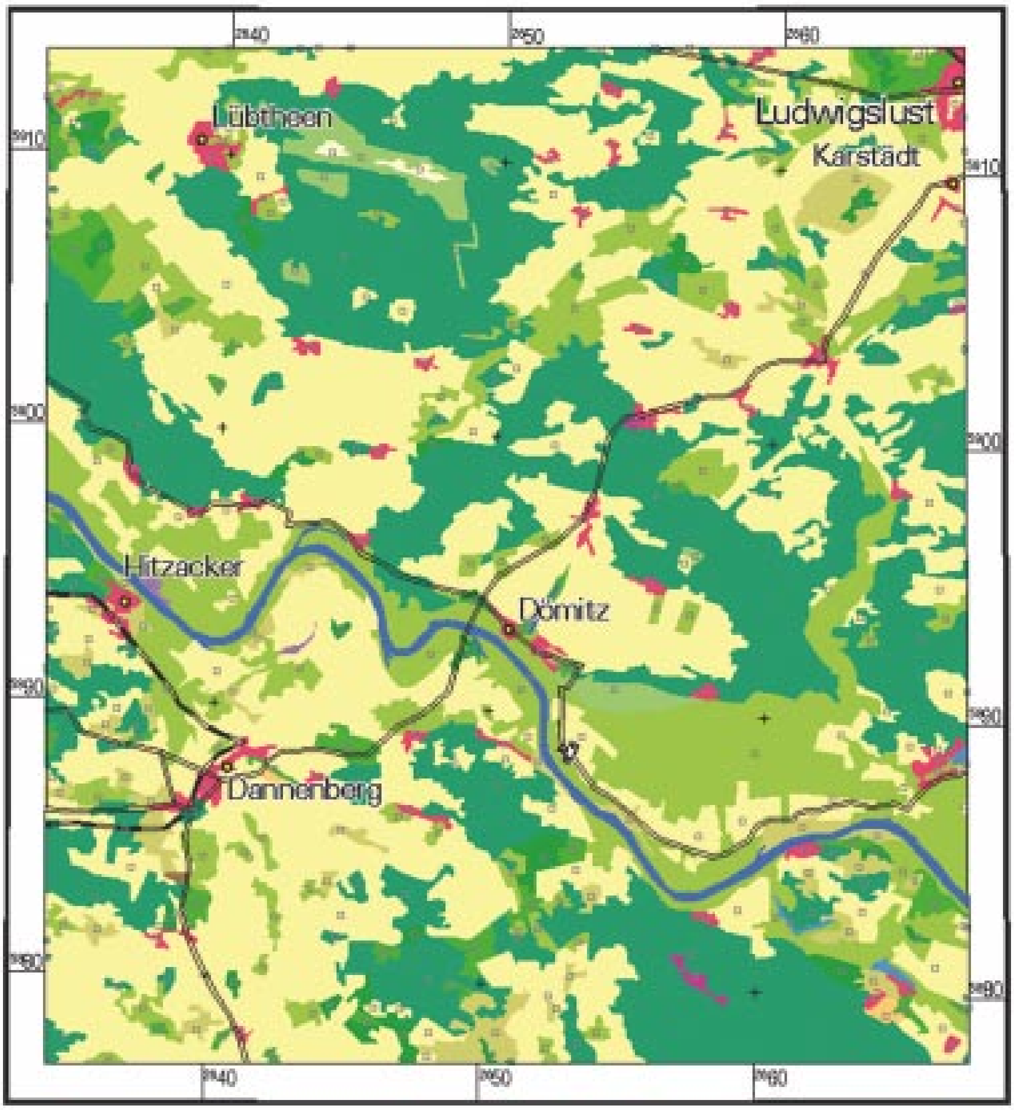

Figure C4.17: *A Typical Landscape*

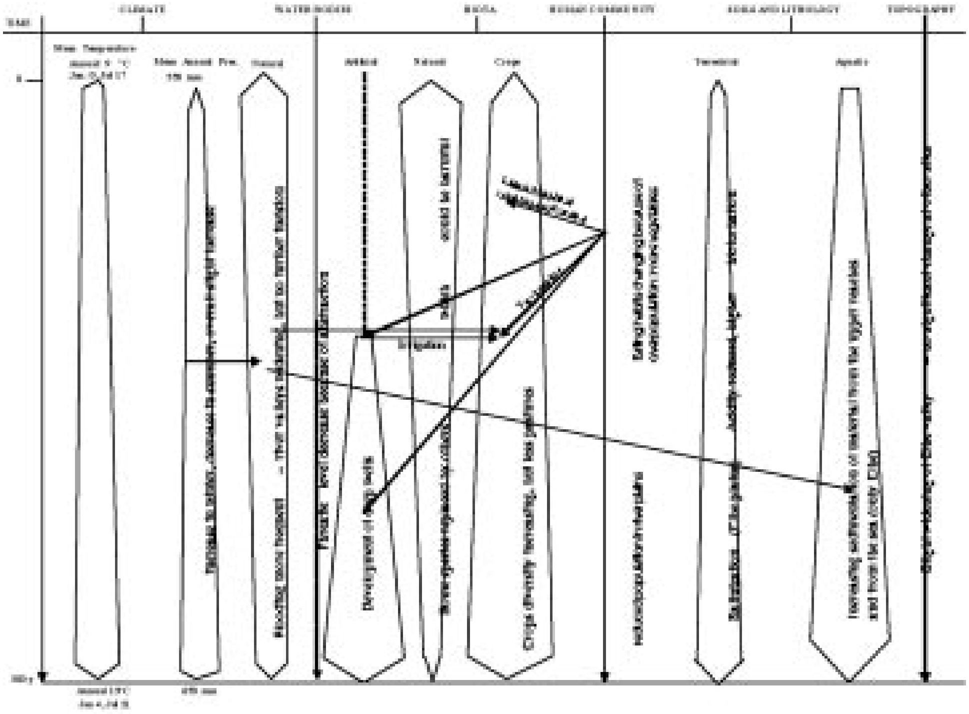

Figure C4.18: Transition Diagram between State 1 and State 2

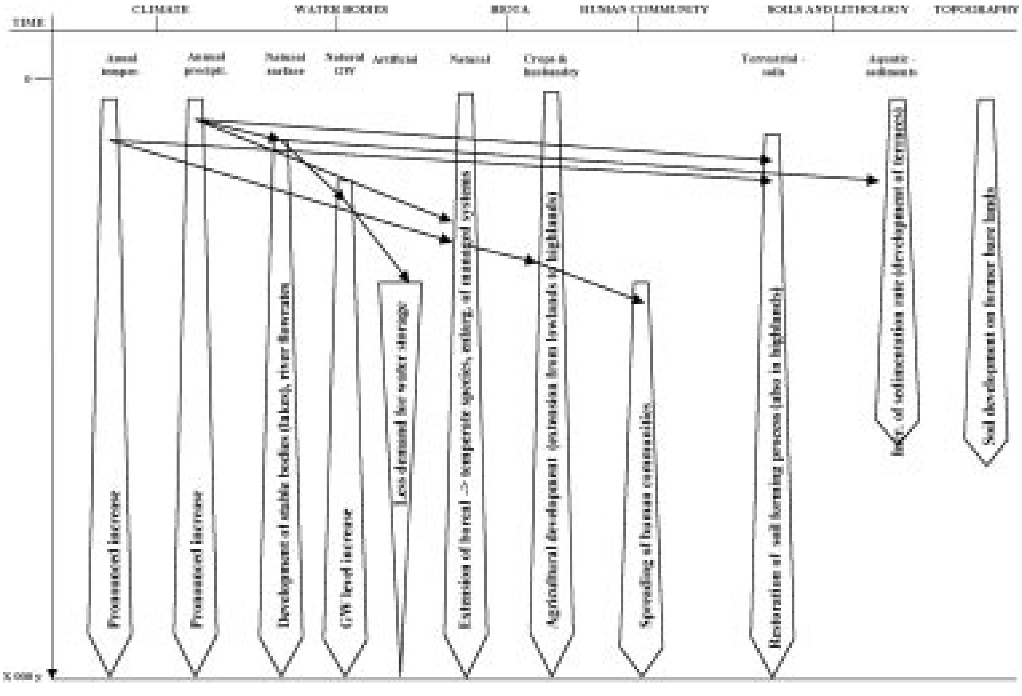

Figure C4.19: Transition Diagram between State 2 and State 1

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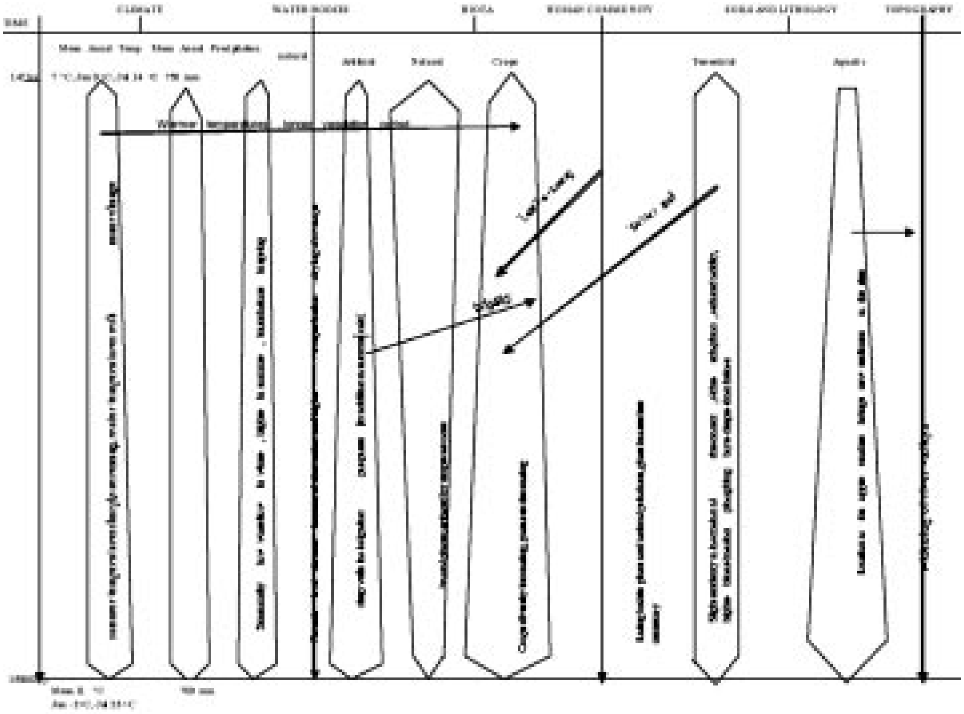


Figure C4.20: Transition Diagram between State 3 and State 4

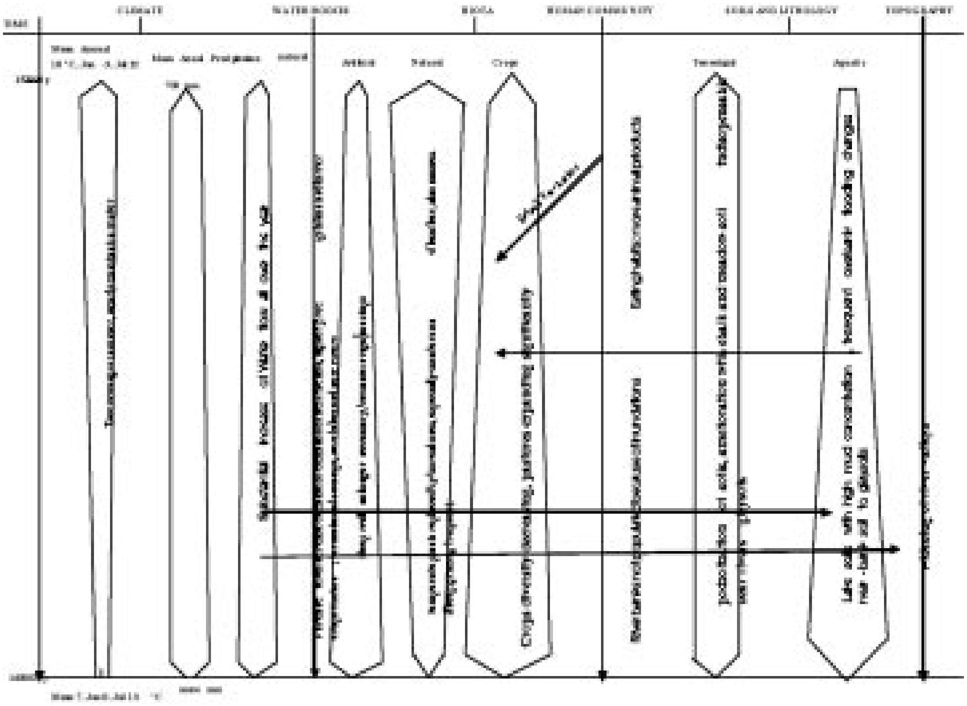
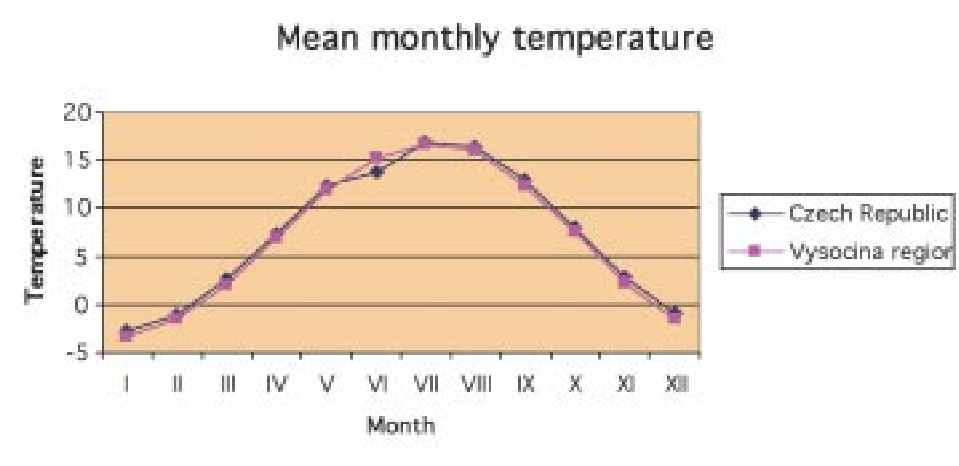
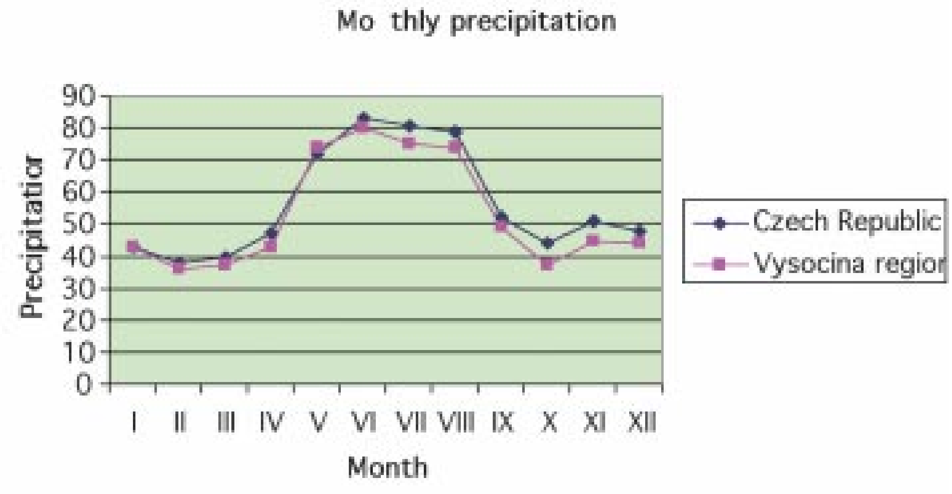


Figure C4.21: Transition Diagram between State 4 and State 3

Figure C5.1: *Mean Monthly Temperature and Precipitation (1960 - 1990 Normals)*





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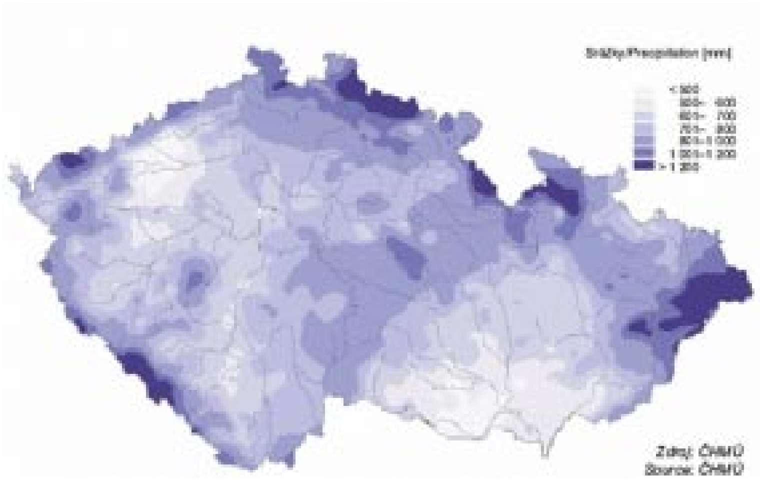
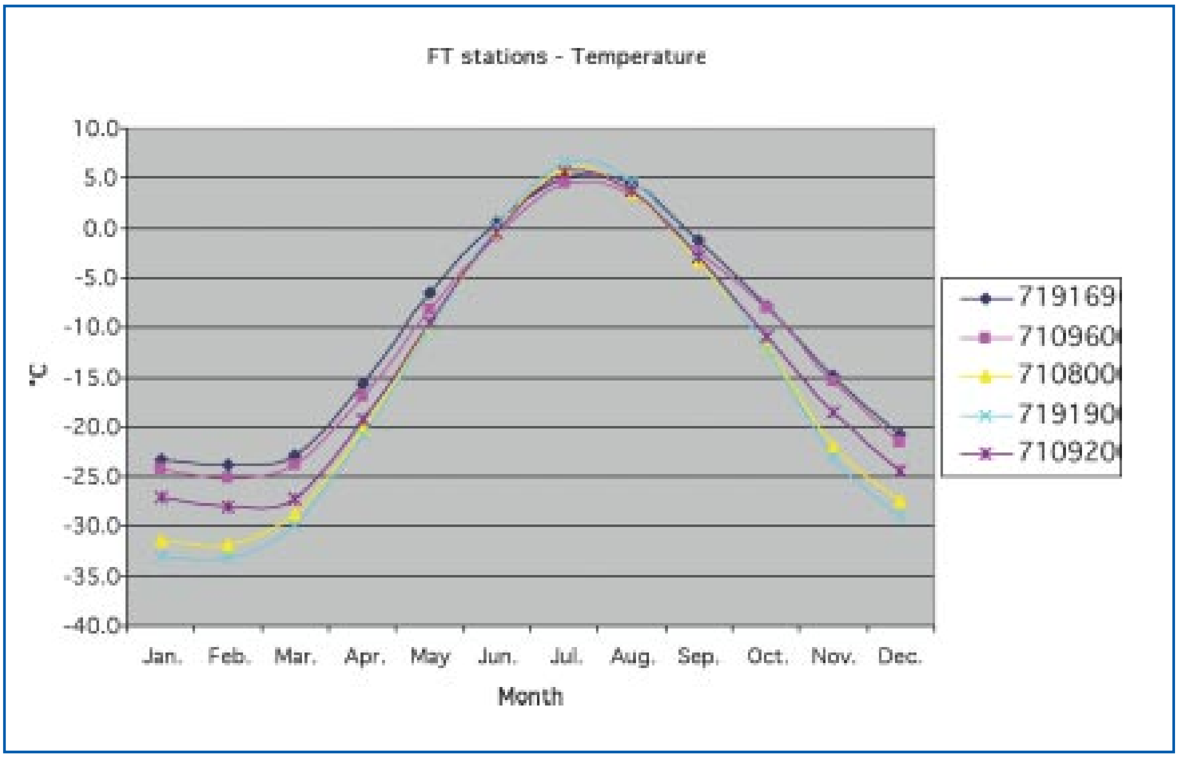
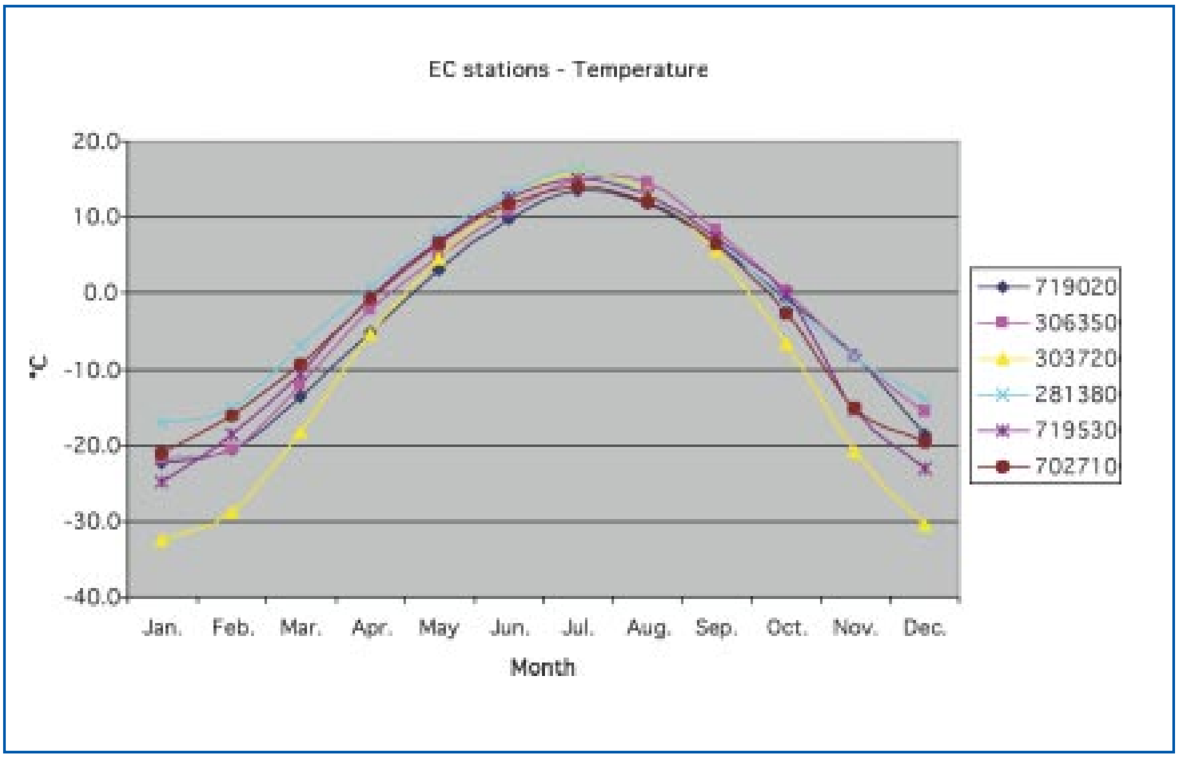


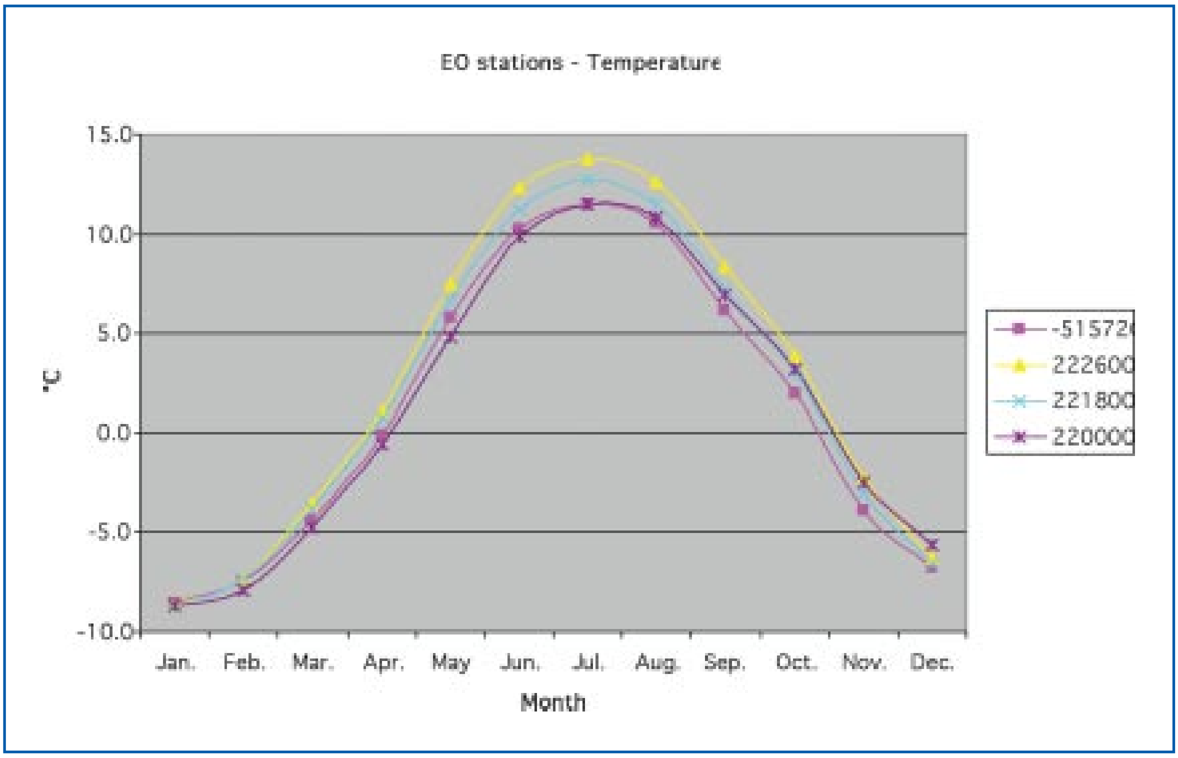
Zdroj: ČHMÚ
Source: ČHMÚ

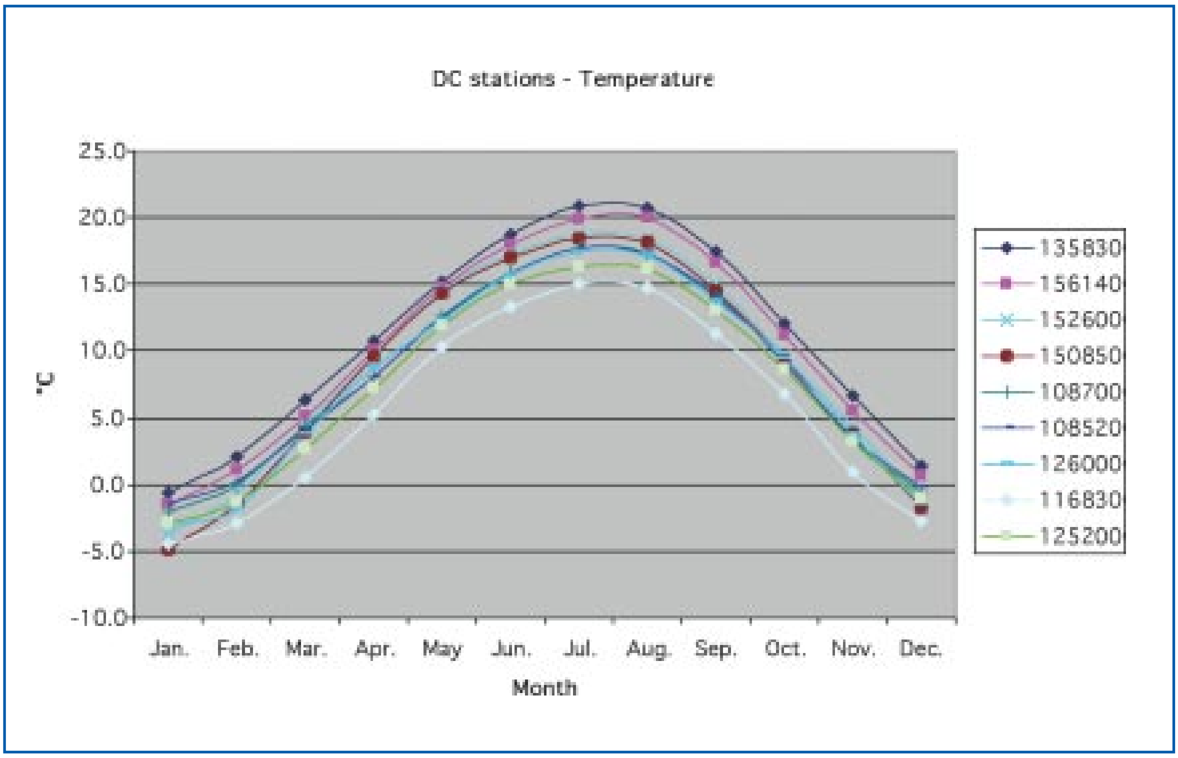
Figure C5.2: *Regional Variability in Total Annual Precipitation (2001)*

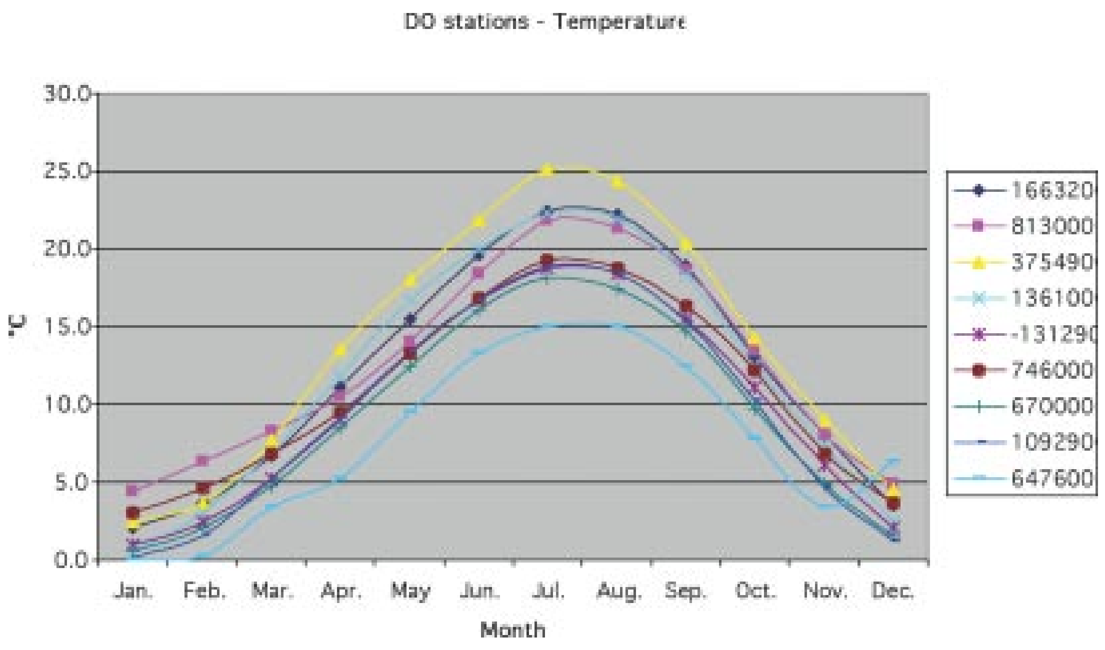
Figure C5.3: *Temperature Data for Analogue Stations for Czech Republic*

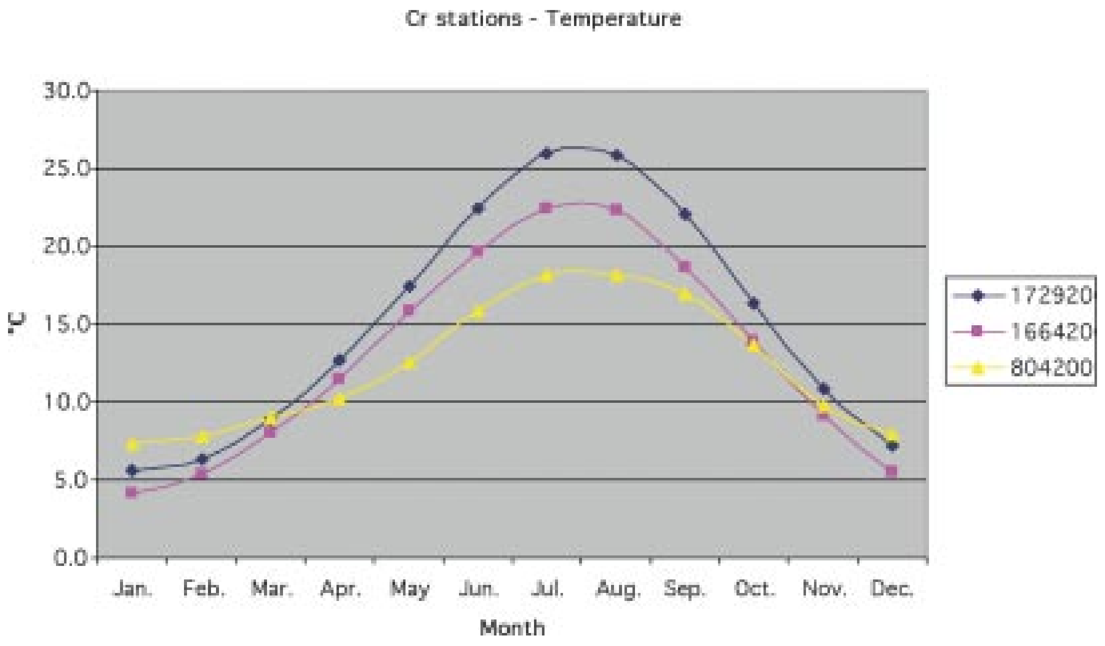


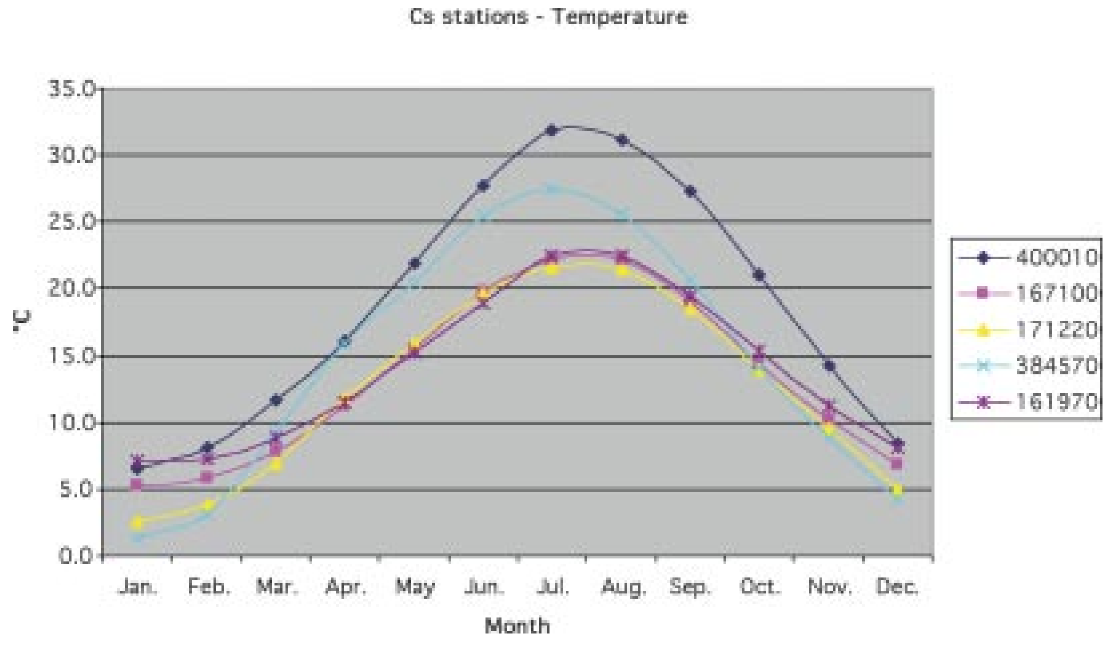



EO stations - Temperature
15.0
10.0
5.0
0.0
-5.0
-10.0
°C
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month
-51572
22260
22180
22000


DC stations - Temperature
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
°C
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month
135830
156140
152600
150850
108700
108520
126000
116830
125200


DO stations - Temperature
30.0
25.0
20.0
15.0
10.0
5.0
0.0
°C
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month
166320
813000
375490
136100
-131290
746000
670000
109290
647600


Cr stations - Temperature
30.0
25.0
20.0
15.0
10.0
5.0
0.0
°C
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month
172920
166420
804200



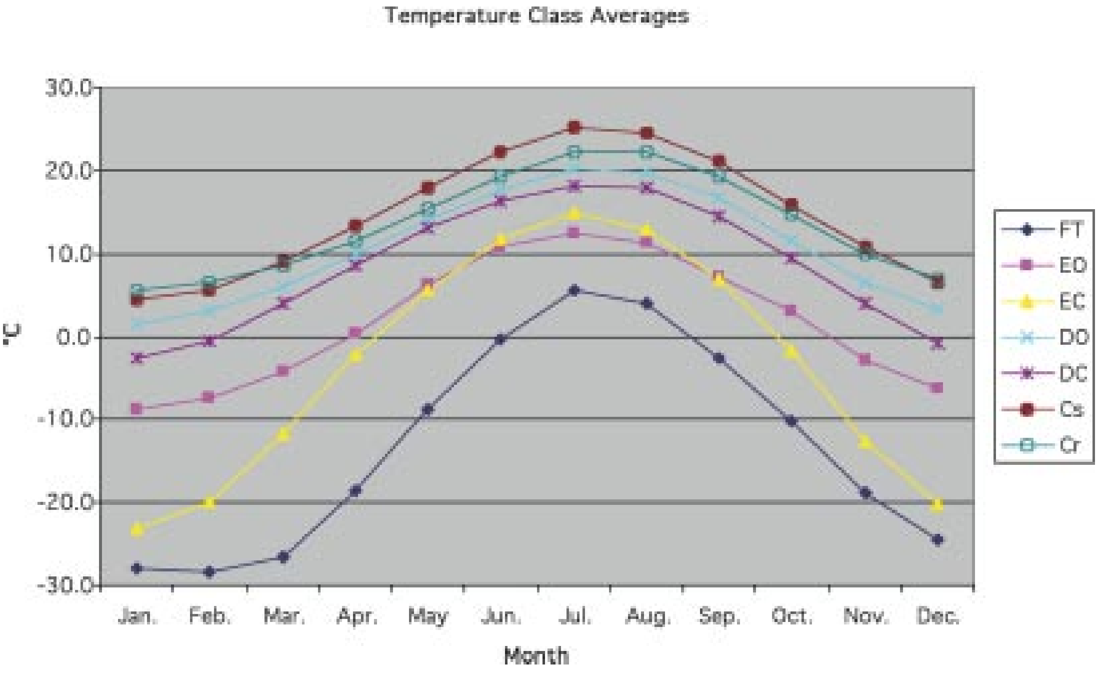


Figure C5.4: *Temperature Class Averages for Analogue Stations for Czech Republic*

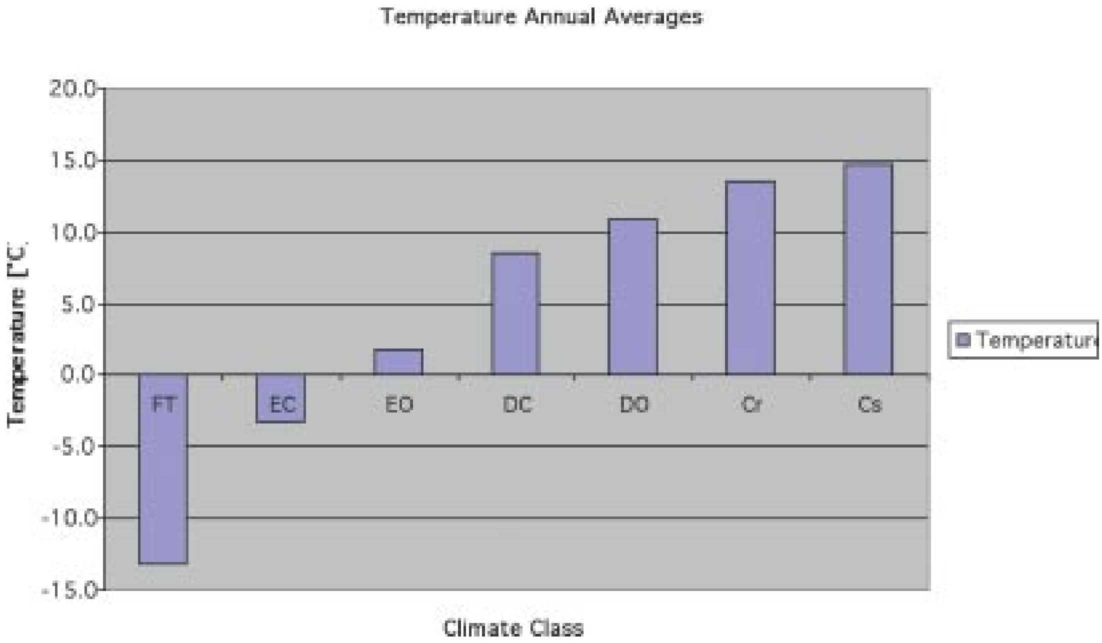
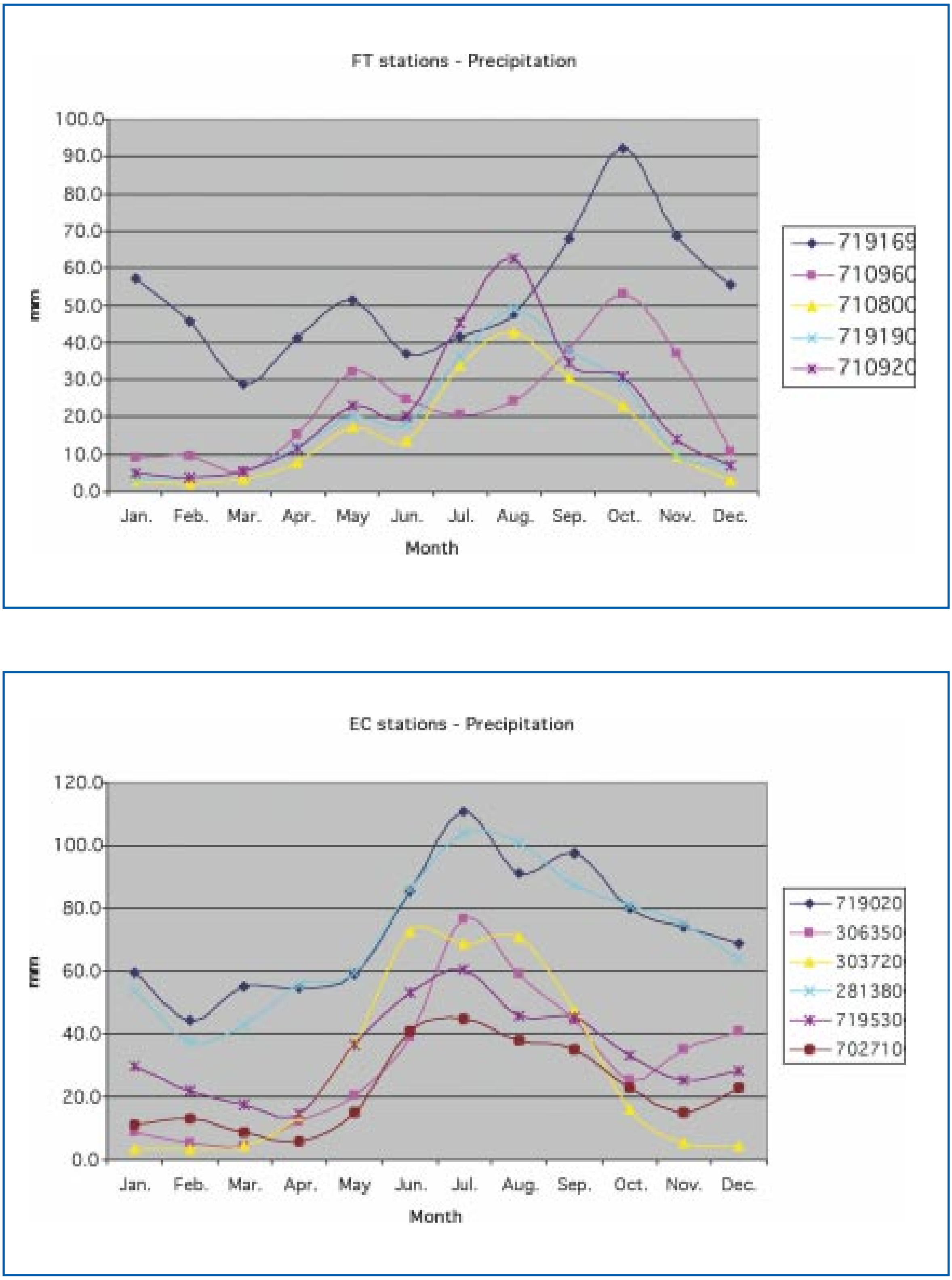
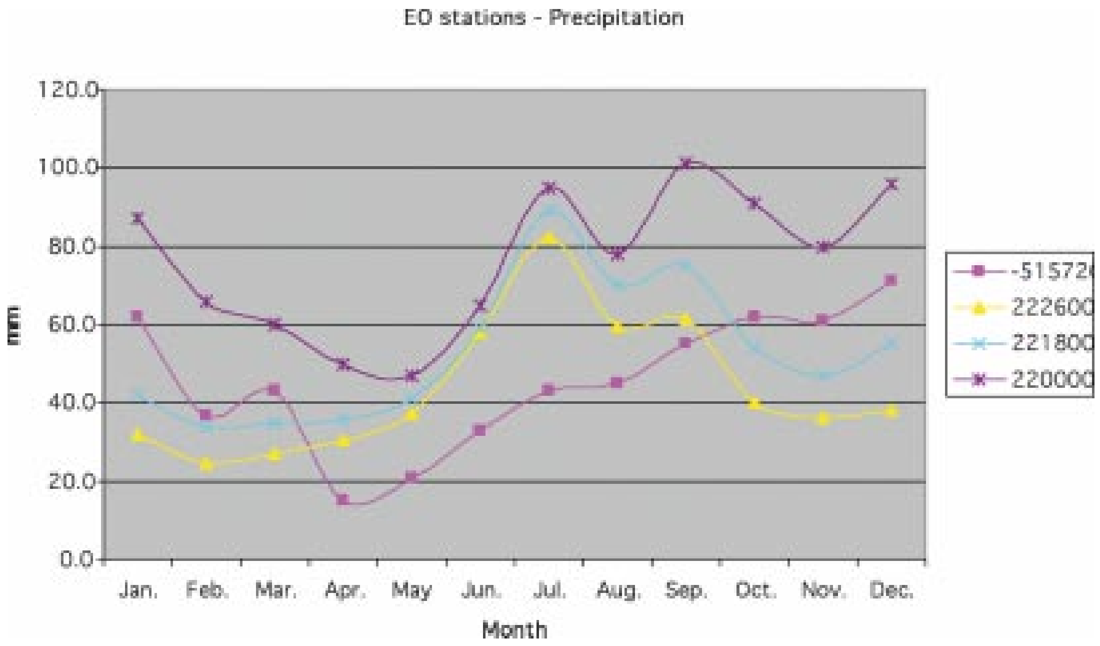
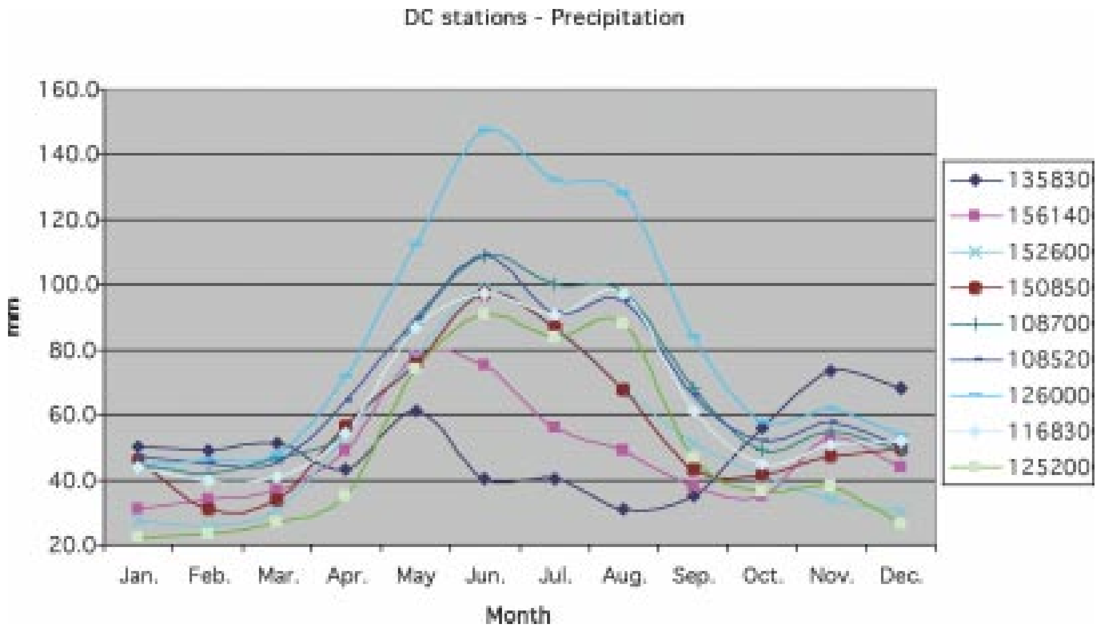


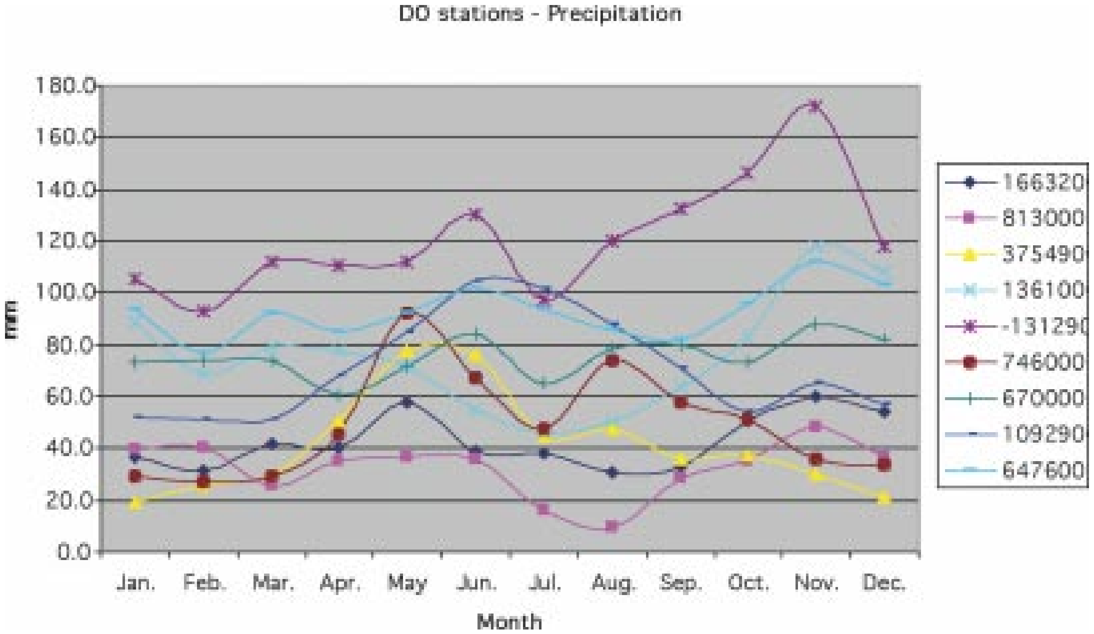
Figure C5.5: *Mean Annual Temperature by Climate Class for Czech Republic Analogue Stations*

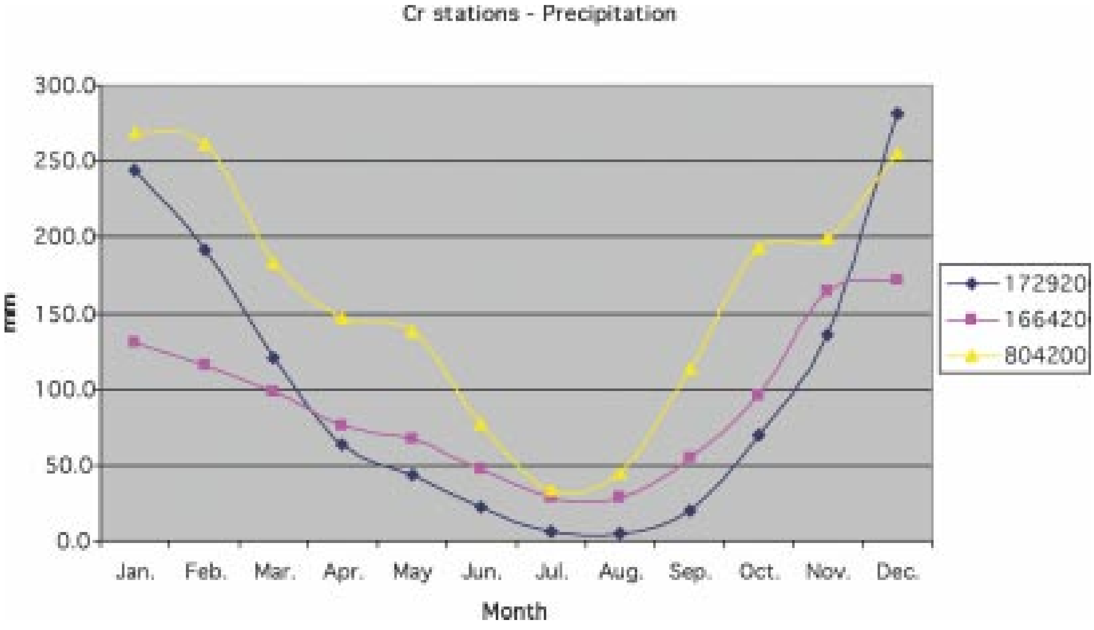
Figure C5.6: Precipitation Data for Analogue Stations for Czech Republic




EO stations - Precipitation
mm
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month
-51572
222600
221800
220000


DC stations - Precipitation
mm
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month
135830
156140
152600
150850
108700
108520
126000
116830
125200


DO stations - Precipitation
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
mm
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month
166320
813000
375490
136100
-13129
746000
670000
109290
647600


Cr stations - Precipitation
300.0
250.0
200.0
150.0
100.0
50.0
0.0
mm
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month
172920
166420
804200

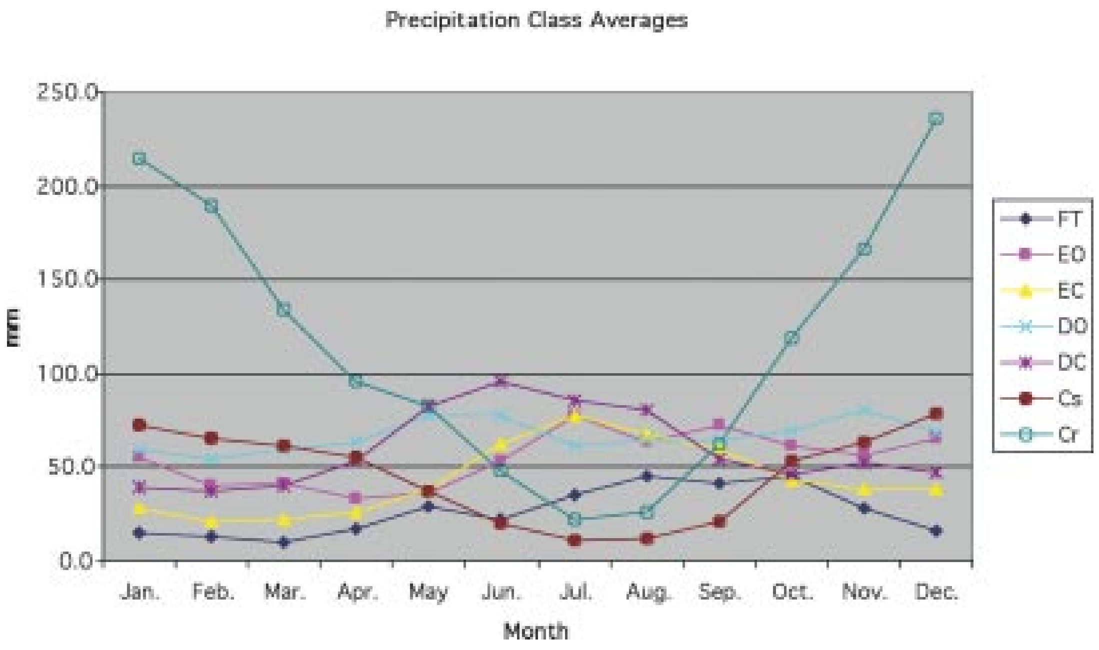


Figure C5.7: *Precipitation Class Averages for Analogue Stations for Czech Republic*

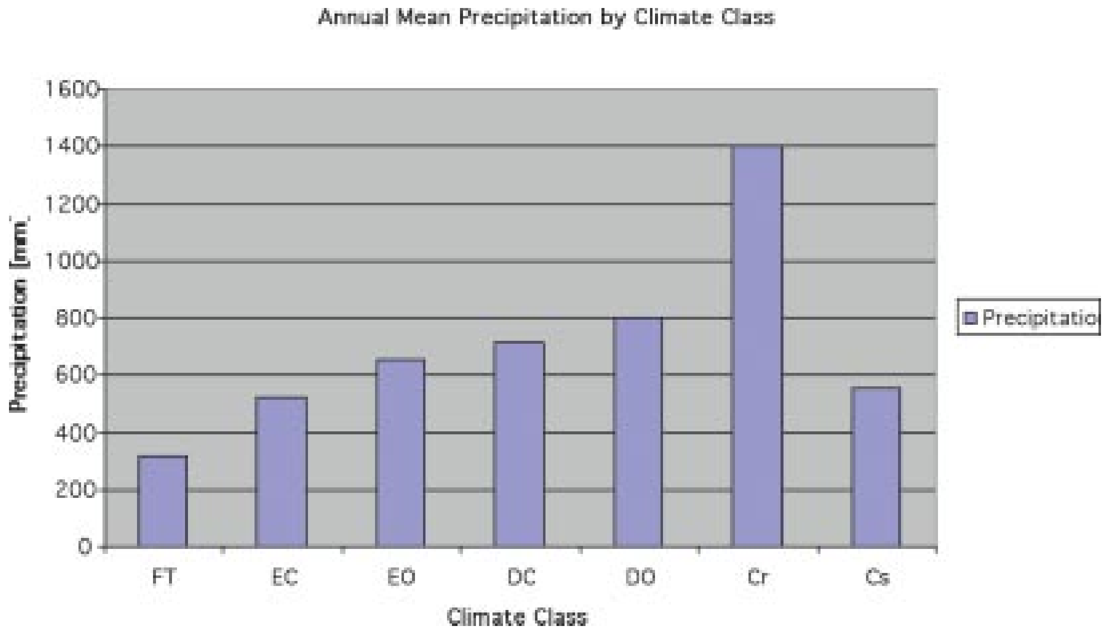
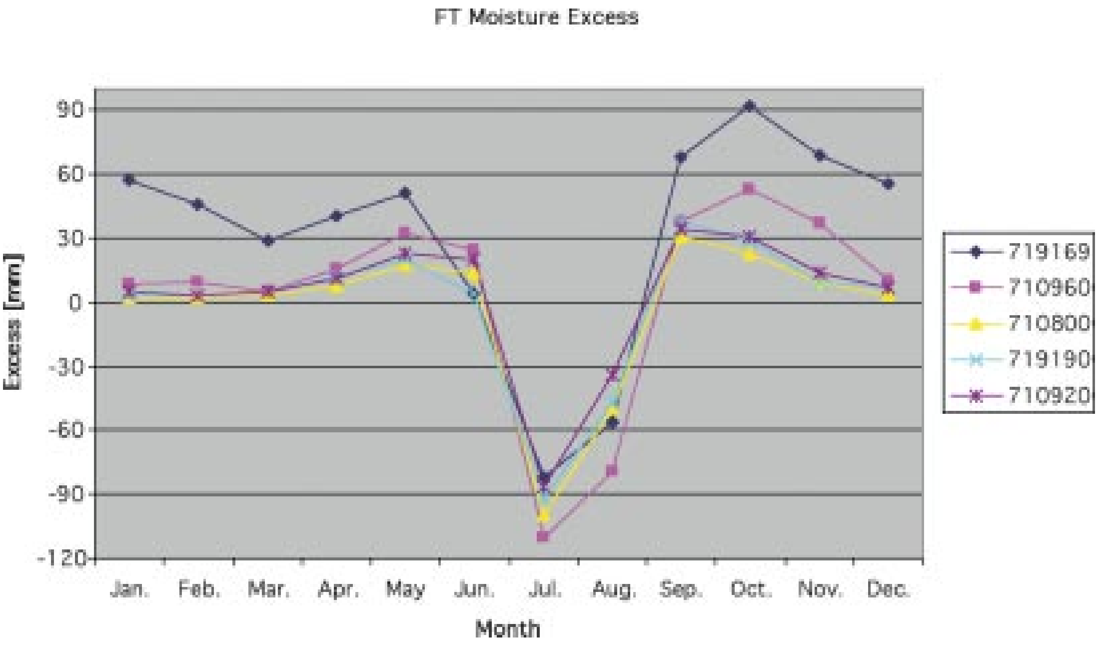
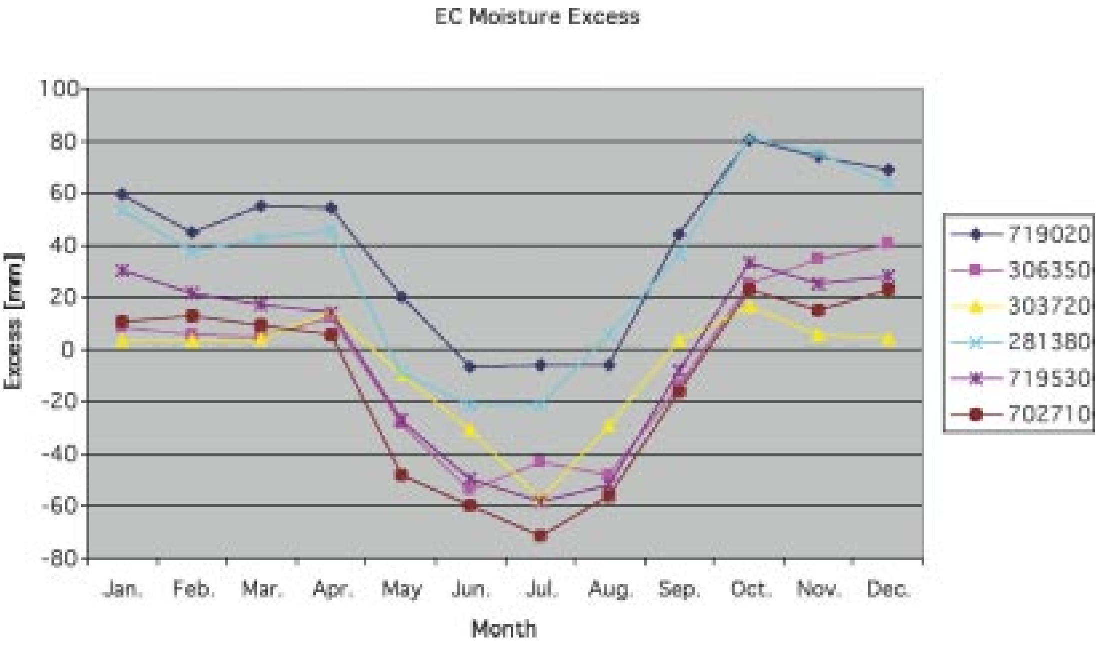
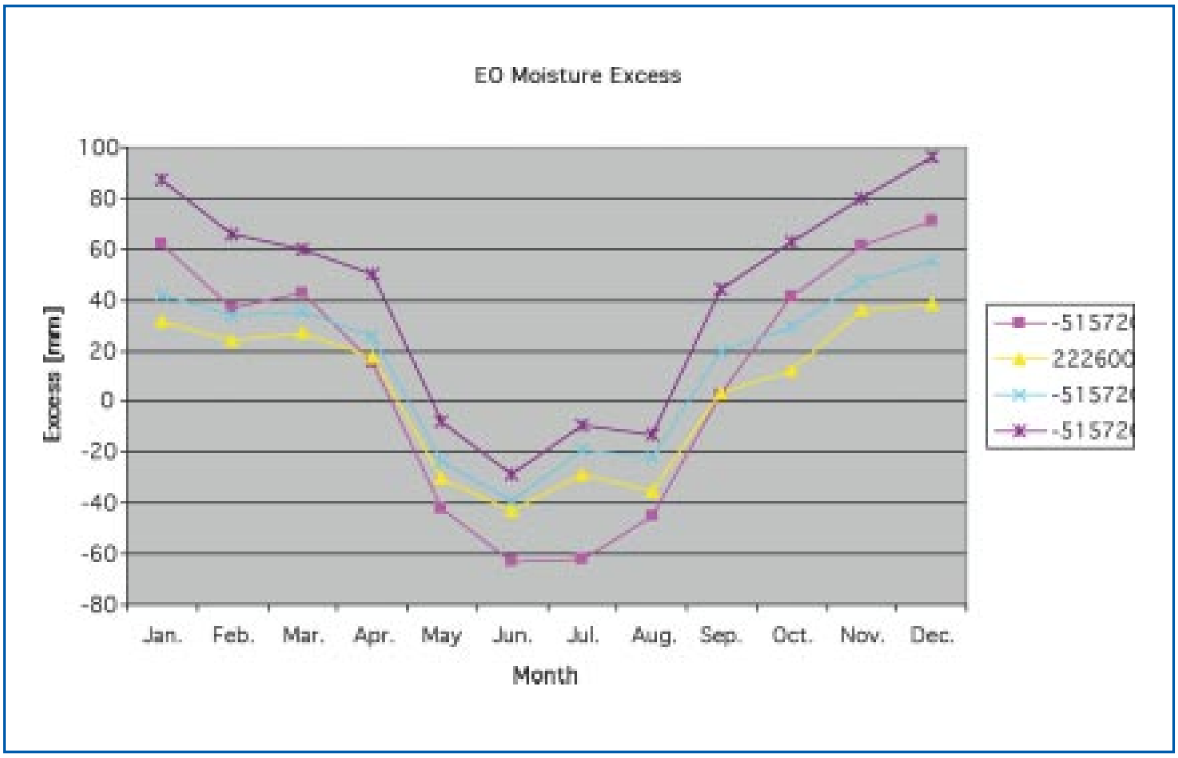


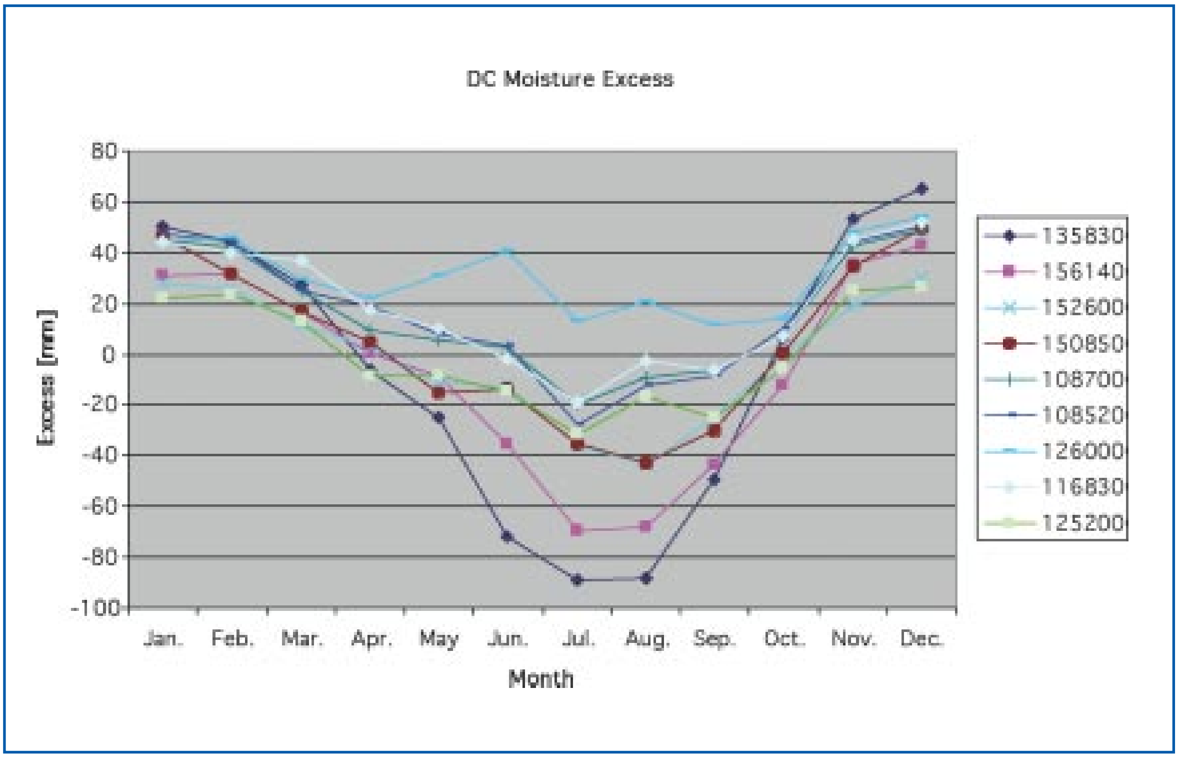
Figure C5.8: *Precipitation Class Averages for Analogue Stations for Czech Republic*

Figure C5.9: *Moisture Excess for Analogue Stations for Czech Republic*






EO Moisture Excess
Excess [mm]
100
80
60
40
20
0
-20
-40
-60
-80
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month
-51572
22260
-51572
-51572


DC Moisture Excess
Excess [mm]
80
60
40
20
0
-20
-40
-60
-80
-100
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month
135830
156140
152600
150850
108700
108520
126000
116830
125200

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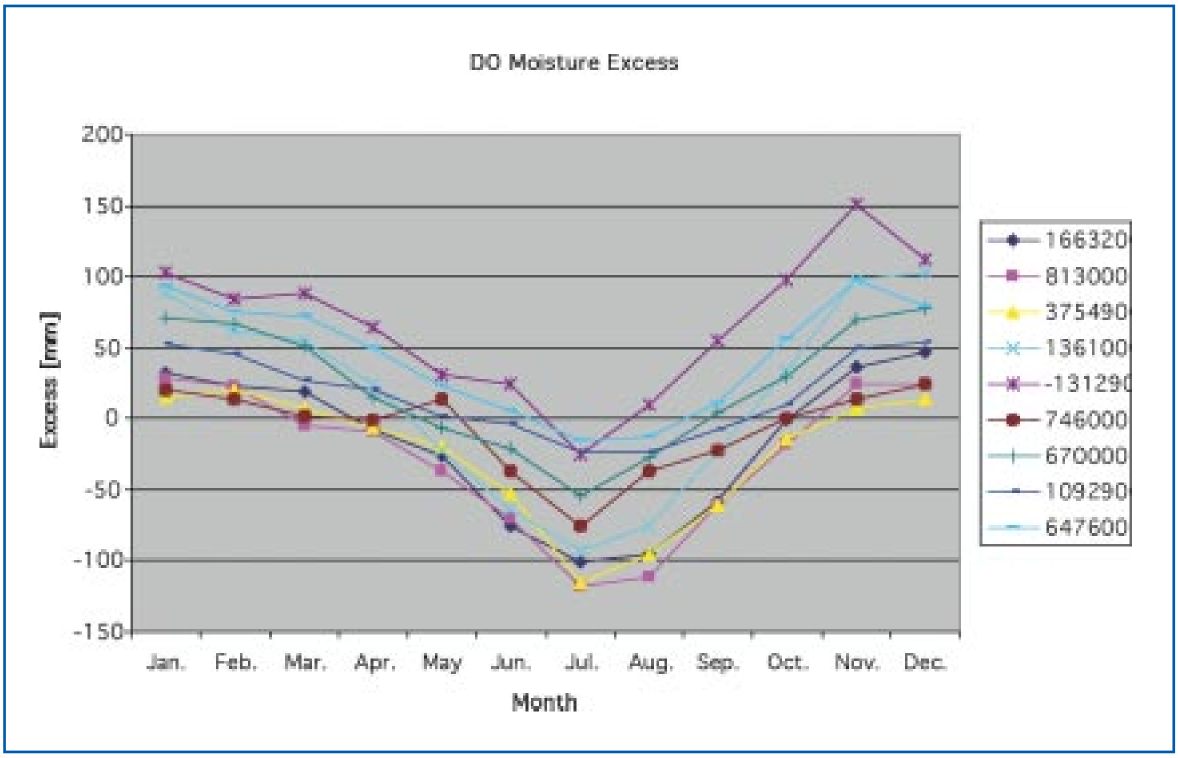
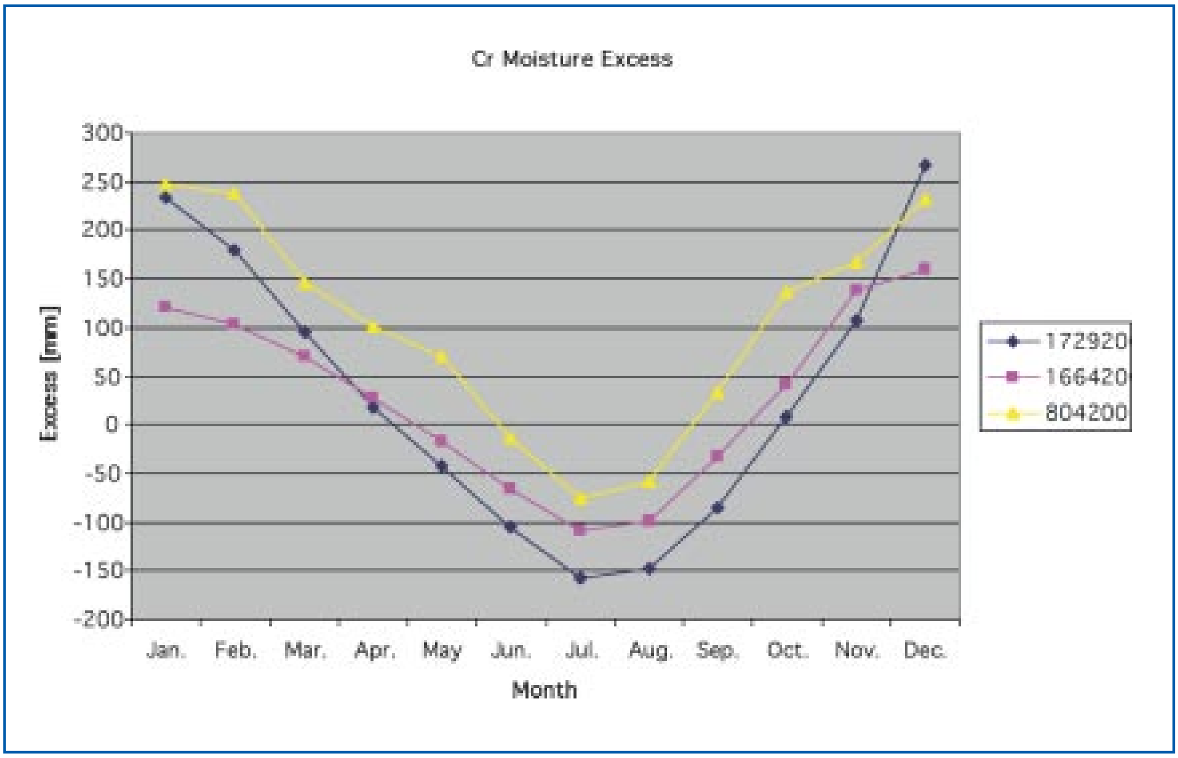
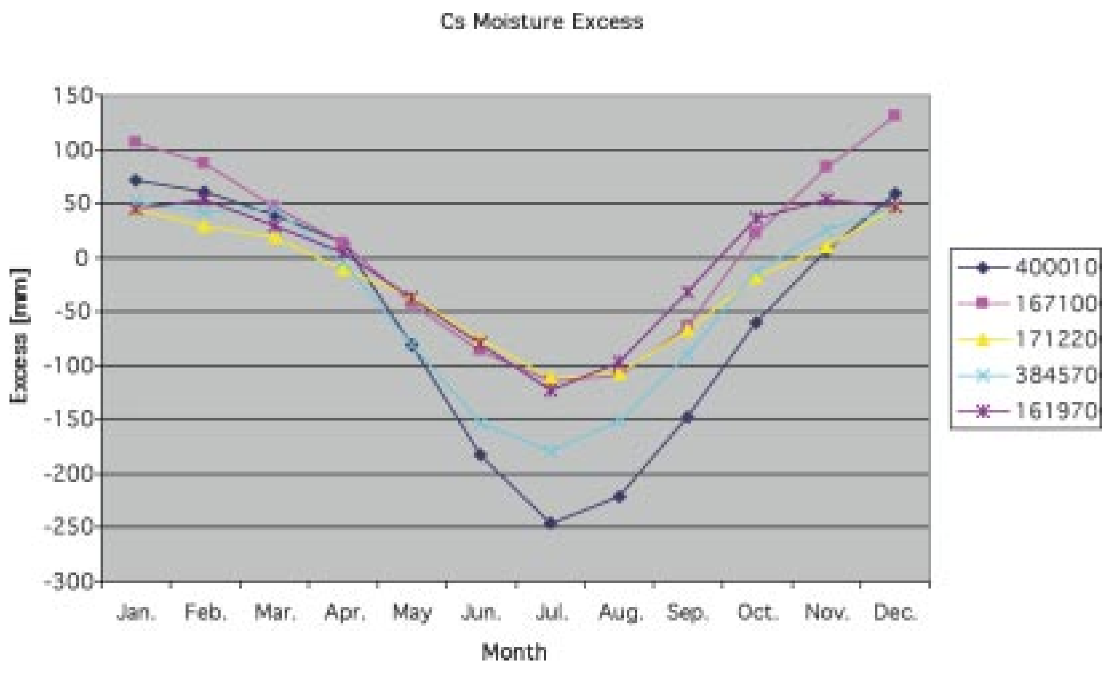

DO Moisture Excess
Excess [mm]
200
150
100
50
0
-50
-100
-150
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month
166320
813000
375490
136100
-131290
746000
670000
109290
647600


Cr Moisture Excess
Excess [mm]
300
250
200
150
100
50
0
-50
-100
-150
-200
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sep.
Oct.
Nov.
Dec.
Month
172920
166420
804200



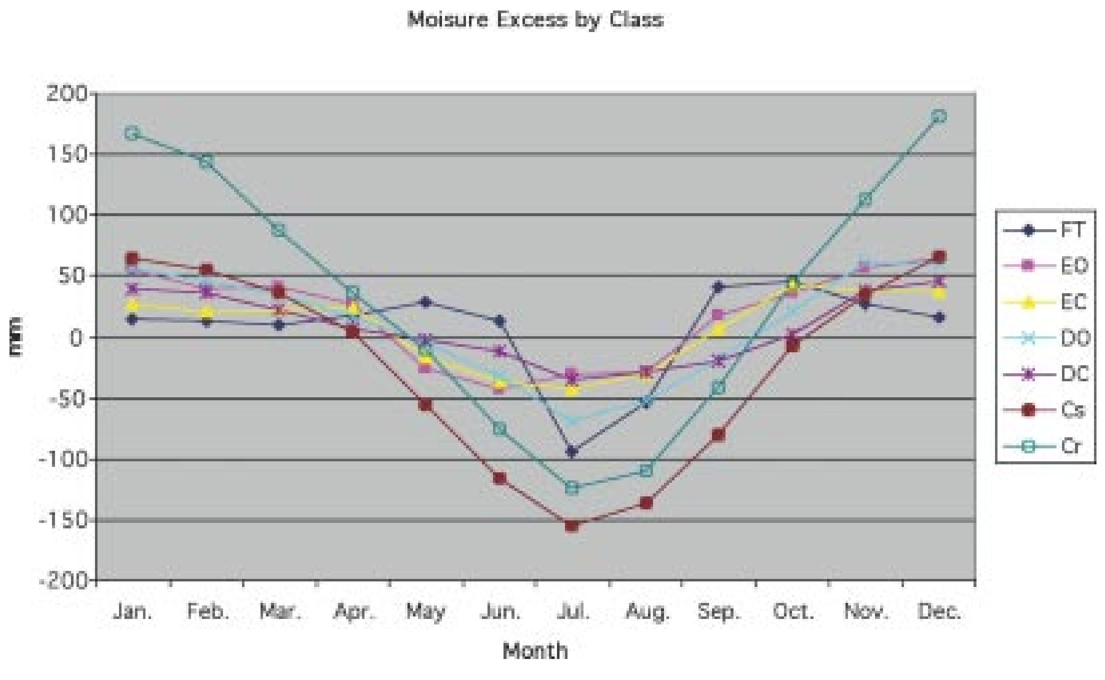


Figure C5.10: *Moisture Excess Class Averages for Analogue Stations for the Czech Republic*

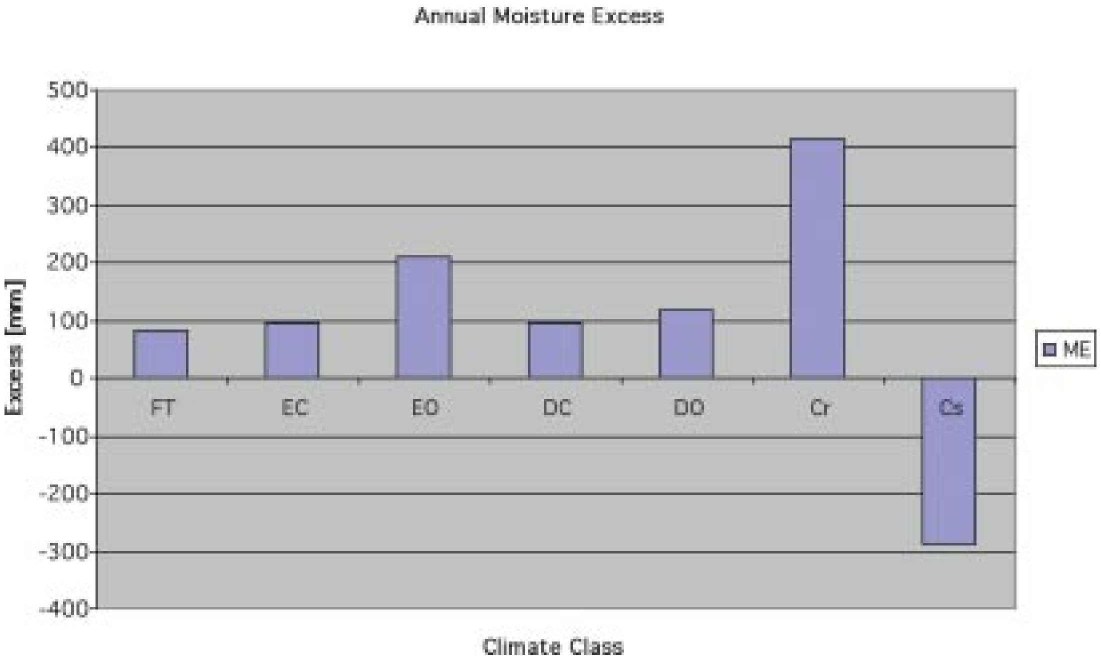


Figure C5.11: *Annual Arithmetic Mean Moisture Excess by Climate Class*

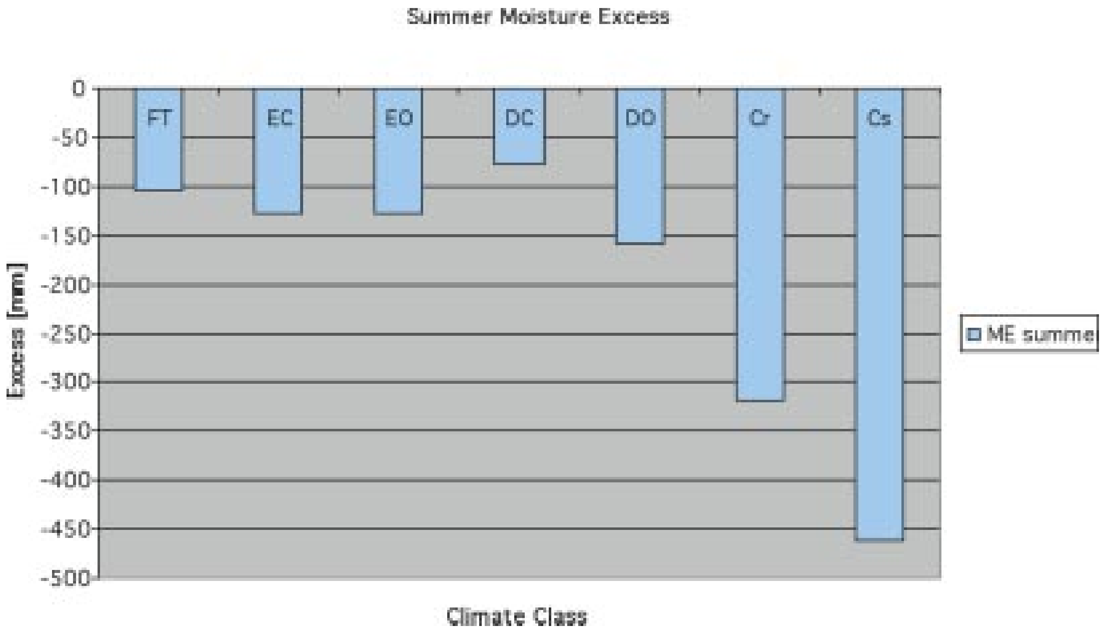


Figure C5.12: *Summer Arithmetic Mean Moisture Excess by Climate Class*

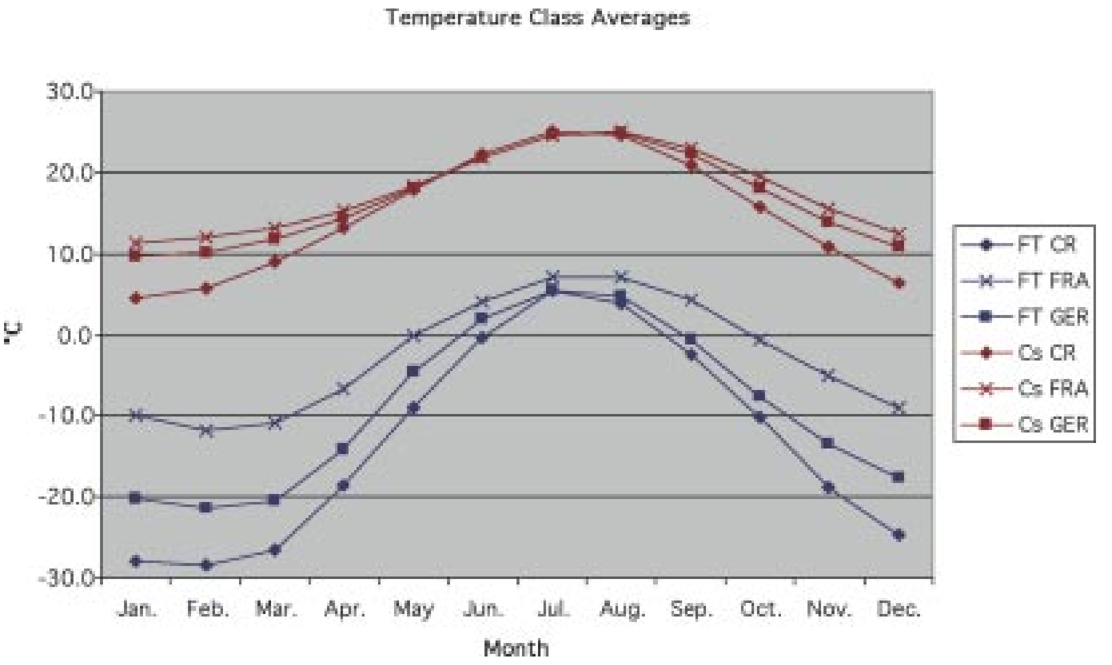


Figure C5.13: *Comparison of the Selected Average French, German and Czech FT and Cs Stations (Monthly Temperatures)*

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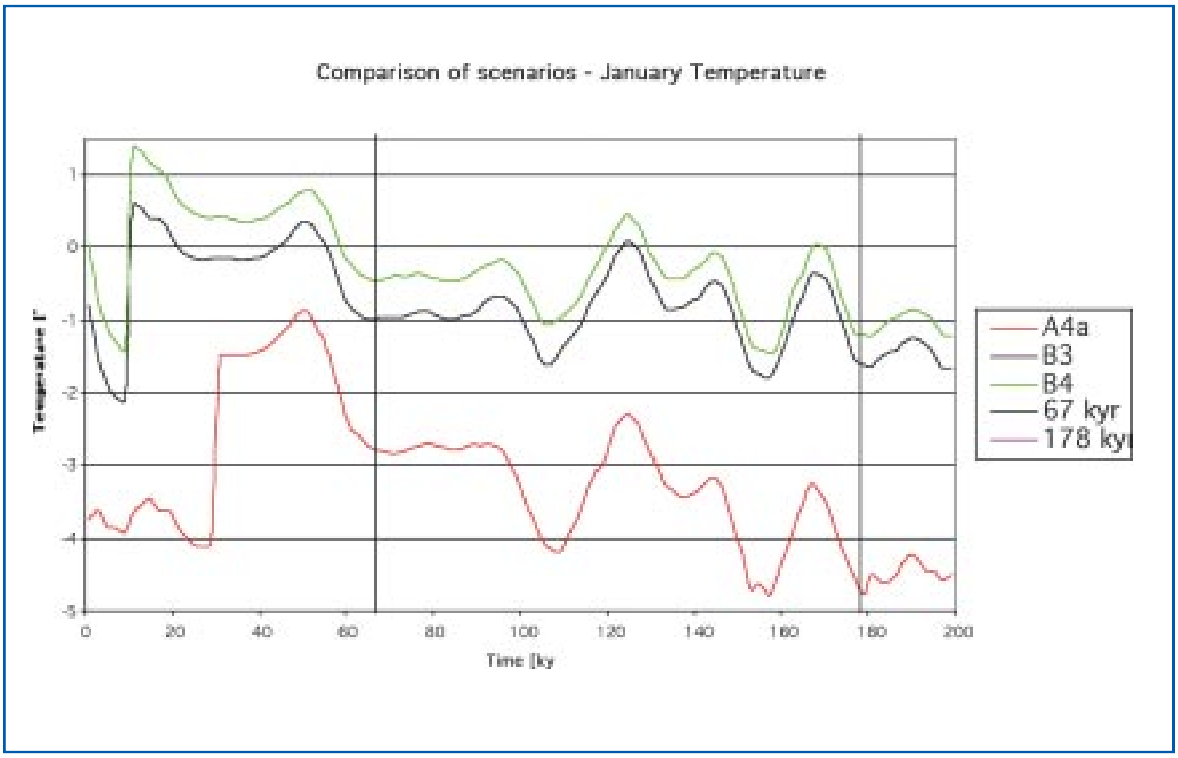
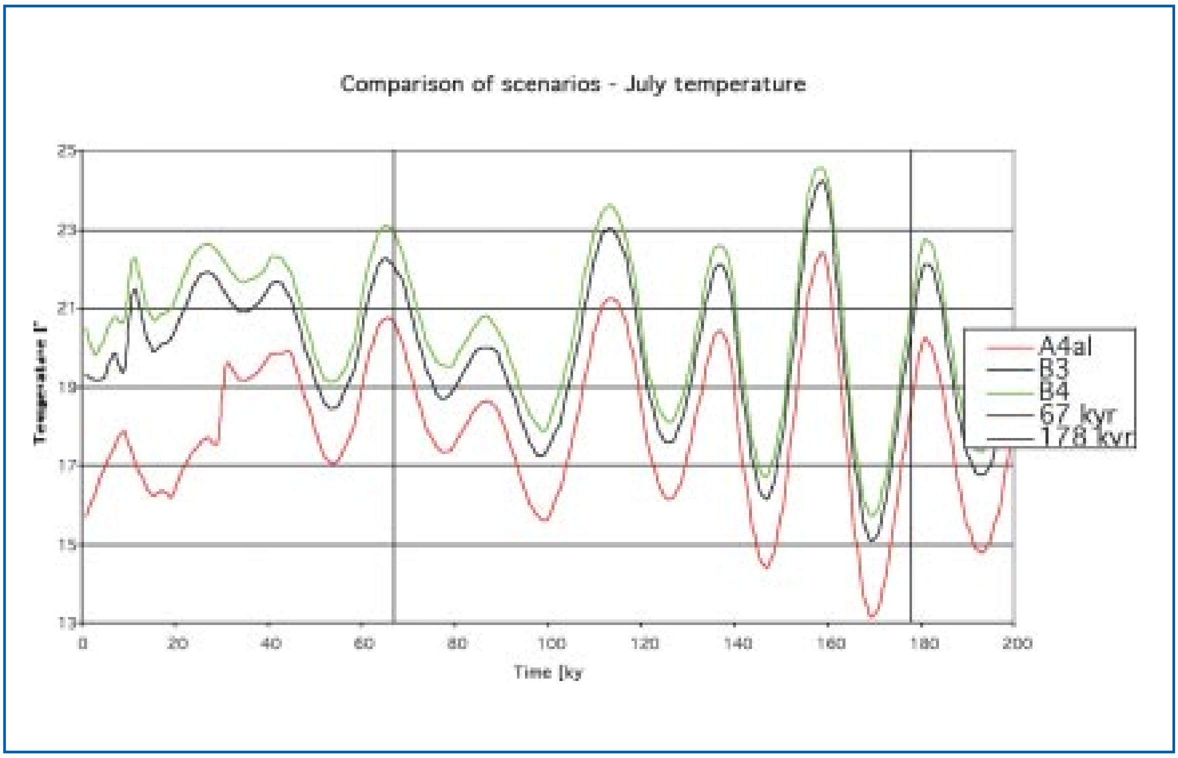
Figure C5.14: *Comparison of Scenarios - Physical-statistical Downscaling of CLIMBER-GREMLINS Simulations*





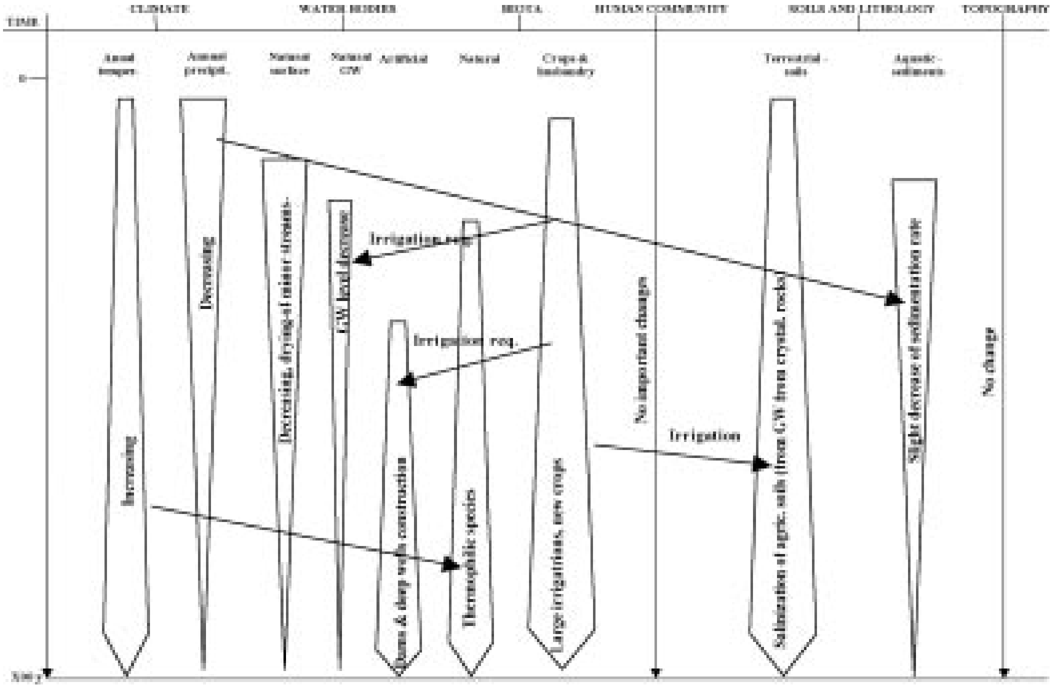


Figure C5.15: Transition Diagram for the South of the Czech Republic from State DC to Cs over a Timescale of some Hundreds of Years

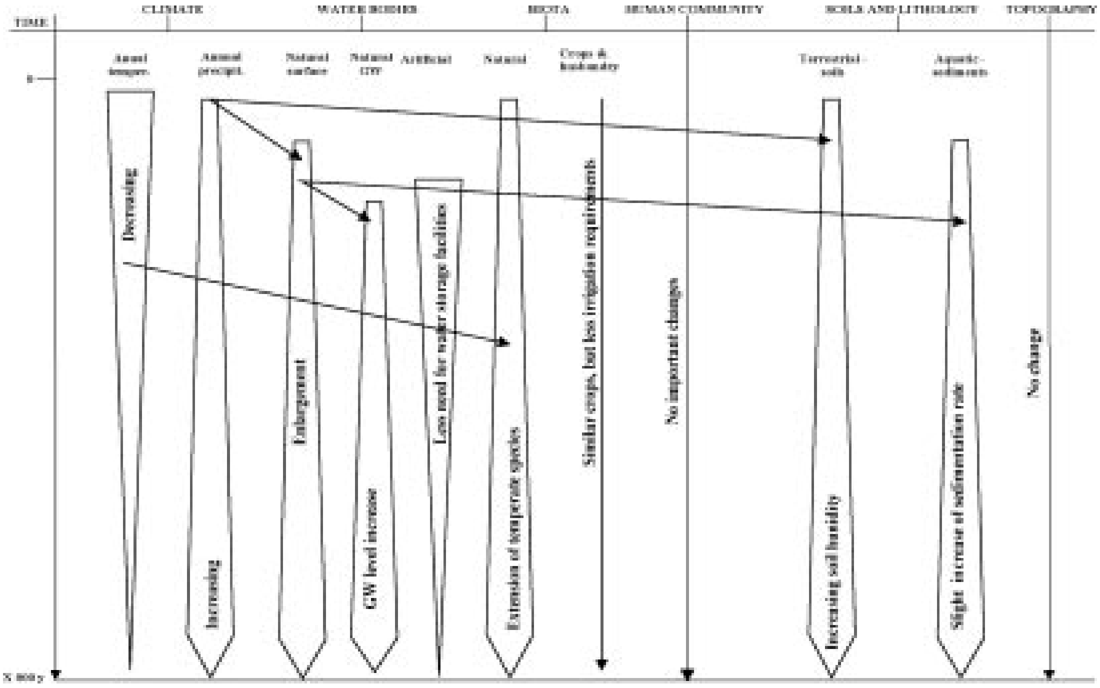


Figure C5.16: Transition Diagram for the South of the Czech Republic from State Cs to DC over a Timescale of some Thousands of Years

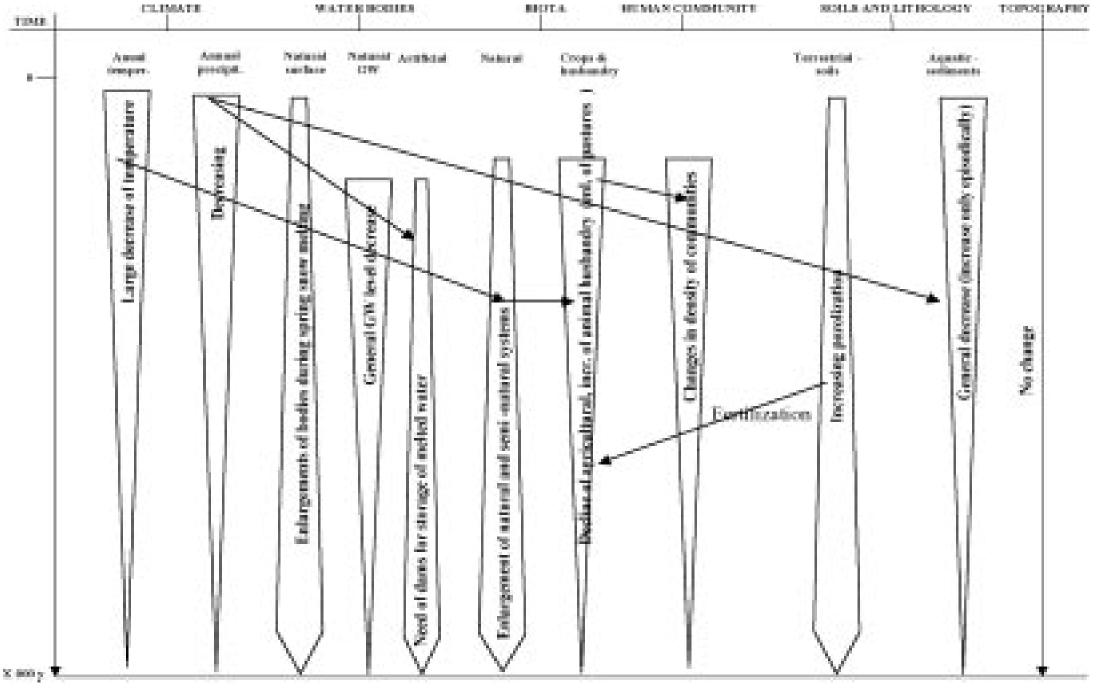


Figure C5.17: *Transition Diagram for the South of the Czech Republic from State DC to EC over a Timescale of some Thousands of Years*

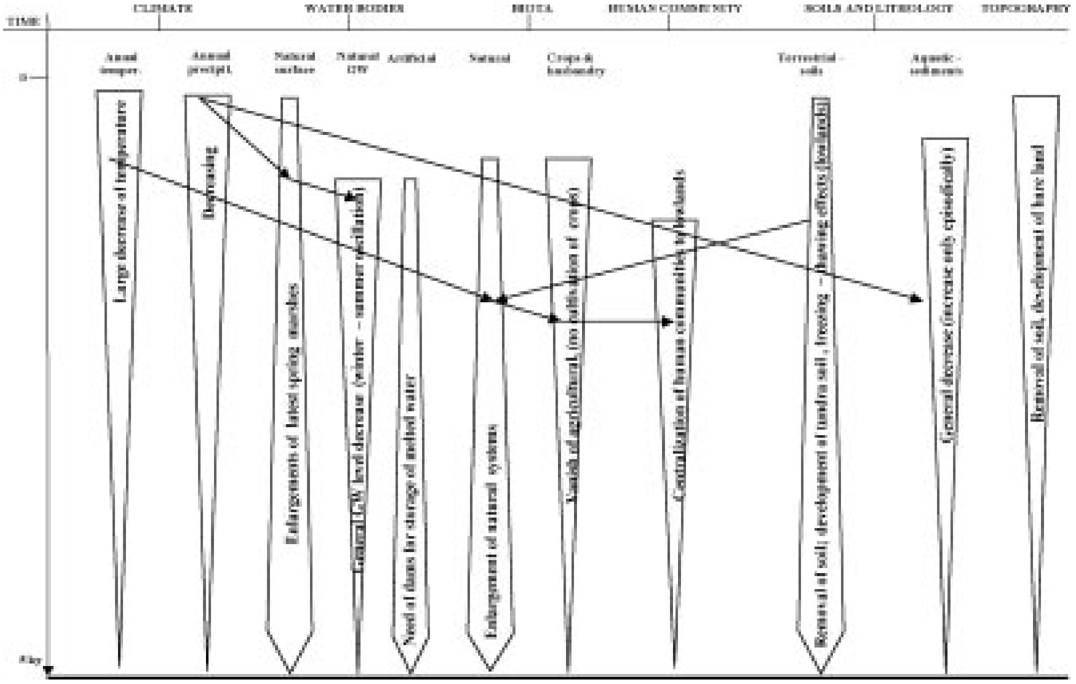


Figure C5.18: *Transition Diagram for the South of the Czech Republic from State EC to FT over a Timescale of approximately 5000 Years*

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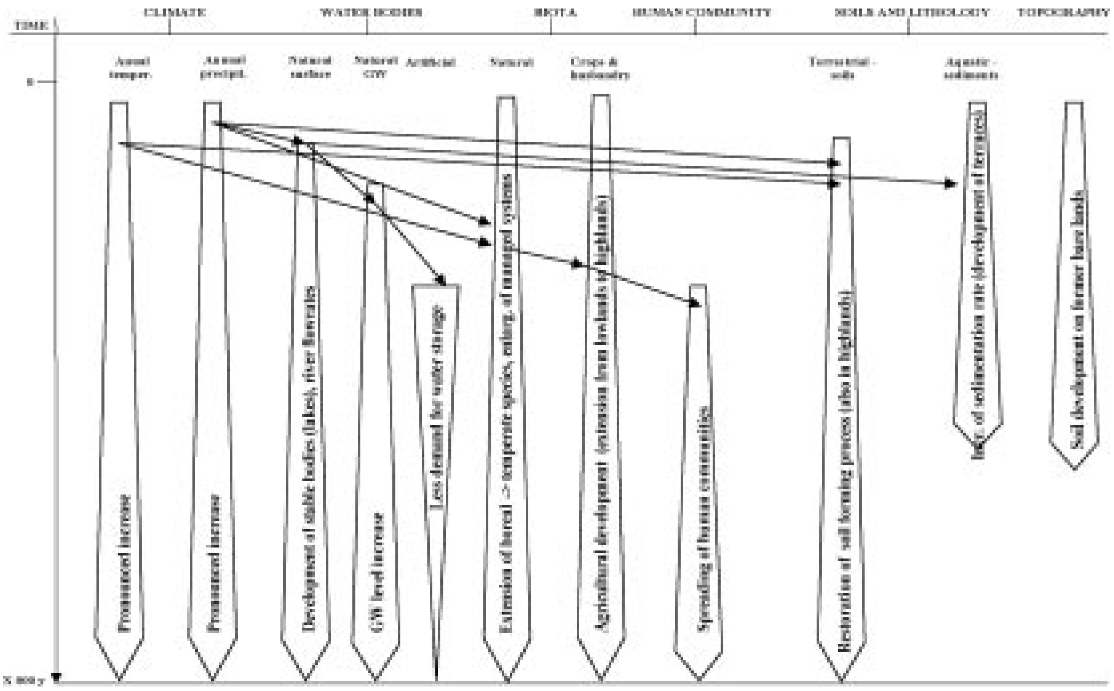

Figure C5.19: *Transition Diagram for the South of the Czech Republic from State FT through EC to DC over a Timescale of some Thousands of Years*

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