Bioclim

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Modelling Sequential Biosphere Systems under Climate Change for Radioactive Waste Disposal

EC-CONTRACT : FIKW-CT-2000-00024

Deliverable D1:

Environmental Change Analysis

Consolidation of the Needs of the European Waste Management Agencies and the Regulator of the Consortium

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.

- Agence Nationale pour la Gestion des Déchets Radioactifs (Andra), France **M. Calvez, J. Brulhet**
- Commissariat à l'Energie Atomique/ Laboratoire des Sciences du Climat et de l'Environnement (CEA/LSCE) France - **N. de Noblet, D. Paillard**
- United Kingdom Nirex Limited (NIREX), UK - **P. Degnan**
- Gesellschaft für Anlagen und Reaktorsicherheit mbH (GRS), Germany - **A. Becker**
- Empresa Nacional de Residuos Radioactivos S.A. (ENRESA), Spain - **A. Cortes**
- Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas (CIEMAT), Spain - **P. Pinedo, F. Recreo, A. Aguero, C. Ruiz, L. Lomba**
- Universidad Politecnica de Madrid Escuela Tecnica Superior de Ingenieros de Minas (UPM-ETSIMM), Spain - **T. Torres, M. Lucini, J.E. Ortiz**
- Nuclear Research Institute Rez, plc - Ustav jaderneho vyzkumu Rez a.s. (NRI), Czech Republic - **A. Laciok**
- Université catholique de Louvain/ Institut d'Astronomie et de Géophysique Georges Lemaître (UCL/ASTR), Belgium - **A. Berger, M.-F. Loutre**
- The Environment Agency of England and Wales (EA), UK - **R. Yearsley, N. Reynard**
- University of East Anglia (UEA), UK - **C. Goodess, J. Palutikof**
- ENVIROS QuantiSci, UK - **B. Watkins, M. Egan**

For this specific deliverable the main contributors are the waste management agencies (Andra, NIREX, GRS, ENRESA, NRI), the regulator (EA) and the consultant company (ENVIROS QuantiSci). Note than **M.C. Thorne** and Associates Limited contributed to this document as subcontractor to NIREX.

Contents List

1. Introduction and objectives

In many countries throughout the European Community (EC) there are national projects to address the safe management of radioactive wastes which arise from activities such as nuclear energy generation, medical treatments and industrial research programmes. Any long-lived intermediate level (ILW) and high-level (HLW) wastes so generated cannot be safely 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[1] often cover very long timescales (up to, and possibly beyond, 1,000,000 years) to demonstrate that future generations will be afforded the same 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.

[1] PA = Performance Assessment

1.1 - General Objectives of Bioclim

Various factors may have impacts on the potential safety of a repository system. Of particular importance and interest are the effects of climate change. A number of mechanisms cause climate change, some of which operate on relatively short timescales of hundreds of years (e.g. climate warming due to anthropogenic impacts on atmospheric composition), whilst others operate on the long timescales of tens or hundreds of thousands of years which is of relevance to a PA. The BIOCLIM project is aimed at providing a scientific basis and practical methodology for assessing the possible impacts on the safety of radioactive waste repositories in deep formations due to long term climate change. The project brings together a number of 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. In particular, BIOCLIM aims to address the important objective of how to represent the development of future biosphere systems by addressing both how to model long-term climate change, the relevant environmental consequences of such changes and the implementation of a sequential approach to such changes. The results from the development of this sophisticated approach will be of great benefit for improving long term radiological impact calculations and the information presented in a safety case.

Simulations will be conducted to represent the time series of long-term climate in three European areas within which disposal sites may be established (i.e. Central/Southern Spain, Northeast of France and Central Britain). Two complementary strategies will provide representations of future climate predictions together with associated vegetation patterns using either an analysis of distinct climate states or a continuous climate simulation over at least one glacial-interglacial cycle and possibly for other selected periods over the next 1,000,000 years. These results will be used to derive the characteristics of possible future human environments (i.e. biosphere systems) through which radionuclides, emerging from the repository, may be transported to the surface environment and lead to the exposure of Man. Several climate scenarios will be explored in the project and selected climate sequences of particular interest for performance assessments will be studied in detail to establish the context for the development of biosphere assessment models. The aim is not to derive mechanistic models of the whole climate sequence for up to a million years but to use output from the climate change models in order to understand the biosphere system responses that are likely to be important in the context of human and environmental safety. Through this work, the basis for undertaking and assessing the radiological safety of deep repositories and confidence in the assessment results will be improved.

The project is designed to advance the state-of-the-art of biosphere modelling for use in PAs via five work-packages as follows:

Work Package 1: To consolidate the PA needs of the European agencies of the BIOCLIM consortium through summarising of the mechanisms causing climate change, providing a synopsis of how environmental change is currently treated in such assessments, and summarising the lessons learned from such applications. Available palaeoenvironmental information will be collated for three sites of interest for input to future climate and environmental simulations of the sites.

Work Packages 2 and 3: To develop two practical and innovative strategies for representing sequential long-term climatic changes by addressing time scales of up to one million years, which is the time scale of relevance to geological disposal of solid radioactive wastes. The two strategies are:

1. A hierarchical strategy that will use different existing models, from simple ones which are able to provide the long term evolution of the global climate, to more complex ones that can provide a more detailed global or regional view of the resulting environmental changes that accompany particular sequences of climate. Downscaling procedures for the three selected sites of interest will be developed and evaluated, and results will be provided in terms of climate and vegetation cover for the specifically selected time sequences (Work-Package 2);

2. An integrated strategy that will consist of building an integrated climate model that can represent the physical mechanisms important for long-term continuous climatic variations. The results will be interpreted in terms of regional climatic, as well as vegetation, changes using the downscaling approaches (Work-Package 3).

Work Package 4: To explore and evaluate the potential effects of climate change on the characterisitics of the biosphere systems in terms of PA requirements and how the biosphere systems could be represented in a biosphere assessment. In particular, innovative guidance will be provided for representation of a transitional biosphere system.

Work Package 5: To disseminate information on the methodologies and the results obtained from the three-year project for further use among the international community.

1.2. - Objectives of Work Package 1 - Deliverable 1

The objectives of this first BIOCLIM report are to identify the mechanisms and process that cause long-term climate change and the environmental consequences of such changes (Section 2). This information is presented in summary form as an extensive literature already exists on these subjects. Some of these references are also provided in the appendix. The lessons that have been learned by the waste management agencies and the regulator through application of methodologies used to date to represent climate change in biosphere assessments are summarised in Section 3 ; further details of current national methodologies and approaches are provided in Appendix A. Section 4 summarises the new approaches that will be used in BIOCLIM to develop and improve long-term climate change models and the consequent impacts on the biosphere systems that have to be represented in biosphere assessment models.

2. Factors affecting climate and environmental change

As noted in Section 1, one of the fundamental principles for the safe management of radioactive wastes is that future generations should be afforded the same protection as those alive today (see IAEA, 1995). For this reason safety assessment calculations often encompass timeframes of up to, or even more than, 1,000,000 years. Given this sort of timeframe, the biosphere system into which radionuclides may emerge from a deep repository will have changed from that which is present today. One of the primary drivers of environmental evolution is considered to be climate and climate change. Climate varies on a wide variety of spatial and temporal scales and is affected by many mechanisms that operate on timescales of up to, and beyond one million years. In the following three sub-sections the mechanisms affecting climate change, the relevance of these mechanisms for climate models, and factors affecting environmental change are summarised. More information can be found in various references and in particular are already summarised in BIOMASS 1999d and 2000c.

2.1. - Mechanisms Affecting Climate Change

The primary driver of environmental evolution is considered to be climate and climate change. Climate varies on a wide variety of spatial and temporal scales and is affected by a large number of factors. The various factors that cause climate change are summarised in Figure 2.1.

It can be seen from Figure 2.1 that climate change mechanisms operate over four main timescales. It is important to identify those climate change processes and related timeframes that could affect the biosphere.

Less than 10 years: On this scale, the main variations are annual and seasonal, forced by strictly astronomical variations in irradiance and by atmospheric autovariation. These variations may cause increased episodes of higher temperatures or heavy run-off of precipitation and consequently influence hydrologial recharge and discharge. These episodes are quite regionally limited.

10 to 1000 years: In this timeframe, variations in the solar constant and in the composition of the atmosphere (thermic pollution, greenhouse gases, aerosols), along with periods of intense volcanism, appear to dominate climatic variations. Autovariations may also have an effect in this timeframe. Related effects are abnormal rates of precipitation or regional overheating due to random meteorological events.

Anthropogenic disturbance of atmospheric gas concentrations due to increased releases of CO2 to the atmosphere (some 20 thousand million tons per year), and the subsequent increase in the greenhouse effect, is becoming a major climatic effect on the time span of the next few centuries. However, there may be important consequences on even longer timescales.

In the late Quaternary there are quasi-periodic episodes of major ice rafted in the North Atlantic (termed Heinrich events). Thirteen such events were recorded in 28 kyr. They should reflect quasi-periodic increases in iceberg calving rates in the North Atlantic. Several of the Heinrich events occurred at the end of prolonged cooling episodes. Following each Heinrich there is an abrupt shift to warm conditions, which took place over just a few decades. Furthermore these cooling cycles can be correlated with similar variations in D18O in ice cores from the Greenland ice sheet. More precisely, Dansgaard (1993) recognised 24 episodes between 12 and 110 kyr BP when isotopic values drop suddenly. The change from low to high D18O is rapid (a few decades) while the recovery to low values is slow (~2 kyr). This shift in D18O can be interpreted as an increase of mean annual surface temperature of up to 7°C.

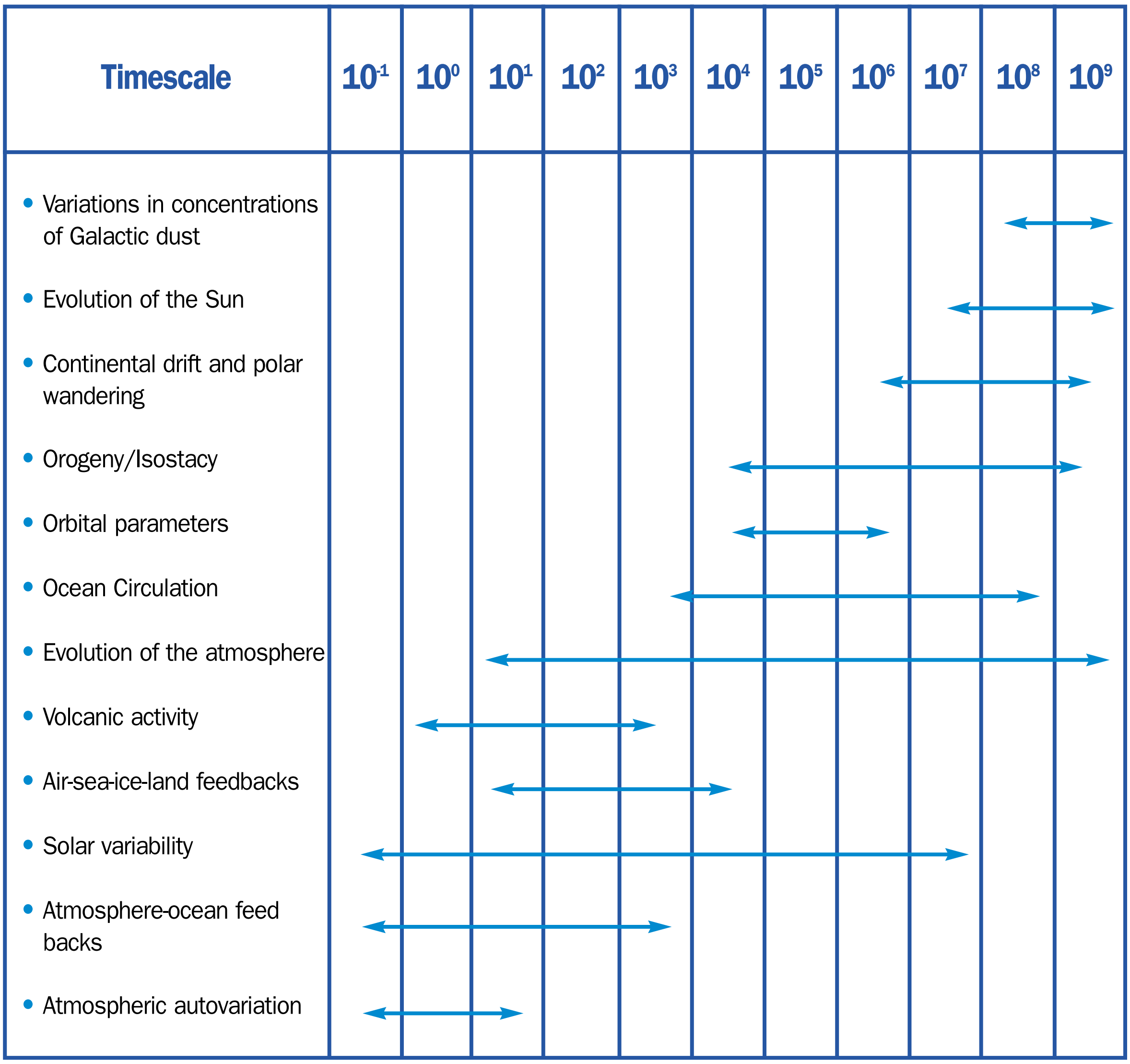

Figure 2.1 : Characteristic Timescales of Factors Affecting Climate Change

10^3 to 10^4 years: This time frame includes the melting of the polar ice-caps, an example of which is the last thaw which occurred between 18,000 and 9,000 years Before Present (BP). The transition from a glacial climate state to interglacial conditions would appear to be controlled by the period of time neccessary for the ice-sheet to melt under conditions of increased irradiance slightly below a given critical value and from ice feedback mechanisms. This transition from glacial to interglacial phases is accompanied by some other changes including the restructuring of ocean currents, which might be the missing element as regards understanding the enormous influence currently exercised by the Atlantic Ocean on the overall climate of the planet.

The change from glacial conditions to interglacial climate states has also been accompanied by a strong variation in the concentration of atmospheric CO_2 and in the levels of methane, as shown in the Vostok ice cores. The Vostok cores and others demonstrate the strong correlation between air temperature and CO_2 atmospheric concentrations over the last hundreds of thousands of years.

10^4 to >10^6 years: The most important climatic phenomenon in this timeframe is the transition to glacial climatic states from non-glacial states (and vice versa) controlled by the astronomical forcing mechanisms frequencies (19 ka, 23 ka, 41 ka and 100 ka). The astronomical forcing mechanisms account for about 60 % of the variance recorded in the past 780,000 years between 19 ka and 100 ka BP, and up to 85 % of the variance if the 'windows' are four narrow bands around the orbital cycles.

There is now substantial evidence of interglacial-glacial changes in oceanic circulation, its chemistry and vertical structure. The impact of glacial climates on the geosphere-biosphere system needs the construction of specific models for the impacts originating from these special conditions.

For time frames over 10^6 years, continental drift and plate tectonics activity would appear to dominate. Structural changes in oceanic currents are also important since they modify the efficiency and form of transport of oceanic heat between upper and lower latitudes. But the main forcing mechanisms are tectonic in origin.

Summary: The non-linear nature of interactions existing between the various climatic variations means that the response of the climate system to external forcing mechanisms is much more complex than would be expected from linear systems. The idealized variance spectrum of the atmospheric temperature may serve as a guide for analysis of the behaviour and variability of the response of the climate system over the different timescales, so illustrating the complexity of the response of the climate system to these forcing mechanisms.

It is possible to consider the climate system over the different timescales as being different systems, at least when modelling or representing its behaviour. In this way, when studying the climate system, certain sub-systems or processes become less relevant than others at certain timescales which may mean that they can be ignored.

2.2. - Relevance of Climate Change Mechanisms in Climate Models

Given the number of mechanisms that can cause climate change, it is useful to distinguish between the processes that are either quasi-periodic, quasi-continuous and/or episodic. This helps to identify those mechanisms that are relevant in terms of climate models for radiological safety assessments and hence need to be represented as climate model drivers. Table 2.1 sets out such a classification.

It can be seen that over the timescales of interest for radiological safety assessments, 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. It is for this reason that these aspects form a central core of the work on the development of the climate models in BIOCLIM (see Section 4).

Specific Factor	Epidosic	Quasi-periodic	Quasi-continuous	Relevance for Climate Modelling
Galactic dust[2]		✔		No
Evolution of the Sun[3]			✔	No
Continental drift and polar wandering[4]			✔	No
Orogeny/isostacy[5]	✔	✔	✔	Yes ?
Orbital parameters[6]		✔		Yes
Ocean circulation[7]	N/A	N/A	N/A	Yes
Evolution of the atmosphere due to[8] - Natural changes in greenhouse gases concentration - Volcanic activity[9] and natural aerosols - Anthropogenic activities	✔	✔	✔	Yes Yes, in so far as they affect atmospheric composition
Air-sea-ice-land feedbacks[10]	N/A	N/A	N/A	Yes
Solar variability[11]		✔		No
Atmosphere-ocean feedbacks[12]	N/A	N/A	N/A	Yes
Atmospheric autovariation[13]		✔		No

✔ : applicable   N/A : not applicable

Table 2.1: Summary of Factors Affecting Climate and their Relevance for Climate Modelling in Radiological Safety Assessments

[2] Hypothetical, poorly substantiated mechanism applying on very long timescales.
[3] Known to occur, but timescale too long to be of interest in assessments.
[4] Known to occur, but timescale too long to be of interest in assessments.
[5] Orogeny is an episodic process. However, isostatic adjustment may be quasi-periodic in response to ice or water loading, or quasi-continuous in response to erosion. Orogeny is unlikely to be relevant on the timescale of assessments, but isostatic adjustment may have substantial effects, e.g. on the groundwater regime.
[6] Almost universally identified as likely to be important on the timescales of interest.
[7] Response to external forcing factors. However, it may be a strongly non-linear modifier of those factors, if the ocean system has several stable states and exhibits hysteresis in switching between them.
[8] Includes natural and anthropogenically induced changes in greenhouse gas concentrations. Natural changes may be partly determined by orbital forcing of the climate system.
[9] Both individual eruptions and periods of enhanced vulcanism are included.
[10] Interactions of continental ice sheets with global, regional and local climate are considered to be particularly important.
[11] The short-term significance of Solar variability is much debated, but it is not considered to be a major long-term factor.
[12] Largely covered by the remarks under ocean circulation changes.
[13] Short-term variability only.

2.3. - Factors Affecting Environmental Change in a Biosphere System

The primary factors that determine environmental change in the vicinity of potential repository sites are climate and climate change, and human activities. Figure 2.2 (based on work undertaken in BIOMASS) summarises the various processes that act on the biosphere causing change. It is these environmental consequences of natural and human induced climate changes, rather than the climate drivers per se, that are of interest for radiological assessments. This is further discussed in Section 4.

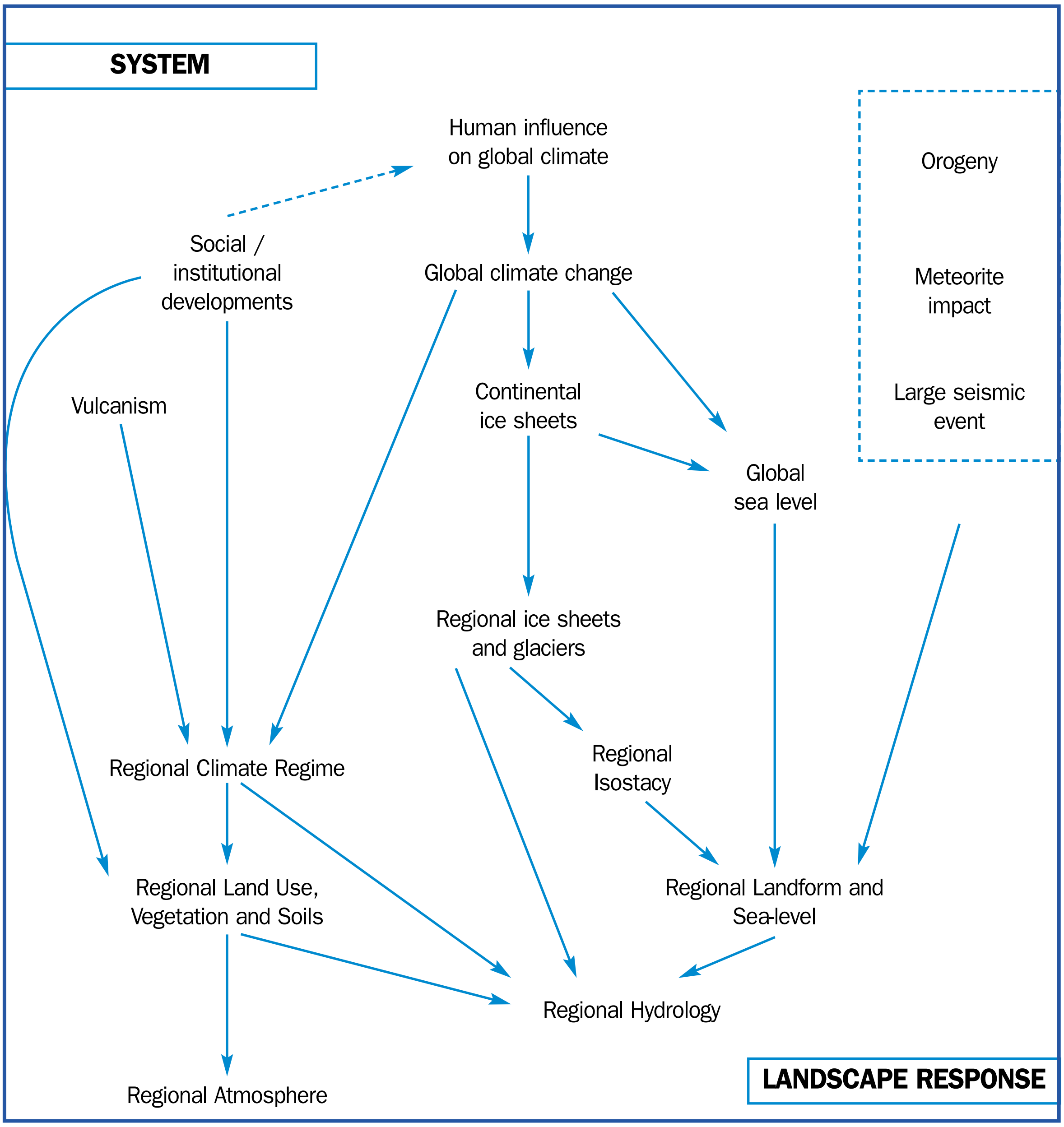

Figure 2.2 : Schematic illustration of factors that influence change in a Biosphere System (from BIOMASS, 2000c)

3. Lessons learned from current approaches to climate and environmental change in performance assesments

In many performance assessments carried out to date, climate models have been used as external drivers to obtain required boundary conditions for running the actual PA models. In these cases, climate and the related environmental characteristics have often been represented as discrete states. However, there have also been attempts to undertake simulations of climate and environmental change. The various approaches used to date to model climate and environmental change by the different waste management agencies participating in BIOCLIM are presented in the Appendix. What is of concern here is to provide a summary of the various lessons that have been learned by the participating organisations in the application of those methods.

3.1. - Andra, France

Andra has not so far integrated environmental change in its biosphere analysis for use in the performance assessments. However extensive work has been carried out and environmental change will be demonstrated in its final PA planned in 2004, relative to the Underground Research Laboratory located in the Meuse/Haute-Marne site. The approach used to date and the main results obtained related to the mechanisms of biosphere system change and geological evolution are presented in the Appendix.

So far, the approach under development uses discrete biosphere states representative of possible future conditions over the site. They rely on past climate and vegetation reconstruction, whereas no environmental simulation has been undertaken to date. The need to validate the information obtained from the past data to possible futures has been recognized and will be addressed in BIOCLIM.

Furthermore the continuous evolution of the climate is also not taken into account with the non-sequential approach pursued so far. A complete safety assessment requires to consider this aspect, whereas this continuous processing demands the use of extremely efficient tools, like environmental simulation. BIOCLIM will help to consider these aspects through two strategies currently under study.

It is recognised that temporal variations can have transient effects; all types of biosphere system can be exposed to significant short-term transformation, both naturally (e.g. by fire and flooding) or artificially (fallow agricultural land, forest clearance). Explicit characterisation of the effects of transitions associated with 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 as part of an overall safety case. These considerations have not been explored to date.

3.2 - Enresa, Spain

The assessment of a Deep Geological Repository (DGR) is the first step in a systematic process that, through successive approximations, will facilitate the prediction of the future performance of the disposal system. One of the main events considered and directly linked with the geomechanical evolution, as well as the hydrogeological, hydrogeochemical and geomorphological behaviour, is the climatic and environmental change (by internal and external forces).

Main lack of knowledge in this field have been :

- To identify main parameters and processes that control the past scenarios of climatic evolution in different timeframe scales (short term / long term), and different spatial scales (global, regional, local), and their effects in the environment.
- To interpret, and to define the most logical sequences of climatic cycles in the Iberian Peninsula in basis of the geological record from the last million years.
- To identify main parameters and processes that control the past and future scenarios of climatic evolution in different timeframe scales (short term / long term), and different spatial scales (global, regional, local), and their effects in the environment.
- To select the long-term climatic and environmental scenarios, and to determine the rates and variability of the main factors controlling the climatic change (natural/internal and anthropic/external FEP´s).
- To model and to simulate, from different approaches (hierarchical and integrated) climatic evolution and environmental evolution in order to calculate the rates of doses of future exposure groups.

According to the above, ENRESA has developed in parallel :

(a) an R&D programme to provide the knowledge and data necessary to carry out Safety Assessment (SA) of the disposal system, specifically focussed in the biospheric model.

(b) several PA exercises for granitic and clay formations in order to assess the long-term system response.

In the Spanish case, the biospheric system has considered the follow scenarios:

- Superficial and deep shaft to evaluate the radionuclide release in the groundwater from geosphere.
- Soil dynamic model to calculate the transference rates in order to a hydraulic model.
- Atmospheric conditions will control the radionuclide rates related to ingestion and inhalation.

The main lessons learned so far, have been:

- Geomechanical and tectonic impact derived from climatic change has not to be considered in the Spanish case.
- Main changes in water mass balance; groundwater reaching to the repository and the groundwater mass balance that reach to biosphere can be estimated on the basis of the geological past record.
- Need to evaluate external forcing (anthropic activities; CO_2, uses of land, etc.) that can modify the normal climatic and environmental evolution in reference to the past geological record.
- Need to develop and to integrate a methodology in PA exercises that consider the climatic and environmental evolution in an integrated approach.

3.3 - Environment Agency, England and Wales

Research activities undertaken by the Environment Agency and its predecessor, Her Majesty's Inspectorate of Pollution (HMIP) have been aimed at providing the regulator with an independent capability to assess the proposals of UK waste management agencies, in relation to both near-surface and deep geological disposal systems. Part of HMIP's work involved development andimplementation of the so-called 'environmental simulation' approach to long-term performance assessment (PA). This adopted a systems approach to representing disposal facilities and their environment, in order to address the complex problem of addressing risk in situations where there are large numbers of interrelated and uncertain phenomena (see, for example NEA, 1992).

It is important to note that the focus of the UK regulators' work has been on the development and implementation of a coherent assessment capability, with rather less emphasis on fundamental research into the mechanisms of environmental change and their effects. Nevertheless, the experience gained through deployment of the environmental simulation approach is believed to be directly relevant in terms of the lessons learned about the role and representation of environmental change in long-term assessments.

The approach and methodologies used to date and the results obtained are presented in the Appendix.

A NEA review report (NEA, 1992) noted that because systems models, like real systems, are complex, the problems of understanding and presenting the results are very challenging. In addition, there may be difficulty obtaining reliable data for many of the large number of input parameters. Notwithstanding these problems, HMIP managed to construct integrated environmental simulation-radiological risk models and to use these in practice.

It is not the intention here to focus on specific aspects of the TIME2 and TIME4 modelling techniques, such as the limitations and drawbacks of the Markov chain approach to generation of climate sequences. Rather, it is to observe that any simulation procedure will inevitably introduce modelling artefacts, reflecting uncertainties linked to the role of Features, Events and Processes (FEPs) represented by the model. The more complex, or more dynamic, the system being represented (such as within the biosphere), the more difficult it can be to disengage the findings of the simulation model from the conceptual uncertainties regarding the processes it needs to represent.

The environmental simulation models developed on behalf of HMIP were developed with two principal purposes. One was to provide changing boundary conditions for the groundwater flow and transport model used to calculate releases of radionuclides from the repository to the biosphere. The second purpose was to model water and sediment movement within the biosphere for use in dose calculations. These two purposes have different requirements and the principal lesson learned from the development and use of these models is that it would be preferable within PA to separate formally the two purposes.

Many of the biosphere/climate related processes included within the HMIP's environmental simulation models have little influence on the groundwater system that controls radionuclide transport in the geosphere. On the other hand, coupling the environmental simulation model within an overall performance assessment model limits the spatial and temporal scales that can be addressed in representing transport in the biosphere. Separating the two purposes of environmental simulation would allow more detailed standalone biosphere modelling and simplify the simulation of changing boundary conditions for the geosphere model.
As far as models of the surface environment are concerned, the application of a more detailed process-based model within a full system model may be impractical because the time scales that characterise biosphere processes are very short compared to those for PA. Moreover, it is not clear – from the experience of the Environment Agency in

attempting to simulate sequential changes – that results will be any more reliable than those obtained by static (time-independent) biosphere models favoured in many PA studies. There are both logical arguments for, and operational advantages in, separating the question of assessing performance of the repository and geological barriers from a detailed assessment of the performance of the biosphere. This does not mean that the biosphere can be neglected, but that the context in which it is investigated is altered, and more freedom may be available to investigate critical biosphere processes and scenarios. For example, time-dependent stand-alone modelling of some biosphere scenarios could be carried out in order to guide simplified biosphere models used in system calculations.

In summary, therefore :

- It is important to keep a firm sight on the context within which biosphere models will be used in repository PA (e.g. what are the impacts to be assessed,over what timescale and what spatial domain?). The biosphere models then needs to be 'tuned' to these.
- Where detailed models (e.g. based on considerations of climate change sequences) are developed to support simpler assessment models, these should focus on building sufficient confidence in the assessment models.
- In evaluating candidate processes for inclusion in models, consideration should be given to temporal and spatial variability, and to whether effects of sequence may be significant or can be ignored. Indeed, a catalogue of processes, identifying which processes are likely to be important at different temporal and spatial scales might be a useful contribution.
- Use can be made of considerable experience in modelling surface hydrological, geomorphological and ecological processes. Models should, however, be examined carefully to check their suitability to the particular temporal and spatial scales, and to site-specific circumstances, for which they will be applied.

3.4 - UK Nirex

United Kingdom Nirex Limited has undertaken a series of post-closure radiological safety assessments of deep geological repositories for solid radioactive wastes since the late 1980s. These studies have been conducted both in the context of generic assessment exercises and to determine the potential of a specific site (Sellafield) for development of a repository. One such assessment (Nirex 95) has been subject to detailed scrutiny in the context of a Public Inquiry and issues arising from that Inquiry have been explored in subsequent studies, notably Nirex 97.

From the late 1980s through to the present day, Nirex has used a broadly similar approach to the geosphere and biosphere components of assessment studies.

a) 2-D and 3-D models of the deep geology and hydrogeology have been used to characterise the groundwater flow field, so as to determine transit times and pathways to the accessible environment and to identify potential discharge locations;

b) Results from the deep groundwater flow and transport calculations have been used to inform Monte Carlo simulations of radionuclide migration in the geosphere undertaken using a simplified assessment model. The resultant fluxes from the geosphere to the biosphere and concentrations in a near-surface aquifer have been used in combination with independently conducted biosphere calculations to determine radiological impacts from natural groundwater discharge and abstraction of groundwater from wells.

c) The biosphere calculations have been undertaken using single or multicompartmental representations of the accessible environment. These calculations have been for constant release rates or concentrations of radionuclides. Time-independent environmental characteristics have been assumed and the calculations have been carried through to equilibrium to yield flux-to-dose or concentration-to-dose factors.

d) The biosphere calculations have been undertaken for several different climate states and results from the whole assessment (including near-field, geosphere and biosphere components) have been presented separately for each climate state as a continuous function of time from closure.

e) In the more recent assessments, certain aspects of the biosphere calculations, notably the routing of radionuclide discharges between soils and surface waters, have been underpinned by detailed calculations using SHETRAN.

Overall, this approach has been found to be useful and has provided a satisfactory basis for identifying research and development requirements. The main issue that could be raised in criticism of the Nirex approach to representing processes in the biosphere in performance assessments relates to the appropriateness of the calculations undertaken, rather than the adequacy of the approach used to undertake those calculations. However, Nirex recognises that it could be argued that there are a number of additional limitations in the approach that has been adopted.

a) The groundwater system is modelled in a time-invariant way, i.e. no account is taken of changes to the geometry of the system or to the boundary conditions applied. In the UK, such changes will occur as a result of glacial-interglacial cycling.

b) The interface between the deep and shallow groundwater systems is not modelled explicitly. Radionuclide transfers across this interface are characterised using expert judgement informed by the results of separate calculations using the deep and shallow groundwater flow and radionuclide transport models.

c) Radionuclide transport in conditions in which significant freezing of ground and surface waters occurs is not modelled in a readily defensible, physically based approach.

In view of the possible significance of these limitations, Nirex has taken actions to enhance the approach adopted. Specifically, initial work establishing the legitimacy of reduced modelling approaches to ice-sheet development has provided a basis for considering how such ice-sheet development can be coupled to isostatic deformation and groundwater flow modelling. If such an integrated modelling approach is pursued, it will provide a way of characterising groundwater flow systems and geosphere-biosphere interfaces throughout a glacial-interglacial cycle. In turn, this should permit investigation of potential temporal and spatial dependencies of radionuclide discharges to the biosphere on long timescales. Information on such spatial and temporal dependencies is a primary input to determining the type of biosphere calculations that should be undertaken. However, it should be recognised that such integrated modelling studies are mainly of interest in specific geological contexts. Therefore, extensive deployment of such an integrated modelling approach may not occur until specific sites have been selected for investigation. In the UK, this site selection and investigation phase is unlikely to be initiated for at least five years.

Extensive studies undertaken to date have determined that the radionuclides of greatest relevance in determining the post-closure radiological impacts of deep geological disposal facilities for low-level and intermediate-level solid radioactive wastes are not very persistent in the environment. This is either because of their intrinsic mobility, e.g. ^{36}Cl and ^{129}I, or their relatively short half lives, e.g. ^{226}Ra, ^{210}Pb and ^{210}Po. Because of this limited persistence, it seems likely that it will continue to be appropriate to define discharges into surface-water catchments of well-defined geometry and that exist under relatively stable climate states. Simulations of radionuclide migration in such catchments and for relatively constant or slowly changing climate conditions (that nevertheless are able to capture interannual to millenial meteorological variability) can be well represented using the physically based SHETRAN model.

In assessments that have been undertaken to date, SHETRAN has been used as an underlying detailed model to determine parameter values for use in simplified assessment models. However, the greater flexibility and ease of use of the forthcoming release of SHETRAN should facilitate its direct use in assessments. This will mean that spatially and temporally distributed radionuclide fluxes or concentrations generated by geosphere models can be accepted directly by the biosphere assessment model of choice. This will reduce the amount of judgement needed and will help to ensure consistency between geosphere and biosphere modelling across the interface. Even greater consistency may be achieved if it is possible to build on work undertaken to date that explored iterative coupling of distinct hydrological models of deep and shallow groundwater systems.

3.5. - NRI, Czech Republic

Environmental changes were not incorporated in simplified performance assessment of a deep geological repository in 1999 at the end of the conceptual phase of repository development. Further development is planned in a step-wise manner. Therefore it is assumed that in a period of 3 – 5 years a much advanced and detailed performance assessment will be laid down, with the aim of the evaluation of new approaches and results of research and development activities.

As a first step in research, concerning environmental modelling, all available information will be evaluated and summarised. Despite a relative abundance of data on paleoclimate and paleoenvironment (excluding isotopic data) in the Czech Republic, a comprehensive picture of the evolution for the last 1,5 Ma was not composed. Therefore a simplified evolution will be described with important data – temperature, rainfall.

In the BIOCLIM project, advantages, limitations and methods of incorporation of environmental changes in the deep repository system performance assessment, in comparison with a constant (static, time-independent) biosphere will be laid down. Capabilities of sequential and discontinuous biospheric models will be assessed. The role of environmental simulation models in the context of total system performance assessment will be explored – direct coupling with performance assessment modules or indirect role in defining simplified environmental models that will be used in performance assessment. It will be needed to define environmental transfer pathways in different biomes (grassland, boreal forest) according to current analogue types along with transfer coefficients. Special importance should be devoted to the evaluation of impacts of sequential environmental changes (glacial – periglacial periods) on the hydraulic system.

3.6 - GRS, Germany

Up to now GRS has not integrated environmental change in its biosphere models for the use in performance assessments of final repositories. Instead, GRS has been modelling various biosphere systems, all of which are supposed to last for a long time under the various climate conditions which have ruled within the last million years at the sites of interest (Lower Saxony). One warmer climate has been added to account for the possible effects of human-induced changes of climate. All these environmental conditions have so far been considered as eternal or lasting until steady state is reached.

In the course of these investigations the significance of environmental change was recognised. It is felt that past climate states completed by one warmer climate will cover the possible climate situations in the coming million years, but not the resulting status of vegetation and soil. This is due to the development of human activities such as forest clearing, agriculture, fertilisation and, last but not least, irrigation.

It is seen that the effect of climate transients as well as the effect of human-induced stress to the environment will result in continuous and perhaps abrupt changes of environmental conditions, e. g. soil properties and ground water conditions. The simulation of these changes has up to now not been undertaken by GRS. The project BIOCLIM will help to explore the mechanisms, extent and significance of environmental change on the radiation exposure of humans and other biota.

3.7 - General summary of "lessons learned" from current approaches

The Agencies involved in the BIOCLIM consortium endorse the central role that is played by PA in building assurance in the long-term safety of disposal facilities for long-lived solid radioactive wastes. However, they also recognise that, whereas the goal must be to provide for the comprehensive appraisal of all potentially relevant factors, there are limits to the extent that PA models can be expected to simulate explicitly the Features, Events and Processes associated with the long-term behaviour of complex environmental systems[14] . Synthesis and simplification are therefore integral to the development and implementation of PA models, and judgment is unavoidable in interpreting the implications of their results as part of an informed decision-making process.

The emphasis in developing and implementing PA models is therefore as much on making proper use of scientific understanding to justify the assumptions and simplifications that are adopted and to understand their implications, as it is on attempting to assimilate such understanding within the assessment tools. Substantial efforts have been made in recent years through international collaborative programmes to develop systematic approaches to long-term assessment that expose to scrutiny the logic of the assumptions on which the evaluation of safety performance is based. For the biosphere component of PA, in particular, such activities have focused attention on the way in which uncertainties regarding the possible long-term evolution of the disposal system environment

[14] For example, Gleick [1987] has argued: "You can make your model more complex and more faithful to reality, or you can make it simpler and easier to handle. Only the most naïve scientist believes that the perfect model is the one that perfectly represents reality. Such a model would have the same drawbacks as a map as large and detailed as the city it represents, a map depicting every park, every street, every tree, every pothole, every inhabitant, and every map. Were such a map possible, its specificity would defeat its purpose: to generalise and to abstract."

are necessarily addressed through the development and justification of suitable representative indicators of future conditions and associated radiological impacts.

A number of Agencies have attempted to incorporate the implications of environmental change into long-term performance assessments. As far as the biosphere calculations are concerned, the approach has tended to involve the use of assessment models based on the identification and justification of time-independent biosphere systems representative of conditions in possible future climate 'states'. In some cases (e.g. in the work of UK Nirex Limited) this has involved research into process-based descriptions of climate change and associated environmental evolution in order to justify the particular simplifications adopted in the assessment calculations. Elsewhere (e.g. in the work of ANDRA and ENRESA) the emphasis has been on identifying qualitatively distinct, representative conditions based on palaeoclimatic and palaeogeographical reconstructions for regions of potential interest.

Following the non-sequential approach to representing possible future change, indicators of radiological impact are obtained by calculating 'dose per unit release' factors corresponding to the equilibrium concentrations achieved in environmental media for constant release rates of radionuclides into the biosphere for each climate state. The results of adopting such a strategy are not altogether surprising: the critical assumptions involved in evaluating potential radiological impacts for each system state tend to be those relating to the implications of change for contaminant dispersion (within the biosphere and at the geosphere-biosphere interface) and intensity of resource exploitation. However, this begs the question of whether a more realistic representation of the dynamics of environmental change might yield different conclusions about the significance of possible future releases taking place into an evolving biosphere system.

One of the participants in the BIOCLIM consortium (the Environment Agency of England and Wales) has experience of attempting to resolve questions about the potential implications of system dynamics, by providing for the continuous simulation of climate and environmental change across all aspects of PA. The conclusion drawn from this experience is that estimated radiological impacts derived from integrating a dynamic representation of biosphere change with a time-dependent simulation of disposal system performance are equally as dependent on underlying assessment assumptions as are more simplified approaches. Furthermore, there is a danger that modelling artefacts introduced by attempting to represent explicitly the dynamic effects of phenomena operating on very different timescales might obscure any useful understanding that could be gained from a fully-integrated, dynamic systems approach to PA.

The emphasis in BIOCLIM is on the role of biosphere assessment modelling in providing suitable, synthesised illustrations of potential radiological impact. Such illustrations need to be sufficiently representative in order that, when combined with appraisals of the projected long-term performance of geological disposal systems, they serve as adequate indicators of overall safety. Consideration therefore needs to be given to identifying possible alterations to the biosphere occurring as a result of climate change, as well as the transitions associated with such changes, that could be relevant in drawing conclusions about long-term safety performance. At the same time, it should not be forgotten that global climate change is not the only driving force of potential interest and relevance; human actions, in particular, have the potential to modify significantly the surface environment and will play a key role in determining radiological impacts.

Based on their experience in the development and use of PA as part of a decision-making process, the Agencies involved in the BIOCLIM consortium tend to favour the use of simplified, rather than more complex, assessment models for the biosphere as part of an overall systematic approach. The main issue to be addressed is then one of justifying the appropriateness of the particular calculations that are undertaken within a given assessment context. Hence, the emphasis is not so much on attempting to simulate the future evolution of the biosphere for all time, but on working from scientifically-justified narrative descriptions of long-term landscape evolution to identify representative periods (including transitional periods, if necessary) that are of particular interest or concern. This implies a requirement for a hierarchy of modelling techniques supporting the PA, building confidence in simpler, generalised assessment tools by synthesising the scientific understanding gained from detailed process-based descriptions of particular aspects of environmental evolution.

In the overall context of performance assessment, however, the biosphere is more than simply the receptor for contamination in which the radiological impact of possible future releases is expressed. Changes that take place within the biosphere – notably as a result of climate change – serve to establish dynamic boundary conditions for groundwater flow and transport and are therefore directly relevant to evaluating the long-term performance of a geological disposal system. Whereas the aim in BIOCLIM is to provide a basis for justifying biosphere assessment calculations relevant to a specific site or regional context, the implementation of such models cannot be entirely decoupled from other components of the PA.

The approach used to synthesise biosphere assessment models from consideration of the potential range and complexity of future environments should therefore also be consistent with the way in which detailed understanding of the underlying processes of change is interpreted to assess the long-term performance of the repository and geological barriers. In particular, a stylised approach to biosphere modelling, consistent with the overall aims of PA, cannot represent explicitly the interface between deep and shallow groundwater systems. Tools and techniques developed within BIOCLIM to interpret predictions of climate change and associated environmental evolution must therefore extend to consideration of the implications for biosphere modelling of changing circumstances of radionuclide release, according to the projected response of the overall disposal system to initiators of change at a regional scale.

4. Bioclim approaches to climate and environmental change

4.1. - Overview

In Section 2, the various mechanisms causing climate and environmental changes were summarised. From the perspective of radiological performance assessments, all these various processes do not necessarily have to be represented in the PA models. Frequently climate models are used to derive the required input parameters and associated data for use in the PA calculations. What is important is to derive relevant information on the potential impacts of climate change on the biosphere systems and how these changes in turn may affect the radionuclide pathways leading to the exposure of Man. Table 4.1 takes the various factors affecting climate change that were identified in Section 2.1 and indicates their potential relevance for input to a PA.

Climate Change Factors	Potential Relevance to a PA
Galactic dust	No
Evolution of the Sun	No
Continental drift and polar wandering	No
Orogeny/isotacy	Possibly, see footnote to Table 2.1
Orbital parameters	Yes
Ocean circulation	Yes
Evolution of the atmosphere	Yes
Volcanic activity	Only so far as it affects atmospheric composition
Air-sea-ice-land feedbacks	Yes
Solar variability	No
Atmosphere-ocean feedbacks	Yes
Atmospheric autovariation	No

Table 4.1 Climate Change Factors and their Potential Relevance to a Performance Assessment

In the absence of a clear understanding of all the detailed climate processes at work in the Earth's system, predictions over one million years cannot be considered as reliable. However, possible future evolution scenarios may be suggested, based on the past his-tory of the climate system. In particular, the last 2 million years has been characterised by a succession of glacial and interglacial episodes. It is relevant therefore to investigate the natural cycles of the Earth and to determine the implications for potential future climate changes for the next 1 million years together with the vegetation patterns that are likely to be associated with such climate conditions. The present knowledge of the processes that drive the glacial-interglacial cycles in the future will therefore be used within BIOCLIM with a view to extrapolating climate states for the simulation of future environmental scenarios.

Of particular interest for the BIOCLIM project is the effect on climate of changes in atmospheric composition of certain gases such as CO_2 due to both anthropogenic and natural process. This topic will form an important input to the climate model simulations to be undertaken in the climate model development Work Packages. Work has already begun on identifying relevant CO_2 scenarios and information on this topic will be provided in future BIOCLIM deliverable reports.

Volcanic activity is noted as being relevant in so far as it affects atmospheric composition; however this factor is not considered within the BIOCLIM project due to the site contexts.

Environmental change is primarily an interaction between erosional and tectonic processes. Tectonic processes, such as uplift, can be driven primarily by factors internal to the Earth, e.g. the long-term uplift of an area underlain by a low-density batholith. However, there is often a close coupling between erosion and uplift. Erosion reduces the overburden and stimulates compensating uplift. In turn, this uplift enhances height differentials and re-activates erosion.

Erosion and associated sedimentation will continue under constant climate conditions. However, rates of these processes may be modified considerably by changes in climate. Although ice sheets are often considered the primary agents of gross bedrock erosion in northern latitudes, the long-term effects of water and wind may be of comparable importance. Indeed, there is an important interplay between the effects of ice and water, with the unconsolidated sediments produced by ice sheets being subsequently incised by streams and rivers.

Generalised erosion and sedimentation are not the only factors to take into account. Stream and river incision are also relevant. However, the lateral migration of streams and rivers may also be important and coastal processes can be very effective at removing and depositing materials, particularly during episodes of rapid sea-level change.

Within an evolving landscape and under changing climatic conditions, soils and vegetation evolve in a highly interactive manner. Although soils and vegetation evolve in response to climate change, patterns of soil and vegetation at the regional scale may also substantially influence climate and the hydrological cycle.

In Northern Europe at the present day, and further south under conditions of cooling climate, freezing of surface waters and goundwaters may be of significance. In boreal conditions, only season freezing occurs, but in periglacial conditions either discontinuous or continuous permafrost may occur, with permanently frozen ground overlain by a seasonally active layer. Ground freezing affects the hydrological and hyrochemical properties of soils, sediments and underlying parent materials. However, it can also affect their mechanical structure, e.g. through the formation of ice wedges.

Table 4.2 summarises the various factors that affect environmental change and indicates their potential relevance to a PA.

Environmental Change Factors		Potential Relevance to a PA
Earth processes	isostacy and tectonics	Yes
Erosion and sedimentation	Generalised erosion	Yes
	Incision	Yes
	Sediment deposition	Yes
	Changes in drainage pattern	Yes
	Coastal processes	Yes, at some sites
Cold region processes	Freezing of surface waters	Yes, at some sites
	Seasonal ground freezing	Yes, at some sites
	Permafrost development	Yes, at some sites
	Ice-sheet development	Yes, at some sites

Table 4.2 : Environmental Change Factors and their Potential Relevance to Performance Assessments

The prediction of climate and environmental conditions in Europe in the thousands and millions of years to come poses the difficult problem of evaluating not only the global changes that will occur on this time scale, but also their more local influence on the regional climates of Europe where the potential repository sites of interest are to be located. As noted in Section 2 and Table 4.2, climate change in particular, will affect landform, ecosystems and near-surface hydrology which in turn may affect the likely timing, location and mode of release of radionuclides to the biosphere system. It is clearly important therefore to obtain a regional context for understanding the impacts of climate change on the regional biosphere systems of interest. For this reason, BIOCLIM will develop methods by which climate model predictions for future climates can be downscaled to three specific European regions, namely northeast France, central /southern Spain and central UK.

In view of the above, BIOCLIM will use the following approaches:

- Narrative descriptions of the major mechanisms responsible for climate change and the associated vegetation patterns during the last million years will be provided for eastern France, central/southern Spain, central England using analyses of palaeological data information for these regions of interest (Work Package 1, Deliverable 2). Utilisation of knowledge of past climate change over one or more glacial-interglacial cycles will be used to check that the extended models can reproduce the palaeoclimates. The work will also be used as input to the development of relevant downscaling rules for the areas of interest. (Work Packages 2 and 3).
- Implementation of complementary approaches using development of models for the prediction of climate over the next tens of thousands to one million years. Discrete climate states and associated vegetation will be derived for selected situations (Work Package 2) or using a more continuous representation (Work Package 3).
- Application of the output from the climate models to identify the important consequences and effects of climate change for PA biosphere systems and examples of how these may be represented in a PA (Work Package 4).

4.2 - Advantages of Approaches to be Used and Justification

Future climate change patterns will be illustrated using reasonable and realistic scenarios for long-term evolution, together with a sequential approach to representing such changes. This approach is rather complex and therefore it will be addressed through two complementary strategies, both based on state-of-the-art knowledge and environmental simulation, and use of available climate models of various complexities. The uncertainties associated with long-term radiological evaluation are very large and the results from simulations appropriate to the three selected European areas characterised by different latitudes and different geographical contexts will help to establish a range of possible future scenarios. Climate change and subsequent effects on the biosphere and the geosphere systems can then be treated in a consistent and logical manner by radioactive waste management organisations and regulators in any future Performance Assessments.

The first strategy (the hierarchical strategy) will use the full hierarchy of existing validated climate change models. Both simple models, which will give a very generalised long term evolution of the global climate, to complex models, which provide a downscaling view of representative discrete climatic conditions at high spatial and temporal resolutions, will be used. The outcome will be regional climatic conditions and the associated vegetation change patterns for specific, discrete future climate states that may exist in the next one million years.

The second strategy (the complementary integrated strategy) will integrate all the physical mechanisms important for long term climatic variations. This will provide a more continuous representation of regional climate (discrete and transitional states) and associated vegetation changes for selected long-term time periods during the next one million years.

The outputs from the above long-term environmental simulations will be used to consider the potential effects of climate change on the the biosphere systems that need to be used in future radiological impact calculations. Discrete biosphere systems representative of the climate and associated vegetation patterns will be derived from the climate and vegetation simulation provided by the hierarchical and integrated strategies. A biosphere system representing a transitional state between two biosphere systems considered to be in equilibrium will be exercised. For each of the three European regions of interest, the important aspects of the biosphere systems to be represented in potential PA will be identified and justified using the BIOMASS Theme 1 Reference Biosphere methodology.

Overall, the outcome of the BIOCLIM project will provide valuable input to future performance assessments and will contribute to the confidence in the regulatory decisions on safety made in connection with the development of the deep radioactive waste repositories.

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Appendix - Environmental change in PAs : contributions from waste management agencies and regulator

A.1. - Andra, France

A.1.1. - Introduction

Andra is responsible for studying a geological disposal system for radioactive waste disposal in France. In order to build an underground research laboratory and to gather the necessary data for compiling the official applications, since 1994 Andra has explored rock formations in three areas, where the geology is as watertight as possible and has a stability that has lasted millions of years. In August 1999, the French Government decided to establish a laboratory in a clay formation in the Meuse department, although another granite formation also must be prospected for a future laboratory.
The work carried out in BIOCLIM is therefore to be applied to the underground research laboratory in the Meuse/Haute-Marne region in the east of France. Andra is also in charge of near-surface facilities at Centre de l'Aube, however environmental and climate change have not been required in these performance assessments to date.

The need to consider long term change in performance assessment for the Meuse/Haute-Marne site comes from several considerations.

Regulatory considerations : According to regulatory requirements, the primary radiological safety indicator is the annual individual effective dose (defined according to ICRP Publication 60 (ICRP, 1991)) to an average adult member of a hypothetical critical group. Definition of the assumed behaviour of the critical group should be consistent with basic assumptions regarding the type of community that could be present when and where the release occurs. Specifically, the regulations require that "…hypothetical critical groups are to be adopted, representative of individuals liable to receive the highest doses" from potential future releases (DSIN , 1991).

The reliability of estimated radiation dose as an indicator of safety decreases with time owing to inherent uncertainties associated with the characterisation of future environmental conditions and human activities (DSIN, 1991; ICRP, 2000). Nevertheless, French regulations state that "quantified estimates of the individual dose" should be made even beyond 100 000 years (DSIN, 1991). Consequently, there is no limit to the time frame over which the radiological impacts of releases are to be calculated, except in so far as the overall PA is able to provide assurance that potential releases beyond a certain time are unlikely to be of particular concern. It must therefore be acknowledged that, during the timescales over which radionuclides may be released from a deep geological repository, significant changes to the biosphere can be anticipated, in particular, the changes that could occur as a result of glaciations.

There is no explicit guidance, or instruction, in the French safety rules regarding the biosphere systems to be considered in long-term assessments as a basis for demonstrating compliance with radiological protection criteria. However, the regulations (DSIN, 1991) note that the nature of the release pathway to be considered is where contamination enters the biosphere in free running water or water abstracted from "shallow water supply boreholes". In addition, it is noted that:

"For the biosphere, it does not appear to be possible to predict the local changes in the environment over very long periods; on the other hand, major climatic changes which are foreseeable at regional scale can be made allowance for by applying the concept of typical biospheres, representative of the different states which might obtain in the biosphere more generally, in view of these events."

The geological stability of the sites, analyzed through the geological evolution scenarios, is an essential selection criterion for the site in the fundamental safety rule for long-lived waste repository projects in deep geological formations (RFS III.2.f.: DSIN, 1991).

It demands consideration of all highly probable and possible natural events to determine the reference situation and the random situations to be addressed in the safety analyses:

- Climatic variations (on the basis of assumed continuation of the Quaternary glacial-interglacial cycles) with their consequences, particularly the formation of a permafrost and the changes in the surface environments with modifications of the surface hydrology and resulting deep circulations;
- Vertical movements and erosion processes, with their consequences, outcropping of the layers, modifications of the surface hydrology and deep circulations.

Hence, although it is ANDRA's responsibility to identify and justify the assessment biospheres used in support of the PA, the relevant regulations appear to lend support to the use of a non-sequential approach in the representation of biosphere change, based on constant climate, contaminant transfer and exposure group characteristics. The focus of attention in current studies has been on the definition of suitable assessment biospheres based on the present-day temperate climate conditions in the region of the Meuse/Haute-Marne site and representations of climate conditions cooler than those at present based on studies of suitable analogue regions.

Certain types of change are, however, explicitly excluded by the regulations. In particular, DSIN (DSIN, 1991) requires that, in an assessment, "the characteristics of man will be considered to be constant (sensitivity to radiation, nature of food, contingency of life, and general knowledge without assuming scientific progress, particularly in the technical and medical fields)". This lends support to an assessment approach in which human behaviour is represented on the basis of typical present-day practices from analogue locations where physical environmental conditions are similar to those anticipated in the future.

Assessment-specific considerations : The overall purpose of the final performance assessment (PA) due for 2004 is to contribute to a demonstration of the technical feasibility and regulatory compliance of the French geological disposal concept for high-level radioactive waste (HLW). In particular, the PA will provide input to strategic decisions concerning the suitability of the Meuse/Haute-Marne site for the potential disposal of HLW.

The fundamental objective assigned to geological disposal system for radioactive waste is to ensure safety after closure of the repository. Therefore the protection of people and the environment must be ensured in the short and long term. In 1991, DSIN edited the basic safety rule (RFS III.2.f) which established the requirements to be followed and the objectives to be adopted in the design and construction phases of the creation of a geological disposal system for solid radioactive waste (DSIN, 1991).

From this perspective, the purpose of the biosphere assessment is to provide information on the radiological significance of potential future releases of radionuclides to the biosphere, in order to support development of the disposal concept.

Source terms for the release of radionuclides to the biosphere involve very long-lived and/or more mobile radionuclides present in HLW. The release from the engineered barrier system to the geosphere and the biosphere might occur in the very far future and therefore there is a requirement to represent the types of biosphere systems that may occur in the future.

A.1.2. - Approaches and Methodologies Used to Date

The approach used consists firstly in identifying the mechanisms of biosphere system change for the Meuse/Haute-Marne site.

The major factors determining environmental change vary depending upon the timescale under consideration (see Section 2). On timescales of up to 1,000,000 years, the primary factors determining the evolution of the landscape and constraining the range of ecosystems that can develop are usually the geology and evolving climate (BIOMASS, 1999a). However, within the constraints imposed by climate, humans currently exert a significant control on the landscape. In present-day temperate regions, a consequence of the practice of agriculture over many centuries is that natural and semi-natural environments are generally uncommon and limited in extent (BIOMASS, 1999b).

Human-induced Change : Of all forms of life, mankind is the least bound by environmental limitations, with the capacity to develop artificial environments across a wide range of conditions. Within the general constraints of climate and landform, humans often have a strong influence on the biotic constituents of their environment, through agriculture, animal herding and industrial exploitation. This, in turn, can have a variety of consequences. For example, soil evolution is strongly determined by vegetational history, and modifications to drainage and infiltration patterns can change the characteristics hydrological flow systems above and below the land surface.

The French regulatory requirements limit the extent to which human-induced changes on the biosphere have to be considered. In particular, the French Basic Safety Rule (DSIN, 1991) implies that there is no requirement to speculate on possible social and institutional developments that lie outside the bounds of present-day practice. Further constraints are imposed by environmental factors such as the availability of water resources. Nevertheless, even within such constraints, shifts in patterns of land use and community structure are largely unpredictable. Assumptions with respect to potential social and institutional developments within the assessment must therefore be directed towards the evaluation of adequate safety indicators, demonstrating a level of protection consistent with that provided for current generations (IAEA, 1995; ICRP, 2000).

The approach adopted to date is therefore to represent human behaviour on the basis of typical present-day practices from analogue locations where physical conditions are similar to those anticipated in the future (BIOMASS, 1999c).

Geological Change : As previously noted the geological environment in the region of the Meuse/Haute-Marne site is considered to be essentially quiescent and believed likely to remain so over the next million years. Local and regional internal geological processes, such as tectonic and seismicity or regional uplift, are therefore considered unlikely to be significant in determining future biosphere systems over periods up to approximately 1 000 000 years. Only regional volcanism could be taken into account.

The region is not volcanic, but major eruptions have occurred locally in the nearest volcanic regions, particularly those of the Eifel, with repercussions as distant as the Meuse/Haute-Marne site through the fallout of volcanic ash. However, the low ash thicknesses and the random, short-lived nature of these events, and the long recurrence period (> 10,000 years) means they can be regarded as irrelevant in terms of their influence on the biosphere over the timescales considered for a repository.

Climate Change : During the glacial eras which have characterized Quaternary climatic cycles, France lay beyond the large ice caps which covered northern Europe, but it was subject to a periglacial type of climate characterized by an annual mean temperature that remained subzero in most of the territory during the glacial stages.

- The field data, attesting to occurrences which actually took place in France during the past glacial periods, indicate that a permafrost developed just about everywhere, only sparing the Mediterranean margin, (map 1:1,000,000 prepared by Antoine et al, 1999; Beaulieu et al, 1999). During this period large mountain-glaciers occurred on French Alps, Jura but also on Central Massif and Vosges.

This permafrost was particularly thick and continuous in the East region where the Meuse/Haute-Marne site is located. In this region, also subject to considerable wind activity, a tundra type plant cover also developed.

- A simulation of the depth reached by the 0°C isotherm in the last glacial state was carried out using the GELSOL software developed by LCPC. A climatic scenario developed by the specialists of the CNRS (Caen and Lille) and the BRGM, was applied as a function of the physical parameters of the subsoil measured on core samples (Andra, 1996; Andra, 1998).

The results of this simulation indicate a rapid and deep penetration of cold conditions on the Meuse/Haute-Marne site during the cold climatic stages, linked in particular to the petrophysical characteristics of the layers and the absence of a surface aquifer. The maximum penetration of the 0°C isotherm on the Meuse/Haute-Marne site reached 315 m (result obtained with a snowless cold scenario) and the presence of a permafrost is the most frequently occurring situation over time. The permafrost was continuous (more than 50 m deep) for 40 to 50% of the time during a 100,000 year glacial-interglacial cycle.

The development of a continuous, thick permafrost in the region in cold periods was accompanied by significant changes in the soils and water reserves, accordingly conditioning the type of biosphere.

- The development of the permafrost had a direct effect on the water availability and changed the flows in all the deep aquifers, frozen at the outcrops, seepage zones and outlets. The comparison with sites currently affected by a thick permafrost in Siberia indicates that the seepage and flows at the outlets could only be nil for a fraction of the year.
- Similar to what is currently observed in the high latitudes where a thick permafrost exists, and as indicated by the fossil traces of periglacial action, in France, a medium latitude region, the seasonal variations are obvious. The surface thaw in summer (undoubtedly of variable duration and depth according to the glacial stages) permitted the maintenance of a plant cover and animal life.
- Paradoxically, the field data demonstrate the maintenance of "warm" plant and animal species alongside the dominant "cold" species, even in the depths of the coldest periods, such as the last glacial maximum. This can be explained by the existence of local refuge areas, privileged sheltered sites, and the role of the millennial oscillations and "warm" events which permitted relative and tempo rary redeployments of any subsisting "warm" species. Thus in the last glacial maximum, a steppe type plant cover, a prostrate tundra with a few shrubs (willows, dwarf birches), in the wettest sheltered sites (snowcombs, networks of thermo-karstic trenches) covered the northern and eastern part of France.

The freeze-thaw cycles also had the effect of fracturing outcropping limestone formations. Screes, pebbly formations resulting from alternating freezing and thawing during the Quaternary glaciations, developed on the surface, particularly on the sides of the valleys and the fronts of the coastlines where they can be observed. The presence of these pebbly formations affected the biosphere by creating surface aquifers in high topographic sectors and altering the soils. This process of congelifraction was sometimes highly effective. It prepared the land for erosion and developed particularly during the climatic transitions, entries into glacial periods and inter-glacial intervals; these conditions recurred throughout the time period to be addressed by BIOCLIM. These pebbly formations, virtually generalized at the margin of the limestone reliefs at the end of the glacial periods, were then stripped by erosion during the inter-glacial periods.

These conditions limit the use of near surface disposal concepts to short-lived wastes for which the need to guarantee containment is restricted to the coming tens of thousands of years (before the entry into the next glacial period).

The variations induced in the subsoil by the climate (hydrogeological and thermal) are taken into account for the phenomenological analysis of the evolution of a long-lived waste repository in a deep geological formation.

On the timescales relevant to post-closure performance assessments conducted by ANDRA, at least one full interglacial-glacial cycle should be anticipated. The hypothesis for future climatic change taken in account by ANDRA is based on climatic simulation (Berger A. et, 1994; Loutre MF et al, 2000a and 2000b): anthropogenically enhanced greenhouse-gas warming may defer or ameliorate the earlier stages of cooling, but a first glacial episode is expected to occur no later than about 50 000-110 000 years After Present (AP). Thus, the full range of climate conditions inferred to have occurred at a site over the Quaternary may be expected to occur at that site in the future and within the assessment period.

Land-form and hydrological change: The erosion processes that modeled the landscape in the last hundreds of thousands of years (incision of the valleys, clearance and stripping of the plateaus, retreat of the coastlines) will continue in the future under the action of climatic factors.

The field data and phenomenological analyses show that this erosion is not uniform; its dynamics is complex, characterized by:

- different velocities, depending on the different locations, according to the types of relief (main valleys, secondary valleys, coasts, plateau, etc) and the lithology of the substratum (marls, massive limestone, bedded limestone, etc);
- velocities varying with time as a function of the dynamics of the climatic cycles, the different mechanisms occurring in erosion being active in different climatic conditions (for example: cold periods for congelifraction of the limestones on the sides of "dry" valleys/periods of scree stripping by momentary river flows, at the end of the glacial periods).

The important point is that in the past, this morphological evolution was accompanied by a major reorganization of the river systems, regional and local flows, due to a sequencing of river capture and the development of karstic networks. Roughly speaking, the "Meuse" system flowing from south to north (a legacy of the initial Pliocene surface), in unconformity with the structuring of the subsoil (stack of sedimentary layers on this margin of the Paris basin), was stripped in favour of the Seine basin and its tributaries, whose general arrangement conforms to the present structuring of the Paris basin.

The consequences of this erosion in hydrogeological, mechanical and thermal terms are taken into account for the phenomenological analysis of the evolution of a long-lived waste repository in a deep geological formation, considering that this development over time will have:

- Effects on the repository site itself:
  - ➜ Progressive disappearance of Barrois limestones containing the surface aquifer, followed by the Kimmeridgian marls;
  - ➜ Descent into the stratigraphy of the permafrost front, which will progressively affect all the cover aquifer levels, and lowering of the minimum temperatures in the host formation during successive glacial periods;
  - ➜ Possibility of development of a karst in the Oxfordian limestones when the Kimmeridgian marls are in the course of erosion.
- Effects on flows at local and regional scale: changes in the characteristics of the catchment basins and shifting of the present aquifer outlets over a time-scale of the next hundred thousand years by the deepening of the valleys and captures.

For the biosphere, the consequences are basically limited to local changes in the types of soil and surface water resources, a simple "translation", in detail, of the present geographic areas.

A.1.3. - Results Obtained

Andra has developed different lines of studies within the R & D programme in order to deal with environmental change and the effects over the geosphere and the biosphere systems.

a) Climate Evolution: Scientific understanding of global climate change during the Quaternary period suggests that it can be broadly characterised in terms of cycling between glacial and interglacial episodes, with a characteristic periodicity of approximately 100,000 years including internal cycles and short time variations.

In France, the range of land surface temperature between the coldest and warmest stages of the climatic cycle is believed to be, on average, 10 to 15°C less than today temperature. Indices of global climate variation based on indicators of palaeoclimate indicate that the present-day global climate is close to the maximum temperature reached in a climatic cycle during interglacial periods.

However the cycle of global temperature change is far from being a simple harmonic variation; the long-term record can, at best, provide only an approximate indicator of the likely timescales on which future changes are likely to occur. Moreover, simple extrapolations cannot account for the long-term effects of possible perturbations to the cycle, such as forcing by anthropogenically-enhanced levels of greenhouse gases within the atmosphere.

It is worth noting that the assessment biospheres under development are representative of cooler climate conditions than those at present. Although the timescales of change are uncertain, provided the amplitude of future climate changes remains within the envelope of variation during the Quaternary period, the palaeoclimate record provides an appropriate basis for determining the range of future conditions that may apply. It can also be interpreted in terms of landform evolution and vegetational history. Indeed, the terrestrial sedimentary cores that are available are generally directly interpretable in terms of the sedimentary regime and vegetational characteristics of particular sites and only indirectly in terms of palæoclimate.

- Major national and international efforts (PANASH, CLIVA3R[16], PEP[17], IMAGES[18], ECLIPSE[18] programs, etc) are currently directed towards a deeper knowledge of the climatic variability at different geographical and time scales. One objective of these studies is to employ modelling to attempt a short and medium term forecast, particularly for the sustainable development of human activities and facilities (creation of the Intergovernmental Panel on Climatic Change, IPCC, related to the global warming observed over the past century).

  This climatic variability can be recorded through its main components (temperature, rainfall, glaciation, insolation, wind), through accumulations of inorganic and/or organic growths, with or without the action of the biosphere (sediments, ice, plants, corals, speleothems, etc); the surface thermal variations can also be temporarily "memorized" at depth as a function of its thermal conductivity and the amplitude and frequency of surface fluctuations.

- **Areas of Study Developed by Andra:**

  Studies conducted at ANDRA concerning global scale climatic modelling are limited to scientific research projects. They include an attempt at a synthesis, and sensitivity analysis of the different existing models for application to the French sites - a study carried out with CEA/LSCE following the publication of the results of the PMIP[19] international project.

Hence Andra's overall contribution does not address the climate modelling aspect, an approach demanding huge resources and which is largely developed by the international community, but consists of a search for ways to fit these simulations to specific situations in the past. This is the context of the CLIMEX[20] project conducted jointly by Andra and the Commission for the

[16]CLIVA3R: Programme "CLImate VARiability and predictibility"
[17]PEP and IMAGES: Inter french laboratories actions for the study of the recent past.
[18]ECLIPSE: pluridisciplinary programme " Environnement et CLImat du Passé : hiStoire et Evolution"
[19]PMIP: International project "Paleoclimate Modelling Intercomparison Project"
[20]CLIMEX: Programme on paleoclimat maps of CCGM ; from the international programme CLIP (CLImates of the Past) of IUGS-UNESCO.

Geological Map of the World– CGMW. This project led to the publication of the World environment synthesis maps showing the latest two climatic extremes (the best documented): the last glacial maximum (18,000 years +/- 2,000 years) and the Holocene climatic optimum (8,000 years +/- 1,000 years). These two maps (Beaulieu et al, 1999) provide a synopsis of the overall data available on the paleoenvironments in these two eras.

The specific studies carried out by Andra concerning climatic variations, are aimed at narrowing the uncertainties on the values of the climatic parameters in France, and specifically for the Meuse/Haute-Marne site located in the east of the Paris basin, in order to clarify the analysis of the repercussions of the climatic variations for a deep repository project.

These points are addressed by researches on the variability of the climate in France during climatic cycles:

- Spatial variability of climatic parameters given the fact that France lies in a region subject to Atlantic, Mediterranean and continental influences, in addition to the direct influence of latitude and reliefs. The aim is to estimate the values of the corrections to be made to the data derived from the reference climatic situations (located in specific geographic contexts) for application to the sites.
- Temporal variability, an area in which global models are capable of providing the answer concerning variations on the scale of glacial-interglacial cycles, stages and interstages, but in which short-term fluctuations of apparently non-astronomic origin detected in the polar ices and oceanic sediments could need to be taken into account for site surveys if they occur in a continental region, and in France in particular, with high amplitudes.

1) Spatial variability of climatic parameters at the scale of France.

For the time being, different approaches to the palaeoclimate have been proposed, either based on data on the major paleontological sequences, more representative of a regional climatic context, or based on pedological data (palaeosoils, crysoils, malacofauna or insects) representative of a local climatic context. The present climatic models based on the concept of biomes (palynology) do not allow accurate regional assessment. The pedological sequences are very representative in space, discrete in their temporal recording; besides, they do not provide any direct idea of the depth reached by the base of the permafrost. The bridging of the three biological, pedological and modelling approaches thus proves to be a promising avenue for research pursued in the studies conducted by ANDRA in collaboration with university laboratories (Lille, Aix-Marseille).

- One of the alternative studies is the search for new data, complementary to the data provided by the climatic sequences already available, possibly allowing a reconstruction of the values of the climatic parameters (temperatures, rainfall, developments in atmospheric circulation) in northern France, and hence an estimation of their space-time variations on French territory and bordering regions. The target period covers at least the Last Glacial Era and the coldest episodes of the Middle Quaternary.

Various tools have been used for this approach: i) stratigraphic field data using soils and cryosoils to characterize the climate; ii) palaeobotanic data produced by the analysis of major drill holes:

- The long French climatic sequences available today, chiefly based on palynological analyses, often cover the Quaternary up to the Isotopic Stages 9 or 11, but are virtually all preserved in altitude, with non-negligible site effects for extrapolation to other sites in France. These include a snowcomb effect for the crater lakes of the Massif Central sequences, a mountain barrier effect as in the case of the Grande Pile in the south of the Vosges. Besides, these sites, of a pronounced continental character, do not permit a direct interconnection with the marine sequences and their chronological fitting (via calibrated ^{14}C datings or tephra datings) is only just beginning to be reliable.

More specifically concerning the northern half of France, only the Grande Pile has essentially proved to cover the Last Glacial-Interglacial Cycle, with the other palynological sequences examined so far only generally beginning in the Late Glacial or the early Holocene.

- The palaeopedological sequences often cover longer sequences (up to Isotopic Stages 8-9) but unfortunately present a discrete recording in time, since pedogenesis is essentially the resultant of a stabilization of the surface in a relatively stable climatic context. In subsident sectors like southern Brittany or the Flemish plain, the coastlines help to reach Isotopic Stages 11 or even 13 (van Vliet-Lanoë et al., 2000).

The coupling of the two approaches, paleopedological and palynological, forced with edaphic data on the sites, should help to have a more accurate reconstruction, region by region, of the evolution of the climatic regime. In this type of use, the proposed approach must culminate in the definition of thermal boundary conditions usable for climatic modelling at continental scale (PMIP) or a more local scale for simulations of the permafrost dynamics (GELSOL ANDRA / BRGM project).

- Another approach has been developed to have a fit of the modifications of the physical and biological environment, the consequences of climatic variations with the preparation of mapping syntheses.

Two maps were prepared jointly with the French National Committee of the International Union for Quaternary Research, CNF-INQUA (Antoine P. et al, 1999). They demonstrate the natural variability of the environments in France during the latest extreme situations of recent geological history: the last glacial maximum (18,000 +/- 2,000 years) and the Holocene climatic optimum (8,000 +/- 1,000 years). All the data plotted on these maps are data for which the age is known with certainty, either by ^{14}C dating, or by a precise stratigraphic situation, in combination with a dated material.

This synthesis supplements the one completed at the scale of the World by providing a detailed and complete view of this specific region of Europe. It offers an overall view of the consequences of climatic variations (position of shorelines, development of permafrost and glaciers, wind formations, vegetation, fauna (large mammals), human occupation), and illustrates the spatial variability of the environment conditions at the scale of a territory like France, a scale inaccessible to modeling, yet indispensable to account for the specificity of the sites in developing repository concepts.

2) Short-term, large-amplitude climatic fluctuations in France.

The questions concern the detailed knowledge of the short-term fluctuations characterizing the climatic cycles to clarify the dynamics of the past/future climatic evolution in evolutionary schemes of the sites investigated by ANDRA and their use (particularly to simulate permafrost penetration and hydrogeological evolution).

It is widely demonstrated that the study of isotopic variations (deuterium and oxygen 18) recorded in the polar ice layers, offers unprecedented possibilities in the field of climatic reconstruction (temperature, rainfall rate, atmospheric circulation). Even if archives of this quality can only be obtained in high-altitude regions, an alternative method is available in the middle latitudes to assess the variations in the isotopic content of the rainfall: reconstruction of the isotopic variations of lake waters from the analysis of the carbonates formed in equilibrium with the waters and preserved in the lacustrine sediments.

The quality of this reconstruction depends on many hydrological factors, of which the influence has been examined in detail for the last two hundred years in the large Bavarian lakes in Germany. These studies show that the lakes reliably record the isotopic content of the rainfall and hence the climatic variations.

This approach was implemented with the Laboratoire des Sciences du Climat et de l'Environnement, UMR CEA-CNRS, supplemented by a PhD dissertation in cooperation with the University of Savoie. The objective is to analyze the climatic variations of the last 15,000 years from a reconstruction of the isotopic content of precipitation in France, recorded in the lacustrine sediments (lake of Annecy, Savoie, where the hydrological conditions are identical to those of the Bavarian lakes), with a fit on the last thousand years (particularly by comparison with the data yielded by the analysis of tree cellulose).

The drill holes reveal an excellent sedimentary resolution: annual laminations permitting isotopic resolution of ten years at the scale of the samples taken for analyses. The sedimentation rates and the age-depth relations are identified by ^{14}C determinations on terrestrial organic particles. These are combined with ^{14}C measurements of ostracoda , formed of pure calcite, on which $\delta\ ^{18}O_p$ measurements are taken. The combination of these two methods serves to correct the effects of the detrital carbonates. The dating is also checked against volcanic dust which corresponds to well dated levels (independently of the sediment dating).

This reconstruction of the $\delta\ ^{18}O_p$ curve serves to estimate the variations in the mean temperature of France, over the last 15,000 years. The curve currently in the course of construction, for early 2001, concerns a resolution of about a hundred years. The development of this study by CEA/LSCE will eventually provide a resolution at the scale of ten years. This resolution is unique in Europe, because even if the associated datings may be more accurate, the other methods (laminated lakes, growth rings of trees) suffer from very large uncertainties concerning the relation between measured parameters and climatological estimations.

A major advantage offered by this isotopic curve is that it can be directly compared with other $\delta\ ^{18}O_p$ reconstructions. For the region north of the Central Alps (Bavaria), the $\delta\ ^{18}O_p$ reconstruction already made shows a large part of the climatic variability is identical to that measured in Greenland, with different relative amplitudes, associated with the specific conditions of this region of the European continent. A verification of this remote connection with the isotopic curve of the lake of Annecy will allow a more detailed extrapolation of the results for the entire region influenced by the North Atlantic.

These rapid fluctuations must be taken into account in reconstructing the past environments and their extrapolation to the future, in support of the indicators of the maintenance at the latitude of France, of "warm" period species in cold periods, in dealing with "means", or the rapid redeployment of the species from the regional refuge zones during climate fluctuations.

It is worth noting that no environmental simulation has been undertaken by Andra to estimate future possible sequences.

b) Permafrost Dynamics: In the glacial period, the annual mean temperatures predicted on the surface in France at the latitude of the Meuse/Haute-Marne site are about 15°C lower than the present temperatures. This estimation is based in a complementary manner on the modelling of the latest past Würm glaciation, on the climatic reconstructions from the analysis of fossil pollens contained in the paleosoils and sedimentary deposits, as well as the indications drawn from nature and from the distribution of the fossil periglacial patterns observed in the field (Antoine P. et al, 1999; Van Vliet-Lanoe B. et al, 2001a) in comparison with the high latitude regions currently subject to comparable climatic conditions. The consequence is the freezing of the subsoil and the installation of a "permafrost" (Van Vliet-Lanoe et al, 2001b).

A simulation of the permafrost depth reached by the 0°C isotherm in the last glacial cycle was carried out using the GELSOL software developed by Laboratoire Central des Ponts et Chaussées, applying a climatic scenario (with its possible variants, "cold" and "less cold") developed by the specialists of the CNRS (Caen and Lille) and of the BRGM, taking account of possible surface conditions (no snow, snow, packed snow) and physical parameters of the subsoil (up to 500 m) measured on core samples (Lebret et al, 1996; Andra, 1998).

- The maximum penetration of the 0°C isotherm on the Meuse site thus estimated ranges from 315 m for the cold and "no snow" scenario to 125 m for the less cold scenario with "packed snow".

- The results of this simulation indicate a rapid and deep penetration of the cold on the Meuse/ Haute-Marne site during cold climatic stages, associated in particular with the petrophysical characteristics of he formations and the absence of a surface aquifer.Even for a moderately cold episode (mean temperature -1°C to -3°C) lasting about a thousand years, the simulations indicate that the 0°C isotherm penetrates to more than 40 m depth on average (up to 80 m in the "cold without snow" scenario). Conversely, the consideration of "warm" episodes during the glacial stages can significantly alter the results.
- These simulations also indicate that the presence of a continuous permafrost, in other words, at least 50 meters deep, is the most frequently found situation: it covers 40 to 50% of the time during a 100,000-year glacial-interglacial cycle.

The development of these studies on the dynamics of the permafrost is motivated by the deep thermal and hydrogeological consequences of the development of this process.

As to the biosphere, these simulations support the naturalistic data concerning the existence of a thick and continuous permafrost in eastern France during the cold stages of climatic cycles, a condition to be considered in defining the type of pertinent biosphere adapted to these periods.

These points will be addressed by generic research projects, with two dissertations beginning in late 2000 and specific actions starting in 1999 scheduled to terminate in late 2003, for the second safety assessment, permitting an adjustment of the climatic scenarios employed for the hydrogeological modelings in the future and the evolution of the biosphere.

c) Dynamics of Erosion and Stability of Flows:

The Quaternary climatic cycles and variations in environmental conditions that accompanied them largely affected the style and flow of the watercourses owing to wide variations in the volumes of water collected. Furthermore, the cold periods during which France was subject to a periglacial climate were characterized by the development of specific processes (associated with freeze-thaw cycles and the formation of the permafrost) which conditioned the effectiveness of the water flows in interglacial periods and stages, and surface topographic evolution.

The development of studies on this subject is motivated by its hydrogeological consequences. Two complementary approaches, field work and modelling, are pursued to clarify the dynamics of the evolution of the morphology, at the time-scale of the climatic cycles which followed each other during the Quaternary, with its spatial variability (valley, coastline, plateau), particularly taking account of the nature and structuring of the substratum.

The consequences of erosion, evolution of morphology, on the surface environment occurred at local scale, with changes in the type of soil and the surface water resources. However, matters remained substantially unchanged at regional scale.

d) Vegetation Reconstruction :

Simplified representations of the past environmental change in the biosphere system for the Meuse/ Haute-Marne site have been undertaken at ANDRA since 1994 and will be updated in 2001.

For this site, the change in the vegetation and climate results from the study of two pollinic sequences:

- the Grande Pile peat bog, the subject of many publications (Woillard, 1975, 1978; Woillard and Mook, 1982; Guiot et al., 1989; Seret et al., 1992). Located in the south of the Vosges at 300 m altitude, pollinic analysis reveals the evolution of the plant landscapes which succeeded each other in the past 140,000 years (Beaulieu et al, 1992). It dominates the surrounding valleys by about 20 m, so that it was never invaded by the watercourses;
- the Late Glacial and the Holocene are analyzed via a palynological study of the Rouzerelle peat bog at Mur-de-Sologne (Loir-et-Cher). N. Planchais (Planchais, 1970) first published a palynological study, resumed later by J.L. de Beaulieu (Beaulieu et al, 1990). The latter results are given below.

The evolution of the biomes at Grande Pile and Mur-de-Sologne in the last cycle shows that the dominant biome of the last glacial era is the cold steppe (COST), which extended over about 60,000 years. The fluctuations in the annual temperatures show that the period was far from stable, because it was intersected by short periods of progression of the forest. However, it is likely that these were rather steppe forests than true boreal forests.

e) Biosphere Modelling : A variety of approaches can be used to represent long-term biosphere change within assessments of the long-term radiological safety of radioactive waste disposal (BIOMASS, 1999a). Since the beginning of BIOMASS, in which ANDRA has always been extensively involved, ANDRA has chosen to implement the BIOMASS methodology.

In common with several other organisations (see Appendix A of BIOMASS, 1999a), the approach currently adopted by ANDRA is to consider a range of biosphere conditions that have existed in the past in France during the Quaternary period and which might therefore exist in the future, and to investigate the impact of releases to 'representative' biosphere systems for each one. The biosphere systems are therefore defined using discrete climate states, associated with transfer and exposure group characteristics.

The approach of using representative, stylized biosphere systems is consistent with the recommendations of the French regulator (DSIN, 1991). Long term radionuclide transfer into the biosphere is indeed studied in the context of the non-sequential approach, where a limited set of biosphere systems is modelled. At this stage, they are considered to be representative of future conditions. Before BIOMASS, a first attempt was provided to characterize a limited number of discrete biosphere systems (Agüero et al, 1996) with the MICE exercice.

Mechanisms for biosphere change and their potential effects at site Meuse/Haute-Marne have been considered and result in the identification of a set of representative, discrete non-sequential biosphere systems of the major climate conditions that may exist in this area. Paleorecords of vegetation have been used to identify the past climatic conditions, namely boreal, tundra and cold steppe biosphere systems. Combinations of several possible land uses have been considered (namely natural/ semi-natural, agriculure, urban and industrial) using information collated for analogous sites. In addition to the three potential future conditions, the French site may also experience temperate conditions similar to those experienced today. The temperate biosphere system is therefore also extensively studied.

Taking account of the natural characteristics of the tundra biome (Torre et al, 2000), analogue regions have been selected on the basis of data reviews for regions in the far north of Russia, including Murmansk region, Arkhangel region and Nenetsia province. Overall, therefore, given the uncertainties inherent in characterising likely future Tundra climate conditions, it is judged that climate analogue regions in the far north of Russia should represent a suitable basis for describing biosphere systems for the preliminary PA.

Given the wide geographical range associated with the boreal forest biome, the range of potentially suitable analogue climate stations is broad. However, the use of European and/or Eurasian regions as analogues for the characteristics of potential cold-climate biosphere systems at Meuse/Haute-Marne carries the advantage of greater consistency with potential future movements of ecosystem boundaries as a result of global climate change. Hence, for the present study, analogue regions for boreal biomes have been selected on the basis of data reviews for three adjacent regions of north-west Russia: Karelia province, St Petersburg region and Vologda region.

Taking account of the natural vegetative characteristics associated with the cold steppe biome, analogue regions have been selected on the basis of data reviews for the Chelyabinsk region of Russia, in the Southern Urals.

A.2 - Enresa, Spain

A.2.1. - Introduction

Safety analysis for the deep geological disposal option has to demonstrate that "Humans and the environment are protected" under any possible circumstance, in present or future situations. From this statement and, due to the long-lived nature of some nuclides contained in radioactive wastes, national waste management organisations have to deal, among other things, with possible implications of environmental change on the repository system barriers, the possible effects on radionuclides transport and the radiological consequences.

With this perspective, the Spanish National Radioactive Waste Management Company (ENRESA) has been working in the high level waste (HLW) area for several years. The R&D Programme is designed to meet the requirements through different lines of study that focus on experimental and field research, as well as, on the development of models and procedures to evaluate individual and global system behaviour.

Environmental change is a known and proved fact that affects the Earth surface and processes at very different spatial and temporal scales (see Section 2). Mechanisms of distinct nature and origin can drive or affect environmental change at different magnitude and frequency.

Climate is a basic and major determining factor of the magnitude of environmental change and of its effects or their rate of ocurrence. Ringrose (1988) has identified two driving forces as fundamental for long-term environmental change: astronomical and tectonic forces. Nevertheless, the climate needs no astronomical variation to suffer a change of regime (Benzi, 1982; Nicolis, 1982) since its dynamic processes are intrinsically stochastic components called "autovariations" (Leith, 1978) or "free variations" (Saltzman, 1985). So, it is necessary to distinguish between astronomical effects (long-term climatic variations) and exclusive climatic effects (short-term climatic variations).

Climate variations are the result of variations in the amount of seasonal distribution of solar radiation on the Earth surface. Fluctuations of climate occur on many scales as a result of natural processes; this is often referred to as natural climate variability (IPCC, 1990). Nevertheless, an important part of the environmental variation is random and caused by processes internal to the system, amplified by feedback mechanisms. Random climate variations may give rise to non-linear responses of sufficient magnitude as to explain climate changes without the need for external forcing mechanisms. In contrast to this background noise there are periodic variation components caused by external forcings.

Besides the natural causes of environmental change, human activities have the potential to affect climate. For example, the enhanced greenhouse effect above the naturally occurring levels due to natural greenhouse gas concentrations; desertification or deforestation and human-made aerosols can modify the albedo of the Earth. Changes in stratospheric ozone due to chlorofluorocarbons (CFC) may also influence climate. Nevertheless, it is impossible for current science to predict processes such as future anthropogenic impact on environmental changes.

So, we can identify three principal forms of environmental change over a period from 100,000 years and 1 million years: climatic change, tectonic change and human-induced change.

Climate change is of primary concern not only because of its characteristic timescales but also because climate is the most fundamental control on the biosphere which is the focus of radiological hazard (Wilmot et al, 1993).

It has been demonstrated that the major factors involved in environmental change will vary depending upon the timescale under consideration and that in the time frame of up to one million years mainly astronomical and climatic factors have to be considered. Besides this, but limited to the next one or two millenia, the consequences of anthropogenic enhanced greenhouse effect on biosphere systems have to be taken into account as well.

The effects of climate change are particularly clear in relation to geomorphological and hydrological processes. The potential impact of climate change on the key hydrological variables (precipitation, runoff and evapotranspiration) is relatively unknown (Zektser et al, 1993) because the complexity of the interactions between the atmosphere, hydrosphere and land makes it difficult to reliably evaluate modifications in the hydrological cycle as a result of long-term environmental impact. Changes in sea level will have repercussions on the equilibrium profile of rivers which will have to readjust until a new equilibrium is reached.

Sea level and topography are important boundary conditions for hydrogeological systems. Changes in both sea level and topography may lead to changes in hydraulic gradients, also affecting the distribution of recharge and discharge points or areas of the aquifer. So, we are facing a time-dependent, delayed response of deep aquifer systems to climate driven changes both in groundwater flow boundary conditions and recharge distribution.

In the context of radioactive waste disposal performance assessments incorporating the effects of climate change, techniques are needed both to reconstruct past climatic and environmental conditions which have affected the Iberian Peninsula during the Quaternary and to describe the environmental evolution with time in order to determine through forward projections of palaeoclimatic data how climate change is likely to affect radionuclide transport from the repository to the biosphere.

The final goal is characterising biosphere systems in both hydrometerological and geomorphological terms in order to allow a continuum to be established from past well characterised climatic episodes to future potential ones that could be taken as a sequence of steps of the long-term landscape evolution of geographical areas under consideration. The ENRESA and CIEMAT focus would be on characterising changes in temperature and precipitation based on both predictive modelling and palaeo-environmental or proxy data in order to use them as input data for groundwater flow and radionuclide transport modellisation.

A.2.2. *- Results Obtained*

Although, it is not yet decided in the Spanish regulations what is the time period of interest for a Deep Geological Repository (DGR) Safety study, it is stated in past and present PAs that there will be no credibility to the barrier system beyond 1 million years. Performance Assessments focus their analysis, therefore, in the 1 million years period after closure.

Natural external mechanisms applying during this period are constrained to those phenomena that are considered within the "climate change" process apart from "isostasy" or "seismicity". For Spain, no relevant isostasy process due to glacial periods are expected since no ice sheet layers are expected to develop, except for some glaciers formed in the high topographical areas. "Seismic" events as well as "human intrusion" are treated separately and have to be incorporated explicitly in the PAs.

Since 1991, ENRESA has carried out a wide programme considering climate change in waste disposal PA, focused on two main lines of work:

(1) Identification of mechanisms that control global climatic evolution and its effects on both a regional and a local scale (specific site) (Recreo et al,1996; Gomit et al, 1997) identification and selection of climatic episodes during the last million years (Bajos et al, 1993); continuous geological record selection that provides information about the last million year in the Iberian Peninsula (Bath et al, 2000);

reference biosphere identification, and climatic scenarios identification (BIOMOVS II /BIOMASS).

(2) FEP´s identification, selection and description for use in the performance assessment exercises (PAGEPA /PHYMOL).

In this respect and, as has been mentioned before, there have been different lines of studies, within the ENRESA R&D Programmes, dealing with environmental change and the effects over the system and radiological consequences:

a) Geological Research, oriented to obtain data from geological records to allow for reconstruction of past environmental conditions. Different indicators are considered in these analyses to try to put in perspective geological, hydro-geological, climatic and biotic characteristics (Bath et al, 2000; PALEOCLIMA Project, in press).

b) Paleo-environmental Reconstruction, oriented to interpretation of data from different information sources to reconstruct the past in a specific area or region (Bajos et al, 1993).

c) Environmental Simulation, oriented to produce future possible sequences of environmental conditions driven by climate change. Several approaches have been studied and explored, taking into account constraints in spatial and temporal variables (ENRESA, 1994).

d) Biosphere Modelling, oriented to develop, on the one hand, models to evaluate the behaviour of radionuclides in the biosphere and the radiological doses under different environmental conditions (Cancio et al., 1997), (Pinedo et al., 1998), (Klos et al., 1999), and, on the other hand, methods to define "Reference Biospheres" for long-term radiological modelling purposes (Agüero et al., 1996), (Van Dorp et al., 1999), (BIOMASS, 1999a to 1999f) (BIOMASS, 2000a to 2000e).

It is relevant to note that each one of the above mentioned lines of study has had different particular objectives, for example: (a) and (b) focus towards the availability and validity of paleo-indicators ; (c) focuses towards the verification of climate models with which to derive predictions of future sequences ; and (d) focuses on assessing the effects of different environmental conditions on the radiological consequences.

Former ENRESA PA exercises (ENRESA, 1997; ENRESA, 1999) were based on the "Reference Scenario", in which no time or space scales changes were assumed. A constant hypothetical "well production" biosphere system was assumed. "Alternative Scenarios" for earlier radionuclide releases to the environment were also analysed, although none of them referred to environmental change consequences.

ENRESA is now developing a new exercise in the performance assessment field. This exercise, ENRESA 2000, has as a main important goal to identify and introduce information that is to be integrated on the basis of palaeoclimatological data from studies carried out in several geological records and their extrapolation to 125 ky AP (Recreo et al. 1997).

The main research lines taken into account by ENRESA in order to feed the ENRESA-2000 PA exercise are:

- Determination and estimation of the main climatic variations inside the Iberian Peninsula during the Quaternary period (regional and local scale).
- Consideration, on the basis of geoprospective codes already developed, of the probable climatic changes that can be identified in the long term after post-closure of the repository.
- Structural and geomechanical performance assessment of the response to the effects of a glacial cycle.
- Reference biosphere identification, critical groups exposure, and dose rates.

The current ENRESA PA exercise (ENRESA, 2000), where new research and development results are being incorporated, considers a "Climatic Scenario" apart from the "Reference Scenario" where current non-change environmental conditions are considered, and other "Alternatives Scenarios".

[22] BIOMOVS II: BIOspheric MOdel Validation Study, Phase II

[23] PAGEPA: Palaeohydrogeology and GEoforecasting for PerformanceAssessment in geosphere repositories for radioactive waste disposal

[24] PHYMOL: A PalaeoHYdrogeological Study of the MOL site

The "Climatic Scenario" takes into account the climate evolution in the Iberian Peninsula for the next 125,000 years (Recreo et al, 1997). Changes in climate and vegetation characteristics are analysed for the sequence of transitions encountered in the past climatic evolution, taking into account a palinological record from the southern part of the Iberian Peninsula covering since 104 ky BP to 4 ky BP. Although a changing biosphere system is expressed in the "thousand of years" time scale, the PA "Climatic Scenario" only considers a discrete climate state, representing a colder and drier situation than the one represented in the "Reference Scenario". That specific selection is based, on the one hand, on the PA Scenarios approach used by ENRESA and, on the other hand, on the intrinsic "conservatism" or "maximising" reasons in calculating radiological doses.

ENRESA's main objective in developing palaeoclimatic and palaeohydrogeologic studies is to establish with the greatest possible precision what climatic changes must be taken into account from the past and their influences on hydrogeology. In this sense, palaeoclimatology references and palaeohydrogeology records can provide valuable information about the past behaviour of the fluvial network and hydrologic system that actually are controlled by climatic and environmental evolution. These methodologies applied to future specific sites are providing information about how the system works and its possible response in relation to climatic changes. Finally, the results obtained will feed into the models used in the PA exercises to assess the performance of selected sites for a future repository.

Techniques	Indicators
• Sedimentology.	• Espeleothems.
• Palaeomagnetism.	• Travertines.
• Dendrochronology.	• Palaeobotanics.
• Amino-acid racemization.	• Ostracodes.
• Organic geochemistry.	• Other biomarkers.
• Palinnology	
• Dating (U-Th; C^{14}).	
• Isotopy ($d^{18}O$; ($d^{13}C$).	
• Fluid inclusion.	
• Tracer Elements.	

Table A2.1: Main techniques and indicators used to interpret past data

So far ENRESA has been analysing samples from specific sites in the south of Spain, the Padul peat bog & Cullar-Baza basin. The information obtained from these two sites has allowed the interpretation of the climatic and environmental evolution in the past (1.8 My). Besides, this information will be the first stage of future geoprospective simulations in order to identify climatic events and environmental scenarios to be taken into account in the next PA exercises. Figure A.2.1 shows the climatic interpretation of the data obtained from Cullar-Baza.

In addition, ENRESA is completing the information available about the past by carrying out works to identify and select continuous geological records in the northern part of the Iberian Peninsula.

The data available from palaeoclimatic and palaeo-hydrogeologic studies of specific sites and the information on global climatic changes in the future (Earth axis inclination, solar fluctuation, magnetic field variation, rate variation of CO_2, vulcanism, tectonics, etc.), has allowed us to analyse the most realistic probable evolution taking into account several climatic scenarios and their incidence on the hydrogeology of the site that has to be evaluated.

In 1994, ENRESA carried out a geoprospective exercise, where a specific river profile was evaluated taking into account the most realistic environmental evolution. This exercise was developed by BRGM (France), and the period of time considered was up to 360 ky AP.

That is the basic information (knowledge) necessary and requested by PA groups to be incorporated in future exercises.

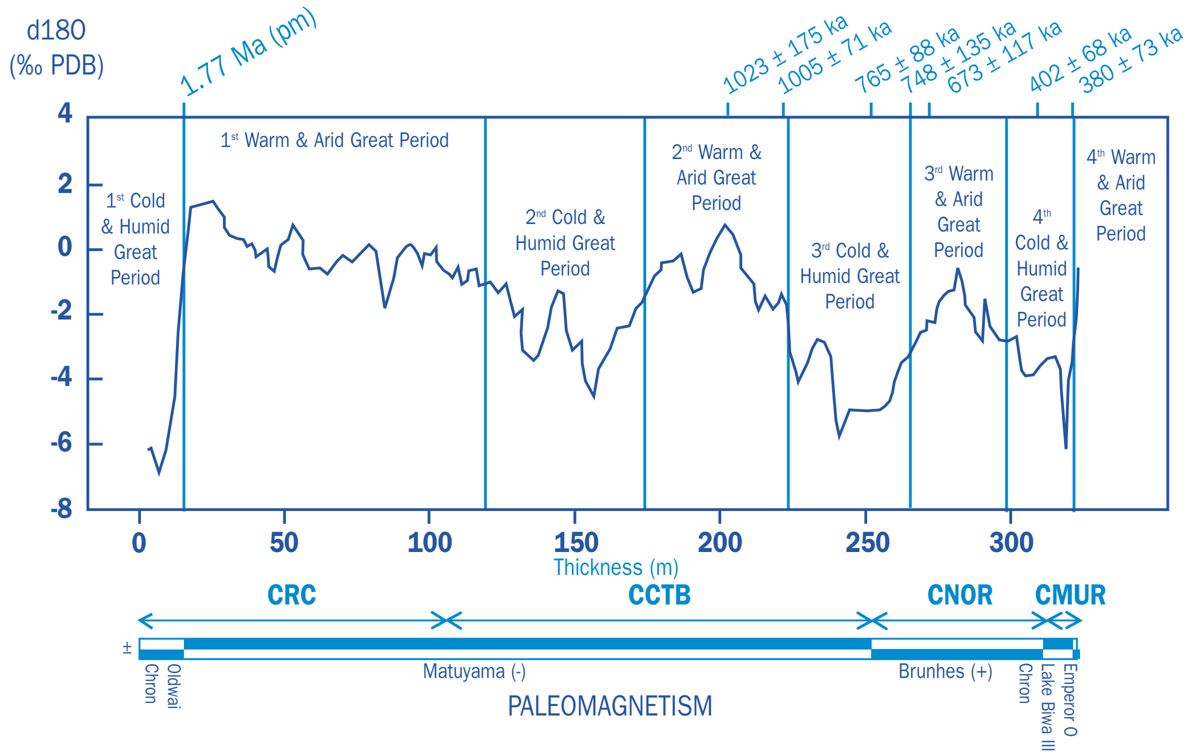

Figure A.2.1 Climatic interpretation of the data obtained from Cullar-Baza (Spain) (Bath et al, 2000)

The main goal expected from the study of climatic evolution and simulation through a geosprospective approach, is to determine the effect of these changes and how the environmental system works over long-term periods at the hypothetical HLW underground disposal level.

To be successful the available continuous geological record must be taken into account as the basis for interpretation of the past events.

The climatic episodes identified in the past (1My) as well as climate evolution up to the present are necessary data to establish the main FEPs that govern and controll the future repository performance assessment and the safety assessment of the system.

It is clear that, for the treatment of environmental change, some lines of investigation are data oriented, showing what has happened in the past in a specific region. Other studies use experimental information, in a bottom–up approach, trying to look for the reasons why several indicators appear in a special sequence, with a certain frequency or whether they occur just randomly. The top level, in these last cases, will be reached when the frequency or random behaviour can be explained by mechanism/s that act at global or regional scales.

In a top-down approach, on the contrary, the treatment of environmental change starts from the development of a series of known mechanisms that can act over the environment at a different time and spatial. Each mechanism is then analysed, accounting for the special conditions of interest (what it is called the "Assessment Context" in a PA). For example, the "evolution of the sun" could be relevant in 10^7-10^8 years time but not at all in 100 years time, due the time scal ; or "isostasy" will be more relevant in Norway than in Italy, due to the spatial scale effects.

The structural behaviour at a regional scale as well as at a local scale in the Iberian Peninsula using a seismic network, helps us to evaluate the current tectonic regime and its possible evolution. Furthermore, this information is essential in order to incorporate the effect of climatic change and associated phenomena (permafrost, ice sheet), that can modify (activate) areas currently considered as inactive.

Climatic studies carried out so far by ENRESA for areas around the Iberian Peninsula, show that in maximum glacial episodes, tectonic effects will be derived from periglacial areas in high altitudes, while in areas close to sea level the impact will be one of permafrost.

This means that the ENRESA 2000 exercise will not consider the impact from the geomechanic and geodynamic behaviour derived from climatic evolution.

A.2.3. - Limitations of the Approaches Used and Improvements Required

An exhaustive review of the state-of-the-art of studies of palaeoclimatic evolution on the Iberian Peninsula is included in Barettino et al., 1993. From this work it may be concluded that the available information shows the following characteristics:

- There are no data on the Lower and Middle Pleistocene palaeoclimates.
- There is a lack of numerical datings.
- The known data are fundamentally placed on the Cantabrian Border and on the Mediterranean Border of the Iberian Peninsula.
- The climatic characterisation is generic: Cold, Warm,etc.
- Most of the records are palaeobotanical in nature, and major areas of geochemical, palaeosalinity and other analyses are not availables.

In short, palaeoclimates are defined qualitatively on the basis of the current climate, assuming some stability of the biogeographical regions (Mediterranean and Eurosiberian) currently existing on the Iberian Peninsula.

Recreo et al (1997) carefully compare the data obtained from the polynic records of the Padul peat bog in Granada (Pons et al, 1988), the records from the KET 8003 off-shore borehole (Tyrrenian Sea), Paterne et al. (1989) and the Grand Pile in France (Woillard et al, 1982). Of special interest in this work, which covers the five first isotopic oxygen stages, is the existence of a good pollen record for the Padul peat bog; however, its peculiar topographic, palaeogeographic and palaeohydrogeological situation implies the lack of perfect tuning between with the palaeoclimatic conditions deduced from the polynic record, and the real palaeohydrogeological evolution.

Padul (750 m. above sea level) is at the foot of the Sierra Nevada (3,500 m. above sea level) and just a few kilometres from the coast, where sub-tropical conditions currently prevail. It may easily be assumed that the pollen records in the peat will show very important climate phase differences.

Padul is hydrogeologically connected to the Sierra Nevada karst (on Triassic dolostones) and receives practically no surface run-off. Consequently, high mountain permafrost development and evolution, will control the lake level.

The Cúllar-Baza Depression is an intra-mountainous basin filled with materials from the upper Miocene, Pliocene and Quaternary age in the central sector of the mountain range of the Cordillera Bética. It has the exceptional characteristic of being one of the few areas in Europe, and the only one in Spain, in which there has been continuous sedimentation throughout almost all the Quaternary. A large amount of palaeontological research work has been carried out throughout the entire area, due to the large number of existing palaeontological remain deposits.

According to the former description of the results, we consider that, $\delta^{18}O$ measured in the shells of ostracods in the Cúllar-Baza basin mainly reflects the variation of $\delta^{18}O$ in the meteoric waters, along with changes in the ratio of evaporation/input to the water mass, albeit it to a lesser extent.

This hypothesis is supported by the centripetal deposition system of the basin, which consists of alluvial fans at the edges, flowing into the lacustrine system, this being made up of a mosaic of small lakes with a shallow body of water. Furthermore, the observations performed in the field show that in the Cortes de Baza area there are thick layers of conglomerates outcropping some 10 km further north, and even in the Río Castril section (CRC-1-1) intersedding of gravels may be appreciated, this indicating proximity to the source area. Consequently, the water from rainfall will run directly to the lacustrine zone via superficial run-off and the channels in the fans, being marked fundamentally by isotopic composition.

A fair amount of polynic and isotopic data is available from the Lago de Bañolas lake (Gerona) record, which covers a span of almost 40 ky. The bioclimatic situation of this record is very different from that of the Padul peat bog.

A.3 - Environment Agency, UK

A.3.1. - Background

Research activities undertaken by the Environment Agency and its predecessor, Her Majesty's Inspectorate of Pollution (HMIP) have been aimed at providing the regulator with an independent capability to assess the proposals of UK waste management agencies, in relation to both near-surface and deep geological disposal systems. Part of HMIP's work involved development and implementation of the so-called 'environmental simulation' approach to long-term performance assessment (PA). This adopted a systems approach to representing disposal facilities and their environment, in order to address the complex problem of addressing risk in situations where there are large numbers of interrelated and uncertain phenomena (see, for example NEA, 1992).

It is important to note that the focus of the UK regulators' work has been on the development and implementation of a coherent assessment capability, with rather less emphasis on fundamental research into the mechanisms of environmental change and their effects. Nevertheless, the experience gained through deployment of the environmental simulation approach is believed to be directly relevant in terms of the lessons learned about the role and representation of environmental change in long-term assessments.

It is important to recognise that term "environmental simulation" should not be tied to modelling of the natural environmental system. Rather, in the context of radioactive disposal assessment, it is any modelling of the physical, chemical, biological, ecological etc. processes (and even human processes and behaviour) that affect the environment (engineered, natural or human) in which radionuclides are released, migrate, disperse and eventually cause exposure.

A.3.2. - Approach and Methodologies Used to Date

HMIP's work focussed on evolution of the repository natural environment (especially the hydrogeological system) as driven by future global and regional changes in climate and associated geomorphological changes. This was motivated by the long time scales for assessment implied by UK regulatory guidance (formerly (DoE et al., 1984) and now (Environment Agency et al., 1997)), and the very significant climate-related changes that could affect a repository site in the UK over such long periods. . For example, multiple glacial periods for a deep site and destruction by ice advance or periglacial processes in the case of a near-surface repository.

Two environmental simulation models were developed by HMIP - TIME2 (for shallow sites) and TIME4 (for deep disposal). The output from these models provided time-dependent boundary conditions to the groundwater flow and transport model, and also to the time-dependent biosphere model.

TIME2: TIME2 (Dames et al, 1988) was developed to represent the possible impact on a near-surface repository of geomorphological changes driven by natural climate processes, and also human actions, up to the next glacial maximum. The time period of interest was restricted to the period prior to the next glacial maximum (estimated to be some 10,000 to 20,000 years in the future), since glacial conditions would be expected to destroy the integrity of such shallow sites.

Two climate evolution models were incorporated in TIME2, both utilising Monte Carlo sampling to account for uncertainty (Dames et al, 1988) in climate state durations derived from the geological record. The first involved a succession of cooler climate conditions representing the onset of boreal and then tundra conditions prior to the nucleation and growth of a British ice-sheet. The second incorporated an initial phase of warming conditions intended to represent the possible effects of climate change induced by greenhouse gases. Other processes modelled by TIME2 included surface water flow, river erosion and disruption of the repository by a variety of human activities.

The code was used to model environmental change at a potential site in south-eastern Central England and later as part of the HMIP assessment of the Drigg LLW site in Cumbria. In both cases, the probabilistic model of environmental change was not linked directly to the radiological consequence model; rather it was used to guide boundary conditions for radiological consequence calculations. In the first application, results were used to construct groundwater and biosphere scenarios for three climate states (temperate, savannah and tundra) which were then analysed individually. For the Drigg site, the results were used to construct a single representative future evolution of groundwater and biosphere conditions. This approach was made possible by the development of the VANDAL code, which includes a network representation of groundwater flow that responds to time-dependent changes in boundary conditions and material properties.

TIME4: In 1987, following Nirex's decision to withdraw from investigation of near-surface sites, work began in preparation for the assessment of an unspecified deep underground site, based on the development of a new environmental simulation code, TIME4 (Wilmot et al, 1993). The goal was to develop a tool that would represent the effect of long-term environmental changes on the hydrogeology and biosphere of a deep site. For the purpose of code development, 'long-term' was defined as a period of up to about one million years in the future, i.e. including the effects of several glacial periods. In parallel, a new version of the VANDAL code was commissioned, that would have the capability to be linked directly to the TIME4 environmental simulation code. This included the development of a new biosphere model, DECOS-MG.

In addition to the longer timescale, the model accounts for isostatic depression and changes in sea-level brought about by the growth and decay of ice-sheets, the development of permafrost and the deposition of glacial sediments (Boulton et al, 1993). The denudation model within TIME4 accounts for erosion by ice and slope processes and for both downcutting and accretion along river valleys. A surface water budget model similar to that in TIME2 is also implemented.

TIME4 generates climate sequences as a series of discrete climate states, using a Markov chain approach to select each subsequent climate state, with the possibilities (warmer/cooler) sampled using data derived from the sequence of climate states in the geological record. Transitions between different climate states lead to corresponding changes in the simulated surface environment and in the boundary conditions for groundwater flow and biosphere processes.

A.3.3. - Different periods considered

Current UK regulations for disposal of solid low- and intermediate- level radioactive waste do not dictate a timescale for which an assessment is required. The period considered in any assessment is thus a function of the types of waste and the disposal concept. The half-lives of the radionuclides and daughter elements of concern in both low and intermediate level radioactive waste are such that periods of up to 10^7 years may need to be considered, but there are limitations concerning the period for which environmental simulation is a sensible proposition. An assessment may therefore need to be presented in several parts with quantitative modelling conducted for an initial period and more qualitative considerations and arguments applied to performance at later times.

The factors governing the period considered in quantitative models differ between disposal concepts:

- For a surface or near surface disposal facility in an area where an ice-sheet might develop, the period of interest may not extend beyond the next 100,000 years. Erosion of such a facility by a developing or receding ice-sheet and the subsequent dispersal of waste over a wider area would need to be considered in a safety case, but cannot be accounted for realistically in an environmental model of the region.
- A deep underground repository should survive glaciation and consequently significantly longer time scales may need to be considered. The current understanding is that glacial cycling such as has occurred over the past two million years will persist for at least the next million years. Beyond this, however, the uncertainties regarding climate become increasingly large and it is inappropriate to use the geological record as the basis for a model of climate cycles.

TIME2, therefore, considers the period up to the arrival of an ice-sheet at the site in question. There is uncertainty about when ice will arrive and this uncertainty is accounted for in the model by sampling the onset of glaciation. As a standalone model, TIME2 converges in about 500 simulations. However, only a few of these simulations would correspond to the arrival of an ice-sheet at, say, 50,000 - 60,000 years. Many more simulations would be required to make meaningful estimates of radionuclide releases at this time. This problem can be partially overcome by using a fixed, illustrative climate sequence to provide a range of boundary conditions for groundwater modelling. Use of such a fixed sequence is not, however, appropriate for estimating risk if there is significant uncertainty about the timing of glaciation.

The development and use of TIME2 ceased before the environmental simulation model was integrated within the overall assessment model and no solution to the problem of risk estimation was developed. In TIME4, which considers a period of a million years, the duration of the final climate state is reduced to ensure that all simulations are of equal duration. Any effects of this approach are considered to be small in comparison to those arising from other modelling assumptions.

A.3.4. - Concept of climate states

Whatever method is used to simulate future climate change, it will most likely be based on the geological record of changes over the past few million years. This record is comprised largely of sediments containing fossilised material. The record is not continuous, and it does not directly record past climate conditions. For a single deposit, past environmental conditions can sometimes be interpreted in a great amount of detail (e.g., proximity to open water, extent of ground cover, and even season of deposition). However, for the purposes of regional correlation, a broader division is more appropriate. A commonly used classification (Goodess et al. 1991) has four environments covering the range of conditions encountered in northern Europe during the past million years. These environments are:

- Temperate - broadleaf forest.
- Boreal - pine and spruce forest.
- Tundra or periglacial - birch forest or treeless tundra associated with permafrost.
- Glacial - site covered by ice.

Confusion can arise, however, if the use of the same classification is applied to evolution of the global climate. It is possible to discretise a measure of global climate (e.g. the SPECMAP (Imbrie et al. 1984) oxygen isotope curve) into a series of climate states. However, use of the terms glacial, tundra etc. to describe the climate states resulting from this discretisation can be confusing since glacial conditions are only experienced at high latitudes. Further south, beyond the ice-sheet, the most extreme climate conditions may be tundra, boreal or even temperate. Similarly, even during the warmest periods, temperate conditions have not been experienced across much of Scandinavia.

In the literature describing the use of environmental simulation by HMIP, the same terms have been used both for the discretisation of the global climate and for the environmental conditions at the site. This is appropriate since Britain experiences glacial conditions at one extreme of the global climate cycle and temperate conditions at the other extreme. However, if similar studies are undertaken in other regions, it may be necessary to adopt a different terminology to avoid confusion, or to discretise the global climate differently so as to reflect the environmental conditions actually experienced in the area. For example, for studies in many parts of southern Europe it would be appropriate to retain a fourfold division of the global climate cycle but to use a different terminology since glacial conditions might never be experienced. For studies in Scandinavia the current discretisation means that for two or even three of the climate states the site will be covered by ice. It would therefore be appropriate to change the discretisation to give more detail in the “ice-free” period or to model more explicitly the evolution of hydrological conditions beneath the ice.

A.3.5. - Use of analogues

The terms temperate, boreal, tundra and glacial are useful, shorthand descriptions of environmental conditions in an area. Environmental simulation models, however, require quantitative information on climatic and other conditions. Both TIME2 and TIME4 used analogue sites (sites that are currently experiencing these conditions) as sources for this information, but there are drawbacks to this approach:

- Restricting analogues to sites with instrumental data.
- Using the last fifty to one hundred years as representative of an entire climate state.
- Using a single site to represent conditions in a region, or combining data from widely separate sites.

If precipitation data from an analogue site are to provide realistic estimates of future conditions at a study site, it is important that the environmental factors that control precipitation are similar at the two sites. Analogue sites must therefore be situated in regions that are comparable in terms of seasonality, proximity to oceans and prevailing wind direction as the site under study. In order to satisfy these requirements for sites in Britain, analogue sites for boreal and tundra conditions must be close to western coastlines at more northerly latitudes. Boreal conditions exist in regions on similar latitudes to Britain but these are unsuitable as analogues as they are less influenced by warm oceanic currents and the associated winds. However, more northerly sites have different day lengths and sun angles, which exert some effect on the climate and also on processes such as evapotranspiration and permafrost development.

Regions identified as suitable analogues for future site conditions may not possess meteorological stations with long records. This is particularly the case where there is significant spatial variability in climate conditions as any suitable analogue region will be small. For study sites in the UK, the analogue regions also tend to be in remote regions where meteorological stations are sparse. The result is that analogue sites selected on the basis of their long instrumental records are unlikely to be the optimal sites in terms of environmental conditions.

The longest available instrumental records for analogue sites are typically for less than eighty years. A climate state on the other hand has a duration of 1,000 to 60,000 years. The instrumental record is unlikely to include the full range of climate conditions for an individual site during a climate state and is even less likely to represent the full range of conditions in the region that the analogue site is selected to represent. In order to incorporate a greater degree of uncertainty, therefore, TIME4 samples from monthly temperature and precipitation data. Averaging or summing of these monthly values is then used to generate a wider range of annual values. However, there is no statistical justification for this approach, nor any means of assessing whether the results do account for the full range of climatic conditions (Dames et al, 1991).

The use of a single site is inappropriate if there is appreciable spatial variability across the region considered in the assessment. For example, if the region includes an upland recharge area and a coastal discharge area, the amount of precipitation will vary across the region. In these circumstances, a single measuring station is inappropriate for defining present day conditions and a single site is similarly unsuitable as an analogue for future conditions.

These drawbacks have been recognised and an attempt has been made to overcome some of them by combining data from several meteorological stations. This approach increases the number of observations used to derive the probability distribution functions (pdfs) but does not address the concern that meteorological observations over a few decades may not represent the temporal variability of an entire climate state. Use of data from additional stations will incorporate some spatial variability. However, unless the spatial variability within the study region is explicitly considered in the selection of analogues, combining sites may lead to analogue data that are even less appropriate.

Overall, if future changes in climate are shown to be significant to the performance of a disposal system, it is important that justifiable data are used in environmental simulation models. The use of relatively short-term instrumental data from analogue sites provides traceability but the ranges of parameter values used are difficult to justify.

A.3.6. - Different approaches to climate sequence

As noted above, TIME2 and TIME4 were designed for different purposes and different time-scales of assessment. Because TIME2 only considers the period prior to the next glaciation, the sequence of climate change modelled is selected from only two alternatives. The first of these is a progressive cooling of the climate from present day temperate conditions, through boreal to tundra, and then glacial. The alternative sequence includes a period of climate conditions warmer than at present to represent the possible effects of continued emissions of greenhouse gases. This savannah period has a fixed duration after which the climate again cools progressively through the temperate, boreal, tundra, glacial sequence.

TIME2 samples from climate state durations derived from the geological record. In order to reflect the difference between climatic cooling and warming cycles, only data from cooling cycles are used to generate the pdfs from which climate state durations are sampled. Even with this restriction, however, it is likely that the model incorporates a greater level of uncertainty concerning the period prior to the next glaciation than would be the case if a model based on a mechanistic understanding of climate change.

TIME4 does not, in general, use a fixed climate sequence. Rather it uses a Markov chain approach (Dames et al 1991) to select each subsequent climate state. The basic model assumes that the climate may become either warmer or cooler at the end of each climate state. These two possibilities are sampled using data derived from the sequence of climate states observed in the geological record. The initial climate state is fixed at temperate (present day conditions) and the next climate state must be cooler (boreal). Beyond that, the sequence may return to temperate conditions or progress to tundra conditions, representing a further cooling of the climate.

The evolution of climate over the past 750,000 years (the period for which there are reasonable data) shows an asymmetry between the cooling and warming segments of the glacial - interglacial cycle. In order to reproduce this asymmetry, the TIME4 climate sequence model distinguishes between different types of boreal and tundra climate states, depending upon whether they are part of a cooling or warming sequence, or represent a climatic maximum or minimum.

A.3.7. - Limitations and drawbacks of the Markov approach

There are two principal drawbacks with the Markov approach used in TIME4: the paucity of available data, and the potential for generating unrealistic climate sequences.

The climate sequence model in TIME4 requires two sets of data: the duration of different climate states and the probabilities of the possible transitions to the next climate state. These data are derived from the geological record by dividing a palaeoclimate record into discrete states and determining the durations for each type of climate and the probability of each transition. Since the model differentiates between different types of tundra and boreal climate state transition probabilities between each of these are required. Depending on which climate record is discretised, and the definition of the boundaries between states, not all of the theoretical transitions may be represented (Kleissen, 1994). Even with longer records or revised boundaries, the number of occurrences of each climate state is small and transition probabilities are very sensitive to the assumptions made in selecting an appropriate record.

The paucity of data, and the resulting sensitivity of the results, is inherent in the use of a Markov model based on a single record of past behaviour. A single, composite climate record has generally been used because individual records are often incomplete or have other deficiencies. Additional data can only be derived by extending the composite record to cover a longer period. However, both the availability and resolution of records beyond 750,000 years BP is poor. An alternative approach would be to derive data directly from several of the component records. This would increase the number of transitions used to define probabilities, and also the resolution of the duration pdfs, by eliminating the averaging that is inherent in the composite record. Care would be required to ensure that no particular part of the geological record was under- or over- represented, so as not to distort the relationships between different parts of the climate cycle.

The Markov model generates sequences of climate change that are statistically consistent with the discretised palaeo-climate record. A criticism of the model is that some of the generated sequences may be inconsistent with what is known about the physical processes that lead to the palaeo-climate record i.e. variation of solar insolation according to changes of the Earth's orbital parameters first described by Milankovich. For example, the Markov model might generate a particular pattern of cycling between two adjacent climate states for several hundred thousand years which could have different implications for repository performance than would the fuller cycles between glacial and interglacial observed in the palaeo-climate record. This criticism was recognised within the HMIP programme and although subject to considerable discussion was not resolved.

The perceived advantages or mitigating qualities of the Markov model were as follows.

- It avoided having to defend any more complex model of future climate state and, by introducing a wider range of uncertainty, might in some way be adding in uncertainty due to possible human influences on future climate.
- Since it was constrained by the same temperate climate starting point it would only tend to produce sequences that were markedly inconsistent with the more scientifically-based model over periods in excess of several tens of thousand or even one hundred thousand years in the future.
- Analysis of the output of the system model e.g. high-risk re-analysis, could be used to identify those types of sequences and conditions that led to highest risk and, hence, to estimate whether there was likely to be a significant bias introduced by the more random generation of climate sequences.

A.3.8. - Approaches to time-stepping

The TIME2 and TIME4 environmental simulation models are designed for single and multiple glacial cycles respectively. This difference leads to two different approaches to time-stepping. In TIME2 the user defines the times at which environmental conditions are calculated. In general, because the duration of the climate states is sampled, these times will not correspond to climate state boundaries. There may be more than one time step in any one climate state and hence climatic conditions may be sampled, and environmental conditions calculated, several times in each climate state. In contrast, TIME4 samples climate conditions, and other variables, only once per climate state. In effect, therefore, the time steps correspond to the climate state boundaries and vary from simulation to simulation. The display and analysis of output from TIME4 and from any coupled models using the same time steps require interpolation if results at particular times are required e.g. mean risk at 100,000 years. This interpolation is made easier by presenting some output as rates (e.g. rates of river downcutting). However, environmental conditions are in general calculated at the start of the climate state and then assumed to remain constant until the next transition.

The assumption of fixed environmental conditions for an entire climate state in TIME4 can lead to large step changes in parameter values at climate state boundaries. These changes may be unrealistic in terms of the processes modelled and may also pose computational problems when models are coupled.

For some processes, e.g. fluvial denudation, calculating conditions at additional time-steps could reduce the magnitude of these steps. For other processes, particularly changes in sea-level, the assumption of step changes per se is unrealistic. Radionuclides that accumulate in an area of deposition during high sea-level will not simply be exposed in terrestrial soils when sea-level is lowered. Rather, they will be re-dispersed during the period that the area of accumulation is subjected to wave action. Consideration of coastal processes in addition to changing the time- stepping is required to account for this effect.

Additional sampling of climatic conditions from the same set of analogue data would not overcome step changes but would simply introduce additional steps of similar magnitude. This is shown in the results from TIME2 which effectively uses this approach. The use of different data sets for different stages of the climate state could reduce the magnitude of change at a time step but this would require the use of additional analogue sites. However, there are insufficient sites available to identify analogues for warm, intermediate and cool boreal conditions etc. and an alternative approach is required if large step changes are to be avoided.

A.3.9. - Water budget

The water budget models in TIME2 and TIME4 are very similar. The model partitions precipitation between the various components of the natural hydrological cycle. It is a deterministic model, with temperature and precipitation the only probabilistic inputs. The study site is divided into several subcatchments, typically three or four, and other inputs to the model, which include soil properties, land use and crop type, can vary between these areas. Soil type can vary between climate states but is the same for all occurrences of a particular climate state.

The amount of recharge calculated by the water budget model can vary across the study site as a result of differences in geology and soil type. There is no mechanism for coupling this surface water model to a model of shallow groundwater conditions. Calculated recharge is therefore the same whether the water table is at the surface or at depth. Recharge is a significant boundary condition for models of deep groundwater flow and hence for radionuclide releases. The lack of a linkage or feedback between groundwater conditions and recharge is potentially significant. Environmental simulation models should be properly integrated with ground water flow models if they are to provide justifiable results.

A.3.10. - Limited number of future ice-sheets modelled

TIME4 incorporates a glacial model so as to include the isostatic effects of ice sheets, changes in relative sea-level and the effects of glacial erosion and deposition. An ice-sheet can affect the environmental conditions at a site prior to overrunning the site and so the area considered by the glacial model must be larger than the study site. Modelling the 3-D evolution of an ice-sheet over a wide area, together with the response of the underlying crust and changes in sea-level, is too complex to be part of an environmental simulation model. The approach adopted has therefore been to use a standalone research model of ice sheet growth to generate a set of outputs representing the effects of particular ice-sheet scenarios. These scenarios correspond to the last glaciation in the region and, if there are sufficient data available, to earlier glaciations.

The research model of regional ice flow is run in forward mode, with parameter values selected to ensure compatibility with the geological evidence. The output of this model, and hence the input to TIME4, does not account for uncertainty. Glacial periods in the simulated climate sequence that are longer or shorter than those represented by ice-sheet scenarios are accounted for by scaling the rates of ice advance and decay. However, there is no scaling or variation of ice extent, ice flow direction or the relative sizes of contributing ice streams. The assumption that future behaviour can be based on models of past behaviour thus imposes a severe restriction on the range of glacial conditions simulated. Ice-sheet behaviour other than that indicated by the last glaciation could be simulated by broadening the parameter ranges of the ice- sheet model. These parameters do not necessarily correlate with glacial state duration or with any other simulated parameter, and judgement would be required to generate additional, feasible ice- sheet scenarios.

A.3.11. - Glacial model inappropriate for sites near nucleation point

The regional ice-sheet model does not have the spatial resolution, nor a detailed ice - rock interaction model, to provide information on erosion and deposition except at a very broad scale. This broad scale is appropriate near the edge of an ice-sheet where reasonably uniform erosion and deposition takes place across a wide area. In regions closer to the nucleation point of the ice-sheet, erosion is likely to be dominant but will not be uniform. Existing models, even at a research level, cannot simulate the extent of differential glacial erosion in a valley, or the location and form of a sub-glacial hollows or channels.

TIME4 makes the assumption that the pattern of rivers and tributaries persists over the assessment period and is not affected by periodic glaciation or by headward erosion and stream capture. Changes in the drainage system would result in different locations for groundwater recharge and discharge. In a particular region, however, the general direction of deep groundwater flow is likely to remain the same. The effect of a changing drainage system will therefore be to disperse radionuclides across a wider discharge region rather than radically alter groundwater flow and radionuclide transport. This is a good illustration of the dichotomy between the two purposes of TIME4. As a means of simulating changing boundary conditions for the deep groundwater system, the use of a fixed drainage pattern is adequate. For a detailed consideration of transport within the biosphere, however, this assumption is difficult to justify.

A.3.12. - Marine / estuarine environment

A version of TIME4 was developed for use in coastal regions and includes a model of estuarine processes. Estuaries are important in radiological assessments because they act as sinks for radionuclides and they are important sources of food. Water and sediment movement within an estuary are controlled by the tide and any process-based model should ideally operate at this timescale. Summation of sediment movements within a tidal cycle to give an annual yield does not account for the dynamic processes within an estuary. For example, net sediment deposition will not persist as this would quickly lead to changes in water velocities and then to sediment erosion. It is not feasible to model these feedback mechanisms within an assessment model but neglecting them can lead to unrealistic rates of erosion or accretion that might invalidate any subsequent dose calculations.

Estuarine processes do not significantly affect the deep groundwater system that controls the release and transport of radionuclides from a repository. There is therefore no requirement to include them in a model intended to simulate changing boundary conditions for this system. There is a need to consider them in models of transport in the biosphere. Different requirements, along with the difficulties and compromises encountered in dealing with them, indicate that separate environmental simulation models for the geosphere and biosphere may be appropriate.

TIME4 does not model marine processes explicitly but is designed to incorporate data derived from research-level 3-D marine models. This aspect of the model has not yet been used in assessment calculations and the ability of marine models to simulate sediment transport under very different boundary conditions has not been investigated.

A.3.13. - Application in Assessment Studies

The UK HMIP Dry Run 3 trial assessment (Sumerling, 1992) illustrated the potential importance of environmental change on the long-term performance of geological repositories and also the value of probabilistic sampling as a method of exploring system behaviour, although effects on the biosphere were not examined in detail. Figure A3.1 compares risk estimates for one radionuclide (I-129) for the following three models of future environmental conditions for the drinking water only pathway:

a) no environmental change (this assumes present-day, temperate climate, conditions are maintained for the next 500,000 years);

b) a fixed sequence of climate states over the next 500,000 years, identical to the past sequence inferred from deep ocean sediment oxygen isotope measurements (hence, environmental change is considered but with no uncertainty in the time sequence); and

c) a fully time-dependent simulation (uncertainty in the sequence and duration of climate states is considered using a Markov model of climate-state transitions derived from the palaeoclimate record).

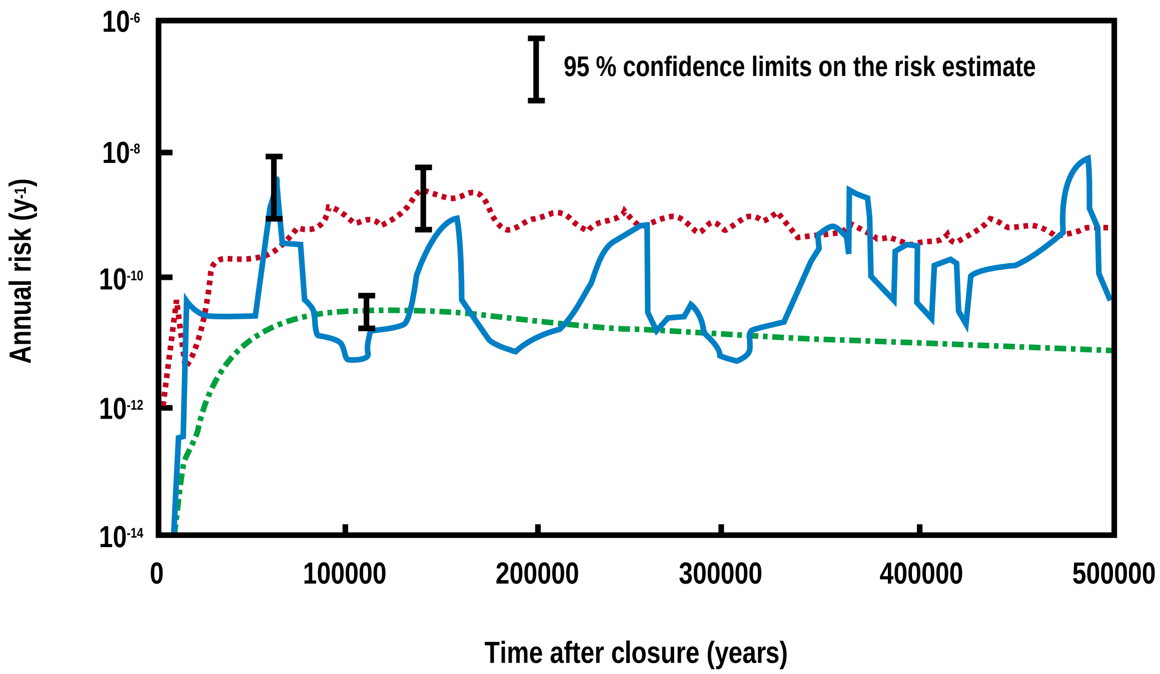

Figure A.3.1 Comparison of risk estimates from probabilistic simulations for three models of future environmental change (from Dry Run 3, (Sumerling, 1992)

Each result is the arithmetic mean of approximately 1,000 simulations. In all cases, the biosphere model is the drinking of spring or near-surface well water. The differences in the results are due to changes in the groundwater transport pathway and dilution, resulting from the time-dependent changes of recharge, episodic permafrost effects and cumulative erosion/ deposition.

Importantly, examination of the Dry Run 3 intermediate results indicated that different pathways for radionuclide movement from the repository to the surface were initiated when environmental change was included. For the Harwell site, and the analysis undertaken, it is the sequences of environmental change that are important; the results could not have been obtained by any linear sum of results from scenarios representing constant environmental conditions. In addition, it is not possible to anticipate with any confidence the particular sequences and combinations of parameters that will contribute most to risk.

As Figure A3.1 indicates, the risk results were higher when environmental change was considered. Conceptually, however, a more important result from Dry Run 3 was the demonstration that the order of events could be important, and moreover, the order and timing of events that led to the highest risk was not a sequence that was identified by subjective reasoning (as in scenario approaches) but was one that was found by the Monte Carlo sampling of the parameter space.

The effect of considering environmental change is illustrated in Figure A3.2. This compares complementary cumulative probability density functions at the time of maximum risk for the full climate simulation. Two effects are notable: (1) approximately 15% more runs give non-zero doses in the case of time-dependent simulation and, more importantly, (2) approximately 5% of runs give doses higher than any seen in the constant temperate simulation, in one extreme case up to almost 4 orders of magnitude higher. It is this high dose tail that dominates risk and causes the mean dose/risk to rise by the two orders of magnitude seen in Figure A3.1.

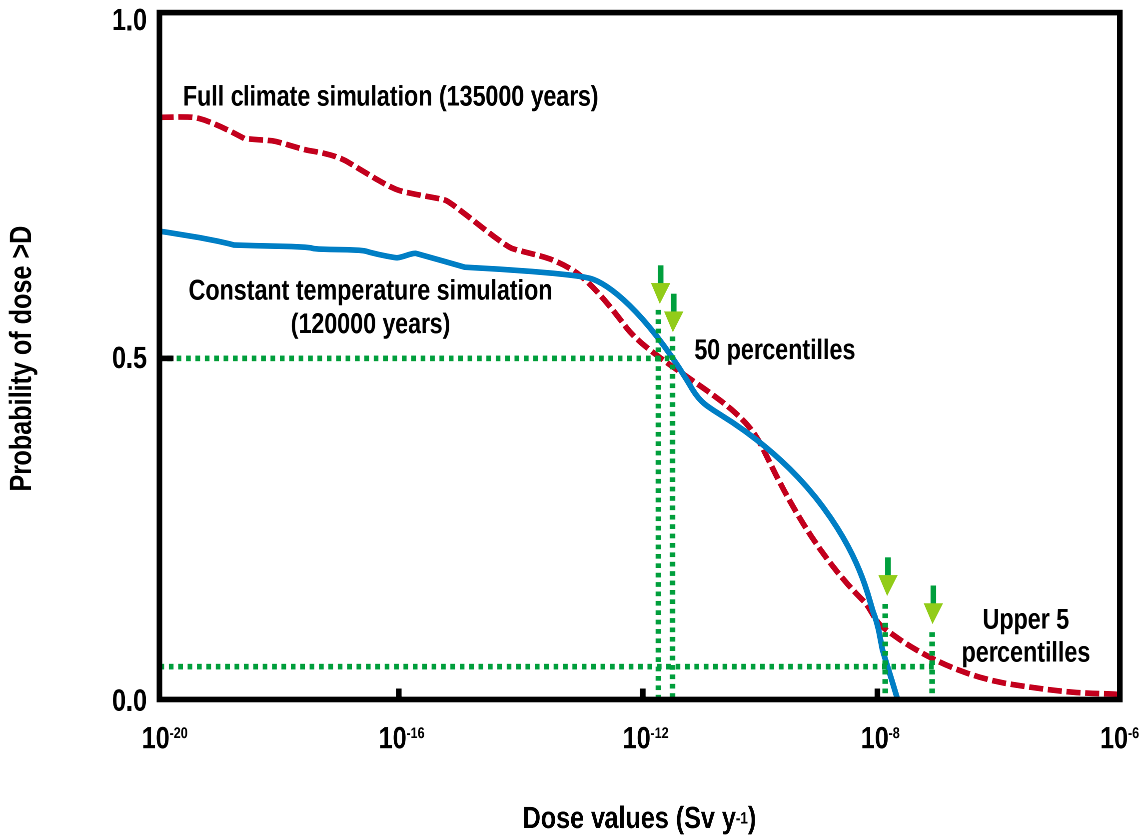

Figure A.3.2 Comparison of complementary cumulative probability density functions of dose at times of maximum risks for climate change and constant temperate simulations (from Dry Run 3, (Sumerling, 1992)

A.3.14. - Conclusion

The environmental simulation models developed on behalf of HMIP were developed with two principal purposes. One was to provide changing boundary conditions for the groundwater flow and transport model used to calculate releases of radionuclides from the repository to the biosphere. The second purpose was to model water and sediment movement within the biosphere for use in dose calculations. These two purposes have different requirements and the principal lesson learned from the development and use of these models is that it would be preferable to separate the two purposes.

Many of the processes included within the current models have little influence on the groundwater system that controls radionuclide transport in the geosphere. On the other hand, coupling the environmental simulation model within an overall performance assessment model limits the spatial and temporal scales considered for transport in the biosphere. Separating the two purposes of environmental simulation would allow more detailed standalone biosphere modelling and simplify the simulation of changing boundary conditions for the geosphere model.

The principal causes of changing boundary conditions for the groundwater system are changes in precipitation, the growth of permafrost and the presence of ice above the site. Environmental simulation modelling undertaken to date has shown that these changes may have a significant effect on radionuclide releases. However, the current models and data suffer from a number of known limitations:

- The data used to sample future climate conditions are traceable to data from analogue sites but may not fully account for uncertainty regarding future climates.

- The data used to model the effects of ice-sheets are not fully traceable since the research code used to generate them is not documented.
- The effects of ice loading during future glaciations on the hydrogeological properties of the underlying rocks have not been fully explored.
- Models of climate change based on a Markov approach may generate many climate sequences that are not realistic in terms of the current understanding of climate processes. Changes in boundary conditions arising from these sequences may lead to radionuclide releases different from those for more realistic sequences. It is possible to select and examine those sequences which lead to high risk and to comment on whether or not they appear credible.

A number of the problems encountered during the development and use of TIME4 have arisen because the model was intended as a generic model that could be used at any site. Specific sites have specific environmental conditions that require additional processes to be considered or different assumptions made. It is recommended that, as far as is possible, environmental simulation models are developed on a site-specific basis, and that a structured approach to model development is used to identify both the processes of interest and the data requirements of associated models.

Ideally, environmental simulation should be integrated within an overall assessment model rather than being a standalone model interfaced to a groundwater model. Environmental simulation models could also be used to provide input to biosphere models operating over spatial and temporal scales appropriate to biosphere variability and processes. Time-dependent stand-alone modelling of some biosphere scenarios could be carried out in order to guide simplified biosphere models used in system calculations. The Dry Run 3 assessment illustrated the potential importance of environmental change on the long-term performance of geological repositories and also the value of probabilistic sampling as a method of exploring system behaviour, although effects on the biosphere were not examined in detail.

Application of a more detailed process-based model of the surface environment within a full system model may be impractical because the time scales which characterise biosphere processes are very short compared to the time scale for PA. Moreover, it is not clear that results would be any more reliable than those obtained by static (time-independent) biosphere scenario models favoured in most PAs. There are both logical arguments for, and operational advantages in, separating the question of assessing performance of the repository and geological barriers from a detailed assessment of the performance of the biosphere. This does not mean that the biosphere can be neglected, but that the context in which it is investigated is altered, allowing more freedom to investigate critical biosphere processes and scenarios.

A.4 - Nirex, UK

A.4.1. - Introduction

United Kingdom Nirex Limited has funded research projects related to environmental change since 1987. In this summary report, a brief account is provided of the scope of this research. This provides a consideration of the factors that affect environmental change over timescales of relevance to performance assessments and a background to how environmental change has been incorporated into the post-closure radiological safety assessments that have been undertaken to date. In particular, emphasis is placed on the most recent assessment, Nirex 97 (UK Nirex Ltd, 1997a).

A.4.2. - Research on Environmental Change

Research on environmental change has mainly been undertaken within the biosphere component of the Nirex Safety Assessment Research Programme (NSARP). A comprehensive overview of that programme was published in 1995 (UK Nirex Ltd, 1995a) and a description of more recent developments appeared in 1998 (Thorne M.C., 1998).

The biosphere component of the NSARP was initiated in 1987 and remains ongoing at the present day. Over this period, it has comprised an inter-linked set of projects relating to climate and climate change; land-form development; mathematical modelling of ice-sheet advance and retreat; development and validation of catchment-scale models of hydrology, sediment transport and radionuclide transport; experimental and modelling studies of radionuclide transport in soils and uptake by plants. In the present context, it is the work on climate and climate change, land-form development and the mathematical modelling of ice-sheet advance and retreat that are of greatest interest. The catchment models are primarily used to simulate snapshots relating to predefined climatic conditions and landforms. Evolution of landforms is not represented in these catchment models. Similarly, the experimental and modelling studies of radionuclide transport in soils and uptake by plants relate to specific sets of environmental conditions.

A4-2.1 Climate and Climate Change

It is considered that the primary factors that determine environmental evolution at sites in the UK are climate and climate change, and human activities. For assessment purposes, human activities in the vicinity of the disposal facility are prescribed (see below). Therefore, research has been concentrated on determining the range of climatic conditions that may prevail at sites of interest in future.

From the inception of the biosphere component of the NSARP, it was recognised that substantial programmes of research on climate and climate change are being undertaken by a wide variety of organisations throughout the world. In view of this, the initial aim of the NSARP work in this area was to review on-going work and to interpret it in the context of its implications for the post-closure radiological safety of the types of deep geological repositories for radioactive wastes under consideration in the UK. To this end, a series of review reports, books and papers has been produced (Goodess et al, 1988, 1990, 1991, 1992a, b, 1993, 1999; Adcock et al, 1997).

However, as a result of the initial review studies, it was recognised that there was a need to develop various scenarios for future climate change on the basis of long-term model simulations. It was further recognised that the current state of the science was such that it would be inappropriate to attempt such simulations over more than the next glacial-interglacial cycle. To undertake such simulations, a model must be used in which the atmosphere-ocean system is coupled appropriately to the long-term evolution of the continental ice sheets. Such a model had been developed at the University of Louvain-la-Neuve (Gallée et al, 1991, 1992). This model was, therefore, adopted for use and a Nirex sponsored PhD student was appointed to undertake the work.

A wide range of scenarios was developed to represent potential patterns of climate forcing over the next 150,000 years. These scenarios were forced by variations in top-of-atmosphere insolation and projected changes in concentrations of carbon dioxide in the atmosphere (Burgess, 1998). The key issue was the choice of scenarios for future carbon dioxide concentrations. For future natural changes in carbon dioxide concentrations, a regression was developed between unlagged and lagged insolation values and the carbon dioxide concentrations observed in the Vostok ice core (Jouzel et al, 1993). This was then applied using calculated future insolation values (Berger, 1978).

The large uncertainties with the global carbon cycle mean that only limited attempts have been made to investigate future anthropogenic changes in atmospheric carbon dioxide concentrations on multi-century timescales (Adcock et al, 1997; Burgess, 1998). The two studies of greatest relevance were identified as those of Sundquist (1990) and Walker et al (1992). A third study, by Archer et al. (1997), has subsequently been published, but was not available at the time of the modelling studies.

After comparing the available results (Sundquist, 1990; Walker et al, 1992) with results from the Intergovernmental Panel on Climate Change (IPCC) second assessment (Schimel et al, 1996), it was decided to use the work of Sundquist (1990) to develop long-term scenarios (Goodess et al, 1999; Burgess, 1998).

Sundquist (1990) used an atmosphere-ocean-sediment model to estimate atmospheric carbon dioxide concentrations for the next 50,000 years, assuming either a high fossil fuel or a low fossil fuel utilisation rate. To extend the Sundquist scenarios into the long-term future, four rates of exponential decay of natural plus anthropogenic carbon dioxide were assumed from 9,000 years After Present (9 ka AP) onward. These exponential decay functions were set so that at 30, 50, 100 or 150 ka AP the contribution from anthropogenic carbon dioxide was zero. Thereafter the regression-predicted natural carbon dioxide concentration was used.

Details of the results obtained from these simulations are presented elsewhere (Goodess et al, 1999; Burgess, 1998). Here, it suffices to note that these results have subsequently been used for two purposes:

- To develop downscaled future climate sequences appropriate to central England;
- To obtain an envelope of future global, eustatic sea-level changes appropriate for use in modelling different scenarios for the future development and retreat of the European and British ice sheets (see Section 2.2).

Various approaches were tried in order to downscale results from the Louvain-la-Neuve model (Goodess et al, 1999; Burgess, 1998). Of these, a rule-based method proved to be the most satisfactory. The following rules were applied in sequence:

- If the limit of the Fennoscandian ice was south of 60°N, a glacial state was adopted;
- If the March zonal land temperature in the 50-55°N band was >-0.24°C, an enhanced warm state was adopted;
- If the February zonal land temperature in the 55-60°N band was >-0.20.5°C, a temperate state was adopted;
- If the Fennoscandian ice volume was greater than 6 10^6 km^3, a tundra state was adopted;
- If the Northern Hemisphere ice volume was greater than 1.5 10^7 km^3, a continental boreal state was adopted;
- Otherwise a maritime boreal state was adopted.

Climatic conditions for each of these states were defined by reference to appropriate present-day analogue stations, using the climate classification of Rudloff (1981).

Use of the various climate scenarios to compute future global changes in sea level is described in a recent Technical Report from the Climatic Research Unit (CRU) (Goodess et al, 2000) that is currently being revised for publication. In the study reported therein, global sea-level change is estimated directly from Northern Hemisphere ice volume, as calculated using the Louvain-la-Neuve model, using a regression approach. The regression has been developed using evidence of past sea levels as the predictand and simulated ice volume as the predictor variable.

The past sea-level records used to develop the regression both relate to the last glacial-interglacial cycle and are for the Huon Peninsula (Papua New Guinea) coral reef record (Chappell et al, 1986; Chappell et al, 1996) and the Barbados coral reef record (Bard et al, 1990). It has been demonstrated that results from these two records can be treated as if they constituted a single population of sea-level data.

For the past, it is also possible to relate the coral reef records to changes in $\delta^{18}O$ observed in foraminifera from deep-sea-sediment cores. This matter is also investigated in the CRU Technical Report (Goodess et al, 2000). Diverges between the two reconstructions of the last glacial-interglacial cycle occur mainly over the interval from 100 ka to 60 ka Before Present (BP).

It is also possible to estimate changes in global sea level directly from model-based estimates of changes in the volume of Northern Hemisphere ice sheets, using the relationship developed by Marsiat et al (1990). However, to do this requires a position to be developed on the degree to which the volumes of Antarctic ice sheets have varied over previous glacial-interglacial cycles and the degree to which they are likely to vary in future. It also requires a position to be taken on the degree to which both the Greenland and Antarctic ice sheets are likely to be affected by future global warming. These matters have been addressed in a recent AEA Technology report to Nirex (Thorne et al, 2000). General conclusions from that report are set out below.

There seems to be little doubt that the area of the Antarctic ice sheets was substantially greater at the Last Glacial Maximum than it is at the present day. The larger of these sheets, the East Antarctic Ice Sheet (EAIS), expanded to only a limited extent, but there was a major advance of the West Antarctic Ice Sheet (WAIS), including expansion into the Ross and Weddell Sea embayments and extensive glaciation of the Antarctic Peninsula. Although the area of the ice sheets was considerably expanded, there is considerable doubt as to whether the overall volume of the total Antarctic ice sheets was larger. This is because there is evidence from both observations and modelling studies of a thinning of the inland part of the EAIS, associated with a reduction in precipitation inputs due to colder conditions over the adjacent oceans. Simple estimation of the change of volume by adjusting the location of the ice margins and assuming a standard profile, as has been done by some authors, is unlikely to be adequate, as it implies a thickening rather than a thinning of the interior of the ice sheet.

Overall, it is concluded that the best estimate of the contribution to sea-level change due to changes in Antarctic ice volume since the Last Glacial Maximum is 8 m. A reasonable range based primarily on field observations is from 4 to 12 m, but this range is not well constrained and modelling studies suggest that an extreme range from –10 m to 30 m could be used. Thus, the contribution from the Antarctic ice sheets could have either reduced the sea-level rise that would otherwise have occurred by as much as 10 m, or could have increased that rise by up to 30 m. All the evidence suggests that the majority of the change (whatever its sign) occurred between about 13000 and 6000 years Before Present (BP).

At the present day, changes in the volume of the Antarctic ice sheets are making only a small contribution to ongoing global sea-level change. Various studies indicate that the global sea-level change over the last 100 years has been about 0.1 to 0.2 m, with a contribution of between –0.14 and 0.14 m from the Antarctic ice sheets. Over the next 100 years, an increase in sea level of about 0.3 to 0.7 m is anticipated, with Antarctica contributing –0.12 to –0.01 m, the negative sign being due to the predominant importance of increased precipitation in the interior causing a growth in thickness of the EAIS. On longer timescales, substantial decay of the Greenland ice sheet could contribute up to 6 m of global sea-level rise by the year 3000 AD, depending on the degree of greenhouse-gas induced warming that occurs. This could be somewhat offset by a contribution of up to about –0.6 m from Antarctica, but, under extreme warming scenarios, the Antarctic contribution would be expected to be positive and might be as much as 0.8 m without basal melting or collapse of the WAIS. However, introduction of basal melting into model simulations leads to a contribution to sea-level rise of between 0.3 m and 1.8 m for a $4xCO_2$ scenario by the year 3000 AD.

Opinions differ as to the likelihood of partial or complete collapse of the WAIS. This divergence of opinion reflects a lack of knowledge of the controls on ice-sheet evolution and associated inability to model the complex dynamics of ice streams and static ice interacting with ice shelves. Issues exist concerning the transition at the grounding line, the nature of movement over a 'sticky' deformable bed, the stability of the locations of the heads of ice streams and their lateral boundaries, the timescales over which behaviour needs to be observed in order to determine the degree of stability of the system as a whole, the role of the ice shelves in controlling flow, and the stability of those ice shelves under climate change. Although it is generally agreed that collapse on a timescale of 100 years is extremely unlikely, collapse on a timescale of a few hundred to 7000 years under the influence of greenhouse-gas induced warming must be considered a real possibility. There is general agreement on the long-term stability of the EAIS, with little likelihood of substantial changes in volume even with a large amount of global warming. Therefore, contributions to sea-level change from the EAIS are likely to be limited over the next few millennia. However, if collapse of the WAIS were to occur, it is estimated that it would contribute between 2 m and 10 m to sea-level rise, depending upon whether collapse were partial or complete.

These conclusions have been taken into account in the development of future scenarios for global sea-level change (Goodess et al, 2000). In all four of the Sundquist high greenhouse gas scenarios, the Greenland Ice Sheet is projected to melt at 5 ka AP. In these scenarios, partial or total collapse of the WAIS is also taken to occur. Various alternatives are explored, with collapse occurring from 2 to 7 ka AP and contributing between 2 and 10 m to sea-level rise.

It is assumed that the WAIS starts to regrow at the same time as the Greenland Ice Sheet reappears in the simulations. This regrowth is taken to be governed by a saturating exponential with a fixed characteristic timescale of 5 ka. This timescale is based on estimates of the transport times for ice flows in the WAIS (Thorne et al, 2000)

A4-2.2 Ice-Sheet Development and Landform Evolution

Development of ice-sheets at a continental scale is clearly a fundamental factor in determining the evolution of the climate at both global and regional scales. However, the advance and retreat of ice sheets can also have direct effects on landform and hydrogeology at a more local level.

During the Quaternary there have been up to eleven periods with ice present in Great Britain, with up to eight of these as extensive as the Late Devensian ice sheet (UK Nirex Ltd, 1997b). About ten more glaciations of comparable extent are anticipated over the next million years (UK Nirex Ltd, 1995a).

Within the biosphere component of the NSARP, an overall history of the Quaternary glaciations of Great Britain has been developed (Clayton, 1994). However, most attention has been directed to developing an understanding of the glacial history of West Cumbria. This was because, between 1989-1997, site investigations were primarily directed at determining whether Sellafield would be a suitable location for a deep geological repository for intermediate-level and some low-level solid radioactive wastes.

Thus, in 1997, a comprehensive history of the Sellafield area was produced (UK Nirex Ltd, 1997b). In brief, in terms of erosion, the history of the last 700,000 years in Cumbria has been a story of an upland landscape becoming more highly incised with each glacial episode and correspondingly, exhibiting an increased contrast in relief. Throughout the period, there may have been a trend for the coastline to move closer to the Cumbrian uplands, as a consequence of lowland denudation. However, the position of the coastline would have oscillated during each glacial-interglacial cycle. In the early part of each cycle, local sea level would have fallen in line with global ice-sheet development, but, in the later stages, isostatic effects due to Fennoscandian and British Ice Sheets could have both enhanced local sea-level falls (through forebulge effects) or compensated for them (as a result of isostatic depression). Each glaciation has largely removed the superficial unconsolidated sediments associated with its predecessor and eroded the underlying bedrock to produce a new suite of sediments.

Quantitative studies of the interactions between tectonic effects, denudation and isostatic adjustment have been facilitated by the development of a digital map of Britain and its offshore waters that incorporates information on height, slope, river distance and underlying geology. The analyses undertaken have emphasised the relatively limited importance of tectonic effects in determining the topography of Britain during the Quaternary. An interesting result is that indices of rock resistance determined on the basis of deviations from expected elevations at outcrop are reasonably well correlated with more traditional geotechnical measures of rock resistance.

At Sellafield, the history since the Late Devensian Maximum at around 18 ka BP is complex, as the area is located close to the margin of the two interacting ice sheets, the Irish Sea ice (originating from Scotland) and the local Cumbrian ice. Thus, glacial, proglacial and lacustrine sediments have been deformed by subsequent ice advances, making interpretation of the lithostratigraphy difficult. The situation is further complicated by the occurrence of active coastal processes in the area over the last 10 ka (the Holocene) making it difficult, if not impossible, to correlate onshore and offshore stratigraphic sequences.

Although specific to the Sellafield area, the conclusions of the Quaternary history report (UK Nirex Ltd, 1997b) in relation to hydrological and assessment modelling are of more general application and are reproduced below.

- **a)** The upland topography has become increasingly incised. Even if all other factors remained unchanged, this would have led to changes in the head distribution driving groundwater flows.
- **b)** The relief contrast between the upland and lowland has altered, influencing groundwater head gradients.
- **c)** The position of the coastline has varied as a consequence of erosional, eustatic and isostatic effects. This will have influenced heads, head gradients and the location of the interface between fresh groundwater and marine water that has infiltrated the underlying Quaternary sediments and pre-Quaternary rocks.
- **d)** Changes in climate will have affected the amount of water available for infiltration, with frozen-ground effects important for much of each glacial cycle. (A detailed review of frozen-ground effects relevant to near-surface hydrological modelling has been produced under the Nirex programme. This review also addresses channel-freezing processes and is being used as a basis for developing the next version of the SHETRAN physically based catchment model; previous version of this model have been described elsewhere (Abbott et al, 1986a, b; Parkin et al, 1999; Ewen et al). Specifically, when boreal conditions occurred in the lowland, periglacial conditions are likely to have characterised the upland, so frozen-ground effects may have been important in recharge areas for up to 80% of each glacial-interglacial cycle. Climate change will also have affected infiltration and groundwater chemistry indirectly through vegetational succession and soil development.
- **e)** During glacial episodes, subglacial and proglacial discharges may have significantly affected the hydrogeological regime (see also (Boulton et al, 1995a; Boulton et al, 1995b). Also, the removal and redeposition of superficial sediments will have altered the controls on recharge to, and discharge from, the underlying rocks.
- **f)** Isostatic deformation, due to long-term denudation, and glacio-hydro-isostatic effects may have affected the hydrological characteristics of the underlying rocks and influenced the local seismic regime.

Understanding of the advance and retreat of past ice sheets has developed on the basis of a combination of field and modelling studies. However, projections of future ice-sheet development will necessarily rely more heavily on theoretical models. It is, therefore, of considerable importance to ensure that such models have an appropriate physical and mathematical basis.

Considerable effort has been expended in the development of mathematical models of ice-sheet growth and decay. However, a review of the literature (Morland, 1994) revealed a variety of potential weaknesses with existing models (UK Nirex Ltd, 1995a).

- Existing models of large ice sheets are essentially uncoupled from the thermomechanics governing the evolution of the atmosphere, oceans and Earth's crust; boundary conditions are prescribed at the interfaces, whereas, in reality, interactions at the interfaces influence the evolution of both the ice sheet and the environment in which it develops.

- Conditions at the base of a grounded sheet are far from clear; for instance, the degree of basal melting, and the relationship between tangential velocity and tangential stress.
- Ice-sheet evolution over large areas must be influenced by the underlying topography, crustal deformation and the essentially three-dimensional nature of the flow. The reduced models that are currently used are really only applicable to small slope topography with prescribed bed form, and the numerical algorithms for vertically plane (or axi-symmetric) flow. Depth-integrated models involve arbitrary, doubtful approximations.
- The treatment of evolution as sequences of steady states is a useful approach, but can lead to an entirely wrong picture. Thus, it can be shown that evolution from an equilibrium state under a sudden change of surface conditions can result in the profile changing in an opposite fashion to that suggested by the equilibrium state for the new conditions.

In view of these potential areas of weakness, Nirex put into place a modelling programme to investigate some of the issues raised. In the first instance, this programme concentrated on the issue of the range of slopes for which the reduced model gives results in good accord with the exact model. From a series of equilibrium comparisons between the exact and reduced model in a 1-D, radially symmetric geometry, it was determined that the reduced and exact models agree extremely well at slopes of up to about 15o. Development of a semi-reduced model applicable at larger slopes has indicated why the reduced model performs so well at slopes that are well beyond its theoretical realm of applicability (Thorne, 1998). Currently, on-going modelling studies are extending the exact and reduced model comparisons to transient cases. However, comparisons for these cases have yet to be reported.

Having obtained confidence in the applicability of the reduced model, attention has now been directed to the issue of appropriately coupling an ice-sheet model to a representation of the deformable upper layers of the Earth. This topic is being studied by M Hagdorn, a PhD student who is being jointly supervised by G Boulton, Department of Geology and Geophysics, University of Edinburgh and K Lambeck, Research School of Earth Sciences, Australian National University, Canberra.

The PhD research began in October 1999. Initial work concerned familiarisation with the Edinburgh ice-sheet model, which is of the standard, 3-D reduced model type, with a prescribed ablation-accumulation function and a modified boundary to represent iceberg calving at marine boundaries. Subsequently, the research has concentrated on an investigation of various alternative formulations of the Earth model. The choices available are:

- Local Lithosphere: The flexural rigidity of the lithosphere is ignored, which is equivalent to crust floating directly on the asthenosphere;
- Elastic Lithosphere: The lithosphere is treated as a thin elastic plate resting on the asthenosphere;
- Diffusive Asthenosphere: The flow within the mantle is approximated by a diffusion equation;
- Relaxed Asthenosphere: The flow within the mantle is represented by an exponentially decaying hydrostatic response function.

These four models have been compared with the full Earth model developed by Johnston (1993). This treats the Earth as a Maxwell body with parameters that vary only radially. Cylindrical ice loads were applied and removed instantaneously in each case, and the time dependencies of sea-level change were examined both within and outside the region of the imposed load. From this study, it was concluded that the Elastic Lithosphere/Relaxed Asthenosphere is a suitable representation for future use.

In operation, the ice sheet and Earth models are loosely coupled, exchanging information through input/output files. Climatological data and bedrock topography are used to compute ice-sheet extent and thickness. The effects of other (far-field) ice sheets are then taken into account to compute changes in sea level and associated changes in water loading. The computed and far-field ice-sheet loadings and the water loading are then used to compute a revised bedrock topography. This process is iterated until convergence is achieved.

Studies with the coupled model are ongoing. Encouraging results for the Fennoscandian ice sheet have been achieved. Consideration is now being given to how the combined model should be driven by the results from the Louvain-la-Neuve model simulations described in Section A4-2.1.

A.4.3. - Approach to Representing Environmental Change in Assessments

Although an extensive programme of research has been undertaken on environmental change, only simplified representations of such change have been used in assessment studies undertaken by Nirex to date. In particular, the deep hydrogeology has been represented using models with time-independent boundary conditions, with the flow regime based upon, and calibrated against, present-day observations (Thorne, 1998). However, radionuclide discharges to the near-surface hydrological regime have been studied in the context of a finite set of alternative climate states, designed to span the range of climatic conditions that are thought likely to occur over the timescale of interest (Thorne, 1998; UK Nirex Ltd, 1995b). Five broad climate states were used to characterise the range of likely future climate conditions at Sellafield, West Cumbria. These comprised Mediterranean (or greenhouse warmed), temperate, boreal, periglacial (or tundra) and glacial. In order to provide detailed characterisation of each of these states, they were related to the climate classification of Trewartha (1968), as modified by Rudloff (1981).

Temperate conditions correspond to those occurring in West Cumbria at the present day, whereas Mediterranean conditions are associated with a climate as least as warm as that of Bordeaux. In both cases, the basic landscape was assumed to be the same as at present, with minor changes to the coastline as a result of rising sea level under greenhouse-warmed conditions. The predominant land use was taken to be pasture, with some arable crops.

Boreal conditions correspond to a climatic regime similar to that of South East Iceland. A global sea-level fall of 30 to 60 m below the present datum was assumed, with much of the bed of the eastern Irish Sea being uncovered. The biosphere in these conditions can be described qualitatively in terms of an extended coastal plain dissected by a number of small to medium sized rivers. The climate is regarded as sufficiently mild for a range of arable crops to be grown in addition to the predominant pasture use. However, primary productivity is reduced relative to temperate and Mediterranean conditions. Also, in terms of soil characteristics, spodosols and gleys cover an increased fraction of the area of interest (UK Nirex Ltd, 1997a; Thorne, 1998).

Periglacial conditions are characterised by very low terrestrial primary productivity, with no agriculture, although coastal communities can rely heavily on the high marine productivity encountered in Arctic seas. An additional fall in sea level, by comparison with the boreal climate state, gives rise to further extension of the Cumbrian coastal plain to the west (Thorne, 1998).

The glacial state has not been modelled in Nirex studies undertaken to date, since the whole of the Sellafield area is considered to lie beneath an ice sheet in such conditions (UK Nirex Ltd, 1997b). However, it is appreciated that overlying ice sheets have a potentially important affect on deeper groundwater systems as they may influence groundwater chemistry and hydraulic gradients.

For natural discharges of radionuclides into the terrestrial environment in Mediterranean, temperate or boreal conditions, two alternative approaches to defining the potentially exposed group have been adopted. In the first approach, average radionuclide concentrations were calculated in environmental materials present within the resource area of a small community consisting of about 300 people and taken to produce all its food from within the resource area. These concentrations were then used to calculate effective dose rates to three age groups (infants, children and adults) with habits and behaviour selected to give dose rates substantially higher than would be associated with typical inhabitants of such a community, but excluding exotic or pathological behaviour. The highest dose rate to any age group was then carried forward for use in the assessment.

With this first approach, variability in dose rates resulting from inhomogeneities in environmental concentrations of radionuclides was neglected. The approach assumed that it was legitimate to make use of a potentially exposed group that was relatively homogeneous with respect to risk (as defined by their habits and behaviour), but not necessarily with respect to dose (see UK Nirex Ltd, 1997a for a detailed discussion of this matter).

However, subsequent to the development of this first approach, the regulatory authorities provided guidance that potentially exposed groups should be relatively homogeneous with respect to radiation exposure (Environment Agency et al, 1997). Responding to this guidance, Nirex also applied a second approach in which the potentially exposed group comprised farmers obtaining all their food and drink from the contaminated area. This new approach uses the relative homogeneity of environmental concentrations of radionuclides as a surrogate for relative homogeneity of radiation exposure. Because of the smaller groups arising in this second approach, distinctions in age were not taken into account (Thorne, 1998).

In the case of periglacial conditions, the two approaches were not distinct. A smaller community of 30 individuals was adopted. The community was assumed to obtain its terrestrial requirements by hunting and herding over an area of 1000 km^2. This area was much larger than the contaminated area. In this case, the concept of a group obtaining all its resources from the contaminated area was not considered appropriate and the communal use of resources indicated that the whole community could be considered to be relatively homogeneous with respect to radiation exposure.

Similarly, two approaches were adopted in the case of wells. In the first approach, the average concentration in abstracted well waters was calculated for all wells drilled in the resource area of the community. In the second, the average concentration in abstracted waters was calculated only for those wells drilled within the plan area of the contaminant plume in the near-surface aquifer.

A.4.4. - Summary of Climatic Data Required for Assessment Modelling

The current state of biosphere modelling undertaken by Nirex is such that climatic data are used at two distinct levels. At a coarse level, future sequences of climatic states are required in order to identify potential broad patterns of evolution of landforms and groundwater flow regimes. This information conditions the calculations of discharges of radionuclides to the accessible environment or of concentrations in near-surface aquifers that are undertaken. The general characteristics of the climate states are also used to make decisions on representative patterns of soils and vegetation. This allows a limited number of surface-water catchments to be defined appropriate to the calculation of radiological impacts of releases of radionuclides in the different climate states. Such releases can occur either in discharge areas or by abstraction from near-surface aquifers.

Having defined representative surface-water catchments, it is necessary to model the transport of radionuclides through them. This requires that precipitation and meteorological data should be available at a suitable level of detail. The largest amount of information is required for SHETRAN simulations. These require data sets such as would normally be acquired from a fully equipped meteorological station as time series with an interval of around 30 minutes. In the past, analogue station data have been used, but model-based data would also be acceptable. Typical SHETRAN runs have represented 30 years of simulated time. However, radionuclide distributions of interest do not always achieve equilibrium on such timescales and longer periods of simulation might be desirable. Such longer timescales could use longer meteorological data sets, but it would usually be adequate to generate longer time series by repeating data from a shorter time series.

In SHETRAN calculations, spatially distributed data are required. For small lowland catchments, values for a single location will be adequate. However, for catchments in which there are substantial distinctions in altitude or aspect, values for two or more locations may be required. Alternatively, derived data, such as stream hydrographs, may be generated for some parts of the catchment and detailed hydrological modelling may be undertaken only for a selected subcatchment. In that case, detailed meteorological and precipitation data will only be explicitly required for that subcatchment, though similar data may be used in generating the derived data used in the simulations.

The simplified assessment models use much more limited climatic data. In general, the requirement is to compute water balances for individual soils or for an inter-linked set of soil areas. Such water balances are only required on a monthly or seasonal basis. Adequately robust formulae are available to compute actual and potential evapotranspiration for a wide variety of land uses based only on mean monthly temperature and precipitation values. However, as irrigation is often an important route for contamination and requirements for irrigation vary from year to year, it is important to be able to evaluate inter-annual variations in seasonal water balance. This, in turn, implies that data should be provided on inter-annual variations in values of mean monthly temperature and precipitation.

A.4.5. - Limitations of the Approach Adopted in Assessments to Date

The underlying modelling studies undertaken as part of the NSARP have provided a good quantitative understanding of the processes that could influence biosphere and geosphere evolution at potential UK sites for deep geological disposal of radioactive wastes. However, these modelling studies have mainly been used to inform assessment calculations, rather than being directly coupled to them. Furthermore, the assessment calculations that have been undertaken have related to a small number of time-invariant biosphere states, rather than to an evolving biosphere. Even for these states, the current state of the art in near-surface hydrological modelling has meant that considerable simplifications have had to be introduced. In particular, it has not been possible to study the potential radiological significance of ground and surface water freezing effects through the application of a physically based model. Such effects are recognised as being of potential significance in colder boreal and periglacial conditions.

With respect to radionuclide transfers in the environment, extensive studies on soil processes and soil plant transfers over a single growing season have been undertaken for the key radionuclide ^{36}Cl, as the environmental behaviour of this radionuclide had previously been investigated to only a limited degree. However, other aspects of ^{36}Cl transport in terrestrial environments, such as longer-term biogeochemical cycling in the soil-plant system, have not been investigated, nor have other radionuclides of potential significance been studied. At an early stage of the research programme, a variety of desk-based reviews of radionuclide transport in the environment and related matters were undertaken. However, these reviews have not been updated in the light of more recent publications in the primary literature and substantial reliance has been placed on secondary sources compiled by research groups and international organisations for a variety of purposes.

Throughout the programme, emphasis has been placed on discharges to terrestrial environments, as these are thought likely to give rise to the largest individual annual doses and risks. If measures of collective impact were to be given greater prominence in assessments, it would be appropriate to give greater emphasis to direct or indirect discharges to estuarine and marine environments. Detailed consideration has been given to the definition of potentially exposed groups for the purpose of individual risk estimation for comparison with the risk target recommended in UK guidance. However, an extension of the proposed approach would be required in order to define appropriate measures of collective impact.

Overall, it is the lack of a well-defined route for transferring detailed modelling results into an assessment context that is regarded as the main deficiency in the approach that has been used to date. However, steps are being taken to remedy this deficiency. For example, initial work establishing the legitimacy of reduced modelling approaches to ice-sheet development provides a basis for considering how such ice-sheet development can be coupled to isostatic deformation and groundwater flow modelling. If such an integrated modelling approach is pursued, it will provide a way of characterising groundwater flow systems and geosphere-biosphere interfaces throughout a glacial-interglacial cycle. In turn, this should permit investigation of potential temporal and spatial dependencies of radionuclide discharges to the biosphere on long timescales. Information on such spatial and temporal dependencies is a primary input to determining the type of biosphere calculations that should be undertaken. However, it should be recognised that such integrated modelling studies are mainly of interest in specific geological contexts. Therefore, extensive deployment of such an integrated modelling approach may not occur until specific sites have been selected for investigation. In the UK, this site selection and investigation phase is unlikely to be initiated for at least five years.

Extensive studies undertaken to date have determined that the radionuclides of greatest relevance in determining the post-closure radiological impacts of deep geological disposal facilities for low-level and intermediate-level solid radioactive wastes are not very persistent in the environment. This is either because of their intrinsic mobility, e.g. ^{36}Cl and ^{129}I, or their relatively short half lives, e.g. ^{226}Ra, ^{210}Pb and ^{210}Po. Because of this limited persistence, it seems likely that it will continue to be appropriate to define discharges into surface-water catchments of well-defined geometry. Such catchments are well characterised using the physically based SHETRAN model.

In assessments that have been undertaken to date, SHETRAN has been used as an underlying detailed model to determine parameter values for use in simplified assessment models. However, the greater flexibility and ease of use of the forthcoming release of SHETRAN should facilitate its direct use in assessments. This will mean that spatially and temporally distributed radionuclide fluxes or concentrations generated by geosphere models can be accepted directly by the biosphere assessment model of choice. This will reduce the amount of judgement needed and will help to ensure consistency between geosphere and biosphere modelling across the interface. Even greater consistency may be achieved if it is possible to build on work undertaken to date that explored iterative coupling of distinct hydrological models of deep and shallow groundwater systems.

In addition, the version of SHETRAN that is shortly to be released will include representations of ground and surface water freezing. This means that the ad hoc approaches previously used for representing the hydrology of colder boreal and periglacial environments will no longer be required.

A stronger link is also being developed between the experimental studies on soil-plant transfers and the SHETRAN modelling scale through the development of a 2-D biogeochemical cycling model that extends the capabilities of the 1-D models previously used for interpretation of the experimental data.

Overall, it is considered that the biosphere approaches used to date have been suitable for scoping calculations of radiological impact and have provided an adequate guide to research and development priorities. However, the advantages of a more comprehensive approach have been recognised and a work programme is being developed to achieve this. It is emphasised that the more comprehensive approach will not necessarily deliver results that differ substantially from those obtained using the simplified approach adopted to date. However, by facilitating the undertaking of a wider range of physically based assessment calculations, it will provide a better substantiated basis for the results obtained.

A.5 - NRI, Czech Republic

A.5.1. - Introduction

The Czech Republic is situated in Central Europe without any access to sea (the nearest point Stetin bay in Baltic Sea is in a distance of 326 km). The area of republic is 78 864 km2 with approximatively 10,3 mil. inhabitants which results in very high mean density of population. Due to position of Czech Republic, the climate is formed both by ocean and continental influences. The average annual temperature is 5.5-10 °C. The moisture is brought mainly by western winds. The annual mean rainfall is 681 mm. The Czech Republic is in the position of main European water-shed.

With regard to electricity production, currently only Dukovany nuclear power plant with 4 WWER 440 MWe units is in operation, while Temelin nuclear power plant with 2 WWER 1000 MW is in the pre-operational phase. In 2002, when 6 units will be in operation, the nuclear power plants will produce approximatively 25% of electricity consumed in the Czech Republic.

Modern legislative framework of nuclear safety and radiation protection based on ICRP-60 requirements and IAEA Basic Safety Standards was established in 1997, when the Atomic Act was approved. The act is complemented by many detail regulations of State Office for Nuclear Safety (SONS) which is independent regulatory body, responsible for regulation and licensing of radiation sources and nuclear facilities. According to SONS regulation on Radiation Safety (184/1997) stands that:

“The compliance with the radiation protection requirements for disposal of radioactive waste at the final repository shall be proved by the safety analysis of possible consequences. The safety analyses shall demonstrably and reliably, on the basis of knowledge on the site, in which the repository ought to be built, evaluate the hazards, taking into account the period after the termination of repository operation. On the basis of the safety analysis, conditions of acceptance for the repository of radioactive waste are derived. The arbitrary criterion for the safety analyses there is the size of effective dose for the individual of critical group of inhabitants.”

Unfortunately there are no detail instructions for treatment of biosphere in post-closure safety (risk) assessments. Also there are no defined cut-offs for quantitative analysis.

In 1997 the Radioactive Waste Repository Authority (RAWRA) was established as a state implementing organisation, responsible for the management of radioactive waste, including preparation, construction, operation and close of repositories. RAWRA is also responsible for assurance ensurance and coordination of research and development in the field of radioactive waste management. The Nuclear Research Institute in Rez (research and development organisation) was entrusted as a national co-ordinator of the Deep Geological Repository Programme in 1993-1998 before institutionalisation of RAWRA. The NRI also performed all safety analysis of Dukovany surface repository. Nowadays, NRI has become the main contractor of RAWRA in the field of research and development of radioactive waste disposal.

In the Czech Republic two near-surface repositories are in operation.

- Richard sub-surface repository (situated in former limestone mine in the depth of approx. 50m) for radioactive waste from research, hospitals, universities and industry (so called institutional radwaste) was put in operation in 1964.
- Surface repository near Dukovany nuclear power plant was put in operation in 1995. The repository will be used for disposal of operational waste and in future for waste from decommissiong from both Dukovany and Temelin nuclear power plants.

Deep repository programme was initiated at the beginning of 90-ties. Up to now, mainly generic studies were performed. In 1999 the Reference Deep Repository Project was formulated forming the baseline for further research, design and geological activities. The concept of deep disposal is based on direct disposal (without reprocessing) of spent nuclear fuel in granitic host rock in the depth of 500 – 1000 m. The bentonitic materials will be used as a buffer, backfill and partially as a sealing material. The reference repository documentation includes the idealised design of surface and subsurface parts, life-cycle and financial aspects of development, operation and closure of repository and also reference simplified post-closure safety assessment.

A.5.2. - Approaches and methodologies used to date

Although the repositories are in operation in the Czech Republic for nearly 50 years, the first post-closure safety analysis have been carried out after 1990. The post-closure assessment of deep geological repository (part of 1999 Reference Deep Repository Project) was based on simplified evaluation of near, far-field and biospheric processes. The simulations were performed only for very limited set of radionuclides. Only ingestion of potable water was evaluated as an exposure pathway. No environmental and climatic changes were incorporated in this documentation. Nowadays the comprehensive safety analysis is being performed for both Richard and Dukovany near-surface repositories with the aim of of post-closure safety evaluation and waste acceptance criteria formulation. The environmental and climatic changes will not be considered in the documentation, according to available information.

The Czech Republic as an associated country of European Union is now firstly participating in the EC Framework Programmes so it was not possible for Czech organisations to be involved in previous relevant projects (EQUIP, PHYMOL).

Up to now, there is no experience with incorporation of environmental changes in performance assessment of repositories in the Czech Republic. On the other hand, Quaternary and paleoclimate research was developed and the results can be in many cases interpreted for repositories safety aims. Therefore, we will start in BIOCLIM project with linking of 2 different and up till to present fully separated research areas: safety of repositories (migration of radionuclides and consequences analysis) and climatic (incl. paleoclimatic and environmental change) research.

Experience in simulation of migration of radionuclides in environment was acquired from various projects in connection with radioactive waste disposal or from similar areas (e.g. remediation of uranium mining and milling). The most valuable experience and know-how has been acquired through participation in BIOMOVS II and then BIOMASS projects (1996 – 2000). The Czech representatives were mainly involved in modelling of radionuclides transfers in environment at Olen in Belgium, where Ra production plant was situated (Theme 2 – environmental releases). The principles and results of BIOMASS project will be further used in safety analysis – reference biosphere, justification and identification of biosphere system, critical and other exposure groups, data. In the last safety analysis of Dukovany surface repository RESRAD and TAME codes were used. Newly acquired AMBER code will enlarge our possibilities in modelling of migration of contaminants in environment. NRI was responsible for safety analysis of remediation of uranium in-situ leaching in the North Bohemian site, with the aim to establish final remediation parameters of contaminated groundwater. For this purpose, NRI team set up a special model for simulation of radioactive and non-radioactive contaminants in biosphere (K2M). Unfortunately there is no experience in model application in other than current ecosystems occurring in Central Europe.

Climatic research is localised mainly in academic and state organisations, mainly as follows:

- Institute of Atmospheric Physics of Czech Academy of Science – focussed on modelling of short and long-term changes including application of downs-caling methods.
- Czech Hydrometeorological Institute (specialised organisation of Ministry of Environment)-Department of Climate Change is fulfilling the role of National Centre of United Nations Framework Convection on Climate Change (UNFCCC) and IPCC. Simultaneously it is a co-ordination centre for inventory of greenhouse gases in the Czech Republic.
- Department of Meteorology at Charles University in Prague.
- National Climatic Programme is a joint of 16 subjects. It functions as a monitoring and coordination body of organisations dealing with the climate change research. The Programme dealt with many projects in the area of assessment of climate change on hydraulic systems and forests in the Czech Republic, set up action programme for reduction of risks of possible future climatic changes.

The Quaternary studies, developed gradually before the second world war. and were at that time mostly concerned with archaeological excavations. However in early 60-ties a new school of the Quaternary geology, lead by G.J. Kukla a V. Lozek, started the research of thick loess series with multiple fossil soils and later the Holocene studies. Two important teams, functioning up to now, participated in following fields: 1. The academic team from the Institute of Geology (nowadays Academy of Science of Czech Republic) focused on the paleoenvironmental and paleoclimate reconstructions. The work was carried out especially by V. Lozek and I. Horacek. J.G. Kukla left the team at early 70-ties, when he joined Lamont-Doherty Earth observatory of Columbia University. 2. The other team was formed at the Czech Geological Institute (now part of the Ministry of Environment). This team focused on geological mapping of Quaternary, on a series of 1 : 200 000, and later 1 : 25 000 and 1 : 50 000 maps, sedimentological studies, palynology and paleontology. While the "academic" team tried to produce a paleoclimatogical synthesis, the "geological" team (J. Tyracek, J. Kovanda, P. Havlicek, K. Zebera, J. Macoun, V. Sibrava and others), described many sites and provided basic geological data. In fact, both teams often worked together and it is difficult to draw a distinct division between them. All important Quaternary sites exposed to direct observation (brickyards etc.) were described during 70-ties and numerous drilling projects and excavations were furthermore carried out all over the area of former Czechoslovakia.

The other, however limited or marginal paleclimatical and paleoenvironmental studies were carried out by Institute of Archaeology (Palaeolithic excavations – J. Svoboda, B. Klima, Holocene – J. Neustupny) and the palynological research mostly of peatbogs was organised by botanists (V. Jankovska and others). The limited Quaternary community co-operated since 50-ties together, as it is witnessed by a common Quaternary journal "Anthropozoikum". The group, composed of university teachers and geographers, was involved in complex study of cave sediments and their fossil content, worked in Brno (R. Musil, K. Valoch, J. Pelisek and others).
The political and social changes after 1990, lead to the unprecedented rise of paleoenvironmental activities. The first PAGES meetings were attended by specialists from 15-18 different local institutions. The paleoclimate research is now mostly associated with PAGES activities and the best reviews of local activities can be found in PAGES meetings proceedings (Ruzickovaet al 1993; Ruzickova et al 1995; Kadlec, 2000). The area of Czech Republic has a very dense network of Quaternary sites that were studied by paleobiological and paleoenvironmental methods (malacozoology, Vertebraete paleontology, pollen analysis), but there are only few sites where isotopic research and dating was performed. The general features of climate oscillations are well known from numerous, now mostly non-existent, sites for the Middle-Upper Pleistocene and Holocene, but the area lacks really detailed fossil record such as lake varvae. The result is a well established but rather general synthesis of Pleistocene climates as deduced from about 60 sites (loess series, cave sediments, speleothems) and even more detailed understanding of Holocene environments established on more than 150 studied sites (mostly karst sediments, peatbogs, tufa deposits). It provides a good background for the understanding not only of past climates but regional differences as well.

A.5.3. - Results obtained

As mentioned previously, no comprehensive safety assessment of deep geological repository was done, and so environmental change (sequential or in a form of defined different ecosystems) was not incorporated in the analysis.
Siting process for deep repository commenced in 1991 when 31 sites were identified in different geological units (granitoids, metamorphic and sedimentary rocks). In 1999 eight sites were selected on the basis of available information for detail geological investigation. All sites are situated in southern part of our republic, in granitoid rock bodies. It is supposed that in 2002 geological investigation at sites will commence.

In the area of paleoclimate and Quaternary studies many results were acquired that can be interpreted for post-closure repository safety.

A5-3.1 Pleistocene period

Quaternary period, which beginning has been assigned at 1,8 Ma, while other scientists are proposing "long" Pleistocene starting at approx. 2,7 Ma. The last million years are marked in the temperate zone with 9 large ice ages, lasting about 100 ka and 9 interglacials, lasting about 20 ka.

In the area of the Czech Republic, we can distinguish several Pleistocene phases:

- Lower Pleistocene glacials were probably, according to the loess development ,more warm and humid than later glacials of the last 1 Ma. The bright red to red deeply weathered interglacial soils are characteristic for a period prior to Brunhes-Matuyama paleomagnetic boundary (Beroun highway outcrop). The fossil content of Lower Pleistocene sediments reflects the presence of thermophilic elements (e.g. outcrops of so called red breccia in

Slovak Karst, Eastern Slovakia - Horacek et al 1988; Lozek 1982). The evidence is scarce and limited to several sites. However the general course of the Lower Pleistocene leads to a milder glacials, warmer and in some phases even more arid interglacials. The frequency of climatic changes was probably higher and the differences between glacial and interglacial lesser than during Middle-Late Pleistocene.

- Middle and Late Pleistocene strata of the Brunhes paleomagnetic period, as recorded in loess series, and calcareous sediments display the alternating sequence of well defined glacial and interglacial sediments. The mean annual temperatures can be estimated in the range –2 to –3°C during pleniglacials, it means some 100C colder than the interglacial conditions. The glacials were drier – we estimate some 300-400 mm of mean annual rainfall in areas below 400 m a.s.l. The glacial ecosystems can be characterised as cold steppe or grassland, but forest refugia (spruce, birch, juniper) were present as „islands". The pollen analyses and even some macrofossils indicate rather enigmatic presence of more demanding tree species such as elm and oak during warm phases of last glacial. The malacofauna is represented for most of the glacials by monotonous assemblage of several species such as Pupilla. While the glacials of the last 1 Ma seem to have almost similar character, the interglacials are more individual as evidenced by fossil fauna (Horacek et al, 1988). It may be caused by random migration from either western Atlantic direction or along Donau-river from SE or even along the outer limits of Carpathian range from area of nowadays Poland. The soils in loess series correspond according to thermoluminiscence-dating and amino-acid racemisation to common marine isotope stages (Frechen et al. 2000).

Paleometeorology and loess deposits

The fact, that loess-transporting winds came from NW, W and SW directions, was established decades ago on the basis of loess dune orientation and the presence of particles from neighbouring rocks (many authors listed in Demek et al, 1969). The same wind direction appears to have been characteristic in the case of most Central European loess deposits, although 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 (Hurrell, 1995). Even more important observations of general sedimentation features of loess deposits points to at least two different modes of loess deposition, as follows:

- 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 the consequence, very variable rate of dust sedimentation, especially in small deposits and dunes in the lee of hills and within the valleys, are to be expected.
- Relatively homogenous and massive loess, without visible stratification, probably corresponds to a steady, uniform westerlies regime. The paleoclimatic data for the last glacial cycle (Tziperman 1997) demonstrate unstable extensions of wind direction and a general variability in the climatic oscillations. This is, in this writer's view, rather demonstrated by the macroscopic features of loess sedimentation, than by for example magnetic susceptibility.

The basic loess textural division between laminar and massive types should not cause several mechanisms of laminar texture origin to be overlooked, as following examples make clear:

1. Dust storms may produce laminae where grain size gradually diminishes as the wind velocity decreases (Zemechy in Central Bohemia, abundant exposures of the lower part of pre-Eemian cycle). However the silty layers (3 - 20 cm thick) are quite often intercalated with narrow (1 – 3 mm) clayey, usually grey or rusty horizons. These horizons may represent the loess surfaces exposed for a longer period of time (days, weeks) to gradual sedimentation of predominantly clay particles (sometimes associated with mica), which appear after storms or during periods of weak wind activity.

2. The lamination, caused by sheet erosion and deposition, snowmelt washing or by any overland water flow, is frequently observed in contemporary brickyards but it is rarely recognisable in the fossil record unless it contains an admixture of fluviatile materials such as rounded quartz gravel. Pellet sands often represent a special example of erosion lamination.
3. The lamination caused by frost creep, solifluction and gelifluction is often associated with weak glacial soils, especially by PK I soil (22 - 29 ka BP, Dolni Vestonice and elsewhere). Typically the lamination looks like a series of 30-100 varvae some 1-10 mm thick, where brown or rusty laminae are mixed with yellow loess laminae. The rusty colour is of epigenetic origin and it represents an originally more calcareous layer partly replaced by Fe-hydroxides coming from a more acidic environment within the surface layer.

We consider these observations to be the most important from the Pleistocene paleometeorological point of view:

- There were at least some periods when the wind pattern during ice ages corresponded to the Holocene pattern of North Atlantic Oscillation (NAO).
- The wind velocity seems to oscillate between two basic regimes – I. steady low velocity NW, W and WE winds; II. stormy, high velocity windy episodes that were many times repeated.

The extent of continental glaciations

The problem of the study of continental glaciation in terrestrial condition is that the new glaciation wipes out the evidence of past glaciations. The extent of past glaciations can be estimated from the geomorphological studies. It is indicated by glacial landforms such as morraines, glacial features – roche moutonneé, striations and sediments such as tills or tillites. The glacial landforms can be found only as the small and rare forms in Krkonose (Giant Mts. – N part of republic), Sumava (SW part) and Hruby Jesenik Mts. (Silesia – NE part) at the heights aprox. 700 m a.s.l. or higher. We therefore suppose the existence of several small (1,5 km or less) mountain glaciers during Pleistocene. No glacial bedrock striation caused by thick continental glaciers was ever reported from the area of Czech Republic.

The 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 Czech Republic:

1. Silesia (a region close to Poland) where the flat ter rain enabled the advance of at least two glaciers (Elster and Saale glaciations) some 20 km into the Czech Republic.
2. Liberec region (N part of republic) where the continental glacier transported abundant erratics and fine grained sediments several km into Bohemian interior.

In both cases we are not even sure if the continental glacier have crossed the boundaries of Czech Republic or if the sediments represent out-wash material of nearby glacier. The absence of morraines and the presence of erratic boulders (especially in Silesia region) point to both proposed solutions.

The permafrost distribution

The different periglacial phenomena are reported from the area of Czech Republic – sorted soils, stone glaciers, nivation cirques, solifluction tongues etc. The problem of permafrost was discussed mostly on theoretical level by many authors (Czudek 1997) without arriving to any final solutions. The deepest level of permafrost as evidenced by microfracturing and plastic deformation is reported from Blahutovice borehole (Silesia region) – 220 m. However the site is located nearby the limits of continental glacier and developed in medium soft shales. The maximal estimate for permafrost thickness is given by Demek (1976) – 300 m. Because very few of these estimates are established on the field observation and because they are mostly concerned with localities developed along the limits of glaciation, we expect that permafrost in the interior of Bohemia could develop as in time and space discontinuous layer some 50 - 100 m thick (or less). Not only the crystalline complexes of Variscan Bohemian Massif but also even the Upper Cretaceous sandstones do not display any enhanced microfracturing that can be attributed to the permafrost action. Microgelivation can be observed in some sandstone areas to cause the formation of rockshelters, small caves and 1 – 2 m thick vertical fissures filled with loose sand.

A5-3.2 Holocene period

The detailed research of the Holocene – mostly calcareous slope sediments, tufa bodies and soil sequences – conducted during several last decades on numerous profiles lead to the collection of a large set of climatic and environmental proxies. The most useful summary of such study seems to be the precipitation and temperature curves constructed for the whole Holocene and regionally based on the network of about one hundred sites scattered over region of the Czech and Slovak republics Lozek et al, 1995).

The curves are constructed by the combination of two principal sources of fossil record:

- paleoenvironmental and paleoclimatic malaco-stratigraphic evidence
- sedimentological approach expressed mainly as calcium-carbonate metabolism – it means as the rate of carbonate leaching or precipitation in soil profiles, karst sediments and spring limestones.

Independent lines of evidence such as palynological data (Firbas 1935, Krippel 1986) and archaeological finds (Bouzek 1993) were taken into account.

The dating of the curves represents a special problem since a limited number of radiocarbon data is available for the studied area. Especially the exact position of dry phases during the Epiatlantic, indicated by soil horizons in tufa bodies, is estimated from the sedimentation rates. The ages expressed in calendar years were mostly obtained by the archaeological finds correlated with the established chronologies. We expect that minor dating shifts may take place but relative chronology is reliably established.

The sensitivity and time resolution varies according to the kind of fossil record. While the karst sediments and slope series provide long continuous record since the Late Glacial to Recent, they can seldom serve to distinguish shorter periods than several centuries. The tufas and other spring limestones yield a more detailed resolution, since the total thickness of freshwater limestones deposited during several thousands years, may exceed 10 m. On the other hand, the tufas are usually limited to either Late Glacial to Boreal, or Atlantic-Subatlantic periods ended by intensive down cutting during the Late Boreal or Subatlantic.

The growing impact on the landscape during the last several thousand years causes the deterioration of the climatic signal. Therefore, other proxies such as the abundance of dated prehistoric grain-pits along riverbanks, the settlement density the development of lacustrine sites (Pfahlbauten) must be taken into consideration. The further development in this field is by no means definite since any paleoclimatic curve – and this is no exception – is subject to further modifications and adding new details according to the new evidence from previously unknown sources.

Environmental changes of the Mid-European Holocene were many times described in detail (Lozek 1973). There exists a set of Holocene sites in Czech Republic where complex biostratigraphic research was carried mostly on the basis of malacostratigraphy or pollen analysis. The basic disadvantage of the majority of the studied sites (about 150) is the lack of radiocarbon dates, indirect datings established on the base of fossil assemblages and archaeological finds and low resolution of fossil record (centuries). The regional patterns of Holocene sedimentation, detailed paleontology and reasonable sedimentology of some sites, enables on the other hand to obtain a reliable general picture of Holocene development, including erosional phases (aprox. 6000 years BP, 2000 years BP, 14th century), soil formation, gradual environmental decalcification, forest-grassland changes and some other aspects.

From the point of view of this study the humidity changes and thus groundwater circulation seem to be more important than e.g. beech forest formation during Atlantic in the places of former oak forest.

A5-3.3 Summary

- The area of the Czech Republic was not covered by continental ice sheet even in most extensive glacial periods.
- The area was influenced by continental ice sheet from north and simultaneously by Alpine mountain ice sheet from south.
- In glacial periods permafrost (grassland) came into existence with uneven distribution. The islands (forest refugia) of more temperate vegetation were also present – supporting indications of rapid spreading of vegetation in integlacials.
- Classical division of Holocene period (Pre-boreal, Boreal, Atlantic, Epiatlantik, Subatlantic, Subrecent) is valid for area of the Czech Republic. Both marine and continental influences formed climate.
- Currently anthropogenic environment is prevailing only with islands of natural ecoystems.

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For further information contact:

BIOCLIM project co-ordinator, **Marianne Calvez**

ANDRA, DS/BE

Parc de la Croix Blanche - 1/7, rue Jean Monnet - 92298 Châtenay-Malabry Cedex - FRANCE
Tél.: +33 1 46 11 83 10
e-mail: marianne.calvez@andra.fr
web site: www.andra.fr/bioclim/