# Modelling Sequential BIOsphere Systems under CLIMate Change for Radioactive Waste Disposal. Project BIOCLIM.

D. Texier, *Agence Nationale pour la Gestion des Déchets Radioactifs, France*.
P. Degnan, *United Kingdom NIREX limited, UK*
M.F. Loutre, *Université catholique de Louvain, Institut d'Astronomie et de Géophysique G. Lemaître, Belgium*.
D. Paillard, *Laboratoire de Modélisation du Climat et de l'Environnement, CEA-CNRS, France*.
M. Thorne, *Mike Thorne and Associates Limited, UK*

***Abstract:*** ***The BIOCLIM project (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. It is coordinated by ANDRA, the French national radioactive waste management agency. The project brings together a number of European radioactive waste management organisations that have national responsibilities for the safe disposal of radioactive wastes, and several highly experienced climate research teams. Waste management organisations involved are: NIREX (UK), GRS (Germany), ENRESA (Spain), NRI (Czech Republic) and ANDRA (France). Climate research teams involved are: LSCE (CEA/CNRS, France), CIEMAT (Spain), UPM-ETSIMM (Spain), UCL/ASTR (Belgium) and CRU (UEA, UK). The Environmental Agency for England and Wales provides a regulatory perspective. The consulting company Enviros Consulting (UK) assists ANDRA by contributing to both the administrative and scientific aspects of the project. This paper describes the project and progress to date.***

## 1 INTRODUCTION AND OBJECTIVES

In many countries throughout the European Community (EC) there are national projects to address the safe management of radioactive wastes arising from activities such as nuclear energy generation, medical diagnosis and treatment and industrial research programmes. Any long-lived intermediate level (ILW) and high-level (HLW) wastes so generated cannot readily be disposed to near-surface facilities with low-level and short-lived wastes. Therefore, waste management agencies and government appointed regulatory bodies are considering either disposal or retrievable storage in deep geological formations. The fundamental purpose of such management options is to isolate the wastes over very long timescales and hence to protect humans and the surface environment from harmful radiological exposures.

In order to demonstrate the satisfactory safety performance of any potential repository, performance assessments (PAs) have to be carried out by the disposal agencies and then examined in detail by the appointed national regulator(s). In line with international guidance (e.g. IAEA, 1995), the calculations undertaken for such PAs often cover very long timescales (up to, and possibly beyond, 1,000,000 years) to demonstrate that future generations will be afforded the same degree of protection as those living today. Over such timescales, radionuclides may begin to emerge from the repository and be transported to the biosphere. The biosphere system in this context is defined as the collation of various radionuclide transfer pathways which may result in releases into the surface environment, where Man may be exposed through the ingestion, inhalation and external exposure of contaminated material. The potential radiological exposure of Man is therefore used as one of the indicators of safety performance of the waste repository.

During the time periods considered, the socio-economical and cultural characteristics, but not necessarily the habits, of Man are often assumed to remain constant. However, the biosphere systems inhabited by Man will be subject to change. Consideration therefore needs to be given to how to represent in the biosphere models of a PA the potential exposure pathways and the corresponding changing biosphere systems where people might live in the future and into which future releases might occur. The concept of an "assessment", or a "reference", biosphere that can serve as a rational basis for judgements regarding the overall acceptability of a disposal system has therefore been developed through international collaboration and agreement under the auspices of the International Atomic Energy Agency's BIOsphere Modelling and ASSessment (BIOMASS) co-ordinated research programme (1996-2001). The Reference Biosphere Methodology, developed in Theme 1 of BIOMASS provides such a systematic framework for the development and justification of assessment biospheres and related models for long-term radiological assessments (BIOMASS, 1999a to f and 2000a to e). Examples of such Reference Biospheres have been developed within the BIOMASS framework. Some of the BIOMASS Example Reference Biospheres assume a constant biosphere system, although consideration has also been given as to how to deal with biosphere change. It is important to evaluate how long-term (on timescales of up to 1,000,000 years) climatic changes and their consequences on the biosphere may affect radionuclide transport and subsequent impacts on man. The EC BIOCLIM project has been established to extend the work of BIOMASS in relation to climate change and the impacts that need to be considered in a PA in order to help answer this question.

For various European areas within which such disposal sites may be established (namely Northeast France, Central England and Central Spain, Northern Germany, and Central Czech Republic), BIOCLIM is developing scenarios for the potential future biosphere systems that could occur. A specificity of BIOCLIM is to use a set of climate models and to develop two complementary modelling strategies, the so-called hierarchical and integrated strategies. Whereas the hierarchical strategy produces snap shots of future climate state, the integrated strategy delivers continuous sequences of climate change. Results obtained from these two strategies are used to condition descriptions of both time-independent future biosphere system states and transitions between those states. Whereas, the development of descriptions of individual states was explored extensively in BIOMASS, much less work was undertaken on state transitions, so substantial innovations in this area are being made within BIOCLIM.

# 2 ORGANISATION

The project is designed to advance the state-of-the-art of biosphere modelling for use in post-closure performance assessments of deep geological repositories for radioactive wastes through five **work-packages** (WP1 to WP5).

## *2.1 WP1 - Consolidation of the needs of European waste management agencies*

The first Work Package of the project has been dedicated to the consolidation of the needs of European waste management agencies through summarising the mechanisms causing climate change, providing a synopsis of how environmental change is currently treated in PA, and summarising the lessons learned from such applications. Available palaeoenvironmental information has been collated for the five regions of interest for input to future climate and environmental simulations. Two documents have been produced to present WP1 work. These are deliverable D1 'Environmental Change Analysis' and deliverable D2'Site-specific and palaeo environmental data'. . Both can be found on the web site of the project (see WP5).

## *2.2 WP2 – Hierarchical strategy*

This strategy uses a hierarchy of existing models, ranging from simple ones which are able to provide the long term evolution of the global climate (the so-called Earth System Models of Intermediate Complexity, EMICs: for review see Claussen et al. 2002), to more complex ones that can provide a more detailed global or regional view of climatic patterns for some discrete future states (General Circulation Models and Regional Climate Models). Work Package 2 essentially focuses on snapshots simulations. Future discrete climatic states to be investigated have been selected from the results of the LLN-2D NH model (Gallée et al. 1991, Gallée et al. 1992), the only EMIC used in WP2. The LLN-2D NH model results are detailed and discussed in section 3. Within WP2, the future climatic states that have been chosen are:

- A very near future for which two simulations are to be run. Simulation A is characterised by a very high atmospheric $CO_2$ concentration (1100ppmv) and present-day continental ice sheets. Simulation B uses a high atmospheric $CO_2$ concentration (550ppmv) and no Northern Hemisphere ice sheet nor West Antarctic Ice Sheet (WAIS). For these two simulations, all other parameters (such as insolation) are taken as at the present. Simulation B is motivated by the fact that all the simulations performed with the LLN-2D model show that the Greenland ice sheet would disappear in the next few millennia, if a high $CO_2$ concentration was to be reached even briefly during the next few centuries (Loutre and Berger, 2000);

- A possible future super-interglacial condition, 67 ky After Present (AP), due to the simultaneous occurrence of an increased summer insolation (relative to present day), a high $CO_2$ concentration and no ice sheets (Northern Hemisphere and WAIS). Two simulations (C and D) are to be performed to test two different atmospheric $CO_2$ concentrations (550ppmv and 350ppmv). Moreover, in order to test the impact of the ice sheets during a super-interglacial, a third experiment (E) is to be performed with a $CO_2$ concentration of 350ppmv and present-day continental ice sheets;

- A possible next episode of widespread Northern Hemisphere glaciation, 178 ky AP characterised by an atmospheric $CO_2$ concentration of pre-industrial level (275ppmv) and an extensive development of the Laurentide and Fennoscandian ice sheets (simulation F).

Simulations A to F will be performed by the IPSL_CM4 rappelé model (an Ocean-Atmosphere General Circulation Model). Global climatic patterns will be translated into global biome distributions using the ORCHIDEE vegetation model (Krinner et al. In Prep). Results from the IPSL_CM4 rappelé model will be downscaled for the selected regions of interest using different procedures. This second Work Package will thus deliver global and regional view of climate and vegetation states for a very near future and at 67 ky AP and 178 ky BP.

## *2.3 WP3 – Integrated strategy*

To complement the hierarchical strategy, an integrated strategy is being developed that will produce several transient simulations of the next 200 ky, thanks to the use of two EMIC models: MoBidiC (Crucifix et al., 2002) and CLIMBER (Petoukhov et al., 2000). These models have been adapted and applied to BIOCLIM specific purposes. More specifically, both models have been coupled to two different Ice Sheets models: GREMLINS (Ritz et al., 1997) for CLIMBER and the Ice Sheet model of Gallée et al (1992) for MoBidiC. Three transient simulations will be run under three different time-dependent atmospheric $CO_2$ concentration scenarios. The climatic response to the natural evolution of the $CO_2$ concentration will first be simulated, then the combined effect of this later and either a low or a high fossil fuel contribution will be tested. The designing of BIOCLIM $CO_2$ concentration scenarios is detailed in the deliverable D3 of the project ('Global climatic features over the next million years and recommendation for specific situations to be considered'), that can be found on the BIOCLIM web site. Here again, downscaling methods will be used to downscale EMICs results to a less crude spatial resolution and the resulting regional climatic evolution will be translated into vegetational evolution thanks to the use of the ORCHIDEE model.

### *2.4 WP4 – Biosphere system description*

Inputs from WP1, WP2 and WP3 will provide a climatological context for describing some possible environmental evolutions of various regions of interest throughout Europe. However, additional information will have to be provided to complete the environmental descriptions to the degree that is necessary for assessment purposes. Completion of the environmental descriptions and interpretation of those descriptions in the context of long-term PA will be undertaken within WP4. Specifically, the detailed aims of WP4 have been defined to be 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.

Output from WP4 will be a single integrated report covering both the methodology for identification and characterisation of climate states and transitions, and the application of that methodology to different regions or locations of interest throughout Europe.

### *2.5 WP5 – Final seminar*

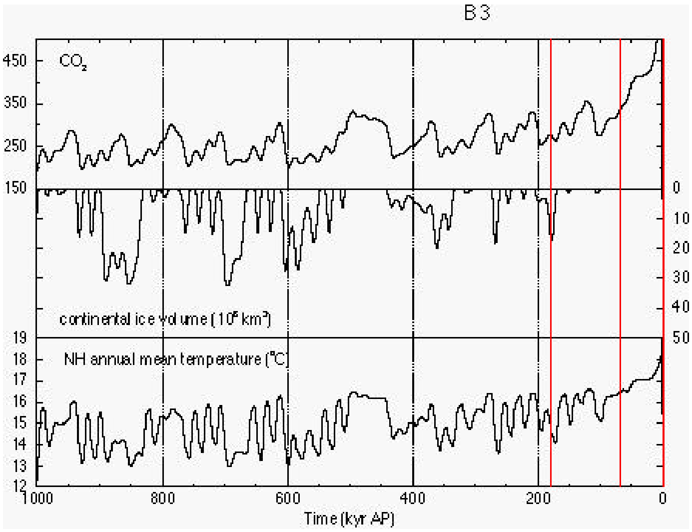
The methodologies developed, and results obtained, during the project will be disseminated throughout the international/technical and waste management community for further use. All the BIOCLIM deliverables are being made publicly available during the course of the project on the project web site (http://www.andra.fr/bioclim). A final seminar will be organised for the autumn 2003, jointly with the BioMoSA project. This seminar will facilitate dialogue between project participants and other interested parties on the significance and implications of the work.

## 3 THE POTENTIAL CLIMATIC EVOLUTION OF THE NORTHERN HEMISPHERE OVER THE NEXT ONE MILLION YEARS

As mentioned above, the first necessary step of Work Package 2 was to simulate the overall long-term evolution of the global climate in order to select which future time states would be further studied in the rest of the project. Results from the LLN-2D NH model simulation are displayed below. They are the Northern Hemisphere continental ice volume (middle of the figure) and annual average temperature (bottom) simulated in response to a combined natural and low fossil fuel contribution $CO_2$ scenario (top). Some vertical lines point out the three climatic states selected within WP2 (from right to left: Near Future, 67 ky AP, and 178 ky AP). The forcing $CO_2$ scenario is the natural $CO_2$ evolution computed by the simple threshold model of Paillard (1998) added to a fossil fuel burning contribution peaking at ~860 ppmv in 2275 then slowly decreasing exponentially. The human related contribution still amounts to ~270 ppmv after 5000 years.

In response to this forcing, the LLN 2D NH model shows the nearly complete melting of the Northern Hemisphere continental ice over the next 150 ky. Moreover the simulated ice volume remains small (less than $3\times10^6$ km$^3$) over most of the next 500 ky, except for some small excursions (up to $20\times10^6$ km$^3$) at 178, 267 and 361 ky AP. After 500 ky AP, the fossil fuel contribution becomes smaller and the climate can recover to its natural state. This interesting result indicates that under such a strong anthropogenic $CO_2$ forcing the next episode of widespread glaciation should not be expected before around 170 ky AP. This result has to be considered in the perspective of the history of attempts to provide long-term projections of future climate evolution.

In the early 1970's, several attempts were made to predict quantitatively future climate at the geological time scale. They were based on statistical rules developed for past climate and projected into the future (Berger et al., 1991). Therefore, the cooling, which started at the peak of the Holocene some 6000 years ago (Johnsen et al., 1995; Dahl-Jensen et al., 1998) was prolonged in the future. The next cold interval was predicted to occur at around 25 ky AP and the next glacial episode would peak around 55 ky AP, according to these former predictions.




The first climate modelling studies of the future climate (Imbrie and Imbrie, 1980; Gallée, 1989) supported the earlier predictions. However, these experiments were implicitly using a constant average $CO_2$ concentration. More recent experiments confirm that forcing the climate system with such an average $CO_2$ value of ~ 230 ppmv, i.e. the average over a glacial-interglacial cycle in the Vostok record (Petit et al., 1990) and lower, leads indeed to an immediate entrance into glaciation (Berger and Loutre, 1997), with the next glacial episode reaching a maximum 60 ky from now. However, Oerlemans and Van der Veen (1984) and Ledley (1995) did not agree with such a prediction and suggested a long interglacial of 50 ky, or even 70 ky.

$CO_2$ records of the most recent glacial-interglacial cycles (Shackleton et al., 1983; Barnola et al., 1987; Petit et al., 1999) show clearly that $CO_2$ concentrations vary through time. Therefore, climate models started to be used for tentatively simulating the climate of the next millennia, using both insolation and atmospheric $CO_2$ forcings (Saltzman et al., 1993; Gallée et al., 1992; Loutre, 1995). Using the past $CO_2$ variations reconstructed from the Vostok record as a scenario for the future, the LLN 2D NH climate model leads first to an exceptionally long interglacial, lasting ~55 ky (from 5 ky BP to 50 ky AP). The next glacial maximum is simulated to occur in ~100 ky from now. A large number of sensitivity experiments have confirmed the likelihood of such a very long interglacial (Loutre and Berger, 2000). The forcing in these additional simulations includes a shortening of the period during which $CO_2$ would remain at an interglacial level, through to a scenario in which $CO_2$ concentrations start to decrease immediately, to reach 230 ppmv at 25 ky AP. They all lead to the same very long interglacial with only very slight differences in the Greenland ice volume. Paillard (1998) developed a simple multi-state climate model that was able to reproduce the timing of the Pleistocene glaciations. When extrapolated over the future, this threshold model also produces an exceptionally long interglacial lasting 50 ky. However, a slight change in the threshold model leads to a completely different result for the next few cycles, i.e. the present-day ice volume is already beyond the glacial inception threshold and the current interglacial becomes as short as the previous one.

Moreover, the future climate prediction must also take into account the increase of atmospheric greenhouse gases due to human activities. On the basis of limited evidence available, Goodess et al. (1992) and Berger et al. (1991) first concluded that, following a period of warming, the next glaciation will be delayed and less severe. However, more recent simulations suggested a stronger effect of anthropogenic perturbations. Simulations were performed assuming that the atmospheric $CO_2$ concentration increases up to 750 ppmv over the next 200 years, and then returns to natural levels by 1000 years from now (Berger and Loutre 1996, Loutre and Berger 2000). The response of the modelled Northern Hemisphere ice sheet to such scenarios suggests that there is a $CO_2$ threshold above which the Greenland ice sheet disappears, and that the climate system may take 50 ky to recover from the impacts of human activities. In such a scenario, the next glacial maximum is not simulated before 101 ky AP (Loutre and Berger 2000). Compared to this last experiment, the BIOCLIM run discussed here uses a larger contribution of human activities to the atmospheric $CO_2$ concentration and therefore simulates a larger delay for the next glacial maximum: 178ky compared to ~100ky. This first BIOCLIM result will be compared to the performances of CLIMBER and MoBidiC that will be used within WP3 to simulate the next 200ky under different $CO_2$ scenarios. The table below summarizes the different steps of the history of attempts to provide long-term projections of future climate evolution, mentioned in this section.

| Methodology | Next Glacial Maximum at around : |
|---|---|
| Statistical rules | 55-60 ky AP |
| Modelling approach with $CO_2$ constant (< 230ppmv) | 60 ky AP |
| Modelling approach with time dependent $CO_2$ : natural variations only | 100 ky AP |
| Modelling approach with time dependant $CO_2$ : natural variations and fossil fuel contribution combined | 100 ky AP (Loutre and Berger 2000)<br><br>178 ky AP (BIOCLIM LLN 2D NH first preliminary run) |

# 4 FUTURE EVOLUTION OF THE BIOSPHERE SYSTEM : A CONCEPTUAL MODEL

In the BIOMASS methodology, two alternative approaches were defined for use in representing biosphere system change. These were described as the non-sequential and sequential approaches, respectively. In the non-sequential approach, it is considered sufficient to conceive of the future biosphere in the region of interest to be in one of a small number of states and to assess the radiological impact of radionuclide discharges to each of those states considered separately. Thus, no consideration is given to the order in which the states occur or to whether the characteristics of transitions between them have implications for radiological impact that are not adequately addressed by considering the individual states. Furthermore, because the approach does not define a duration for each state, it implicitly assumes that the duration is sufficiently long that radionuclide transport pathways through the biosphere can be fully expressed during each state.

In the sequential approach, the concept of biosphere system states is retained. However, these are now arranged in a temporal sequence and periods of finite duration, ‘transitions’ are regarded as existing between these states. It is recognised that this still represents a simplification of a system that will be subject to continuous change. However, the aim is not to represent explicitly all aspects of change, but rather to provide a conceptual framework in which all aspects of change relevant to PA can be represented at an appropriate level of detail. In particular, it is envisaged that many of the results from PA will still relate to the individual biosphere system states even in the sequential approach, with only a limited set of results depending either on the particular sequence of states studied or the characteristics of the transitions.

In the BIOMASS methodology, mechanisms of change are represented through the influence of External Features, Events and Processes (EFEPs) on the regional landscape. The biosphere process system, within which the transport, accumulation and radiological impact of repository derived radionuclides occur, is taken to be embedded within this regional landscape. In the context of BIOCLIM, the EFEPs of relevance relate to climate and climate change.

The EFEPs of human influences on global climate, global climate change, the advance and retreat of continental ice sheets and changes in global sea level are all being addressed in WP2 and WP3. Explicit calculations or downscaling techniques will also provide information on the regional climate regime, and some aspects of vegetation and soils in the regions of interest. However, other aspects of the environment have to be constructed explicitly in WP4, consistent with the EFEP information provided from WP2 and WP3. In developing descriptions of these other aspects of the environment, the biosphere system decomposition headings developed in BIOMASS are being used. These headings are:

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

Because BIOMASS expended considerable effort in developing non-sequential analyses of biosphere systems, the emphasis in BIOCLIM is being placed on the sequential approach. This sequential approach is being developed through the following stages:

a) Development of descriptions of the regions of interest at the present day;
b) Development of potential patterns of future climate evolution in those regions using the output from WP2 and WP3;
c) Development of narratives describing the future evolution of the biosphere in the regions of interest using the BIOMASS headings and the information from (a) and (b);
d) Identification of environmental states and transitions of radiological interest on the basis of the narratives developed under (c);
e) Development of conceptual models of the biosphere system for each of the states using the BIOMASS methodology;
f) Use of transition diagrams to identify those aspects of transitions between the individual biosphere system states that are of importance in PA.

Item (a) has been completed under WP1. Item (b) is an ongoing activity under WP2 and WP3. However, already sufficient results are available to develop provisional narratives under (c) that will be refined as further information is provided (see Section 5). Items (d) and (e) have yet to be undertaken. However, the experience obtained in BIOMASS is directly applicable to those steps, so no major issues are anticipated. For item (f), illustrative transition diagrams have been developed. However, these have not yet been used to undertake an analysis of those aspects of transitions that are of importance to PA. This is a major item in the forward work programme for WP4.

# 5 ILLUSTRATION : THE POTENTIAL CLIMATIC AND LANDSCAPE EVOLUTION OF CENTRAL ENGLAND OVER THE NEXT 200 000 YEARS

As mentioned in Section 4, one aspect of BIOCLIM is the development of narratives describing the future evolution of the biosphere in the regions of interest. Here, the approach adopted is illustrated for one of those regions, i.e. Central England. It is emphasised that this narrative has been developed solely on the basis of simulations undertaken using the LLN 2D NH model. As further results are generated under WP2 and WP3, this narrative will be updated and refined.

At the present day, Central England is best described as an undulating lowland, where lines of low hills are separated by broad open valleys and where 'islands' of upland break the monotony of more level areas. The soils tend to be deep and rich, there are few steep slopes to interrupt cultivation and plough lands are to be found right to the tops of the hills. Consequently, there is little to hinder man's use of the environment: human settlement is essentially continuous and the cultivated land of one parish merges into that of the next. Villages and towns are closely and evenly scattered, although their siting has sometimes been dictated by convenience of a water supply or by situation on a natural route. It follows that the greater part of Central England is occupied by farmland, which includes both cultivated land for agriculture and grass land for grazing livestock.

Based on long-term simulations undertaken as part of WP2, and using the first two letters of the Köppen-Trewartha climate classification system (Rudloff 1981, see Appendix) as a basis of description, the scenario adopted for the future climatic evolution of Central England over the next 200,000 years (200 ka) is:

- A rapid transition from DO through Cr to Cs on a timescale of a few hundred years;
- A long period of Cs, with a cooling transition to Cr at around 50 ka AP;
- A cooling transition to DO at about 90 ka AP, then a rapid transition through DC to a short period of EO around 100 ka AP;
- A subsequent warming through DC to DO, with DO persisting until about 130 ka AP;
- A brief cooling through DC to EO followed by a rapid warming through DC to DO, with the whole sequence complete by 150 ka AP;
- A cooling through DC, EO and EC to FT, with FT persisting for a short period around 180 ka AP;
- A warming through EC, EO and DC to DO at around 210 ka AP.

In summary, the following transitions are of relevance:

**FT ⇔ EC ⇔ EO ⇔ DC ⇔ DO ⇔ Cr ⇔ Cs**

Based on this sequence, descriptions of the biosphere system in each of the climate states and during the transitions between them have been developed. A brief summary is provided below. The narrative is structured by climate class, and the text for each climate class is ordered according to the BIOMASS categories plus some supplementary remarks on the characteristics of transitions to and from that climate class.

## *5.1 Climate class DO: temperature oceanic*

The current climate (DO) is temperate oceanic. 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.

Under future DO conditions, a mature, farmed landscape very similar to that at the present day is anticipated. However, it is also possible to envisage a low-population-density scenario with small settlements existing in clearings in a mainly forested environment.

### *5.2 Climate class Cr: Subtropical rain*

Climate class Cr is envisaged as commencing a few decades into the future. Annual temperatures would be about 4-5$^{o}$C higher than at the present day, with a possible slight strengthening of the seasonal cycle. Summer precipitation would decrease, possibly very markedly. Overall, summer soil moisture deficits would be markedly greater, leading to an increased and more variable irrigation demand. The thermal growing season would probably be in excess of 300 days and would extend throughout the year in some years.

The near-surface lithostratigraphy and topography would be essentially unchanged. Changes in water bodies relative to the present day are difficult to determine. 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. River and stream flows at other seasons of the year could increase somewhat. Therefore, in the transition from DO to Cr, the frequency of overbank flooding could increase and the magnitude of such floods could be larger. 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 annual precipitation remained similar to that at the present day, it seems likely that groundwater resources would be reduced. 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 increasingly dry summers.

In respect of biota, a wide range of crops could be grown, as at the present day. There is also no reason why animal husbandry practices should be very different, except that the prolonged vegetation growth period would allow animals to graze pastures throughout the year. With a similar pattern of agriculture and a timescale of only a few hundred years on its first occurrence, it seems likely that human community characteristics would be similar to those at the present day.

### *5.3 Climate class Cs : Subtropical winter rain*

Only a single period of Cs conditions is envisaged, commencing a few hundred years in the future and terminating at about 50 ka AP. The mean annual temperature would be about 7$^{o}$C warmer than at the present day. The seasonal cycle would be slightly increased, with winter about 6$^{o}$C warmer and summer about 8$^{o}$C warmer. A strong seasonal cycle of precipitation is expected, characterised particularly by long dry summers. Total annual precipitation would be similar to that at the present day. Overall, there would be a strong soil moisture deficit between May and September and an extended summer moisture deficit of about 450 mm, corresponding to an irrigation requirement of about 500 mm. The near-surface lithostratigraphy and topography would be essentially unchanged from the present day, although there could be some soil modification to produce typical red earths. A limited increase in rates of generalised erosion and valley incision could occur. Moisture excesses in winter might be somewhat reduced relative to Cr, so stream channels might be over-sized relative to peak discharges. The very dry summers are likely to result in an increased proportion of ephemeral streams. Groundwater sources are likely to be reduced relative to the previous Cr state and there may be an increased emphasis on the implementation of surface-water storage schemes. Irrigation may be from either groundwater or stored surface water. 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 also no reason why animal husbandry practices should be very different from those at the present day, except that pasture would be irrigated and animals would be able to graze such irrigated pasture throughout the year. With a similar pattern of agriculture to the present day, there is no climate-driven reason to propose any substantial change in human community characteristics. However, it is noted that the long duration of future Cr and Cs conditions is likely to mean that a greater diversity of community structures would flourish at some time, relative to the mix observed at the present day.

### 5.4 Climate Class DC : Temperate continental

The DC state occurs briefly on a number of occasions, as the system moves from DO to EO and back again during the pre-glacial period. It also occurs briefly during a warming trend after a future glacial (FT) state. This state would be characterised by mean annual temperatures about 4°C colder than those of the present day. The seasonal temperature cycle would be more pronounced, with summer temperatures about the same as at present, but winter temperatures about 9°C colder. The total amount and monthly pattern of precipitation are very similar to those at the present day. Similarities of summer temperature and precipitation mean that summer moisture deficits in DO are very similar to those 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. In respect of near-surface lithostratigraphy, in the pre-glacial period this would be essentially unchanged from that of the present day, although there could be some soil modification to produce podsols. In the post-glacial period, some disruption of the stratigraphy due to frozen-ground effects might occur. Overall, the topography would be very similar to that at the present day. The main change in water bodies relative to the present day is likely to be an enhanced spring flood associated with snowmelt processes. However, the winters are not extremely cold and thaws during the winter months might mitigate this effect.

If DC is entered by cooling from DO, the mix of arable agriculture and livestock husbandry is likely to be similar to that at the present day. The range of crops grown might be somewhat restricted, but the main effect could be selection of varieties that are appropriate to a shorter growing season. Animals are likely to have to over-winter indoors. If DC is entered by warming, notably in post-glacial conditions, a heavily wooded landscape, with clearings for arable agriculture and pasture, might be characteristic. Although heavily wooded and open landscapes are both possible, these should be regarded as end-members of a sequence in which varying degrees of mixed coniferous and deciduous woodland are present in the landscape. If DC is entered from DO, a pattern of human communities similar to that at the present day is envisaged. In contrast, if DC is entered from EO, the pattern of communities might either be similar to that at the present day (hamlets, villages and market towns in an open landscape) or, at the other extreme, might predominantly comprise individual homesteads in clearings in an extensive forest.

### 5.5 Climate Class EO : Subarctic oceanic

Climate state EO would be characterised by cool summers (mean temperature of the warmest month just over 10°C) and winters that exhibit similar temperatures to those of DC. The total precipitation would be very similar to that at the present day and is 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. For the same reasons as given for DC, there is not considered to be a significant demand for irrigation with groundwater. As with DC, EO can occur as an intermediate in cooling or warming trends. However, it can also occur as the coldest period in a transition from a cooling trend to a warming trend.

In the pre-glacial period, the near-surface lithostratigraphy would be essentially unchanged from that of the present day, although there could be some soil modification to produce gelic histosols. In the post-glacial period, some disruption of the stratigraphy due to frozen-ground effects might be observed. The topography would be essentially unchanged from that at the present day. In respect of water bodies, high groundwater levels would be characteristic. 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.

Whether EO is entered by warming or cooling, a largely treeless landscape is likely to develop, either from forested or unforested antecedent warmer or colder 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 be present. 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.

### 5.6 Climate Class EC : Subarctic continental

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. Changes to 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 are likely to closely resemble those of the preceding EO state in the cooling stage prior to glaciation at 180 ka AP. As agriculture is likely to be abandoned in the following FT stage, it may not be re-established in the transient EC stage that follows. In the cooling stage prior to glaciation, human communities are likely to be similar to those of the preceding EO stage. Post-glaciation, the landscape may be mainly utilised by hunters and herders.

### *5.7 Climate Class FT : Polar tundra*

Based on analogue station data, climate state FT is associated with cooler summers and warmer winters than EC and the overall annual average temperature is only marginally lower. However, it should be noted that palaeoenvironmental data imply intensely cold winters in Central England in these conditions. Because the northern hemisphere ice volume during the projected FT state is much smaller than it was at the Last Glacial Maximum, only limited upland ice might be present in Britain and Central England would not be substantially affected by ice-marginal phenomena. The near-surface lithostratigraphy and topography would be changed to only a limited degree, but cryoturbated soils and other frozen-ground effects would occur. Effects on water bodies would be similar to those discussed in the context of climate state EC, but with the possibility of continuous permafrost. 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 by nomadic groups involved in the herding and hunting of reindeer. These groups may have permanent settlements at the coastline and supplement their diet with marine organisms from highly productive polar waters.

## 6 CONCLUSIONS

The BIOCLIM project is proving to be a very fruitful collaboration of climatologists and specialists in PA. For more than a decade, simple, non-sequential approaches to representing climatic and environmental changes have been the main approach used in PA. The coupling of explicit scenarios for climate and environmental evalution with the formal systems analysis techniques developed in BIOMASS is likely to provide a powerful tool for identifying the factors that could have a substantial influence on the potential radiological impact of deep geological repositories. However, BIOCLIM is limited to identification and definition of those factors, i.e. it will provide conceptual models of landscape and biosphere system evolution suitable for use as a basis for the development or adaptation of mathematical models. In future, the lessons learned from BIOCLIM will need to be carried forward in a new generation of mathematical models, so that the implications of climatic and environmental evolution can be investigated in quantitative terms, both in generic studies and for specific sites.

## APPENDIX: RULES FOR CLIMATE CLASSIFICATION

Rules for climate classification as taken from pages 84-85 of Rudloff (1981). Rann is the mean annual precipitation, Rwin is the mean precipitation in winter (October-March), Rsum is the mean precipitation in summer (April-September), and Rmin is the mean precipitation of the driest month. Tc is the temperature of the coldest month and Tw is the temperature of the warmest month. The first column gives the climate classification at one letter level and the second column gives the climate classification at two letters level.

| | |
|---|---|
| **A tropical climates:**<br>over 17°C in all months | **Ar tropical rain:**<br>least 9 rainy (> 60mm) months<br>**Am tropical monsoonal rain:**<br>Rann ≥ 25(100-Rmin)*25<br>**Aw tropical summer rain:**<br>Rwin < Rsum<br>**As tropical winter rain:**<br>Rsum < Rwin |
| **C subtropical climates:**<br>over 9°C 8-12 months | **Cr subtropical rain:**<br>not Cw/Cs or driest summer month > 29mm,<br>**Cw subtropical summer rain:**<br>Rsum > Rwin * 10<br>**Cs subtropical winter rain:**<br>Rann < 890mm & Rwin > Rsum * 3 |
| **D temperate climates:**<br>over 9°C 4-7 months | **DO temperate oceanic:**<br>Tc ≥ 0°C<br>**DC temperate continental**:<br>Tc < 0°C |
| **E subarctic climates:**<br>over 9°C 1-3 months | **EO subarctic oceanic:**<br>Tc ≥ -10°C<br>**EC subarctic continental:**<br>Tc < -10°C |
| **F polar climates:** | **FT tundra:** |

| | |
|---|---|
| over 9° no month | Tw ≥ 0°C<br>**FI ice:**<br>all months < 0°C |
| **B dry climates:**<br>evaporation > precipitation | **BS steppe:**<br>Rann < RW x 2<br>**BW desert:**<br>Rann < RW<br>**BM marine desert:**<br>Rann < RW, near coast & high air humidity<br>[RW = 10(Tann-10) + 300 * Rsum/Rann)] |

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