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IAEA-TECDOC-1904

Development of a Common Framework for Addressing Climate and Environmental Change in Post-closure Radiological Assessment of Solid Radioactive Waste Disposal

Report of Working Group 6
Common Framework for Addressing Environmental Change in Long Term Safety Assessments of Radioactive Waste Disposal Facilities
MODARIA Topical Heading Uncertainties and Variability

Modelling and Data for Radiological Impact Assessments (MODARIA) Programme

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DEVELOPMENT OF A COMMON FRAMEWORK FOR ADDRESSING CLIMATE AND ENVIRONMENTAL CHANGE IN POST-CLOSURE RADIOLOGICAL ASSESSMENT OF SOLID RADIOACTIVE WASTE DISPOSAL

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REPORT OF WORKING GROUP 6
COMMON FRAMEWORK FOR ADDRESSING
ENVIRONMENTAL CHANGE IN LONG TERM SAFETY
ASSESSMENTS OF RADIOACTIVE
WASTE DISPOSAL FACILITIES
MODARIA TOPICAL HEADING
UNCERTAINTIES AND VARIABILITY

MODELLING AND DATA FOR RADIOLOGICAL IMPACT
ASSESSMENTS (MODARIA) PROGRAMME

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FOREWORD

Models are essential tools for evaluating radiological impacts within the safety assessment process and for regulatory control of nuclear facilities and activities in planned, existing and emergency exposure situations. Modelling the fate of radionuclides in the environment and assessing the resulting radiation doses to people and the environment is needed, for example, in the evaluation of the radiological relevance of routine and accidental releases of radionuclides, to assist in decision making during remediation activities, in the framework of long term safety assessments of radioactive waste disposal facilities, and for clearance and exemption of material with low levels of radioactivity from the need of regulatory control.

The IAEA has been organizing programmes of international model testing since the 1980s. These programmes have contributed to a general improvement in models, in the transfer of data and in the capabilities of modellers in Member States. IAEA publications on this subject over the past three decades demonstrate the comprehensive nature of the programmes and record the associated advances.

From 2012 to 2015, the IAEA organized a programme entitled Modelling and Data for Radiological Impact Assessments (MODARIA), which concentrated on testing the performance of models; developing and improving models for particular environments; reaching consensus on datasets that are generally applicable in environmental transfer models; and providing an international forum for the exchange of experience, ideas and information.

Different aspects were addressed by ten working groups within MODARIA covering four thematic areas: remediation of contaminated areas; uncertainties and variability; exposures and effects on biota; and marine modelling. This publication describes the work of the Common Framework for Addressing Environmental Change in Long Term Safety Assessments of Radioactive Waste Disposal Facilities Working Group (Working Group 6).

The IAEA would like to thank to all those who participated in Working Group 6 of the MODARIA programme and gratefully acknowledges the valuable contributions of T. Lindborg (Sweden), Leader of Working Group 6, and M. Thorne (United Kingdom), as well as the organizations that hosted Working Group interim meetings, namely, the Swedish Nuclear Fuel and Waste Management Company, the University of Bristol (United Kingdom) and the Research Centre for Energy, Environment and Technology (Spain). The IAEA officers responsible for this publication were G. Proehl and J. Brown of the Division of Radiation, Transport and Waste Safety.

CONTENTS

SUMMARY

This report describes the work undertaken by Working Group 6 (WG6) of the IAEA's MODARIA programme regarding the development of a common framework for addressing climate and environmental change in post-closure radiological assessment of solid radioactive waste disposal. More specifically, the overall objective of WG6 was to further develop the understanding and possible implications of how the biosphere may change from the present into the far future in a wide range of regional and local contexts relevant to the disposal of solid radioactive wastes.

This overall objective was addressed by undertaking the following activities:

— Identifying the key processes that drive environmental change (mainly those associated with climate and climate change), and describing how a future relevant to the timescale of radioactive waste disposal safety assessments may develop on a global scale. Existing scientific consensus on global historical climate evolution can be used to quantify the processes. The results can be used to describe possible future environments; these are not predictions, but relevant examples that provide valuable input for addressing specific issues in a safety assessment.
— Developing a conceptual methodology for environmental change that is valid on a global scale, and showing how that can be downscaled to provide information that may be needed for site specific safety assessments.
— Illustrating the application of different aspects of the methodology to a number of case studies (sites) that show the evolution of site characteristics and the implications for dose assessment models, including the justification of abstraction into simplified assessment level models. This was intended to address: (a) changes in the potentially affected environment prior to any assessed radionuclide release to the biosphere; and (b) changes occurring after or while releases are assessed to occur, including possible transient effects that may be relevant to resulting potential doses.

Working Group 6 has developed a methodology that can be presented as a step-by-step process addressing the above issues, as illustrated in the road map (Figure 1) below. The first two steps define the context in which climate change and landscape development need to be addressed.

The type of facility (e.g. near surface or geological) and its location (e.g. coastal or inland) defines the types of landscape changes and processes that are likely to be the most important. The types of waste disposed, e.g. predominantly short lived or long lived, influence the timescale of any possible radiological impact, but other factors may also need to be taken into account, e.g. regulatory guidance on the timescale over which an assessment is required and the likely durability of waste packaging in containing radioactivity and isolating it from the biosphere. The timescale of assessment may also be influenced by consideration of the maximum duration over which the evolution of the disposal system can reasonably be quantified. The timescale, as influenced by these factors, also helps to determine the types of landscape changes and processes that are most likely to materially affect the dose assessment.

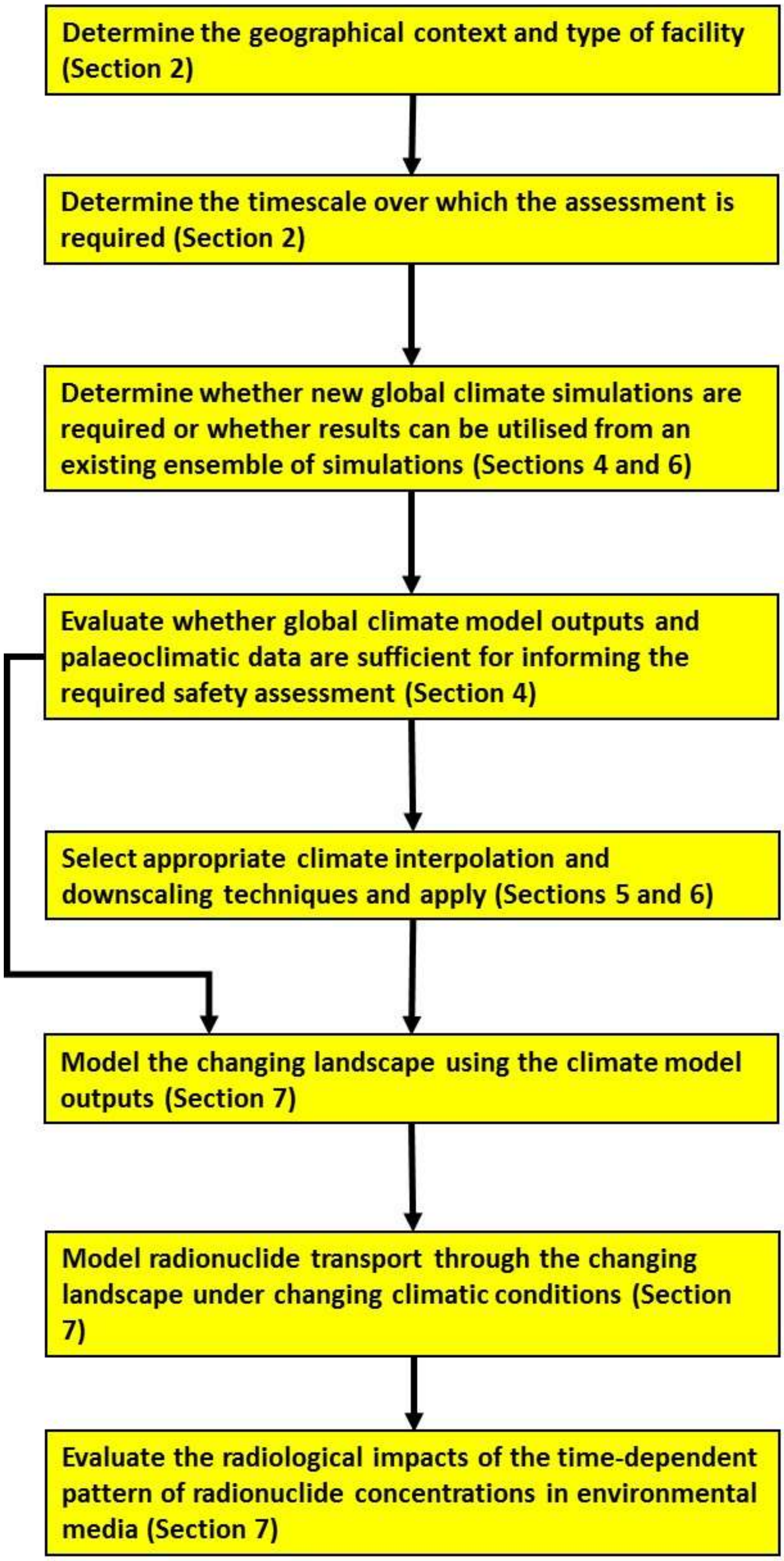

FIG. 1. Road map for performing an assessment taking climate change and landscape development into account.

Having defined the timescale that the assessment has to address, consideration needs to be given to establishing potential future patterns of development of the climate at the site or within a broader region where a facility may be developed. It is recognized that not all assessments will require detailed or continuous projections of climate. For example, an assessment may be based on the identification of a limited number of fixed climate domains (e.g. temperate, periglacial and glacial) and performing assessment calculations for each of those domains either separately or as a stylized sequence. Whichever approach is adopted, an overall narrative of potential future climatic changes is required to justify the selection of particular sets of conditions to be studied in a quantitative assessment process. Thus, the first issue to address is how to obtain long term projections of future climate.

Climate change is intrinsically a global phenomenon and projections of future climate are necessarily made using global models of the climate system. Such projections depend upon the assumptions made as to future patterns of release of greenhouse gases, notably carbon dioxide, and aerosols. For example, the Intergovernmental Panel on Climate Change (IPCC) reports were used as input to the Working Group activities. A range of possible scenarios for long term forcing of the climate system by carbon dioxide is investigated in the WG6 study. This range provides a context within which models of long term climate change may be employed.

To capture the effects of both conceptual and parametric uncertainty in model projections under particular forcing conditions, ensembles of climate model simulations can be utilized. However, the undertaking and scrutinizing of such simulations is a very resource intensive activity. It is, therefore, considered good practice by the Working Group that when climate change is being addressed for radiological safety assessments, a decision is made on whether the assessment under consideration requires new global model climate simulations or whether the results from existing ensembles of climate simulations can be acquired and utilized.

Various types of climate model may be used in making projections of future climate on a global basis. These include the more detailed Atmosphere–Ocean General Circulation Models and Earth System Models that additionally include the representation of biogeochemical cycles. Alternatively, simplified models may be used, as may be appropriate for making longer term projections. Whichever global models or combinations of models are used, the climate outputs provided will be at a coarse spatial scale, currently typically 100 km or more, compared with the extent of a typical repository site of potential interest. If a safety assessment only requires a broad overall projection of future climate changes, then the lower spatial resolution of the climate model may not be an important consideration. Thus, for example, such low resolution output may be sufficient to establish an associated succession of broadly defined climate domains at a site, together with estimates of the approximate duration of each. Alternatively, results may be used to inform simulations of time dependent future climatic conditions at similar grid scales using a climate emulator. Such an emulator permits a set of 'snapshot' climate simulations to be used to construct a projected continuous narrative of climate change (i.e. a scenario), but does not, intrinsically, improve upon the spatial resolution of the underlying climate simulations used in its development.

If more spatially detailed projections of climate need to be considered, then downscaling of the results from global climate models is necessary. Three broad approaches to downscaling are available: dynamical, physical–statistical and rule based, each having advantages and disadvantages. On the basis of this information, identification can be made of the approach or combination of approaches to be used to inform the landscape development and radiological impact modelling to be undertaken in subsequent stages of the assessment process.

Climate data taken directly from the outputs of global climate models or obtained by downscaling those outputs are principal inputs to landscape modelling. Landscape models may apply at a variety of spatial scales, ranging from a domain with characteristic dimensions of a few kilometers up to many hundreds of kilometers. Ideally, the climate model outputs should be matched to the spatial scale defined by the landscape model inputs. Because there is a considerable commonality in climate models, it is meaningful to use the concept of ensembles of outputs from model simulations to quantify uncertainties. In contrast, although there may be some commonalities in landscape modelling for sites located in similar geographical contexts, in practice landscape models will generally need to be tailored to the particular location and repository concept under consideration.

After conceptual or quantitative models of climate and landscape change have been developed, consideration can be given to representation of radionuclide transport within that time varying framework. It is emphasized, however, that although the climate and landscape may be considered to show a continuous pattern of development, it may not be necessary to represent radionuclide transport in a continuously varying framework. Instead, it may be possible to bound the range of impacts that can occur by selecting a limited number of time independent calculation cases representing ‘snapshots’ of environmental conditions at different times. Illustrations are provided in the report of how landscape modelling may be used to inform radionuclide transport modelling and how uncertainties in landscape modelling may be propagated into the radionuclide transport modelling.

The output from radionuclide transport modelling is a time varying pattern of the distribution of radionuclides in environmental media. On the basis of this distribution, calculations can be made of potential radiation dose rates to humans and non-human biota and these compared with relevant safety criteria. Such radiological impact modelling is a mature discipline and developments in this area in the context of long term releases to the biosphere from radioactive waste repositories have been explored internationally in the IAEA Environmental Modelling for RAdiation Safety (EMRAS) II programme and within the BIOPROTA forum[1].

The use of a traceable and systematic approach for making projections of long term climate and landscape change, based on the latest scientific understanding, helps to build confidence in the resulting safety and performance assessments. The road map developed within WG6 has drawn on experience and expertise from a range of countries and contexts to establish an approach that may be applied to different radioactive waste disposal programmes. Indeed, updated projections of global climate for a wide range of different CO_2 emission scenarios provides a suite of global climate projections that may be used as a starting point for assessments, which encourages consistency in the treatment of long term environmental change across different national radioactive waste disposal programmes.

It can be concluded that quantitative long term climate modelling is sufficiently developed and robust to define the envelope of reference futures for use in safety assessments of radioactive waste repositories, as supported by understanding of palaeo–climatic conditions. Such models, however, do have limited spatial resolution and in some cases downscaling is necessary.

Quantitative modelling of landscape evolution and the linkage with climate modelling has been significantly developed in recent years but not for all potentially relevant climates and landscapes.

[1] www.bioprota.org

Illustrative results of simulations relevant to climate and landscape change have been prepared in the course of WG6 activities. It would be good practice for detailed results of simulations to be archived for potential use in subsequent assessments, possibly in a central archive.

It may be noted that while the focus of MODARIA is dose assessment, the methodology and results of WG6 may be valuable in a wider safety assessment context, e.g. for other types of facilities and sites.

1. INTRODUCTION

1.1. BACKGROUND OF THE MODARIA PROGRAMME

The IAEA organized a programme from 2012 to 2015, entitled MOdelling and Data for Radiological Impact Assessments (MODARIA), which had the general aim of improving capabilities in the field of environmental radiation dose assessment by means of acquisition of improved data for model testing, model testing and comparison, reaching consensus on modelling philosophies, approaches and parameter values, development of improved methods and exchange of information.

The following topics were addressed in ten working groups:

Remediation of Contaminated Areas

- Working Group 1: Remediation strategies and decision aiding techniques
- Working Group 2: Exposures in contaminated urban environments and effect of remedial measures
- Working Group 3: Application of models for assessing radiological impacts arising from Naturally Ocurring Radioactive Material (NORM) and radioactively contaminated legacy sites to support the management of remediation

Uncertainties and Variability

- Working Group 4: Analysis of radioecological data in IAEA Technical Reports Series publications to identify key radionuclides and associated parameter values for human and wildlife exposure assessment
- Working Group 5: Uncertainty and variability analysis for assessments of radiological impacts arising from routine discharges of radionuclides
- Working Group 6: Common framework for addressing environmental change in long term safety assessments of radioactive waste disposal facilities
- Working Group 7: Harmonization and intercomparison of models for accidental tritium releases

Exposures and Effects on Biota

- Working Group 8: Biota modelling: Further development of transfer and exposure models and application to scenarios
- Working Group 9: Models for assessing radiation effects on populations of wildlife species

Marine Modelling

- Working Group 10: Modelling of marine dispersion and transfer of radionuclides accidentally released from land based facilities

The activities and results achieved by the Working Groups are described in individual IAEA Technical Documents (IAEA-TECDOCs). This report describes the work of the common framework for addressing environmental change in long term safety assessments of radioactive waste disposal facilities Working Group.

1.2. BACKGROUND FOR MODARIA WORKING GROUP 6

For several decades it has been recognized that the safe performance of disposal facilities for radioactive waste has to be assured over multi-millennial time scales and that, over such timescales, significant changes in climate and the landscape are likely to occur. In the 1980s and 1990s, such changes were taken into account in biosphere modelling in various national programmes. In the late 1990s, an integrated approach to the justification, characterization and application of reference biospheres for use in post-closure radiological impact assessments was developed through the IAEA as part of the BIOMASS project. This resulted in a comprehensive reference biospheres methodology that was fully documented in a major report arising from the project [1].

The BIOMASS methodology explicitly recognized that it might be necessary to take climate and landscape changes into account in post-closure radiological impact assessments. It was observed that, if biosphere change is to be represented, then this might be done by simulating the consequences of radionuclides emerging into a set of unchanging biospheres, chosen to encompass the range of possible futures of interest [1]. However, it was also stated that additionally, or alternatively, one might wish to consider an inter-related sequence of biospheres, with the interest focused on the changes from one system to another [1]. These alternatives and their appropriate application in different circumstances were considered by WG3 of the IAEA Environmental Modelling for RAdiation Safety (EMRAS) II programme [2].

The BIOMASS report also reported on a number of Example Reference Biospheres (ERBs) that were developed as part of the project [1]. Three ERBs were developed relating to a temperate climate and unchanging biosphere conditions. All three were generic examples addressed in quantitative detail. The project also produced a further three ERBs that were used to illustrate the BIOMASS methodology for biosphere conditions that change with time. These examples considered two real locations and a generic site, but were only examined qualitatively.

Following BIOMASS, the European Union sponsored the international BIOCLIM project. This brought together climatic modellers and post-closure radiological impact assessment specialists to give detailed consideration as to how long term climate projections should be generated for, and taken into account in, post-closure radiological impact assessments. The BIOCLIM project refined the BIOMASS reference biospheres' methodology, giving detailed consideration to the development of conceptual models of both time independent states of the biosphere and of protracted transitions between those states. Illustrative applications of the methodology were reported, relating to Lowland Britain, the Meuse/Haute-Marne region of north-east France, central Spain, north Germany and the Czech Republic [3].

Subsequent to BIOCLIM, further work on incorporating climate and landscape change into post-closure radiological impact assessments has largely been undertaken within the framework of individual national programmes (see, e.g. Section 7 and Appendix I of this report). In addition, a project within the international BIOPROTA programme[2] has addressed climate change and landscape development in terms of their effects on the transition zone between the geosphere (i.e. the solid geology within which the engineered facility will be located) and the superficial biosphere. This zone is typically described as the Geosphere–Biosphere Interface, though it is actually a spatially extended three dimensional (3-D) zone extending from some

[2] http://www.bioprota.org/

depth in the solid rock up to close to the surface of the soil/sediment system[3]. This project, reported in Ref. [4], made use of the BIOMASS [1] and BIOCLIM [3] methodologies, expanded upon them and applied the approach to the Geosphere–Biosphere Interface rather than restricting it to the biosphere as conventionally defined in post-closure radiological impact assessment studies. However, no new climate modelling was undertaken in that project and only a limited review was undertaken of research activities related to the modelling of landscape development. Thus, whereas individual national programmes have included substantial research and assessment activities relating to climate change and landscape development, in the decade since the BIOCLIM work was completed, this work has not previously been brought together at an international level. It was this consideration that led to the formulation of the work programme for MODARIA WG6, as outlined below.

1.3. OBJECTIVES AND SCOPE OF MODARIA WORKING GROUP 6

MODARIA WG6 had the remit of developing a common framework for addressing climate and environmental change in post-closure radiological assessments of solid radioactive waste disposal. The intention was to be inclusive of a wide range of disposal facility types. More specifically the overall objective of WG6 was to further develop the understanding of how the biosphere may develop from the present into the far future in a wide range of regional and local contexts relevant to the disposal of solid radioactive wastes. This overall objective was addressed by undertaking the activities covered by the bullet points in the Summary Section above.

1.4. APPROACH TO THE PROJECT AND OUTLINE OF THE REPORT

1.4.1. Approach

As discussed in Ref. [1], landscapes change as a result of alterations in climate, the effects of human activities including alterations in uses of the land, internal Earth processes, such as uplift and external factors, such as meteorite impact. Setting aside external factors, which generally have very low frequencies of occurrence and are either neglected in long term safety assessments or are treated schematically in separate analyses, the remaining factors require further consideration in developing a suite of scenarios appropriate to analysing the long term radiological impacts of proposed or existing disposal facilities.

Human activities may directly impact the disposal facility, e.g. through the drilling of deep boreholes or through underground excavations. The implications of such activities are usually explored in distinct human intrusion scenarios. As such activities could occur as soon as knowledge of the nature and location of the facility has been lost, their impacts are typically evaluated in the near future, before substantial decay of the longer lived radionuclides present in the disposal facility has occurred. This approach results in cautious estimates of the radiological risks arising, but also means that consideration of long term changes in the landscape are a secondary consideration. An important exception may be made for facilities located offshore, where changes in sea level due to land uplift over the next few hundred or few thousand years may lead to emergence of the area above the disposal facility and hence a greater potential for intrusive activities.

Human activities may also have a significant impact on the surface landscape, e.g. through urbanization or changes in agricultural practices. Although such changes are not necessarily

[3] In some cases, this may extend to the surface and include the surface hydrological system.

linked to climatic changes, they are often conditioned by climate to some degree. Similarly, although some intrinsic Earth processes are independent of climate, e.g. tectonic uplift due to the presence of a body of lower density rock at depth in the crust, there is often a close and reciprocal relationship between Earth processes and climate change. Thus, for example, uplift leads to an increase in topographic relief, which in turn affects both the local climate and the erosional regime. On a shorter timescale, global and regional changes in climate can lead to the advance and retreat of ice sheets. Increasing ice load leads to depression of the crust and recovery from this depression requires a period of many thousands of years after the ice has retreated.

In general, the timescales of relevance in post-closure radiological impact assessments of radioactive waste disposal facilities range from a few thousand up to about 1 million years [2, 5]. Over these timescales, climatic conditions and changes in climate are considered to be the principal factors determining the development of the landscape that overlies a disposal facility. Land uses and land use changes are considered to be conditioned by climate, but not fully determined by it, so various alternative patterns of land use may need to be examined within a particular climatological context. On these timescales of interest, Earth processes are considered to be mainly responsive to climate rather than being drivers of climate change [1]. Based on these considerations, the focus of the work described in this report has been on making projections of future climatic conditions at global, regional and local scales and analysing their potential implications in terms of landscape development. This has been done for illustrative locations at which disposal facilities exist or are proposed and for broader regions within which such facilities might be sited in the future.

This work builds on international collaborative activities undertaken within the BIOMASS [1], BIOCLIM[4] and BIOPROTA[5] projects. These projects brought together experts on solid radioactive waste disposal and relevant environmental sciences from a wide variety of countries. In particular, the BIOCLIM project involved close collaboration between experts in solid radioactive waste disposal and experts in climatology. The latter included specifically, specialists in the development of global and regional mathematical models of the climate system and their application in making long term projections of potential patterns of future climate change, as well as experts in palaeo–climatic reconstructions that are relevant to the validation of such models.

In common with these previous projects, MODARIA WG6 comprised specialists in assessing the safety of solid waste disposal. Many of these specialists are employed by national organizations tasked with developing and operating disposal facilities and other organizations concerned with their regulation. In addition, participants applied their specialist knowledge of climatology, geomorphology, hydrogeology and other relevant environmental sciences. In addition, the individuals who participated in WG6 were able to draw on a wider body of knowledge and experience from their institutions and from research organizations funded by those institutions. Interim WG6 meetings in between the annual meetings held each year at the IAEA in Vienna were hosted by Svensk Kärnbränslehantering AB (SKB) in Stockholm, Sweden in 2013, by the University of Bristol, UK, in 2014 and by the Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) in Madrid, Spain, in 2015.

[4] http://www.andra.fr/bioclim/
[5] http://www.bioprota.org/

1.4.2. Report outline

Section 2 characterizes the types of facility that are of relevance. These include near surface facilities that may be more vulnerable to landscape change and deeper facilities that are to some degree isolated from such change by the overlying strata. This leads to a classification of types of facilities that are of potential relevance and the selection of a set of illustrative sites and regions to which the methodology developed in this study has been applied.

Section 3 provides background on the processes that affect climate on different timescales. These timescales vary from less than one year to billions of years. However, on a timescale of thousands up to a few million years (about the limit of consideration for post-disposal safety assessment identified above), the primary controls are the amount and distribution of solar radiation (insolation) incident at the top of the Earth's atmosphere and the concentrations of greenhouse gases and aerosols in the atmosphere. Insolation is determined by the orbital characteristics of the Earth: the eccentricity of the orbit, the inclination of the axis of the Earth and the orientation of the axis when the Earth is at different distances from the Sun. These various orbital elements can be calculated quite precisely for the last few million years and also for the next few million years. Therefore, this factor controlling climate change is well determined, both in the context of simulating past climates and in the context of projecting future climates. In contrast, atmospheric greenhouse gas and aerosol concentrations fluctuate substantially due to a variety of natural causes. Furthermore, in the last two hundred years, in addition to changes in anthropogenic aerosol concentrations, there has been an increasing trend in the concentration of carbon dioxide in the atmosphere due to the emission of this gas from the combustion of fossil fuels, as well as due to land use changes throughout the world. At the present day, this increase is continuing at a faster rate than ever before and a wide range of scenarios has been proposed for how emissions may vary in the future, with associated implications for how atmospheric concentrations may change timescales from decades to hundreds of thousands of years.

Once future changes in insolation, and greenhouse gas and aerosol concentrations, have been specified, it is possible to use a wide variety of types of climate model to simulate future climates. The various models that are available are reviewed in Section 4.1. Most operate at a global scale, but some are specifically used at a regional scale. The regional models typically take their boundary conditions from the global models and are used to downscale results obtained at resolutions ranging from 100 km or more, down to 10 km or less.

Climate models have largely been used for projecting climate changes over the next 100 years [6]. This is clearly a priority for defining the magnitude of changes that will have an impact on society over the next few generations. Many different climate models have been applied to this period, so that appropriate account can be taken of both conceptual uncertainties (expressed through the rather different structures of the various models) and data uncertainty (expressed through the use of ranges of parameter values to quantify key aspects of each of the models). Thus, in making projections of future climate, reliance is now placed on ensembles of model simulations rather than the results from a specific model run with a particular set of parameter values. It is emphasized that the projections should not be considered as predictions, since alternative scenarios for greenhouse gas and aerosol emissions have very different climatic consequences and there is also the potential for geoengineering approaches to limiting the impact of greenhouse gas emissions.

Although the main emphasis has been on making climate projections for the next 100 years, there is now increasing interest in making projections on longer timescales, since many impacts, such as those arising from the loss of mass of ice sheets and sea level rise, will be expressed on these longer timescales. Specifically, releases of greenhouse gases and aerosols on decadal timescales may exhibit their most significant impacts on millennial timescales. The latest generations of detailed climate models are capable of making time dependent simulations out to a few thousand years after present and they are being increasingly deployed for this purpose. This timescale is sufficient to be of interest in some solid radioactive waste disposal contexts. However, in other contexts, timescales of up to a few million years are of interest and these cannot be directly simulated using such detailed models. However, simplified models (Earth Models of Intermediate Complexity – EMICs) are available that can be applied over such timescales and climate emulators can be used to combine snapshot studies of alternative climatic conditions to provide continuous descriptions of long term climate change over timescales of hundreds of thousands of years. Over the longest timescales, if greenhouse gas and aerosol concentrations can be assumed to have decreased to pre-industrial levels, it is reasonable to use palaeo–environmental reconstructions of climate at a local or regional scale to provide a basis for post-closure radiological impact assessments. The identification of various potential future, time dependent patterns of atmospheric greenhouse gas and aerosol concentrations are discussed in Section 4.2. Section 4.3 describes projected patterns of future climate evolution to 2100 Anno Domini (AD) (Section 4.3.1), out to 10 thousand years (ka) AP (Section 4.3.2), out to 100 ka AP (Section 4.3.3) and beyond 100 ka after present (AP) (Section 4.3.4). These timescales correspond to the IPCC projections, the limiting timescale for detailed modelling (and also the duration of a typical interglacial period), the typical timescale for EMIC modelling (and also the characteristic duration of a glacial–interglacial cycle), and the timescale over which increased reliance can be placed on palaeo–climatic reconstructions, respectively.

Regional climate models (RCMs) can be embedded in global climate models to give climate projections at spatial scales of down to 10 km or less (dynamical downscaling). However, two alternative classes of downscaling approach are also available. The first of these can be broadly characterized as a physical–statistical approach, where regression techniques are used to relate outputs from global climate models to local climatic variables, with the variables used and regressions adopted being conditioned by physical arguments, e.g. in respect to how climate is affected by degree of continentality, altitude and aspect. The second is a rule based approach, in which outputs from global climate models are used to identify climate stations with long instrumental records that can be used as analogues for the site of interest under future climatic conditions. The various types of downscaling approach are described in detail in Section 5.

Through application of the models described in Section 4 and the downscaling techniques set out in Section 5, patterns of future climate at a site, or in a region, of interest can be described. The climatic characteristics, e.g. time series of temperature and precipitation, defined at both regional and local scales can be used to force a model of landscape developments. Landscape modelling is the topic of Section 6. In high latitudes, cold region phenomena can play a particularly important role in landscape development. Beyond the margins of the continental ice sheets, frozen ground effects (including permafrost development) may constitute a fundamental control on hydrogeology and hydrogeochemistry, whereas the advance and retreat of an ice sheet across a site may result in substantial erosion in some areas and deposition in others, as well as causing substantial depression of the Earth's crust and inducing a subglacial hydrological regime with patterns of groundwater flow that are very different from those observed in temperate or periglacial conditions. In lower latitudes or under greenhouse gas induced global warming, desertification may be the primary consideration, with the concomitant changes in the erosional and hydrogeological regimes. Elsewhere, altered patterns of drainage and fluvial incision may be the predominant factors, whereas, at the coast, the effects of sea level changes on coastal erosion may be important.

By the end of Section 6 an overall picture is available of potential future patterns of climate change, and of how these patterns of climate may affect landscape development at illustrative sites and in illustrative regions. In Section 7, consideration is given to how these changes in climate and landscape will influence the transport of radionuclides from disposal facilities to the biosphere, their subsequent distribution and impacts on human health and the environment. As with the climate models discussed earlier, the significance of both conceptual and parameter value uncertainties is explored though analyses related to the illustrative sites. The studies reported in Section 7 are used to evaluate implications for future radiological impact assessment modelling and for enhancing confidence in the results of such assessment modelling.

Overall conclusions from the study and advised areas for future work are set out in Section 8. Appendix I describes site specific experience of development and application of climate change narratives.

1.4.3. Road map of the proposed methodology and guidance on how to use this report

Based on the work undertaken in this project, an overall methodology for taking climate changes and landscape development into account in post-closure radiological impact assessments of disposal facilities for solid radioactive wastes is proposed. That methodology is summarized in the road map for assessments shown in Figure 1 (above), which also lists the sections of the report where each aspect of the methodology is discussed. In several of the following sections of the report, the road map shown in Figure 1 is reproduced, highlighting the particular aspect or aspects that are considered in detail in that section.

The first two steps of the road map define the context in which climate change and landscape development need to be addressed. These steps are covered in detail in Section 2. In broad terms, they are two aspects of defining the overall assessment context, as discussed in Ref. [1]. The type of facility (e.g. shallow or deep, coastal or inland) defines the types of landscape changes and processes that are likely to be of predominant importance. The types of waste disposed, e.g. predominantly short lived or long lived, influence the timescale over which an assessment is required, but other factors may also need to be taken into account, e.g. regulatory guidance on the timescale over which an assessment is required and the likely durability of waste packaging in achieving isolation of the wastes from the biosphere. The timescale, as influenced by these factors, also helps to determine the types of landscape changes and processes that are likely to be of predominant importance. However, it is also possible that the timescale of assessment may be influenced by consideration of the maximum duration over which the development of the disposal system can reasonably be quantified, with a more general requirement to demonstrate that radiological impacts are not likely to increase substantially beyond that timescale.

Having defined the timescale over which an assessment is required, consideration needs to be given to establishing potential future patterns of development of the climate at the site or within a broader region where a facility may be developed. It is recognized that not all assessments will require detailed or continuous projections of climate. For example, an assessment may be based on the identification of a limited number of constant climate domains (e.g. temperate, periglacial and glacial) and performing assessment calculations for each of those domains either separately or treated as a stylized sequence. Nevertheless, an overall narrative of potential future climatic changes is required to justify the selection of particular sets of conditions to be studied in the quantitative assessment process. Thus, the first issue to address is how to obtain long term projections of future climate.

Climate change is intrinsically a global phenomenon and projections of future climate are necessarily made using global models of the climate system. Such projections depend upon the assumptions made as to future patterns of release of greenhouse gases, notably carbon dioxide and aerosols. In Section 4.2, a range of possible scenarios for long term forcing of the climate system by carbon dioxide is investigated. This range provides a context within which models of long term climate change may be employed.

To capture the effects of both conceptual and parametric uncertainty in model projections under particular forcing conditions, ensembles of climate model simulations can be utilized. However, the undertaking and scrutinizing of such simulations is a very resource intensive activity. It is, therefore, advisable that assessment groups decide whether the assessment under consideration requires new global model climate simulations or whether the results from existing ensembles of climate simulations can be acquired and utilized. If assessment groups identify that new simulations are required, it is also advisable that results of those simulations should be archived for potential future use in subsequent assessments. Indeed, a central archive of the results of such simulations could be an important international resource and further thought could be given to the implementation of such an archive.

Various types of climate model may be used in making projections of future climate on a global basis. These comprise the more detailed Atmosphere–Ocean General Circulation Models (AOGCMs) and Earth System Models (ESMs) that include the representation of biogeochemical cycles. Alternatively, simplified models, such as EMICs, may be used for making longer term projections. The roles of these various types of model in making climate projections for assessment purposes are discussed in Section 5. However, whichever global models or combinations of models are used, the climate outputs provided will be at a rather coarse spatial scale, currently typically 100 km or more. If all that is required for safety assessments is a broad overall projection of future climate changes, then the low spatial resolution of the results may not be an important consideration. Thus, for example, such low resolution output may be sufficient to establish an associated succession of broadly defined climate domains at a site, together with estimates of the approximate duration of each. Alternatively, results from EMICs (including both atmospheric carbon dioxide concentrations and ice sheet configurations) may be used to inform simulations of future climatic conditions at AOGCM grid scales using snapshot AOGCM simulations within the framework of a climate emulator. This approach is explained in more detail in Section 4.3.4.

If more spatially detailed projections of climate are required, then downscaling of the results from global climate models will be necessary. Three broad approaches to downscaling are available (dynamical, physical–statistical and rule based). Section 5 describes the advantages and disadvantages of each of these approaches in different contexts. On the basis of this information, it should be identified which approach or combination of approaches is to be used to inform the landscape development and radiological impact modelling to be undertaken in subsequent stages of the assessment process. It is emphasized that assessment groups undertaking studies relating to different facilities may use the same sets of outputs from global climate models, but may place emphasis on different subsets of those outputs and may adopt different downscaling techniques depending upon the context in which the results are to be employed.

Climate data taken directly from the outputs of global climate models or obtained by downscaling those outputs are principal inputs to landscape modelling. Such models may apply at a variety of spatial scales, ranging from a domain with characteristic dimensions of a few kilometers up to many hundreds of kilometers. Thus, the climate model outputs will have to be matched to the spatial scale defined by the landscape model inputs. Section 6 describes the considerations that arise in selecting or developing landscape models. Because there is a considerable commonality in climate models (in terms of the processes modelled, the inputs required and outputs generated), it is meaningful to use the concept of ensembles of outputs from model simulations to quantify uncertainties. In contrast, although there may be some commonalities in landscape modelling for sites located in similar geographical contexts, in practice, landscape models will generally need to be tailored to the particular location and design concept under consideration. Thus, it will be for each assessment group to develop or adapt its own landscape model. Potential approaches to such development and adaptation are illustrated in the various specific illustrative applications and are also set out in Section 6.

Only when conceptual or quantitative models of climate and landscape change have been developed is it appropriate to give consideration to an appropriate representation of radionuclide transport within that time varying framework. It is emphasized that although the climate and landscape may be considered to show a continuous pattern of development, it may not be necessary to represent radionuclide transport in a continuously varying framework. Instead, it may be possible to demonstrate the range of impacts that can occur by selecting a limited number of time independent calculation cases representing 'snapshots' of environmental conditions at different times. Guidance on how landscape modelling may be used to inform radionuclide transport modelling and how uncertainties in landscape modelling may be propagated into the radionuclide transport modelling is given in Section 7. Discussion and conclusions are provided in Section 8.

The output from radionuclide transport modelling is a time varying pattern of the distribution of radionuclides between various environmental media. On the basis of this distribution, radiation dose rates to humans and non-human biota may be calculated and compared with compliance criteria. Such radiological impact modelling is a mature discipline and developments in this area in the context of long term releases to the biosphere from radioactive waste repositories have been explored internationally in the IAEA EMRAS II programme and within the BIOPROTA forum[6].

[6] www.bioprota.org

2. ENVIRONMENTAL CHANGE BASED ON THE CONTEXT OF DISPOSAL FACILITIES

This Section focusses on the first two steps in the methodological road map. Introduced in the Summary, the road map is repeated here and throughout the document to keep track of which parts of the road map is the focus of each section. This is done by highlighting the appropriate parts of the figure in blue as shown for the first two steps in Figure 2.

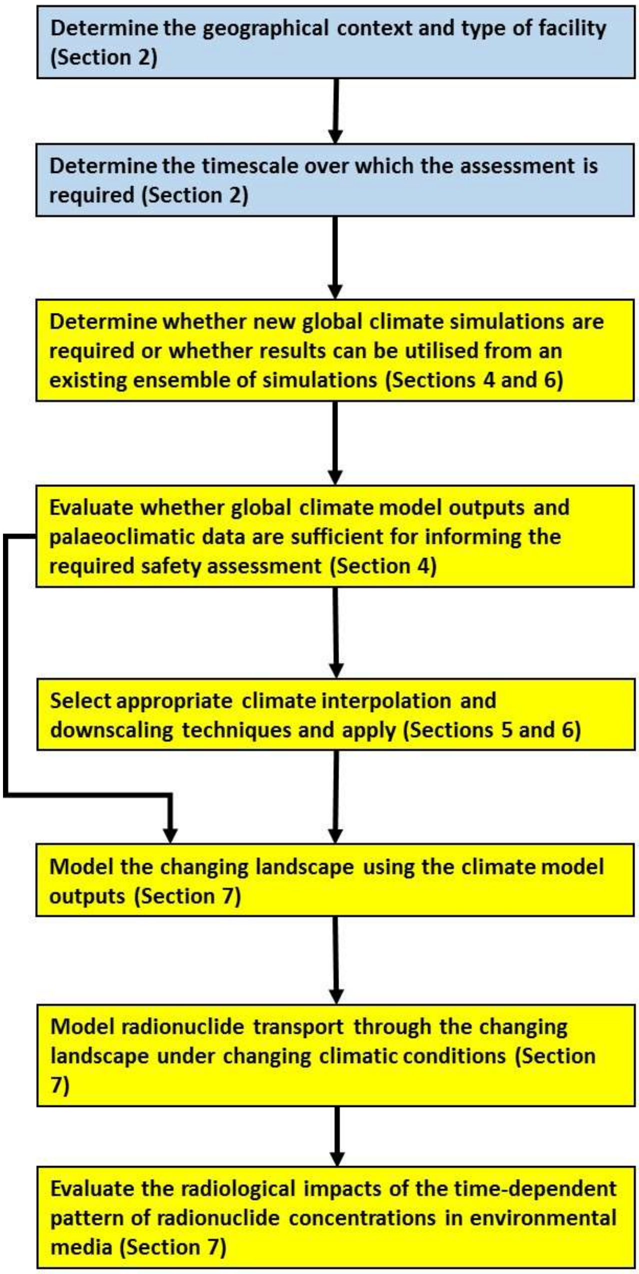

FIG. 2. Road map for performing an assessment taking climate change and landscape development into account.

2.1. CATEGORIES OF FACILITY

MODARIA WG6 was set-up to develop a common framework for addressing environmental change in long term safety assessments of disposal facilities for solid radioactive wastes. However, there are a wide variety of existing or planned facilities, and the ways that these are impacted by climate change and landscape development are likely to be substantially different. In order that a comprehensive common framework for addressing environmental change could be developed, these various categories of facilities needed to be identified and the different ways in which they may be impacted by environmental change needed to be characterized. In this report, a categorization scheme for various disposal facility types is proposed and some comments are made as to how the various categories of facilities may be impacted by environmental change. It is emphasized that the methodological approach set out in the remainder of this report is intended to be applicable across a wide range of different types of facilities that are characterized generically, as described in this Section. In a site specific context and in relation to a particular facility design, it would be appropriate to adapt and elaborate the methodology taking into account the detailed characteristics of the site and adopted design.

The general categorization scheme adopted is shown in Figure 3 below. The scheme does not include the type of radioactive waste to be disposed. This may clearly influence the type of safety assessment calculations to be undertaken, e.g. the timescale over which a quantitative assessment is required, but it will only be a secondary consideration in determining how environmental change will affect the facility on a specific timescale. Timescale is taken into account in the methodological approach proposed in Section 2.3 for identifying how the various types of facility may be impacted by environmental change.

2.1.1. Mode of construction

The distinction made is between facilities that are constructed in bulk excavations from the surface from those that are accessed by shafts or adits, with the excavation of the storage volumes occurring at depth. It is emphasized that facilities constructed in bulk excavations from the surface range from simple unlined pits and trenches through to highly engineered structures. Both El Cabril (Spain) and the Low Level Waste Repository (LLWR) (UK) are excavated from the surface, whereas the SFR (Sweden), the proposed KBS-3 repositories (Sweden and Finland) and the proposed Yucca Mountain repository (USA) are, or would be, excavated at depth. Borehole disposal, as described for example for deep boreholes in Ref. [7] and for less deep boreholes in Ref. [8], implies little or no further excavation below ground. The implications of climate change will depend largely on the depth of the borehole and depth of waste emplacement within it.

It should be noted that facilities excavated from the surface can have the wastes disposed entirely below grade, or they can have a waste stack that has its base below grade, but is sufficiently high that the top of the stack is above grade. Whether disposal is entirely or partly below grade, the waste stack would likely be covered by some form of cap that would typically form a dome or more complex mound structure rising above the general level of the ground. In some contexts, wastes may be disposed entirely above grade in an artificially constructed mound. While some aspects of the proposed methodology will be applicable to such facilities, it is recognized that these are predominantly engineered structures and that additional or substantially different considerations may apply. Similarly, some aspects of the methodology are likely to be applicable to contaminated sites, including waste dumps and pits arising from uranium mining, but it is emphasized that the approach has not been developed for contaminated sites and that it would need to be carefully scrutinized and adapted before being applied in such a context. Both EMRAS II WG2 and MODARIA WG3 specifically addressed the application of models for assessing radiological impacts arising from NORM and radioactively contaminated legacy sites, and the corresponding reports, respectively Refs. [9] and [2], may be consulted for further discussion. See also the results of related international discussion [10].

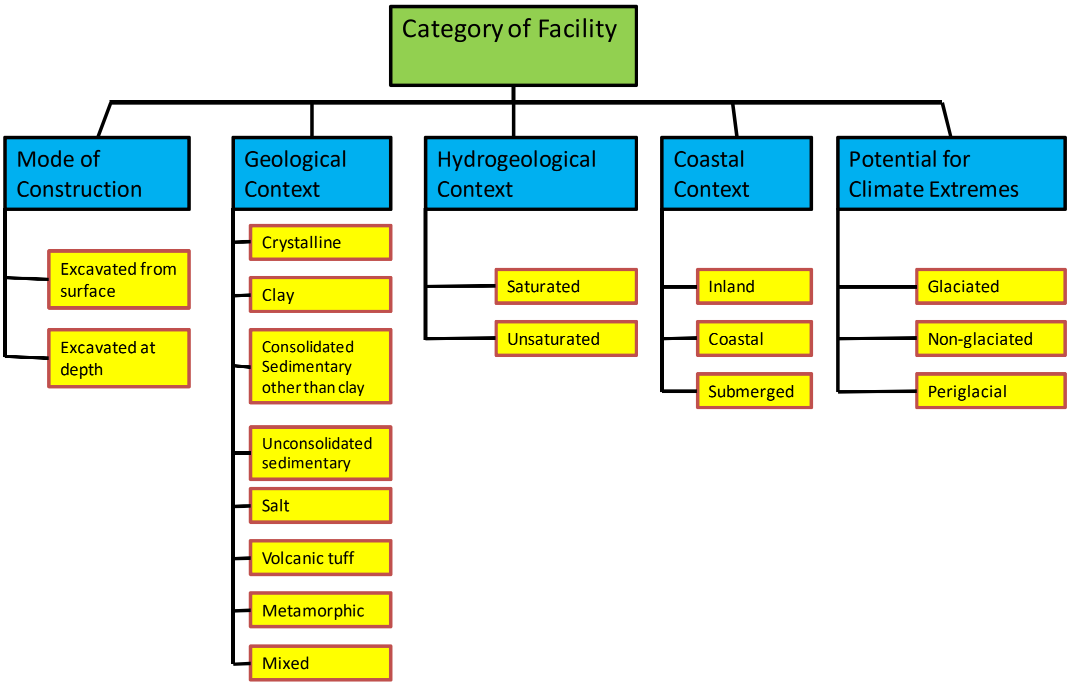

FIG. 3. Categories of facility.

2.1.2. Geological context

The primary consideration is the host geology. In some contexts, the same category of rock extends from repository depth to the surface, but there are other contexts in which a sequence of different types of formation is present. Such a sequence is described as mixed. In such systems both the host rock and the overlying rock may have safety related functions, but these will often be complementary and the two components of the sequence may be considered as distinct barriers in a multi-barrier concept. In general, salt (either bedded or as a dome or pillow) would be present in a mixed sequence, as it would be overlain by a cap rock preventing dissolution of the salt. However, as this is necessarily the case where the host rock is salt, this determines the categorization. Thus, the proposed repository in a salt dome at Gorleben (Germany) would be classified as 'salt' rather than 'mixed'. Sedimentary formations are distinguished into consolidated materials (e.g. sandstone) and unconsolidated materials such as many Quaternary sediments that have not been subject to a significant degree of post-depositional compaction. Clays are distinguished by their plasticity from harder rocks derived by consolidation of the same material, e.g. shales. Mudstones fall close to the boundary and might be classified either with clays or with other sedimentary rocks, depending on their local characteristics. Facilities that are excavated from the surface will typically be located in unconsolidated sediments, but this is not necessarily the case. Given the focus of this report, it will often be appropriate to focus on the upper part of the geological sequence overlying a deep disposal facility, since this is the domain that will be most directly impacted by climate change and landscape development.

2.1.3. Hydrogeological context

Here the distinction is between whether the repository is located above or below the regional water table. If it is located below the regional water table, it will eventually become saturated, though it may remain unsaturated for a considerable time after repository closure depending on the hydraulic conductivity of the host rock. A repository located above the regional water table will generally be unsaturated, though saturated regions may occur, e.g. due to perched water present in the local geological strata or ponding of water in the engineered structures. Thus, the El Cabril facility in Spain and the LLWR facility in the UK are near surface unsaturated facilities, the proposed Yucca Mountain repository would be an unsaturated facility excavated at depth and the proposed KBS-3 facilities are saturated facilities excavated at depth.

2.1.4. Coastal context

The current global sea level is within a few meters of the highest sea levels that have been experienced during the Quaternary and future sea level increases due to melting of ice sheets and thermal expansion of the oceans are likely to be less than 20 m (see Appendix A of Ref. [11], Thus, sites that are currently well inland are likely to remain so for the whole period for which quantitative assessment studies are required. In contrast, during glacial episodes, global sea levels have fallen to as much as about 120 m below their current position. A fall of this magnitude would result in much of the continental shelf becoming exposed. Thus, sites that are submerged at the present day may become coastally located in the future. However, these sites are classified as submerged for the purpose of this scheme. They would typically be located offshore, but accessed from land. The SFR facility in Sweden is an example of this type. Coastal facilities are located onshore, but at an elevation of less than about 20 m. Such facilities may be subject to processes such as coastal erosion and inundation, particularly under conditions of rising sea level due to anthropogenic greenhouse gas induced global warming. Additionally, alterations in sea level may affect the groundwater flow regime and change the distribution of salinity. For example, the position of the coastline may affect the location of the interface between terrestrial, meteorically derived groundwater and saline marine groundwater. At this interface, terrestrial meteoric water may be deflected upward to discharge in the immediate coastal zone. However, coastal facilities may also become protected from these processes if global sea levels fall or if there is local isostatic uplift of the land. The LLWR (UK) in West Cumbria is within a few hundred meters of the sea and is categorized as 'coastal' in this scheme. It is emphasized that the interplay of eustatic and isostatic changes in sea level is strongly dependent on the site under consideration. For example, eustatic sea level changes will differ substantially on a regional basis due to alterations in the geoid arising from changes in the distribution of the Earth's mass, e.g. from the loss or significant diminution of the Greenland ice sheet, and isostatic changes will be strongly dependent on the history of ice loading and unloading local to the site.

2.1.5. Potential for climate extremes

Here, the main distinction is between areas that have been subject to glaciation in the past (with the assumption that there is the potential in the future for further glaciations), those that were never glaciated but experienced subzero ground temperatures giving rise to periglacial processes, and those that were never glaciated nor experienced subzero ground temperatures giving rise to periglacial processes. In this context, 'glaciation' is defined to mean the occurrence of ice cover at the location of the facility. This distinction is made because glacial, periglacial and non-glacial processes have very different effects on the disposal system that is comprised of the engineered facility, host geological environment and overlying biosphere. Glacial processes include those originating from isostatic adjustment under the weight of the ice, erosion and deposition due to the advancing and retreating ice sheet, and those processes associated with the very active hydrological regime that exists below and at the margin of an ice sheet. In particular, the groundwater flow regime may have profound effects on groundwater chemistry down to depths of hundreds of meters, with implications both for the integrity of the engineered barriers of a facility and for the rate and pattern of radionuclide transport arising if those barriers are breached. Periglacial processes include enhanced solifluction, the formation and decay of ground ice, and gross changes in the hydrological characteristics of the regolith and underlying solid rock due to ground freezing. In non-glaciated regimes, fluvial and aeolian processes play a predominant role in reshaping the landscape. In principle, the non-glaciated regions could be further distinguished, e.g. into temperate, subtropical and semi-arid and arid regimes. However, the processes of relevance in these regimes are similar, though their rates may vary substantially, whereas both periglacial and glacial regimes are associated with suites of processes that do not apply in warmer climatic conditions. Furthermore, it is a consideration that many of the repositories that are currently being planned are located in areas subject to glaciation or frozen ground effects at some stage of the global glacial–interglacial cycle.

2.2. EVALUATION OF PROCESSES THAT COULD AFFECT DIFFERENT CATEGORIES OF FACILITY

As discussed in Ref. [1], there is a wide variety of external features, events and processes that could have an impact on different types of facility. These external features, events and processes include climate, human actions, Earth processes (such as those associated with orogeny) and meteorite impacts. The likelihood and magnitude of such impacts will be strongly determined by the type of facility under consideration. Furthermore, there are a large number of different types of facility that can be defined by combining the various characteristics shown in Figure 3 (above). However, of these only a few correspond to existing or proposed disposal facilities. Thus, rather than evaluating the processes relevant to all possible combinations, it is preferable to develop a methodology that allows those processes to be identified and evaluated for importance for any one selected combination. This is discussed below, taking each of the characteristics in turn.

2.2.1. Consideration of the mode of construction

For facilities located in surface excavations, various types of erosion are likely to directly impact the engineered facility as well as the host strata within which it is embedded. Furthermore, hydrological, hydrogeological and hydro–geochemical changes are likely to affect the engineered facility, the host strata and the surface environment. Therefore, it is appropriate to consider environmental change as acting upon the whole disposal system, rather than on the engineered system, host strata and biosphere separately. In contrast, for a system excavated at depth only the access routes, superficial geology and biosphere are likely to be directly affected by erosion, whereas hydrogeological and hydro–geochemical changes originating at or near the surface have the potential to be propagated downward to the engineered facility. Thus, in the analysis process, it is proposed that for facilities excavated from the surface, the impacts of environmental change should be evaluated for the disposal system considered as a single integrated whole.

For facilities excavated at depth it may also be appropriate to evaluate the impacts of environmental change on the disposal system considered as a single integrated whole. However, bearing in mind the consideration that the effects are likely to be directly expressed in the near surface environment and then propagated downward to the depth of the facility, it may be more convenient to first evaluate the impacts of environmental change for the near surface environment, typically down to a few tens of meters (though possibly somewhat deeper if permafrost is an issue), with the consequences of those changes then propagated to facility depth in a second step.

Whether the effects of environmental change on the disposal system are evaluated in a single step or in two steps, it is important that this evaluation is undertaken in an integrated, consistent way involving all the specialist disciplines associated with performance assessment, ranging from waste conditioning and repository design through to radioecology. It is also important that the potential impacts of future human actions on the disposal system are considered within, and as a factor influencing, the environmental changes that may affect the disposal system. The scope for and implications of future human actions resulting in direct disturbance of a radioactive waste disposal facility have been addressed internationally [12, 13].

2.2.2. Consideration of the geological context

The key processes affecting the disposal system will be strongly determined by the geological context. Some of the main considerations to be taken into account are set out below.

Crystalline rock is likely to be highly resistant to erosion, except in upland areas with steep slopes where rapid valley incision may be ongoing, but it may be subject to fracturing or fracture reactivation when subject to ice loading. However, some of the main considerations are likely to be propagation of hydrological and hydrochemical changes through the fracture system as a result of changing surface boundary conditions. Crystalline rock may be exposed at the surface or overlain by unconsolidated deposits of variable thickness and composition. These deposits will be subject to considerable development under environmental change (e.g. erosion, sedimentation, peat formation) and this will affect the hydrological and hydrochemical changes that are transmitted to depth.

If clay or mudstone is the host rock, it seems likely that the degree of propagation of hydrological and hydrochemical changes will be limited because of the low hydraulic conductivity of the medium. Also, for a deep repository in such a formation, timescales for the transport of radionuclides to the biosphere subsequent to their release from the engineered facility will be extremely long. Therefore, for both systems excavated from the surface and those excavated at depth, mechanical processes such as erosion may be of principal interest. However, for systems excavated from the surface, the hydrology and hydrochemistry of the engineered system may require particular consideration, since it may be isolated from the underlying and surrounding environment, but not from the surficial environment, by the surrounding clay.

For other consolidated sedimentary rocks, e.g. sandstone, limestone, chalk, mechanical processes such as erosion will affect and be affected by hydrological processes and hydrochemical processes, e.g. dissolution of chalk. For these rock types, detailed study may be required to determine whether any one set of processes dominates or whether various sets should be considered as closely coupled, exhibiting strong and possibly non-linear feedbacks between them.

Sedimentary systems also include unconsolidated deposits. These will generally be relevant to facilities excavated from the surface. As in the case of clay or mudstone, mechanical processes such as erosion may be of principal interest. Also, the hydrology and hydrochemistry of the engineered system may require particular consideration both in relation to the underlying and surrounding environment and in relation to the surficial environment. The degree of hydrological and hydro–geochemical coupling between the engineered facility and the host strata may be substantially greater than for a facility located in clay or mudstone.

For salt, the major concern is whether the bed or dome will maintain its integrity in the long term. Therefore, there is a particular interest in processes that could remove or alter the properties of the cap rock (or overlying strata in the case of bedded salt). Diapirism and subrosion have been identified as the main natural processes of concern in respect of salt domes and salt pillows, but they are less important with respect to salt beds [14]. For bedded salt, incision may be the dominant natural factor. For all types of salt formation, the potential for human intrusion should be taken into account, bearing in mind the uses of salt as a natural resource.

Volcanic tuff has only been given detailed consideration as a host rock at Yucca Mountain. In this case, a repository excavated at depth was proposed. Erosion of the mountain ridge down to the proposed repository level is possible on timescales of hundreds of thousands to millions of years [15]. However, the primary concern is with changes in the pattern and intensity of precipitation that could lead to alterations to the amount and spatial and temporal distribution of deep percolation. Thus, the propagation of changes in climate through the unsaturated zone is a topic that has occasioned particular interest [16].

Metamorphic rocks are generally massive and brittle. Therefore, the considerations will typically be similar to those for crystalline rocks. Mixed sequences of rocks will have to be evaluated based on the particular characteristics of the individual rock types composing the sequence.

2.2.3. Consideration of the hydrogeological context

For a saturated flow regime, the main considerations are climatically induced changes in specific flow through the facility, the chemical composition of the inflowing and outflowing water, the path length from the repository to the near surface and transport characteristics of that path (water flow velocity, sorption properties). For a repository in the unsaturated region, these properties will again be of relevance (both for the unsaturated zone and for any saturated zone into which radionuclides are transported). However, there will also be an interest on controls on episodic flow and how the chemistry of the groundwater alters during and after episodic flow events. In addition, changes in the degree of saturation of the unsaturated zone, including the creation or elimination of perched water, may be important for safety assessment.

2.2.4. Consideration of the coastal context

Here the main distinction is that at inland sites coastal processes, such as cliff erosion, can be ignored, provided that a robust argument can be developed that the site will lie beyond the geographical limits of such processes over the entire assessment timescale. At submerged locations, evaluation on timescales of a few thousands of years may be straightforward, as coastal processes can be ignored until the local sea level falls substantially. However, on longer timescales there will be periods when currently submerged sites have to be treated as coastal. The assessment of sites that are coastal at the present day present an additional level of complexity. This is because coastal processes operating on both short and long timescales and under both rising and falling sea levels, governed by both isostatic and eustatic factors, might contribute to the evolution of the site.

2.2.5. Consideration of the potential for climate extremes

As sites subject to glaciation also typically experience periods of temperate/boreal and periglacial conditions, the sequence of increasing complexity is non-glaciated → periglacial → glaciated. In non-glaciated conditions (ranging from temperate to tropical), fluvial and aeolian effects will need to be addressed, with the balance between them determined by the degree of aridity projected to occur and the extent to which precipitation is concentrated into intense storm events. Inclusion of periglacial conditions will give an emphasis to frozen ground effects, both in terms of the active layer and underlying permafrost. Although mechanical effects, such as solifluction, may be of some significance, the main emphasis is likely to be on the altered hydrological regime. Also, in periglacial conditions, aeolian transport will often dominate over fluvial, and water abstraction from wells may not be of relevance as a radionuclide transport pathway.

Where glaciation is included, isostatic effects, erosion and deposition by the ice, and the effects of the very active hydrological regime close to the ice margin will need to be given emphasis.

2.3. TIMESCALES OF POST-CLOSURE PERFORMANCE ASSESSMENT

Appendix IV of Ref. [2] reviewed international recommendations, standards and guidance and national level regulatory requirements on post-closure repository safety. In particular, requirement 8 of Ref. [17] says that, “Containment shall be provided until radioactive decay has significantly reduced the hazard posed by the waste.” According to this, the timeframe for assessment will depend on the half-life of the more hazardous radionuclides and interpretation of a significantly reduced hazard. In the same Appendix, national level requirements and regulatory guidance were also reviewed and they demonstrate a range of assessment timeframe objectives, and include periods of up to 1 million years into the future, but with a quantitative focus on the first few thousand years.

The importance of various types of processes discussed in Section 2.2 will differ depending on the timescale considered. Herein, evaluations of the significant factors in environmental change are made over the following periods after closure of the facility:

- 0 to 100 years;
- 100 to 1000 years;
- 1000 to 10 000 years;
- 10 000 to 100 000 years;
- 100 000 to 1 million years.

On the shortest timescales (0 to 100 years and 100 to 1000 years), there is likely to be an emphasis on processes associated with recovery from the disturbance associated with facility construction (e.g. resaturation) and degradation of some (but not all) engineered components (e.g. structural concrete and capping structures). On timescales of up to about 10 000 years, the landscape at many locations is likely to remain similar in form to that observed at the present day, whereas the climate is likely to be as warm, or somewhat warmer, than at the present day. Thus, the processes of relevance are likely to be similar to those of relevance at the present day, though their relative importance may change somewhat depending on the degree to which the climate changes and the extent to which this influences other factors, such as vegetation cover. On a timescale of 10 000 to 100 000 years, periglacial and glacial processes are likely to be of significance at those sites that have the potential to experience cold climates, which will depend on the atmospheric CO_2 concentration at that time. For sites that do not have the potential to experience cold climates, the main consideration may be the alternation of arid and pluvial episodes, with their concomitant effects on processes such as erosion and infiltration. On timescales of up to 10 000 years, isostatic effects are likely to be largely limited to the last stages of recovery from the crustal and asthenospheric deformations that occurred during the last glaciation (Marine Isotope Stage 2), but on timescales of 10 000 years or more, ice loading and crustal deformation may be repeated.

On the longest timescale of 100 000 to 1 million years, multiple glacial–interglacial cycles may be expected to occur, but the major additional consideration is that long term Earth processes may become of significance. For example, long term erosion may result in compensating tectonic uplift and areas underlain by less dense crustal material may be also subject to tectonic uplift even in the absence of significant erosion.

It is emphasized that only the shorter timescales are likely to be relevant for surface or near surface facilities, or for those facilities at which operational wastes from nuclear power plants are disposed. The longest timescales are primarily of relevance to the deep disposal of radioactive wastes containing substantial concentrations of long lived radionuclides. Such wastes include spent nuclear fuel and the high level wastes that arise from reprocessing.

2.4. CLASSIFICATION OF THE ILLUSTRATIVE SITES

In Sections 6 and 7, illustrations are provided of the application of the methodology developed in this study to specific regions and sites. Table 1 lists these sites and summarizes how they are classified under the above scheme. For more details of the regions and sites, and for an understanding of the basis of the classification in Table 1, Sections 6 and 7 should be consulted.

TABLE 1. CLASSIFICATION OF ILLUSTRATIVE SITES

Region or site	**Mode of construction**	**Geological Context**	**Hydrogeological Context**	**Coastal Context**	**Potential for glaciation**
Mol, Belgium	Near surface	None	Unsaturated	Inland	Unglaciated
Mol, Belgium	Excavated at depth	Clay	Saturated	Inland	Periglacial
Switzerland	Excavated at depth	Clay	Saturated	Inland	Glaciated
Forsmark (SFR), Sweden	Excavated at depth	Crystalline	Saturated	Submerged	Glaciated
Forsmark (KBS-3), Sweden	Excavated at depth	Crystalline	Saturated	Coastal	Glaciated
El Cabril, Spain	Excavated from surface	Unconsolidated sedimentary	Unsaturated	Inland	Unglaciated
Lowland Britain	Excavated at depth	Mixed	Saturated	Inland	Glaciated or Periglacial
Olkiluoto, Finland	Excavated at depth	Crystalline	Saturated	Coastal	Glaciated
Canada, deep L/ILW	Excavated at depth	Consolidated sedimentary	Saturated	Inland but lakeside	Glaciated
Canada, spent fuel	Excavated at depth	Not selected	Saturated	Not selected	Glaciated
Yucca Mountain	Excavated at depth	Volcanic tuff	Unsaturated	Inland	Unglaciated

2.5. METHODOLOGY

Based on the above discussion and more general considerations, the following methodological approach is proposed to addressing the effects of environmental change on the post-closure performance of facilities for the disposal of solid radioactive wastes. It is emphasized that this methodological approach is necessarily nested within a broader methodology that defines the overall approach to developing a safety case for the disposal of solid radioactive wastes. This broader methodology would define, for example, the overall assessment context, as addressed in Ref. [1], but applied to the entire disposal system and not just the biosphere component. As discussed in Section 2.1, the methodological approach set out here is intended to be applicable across a wide range of different types of facilities that are characterized generically. In a site specific context and in relation to a particular facility design, it would be appropriate to adapt and elaborate the methodology. Nevertheless, the broad principles implicit in this methodology would remain applicable in a site specific context:

(a) For facilities excavated from the surface, the impacts of environmental change should be evaluated for the disposal system considered as a single integrated whole. For facilities excavated at depth it may also be appropriate to evaluate the impacts of environmental change on the disposal system considered as a single integrated whole. However, bearing in mind the consideration that the effects are likely to be directly expressed in the near surface environment and then propagated downward to the depth of the facility, it may be more convenient to first evaluate the impacts of environmental change for the near surface environment, typically down to a few tens of meters (though possibly somewhat deeper if permafrost is an issue), with the consequences of those changes then propagated to facility depth in a second step.

(b) A list of relevant processes should be developed and screened specific to the geological context, hydrogeological context, coastal context and potential for climate extremes. This list of relevant processes could be constructed from an 'inclusive' list covering all the regimes, omitting processes that are of no, or little, relevance in the specific context, but also including processes not previously identified in the 'inclusive' list, and determined to be relevant in the specific context. Such an 'inclusive' list could be developed and expanded through application of the proposed methodology to a variety of types of facility and at a variety of sites. Thus, the 'inclusive' list would be a 'living document' capturing experience and insights from a variety of assessments.

(c) The screened list should be examined for each assessment time interval to determine those processes that apply (or, more restrictively, that are the primary controls on environmental development) within that time interval.

(d) Time intervals over which similar sets of processes apply should be aggregated to reduce the resources required for subsequent conceptual model development.

(e) For each aggregated time interval, the processes of relevance should be used to develop a conceptual model or to audit an existing conceptual model. This conceptual model may either be for the disposal system considered as a single integrated whole or for the near surface environment.

(f) Where the conceptual model is developed for the near surface environment, its implications should be propagated downward to derive a conceptual model applicable from the surface to repository depth.

(g) The conceptual models developed under (e) and (f) should be used to develop or audit descriptive or mathematical models used to characterize environmental change in an assessment context.

There is likely to be a need to iterate between the above steps. For example, when giving consideration to aggregation (step d), it may be convenient to include processes in a time interval even though they are of limited or subsidiary importance in that time interval (step c). As another example, descriptive or mathematical models arising at step g may be used to re-evaluate the primary controls on environmental development (step c). A further consideration is that the scope of the conceptual, descriptive and mathematical models may be partly determined by the degree of process understanding or availability of relevant data for the different time intervals. This may result in the use of models of limited capability in exploratory studies, coupled with the identification of requirements for research and development. In turn, the results from such exploratory studies plus outputs from the research and development programme are likely to require a further iteration of all, or some, of the methodological steps set out above.

It would also be possible, and may be appropriate in a specific context, to use only a part of the above methodology. Thus, for example, if an existing conceptual model was available, this could be audited against the 'inclusive' list mentioned in step b and any deficiencies could be remedied by applying steps c through e to enhance the existing conceptual model.

Various outputs may be obtained by applying this methodology generically to a particular type of facility. These include an update of the 'inclusive' list of processes suitable for use in the auditing of existing conceptual models, and conceptual, descriptive or mathematical models for that type of the facility that can be used directly in generic assessments, e.g. evaluation of the viability of a disposal concept prior to site selection. Also, conceptual, descriptive and mathematical models developed for a generic type of facility are likely to provide a well justified starting point for developing models tailored to assessing the post-closure performance of that type of facility as adapted to a specific site.

3. CONTROLS ON LONG TERM CLIMATE CHANGE

In post-closure radiological impact assessments, a range of future climate evolutions relevant to the region chosen for a specific repository should be determined. This range should be defined based on current scientific knowledge on the past and future projected climate evolution. This Section describes characteristics of the past climate (Section 3.1) before addressing controls on climate change (Section 3.2).

3.1. CHARACTERISTICS OF PAST CLIMATES

Geological records show that over the past 2.5 million years (Ma) the Earth's climate has varied from warm (interglacial) to cold (glacial) periods characterized by extensive ice sheets in high northern latitudes and Antarctica. For the past ~900 ka interglacials have occurred every 80 to 120 ka [18–21]. To illustrate these variations, atmospheric CO_2 concentrations as measured in Antarctic ice cores and stacked $\delta^{18}O$ as measured in marine sediment records, a proxy for global ice volume, are displayed in Figure 4 with June insolation at 60ºN (which means the incident solar radiation received by the Earth at 60 degrees latitude).

The last glacial cycle is relatively well known, both from geological data and modelling studies, and therefore it serves well to exemplify the global climate evolution and associated spatial patterns of climate change during a glacial cycle. The end of the last interglacial (which occurred at circa 115 ka Before Present, BP) and the transition into the last glacial period is thought to have been initially triggered by a decrease in summer insolation at high northern latitudes [22]. The transition from interglacial conditions to full glacial conditions (the last glacial maximum, LGM, circa 21 to 18 ka BP) was interrupted by a number of warmer (interstadial) and colder (stadial) periods. To illustrate these variations, $\delta^{18}O$, as measured in a Greenland ice core [23], is displayed in Figure 5.

During the last glacial cycle, climate shifted many times between warmer and colder periods, as reflected in the growth and decay phases of the ice sheets. The variability and range within which the climate shifted during the last glacial cycle could be expected also during future glacial cycles, in the absence of human intervention.

The period of maximum extent of Northern Hemisphere ice sheets, the LGM, occurred circa 21 to 18 ka BP. During this period, surface air temperatures (SATs) were more than 20°C lower than today in regions covered by an ice sheet (see Figure 6 below) [24]. These large differences as compared with today are primarily due to the high albedo and high altitude of the ice sheets. However, also in regions distant from the ice sheets, the SAT was several degrees lower than today. Permafrost is an important feature of such glacial periods especially in high latitude periglacial regions (see also Figure 7).

An example of air surface temperature in a period of less extensive Northern Hemisphere ice sheets circa 44 ka BP, during one buildup phase of the Northern Hemisphere ice sheets, is displayed in Figure 7. The global average SAT was higher during this period than during the LGM. As for the LGM, SATs were more than 20°C lower than today in regions covered by an ice sheet (see Figure 7 below) [25].

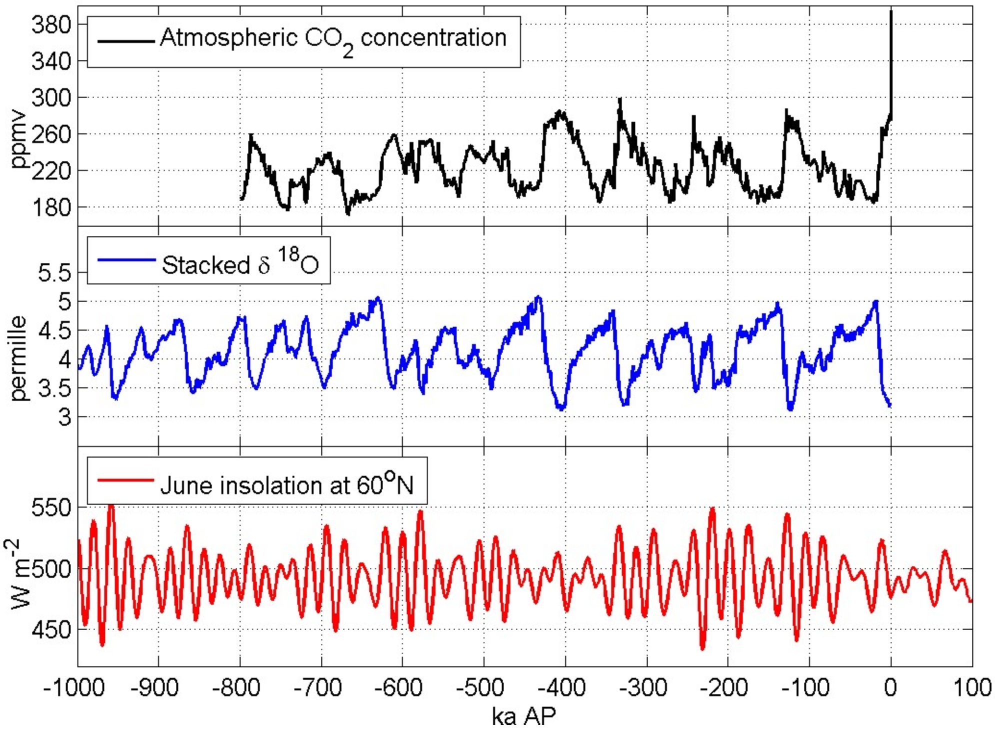

FIG. 4. CO_2 composite record (upper panel); complemented with the observed annual average atmospheric CO_2 concentration in 2012 AD (393.8 parts per million by volume (ppmv)) [26]. High values of CO_2 correspond to a warmer climate (interglacial state). A stack (middle panel); of 57 benthic $\delta^{18}O$ records. The $\delta^{18}O$ is a proxy for the global ice volume and temperature [27]. High values of $\delta^{18}O$ correspond to a colder climate (glacial state). June insolation at 60ºN (insolation explanation provided in Section 3.2.1) (lower panel) [28, 29]. Figure reproduced with permission courtesy of SKB).

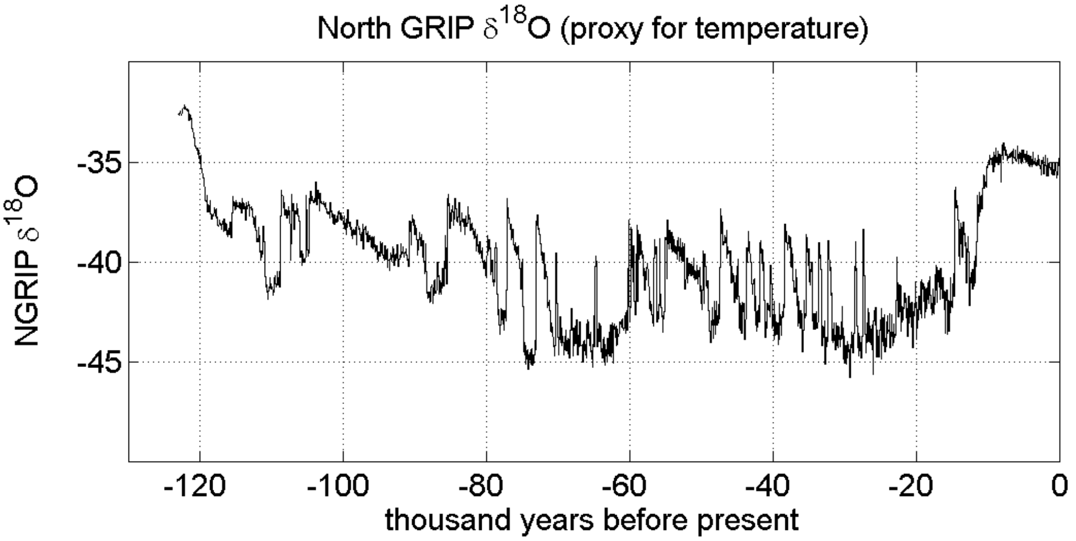

FIG. 5. The NorthGRIP $\delta^{18}O$ record [23]. Low values of $\delta^{18}O$ correspond to a colder climate. (Reproduced with permission courtesy of SKB).

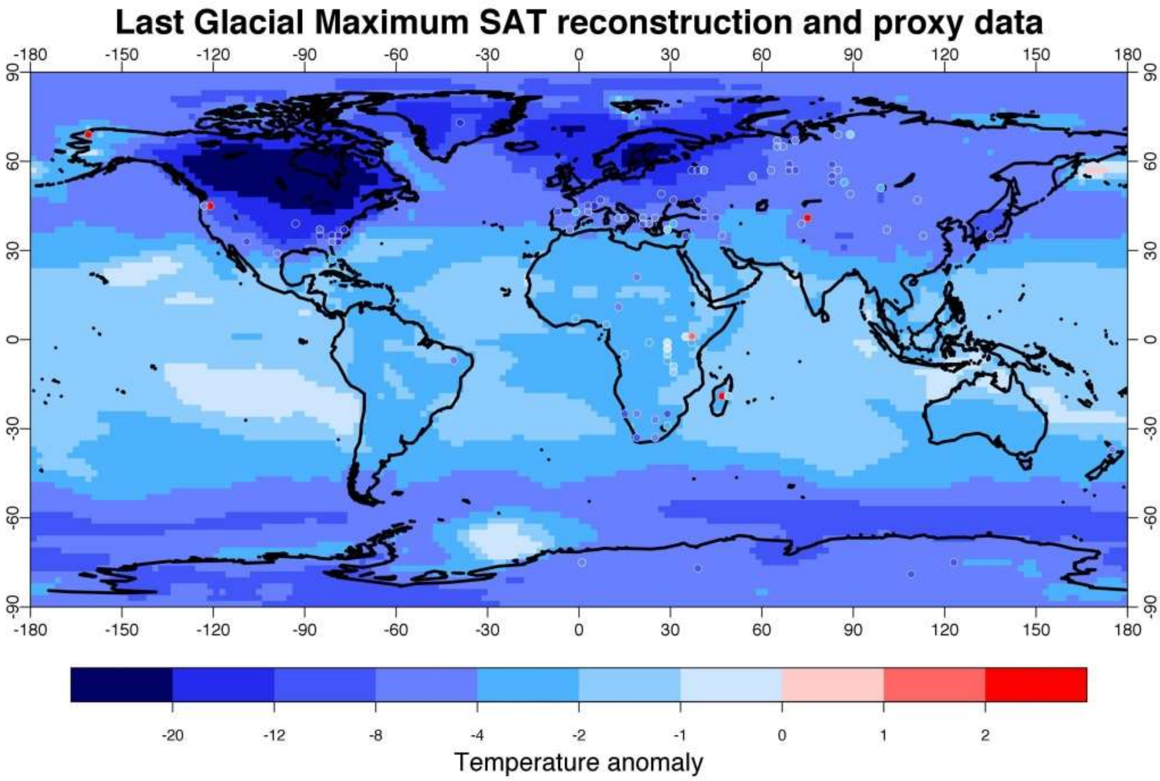

FIG. 6. SAT anomaly, °C, as compared to the present. From Ref. [24] (licensed under CC BY 3.0 https://creativecommons.org/licenses/by/3.0/legalcode), who combined a number of new proxy data sets with the ensemble of state of-the-art climate models which participated in the Palaeo–climate Modelling Intercomparison Project (PMIP2) [30] to generate a spatially complete reconstruction of surface air (and sea surface) temperatures for the LGM. Proxy data reconstructions at specific locations are indicated by coloured dots superimposed on the continuous field derived from the model reconstructions.

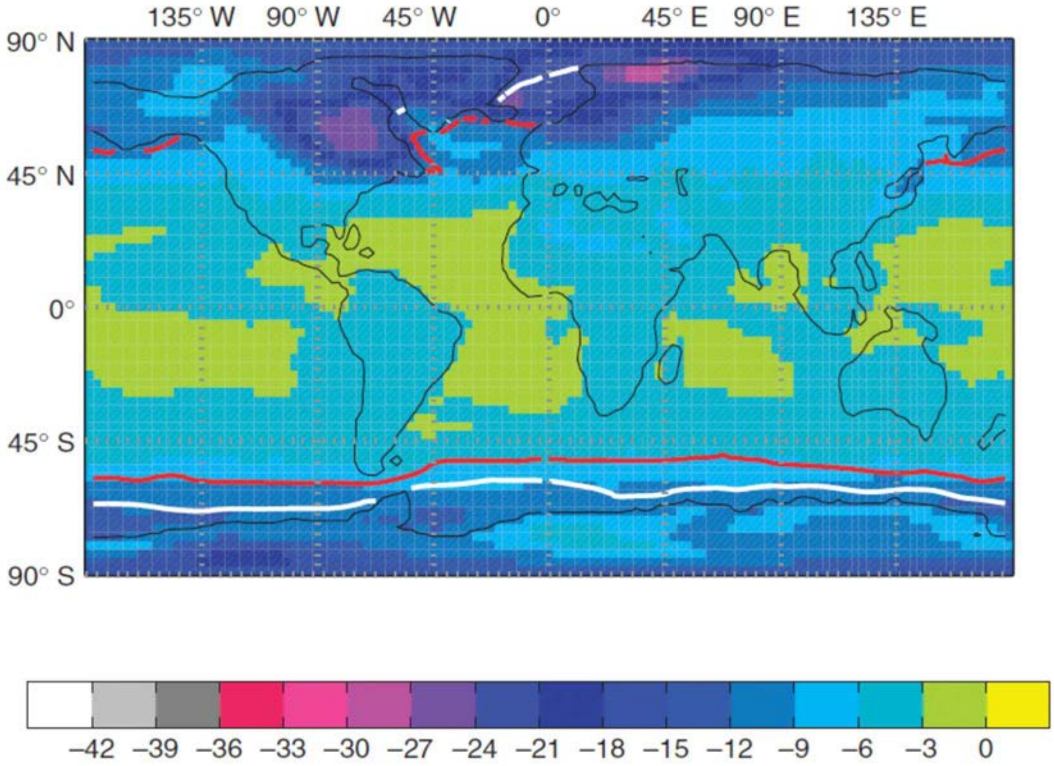

FIG. 7. Mean annual SAT anomaly, °C, relative to the present day with the global climate simulated during a period circa 44 ka BP with relatively small ice sheets in the Northern Hemisphere. From Ref. [25] (licensed under CC BY 3.0 https://creativecommons.org/licenses/by/3.0/legalcode). The geopotential isolines have been removed from the original figure.

The current interglacial (the Holocene) started circa 11 ka BP. The first part of this interglacial, the Holocene thermal maximum, circa 11 ka to 5 ka BP, was a period of relatively warm climate most clearly recorded in the middle and high latitudes of the Northern Hemisphere, where it is generally associated with the local orbitally forced summer insolation maximum [31]. This period is one of the foci of the Palaeo–climate Modelling Intercomparison Project (PMIP). The PMIP2 multi-model summer average near SAT simulated for the period 6 ka BP is displayed in Figure 8.

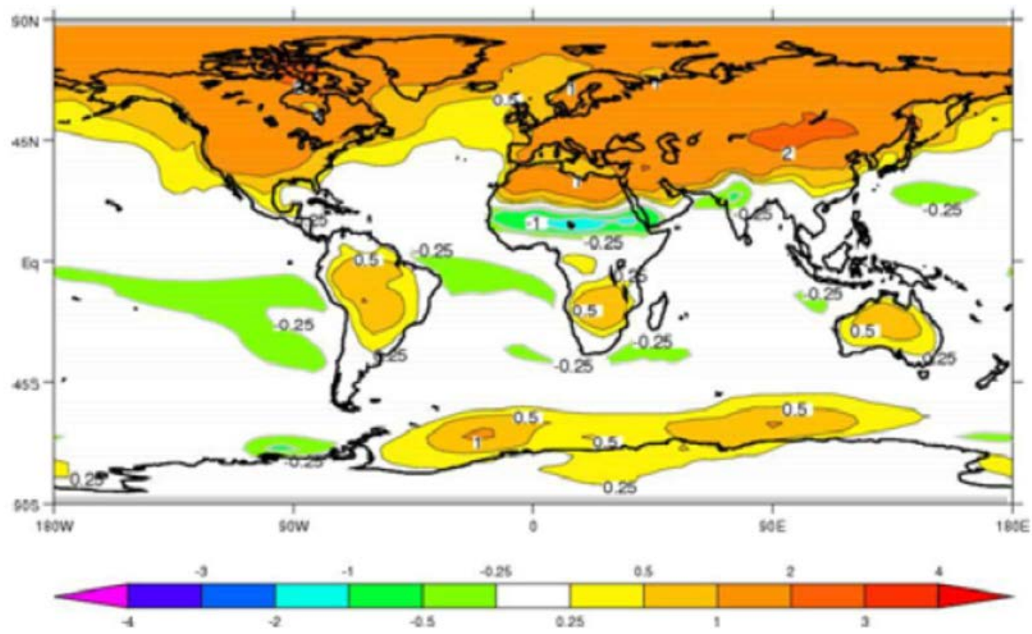

FIG. 8. Summer SAT anomaly ˚C of the mid-Holocene at 6 ka BP as compared with the present (taken from PMIP2- licensed under CC BY 4.0 https://creativecommons.org/licenses/by/4.0/legalcode).

3.2. CONTROLS ON CLIMATE VARIATION

Understanding of the dynamics of past climate evolution and variability is essential in assessing potential patterns of future climate evolution relevant to post-closure radiological impact assessments. Global climate varies on a wide range of timescales, with those variations determined by a variety of mechanisms and processes, as illustrated in Figure 9.

Bearing in mind that quantitative post-closure radiological impact assessments seldom extend for periods of more than one million years AP, the first three mechanisms shown in Figure 9 (variations in concentrations of galactic dust due to the passage of the Sun through the spiral arms of the Galaxy, evolution of the Sun, and the effects of continental drift) can be neglected.

Several of the shorter term mechanisms, including atmospheric auto-variation, atmosphere–ocean feedbacks and air-sea-ice-land feedbacks are all represented in the types of climate model that are discussed in subsequent sections of this report, so they are not considered further here. This remark applies also to shorter term changes in ocean circulation, whereas longer term changes in ocean circulation are governed by factors such as alterations in the geometry and connectivity of the ocean basins that would be expected to occur on timescales much longer than one million years. Individual volcanic effects can have substantial cooling effects on global climatic conditions on timescales of up to a few years, but there is no evidence that they alter the climate on a longer timescale (except related to long timescale variations in their total CO_2 emissions), so they are appropriately considered as short term perturbations. The effects of solar variability extend across a wide range of timescales, but this mechanism is not generally considered a dominant control of global or regional climate.

Thus, of the mechanisms identified in Figure 9, three remain as potential major drivers, or forcing factors, for climate change on multi-millennial timescales. These are orogeny and isostacy, changes in the orbital parameters of the Earth and evolution of the atmosphere. Over the next one million years, it is not anticipated that a major period of mountain building will take place, though changes in elevation of existing, young mountain ranges, notably the Himalayas and Alps, will occur [31], so isostacy rather than orogeny is the principal focus of interest. Isostatic adjustments will occur on this timescale mainly through the differential loading and unloading of the Earth's crust by continental ice sheets and concomitant changes to the distribution of water in the ocean basins that affect the crustal load exerted by the overlying oceanic water column. Such isostatic effects are taken into account in the types of climate model that are used for very long term simulations (EMICs, which are described further below).

The remaining mechanisms, changes in the Earth's orbital parameters and atmospheric evolution, are described in more detail in the following subsections.

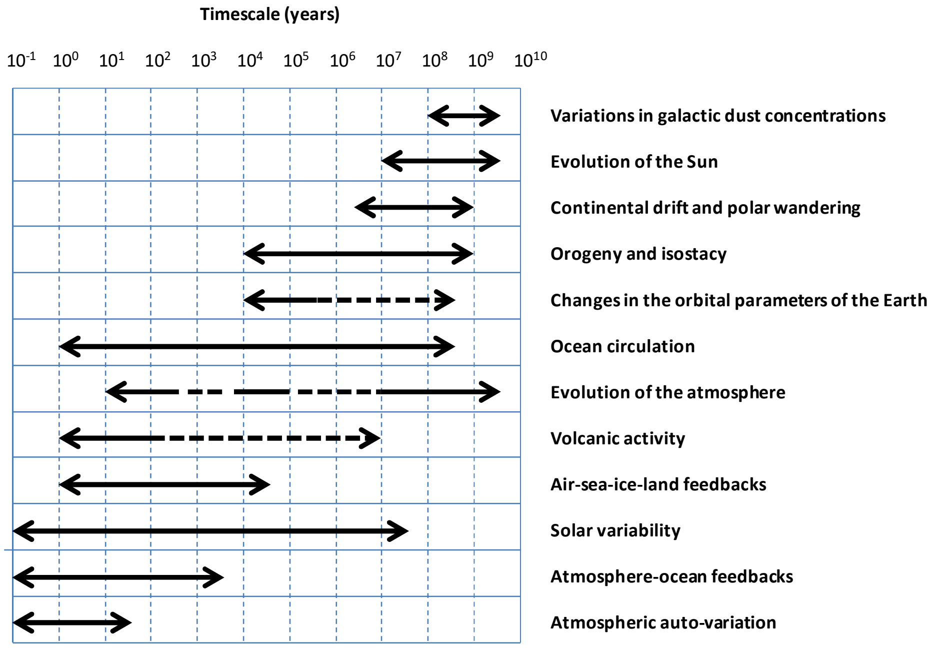

FIG. 9. Major mechanisms of climate change and their timescales of operation (redrawn from Ref. [32]).

3.2.1. Insolation

Changes in the orbital characteristics of the Earth alter the spatial and temporal pattern of insolation received at the top of the atmosphere, though they have only a very small effect on the total amount of insolation received annually over the Earth as a whole.

These include variations in the eccentricity of the orbit, the obliquity (i.e. the tilt of the Earth's axis of rotation), and in the precession of the equinoxes, with dominant frequencies at about one cycle per 100 ka and per 400 ka (eccentricity), 41 ka (obliquity) and 21–23 ka (precession). The ~100 ka timescale in the glacial–interglacial cycles of the last ~900 ka is commonly attributed to control by these variations in the Earth's orbit. Milankovitch proposed that the Earth is in an interglacial state when it's rotational axis both tilts to a high obliquity and precesses to align the Northern Hemisphere summer with Earth's nearest approach to the Sun.

June insolation at 60°N is displayed in Figure 4 for reference. Statistical analyses of long climate records support this theory [20, 33–35], but many questions remain about how orbital cycles in insolation produce the observed climate response [20, 21, 36].

The amplitude and the saw tooth shape of the variations in the climatic records imply that non-linearities and amplifications, e.g. through ice/snow albedo, atmosphere and ocean circulation and the carbon cycle, exist. A number of modelling studies have been performed to enhance understanding of the physical mechanisms associated with deglaciation and glaciation (see e.g. Ref. [37] for a review of modelling studies of glacial inception). Studies with EMICs that include simplified descriptions of the main components of the climate system, i.e. atmosphere, ocean, sea ice, ice sheets and sometimes vegetation, indicate that the combination of orbital insolation variations and glacial–interglacial atmospheric CO_2 variations give a reasonable agreement between simulated and reconstructed glacial cycles [38, 39].

The most contentious problem is why late Pleistocene climate records are dominated by 100 ka cyclicity. Insolation changes are dominated by the 41 ka obliquity and 23 ka precession cycles, whereas the 100 ka eccentricity cycle produces negligible 100 ka power in seasonal or mean annual insolation. Recently, Ref. [18], used comprehensive climate and ice sheet models to simulate the ice sheet variation for the past 400 ka forced by the insolation and atmospheric CO_2 content. Their model realistically simulates the saw tooth characteristic of glacial cycles (Figure 4), the timing of the terminations and the amplitude of the Northern Hemisphere ice volume variations, as well as their geographical patterns at the LGM and the subsequent deglaciation [18]. They conclude that insolation and internal feedbacks between the climate, the ice sheets and the lithosphere–asthenosphere system explain the 100 ka periodicity.

3.2.2. Atmospheric greenhouse gas concentrations

Evolution of the atmosphere is closely associated with the effects of variations in orbital parameters. From analyses of gas inclusions in long ice cores extracted from the Greenland and Antarctic ice sheets, it has been found that atmospheric CO_2 concentrations vary systemically during glacial–interglacial cycles, being low during glacial episodes and higher during interglacials (see Figure 4). However, at the present day, the primary factor determining changes in the atmospheric concentration of CO_2 is the burning of fossil fuels. Changes in vegetation, e.g. from deforestation, are an important secondary consideration. As CO_2 is an effective greenhouse gas, changes in atmospheric CO_2 concentrations are associated with changes in global and regional climates. An increase in the atmospheric concentration of carbon dioxide is associated with overall warming at the global scale. However, at a regional level a more complex pattern occurs. Although most regions are projected to experience warming at increased CO_2 concentrations, some areas of cooling may occur due, for example, to changes in the patterns of atmospheric and ocean circulation.

Global atmospheric concentrations of greenhouse gases have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years. Humankind has up to now released circa 300 Petagrams (Pg) (1 Pg = 1.0×10^{15} g) carbon (PgC) to the atmosphere and the total cumulative emissions will exceed 1000 Pg carbon before the end of this century under business as usual scenarios [40]. The remaining fossil fuel reserves that are estimated as technically and economically viable currently are about 1000 PgC. However, a wider range of releases is used because there are about an additional 4000 PgC of identified fossil fuel reserves for which economic extraction may be possible in the future. Additionally, there are about 20 000 to 25 000 PgC of non-conventional resources, such as methane clathrates, that could also be exploited in the future [41]. CO_2 concentrations in the atmosphere have increased from 280 parts per million by volume (ppmv) prior to industrialization in 1750 AD to 394 ppmv in 2012 AD[7] due to human emissions. CO_2 concentrations in the atmosphere increasing at the same rate as during the last decade (circa 2 ppmv per year) means that by 2100 AD the concentration of CO_2 in the atmosphere will be circa 570 ppmv.

To geologists of the future, the present interglacial, the Holocene, will look different from the previous major interglacial, the Eemian, which began around 130 ka BP (e.g. Ref. [42]). During previous interglacials, the atmospheric CO_2 concentration reached a peak value of about 300 ppmv and thereafter began to fall; in the present interglacial, CO_2 will instead rise by an amount that will be determined by human activities. Ref. [43] reconstructed regional and global temperature anomalies for the past 11.3 ka from 73 globally distributed records (Figure 10). This reconstruction is based on records of relatively low temporal resolution, which is why only longer term variations are reconstructed. They conclude that early Holocene (10 ka to 5 ka BP) warmth was followed by ~0.7°C cooling through the middle to late Holocene (<5 ka BP), culminating in the coolest temperatures of the Holocene during the Little Ice Age, about 200 years ago. They further state that current global temperatures of the past decade have not yet exceeded peak interglacial values, but are warmer than during ~75% of the Holocene temperature history.

The uncertainty in future atmospheric greenhouse gas concentrations and in the associated evolution of the Earth's climate should be taken into account in post-closure radiological impact assessments.

Other changes in atmospheric composition, e.g. variations in methane concentrations or aerosol load, may also affect climate. These effects are typically much less persistent than the effects of releases of carbon dioxide from fossil fuel consumption, because a significant fraction of the released carbon dioxide remains in the atmosphere for many millennia [44]. For example, the atmospheric lifetime of methane emissions is about a decade (see Section 6.3.3.3 of Ref. [6]) and that of N_2O is slightly more than 100 years (see Section 6.3.4 of Ref. [6]) and that of aerosols may be a few years.

Based on the above discussion, it will be appreciated that computational models of past climates during the Quaternary, of present climate and of climates for periods of up to one million years into the future are typically forced by variations in the spatial and temporal pattern of insolation at the top of atmosphere that are determined by changes in the orbital characteristics of the Earth together with variations in atmospheric CO_2 concentrations with time. These variations in atmospheric CO_2 concentrations may either be prescribed or generated within the computational model (if a carbon cycle model covering both terrestrial and aquatic environments is included). The alternative types of climate model that are available for this purpose are discussed in Section 4.2.

[7] www.esrl.noaa.gov

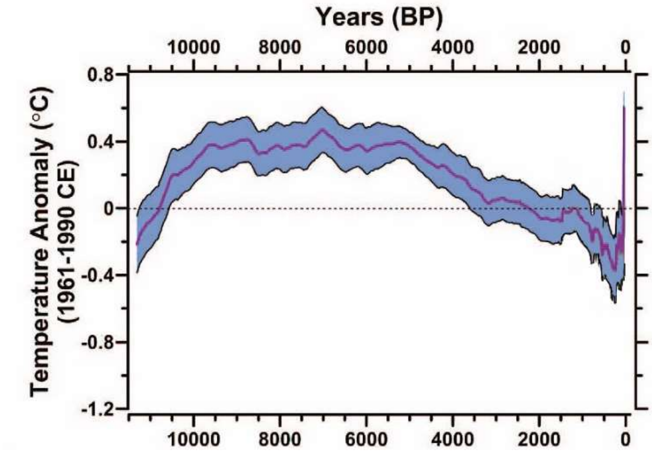

FIG. 10. Globally stacked surface temperature anomalies with respect to the period 1961–1990 AD (purple line) with one standard deviation uncertainty (blue band). Adapted from Ref. [43] with permission courtesy of SKB.

4. MODELLING OF GLOBAL CLIMATE

This Section focusses on steps 3 and 4 in the methodological road map. To help keep track, the Figure initially shown in the Summary is repeated below with the areas covered by this Section highlighted in blue as show in Figure 11.

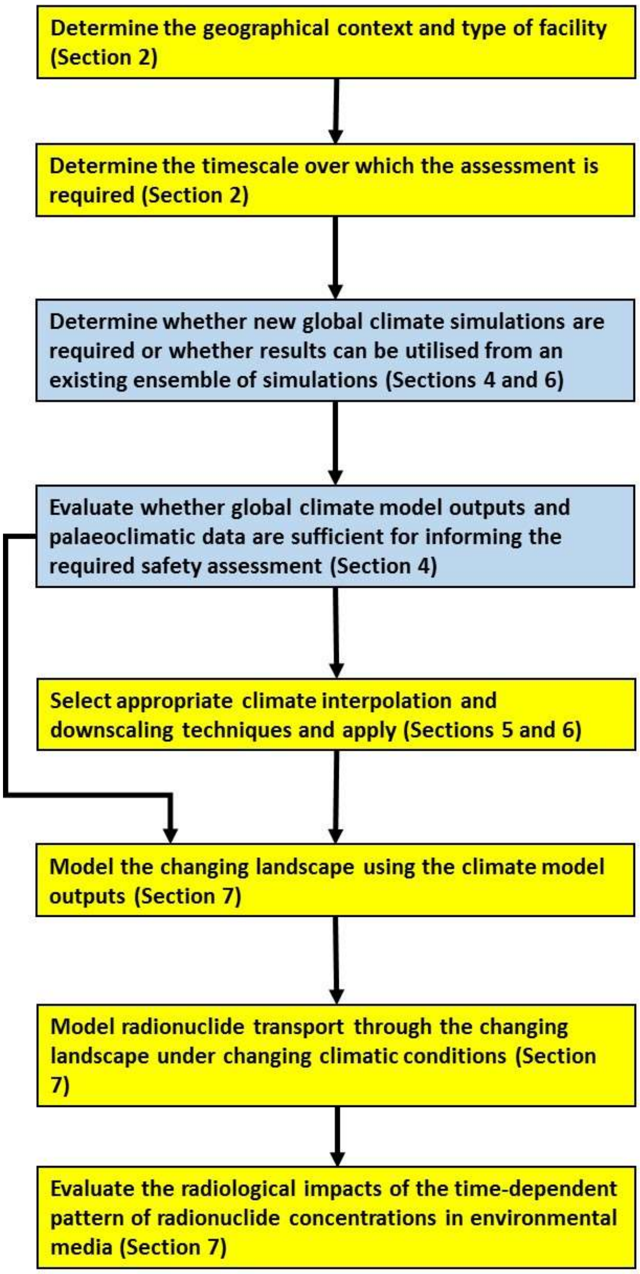

FIG. 11. Road map for performing an assessment taking climate change and landscape development into account.

Due to incomplete knowledge of the dynamics and interactions of the Earth's climate system, the future evolution of Earth's climate cannot be precisely predicted on the time scales of interest for safety assessments of nuclear waste repositories. Nonetheless, abundant knowledge exists and projections of future climate evolution based on this knowledge provide valuable information and a range of possible future climate evolutions. In this Section, the current knowledge on the Earth's future climate evolution in the coming ~100 ka is described in terms of global average evolution and large scale patterns of climate change.

As described in Section 3.2, atmospheric greenhouse gas concentrations (see Section 3.2.2) and insolation variations due to variations in astronomical parameters (see Section 3.2.1) are the major drivers of global climate variability on the timescales of relevance to post-closure radiological impact assessment. In the following subsection, computational models used in order to study the range of future climate evolution are described.

4.1. COMPUTATIONAL MODELS OF LONG TERM CLIMATE CHANGE

Various types of climate model are available, with these differing both in the modelling approach adopted and the level of detail at which the modelling is conducted. For modelling short term changes in climate, typically AOGCMs are used. These can be employed either with fixed or transient boundary conditions. Fixed conditions could, for example, include atmospheric CO_2 concentrations of twice or four times pre-industrial values, with the results of the model runs compared with a control run in which all other boundary conditions were identical, but in which the atmospheric CO_2 concentration was set at its pre-industrial level. Transient conditions might typically be an increase in atmospheric CO_2 concentration of 1% per year. With either fixed or transient boundary conditions, comparison of modelled results with a control simulation is preferred, since it is thought that changes in climatic characteristics are likely to be more accurately predicted than absolute values of those characteristics. Currently, attention is concentrated on moving beyond AOGCMs to ESMs, since these generally include biogeochemical processes and a full carbon cycle, permitting changing atmospheric carbon dioxide concentrations, based on CO_2 emissions scenarios, to be computed rather than having them imposed by the user. Such computations can also be made in specific EMICs, but not with the spatial or temporal resolution obtained from using an AOGCM component embedded in the model. The intention with ESMs is to use them for decadal to centennial, and possibly longer, studies of climate change and variability.

AOGCMs are 3-D gridded models. The surface of the Earth is represented as a two dimensional (2-D) net of cells. In each cell, the atmosphere is represented in terms of multiple layers and a multilayer system is also used to represent the ocean for each appropriate cell in the 2-D network[8]. The need to represent the whole of the Atmosphere–Ocean system in such a 3-D grid and the short time steps needed to capture the dynamics of the system mean that it is not currently feasible to reduce the size of the 2-D cells below about 100 km × 100 km. This means that local climate characteristics cannot be resolved in such a model.

One way of overcoming this is to embed (or nest) an RCM within an AOGCM, matching the boundary conditions of the RCM with output from the AOGCM. Typically, RCMs have a resolution of a few tens of kilometers. Thus, for example, HadRM3, which is the UK Meteorological Office RCM, was used to produce ~25 km scale future projections of climate

[8] In practice, a finer resolution may be used in the ocean model than in the atmosphere model, for example the Hadley Centre model HadCM3 has 6 ocean grid points per atmospheric grid point in the horizontal.

in the UK as part of the UKCIP09 project[9]. However, model based downscaling is not the only possible approach; physical–statistical and rule based procedures can also be used (see Section 5).

For longer term projections of climate, it is necessary to use EMICs. EMICs are more coarsely gridded than AOGCMs and typically include simplified representations of atmospheric and ocean circulation processes. However, they may include longer term processes, such as biogeochemical cycling and ice sheet development that are not included in AOGCMs. A recent example is LOVECLIM 1.2 [45]. This includes representations of the atmosphere, the ocean and sea ice, the land surface (including vegetation), the ice sheets, the icebergs and the carbon cycle. The atmospheric component is a 3 level quasi-geostrophic model. The ocean component consists of a 20 level ocean general circulation model coupled to a comprehensive thermodynamic–dynamic sea ice model. Its horizontal resolution is 3° by 3°, i.e. about 300 km by 300 km. LOVECLIM 1.2 also includes a vegetation model that simulates the dynamics of two main terrestrial plant functional types, trees and grasses. Desert conditions with sparse vegetation cover are also simulated. The evolution of the carbon cycle is represented, with distinct terrestrial and oceanic components. The ice sheet component is made up of a 3-D thermomechanical model of ice sheet flow, a visco–elastic bedrock model, and a model of the mass balance at the ice atmosphere and ice ocean interfaces [45].

The cGENIE EMIC also includes a full representation of the carbon cycle, in which atmospheric CO_2 concentration is predicted by the model, rather than prescribed by the user; instead, CO_2 emissions are prescribed. This model simulates the sedimentary, oceanic, biosphere, and atmospheric reservoirs of CO_2, and the processes that govern the fluxes between them. This is a comprehensive, physically based approach to carbon cycle modelling (see, e.g. Ref. [46]). Recent model developments include the addition of key biogeochemical cycles such as those for phosphate and sulphur. The enhanced model has been shown to represent long term biogeochemical cycles in good agreement with observations (see e.g. Ref. [47]). An application of cGENIE to the projection of future atmospheric carbon dioxide concentrations for various emissions scenarios is provided in Section 4.2.

In the initial stage of the current project, MODARIA WG6 developed an overall flow chart showing how different types of climate model might be used to develop projections of long term changes in climate in a particular region or at a specific site. That flow chart is reproduced as Figure 12. Here it is proposed that ensembles of climate models are run, rather than relying on results from a single model. This approach is becoming relatively standard in long term climate modelling for a variety of applications and ensures that the effects of uncertainties in model structure are quantified, as well as uncertainties arising from uncertainties in the values that should be adopted for model parameters.

For simulation periods of less than a few thousand years it is now feasible to carry out transient calculations with AOGCMs. As AOGCMs generally have a higher temporal and spatial resolution than EMICs, and often include representations of climatic processes that are physically based rather than being simplified approaches, use of an ensemble of AOGCMs is preferred over use of an ensemble of EMICs where this is possible. However, it is noted that EMICs may include explicit computation of slowly changing boundary conditions on the climate system, e.g. the extent and elevation of continental ice sheets. Such changes are not

[9] http://ukclimateprojections.defra.gov.uk/

computed by AOGCMs, so the required boundary conditions will either have to be specified in time independent form or as predefined time series.

For timescales of more than a few thousand years, running an ensemble of AOGCMs is not feasible. In this case, an ensemble of EMICs can be run instead. However, the EMICs will typically only give low resolution climatic outputs, so it is likely to be useful to complement these results by running snapshot or transient AOGCM simulations for key time intervals, or to interpolate between multiple AOGCM simulations using a climate emulator, as described in Section 4.2. These key time intervals, e.g. periods of permafrost development, should be identifiable from the EMIC outputs, which also provide a long term context within which the shorter term AOGCM studies can be located.

Whether results from AOGCMs or EMICs are being considered, there will be a need to downscale the results obtained to the site or local scale. Various different types of downscaling may be undertaken and these are discussed in detail in Section 5.

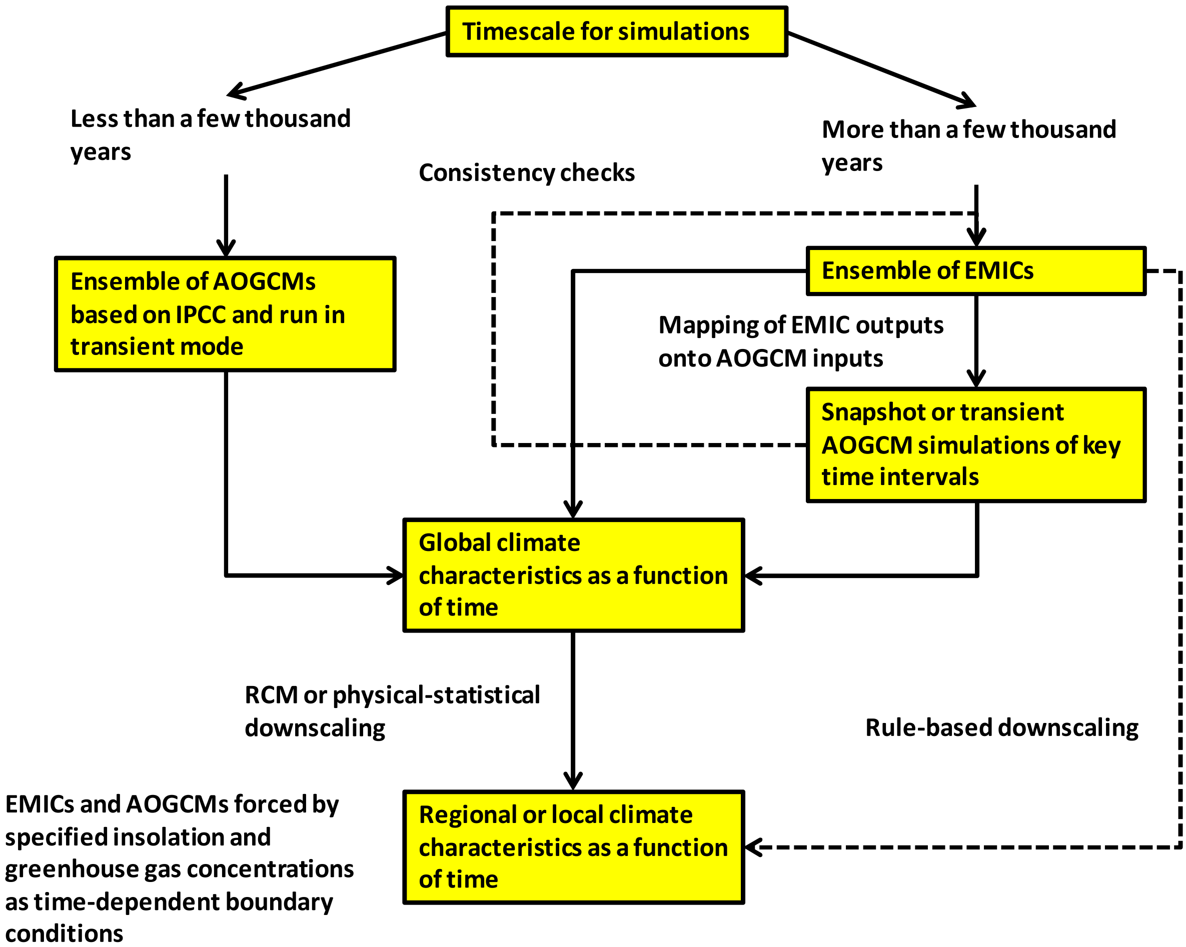

FIG. 12. Selection of climate models for use in post-closure radiological impact assessments.

4.2. PROJECTED FUTURE EVOLUTION OF ATMOSPHERIC CARBON DIOXIDE CONCENTRATIONS

As discussed in Section 3.2, the primary external factors determining long term changes in global and regional climates on a multi-millennial timescale are top of atmosphere insolation and atmospheric concentrations of greenhouse gases and aerosols, predominantly atmospheric concentrations of carbon dioxide. Over timescales of up to one million years, changes of insolation can be accurately computed using the equations of celestial mechanics [48, 49]. Thus, little uncertainty arises in this aspect of the boundary conditions required for climate modelling. However, long term changes in atmospheric concentrations of CO_2 are determined by the projected total amount of future emissions from fossil fuel consumption and from the pattern of emissions as a function of time. The situation is complicated since changes in the concentration of atmospheric CO_2 will affect the climate, which will in turn affect the distribution of CO_2 between the atmosphere and various terrestrial and aquatic reservoirs. Thus, there will be a feedback effect in which atmospheric concentrations of CO_2 affect its long term retention in the atmosphere.

This matter has been investigated on behalf of Radioactive Waste Management Limited (RWM) in the UK in a series of studies conducted at the University of Bristol using the cGENIE EMIC [41, 50]. As an example approach of how to project future evolution of atmospheric CO_2, this study is discussed in more detail here. Various amounts and patterns of fossil fuel emissions were studied, and projections obtained of atmospheric carbon dioxide concentrations from the present day to several hundreds of thousands of years into the future. The long term air concentration response in each case was fitted using a multi-exponential function, starting from a pre-industrial concentration of 280 ppmv of carbon dioxide. Results from these studies are reported below.

Two series of model experiments were performed. The first comprised a set of pulse releases of 1000 to 20 000 PgC[10] in 1000 PgC increments. This range can be set in context by noting that anthropogenic emissions to date have been about 300 PgC and that remaining fossil fuel reserves that are currently estimated as technically and economically viable are about 1000 PgC. However, a wider range of releases is used because there are about an additional 4000 PgC of identified fossil fuel reserves for which economic extraction may be possible in the future. Additionally, there are about 20 000 to 25 000 PgC of non-conventional resources, such as methane clathrates, that could also be exploited in the future [41]. This set was used to explore how CO_2 sinks may weaken and saturate with the release of different amounts of CO_2 to the atmosphere. A multi-exponential response function was then fitted to the results of these experiments to provide an empirical representation of the decrease in atmospheric CO_2 concentrations with time following pulse releases of different magnitudes. The coefficients of the fitted multi-exponential response function were found to be functions of the magnitude of the pulse of emitted CO_2, due to feedback effects of climate change on the global carbon cycle [41].

Having developed multi-exponential response functions to pulse releases of different magnitudes, a generalized multi-exponential response function for pulse releases of any magnitude was developed [41]. In this generalized response function, the coefficients of the exponential components were defined as polynomial functions of the total magnitude of the pulse release, μ (PgC). An examination of the goodness of fit of this generalized response

[10] 1 PgC is 1 x 10^{15} grams of carbon.

function to the results of the pulse release simulations demonstrated that a cubic polynomial provided a better representation than either a linear or a quadratic form [41]. Thus, the final model adopted was:

$$C_P(t,\mu) = B + E\, \Sigma_{i=1,5}\, (\alpha_i + \beta_{1i}\mu + \beta_{2i}\mu^2 + \beta_{3i}\mu^3)\, \exp\{-(t-t_0)/(\gamma_i + \delta_{1i}\mu + \delta_{2i}\mu^2 + \delta_{3i}\mu^3)\} \quad (1)$$

where $C_P(t,\mu)$ is the atmospheric concentration (ppmv) of CO_2 at time t (in years (y)), B is the pre-industrial baseline concentration (280 ppmv), and E is the initial atmospheric concentration of CO_2 (ppmv) resulting from a pulse release of μ (PgC) at time t_0 (y) (not including the baseline concentration) and is estimated as 0.469 ppmv PgC^{-1}. Values of the fitting coefficients are given in Table 2. The optimal fit required five exponential components, as indicated by the summation included in the above equation.

The second set of experiments comprised a set of time dependent releases in which the time dependence was characterized as having a logistic form. Total emissions and the release periods over which they were taken to occur are listed in Table 3.

Results from these experiments were compared with a convolution approach based on the pulse emission results in which the atmospheric concentration of CO_2, $C(t,\mu)$ (ppmv) at time t (y), was calculated using:

$$C(t,\mu) = B + \int dx\, q(x) C_P(t - x,\mu) \quad (2)$$

where $q(x)$ (ppmv y^{-1}) is the emission rate at time x, expressed in terms of its initial effect on the atmospheric concentration, i.e. 0.469 times the emission rate expressed as PgC y^{-1}. The integration is over the period from the beginning of significant anthropogenic emissions to the time of evaluation, t. Note that the value of μ used is the integral of the emissions rate over the whole period of anthropogenic emissions until time t.

It was found that the convolution approach gave a very close representation of the time dependent release calculations. After the first 200 years of the emissions period, differences between the two approaches were never more than a few per cent of the total atmospheric CO_2 concentration [41]. Thus, the convolution approach can relate time dependent emissions scenarios to atmospheric CO_2 concentrations in solid radioactive waste disposal contexts for which such scenarios are required over a range of timescales from the next few hundred years out to one million years after present.

However, the robustness of the approach should be explored further using other EMICs that include a representation of the global carbon cycle aside from cGENIE.

TABLE 2. COEFFICIENTS OF THE EMPIRICAL MULTI-EXPONENTIAL FUNCTION RELATING ATMOSPHERIC CONCENTRATIONS OF CARBON DIOXIDE TO AMOUNTS RELEASED IN PULSE EMISSIONS SCENARIOS. Table is from supporting material used for Ref. [41]

Parameter	***I***				
	1	**2**	**3**	**4**	**5**
α_i	0.253	0.245	0.312	0.079	0.075
β_{1i}	-4.63×10^{-05}	-3.54×10^{-05}	5.00×10^{-05}	3.96×10^{-05}	-8.57×10^{-07}
β_{2i}	3.44×10^{-09}	2.40×10^{-09}	-5.87×10^{-09}	-4.83×10^{-10}	5.89×10^{-11}
β_{3i}	-8.42×10^{-14}	-5.57×10^{-14}	1.65×10^{-13}	-1.46×10^{-14}	-1.15×10^{-15}
γ_i	6.28	58.7	112.6	2780	246 294
δ_{1i}	-1.05×10^{-03}	-2.99×10^{-03}	0.121	0.816	0.450
δ_{2i}	6.90×10^{-08}	6.15×10^{-08}	-7.87×10^{-06}	6.29×10^{-06}	2.55×10^{-04}
δ_{3i}	-1.49×10^{-12}	1.69×10^{-12}	1.86×10^{-10}	-7.27×10^{-10}	-9.69×10^{-09}

TABLE 3. TIME DEPENDENT EMISSIONS SCENARIOS. Table adapted from Ref. [41]

Total Emissions (PgC)	**Release Period (AD)**
1000	2010–2810
2000	2010–2972
3000	2010–3050
4000	2010–3098
5000	2010–3132
6000	2010–3158
8000	2010–3196
10 000	2010–3223

Note: A logistic profile was used in each case to represent the time dependence of the emissions.

4.3. PROJECTED FUTURE CLIMATE EVOLUTION

As discussed in Section 4.1, projections of future climate evolution are obtained using models of varying complexity ranging from ESMs through AOGCMs, ESMs of Intermediate Complexity (EMICs) to Simple Climate Models (SCMs). In modelling studies of future climate evolution, assumptions regarding future variations in the forcing conditions, e.g. human carbon emissions, are made. In general terms, the range from ESMs to SCMs involves decreasing complexity of the model physics and dynamics of the different components of the climate system as compared to the real world, as well as decreasing spatial and temporal model resolution. The computational cost of state of the art ESMs and AOGCMs prevents use of these models for modelling of more than a few centuries to millennia. To reflect both the complexity of the models used to assess the future evolution, and, the increased spread in possible future climate evolution, projected future climate evolution is described for the current century (Section 4.3.1), for the next 10 ka (Section 4.3.2) and for the next 100 ka (Section 4.3.3). The range of future climate evolution widens with time and therefore climate evolution beyond circa 100 ka AP is treated differently (Section 4.3.4).

4.3.1. Projected climate evolution until 2100 AD

Atmospheric greenhouse gas concentrations are expected to increase until 2100 AD at a rate mostly determined by human emissions [6]. This increase is expected to result in an increase in global average surface temperature [6]. Based on the Coupled Model Inter-comparison Project Phase 5 (CMIP5)[11] simulations, the following conclusions can be drawn [6]:

- The global annual mean SAT anomalies for 2081–2100 relative to the 1986–2005 AD reference period ranges from 0.3°C–1.7°C for the Representative Concentration Pathway (RCP) 2.6 scenario through 1.1°C–2.6°C for the RCP4.5 scenario and 1.4°C–3.1°C for the RCP6.0 scenario to 2.6°–4.8°C for the RCP8.5 scenario;
- Globally averaged SAT changes over land will exceed changes over the ocean at the end of the twenty-first century and the Arctic region is projected to warm most;
- Global precipitation will increase with increased global mean SAT; and
- Changes in average precipitation will exhibit substantial spatial variation with an increase in the contrast of annual mean precipitation between dry and wet regions and between dry and wet seasons.

The spread of projected global mean temperature increase for the RCP scenarios used in CMIP5 is considerably larger (at both the high and low response ends) than for the three scenarios (i.e. those of the IPCC's Special Report on Emissions Scenarios, SRES) used in CMIP3, as a direct consequence of the larger range of radiative forcing across the RCP scenarios compared with that across the three SRES scenarios (see Chapter 12 of Ref. [6]).

Almost all climate model projections reveal an enhanced increase of high latitude temperature and high latitude precipitation [51, 52]. Both of these effects tend to make the high latitude surface waters lighter and hence increase their stability. All the models included in CMIP5 show a weakening of the Atlantic Meridional Overturning Circulation (AMOC) over the course of the twenty-first century [6]. Once the radiative forcing is stabilized, the AMOC recovers, but in some models to less than its pre-industrial rate of turnover. The recovery may include a significant overshoot if the anthropogenic radiative forcing is eliminated [53]. The AMOC overshoot could give an extended period of anomalously strong northward heat transport, maintaining warmer northern high latitudes for decades after the atmospheric CO_2 concentration declines towards pre-industrial values.

Based on the assessment of the CMIP5 RCP simulations and on understanding from analysis of CMIP3 models, observations and understanding of physical mechanisms, the IPCC conclude that it is very likely that the AMOC will weaken over the twenty-first century. It is however very unlikely that the AMOC will undergo an abrupt transition or collapse in the twenty-first century (see Chapter 12 of Ref. [6]). This was concluded taking both the high latitude temperature and precipitation increase and a possible rapid melting of the Greenland ice sheet into account. For a review of current knowledge, reference should be made to the IPCC report. The weakening of the AMOC in the twenty-first century contributes to reducing the warming in Europe, but, overall, the radiative forcing caused by increasing greenhouse gas concentrations is expected to overwhelm the cooling.

4.3.2. Projected climate evolution until 10 ka AP

At this timescale, CO_2 induced warming is projected to remain approximately constant for many centuries following a complete cessation of emissions. A large fraction of climate change is thus irreversible on this timescale, unless net anthropogenic CO_2 emissions became strongly negative over a sustained period (see Chapter 12 of Ref. [6]). For scenarios driven by CO_2

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[11] http://cmip5.whoi.edu/

alone, the global average temperature is projected to remain approximately constant for many centuries following a complete cessation of emissions. The contribution from CO_2 may be enhanced by the effect of an abrupt cessation of aerosol emissions, which would cause warming. By contrast, cessation of emissions of atmospherically short lived greenhouse gases, such as methane, would contribute a cooling effect.

In the last few years a number of modelling studies of the climate evolution in the next 1 to 10 ka have been performed. These studies were generally performed with models of less complexity and/or coarser resolution than the ESMs and AOGCMs used for CMIP3 and CMIP5. The studies were designed to investigate the long term response to anthropogenic carbon emissions and do not include the effect of variations in insolation due to variations in the orbital parameters. These variations will be small as compared to the variations during the last glacial cycle [54], which is why anthropogenic carbon emissions are expected to be the primary forcing during the next 10 ka, or even longer [55].

Recent modelling studies of the climate evolution in the next 1 to 10 ka are summarized in [56]. The general shape of the global annual average SAT evolution is similar in different studies [57–60]. In all these investigations, anthropogenic carbon emissions are assumed to occur in the current and next century followed by an instant or rather rapid decrease to zero emissions. Some studies include modelling of the global carbon cycle [57, 59, 60], whereas others use prescribed atmospheric greenhouse gas concentrations [58]. Due to the slow equilibration of the oceans, the simulated annual global average SAT reaches a maximum anomaly as compared to the present around 0.5 to 1 ka AP, i.e. a few centuries to a millennium after the maximum in atmospheric CO_2 concentration. The maximum SAT varies from 0.2°C to almost 11°C depending on the assumptions on carbon emissions and on the models used. Subsequently, the annual global average SAT slowly decreases until 10 ka AP. According to [57], the lifetime of the SAT anomaly might be as much as 60% longer than the lifetime of anthropogenic CO_2 and two thirds of the maximum temperature anomaly will persist for longer than 10 ka. A generalized evolution of the annual global average SAT in these studies is displayed in Figure 13. Decadal, centennial and millennial variability, with maximum amplitude of circa 1 to 2°C is superimposed on this slow evolution for any specific simulation of the next 10 ka. Such variability arises due to internal climate dynamics, e.g. the El Nino, the Atlantic Multi-decadal Oscillation and AMOC variability. Further, an increased greenhouse effect may result in changes in the mean state of these internal processes, such as e.g. a reduction in the AMOC strength, see Section 4.3.1.

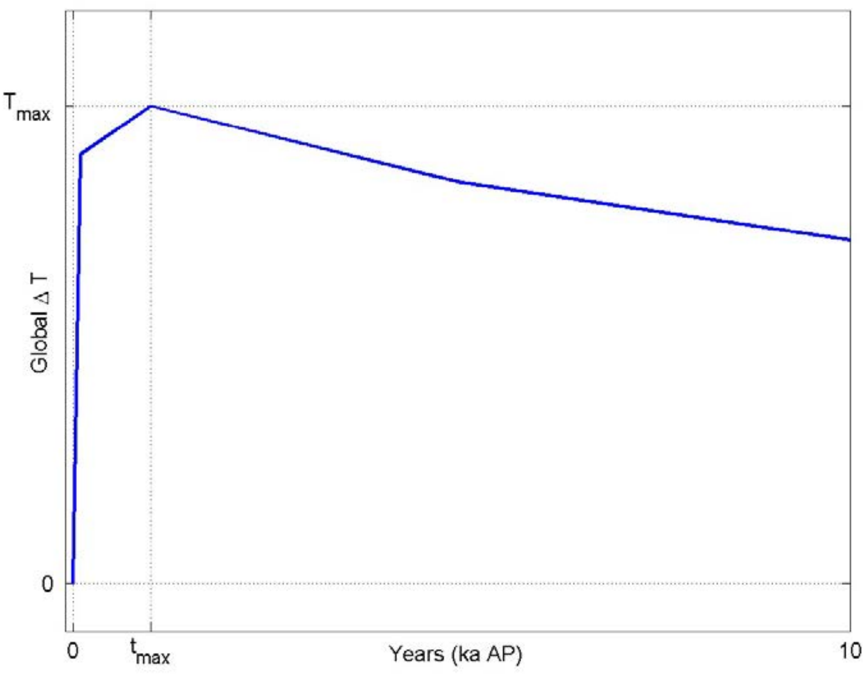


FIG. 13. Generalized evolution of the global annual average SAT displayed as the anomaly with respect to the year 2000 AD (ΔT). T_{max} is the maximum increase, which occurs at t_{max} ka AP.

For repository sites in coastal or near coastal regions, changes in relative sea level are of relevance for post-closure radiological impact assessments. Changes in relative sea level are determined by the net effect of eustatic changes (i.e. sea level rise associated with changes in the volume and spatial distribution of ocean water) and isostatic changes (i.e. the response of the solid Earth to loading or unloading by ice or water, and/or unloading and loading due to denudation and sedimentation).

Proxy and instrumental sea level data indicate a transition in the late nineteenth to the early twentieth century from relatively low mean rates of rise over the previous two millennia to higher rates of rise [61]. It is likely that the rate of global mean sea level rise has continued to increase since the early twentieth century.

Ocean thermal expansion and glacier melting have been the dominant contributors to twentieth century global mean sea level rise. The main conclusions related to sea level change beyond 2100 AD presented in IPCC AR5 [61] are the following.

(1) It is expected from current evidence that, beyond 2100 AD, there will be a continued rise in the global mean sea level and the thermal expansion of oceans will result in sea level rises carrying on for many centuries. Sea level rises over the longer term are dependent on future emissions. The model results currently available that go further than 2100 AD signify that a radiative forcing corresponding to concentrations of CO_2 that reach then decline and stay less than 500 ppm, as in the RCP2.6 scenario, results in the mean global sea level increase above the pre-industrial level by 2300 AD to be below 1 m. A rise of 1 m to more than 3 m is projected for a radiative forcing that corresponds to concentrations of CO_2 below 1500 ppm but above 700 ppm, as in the scenario RCP8.5.

(2) The available evidence indicates that global warming greater than a certain threshold would lead to the near complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea level rise of about 7 m.

— Ocean heat uptake and thermal expansion take place not only while atmospheric greenhouse gas concentrations are rising, but continue for many centuries to millennia after stabilization of radiative forcing, at a rate which declines on a centennial time scale.

— On a multi-millennial timescale, the range of results from ESMs of Intermediate Complexity suggests that thermal expansion contributes between 0.20 and 0.63 m per °C of global mean temperature increase.

The distribution of the eustatic change is not uniform in space. Some regions experience less than the global mean whereas the situation is the opposite for other regions. These regional differences are due to gravitational effects, ocean dynamics, regional differences in water temperature and salinity, winds and air pressure and air sea heat and freshwater fluxes, see Ref. [61] and references therein. Similarly, the isostatic contribution to sea level change varies in space due to variations in loading or unloading by ice or water, and/or unloading and loading due to denudation and sedimentation. Therefore, shoreline migration should be assessed with knowledge of the eustatic and isostatic contributions relevant for the specific region of interest.

4.3.3. Projected climate evolution until 100 ka AP

State of the art AOGCMs and ESMs have not been applied for studies of climate evolution beyond 10 ka AP, since these models are too computationally expensive[12]. However, several modelling studies of climate evolution in the next 100 ka AP have been performed with simplified models (SCMs and EMICs). A question that has engaged many scientists is the timing of the next glacial inception, i.e. initiation of ice sheet buildup. For the purpose of post-closure radiological impact assessments at sites in relevant latitudes, this question is of importance.

Following Ref. [62], seven studies of Earth's climate evolution in the coming 100 to 200 ka, performed with five different EMICs and one SCM, are briefly described here with a focus on the timing of glacial inception. In all the EMIC studies, the models are forced by the known future variations in orbital parameters and different scenarios for future atmospheric CO_2 concentrations. The timing of glacial inception in these different studies is displayed as a function of the atmospheric CO_2 concentration in Figure 14.

In this context it should be mentioned that the results of these models may be sensitive to small disturbances and variations of model parameters [63]. The sensitivity of the results to model parameters has been studied [64]. They found large differences in the simulated ice sheet evolution depending on the chosen parameterization. Further, it had been shown that the timing of the next glacial inception, simulated with conceptual models designed to capture the gross dynamics of the climate system, is sensitive to small disturbances [65], where it was concluded, in agreement with Ref. [66], that the target of developing a dynamical system to convincingly model glacial cycles 'is still elusive'.

[12] However, a new approach has been developed by RWM in support of MODARIA WG6 in which an ensemble of AOGCM simulations is used within the framework of a long term climate emulator to simulate potential patterns of climate evolution over timescales of several hundred thousand years. This approach is described in Section 4.3.4.

In summary, the modelling studies reviewed indicate two potential future timings of the next glacial inception, around 50 ka AP and around 100 ka AP (Figure 14). These timings occur in periods of low summer insolation at high northern latitudes. Low summer insolation is however not sufficient for glacial inception to take place in these models. A further requirement is that the atmospheric CO_2 concentration has decreased from the present high level (almost 400 ppmv) to the pre-industrial (280 ppmv) level or below. As previously mentioned, the uncertainty is large concerning the future atmospheric CO_2 concentrations on these timescales. However, it is not unlikely that a pre-industrial level will be reached at 50 ka AP, and the same is valid also for the period around 100 ka AP.

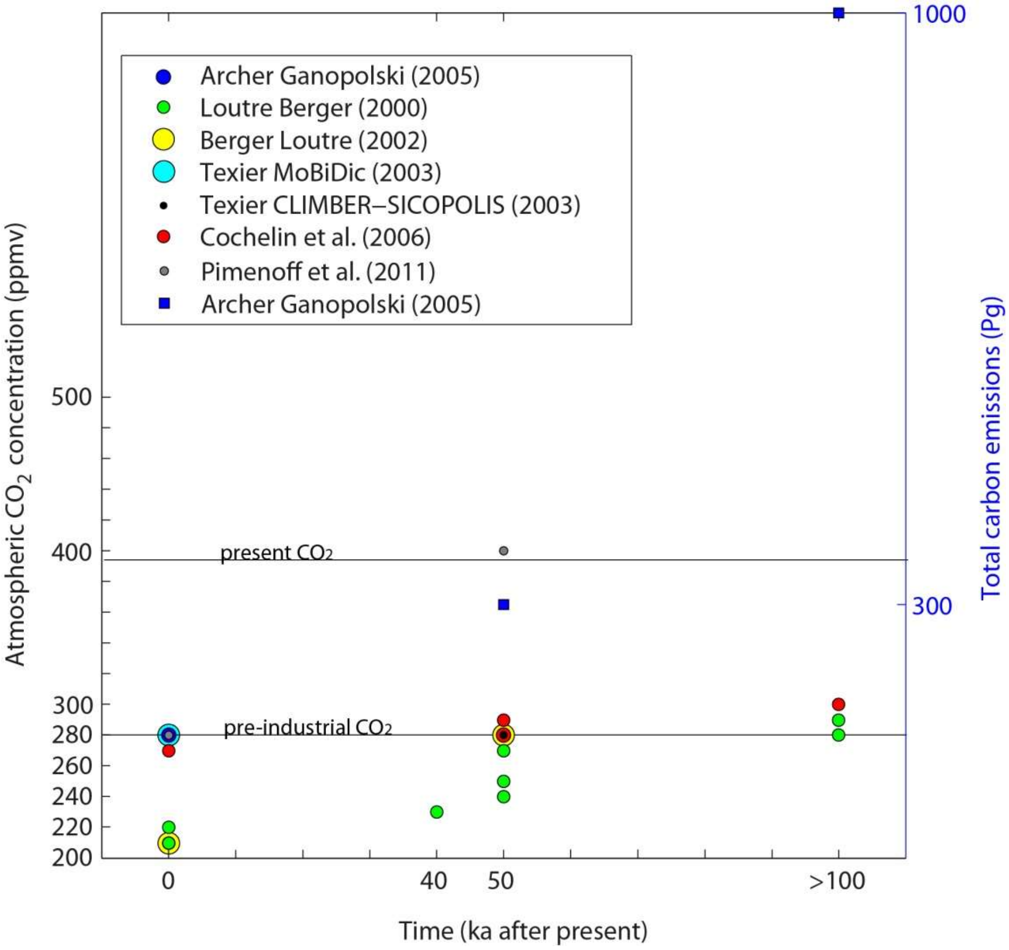


FIG. 14. Approximate timing of glacial inception versus atmospheric CO_2 concentration (circles) or total carbon emissions (squares) for the studies summarized in the text. In these model studies, glacial inception occurs in periods of minima in the incoming summer solar radiation at high northern latitudes, i.e. around circa 0 ka AP, 54 ka AP and 100 ka AP. Reproduced from Ref. [62] with permission courtesy of SKB.

4.3.4. Future climate evolution beyond 100 ka AP

At about 100 ka AP, the effects of anthropogenic greenhouse gas emissions are likely to have substantially diminished and a glacial episode may have occurred (at around 50 ka AP) or be just beginning (see Section 4.3.3). Although EMICs can be run to make projections of climate on timescales of longer than 100 ka, the robustness of such calculations is debatable. A more robust approach for use in post-closure safety assessments can be based on the argument that beyond 100 ka AP the range of climatic conditions experienced at a site is likely to be similar to the range of conditions experienced at that site during the Quaternary, since by that time human perturbations to the climate system due to greenhouse gas and aerosol emissions may have diminished substantially. Furthermore, it seems plausible to assume that the time pattern of changes in climate beyond 100 ka AP is likely to resemble that seen during the Quaternary, i.e. a sequence of glacial–interglacial cycles. If the Late Quaternary is an adequate model for this future period, then the duration of each glacial–interglacial cycle would be about 100 ka, but it is possible that shorter cycles, as occurred earlier in the Quaternary (before about 800 ka BP, see Ref. [67]) might recur. If so, it seems likely that such cycles would exhibit less extreme glacial conditions than those that occurred during the subsequent 100 ka cycles [67].

Although the assumption of 100 ka cycles of an intensity similar to those recorded in the Late Quaternary seems to constitute a reasonable basis for safety assessment beyond 100 ka AP, the timing of such cycles relative to the present day is debatable. However, the precise timing is unlikely to have significant implications for repository safety, as the state of the engineered system and the radioactive inventory will be changing only slowly in the period beyond 100 ka AP (see for example Figure 15).

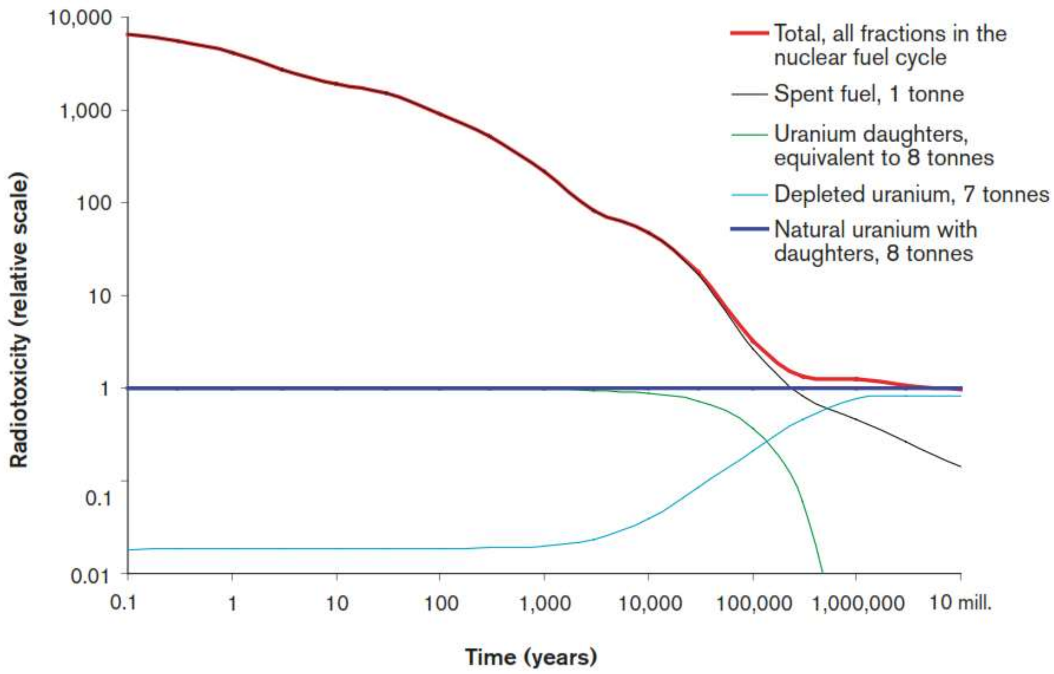


FIG. 15. Radiotoxicity on ingestion of uranium and daughters in ore (blue line), and of the sum of all fractions that arise when the same quantity of uranium is used in the nuclear fuel cycle (red line). The time refers to the time after reactor operation. The different fractions comprise the spent fuel (38 Mega Watt days thermal energy/kg U), the depleted uranium and the uranium progeny that are separated in the uranium mill (Reproduced from Ref. [68] with permission courtesy of SKB).

According to projections from some EMIC modelling (Section 4.3.3), it is reasonable to adopt the position that glacial inception should be taken to first occur at 100 ka AP. This would be followed by a long period of slow, oscillatory cooling resulting in a glacial maximum with maximum continental ice sheet volume at around 180 ka AP, a rapid warming to interglacial conditions at around 190 ka AP and an interglacial episode from 190 ka AP to 200 ka AP. Such a cycle could then be repeated throughout the remainder of the assessment period. The effects of variations in this cycle could be explored in sensitivity studies, e.g. the maximum extent and volume of continental ice sheets could be varied based on the maxima inferred for the various glacial–interglacial cycles that have occurred over the last 800 ka, short intensely cold episodes like the Younger Dryas could be included in the 10 ka warming period following the glacial maximum, and the characteristics of the oscillatory cooling could be varied to give shorter or longer periods of periglacial conditions and different dynamics of ice sheet advance and retreat.

Recently, a new approach to simulating climate on timescales beyond 10 ka AP has been developed at the University of Bristol on behalf of RWM in the UK. This approach is to be used in support of safety assessments undertaken by RWM, but was also developed within the context of MODARIA WG6 to provide a tool for use by other organizations involved in assessing the long term safety of radioactive waste disposal facilities.

The approach is described in detail in Ref. [69]. In brief, a comprehensive set of AOGCM simulations is being undertaken covering the range of insolation conditions and atmospheric carbon dioxide concentrations that could occur over the next one million years. These simulations are being used to build a climate emulator that allows emission scenarios to be translated into time dependent future projections of climate with the spatial resolution of an AOGCM, but covering the next 1000 to 1 million years, rather than the few hundred years that AOGCMs are typically used to simulate. A first ensemble of AOGCM runs has been completed. The boundary conditions for the 40 runs included in this ensemble are listed in Table 4.

Conditions intermediate between these situations can be interpolated using the emulator. However, here it is sufficient to illustrate the considerations that arise by selecting a few of the AOGCM runs for comparison.

In all of these runs, examination of time trends in land and ocean temperatures indicated that the climate system is close to equilibrium at the end of the 500 year simulation period. Therefore, results from the last few decades of each run are taken to be representative of the boundary conditions under which they are run and, for example, can be used to compare the degree of global warming with which those conditions are associated. Figure 16 shows how the change in global annual average land temperature is related to concentration of atmospheric carbon dioxide. This shows a close to linear relationship with little scatter[13]. This is because the influence of orbital factors on global mean temperature is weak in comparison with the range of CO_2 concentrations included in the ensemble of simulations (as shown by the lack of correlations in Figure 17).

At a regional scale, orbital effects may be of greater significance, particularly when seasonal variations in climate are addressed. Nevertheless, as an illustration of the extent to which the climate of the Earth may be impacted by long term climate change, it is appropriate, in the first instance, to neglect orbital effects on insolation, which will be limited over the next 50 000 years [54] and consider how global temperature and precipitation fields will change at different atmospheric carbon dioxide concentrations. This is done by selecting for comparison Run 9 (260.6 ppmv CO_2, which is the lowest concentration simulated and is typical of past interglacial concentrations), Run 29 (362.0 ppmv CO_2, which is a typical concentration during the standard 1961–1990 climate period used in UK analyses), and Run 13 (555.6 ppmv CO_2, which is the

[13] In general, as reported in the literature, this relationship is found to be log-linear, with each doubling of the carbon dioxide concentration giving an approximately equal change in temperature. However, over the limited range of concentrations studied, this approximates to a linear relationship.

maximum value from the ensemble). These three runs have mean annual global land temperatures of 8.5°C, 11.6°C and 14.3°C, respectively[14]. Global patterns of annual SAT and precipitation from these three runs are shown in Figure 18 and anomalies relative to a corresponding standard run with a pre-industrial atmospheric CO_2 concentration of 280 ppmv and present day orbital characteristics are shown in Figure 19. The orbital parameters are the obliquity, esinϖ and ecosϖ. Obliquity is the tilt of the Earth's axis of rotation. esinϖ and ecosϖ refer to the eccentricity (ε) of the orbit combined with the sine and cosine of the longitude of the perihelion (ϖ) with eccentricity being how far the orbit deviates from a circle and the longitude of perihelion being the angular position of the perihelion (closest point in the Earth's orbit to the Sun) from the vernal equinox. The parameters for the 40 runs included in this ensemble are given in Table 4. The parameters for each of the three comparison runs are:

- Obliquity: 23.82 degrees (Run 9); 23.65 degrees (Run 29) and 22.65 degrees (Run 13);
- esinϖ: 0.0298 (Run 9); 0.0274 (Run 29) and 0.0462 (Run 13); and
- ecosϖ: 0.0266 (Run 9); 0.0469 (Run 29) and -0.0104 (Run 13).

[14] Note that these are global land temperatures, so that the difference between the runs is larger than for global land plus ocean temperatures (see Figure 19). Also, the results are applicable after 500 years at the specified concentration, by which time the climate system is close to equilibrium. Differences are smaller at earlier times.

TABLE 4. RUNS INCLUDED IN THE FIRST ENSEMBLE OF AOGCM CALCULATIONS UNDERTAKEN FOR USE WITH THE RWM CLIMATE EMULATOR [69]

Run	Obliquity (degrees)	CO_2 (ppmv)	$e\sin\varpi$	$e\cos\varpi$
1	22.99	375.7	-0.0309	0.0369
2	23.02	516.9	0.0290	0.0143
3	22.81	470.4	-0.0210	0.0433
4	24.03	390.3	0.0535	0.0048
5	23.09	325.3	-0.0269	0.0119
6	23.58	337.5	-0.0056	0.0081
7	23.72	489.2	0.0128	0.0036
8	24.17	346.0	0.0007	-0.0065
9	23.82	260.6	0.0298	0.0266
10	23.39	409.5	0.0332	0.0243
11	22.89	436.6	0.0480	-0.0226
12	23.34	504.4	0.0202	-0.0195
13	22.65	555.6	0.0462	-0.0104
14	23.20	385.1	-0.0006	-0.0367
15	23.96	403.4	0.0149	0.0178
16	24.27	341.1	-0.0406	0.0217
17	22.35	522.1	-0.0390	-0.0028
18	23.91	318.6	-0.0105	0.0346
19	22.33	264.5	-0.0283	0.0393
20	22.94	540.8	-0.0349	-0.0008
21	22.68	531.5	-0.0150	0.0286
22	24.28	446.7	0.0339	-0.0186
23	23.60	310.5	-0.0474	0.0101
24	24.19	548.3	-0.0080	0.0327
25	24.14	425.4	0.0085	0.0414
26	22.20	303.0	0.0035	0.0003
27	22.78	480.4	-0.0037	-0.0059
28	22.72	280.0	-0.0455	-0.0264
29	23.65	362.0	0.0274	0.0469
30	23.24	411.9	-0.0122	-0.0329
31	23.87	287.5	0.0110	-0.0253
32	22.25	365.3	-0.0241	-0.0437
33	22.54	471.1	0.0496	-0.0119
34	22.58	544.5	-0.0375	0.0152
35	22.87	498.2	0.0189	0.0496
36	23.53	507.0	0.0225	-0.0347
37	22.39	393.9	0.0084	-0.0141
38	22.43	484.8	0.0047	-0.0535
39	24.38	418.3	-0.0142	0.0461
40	23.76	528.1	0.0403	-0.0303

Note: The eccentricity (ε) of the orbit is combined with the sine and cosine of the longitude of the perihelion (ϖ), since this gives two variables that are approximately independent in terms of their influence on insolation. The orbital parameter values used cover the full range that could be encountered over the next one million years, but the CO_2 concentrations do not include the highest values that could be attained over the next 100 000 years. These will be studied in a second ensemble of simulations with a restricted range of orbital characteristics. Further ensembles will study cases with Greenland and Antarctic ice sheet configurations differing from that at the present day.

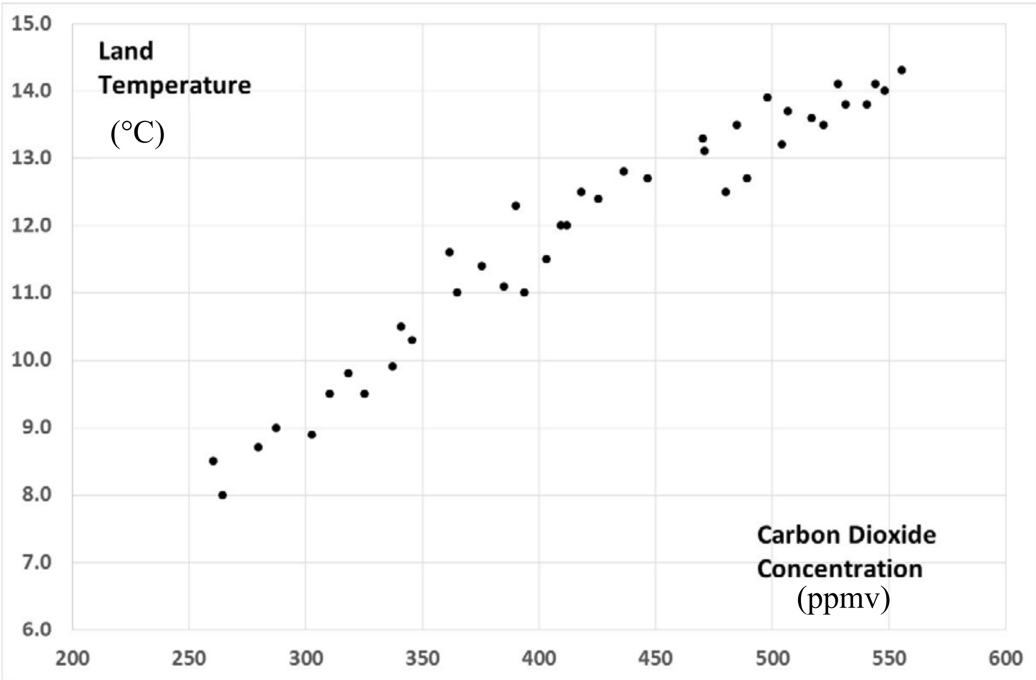


FIG. 16. Relationship between annual average global land temperature (°C) and atmospheric CO_2 concentration (ppmv) for the first ensemble of AOGCM runs. Reproduced courtesy of the Nuclear Decommissioning Authority.

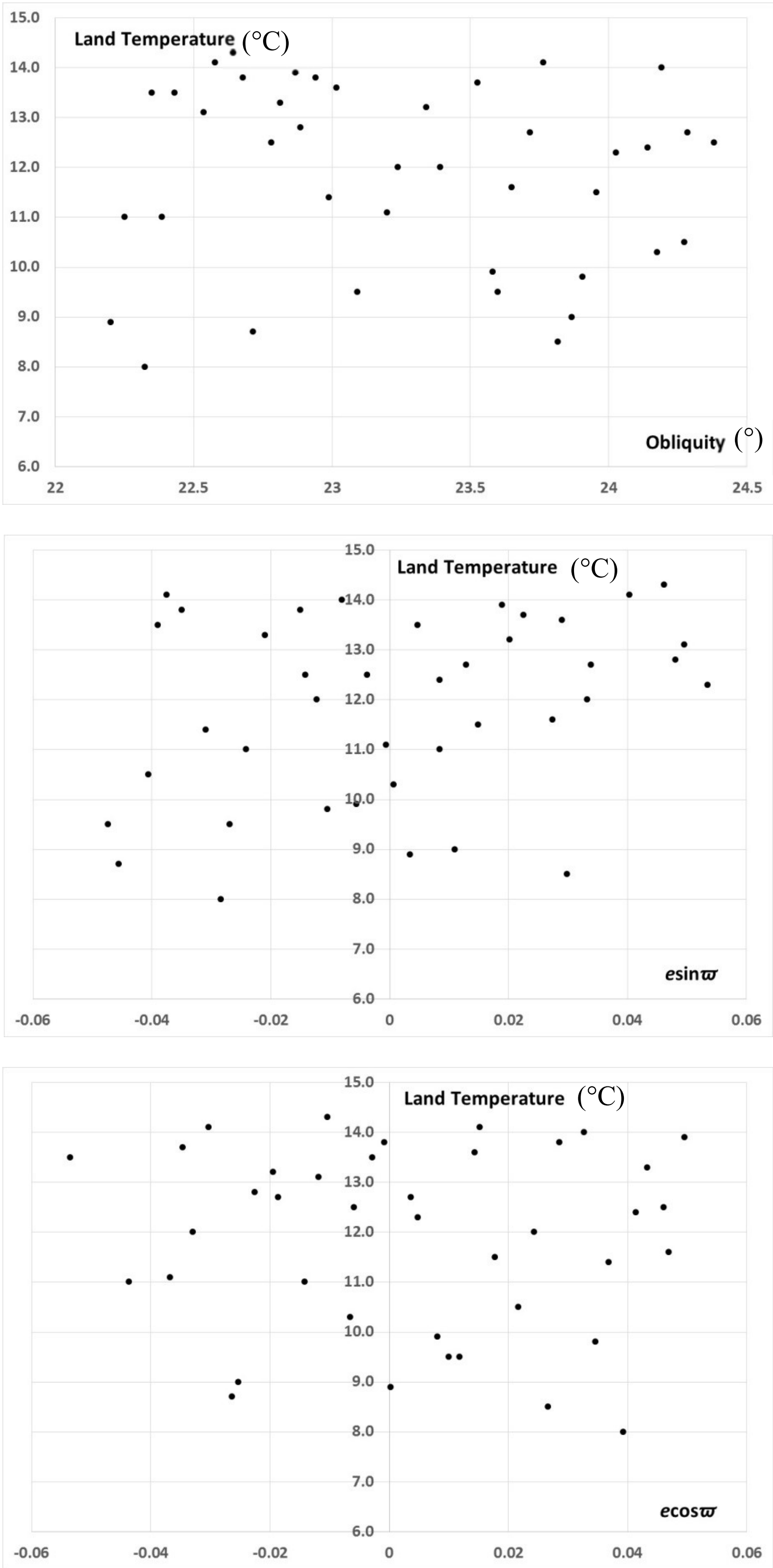


FIG. 17. Relationship between annual average global land temperature (°C) and orbital characteristics for the first ensemble of AOGCM runs. Reproduced courtesy of the Nuclear Decommissioning Authority.

Run 9

Run 29

Run 13

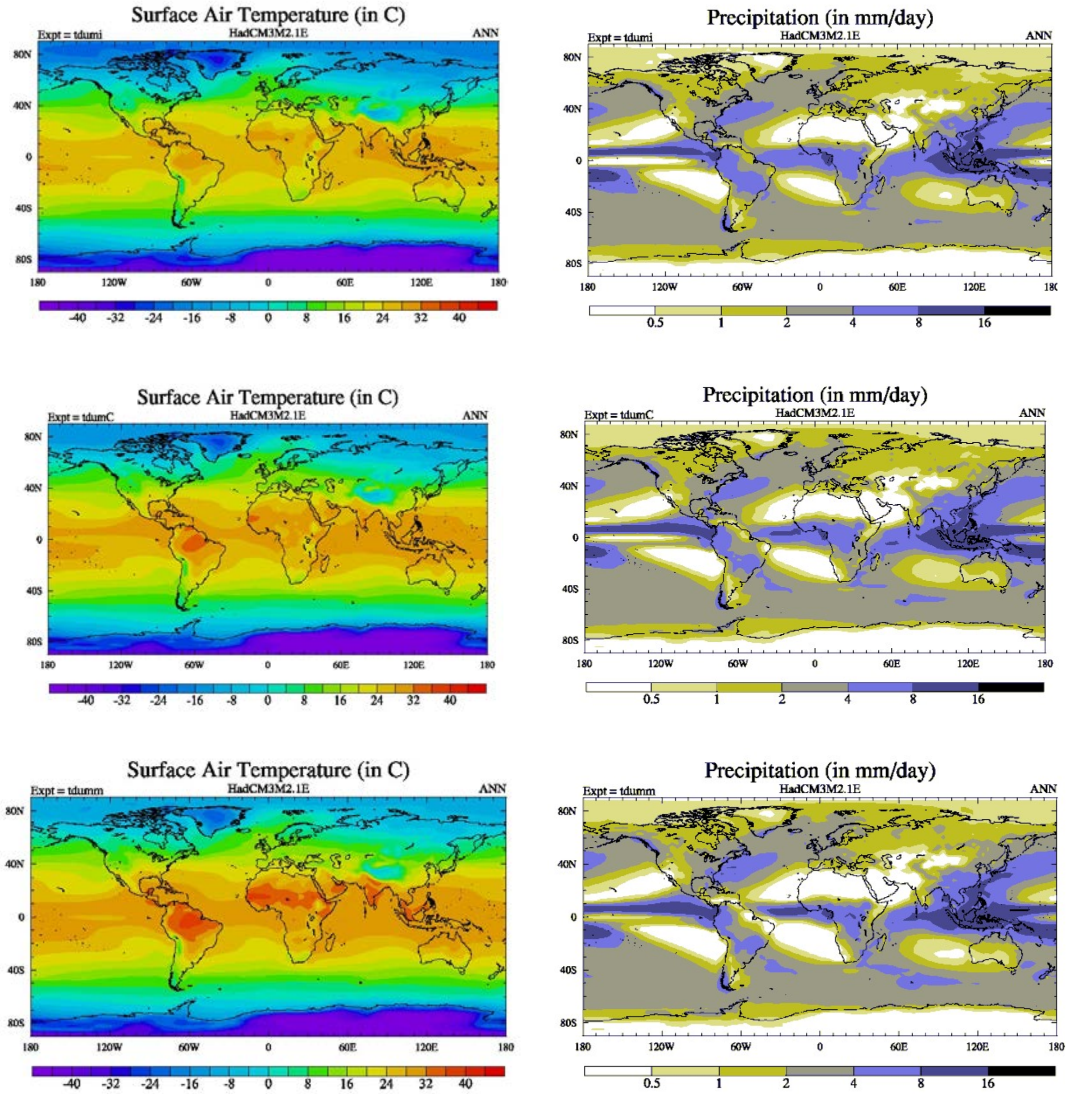


FIG. 18. Global patterns of air surface temperature and precipitation from three runs from the first ensemble. Atmospheric CO_2 concentrations are 260.6, 362.0 and 555.6 ppmv, respectively.

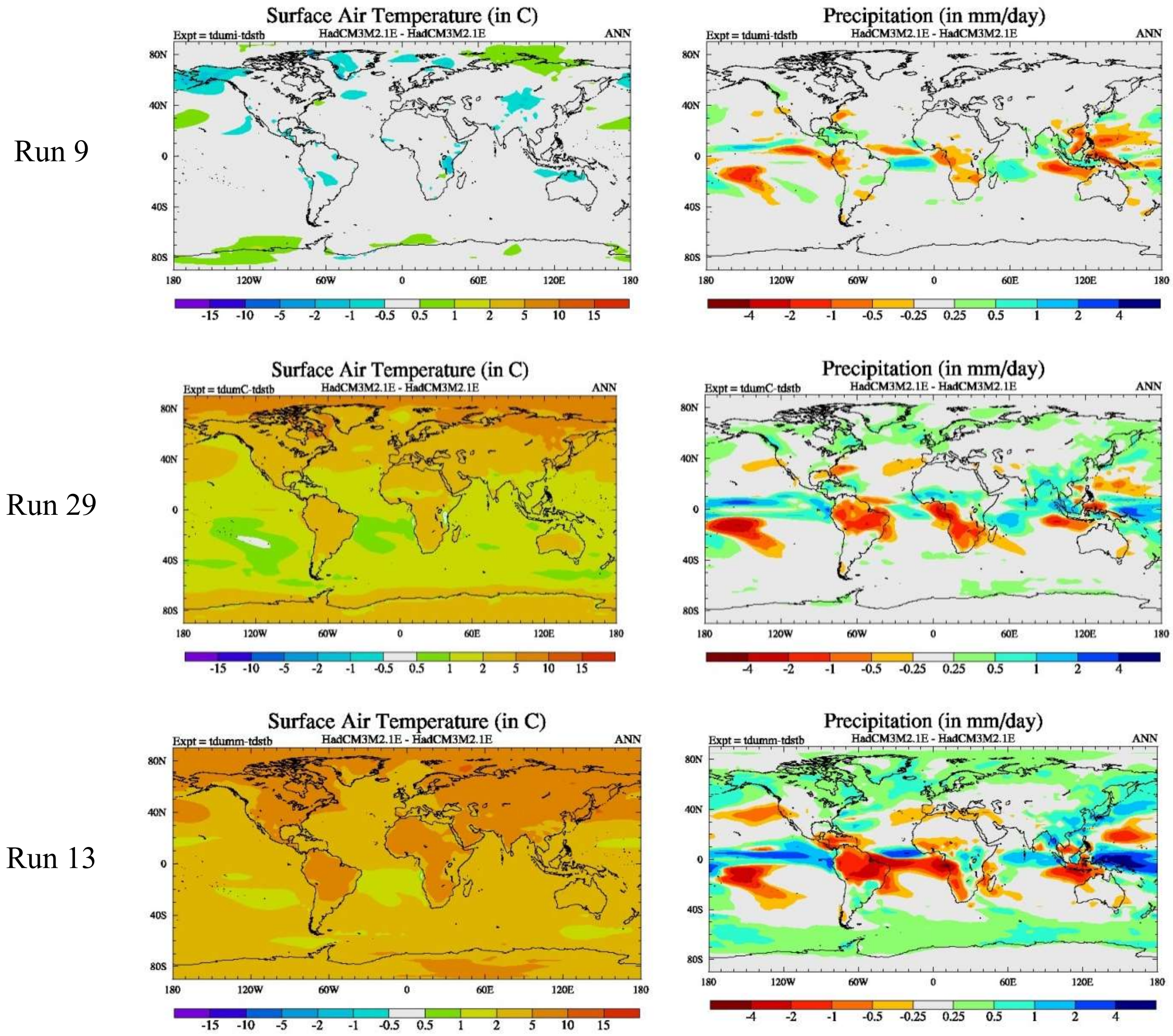
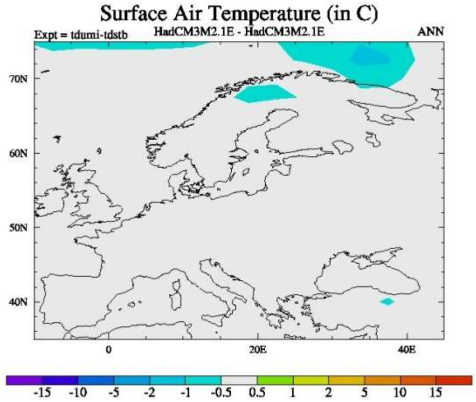
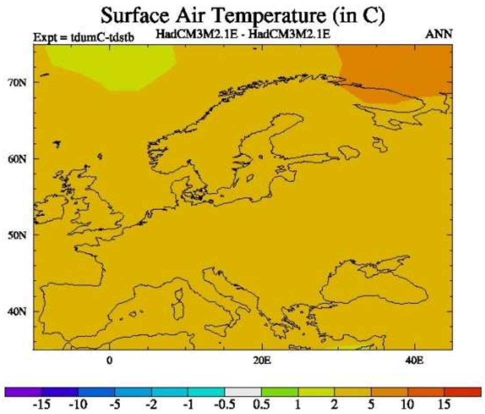


FIG. 19. Global patterns of air surface temperature and precipitation from three runs from the first ensemble expressed relative to a pre-industrial run. Atmospheric CO_2 concentrations are 260.6, 362.0 and 555.6 ppmv, respectively.

Run 9



Run 29



Run 13

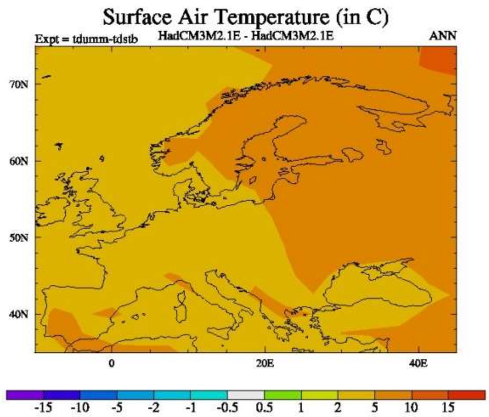


FIG. 20. European patterns of air surface temperature from three runs from the first ensemble expressed as anomalies relative to a pre-industrial run. Atmospheric CO_2 concentrations are 260.6, 362.0 and 555.6 ppmv, respectively. Note that contouring of the results introduces an impression of structural resolution at a spatial scale rather smaller than the intrinsic grid scale of the model.

These values span a substantial part of the ranges sampled, so some of the differences between results at a regional scale may be due to orbital effects rather than the different CO_2 concentrations.

In broad terms, these spatial patterns are very similar, being dominated by the latitudinal gradient, but also having similar regional characteristics, and suggest that a smooth pattern of change across this range of atmospheric carbon dioxide concentrations can be assumed. It would be of interest to examine whether this smoothness of response occurs also when using other climate models, but this was not done as part of the RWM study.

The SAT anomaly across Europe relative to the standard pre-industrial run for these three runs is illustrated in Figure 20. It is clear from Figure 20 that there is only a limited change in SAT gradients across much of Europe between these three runs relative to pre-industrial conditions.

By interpolating between the full range of AOGCM results, the emulator permits time dependent patterns of global and regional climate to be simulated, provided that the boundary conditions applicable remain within the range simulated using the AOGCM. However, the spatial resolution of these time dependent patterns is determined by the spatial resolution of the AOGCM used, which will typically be of the order 100 to 200 km. Thus, downscaling of the results obtained to a local (site) scale of a few kilometers remains to be addressed. This is the subject of Section 5.

4.3.5. Application to future climate in central England

A particular benefit of the emulator is that it can be used to produce time series of climatic variables that cover long periods of time (i.e. several thousand years or more), which would not be feasible using AOGCMs due to the significant time and computational requirements involved. An example of such an application is provided below. For this application, an emulator has been created by the University of Bristol that has been trained on mean annual 1.5 m SAT data produced using the Hadley Centre AOGCM for an ensemble of experiments with comparatively low atmospheric CO_2 concentrations (ranging from 260 to 560 ppmv) and ice sheet configurations characteristic of Quaternary interglacial episodes, i.e. nucleation and development of the Laurentide and Fennoscandian ice sheets, and expansion of the Greenland ice sheet to greater than its present day extent were not addressed. The emulator was then used to project mean annual SAT and precipitation at 1 ka intervals for the next 200 ka to cover a wide range of scenarios that do not involve initiation of the next period of Northern Hemisphere glaciation. The current interglacial is projected to be much longer than previous Late Quaternary interglacials as a consequence of greenhouse gas warming and a variety of studies are ongoing worldwide to estimate the potential duration of this projected episode. The projected evolution of climate is a result of future variations in the three main orbital parameters (eccentricity, obliquity and precession) and atmospheric CO_2 concentrations, which were provided as input data to the emulator (again, at 1 ka intervals). Four CO_2 scenarios were modelled. These adopted logistic CO_2 emissions of 500, 1000, 2000 and 5000 PgC are released over the first few hundred years, followed by a gradual reduction of atmospheric CO_2 concentrations by the long term carbon cycle. These four scenarios covered the range of emissions that might occur given currently economic and potentially economic fossil fuel reserves, but not including other potentially exploitable reserves, such as clathrates.

The evolution of climate for a single grid box is illustrated here, but it is emphasized that a similar set of results could have been presented for any grid box included in the underpinning AOGCM simulations, i.e. coverage of the emulator is worldwide. Similarly, the annual mean temperature and precipitation is presented here, but the emulator can represent any variable output by the AOGCM, and for any season or month. The grid box selected as an example represents central England (52.5N latitude, 0W longitude) and is highlighted in red in Figure 21. The evolution of the mean annual SAT and precipitation for the next 200 ka for that grid box are illustrated in Figures 22 and 23, respectively, for the four CO_2 scenarios. These are shown as anomalies compared with the mean annual SAT and precipitation values for the grid box in the pre-industrial control experiment, which was run to equilibrium, i.e. averages were taken over the latter part of the simulation when long term equilibrium had been established. The control simulation used present day insolation values and a pre-industrial CO_2 concentration of 280 ppmv. The presentation of anomalies relative to a reference run is preferred, because the calculation of such anomalies is more robust than of absolute values, since it largely eliminates the effects of systematic biases in the underpinning AOGCM. For comparison, the mean annual SAT for central England in the late twentieth century was about 10°C and the mean annual precipitation was about 700 mm. Pre-industrial values were similar to these [69].

Across the four experiments, the maximum temperature increase in the central England grid-box was between 2.8 and 9.5°C and the maximum increase in precipitation was between 0.17 and 0.49 mm day^{-1} (or 60 to 180 mm y^{-1}) in the 500 PgC and 5000 PgC scenarios, respectively. This peak in temperature and precipitation occurs up to the first thousand years, when atmospheric CO_2 is at its highest following the emissions period, after which both decrease with declining atmospheric CO_2 until around 20 ka AP. Until this time, behaviour of the climate is primarily driven by the high levels of CO_2 in the atmosphere caused by fossil fuel emissions and other human activities. However, after this time, changes in orbital conditions appear to exert a greater influence on climate, as the periodic fluctuations in SAT at this location have a time span of approximately 40 ka, the same as obliquity. The peaks in SAT generally coincide with periods of high obliquity, a result of the increase in solar radiation received at these higher latitudes in summer, with some precessional pacing apparent after ~120 ka, as well as before this time in the 5000 PgC scenario. The influence of declining CO_2 is still evident after 20 ka, particularly for the higher emissions scenarios, in the slightly negative gradient of the general evolution of SAT. Due to its periodicity of slightly less than 25 ka, precipitation appears to be more closely influenced by precession, with peaks in precipitation generally coinciding with periods of high precession. However, an increase in the intensity of precipitation fluctuations from approximately 140 ka onwards suggest eccentricity also has an impact, as it is relatively high over this period. The impact of excess atmospheric CO_2 on the long term evolution of climate appears to be fairly linear, as no significant differences are evident between the scenarios, discounting the overall offset of SAT and precipitation for different total emissions. However, it is not certain that an AOGCM at relatively low resolution captures possible non-linear responses of the ocean circulation.

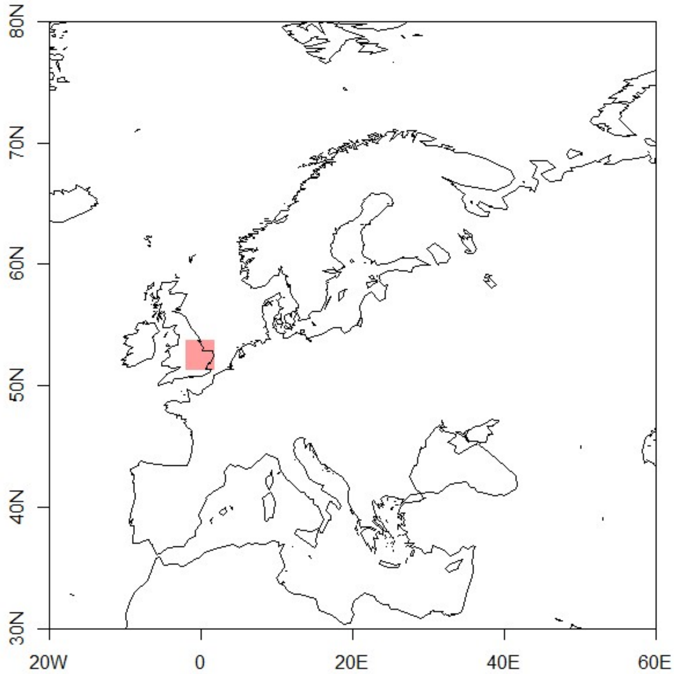


FIG. 21. Map of Europe highlighting the grid box that represents central England.

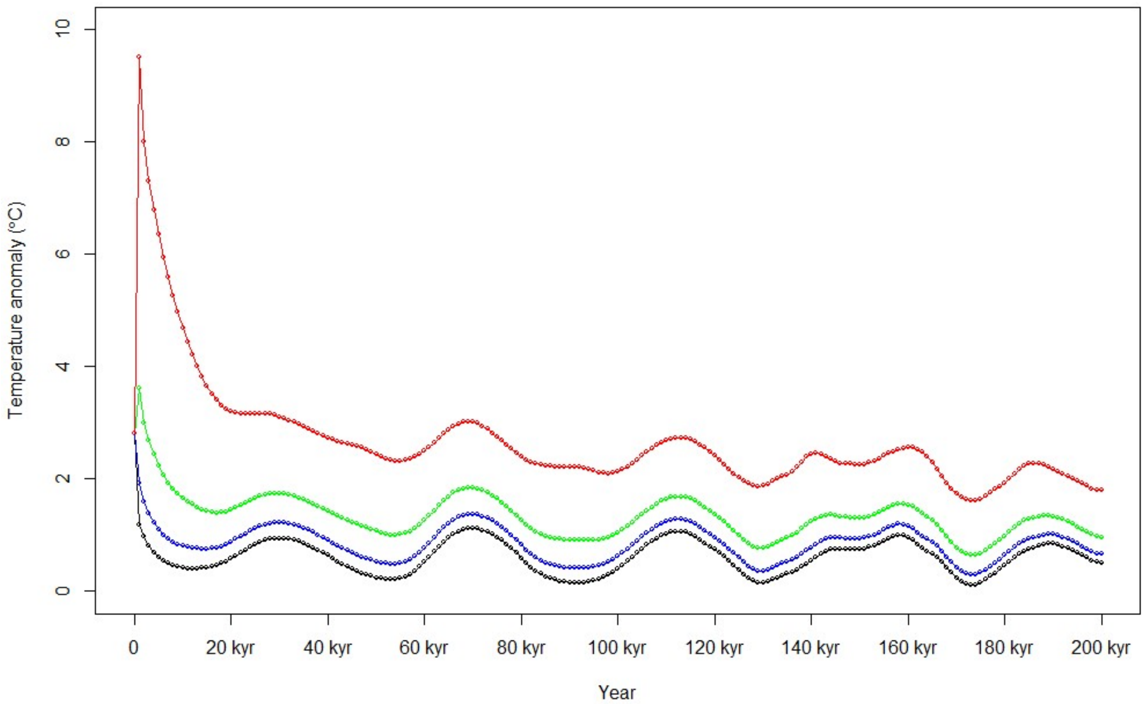


FIG. 22. Mean annual 1.5 m SAT for the central England grid box for the next 200 ka (denoted as kyr in the figure). Each series represents a CO_2 scenario; 500 PgC (black), 1000 PgC (blue), 2000 PgC (green) and 5000 PgC (red). Temperature is shown as an anomaly compared with the pre-industrial control experiment.

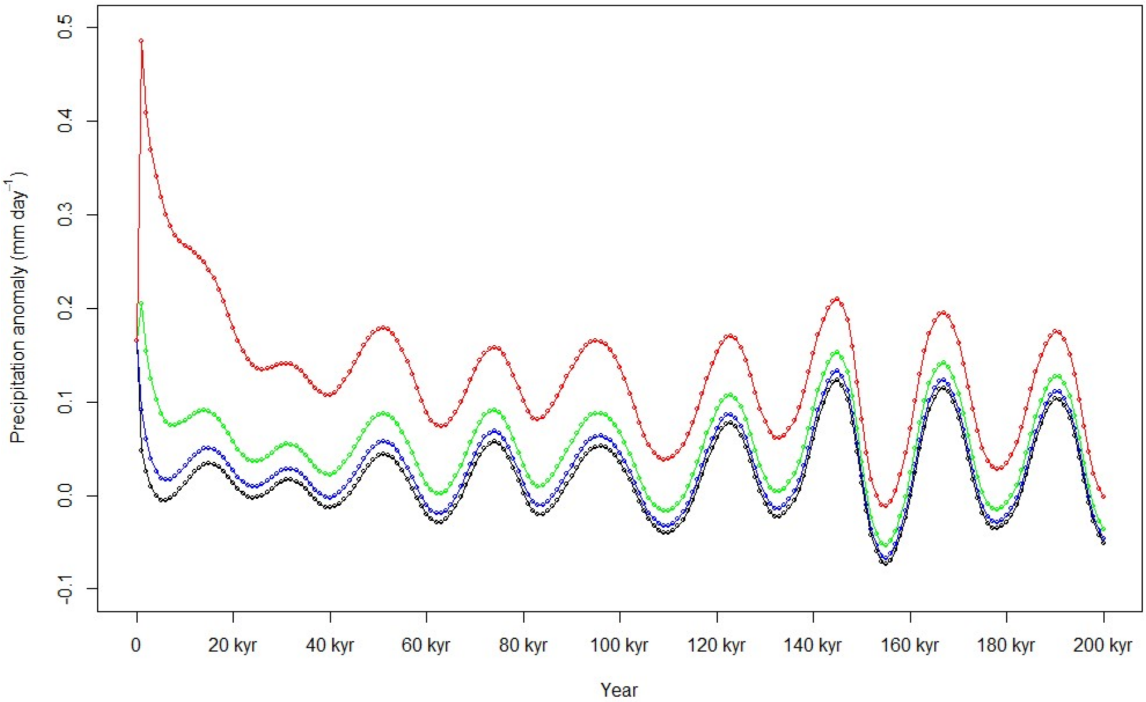


FIG. 23. Time series of mean annual precipitation for the central England grid box for the next 200 ka (denoted as kyr in the figure). Each series represents a CO_2 scenario; 500 PgC (black), 1000 PgC (blue), 2000 PgC (green) and 5000 PgC (red). Precipitation is shown as an anomaly compared with the pre-industrial control experiment.

5. DOWNSCALING GLOBAL CLIMATE

This Section focusses on downscaling aspects of step 5 in the methodological road map as shown in Figure 24.

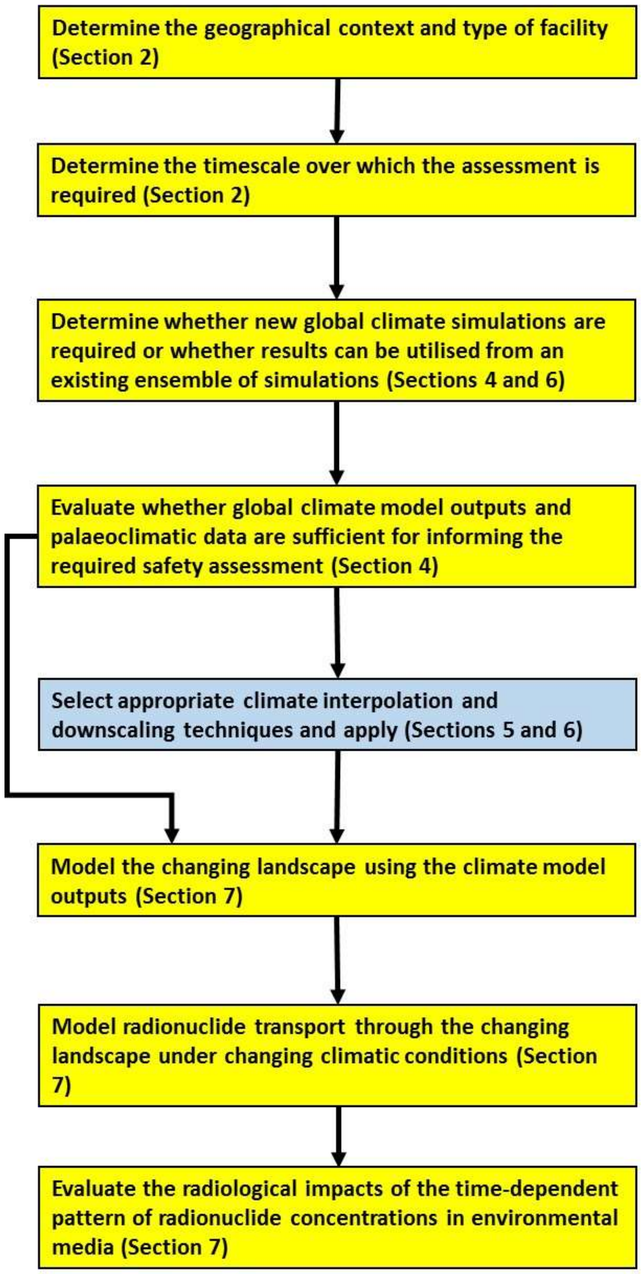


FIG. 24. Road map for performing an assessment taking climate change and landscape development into account.

Both AOGCMs and EMICs provide climatic outputs at a coarse spatial scale, typically on a 100 km × 100 km grid or larger. This limitation also applies when a climate emulator is used for long term simulations to interpolate between results from individual AOGCM calculations (see Sections 4.3.4 and 4.3.5). There is, therefore, a need to downscale the results to obtain results applicable to a local area or a specific site. In broad terms, three approaches to downscaling exist. These are dynamical downscaling, physical–statistical downscaling and rule based downscaling. All three of these approaches were used in the BIOCLIM project and they are discussed in that context and in general terms below, before giving consideration to more recent work on this topic.

5.1. DOWNSCALING APPROACHES USED IN BIOCLIM

5.1.1. Dynamical downscaling

In dynamical downscaling, the approach is to embed (or nest) a Regional Climate Model (RCM) within an Atmosphere–Ocean General Circulation Model (AOGCM), matching the boundary conditions of the RCM with output from the AOGCM. Typically, RCMs have a resolution of a few tens of kilometers, though several studies have recently been undertaken at a resolution of around 1 km [70]. As a point of reference, HadRM3, which is the Hadley Centre UK Meteorological Office RCM, was used to produce ~25 km scale future projections of climate in the UK as part of the UKCIP09 project [71]. Thus, dynamical downscaling can only be used for situations for which an AOGCM is to be used (either by nesting an RCM computationally with the AOGCM or by exporting very detailed datasets from the AOGCM to provide boundary conditions for one or more runs of that RCM). For long term safety assessments, one possibility is that AOGCM simulations are used to provide transient simulations of climate over the next few thousands of years and snapshots or transient simulations of periods of particular interest, as identified from studies using EMICs, at more distant future times (see Figure 12 above). Alternatively, a climate emulator may be used to provide interpolated AOGCM results over very long timescales. However, with the emulator approach it would be extremely difficult to generate sufficiently detailed outputs to use as boundary conditions for subsequent RCM calculations. From the above, it can be seen that dynamical downscaling will typically deliver climatic results with a resolution of about 25 km. This is likely to be adequate in regions of subdued topography, where the dominant effect that has to be taken into account is the regional climate gradient. However, in mountainous districts, altitude and aspect may have a significant effect, as illustrated in the detailed, instrumentally based climatology of the British Isles [72] or the more recent UKCIP09 5 km gridded climatology [73], see Figure 25 and Figure 26. Thus, it may be necessary to combine dynamical downscaling with physical–statistical downscaling at the smallest scales. The alternative is to use a very high resolution RCM, which is likely to be prohibitive in resource terms, given the range of situations that will often need to be represented. Furthermore, physical–statistical downscaling may be used directly with AOGCM results. This is the approach being adopted by RWM in its new climate emulator, since this provides synthetic AOGCM results applicable over the full assessment timescale. Physical–statistical downscaling is discussed further below.

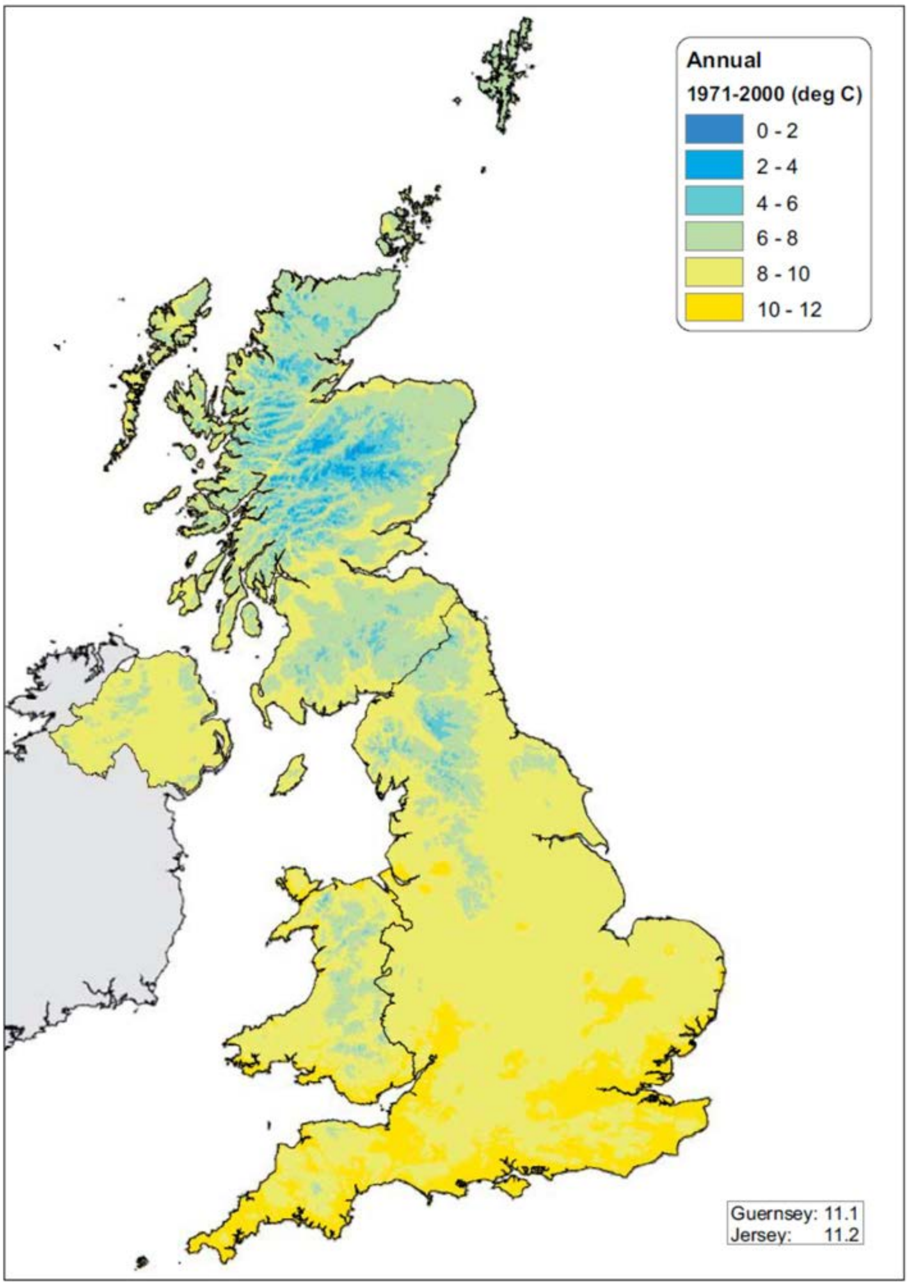


FIG. 25. Mean annual temperature over the British Isles from 1971 to 2000 from the UKCIP09 5 km gridded climatology [73].

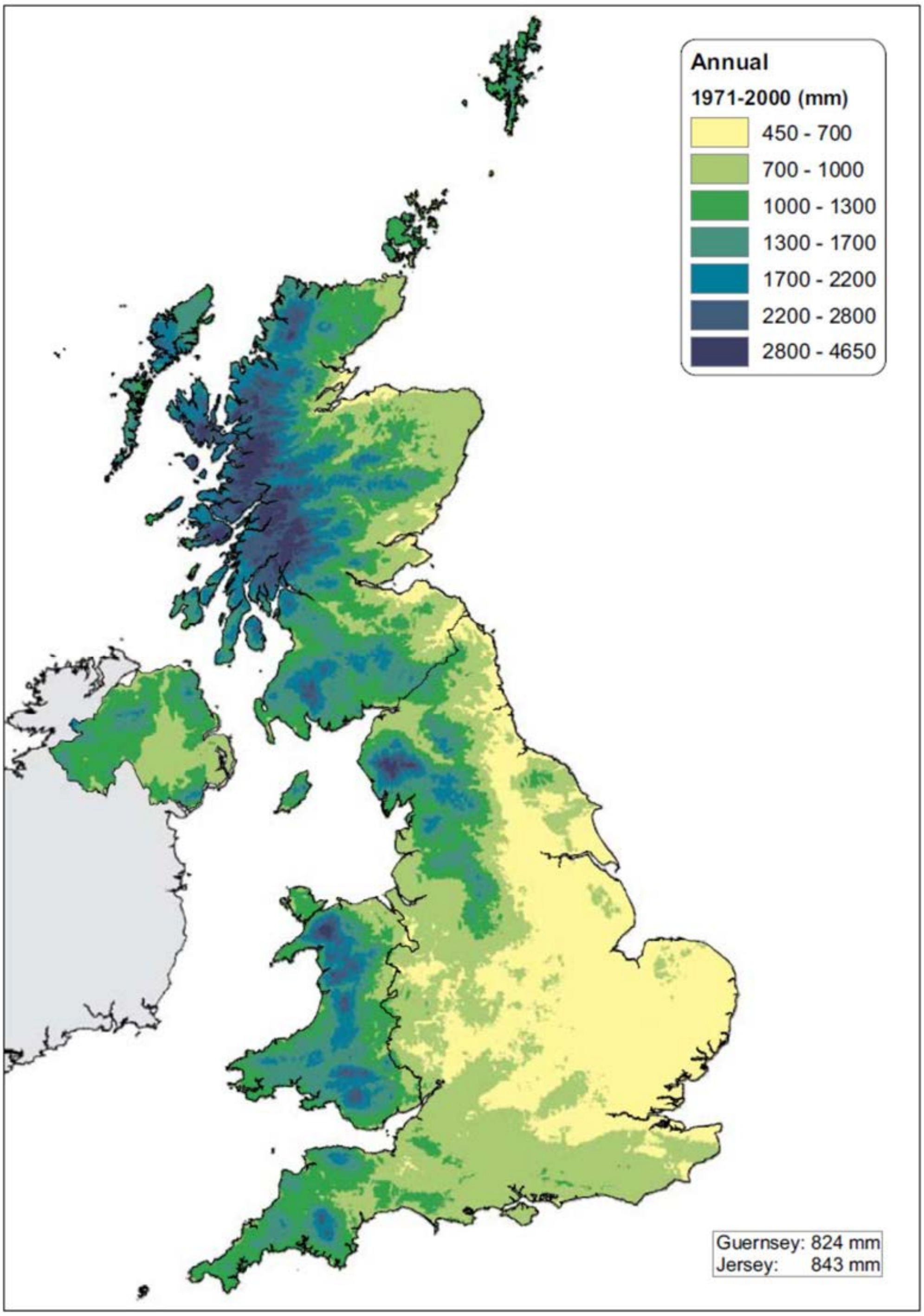


FIG. 26. Mean annual precipitation over the British Isles from 1971 to 2000 from the UKCIP09 5 km gridded climatology [73].

5.1.2. Physical–statistical downscaling

In statistical downscaling (which includes physical–statistical downscaling), relationships between local surface climate variables (for example, daily or monthly precipitation and temperature) and larger scale climate variables (for example circulation of the atmosphere) are empirically derived with observed data and used with ECM or AOGCM large scale output to generate local scale climate projections. An assumption is made by this approach that, in a changed climate, the large scale and regional/local scale variables have relationships that remain valid (often this is known as the assumption of stationarity).

The alternative approaches that were available at the time of BIOCLIM [3, 74] included multiple regression; artificial neural networks; canonical correlation analysis; non-parametric models; studies in which circulation classifications are used to describe the large scale climate; stochastic weather generators; and analogue methods.

Subsequent to BIOCLIM and the IPCC Fourth Assessment Report, the development of statistical downscaling has been quite vigorous [6] and many state of the art approaches combine different methods. In particular, there is an increasing number of studies on extremes and on features such as hurricanes, river flow and discharge, sediment, soil erosion and crop yields. Techniques have also been developed to consider multiple climatic variables simultaneously in order to preserve physical consistency. Various methods have been used to evaluate statistical downscaling approaches and these have included metrics related to intensities, temporal behaviour and physical processes, as well as secondary variables such as runoff, river discharge and stream flow [6].

In principle, physical–statistical downscaling can be used with AOGCM results or EMIC results. In BIOCLIM, a physical–statistical approach was applied to downscale results from the CLIMBER-GREMLINS (CLIMate-BiosphERe - GRenoble Model for Land Ice in the Northern hemisphere) EMIC. The approach was termed physical–statistical because it proceeded in two steps. First, physical considerations were used to define variables (predictors) that were expected to have links with climatological variables (those adopted were continentality and topography); secondly, a generalized additive statistical model was used to find the links between these predictor variables and the high resolution climatology of temperature and precipitation for Europe that was available. Thus, the method involves physically based assumptions to compute predictors from model variables and then relies on statistics to find empirical links between these predictors and the climatology. These 'physically based assumptions' were necessary because the climate data were provided by an EMIC that gives only limited information about space and time variability and provides only coarse data at a global scale that cannot be directly linked to regional climate change. A similar physical–statistical approach could also be used to downscale results from a RCM to local areas of a few kilometers extent using a high resolution gridded climatology such as that described by Ref. [73].

For Europe, an appropriate gridded climatology is available from The European Climate Assessment & Dataset (ECA&D) project. This provides information on changes in weather and climate extremes, as well as the daily dataset needed to monitor and analyse these extremes. ECA&D was initiated by the European Climate Support Network[15] in 1998 and has received financial support from the EUMETNET[16] and the European Commission. ECA&D receives data from 61 participants for 62 countries and the ECA dataset contains 36980 series of

[15] The objective of the European Climate Support Network is to organize improved cooperation of its members in the field of climate and related activities in order to expand their capabilities to support the European user community through enhanced provision of: a) high quality climate data and products, b) services and advice based on the climate expertise of its members.

[16] EUMETNET is a grouping of 29 European National Meteorological Services that provides a framework to organize cooperative programmes between its members in the various fields of basic meteorological activities.

observations for 12 elements at 7848 meteorological stations throughout Europe and the Mediterranean. Furthermore, 61% of these daily series can be downloaded from this web site for non-commercial research and education. Participation in ECA&D is open to anyone maintaining daily station data.

A recent product from the ECA&D project is E-OBS version 8.0. E-OBS is a daily gridded observational dataset for precipitation, temperature and sea level pressure in Europe based on ECA&D information. The full dataset covers the period 1 January 1950 until 31 December 2012[17]. It was originally developed as part of the ENSEMBLES project[18] and is now maintained and elaborated as part of the European Reanalysis and Observations for Monitoring (EURO4M) project[19].

Useful guidance is provided on the temperature and precipitation data included in E-OBS in Ref. [75] and extensive illustrations of these data are provided in Ref. [69].

5.1.3. Rule based downscaling

Although statistical downscaling was used in BIOCLIM, as one aspect of the project was to investigate the power of different downscaling methodologies, the main emphasis in the final interpretation of the results from the EMIC simulations was by the use of rule based downscaling [76, 77].

The rule based methodology assigned a climate class from the Køppen–Trewartha scheme [78] to a region for each time of evaluation according to a combination of simple threshold values that were determined from the EMIC that was being used. Once climate classes had been defined, monthly temperature and precipitation characteristics were constructed using analogue stations identified from a database of present day climate observations. The Køppen–Trewartha scheme that was used has the advantage of being widely adopted and empirical, and only requires monthly averages of temperature and precipitation as input variables (see Table 5).

[17] Subsequent updates are available. In application, it would be appropriate to use the most recent version of the E-OBS dataset available, as this would provide the longest available period of daily data.

[18] The ENSEMBLES project was a 5 year programme involving 66 partners from across Europe. Led by the UK Meteorological Office, and funded by the European Commission, it studied the likely effects of climate change across Europe as a whole. The project has provided: an ensemble prediction system giving the first probabilistic climate projections of temperature and rainfall changes this century; an assessment of the impact of climate change on a range of sectors including agriculture, health, energy, water resources and insurance relevant to decisions being made today; a clearer picture of the physical, chemical, biological and human related feedbacks in the climate system and how to represent them in models that will increase certainty in climate predictions; the development of the first high resolution climate observation datasets for Europe that can be used to validate ensemble predictions.

[19] www.euro4m.eu – EURO4M is an EU project that provides timely and reliable information about the state and evolution of the European climate. It combines observations from satellites, ground based stations and results from comprehensive model based regional reanalyses.

TABLE 5. KØPPEN–TREWARTHA CLIMATE CLASSIFICATION SCHEME BASED ON REF. [78] AND TAKEN FROM BIOCLIM [76]

Climate type	Temperature	Precipitation
A tropical climates	Over 17°C in all months	Ar tropical rain Am tropical monsoonal rain Aw tropical summer rain As tropical winter rain
C subtropical climates	Over 9°C 8–12 months	Cr subtropical rain Cw subtropical summer rain Cs subtropical winter rain
D temperate climates	Over 9°C 4–7 months	DO temperate oceanic DC temperate continental
E subarctic climates	Over 9°C 1–3 months	EO subarctic oceanic EC subarctic continental
F polar climates	Over 9°C no month	FT tundra FI Ice
B dry climates	Evaporation > precipitation	BS steppe BW desert BM marine desert

To a large extent, the indicator variables and their thresholds were assigned based on general reasoning and a comparison of palaeo–climatic data with model simulations of the relevant period (MoBidiC, a sector based EMIC was the model used). For central England and northern France, the indicator variables were mean annual (and, if necessary, monthly) temperature for the Eurasian continental sector at 50 to 55°N and the Northern Hemisphere ice volume. For future greenhouse warmed conditions without corresponding analogues, a rather different approach was used. Thus, for example, for central England (broadly corresponding to Lowland Britain in geographical terms), the temperate/subtropical boundary (DO/Cr in the Køppen–Trewartha scheme) was selected by identifying the maximum 50 to 55° Eurasian continental sector temperature simulated by MoBidiC over the last glacial–interglacial cycle and taking a slightly higher value (based on the argument that the coolest subtropical climate class did not occur over this period).

Because rule based downscaling only identifies a sequence of climate classes appropriate to a particular region or location, a further step in the procedure is required to assign quantitative climatic characteristics to the region or location for each climate class. This is done by identifying instrumented climate stations that are, at the present day, associated with each specific climate class of relevance. However, when selecting appropriate climate stations, it is not sufficient that they should be associated with the specific climate class. In addition, they have to be located in an appropriate geographical context. Thus, for example, in BIOCLIM [76] only lowland (altitude less than 200 m) stations were selected as representative of central England. In addition, further specific selection rules were applied in relation to the individual climate classes. Thus, for the coldest (FT) class, stations were selected that were south of 67°N, as an extended polar night would not be characteristic of central England in any circumstances. In addition, individual stations were also excluded from employment as analogues on a case by case basis. Thus, two stations from the Azores, for example, were considered unsuitable as Cr analogues because of their hyper-oceanic conditions, and Bodo and Orland in Norway were considered unsuitable as DC analogues because of heavy winter precipitation that might be more representative of western Britain than central England.

5.2. WORK ON DOWNSCALING SUBSEQUENT TO THE BIOCLIM PROJECT

Several initiatives on downscaling have been undertaken since BIOCLIM and globally an ongoing programme of research in this area is coordinated through CORDEX[20]. CORDEX is a World Climate Research Programme (WCRP) initiative. Its sponsors include the World Meteorological Organization, the International Council for Science and the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization.

The CORDEX initiative arose because it was recognized that both dynamical and statistical downscaling were beginning to be widely used in climate change research, but this growth in applications was occurring, to some degree, through numerous independent local efforts targeted at very specific regional to local needs. As a result, a large heterogeneity of different approaches was emerging, with little formalized guidance on best practices to be used and common pitfalls to be avoided. This created a risk that newcomers to the field, would utilize data from methods of questionable quality, over interpret levels of certainty or exaggerate apparent spatial detail, with potential negative consequences for subsequent impact, adaptation and vulnerability studies [79].

Recognizing these risks, the WCRP established a Task Force on Regional Climate Downscaling whose mandate was [79] to:

- Develop a framework to evaluate and where possible improve techniques for use in downscaling global climate projections;
- Foster an international coordinated effort to produce improved multi-model based high resolution climate change information and related uncertainties, over regions worldwide, for input to impact, adaptation and vulnerability studies;
- Promote greater interaction and communication between the climate modelling and end user communities, in order to better support impact, adaptation and vulnerability studies and national to regional decision making.

The Task Force, in consultation with the wider community, developed the Coordinated Regional Downscaling Experiment, or CORDEX, framework to directly address points 1 and 2 of the mandate and to initiate efforts to address point 3.

As part of the global CORDEX framework, the EURO-CORDEX initiative[21] provides regional climate projections for Europe at 50 km (EUR-44) and 12.5 km (EUR-11) resolution, thereby complementing coarser resolution data sets produced through former activities, such as the EU sponsored PRUDENCE and ENSEMBLES projects. The regional simulations downscale the recent CMIP5 global climate projections [80] and the new Representative Concentration Pathways (RCPs) [81, 82]. Twenty-six modelling groups contributing 11 different RCMs, partly in different model configurations, actively support EURO-CORDEX [83].

In its initial phase, EURO-CORDEX mainly focused on model evaluation in present day climate [84]. So far[22], more than 30 evaluation simulations have been conducted. Further activities include the coordinated analysis of future climate simulations, the joint analysis of

[20] http://www.cordex.org/
[21] http://www.euro-cordex.net/
[22] Meaning, at the time the WG6 report was submitted by WG6 participants to IAEA for publication.

dynamical and empirical statistical methods and the design of suitable bias correction techniques to tailor EURO-CORDEX data for direct application in climate impact research. Particular emphasis is put on the construction of a simulation matrix that covers uncertainty in emission scenarios, the driving global climate model and the downscaling method in the best affordable manner.

A number of regional limited area models were used in the ENSEMBLES project to downscale transient global climate projections over Europe at a 25 and 50 km resolution over the second half of the twentieth century and into the twenty-first century. The ENSEMBLES climate projections were carried out under the assumptions of the IPCC SRES A1B scenario. This scenario follows the storyline of the IPCC family of A1 scenarios. It assumes rapid economic growth and technological development, with a worldwide population peaking in the middle of the twenty-first century, and a balanced use of energy resources. This scenario leads to a rapid increase in fossil CO_2 emissions until 2050 and a decrease afterwards. As compared with other SRES scenarios, the CO_2 emissions lie in the middle of the scenario range.

EURO-CORDEX scenario simulations use the new RCPs defined for the Fifth Assessment Report of the IPCC [81]. In contrast to the SRES scenarios, RCP scenarios do not specify socioeconomic scenarios, but assume pathways to different target radiative forcings at the end of the twenty-first century. For instance, scenario RCP8.5 assumes an increase in radioactive forcing of 8.5 W m^{-2} by the end of the century relative to pre-industrial conditions. A comparison between the climate effects of SRES and RCP scenarios indicated that the A1B scenario leads to a global mean temperature increase in the likely range of 2.8 to 4.2°C, which approximates to RCP6 and lies clearly between RCP4.5 and RCP8.5.

The analysis carried out in Ref. [83] addressed the changes in annual mean temperature and total precipitation for the scenarios A1B, RCP4.5 and RCP8.5. In addition to the mean values, a range of climate indices important for climate impact studies in different sectors were calculated for subregions of Europe including heavy precipitation events, dry spells and heat waves.

Seven different RCMs and five different General Circulation Models (GCMs) were used [83]. Two of the RCMs were driven by four/five different GCMs; five GCM–RCM chains were used to simulate both RCP scenarios. They all provided data at least until the middle of the twenty-first century. Eight RCP4.5 simulations and nine RCP8.5 simulations were continued out to the end of the century.

From the ENSEMBLES data set, 20 transient RCM simulations reaching the end of the century are used for most of the analysis. Maximum and minimum temperature values were only available from nine simulations. The ensemble included simulations on 50 and 25 km grid scale, but most simulations were carried out on a 25 km grid (16 out of 20 and 7 out of 9). The coarser resolution simulations were included to enlarge the sample size for the statistical analyses. A sensitivity study using only the 25 km simulations for the analyses of changes in the mean fields of temperature and precipitation and in the indices showed that there are only minor differences in the horizontal pattern of the meteorological parameters as well as in the regions with a significant and/or robust change.

The significance and robustness of changes in climate were tested using a method adapted from Ref. [85]. This method identifies regions with relatively strong and robust climate changes from an ensemble of climate change simulations. It can be applied to simulation results on regular model grids or to data aggregated onto larger regions.

Here results are illustrated only for mean annual temperature and total annual precipitation. Results indicate robust and statistically significant warming, with regional differences, in the range of 1 to 4.5°C for RCP4.5 and of 2.5 to 5.5°C for RCP8.5. These ranges encompass the warming range projected for the A1B scenario, where temperature increases between 3 and 4.5°C were projected. The projected spatial patterns are very similar in all scenarios with greater annual mean warming in southern Europe and towards the north-east. Under RCP8.5, large parts of northern Scandinavia, eastern Europe and the Alpine ridge might be exposed to a warming of more than 4.5°C compared with 1971–2000. This could be avoided if RCP4.5 was achieved.

Associated with the large increase in temperature in RCP8.5 are robust changes in annual precipitation. The ensemble mean projects a statistically significant increase in large parts of central Europe and northern Europe of up to about 25 % and a decrease in southern Europe.

The pattern of the changes is very similar for RCP4.5, but is less pronounced. The spatial pattern for A1B precipitation changes qualitatively agrees with the changes for RCP4.5 and RCP8.5, and the magnitude of the changes mostly lies in between the two RCPs. However, differences in the spatial patterns are seen over the British Isles, Benelux and Germany.

For mean temperature and precipitation change, a spatial correlation analysis was undertaken between RCP8.5 and A1B results. For all subregions, the spatial correlation is very high, at 0.82 to 0.97 for temperature changes and 0.59 to 0.92 for precipitation changes, depending on the region, at the middle of the twenty-first century. Towards the end of the century, the correlation is even stronger for both parameters.

5.3. ILLUSTRATIVE APPLICATION OF SPATIAL DOWNSCALING

Physical–statistical downscaling for application in safety assessments of the disposal of solid radioactive wastes has recently been studied in detail on behalf of RWM for geological disposal in the UK [69], building on and substantially extending earlier work [72]. The approach uses the 5 km resolution gridded climatology of the UK reported in Ref. [73] in combination with a 50 m resolution digital elevation map that was processed to yield various altitude related variables at the same 5 km grid scale as was used for the climate data. Physical arguments were used to identify various combinations of location and altitude related parameters that could be used to explain the spatial variability in mean monthly temperature and precipitation[23]. The usefulness of these various combinations was then explored through a multiple linear regression approach using a least squares minimization of differences between observed and predicted climate characteristics over all 5 km by 5 km elements of the gridded climatology.

For mean monthly, and mean annual, temperature, the most useful explanatory variables were found to be distance east from the grid origin, distance north from the grid origin and average altitude of the 5 km grid square. This is well illustrated by the comparison of observed and predicted mean January temperatures shown in Figure 27.

The adequacy of this relationship over the full temperature range observed is illustrated by the associated scatter plot (Figure 28).

[23] These are the two main climate related variables that influence the assessment calculations for the biosphere undertaken by RWM in support of its long term safety assessments.

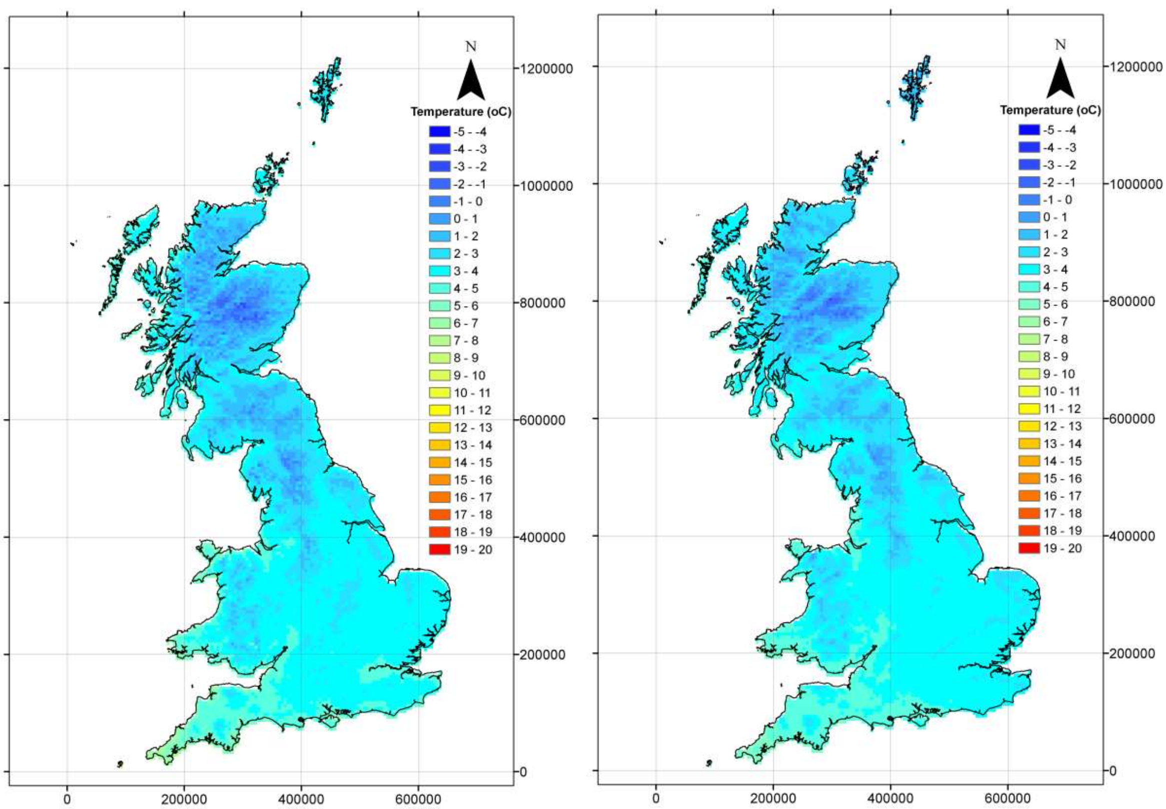


FIG. 27. Observed (left) and predicted (right) mean January temperature for Britain using a regression applied to the 1961–1990 gridded 5 km by 5 km climatology provided by the Meteorological Office reproduced from Ref. [69] with permission courtesy of the Nuclear Decommissioning Authority.

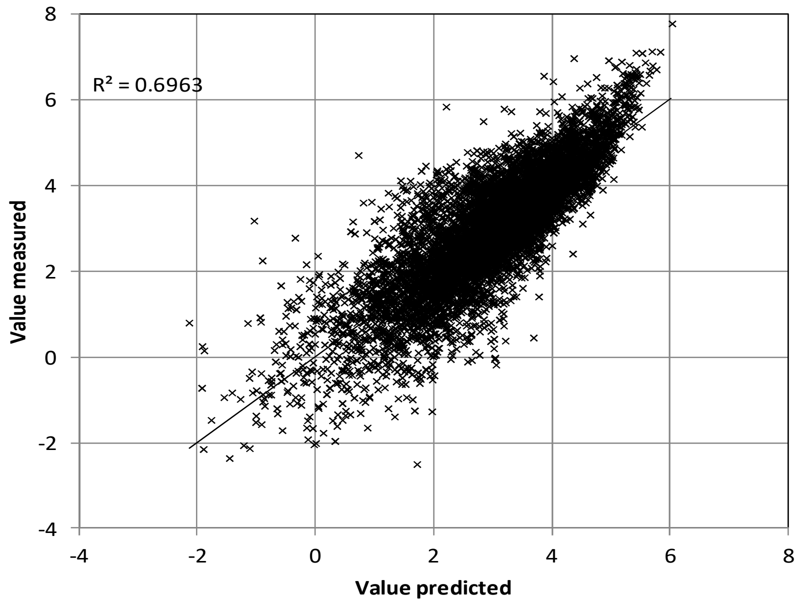


FIG. 28. Scatter plot of measured against predicted mean January temperature (°C) for Britain using a regression applied to the 1961–1990 Gridded 5 km by 5 km Climatology provided by the UK Meteorological Office reproduced from Ref. [69] with permission courtesy of the Nuclear Decommissioning Authority.

As expected, there are seasonal variations in the regression coefficients. These are illustrated for all months in Figure 29. The four regression coefficients (*A0, A1, A2, A3*) shown there are used in the overall relationship:

$$V_{\mathrm{Calc}} = A_0 + A_1 * z + A_2 * x + A_3 * y \quad (3)$$

where V_{Calc} is the calculated climatic quantity (temperature or precipitation) and the variables *z, x* and *y* are the altitude (*m*), the west-east distance from the origin of the grid (km) and the south-north distance from the origin of the grid (km).

For precipitation, the regression against altitude, distance east and distance north works less well than for temperature. This is illustrated for mean annual precipitation in Figure 30.

The regression is not able to achieve the observed contrast in precipitation between north-west and north-east Scotland. This is thought to be because it neglects rain shadow effects. The failure to achieve this contrast is illustrated in the associated scatter plot (Figure 31) through a non-linear relationship between measured and predicted values.

In order to take better account of rain shadow and other altitude related effects, various other regression variables were used. Some of these were found to improve the fit (see Figure 32), but it remains less good than for temperature.

Further investigations into preferred regression relationships for precipitation are ongoing. In particular, it is being considered whether it would be better to develop a regression against the original meteorological station data than against the gridded data, since artefacts may have been introduced into the gridded data through the interpolation approach adopted. This is less of an issue for temperature than precipitation because the degree of variation of the temperature field is less [69].

Having defined a regression relationship of the form:

$$V_{\text{Calc}} = A_0 + A_1{*}z + A_2{*}x + A_3{*}y \quad (4)$$

the actual value at each grid point for the present day climatology, V_{Obs}, is given by:

$$V_{\text{Obs}} = A_0 + A_1{*}z + A_2{*}x + A_3{*}y + \varepsilon \quad (5)$$

where ε is the local variability that is not explained by the regression.

For potential future climatic conditions, modified values of A_0, A_2 and A_3 can be obtained from AOGCM modelling, since these quantities are well defined at multi-grid element resolution. In practice, by comparing an AOGCM run for future conditions with one for the period for which the reference climatology is defined, changes in these quantities, i.e. ΔA_0, ΔA_2 and ΔA_3, can be defined. Thus, the projected value of the climate variable under these future conditions, V_{Proj}, is given by:

$$V_{\text{Proj}} = (A_0 + \Delta A_0) + A_1{*}z + (A_2 + \Delta A_2){*}x + (A_3 + \Delta A_3){*}y + \varepsilon \quad (6)$$

As AOGCMs do not estimate effects of local variations in altitude or other residual local effects, these are assumed to be the same under future conditions as over the period for which the reference climatology is defined. This is a more limited version of stationarity than has typically been assumed in the past.

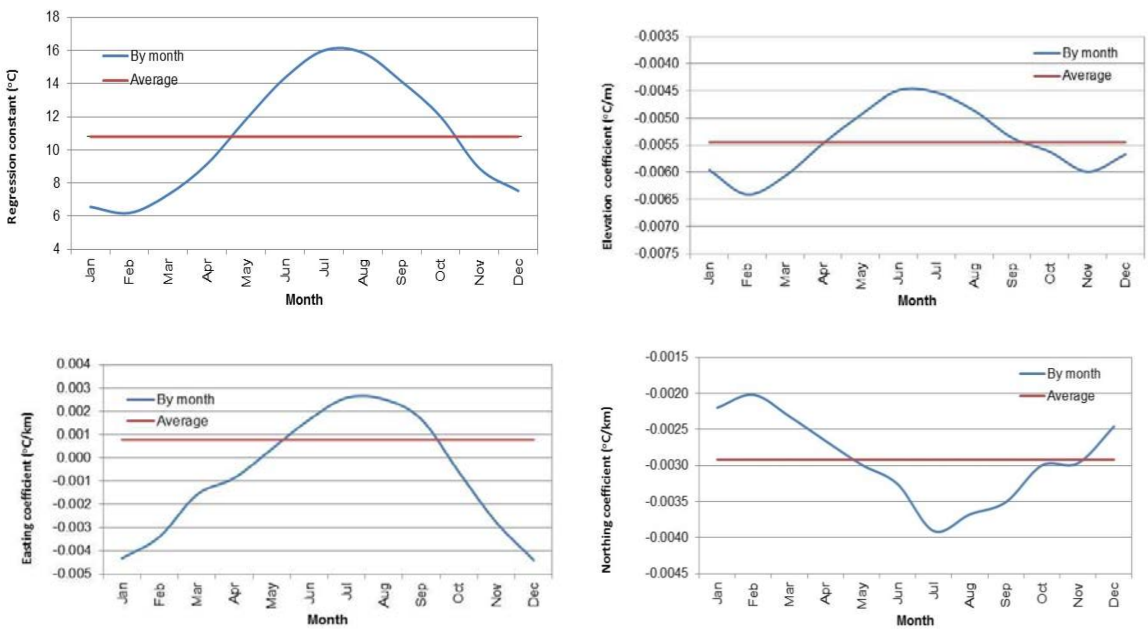


FIG. 29. Monthly variations in the regression coefficients for temperature obtained for the 1961–1990 gridded 5 km by 5 km climatology provided by the UK Meteorological Office [A_0 – top left (°C), A_1 – top right (°C m^{-1}), A_2 – lower left (°C km^{-1}), A_3 – lower right (°C km^{-1})] reproduced from Ref. [69] with permission courtesy of the Nuclear Decommissioning Authority.

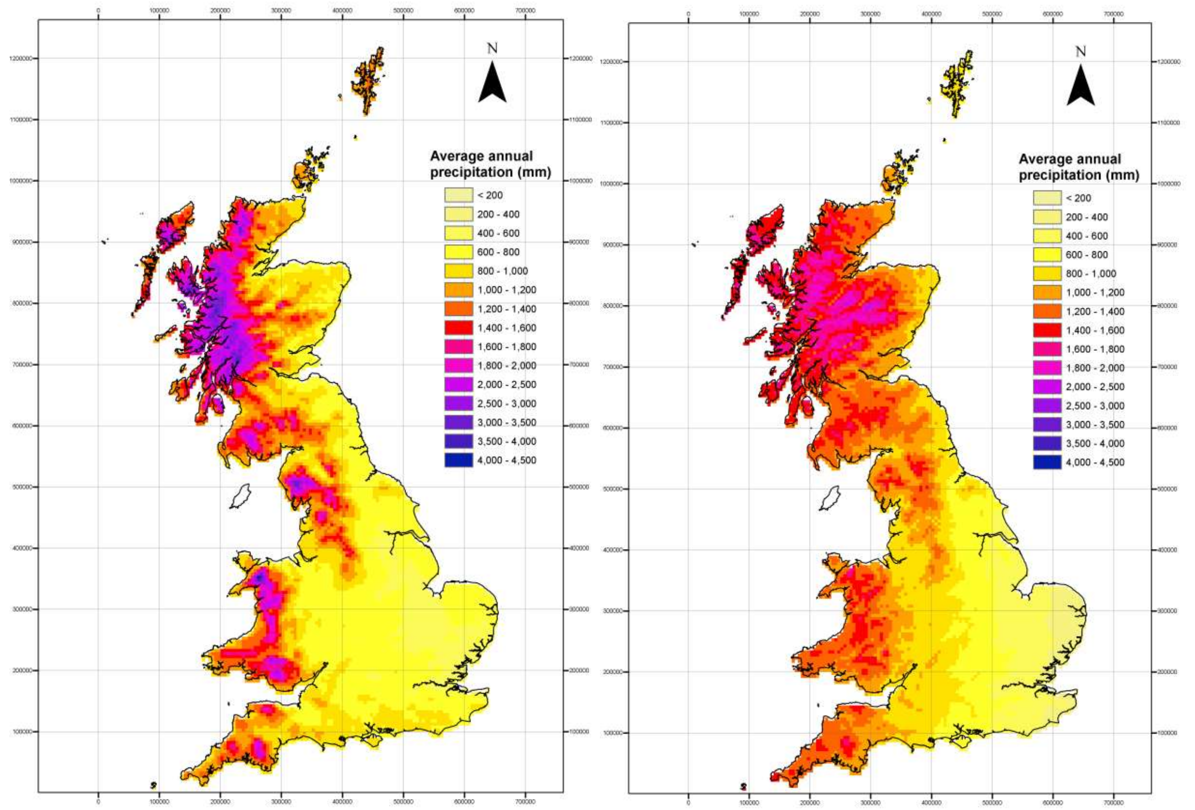


FIG. 30. Observed (left) and predicted (right) mean annual precipitation for Britain using a regression applied to the 1961–1990 gridded 5 km by 5 km climatology provided by the UK Meteorological Office reproduced from Ref. [69] with permission courtesy of the Nuclear Decommissioning Authority.

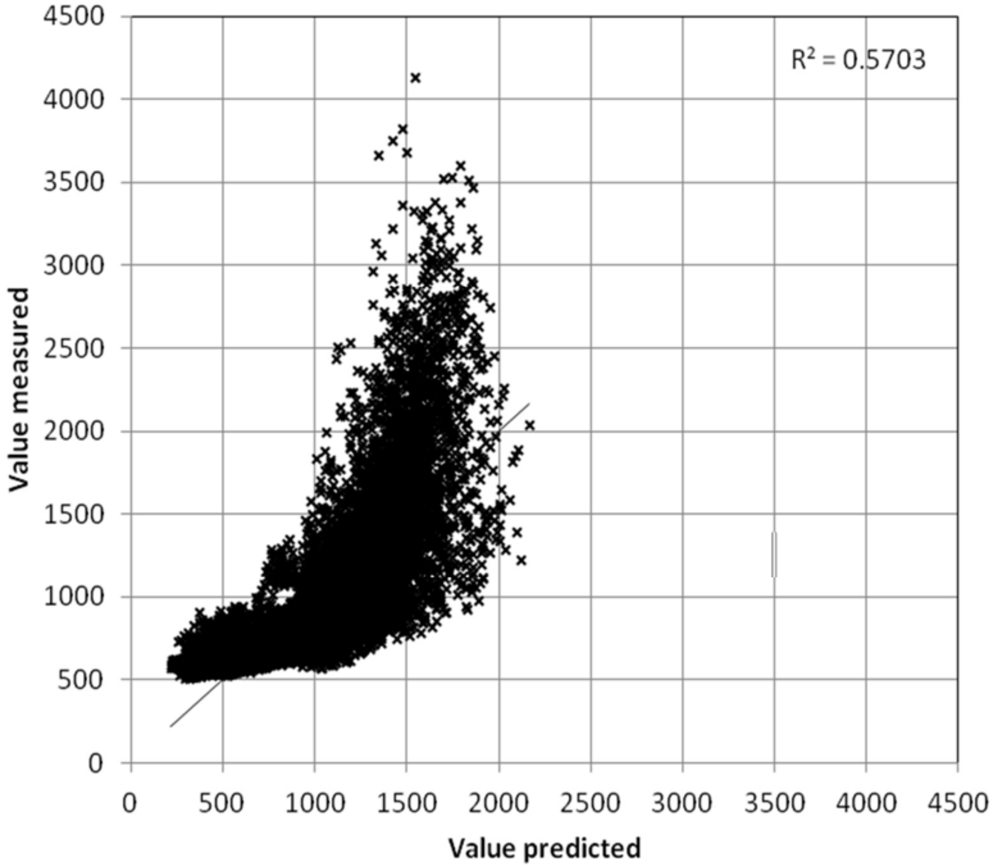


FIG. 31. Scatter plot of measured against predicted mean annual precipitation (mm) for Britain using a regression in altitude, distance east and distance north applied to the 1961–1990 gridded 5 km by 5 km climatology provided by the UK Meteorological Office reproduced from Ref. [69] with permission courtesy of the Nuclear Decommissioning Authority.

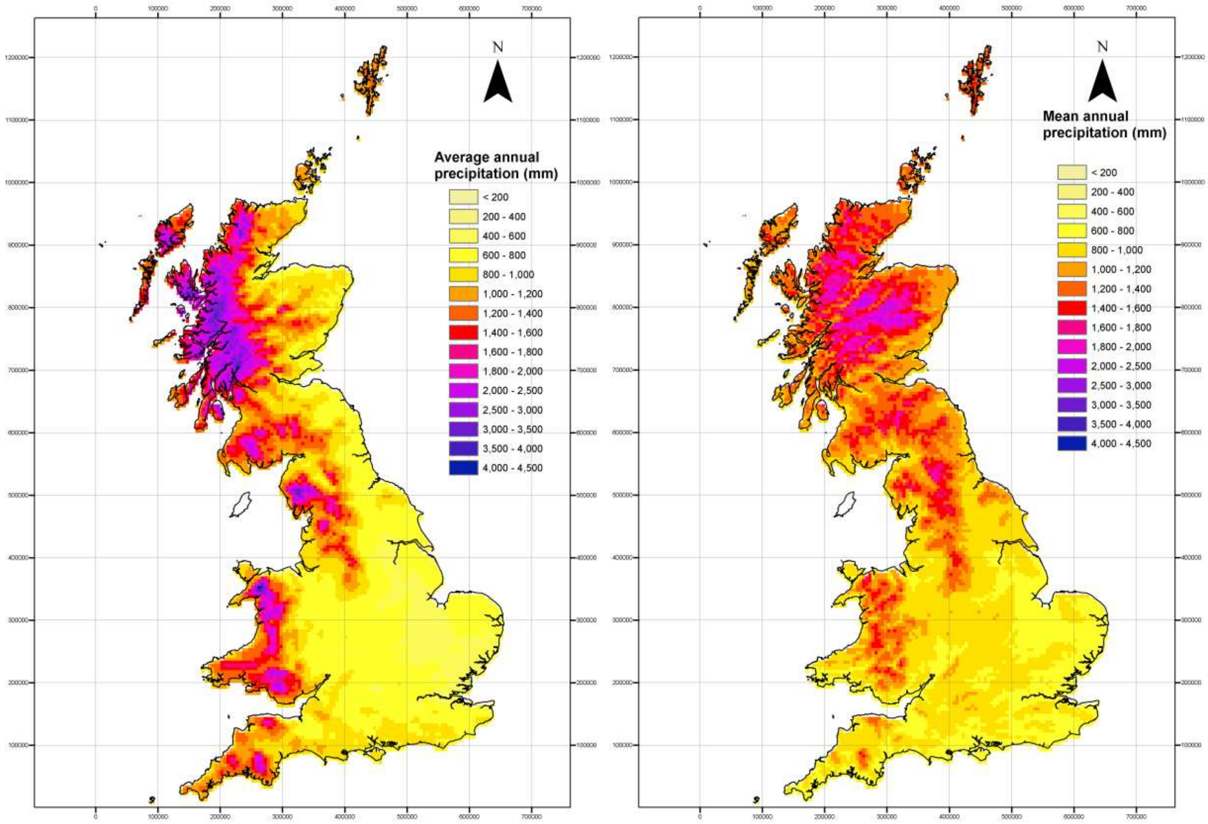


FIG. 32. Observed (left) and predicted (right) mean annual precipitation (mm) for Britain using a modified regression applied to the 1961–1990 gridded 5 km by 5 km climatology provided by the UK Meteorological Office. In this modified regression, the maximum altitude to the west of the grid element at each distance north is used instead of the average altitude in each grid square. This is based on the concept that the maximum altitude to the west is an important influence on rain shadow effects associated with Atlantic storms reproduced from Ref. [69] with permission courtesy of the Nuclear Decommissioning Authority.

6. INFLUENCES OF DOWNSCALED CLIMATE AT THE REGIONAL OR SITE LEVEL

This Section focusses on the influence of downscaling at the regional and site level within step 5 of the methodological road map shown in Figure 33.

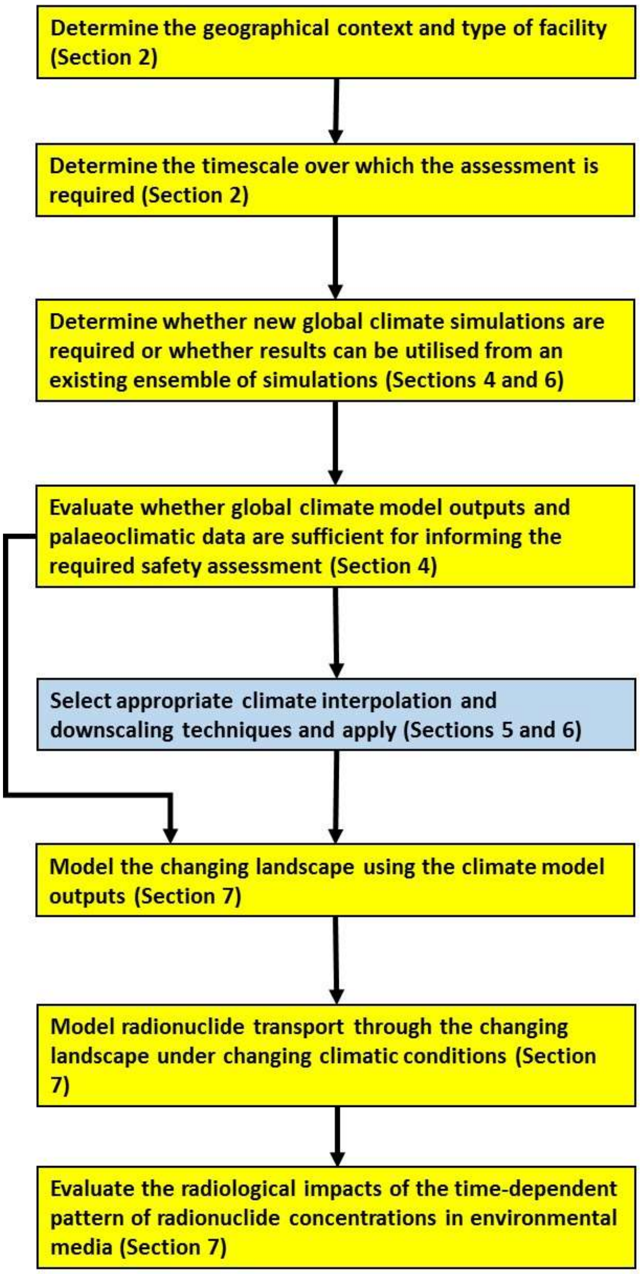


FIG. 33. Road map for performing an assessment taking climate change and landscape development into account.

In line with international recommendations (e.g. Ref. [17]), post-closure radiological impact assessments of geological disposal facilities for radioactive wastes typically extend to cover periods of thousands to hundreds of thousands of years after closure of the facility [68, 86]. To meet similar long term safety objectives, assessments of disposal of environmentally persistent toxic chemicals, such as heavy metals, would need to cover similar periods, though this is seldom the case [87]. Over such timescales, both climatic conditions and the landscape at the radioactive waste disposal facility are expected to alter to a sufficient degree that such changes need to be taken into account in the radiological impact assessment [68]. It is not possible to exactly predict future changes in climate and landscape over such timescales. However, it is possible to develop a set of scenarios for a disposal facility site that explore the range of possible long term changes in climate and landscape. This approach allows the development of a set of assessment calculations consistent with those scenarios that can be used to explore the range of time dependent radiological impacts that could arise from disposal of long lived radioactive wastes in such a disposal facility [68, 88–90].

Earlier sections of this report have addressed how projections can be made of future climates over the very long timescales involved in post-closure radiological impact assessments. Climatic projection at the global scale can be complemented by the application of downscaling techniques to generate projections of climate change at local scales appropriate to application of those projections at specific sites. By this approach, a continuous narrative describing projected climate changes at a specific site can be developed. However, describing climate change at a specific site may not provide a sufficient basis for post-closure radiological impact assessment. Rather, the narrative of projected climate change should be used to develop a narrative of future landscape development at the site. Taken together, the narratives of climate change and landscape development provide a spatially distributed framework within which a conceptual model of the changing repository system and its host environment can be developed [91]. In turn, this provides the context within which the potential impacts of the repository (arising from release and transport of radionuclides, or indeed, other contaminants) can be evaluated.

In this Section, an account of the influence of downscaled climate to the regional or site level is given. Linkages from models of climate and climate change to representations of landscape development is provided. As such linkages are particularly strong and complex in colder regions affected by permafrost and ice sheet development, and because several of the most advanced programmes for repository development are located in those regions, these cold region aspects are emphasized in this review, which is general in nature. Applications to specific geographic regions or sites are covered in Section 7. Sections 6.1 through to 6.4 are based closely on Ref. [92].

6.1. RELATIONSHIP BETWEEN CLIMATE AND LANDSCAPE AND OUTPUTS FROM CLIMATE MODELS

Earth is a dynamic planet and every point on its surface is subject to continuous changes in elevation. These changes are the results of tectonic uplift, erosion and other processes, and the rates at which they occur may vary over several orders of magnitude at different locations [93]. Examples of such changes are erosion by fluvial processes in a river system including both down cutting and overall changes in the pattern of drainage (see, e.g. Refs. [94–97], glacial erosion and the over deepening of subglacial valleys, and isostatic readjustment because of loading and unloading of the crust by, e.g., the melting of ice sheets [98]. Whereas fluvial erosion is often observable in the short term (though it continues over many thousands of years) and depends strongly on the amount and intensity of precipitation, as well as on topographic factors, isostatic rebound occurs rather slowly over thousands or tens of thousands of years and depends on, among other factors, temperature and precipitation (because these govern the growth and decay of continental ice sheets), and the rheological characteristics of the lithosphere and asthenosphere [99, 100]. Even from these simple examples, it is immediately obvious that recurring patterns of climate change and alterations in the landscape are closely interlinked, and that they can have substantial impacts on repository safety. A change in climate may cause increased or decreased precipitation/evapotranspiration [77] and, in more extreme cases, an increase or decrease in the volume and distribution of ice sheets, ice caps and glaciers [90, 98, 100]. Both the persistence of particular climatic conditions and changes in climate with time will inevitably lead to various changes in the landscape expressed on timescales ranging from a few hours (for a single extreme climatic event) to many thousands, or even millions of years. During stable climatic conditions, landscape changes are often slow and reasonably predictable, e.g. interglacial fluvial incision into till deposits in lowland Britain [101]. However, during periods of climate change, alterations in the landscape may be both fast and less predictable, e.g. in the very active hydrological regime that occurs at the margin of a retreating ice sheet where complex sequences of river terraces may be formed [102].

In terms of landscape response, crustal deformation and recovery as a result of ice sheet loading and unloading in turn influence local sea level variations [56, 103, 104]. Such effects are commonly handled in a landscape development model distinct from the model used for making climate projections. However, the last 400 ka that includes coupling to an ice sheet model has been simulated with an EMIC [18]. They hypothesize that crustal rebound, which is included in the model used, has a significant effect on climate change, so feedbacks between landscape response models and climate models may merit further consideration at a regional to global scale.

The outputs from climate modelling and associated downscaling that may be used to inform landscape modelling comprise the following:

(a) Standard meteorological variables, with temperature projections, although subject to considerable uncertainty, being the most reliably estimated, with precipitation rather less well estimated. Other variables are typically even less accurately estimated than precipitation (see Section 9 of Ref. [6] and Ref. [77]).

(b) Overall regional vegetation patterns. Several dynamic global vegetation models have been developed and deployed in ESMs, and simpler vegetation response models are also used in AOGCMs and EMICs. Although agriculture and managed forests are not yet generally incorporated, these models can simulate interactions between natural and anthropogenic drivers of global warming, the state of terrestrial ecosystems and ecological feedbacks on future climate change (see Section 9.1 of Ref. [6]).

(c) The extent and thickness of continental ice sheets, ice caps, valley glaciers, ice shelves and sea ice. In particular, the advance or retreat of an ice margin over a repository may be of particular significance because of the high hydraulic gradient that is developed [68].

The spatial resolution of any outputs will depend on the model or combination of models adopted, but could range from hundreds of kilometers per grid square for coarsely gridded EMICs down to about 10 km or less for a RCM used in conjunction with an AOGCM to determine the boundary conditions to impose on the RCM or if physical–statistical downscaling is used. The temporal resolution will also depend on the models used. Outputs every few minutes may be obtained for meteorological variables in snapshot AOGCM/RCM simulations, but the use of EMICs together with rule based downscaling may provide only estimates of mean monthly temperature and precipitation [77]. Also, although the intrinsic, computational time steps of AOGCM/RCM simulations may be as little as a few minutes, the archived output may have a much coarser time resolution, e.g. monthly or daily. Only recently has the output data been archived at sub-daily time steps. For landscape development modelling, climate projections will be required over periods of thousands of years or longer, but these projections can be in terms of a sequence of 'snapshots' separated by intervals of hundreds or thousands of years, but with a much higher internal temporal resolution, thus allowing variability on these shorter timescales to be taken into account.

More indirect outputs from climate modelling are discussed later in this Section and include eustatic changes in sea level, isostatic alterations in crustal elevation resulting from changes in ice and water loading, and the development of frozen ground, including permafrost.

6.2. RESPONSES OF LANDSCAPES TO CLIMATE MODEL OUTPUTS

Whereas climate models operate at global to regional scales, landscape models typically operate at regional to local scales. Though there are numerous climate controlled processes involved in landscape development (e.g. fluvial and aeolian erosion depend on patterns of precipitation and airflow), the development of ice sheets, where they occur, has the most dramatic and widespread effects over a range of timescales [93]. Shorter term effects of ice sheets may include accelerated episodes of erosion and broadening of valleys, redistribution of large amounts of mass (e.g. in the form of moraines), the eroding of over deepened valleys and changes in the flow directions of rivers [101]. On longer timescales, the isostatic response of the lithosphere may be of importance because it leads to a downward movement of the lithosphere during ice sheet growth and to uplift during ice sheet decay, possibly long after the ice sheet has disappeared [102]. In particular, because the response involves viscous flow, the effects of loading and unloading exhibit spatially complex patterns and do not occur immediately, but persist for thousands or tens of thousands of years [105]. Although some models of the response to ice loading and unloading are developed at a regional scale, others are developed at a global scale, e.g. expressing the imposed ice load and the response to it in terms of sets of spherical harmonics [104]. Here, attention is focused upon local scale landscape development models, with both climate and regional sea level changes derived from the use of AOGCM/RCMs and global/regional crustal response models. Also, as discussed in the introduction to this Section, an emphasis is placed on the changes that are projected to occur in colder regions, typically north of 45°N in the Northern Hemisphere.

Fluvial responses to climate change have been described in Ref. [106]. They list several climatic factors that may directly influence fluvial deposits. These include the intensity of precipitation and its seasonal distribution. According to Ref. [106], extreme storm events (the intensity and duration of which are much more challenging to model than the 'average' temperature and precipitation regime) have a much larger impact on sediment deposition and erosion than does 'regular' precipitation throughout the year. This is supported by the classification of rivers in high latitudes, which is largely determined by the amplitude and duration of peak flows and not by mean temperature or mean precipitation [107, 108]. Snow and ice may also be important controls on sediment deposition and erosion, because they have the ability to dam rivers. In addition, water released during rapid thawing of the snow and ice greatly contributes to the peak runoff during spring thaw [109]. An example of an indirect effect of climate on fluvial development is permafrost [110, 111]. Frozen ground reduces the permeability of the soil therewith enhancing surface runoff and concentrating it in a short time period [107, 108]. However, there may be less total (surface and sub-surface) runoff and increased sublimation plus evaporation. During cold climates, most runoff may occur as overland flow, whereas, in the same locations and during warmer climates at least some runoff would be sub-surface [111], but with the proportion of such sub-surface flow being dependent upon the hydrological characteristics of the underlying rocks. This contrast often arises because of the small capability of the permafrost for groundwater storage [112], but it can also be characteristic of areas where only seasonal freezing of the ground occurs, since this also inhibits water penetration and sub-surface storage. The high surface runoff during thawing of the permafrost or seasonally frozen ground leads to higher stream densities during thawing [113]. However, some periglacial areas are very dry, so this effect does not always occur. This also has an impact on total sediment availability and transport [114]. Slope stability would possibly also be affected due to an increased pore water pressure during thawing of the permafrost [115]. Taking the above considerations into account, it is clear that sediment delivery to arctic and subarctic rivers is largely determined by the presence or absence of permafrost and seasonally frozen ground.

In summary, the main information needed from climate models to determine landscape evolution is temperature, precipitation at both short (individual event) and longer timescales, and, to a lesser extent, wind speed and direction. In addition, the intervals between and duration of events (e.g. storm return periods and durations) is of great importance. Temperature and precipitation determine the development of ice sheets and permafrost, both of which have a substantial effect on the landscape. Longer term effects of climate on the landscape include those due to loading by ice sheets and glacial erosion, but, in addition, include other erosional and depositional processes due, for example, to fluvial and aeolian impacts.

6.3. EFFECTS OF CLIMATE CHANGE AND LANDSCAPE DEVELOPMENT ON REPOSITORY SITES

In this subsection, a brief discussion is provided of several important climatic and landscape factors that may have a great influence on the long term safety of proposed repository sites.

As has been stressed earlier, ice sheets on land masses play an important role and their impact extends into the offshore domain. This extension into the offshore domain arises because sea levels are typically tens of meters lower during glacial episodes than during interglacial episodes, meaning that much of the continental shelf is exposed to terrestrially based ice that can erode existing unconsolidated deposits and transfer them further offshore, as well as generating new unconsolidated deposits during their retreat phase [101]. The effects of terrestrially based ice sheets include valley erosion in upland areas and more generalized erosion and sediment transport in lowland areas [101]. Furthermore, tunnel valleys can be formed beneath glaciers and ice sheets. These valleys are formed by subglacial erosion by water and serve as subglacial drainage pathways carrying large volumes of melt water. Their cross sections exhibit steep sided flanks similar to fjord walls and their flat bottoms are typical of subglacial erosion. They can be up to 100 km long, 4 km wide and 400 m deep and occur as dry valleys, lakes, seabed depressions and as areas filled with sediment. If they are filled with sediment, their lower layers are filled primarily with glacial, glaciofluvial or glaciolacustrine sediment, supplemented by upper layers of temperate infill (see Ref. [116] and references therein, also Ref. [117]). At coastal locations, the interaction between land based ice sheets and ice shelves may require special attention [118]. The extent of an ice shelf may be topographically controlled, e.g. if it is located in a bay with a restricted outlet. Also, its stability may be controlled by outputs from the climate model that are of limited relevance in other contexts, e.g. water temperatures below the ice shelf. Furthermore, the presence and extent of an ice shelf may control the flow of land ice that feeds it, such that degradation of an ice shelf may result in the acceleration of land based ice streams [119, 120]. However, while this is a topic of considerable interest in the context of ice sheet stability and projected global sea level changes (see Section 13.4 of Ref. [6]), it has yet to be identified as a significant local issue in the context of the post-closure safety of proposed facilities for the disposal of radioactive wastes.

The above discussion presupposes that continental ice sheets, ice caps or valley glaciers will have a direct impact at the location of a disposal facility, as is projected to be the case in Sweden [68]. However, beyond the margins of the ice sheets, other cold region effects may be of considerable significance to repository safety. In particular, permafrost may develop down to depths of tens or hundreds of meters [121, 122]. Taliks may also be of great importance in the context of repository safety [68]. Depending on thermal, hydrological and/or hydro–geochemical effects, small areas within a frozen landscape may stay above freezing temperature. These taliks may act as conduits concentrating all (though volumetrically small) groundwater flow into localized areas [121, 123].

Thus, results from climate models may need to be used as inputs to models of permafrost development. The other main input to such models is the geothermal heat flux from depth that enters the near surface zone in which permafrost may develop. As permafrost development may require thousands to tens of thousands of years, the long term time dependence of climate model output is important [56, 123]. The main information required is ground (or air) temperature expressed on a monthly or seasonal basis, including long term (decadal to millennial) variations in these temperature estimates. Precipitation as snowfall may also be relevant, if snowpack effects are taken into account in the permafrost model. The development of peat deposits may have a strong effect, for example, on permafrost conditions [124].

Issues associated with permafrost development are comprehensively explained in various publications, e.g. Refs. [121, 125–127] and reviewed in publications such as Refs. [128, 129]. Experimental investigations of thermal, hydrochemical and mechanical impacts of freezing on bedrock properties have been reported [130–132], whereas model studies of present and future permafrost development influenced by increasing atmospheric greenhouse gas concentrations can be found in Refs. [133–135]. Additionally, some model studies on the thermo–hydro–mechanical impacts of freezing processes on bedrock properties with implications for interactions between glaciers and permafrost in a time frame of a glaciation cycle (~100 ka) have been conducted [124, 136–143]. The effects of freezing of the geosphere on groundwater flow have been studied [144–146].

Although vegetation will, most likely, not directly impact repository safety, it may have an impact on land use which, in turn, is an important factor if, e.g., the distribution of possible contaminants from the repository needs to be addressed. Although climate models may provide information on vegetation characteristics, these will be in generalized, regional terms. This information may be used qualitatively to select the type of vegetation present locally, but often it will be more appropriate to use the temperature and precipitation data, together with known site characteristics and the assessment basis, to determine the type of vegetation that should be assumed to be present locally.

The temporal and spatial resolution required of the temperature and precipitation data will depend strongly on the type of facility and site that is under consideration. For example, for a near surface facility protected by a cap that rises above the general level of the ground, the intensity of individual precipitation events may be relevant to determining the susceptibility of the cap to erosion, including both surface wash processes and gullying [147]. For a facility located in the unsaturated zone in fractured rock, as has been proposed at Yucca Mountain, the intensity of individual rainfall events may again be important, but in this case in relation to the degree of infiltration, since the amount of infiltration may depend in a complex non-linear fashion on both the amount and intensity of precipitation [16, 148].

To estimate changes in land use and to evaluate the effectiveness of erosion, it may be relevant to simulate the surface water hydrology and near surface hydrogeology at a site, by employing spatially distributed, surface water catchment models, such as MIKE-SHE/MIKE11 [149–151]. These models typically use high resolution climate data (with precipitation specified over 15 minute to 1 hour intervals) and require spatially distributed information (grid cells may be of as little as a few tens of meters across and would seldom be more than a few hundred meters). However, in many contexts, it may be adequate to use data of much coarser resolution. For example, in water balance calculations or to determine irrigation requirements, it may be sufficient to use monthly values of temperature and precipitation [77]. Also, it may be sufficient to use values averaged over spatial domains of up to a few kilometers in extent. The topographic characteristics of the catchment, the parameter values determining the hydrological properties of the soils, sediments and rocks of which it is composed, and the vegetation present may be specified based on present day conditions or on postulated future conditions.

Relevant hydrological properties and vegetation characteristics may be obtained from present day sites that are considered to be analogues of the site of interest under the future conditions that are being simulated. In turn, results from the catchment simulations may be used iteratively to adapt the vegetation characteristics to the simulated hydrological conditions.

Where monthly or seasonal averages are used, it is appropriate to consider whether inter-annual variations need to be taken into account. For example, in considering long term infiltration to the saturated zone (as might be used to determine rates of solubilization of sub-surface strata), it may be sufficient to use mean monthly temperature and precipitation data averaged over many years (typically an interval of 30 years is used to define ‘current’ climate). However, in dealing with, for example, the proportion of years in which irrigation would be carried out, and the amount of irrigation demand in those years (pertinent to ascertaining the kinds of well abstraction that may be carried out, which is a vital consideration in radiological impact assessment), annual values of mean monthly temperature and precipitation would be required and averaging over multiple years would not be acceptable [77].

As considered above, climatological information might be utilized not just to determine hydrological characteristics, but also to assess the possible effects of erosion. Data on precipitation and temperature should be the sole outputs from models needed for this evaluation. However, for aeolian erosion, data on wind speeds and, in particular, extreme winds would be required.

Although climate model outputs are directly pertinent as inputs to hydrogeological and hydrological models, they will mostly make a restricted contribution only to hydro–geochemical modelling, because the chemical compositions of the various water types will also be required. Compositions may be needed for water types such as meteoric water, subglacial melt water, surface freshwaters and near coastal brackish and marine waters (see, e.g. Section 8 of Ref. [152]).

In addition, compositions may need to be estimated for pre-existing groundwaters or groundwaters modified by salt expulsion during the development of permafrost (since ice has less capacity for solutes than liquid water). To a large extent, the climate modelling can be viewed as an input to the hydrological and hydrogeological modelling that then determines the flow fields to be used in hydro–geochemical modelling. Hydro–geochemical modelling is typically of primary relevance in determining radionuclide solubility and sorption for use in reactive transport modelling, and for evaluating the period over which waste packages will remain intact (see, e.g., Sections 10 and 13 of Ref. [68]), but it may also influence projected rates of sub-surface erosion, as these will be determined by the solubility of minerals encountered by flowing groundwaters.

Overall, the above discussion relates to the relevance of climate model outputs in a terrestrial context. At coastal locations, some further considerations arise [11, 153]. Climate and sea level are strong determinants of coastal processes, such as cliff erosion and inundation [11, 154, 155], which may lead to disruption of a near surface engineered facility located close to the coast on a timescale of centuries to millennia [11]. In general, local sea level will be of greater importance than changes in climate, since the shoreline will have to adapt to the altered sea level in the event of an increase, whereas a decrease will result in relict coastal features being left in the terrestrial environment. Changes in sea level will also alter the hydrogeological and hydro–geochemical regime, e.g. by displacement of the interface between fresh and marine groundwaters (see, e.g. Ref. [156] for illustrations of how the interface between fresh and marine groundwaters can control the overall flow regime).

However, although the effects of sea level change are likely to be a significant consideration, the more direct effects of climate should not be neglected. These include changes in the wave field and storm surge heights. Changes in ocean wave conditions are determined by changes in the major wind systems of the Earth. In general, there is currently low confidence in projections of future storm conditions [see, e.g. Sections 12 and 14 of Ref. [6]) and hence in projections of ocean waves. Nevertheless, there has been continued progress in translating climate model outputs into wind wave projections and a number of dynamical wave projection studies have been carried out with a regional focus, including the north-east Atlantic, the North Sea and the Bay of Biscay [see, e.g. Section 13.7 of Ref. [6]). Finally, it should be mentioned that changes in sea level can have effects inland, with the degree of influence determined, in part, by the bathymetry. Specifically, as sea level changes, rivers will adjust their long profiles to the altered sea level. This process of erosion and deposition may require tens of thousands to millions of years to modify the landscape, so river profiles will tend to lag behind sea level changes.

The long term geomorphological evolution of catchments under altered climatic conditions and sea level changes is an important area to which long term climate model outputs can be applied [89, 157–160]. Thus, aspects such as river cutback and stream capture may affect the overall geometry and detailed characteristics of the surface water system, while generalized erosion may lower interfluves, whereas incision may deepen river valleys [101]. In this context, both climatic conditions and sea level changes may play important roles. Furthermore, where ice sheet development directly affects the landscape, substantial transport of existing sediments and the generation of new sediments from the underlying bedrock may occur [101].

6.4. INTEGRATION OF CLIMATE AND LANDSCAPE MODELLING

Outputs from climate models are used at a wide range of spatial and temporal scales to inform models of landscape development. At the longest timescales, climatic conditions determine the development of continental ice sheets and associated isostatic responses. Continental ice sheet development is normally included within the framework of long term global climate modelling using EMICs, but isostatic responses are typically modelled separately, so ice sheet characteristics need to be exported from climate models and used in isostatic response modelling. Alternatively, climate model outputs may be used as boundary conditions in detailed ice sheet models coupled to isostatic response models.

Also, at large spatial and temporal scales, climate models define input data for geomorphological models of landscape evolution (see, e.g. the discussion of geomorphological modelling by ANDRA provided in Appendix E of Ref. [161]). In this context, a wide range of different types of information may be required. Local to the site of interest, temperature and precipitation data may be used to determine the erosional regime, which may also be conditioned by the vegetation characteristics adopted, based both on climatic and other considerations. However, geomorphological changes may be governed by regional rather than local considerations, e.g. alteration of river base levels, river capture and drainage network reorganization or the progression of an ice sheet or valley glacier across the site [101].

Permafrost development is also a regional scale phenomenon, but it can often be modelled at a local scale, e.g. using a one dimensional (1-D) vertical heat transfer model or a two dimensional (2-D) model of a limited spatial domain [68, 138]. Also, 3-D permafrost modelling has been carried out [124]. A commonality with ice sheet and geomorphological modelling is that permafrost modelling can be undertaken using long term average (decadal to millennial) climatic characteristics as boundary conditions.

Although this is true for much geomorphological modelling, some geomorphological models, e.g. for incision or gully erosion, may require short term climate data. However, where this is so, it will generally be sufficient to characterize the statistical distribution of events of interest rather than having to develop full time series of such events. Similarly, the statistical distribution of event sizes may be sufficient in other contexts, e.g. when estimating infiltration into a fractured domain. However, in the context of modelling surface hydrology and sub-surface hydrogeology, a statistical representation may not be sufficient. The flow characteristics of the system may depend in a non-linear way both on the antecedent conditions and on short term climatic conditions. Thus, it may be necessary to use time series data with fine time resolution. Clearly, climate models will not be able to provide such data for the entire post-closure period for which safety assessment is required. In this case, alternative approaches should be employed. One alternative is to use long term climate modelling with EMICs or a climate emulator to identify situations of particular interest in an assessment context. The output from the EMIC or emulator calculations (and supplementary calculations as necessary, e.g. of ice sheet development) could then be used to define boundary conditions for snapshot or short term transient AOGCM/RCM calculations to provide time series data for use in hydrological and hydrogeological modelling of those situations. Another alternative is to use EMIC output in a rule based downscaling procedure to identify particular instrumented climate stations from various locations worldwide appropriate to projected future climatic conditions at the site of interest. The multi-year high resolution records from these stations could then be used as input to detailed hydrological and hydrogeological models.

In addition, where future situations are considered to be analogous to those that have occurred in the past, palaeo–climatological data may be used directly in defining the climate conditions to be adopted. However, the use of data from analogue stations is not without its difficulties. At best, such analogue stations will be only approximate representations of future conditions at the site of interest. For example, they will necessarily be at different geographical locations and exhibit different topographic characteristics. Similarly, potential future conditions at the site may differ from those encountered in the past, e.g. when addressing substantial greenhouse gas induced global warming, making palaeo–environmental data from the site of limited relevance. In some cases, the postulated future climatic conditions at the site will lie outside the range that can be represented by present day or palaeo–environmental analogues, and reliance will have to be placed directly on the modelling of those climatic conditions and their environmental implications. However, where analogue situations can be identified, they can be extremely useful, because they implicitly include the effects of a wide variety of interactions between the climate and the landscape that may not be included in current models of landscape development.

Temporal downscaling from AOGCM results to provide information suitable for use in hydrological and hydrogeological modelling is not likely to be an issue. These models can typically provide output on sub-hourly time steps, which should be an adequate time resolution for most applications[24]. Therefore, it seems unlikely that it will be necessary to deploy supplementary modelling tools such as stochastic weather generators [162].

Models of long term climate change and landscape development are already being used in the development and application of post-closure safety cases for both shallow and deep geological disposal of solid radioactive wastes [68, 163–169]. Furthermore, the changes in climate and landscape projected using these models have been found to influence the safety case, e.g. by determining the timescale over which erosion of the engineered facility occurs [163] or by determining the distribution of radionuclides released into and retained in the changing landscape in the vicinity of the facility [68]. It may be anticipated that a wider variety of climate models will be needed to provide the assumptions and boundary conditions for studies of landscape development. In the area of shorter term climate modelling, it is now commonplace to use ensembles of climate models and multiple simulations with individual models to study the effects of model and parametric uncertainties (see Section 9 of Ref. [6]). As uncertainty analyses are commonly conducted in relation to other aspects of post-closure performance assessments of geological waste repositories, it seems inevitable that future climatic and landscape development modelling will also be undertaken using ensembles of models and will include investigations of the effects of parametric uncertainty within that framework. Development of robust, efficient and well justified climate and landscape models for application within such an assessment framework constitutes a challenging research and development programme for the future. In the following subsection, consideration is given to the conceptual structure of the types of climatic and landscape models that may be appropriate to different climatic and landscape contexts.

6.5. CONCEPTUAL MODELS OF CLIMATE CHANGE AND LANDSCAPE DEVELOPMENT

From the discussion in previous subsections, it is clear that the dominant processes governing landscape development will differ greatly depending on the geographical context and climatic conditions under consideration. Upland, inland lowland and coastal contexts need to be considered separately, and warm arid, temperate, periglacial and glacial landscapes differ substantially from each other. To some degree, these distinctions are recognized through the categorization of facilities discussed in Section 2.1. Here, influence diagrams are developed and used to illustrate the key processes and interactions that apply in these various environments. As there are many commonalities between warm arid and temperate environments, these are considered together in the following discussion. Thus, only three states of climate (warm arid/temperate, periglacial and glacial) are distinguished herein. However, the 'temperate' domain as defined here includes also the boreal/subarctic non-periglacial environments. This means that the 'warm arid/temperate' domain covers all regimes excluding the tropics and the Arctic. In future work, it may be useful to separately distinguish subdomains within this overall category. In particular, it should be kept in mind that there are substantial

[24] Note that consideration needs to be given to the handling of the large datasets that will arise if comprehensive data are archived on a sub-daily timescale.

distinctions between these broadly defined ‘temperate’ types of environment, for example, the much greater significance of aeolian processes in an arid environment.

In the following, upland, inland lowland and coastal environments are first discussed in the context of their development in warm arid and temperate conditions. Following this discussion, the specific factors relevant to periglacial and glacial environments are discussed. This discussion is illustrative rather than comprehensive. Where an assessment of a specific site is to be undertaken, a conceptual model of climate change and landscape development should be developed for that site, using procedures similar to those adopted here. The mathematical models used in the assessment should then be developed, if appropriate, and adapted or configured to conform to the overall conceptual model of climate change and landscape development at the site of interest, within the overall assessment context that has been adopted.

In practice, the transitions between these states may also be of importance to landscape development. This consideration is discussed further in Section 6.5.4.

6.5.1. Warm arid and temperate conditions

6.5.1.1. Upland landscapes

Upland landscapes are typically characterized by steep slopes. Under warm arid and temperate conditions an active hydrological regime is likely to exist. However, the nature of that regime will differ depending on the climate. In arid conditions, the hydrological regime is likely to be episodic, with ephemeral flows in stream channels. Fluvial erosion will similarly be episodic with the main transport of sediments taking place in individual flow and flood events. In contrast, in many temperate contexts, stream and river flow will be continuous, with erosion and deposition of sediments also a continuous or quasi-continuous process.

In arid environments, aeolian erosion may also be a significant factor leading to the weathering of surface features, a lowering of the land surface in exposed locations and the deposition of wind eroded sediments in more sheltered locations.

In general, uplands (excluding upland plateaux) will be landscapes far from equilibrium. Therefore, there will be a general tendency for surface lowering and an overall reduction in relative relief with time. However, the overall timescale for smoothing and lowering of mountain landscapes will generally be many millions of years (the Alpine orogeny in Europe occurred mainly between 65 million and 2.5 million years BP, whereas the Caledonian orogeny, which formed mountain ranges in Scandinavia and Scotland occurred between about 490 million and 390 million years ago). Therefore, on assessment timescales of up to about one million years, the degree of overall lowering of upland landscapes during warm arid or temperate periods is likely to be limited. Nevertheless, some stream cutback may occur and there may be a degree of reorganization of the drainage network if such cutback breaches interfluves between surface water catchments. Notwithstanding these considerations, the overall geometry of the environment is unlikely to change markedly during individual warm arid/temperate periods, and reorganization of the drainage system is considered possible, but unlikely. In practice, such reorganization is more likely to occur due to remodelling of the environment during glacial episodes, if these can occur at the site of interest (see Section 6.5.3).

If more soluble rocks, such as chalk and other types of limestone are present at the surface or in the sub-surface, erosion may occur by dissolution of these rocks in flowing surface waters or groundwaters. Again, these processes are likely to be relatively slow, so the degree of surface lowering or increase in sub-surface macroporosity during a single warm arid/temperate period is likely to be limited. Nevertheless, such solubilization effects may need to be taken into account in the context of radionuclide transport. In particular, on longer timescales, solubilization processes in limestone could constitute the dominant contribution to surface lowering. For example, in the UK, most cave development is thought to have occurred within the last one million years and it has been observed [170] that lowering rates of as much as 0.5 m over the last 15 ka (i.e. 0.033 m ka^{-1}) have been reported, but that a re-evaluation of the field evidence suggests that solution rates on interfluve areas are rather lower at 0.05 to 0.2 m over the last 15 ka (i.e. 0.003 to 0.013 m ka^{-1}).

Variability of climate during warm arid/temperate periods will result in changes in vegetation, typically expressed in the vertical migration of vegetation zones, and alterations in both surface and sub-surface hydrology, expressed in changing stream flows and lake levels. These responses to climate variability will be expressed on sub-annual to decadal timescales.

It is noted that upland landscapes experiencing temperate conditions may lie downslope of glaciated landscapes. The implications of the local presence of valley glaciers and ice caps are discussed further in Section 6.5.3.

Based on the above discussion, a conceptual model for development of an upland landscape under warm arid/temperate conditions has been developed (Figure 34). In this and the following figures the inputs provided from climate models are highlighted.

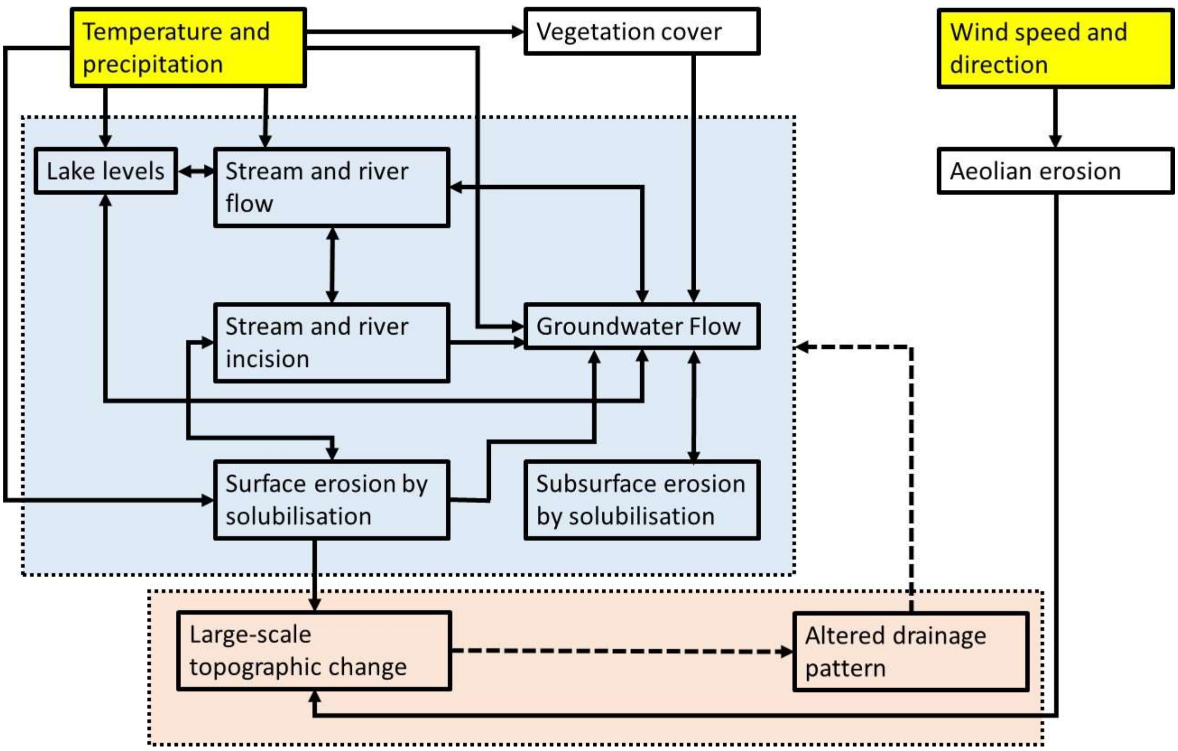


FIG. 34. Conceptual model for development of an upland landscape under warm arid/temperate conditions.

In this figure, the emphasis is on fluvial processes, with aeolian erosion seen as a modifying factor of limited importance in controlling large scale topographic change. In most contexts, large scale topographic change will be of limited significance, but there may be cases in which it influences the overall drainage pattern, which will, in turn, have feedback effects on the whole fluvio–erosive system.

Vegetation cover is considered to be primarily driven by climate. However, there may be a secondary influence due to changes in the topographic and fluvial regime. As this is considered to be of limited importance compared with the direct effects of climate (or can be represented in modelling by reference to climate), it is not shown on Figure 34.

Temperature and precipitation affect the surface water regime. This is expressed through changing lake levels (if lakes are present) and alterations in stream and river flow. There may also be a limited degree of erosion due to sheet flow at the surface, but this is considered to be a secondary factor and is not shown explicitly. Gullying erosion due to episodic events is implicitly included in incision due to stream and river flow, since ephemeral streams are taken into account.

Within the fluvio–erosive system, there are strong feedbacks between the flow regime and erosion, with the flow regime determining stresses in the surface environment and hence the potential for sediment mobilization, transport and deposition, but with the changing shape of stream channels in turn influencing the flow regime. In both the surface and sub-surface, water flows influence the rate of solubilization, which in turn changes the amount and pattern of water flow leading, e.g., to cave system development in limestone.

In Figure 34 (above) and subsequent figures, an emphasis is placed on erosion processes that result in both general surface lowering and incision. However, the sediments removed by erosion from some parts of the landscape will be deposited elsewhere, often in river valleys and on their associated floodplains, and this associated deposition should be taken as implied in the various references to erosion. For the UK, sediment balances associated with erosion, transport and deposition in different types of lowland catchment are explored in the hillslope model [171] and described below in Appendix I.

6.5.1.2. Inland lowland landscapes

In lowland landscapes, many of the same processes apply as in the case of upland landscapes. Although such landscapes are often closer to equilibrium than in upland areas, this is not necessarily the case. Whereas the disequilibrium in an upland area typically arises from the original or ongoing uplift of the area, in a lowland area it often arises from long term changes in sea level that have affected the base level to which rivers and streams grade. Thus, rivers that discharge directly to the sea eventually develop an equilibrium long profile that has a high gradient near the source and a low gradient at the outlet. If the sea level changes, there is a slow adjustment of the long profile through erosion in some locations and deposition in others until equilibrium is achieved and a detailed sediment balance exists along the profile. Tributary rivers and streams will eventually grade to the height of the main river or stream at the location where they flow into it. However, where rivers flow over an erosion resistant stratum overlying less resistant strata, the river upstream of the resistant stratum may grade to the height at which the stratum is exposed, resulting in a step change in the height of the river at that point. The occurrence of waterfalls in major rivers illustrates this phenomenon.

Although lowland landscapes are typically closer to equilibrium than upland landscapes, this does not necessarily imply that there is less likelihood of altered drainage patterns. Because the topography is more subdued, the distinctions in height between interfluves and valleys is less, so the extent of sediment loss required to cut back through an interfluve may be limited.

Furthermore, in regions subject to glaciation during the Quaternary, a relatively recent, smooth glacial deposit (till) may be currently subject to active incision by streams. In this case, disequilibrium arises because the smooth palaeo-surface did not have any stream channels, so these have to be formed subsequently as a drainage network establishes itself by amplification of minor variations in the height of the original palaeo-surface.

Bearing these considerations in mind, a conceptual model for the development of an inland, lowland landscape is shown in Figure 35.

Comparing Figure 35 with Figure 34, the only difference is the addition of 'Sea level' to the right of Figure 35. It is emphasized that this is the local sea level at the point of outflow of the river draining the area of interest. It is determined by both eustatic and isostatic components, and hence by the global history of climate change and ice sheet development and retreat, as discussed in earlier sections of this report.

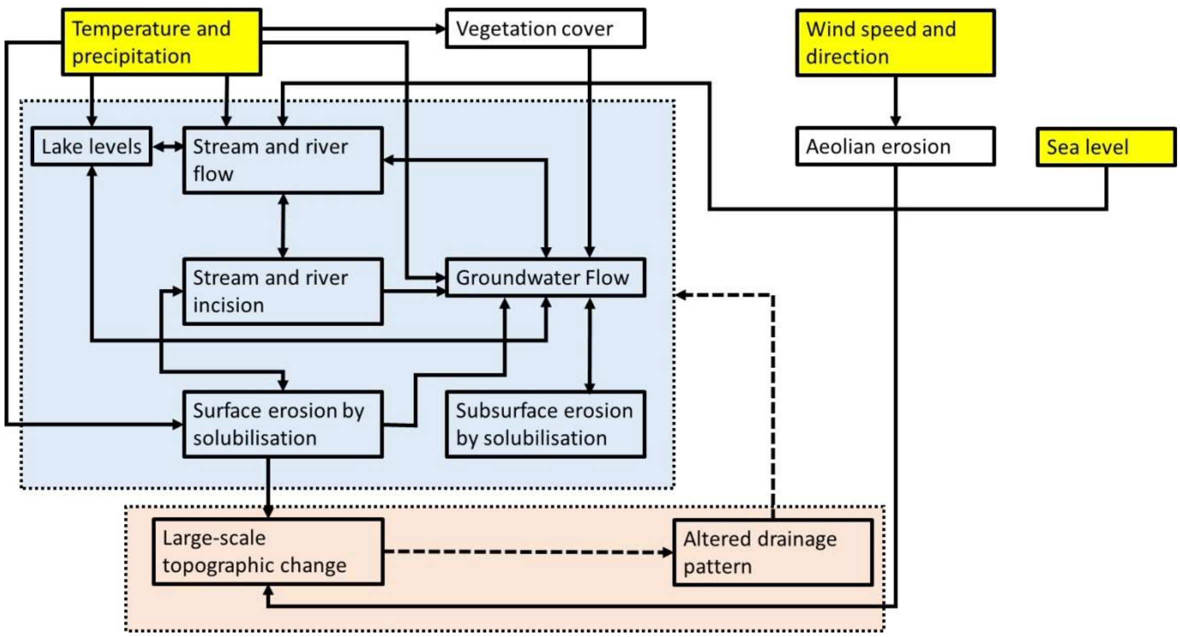


FIG. 35. Conceptual model for development of an inland lowland landscape under warm arid/temperate conditions.

6.5.1.3. Coastal landscapes

Coastal landscapes are affected by the same fluvial and aeolian processes as are applicable to inland landscapes. For these aspects, the conceptual model illustrated in Figure 35 may be used. Here attention is focused on the additional processes that need to be addressed in a coastal context. In this context, the main factor governing landscape development is changes in sea level, with a secondary factor being changes in storminess governed by changes in the global pattern of winds that will occur as the climate changes. Here local sea level and storminess are taken to be the drivers of landscape change, being obtained from the use of global climate models and ice sheet models that include appropriate representations of glacio–isostatic and hydro–isostatic adjustment.

In the present context, the coastal environment potentially comprises an area inland of the coast that is susceptible to inundation either by flooding or as a consequence of sea level rise, a coastal strip in which coastal processes are currently active (which may include open coastline, estuaries and lagoons) and an offshore zone that could become exposed in the event of sea level fall. In the long term, if sea level remained constant, the coastline would be expected to stabilize. However, in practice, coastal systems are susceptible to change under even small variations in external conditions, so coastal landscapes are typically associated with transient structures, such as estuaries, that alter substantially on timescales that are short compared with the overall timescale of post-closure radiological safety assessments.

Under conditions of rising sea level, the main processes that require consideration are inundation and coastal erosion. Inundation may occur either at the coastline or inland. The latter might occur, for example, if a low lying inland area is connected to the coast by a similarly low lying channel or valley. Coastal erosion varies in style and rate depending not only upon changes in sea level and storminess, but also on the alignment of the coastline in relation to predominant wave fields and the amount and particle size distribution of available sediments. Sediment transport occurs both alongshore and offshore, depending on the local conditions and coarser sediments may be deposited in a back beach area, preventing or retarding further erosion of finer sediments. Similarly, foreshore beaches may become protected by a lag of coarser material left in situ following erosion of finer grained sediments.

Sediments mobilized as a consequence of coastal erosion can be moved offshore, but they can also be transported along the coastline and deposited elsewhere. The pattern of erosion and deposition will be determined by the shape of the coastline, and headlands of more resistant rock can constrain the longshore movement (transported along the coastline) of sediments to individual transport ‘cells’, with only limited transport of sediments across the cell boundaries. Sediments transported along the coast may be deposited in estuaries or in spits that can eventually develop across the mouths of estuaries or across coastal bays to form lagoons. Sediments deposited in estuaries or in associated offshore deltas may arise not only from longshore transport, but also as material delivered to an estuary from its associated river system.

Other structures in the coastal strip, such as dune fields, are likely to be transient, but this is not necessarily the case. For example, the location of dunes may be ‘pinned’ by the existence of an underlying structural feature, such as a glacial moraine, as well as influenced by supply of sediments.

Under conditions of falling sea level, the main considerations are the emergence of a new land area, with the subsequent development of that area in terms of soils, vegetation and surface water drainage. This may include the development of sea bays through some or all of the stages of lake formation, lake infill, wetland formation and drainage and reclamation for agriculture. This process of transition can result in primary mire formation (at the shoreline), the paludification of mineral soils (change to waterlogged conditions) and the terrestrialization of water bodies large and small. It may also result in early desalination and immediate use for pasture or agriculture depending on the context. A wide variety of other uses are also possible, including forestry, preservation as a natural or semi-natural environment, or development as a built environment. As the range of potential developments is large, is partly determined by the local context, and will be constrained by the assessment context adopted, details of alternative development possibilities are not explored here.

Based on the above considerations, two conceptual models for coastal environments are shown in Figure 36. These relate to rising sea levels and falling sea levels, respectively. It should be kept in mind that these conceptual models apply in addition to the fluvio–erosion model illustrated in Figure 35.

Note that for falling sea level the various land uses can arise directly on emerged land after a drainage system has developed, or can arise following an antecedent stage of lake and/or wetland formation. Once terrestrial land uses have developed, they may be subject to further change.

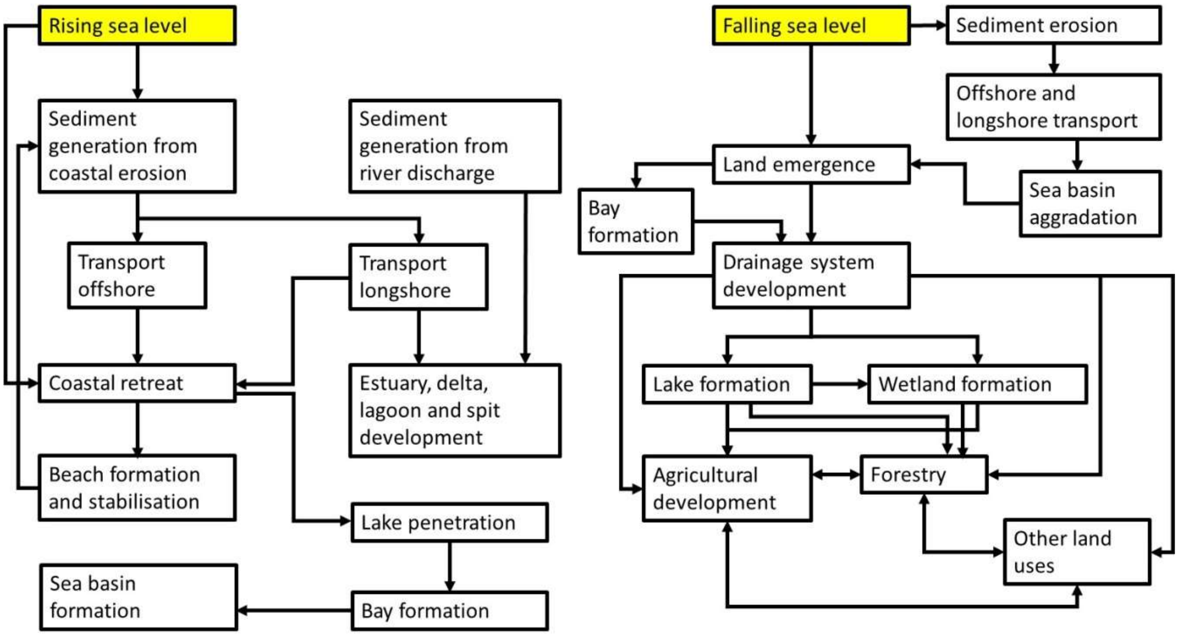


FIG. 36. Conceptual model for development of a coastal landscape under warm arid/temperate conditions.

6.5.2. Periglacial conditions

In periglacial conditions, an active layer that freezes and thaws on a seasonal basis overlies a layer that is perennially frozen, but that is typically penetrated by taliks that connect the deeper groundwater system to the surface. Such taliks typically underlie lakes of more than about 2 m depth, which effectively insulate the underlying ground and prevent it freezing during the winter. As the perennially frozen ground has low hydraulic conductivity, the development and degradation of permafrost has major effects on groundwater flow. In turn, these changes in flow can affect the geochemical composition of the groundwaters. In addition, the geochemical composition of the groundwaters can be affected more directly by permafrost development, as the process of freezing can expel solutes from groundwaters, so increasing the dissolved solids content of groundwaters just below the freezing front. In turn, this can affect the density of those groundwaters, so modifying the groundwater flow regime. Conversely, when permafrost melts, groundwaters low in dissolved solids will be generated.

At the ground surface and in the active layer, the conceptual model of the fluvio–erosive system is similar to that shown in Figure 34 (above) for warm arid/temperate conditions. However, sub-surface erosion by solubilization is likely to be of very limited significance, as the active layer is typically no more than 1 to 2 m thick. Also, fluvial erosion may be enhanced in effectiveness because the underlying frozen ground is likely to reduce the degree of infiltration, resulting in more water availability for surface and near surface flow (unless, as is sometimes the case, the periglacial climate at a site is significantly drier than the temperate climate at that site). A further enhancement may occur due to the episodic nature of the flow system, particularly in respect of the spring snowmelt, during which rapid melting of the snowpack occurs compounded by high short term discharges due to the break-up of ice dams in rivers. In general terms, tundra type vegetation is likely to apply in periglacial conditions.

Based on the above considerations, a conceptual model for the periglacial environment is shown in Figure 37.

Compared with Figure 34 (above), the main additions in Figure 37 are on the left hand side. Seasonal development of the active layer is determined by the seasonal pattern of temperature and precipitation. In turn, the hydrological characteristics of the active layer affect the overall fluvio–erosional regime, but also affect permafrost development and degradation, which is primarily determined by seasonal and annual temperatures. Permafrost development influences talik formation, which is also affected by lake levels (through insulation effects) and deep groundwater flow (through the upwelling of relatively warm groundwaters). Permafrost and talik development influence the deep groundwater flow regime. Note that deep groundwater flow and groundwater flow in the near surface environment correspond to parts of the same overall groundwater flow regime, hence the link between them. The groundwater flow regime affects the composition of deep groundwaters through the transport and mixing of waters of different chemical composition. Permafrost development or degradation affects groundwater chemistry through salt expulsion during freezing or the release of water low in dissolved solids during melting. Groundwater composition affects flow through density effects and affects permafrost development through its influence on the freezing point of that groundwater.

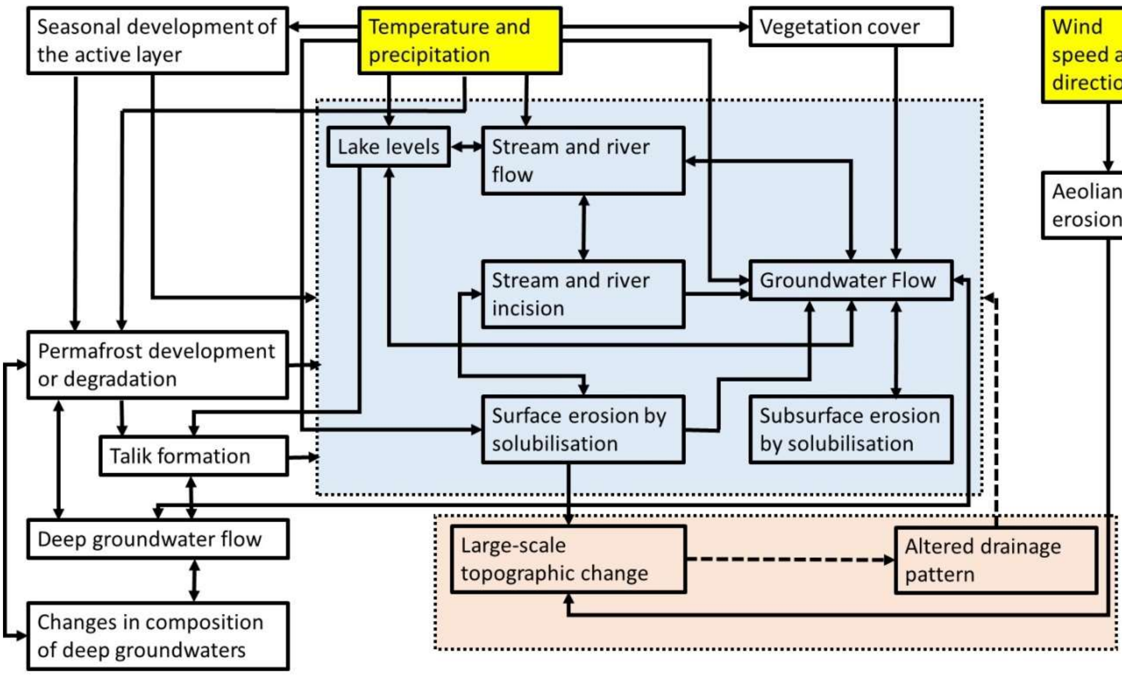


FIG. 37. Conceptual model for development of an inland landscape under periglacial conditions.

6.5.3. Glacial conditions

Under glacial conditions, it is important to distinguish three cases. These are when an ice margin is advancing over the site, when the ice sheet overlies the site and when the ice margin is retreating over the site. When an ice sheet advances over a site, it may or may not encounter existing permafrost. When it retreats, this may be over either frozen or unfrozen ground, depending on the duration of the period for which the ice sheet has covered the site, its thickness and temperature profile, and its pattern of movement, as well as on the salinity of the groundwater present in the underlying rock. When thick ice covers the site, the underlying ground may again be either frozen or unfrozen, depending on the same considerations.

One of the main effects of passage of an ice sheet relates to its influence on the subglacial hydrological regime. Water flows may develop at the base of the ice sheet or water may be forced into the underlying rock (but only to a significant degree if the ground is unfrozen and the superficial strata are relatively permeable). In addition, the mass loading of the ice will affect the sub-surface stress regime and a significant degree of fault movement may occur due to stress relief on or after removal of this mass loading. At the ice margin, during retreat, a very active hydrological regime is likely to develop driven by melting of the ice at both its surface and base.

The passage of an ice sheet can also result in substantial removal of superficial deposits (in the UK, the passage of a single ice sheet has been estimated to remove, on average, about 30 m of unconsolidated sediments [101]), whereas newly eroded bedrock material is typically emplaced as the ice sheet retreats. Upland areas that are subject to glaciation typically exhibit characteristic features such as U-shaped and hanging valleys. Although such features are much less characteristic of lowland areas, substantial glacial erosion of such areas is known to occur [101] and glacial or post-glacial depositional features (e.g. till sheets, moraines, eskers and drumlins) are widely observed.

Based on the above comments, a conceptual model for landscape evolution during the passage of an ice sheet across a site is set out in Figure 38.

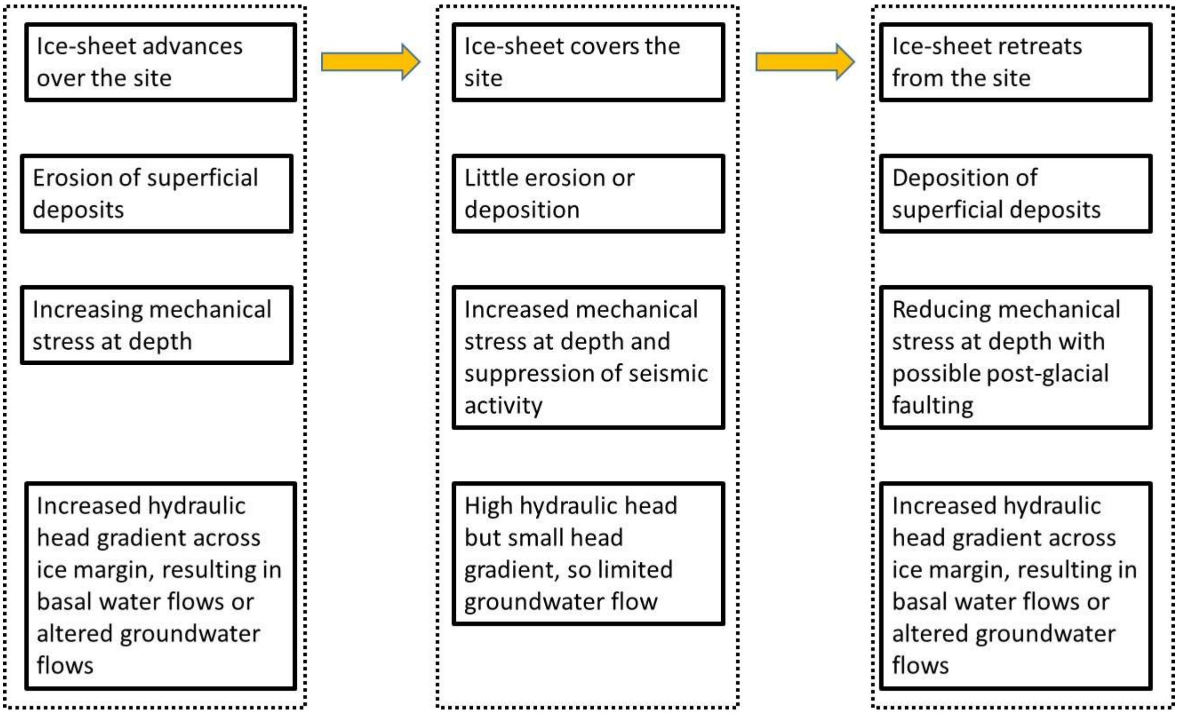


FIG. 38. Conceptual model of the passage of an ice sheet across a site.

6.5.4. Transitions between climatic conditions

As three distinct states are identified for consideration, in principle the following six transitions should be considered:

- Warm arid or temperate to periglacial;
- Warm arid or temperate to glacial;
- Periglacial to glacial;
- Glacial to periglacial;
- Glacial to warm arid or temperate;
- Periglacial to warm arid or temperate.

In practice, warm arid or temperate to periglacial and periglacial to warm arid or temperate transitions do not introduce any new issues in the conceptual model, as Figure 34 is a reduced version of Figure 37, i.e. in the warm arid or temperate to periglacial transition, the additional cold region processes become of increasing importance, whereas in the reverse transition they become of decreasing and, eventually, of no significance. Also, the warm arid or temperate to glacial transition is unlikely to occur, as glacial periods are generally entered through a slow cooling trend, i.e. there would be likely to be an intervening periglacial period of significant duration. The periglacial to glacial transition is addressed in Section 6.5.3, which deals with the passage of an ice margin across the site.

This leaves the glacial to periglacial and glacial to warm arid or temperate transitions to be addressed. These transitions are best considered together, since glacial episodes are typically characterized by one or more phases of rapid warming. Thus, for example, the entire Late

Glacial – Younger Dryas – Holocene transition occupied a period of no more than about 5000 years. In such a rapid warming phase, following retreat of the ice margin across the site, a very active hydrological regime may exist and this can rapidly remodel the sediments deposited during glacial retreat. Alternatively, at coastal sites that have been subject to isostatic depression due to ice loading, submerged conditions may exist in the immediate post-glacial period to be followed by a phase of land emergence. In principle, all the relevant processes occurring during such transitional periods are shown in Figures 34–37. However, it is important to recognize that during such a transitional phase, landscape processes will be operating far from equilibrium and that processes of change may be rapid. Thus, complex sequences of deposits may be laid down and modified by erosion over a period of a few thousand years. This means that such periods will need to be given careful scrutiny on a site specific basis, since local factors will be a major consideration in determining which processes are likely to be of particular importance and in quantifying the effects of those processes.

7. REPRESENTING ENVIRONMENTAL CHANGE AND BUILDING CONFIDENCE IN DOSE MODELLING

This Section focusses on the final three steps of the methodological road map as shown in Figure 39.

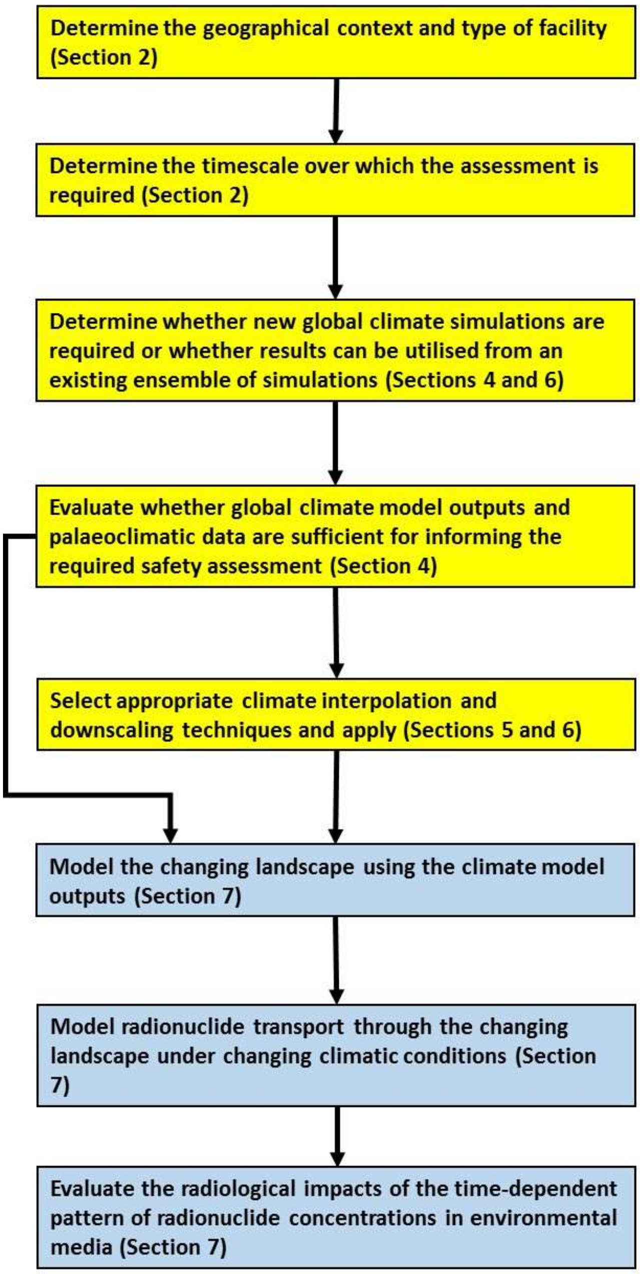


FIG. 39. Road map for performing an assessment taking climate change and landscape development into account.

The preceding sections of this report draw on international experience to describe how key processes that drive environmental change (most notably climate change) can be identified and assessed, leading to narratives of environmental change that provide a basis for radiological assessments. This Section of the report discusses and illustrates the use of such narratives in radiological assessments, drawing on experience of the application of biosphere assessment approaches.

Uncertainties in both descriptions of environmental change and in the representation of radionuclide releases, transport and potential exposures within the biosphere are unavoidable. These uncertainties can be managed, for example, by assessing a range of potential future evolutions/scenarios. However, uncertainties will remain, and it is emphasized that assessments must not be considered as predictions of the future, rather they should be considered as providing a range of illustrative projections that encompass plausible future situations to an extent that is sufficient to provide increased confidence in the safety of a disposal facility.

The following subsections discuss how plausible and coherent narratives of long term climate change, landscape evolution and land use can be used in support of radiological assessments. Although the focus is on radiological impacts and hence the release and transport of radionuclides in situations where both the characteristics of the climate and the landscape are changing, similar considerations and approaches would be generally applicable in assessing adverse effects of non-radioactive chemical contaminants on both human health and the environment.

7.1. DOSE ASSESSMENT METHODOLOGY

A methodology on biosphere modelling for radiological assessment was developed at an international level within Phase II of the collaborative Biosphere Modelling and Validation Study (BIOMOVS II), which ran from 1991 to 1996 [172, 173]. The study included a working group on 'Reference Biospheres', the aim of which was to consider the potential to develop internationally accepted standardized biosphere models for use in long term radiological assessments concerning radioactive waste disposal. The working group concluded that standardized models were inappropriate due to the need for biosphere models to reflect the context specific to each assessment. The working group instead sought to encourage transparency, consensus and harmonization in biosphere modelling through the development of a reference methodology, supported by a list of biosphere Features, Events and Processes (FEPs). The FEP list explicitly includes environmental evolution, specifically environmental dynamics and climate driven changes, but without elaboration as to how this might be done. Thus, environmental change was highlighted as a topic that needed further consideration.

The IAEA BIOMASS project [1], which ran from 1996 to 2001, further developed and refined the biosphere methodology (Figure 40), drawing on experience of its application (see e.g. Ref. [174]) and development of several examples. The importance of environmental change is recognized within the BIOMASS methodology, where it is treated as a fundamental question that drives the development of biosphere models and whether: (a) change should be considered or not; and (b) if considered, whether the change need be explicitly modelled (sequential biosphere states with transitions), or whether a non-sequential representation is appropriate (Figure 41). The BIOMASS project included example applications of the methodology. One example application specifically aimed to demonstrate how to address the implications of biosphere changes that may occur during the period in which releases to the biosphere from a disposal facility could occur. Three sub-examples were examined, two relating to hypothetical disposal facilities at Äspö in Sweden and at Harwell in the UK, and a third considered a generic inland agricultural context. Identification of mechanisms causing change was conducted for each example, along with assessments of the impacts on each biosphere system (Step 2 in Figure 41), although none of the examples were carried through to model development.

The BIOCLIM project, which ran from 2000 to 2003, sought to build on BIOMASS and establish a practical methodology for assessing climate and environmental change [3]. BIOCLIM established long term projections of global climate and explored approaches for downscaling the global projections to regional and site scales. The project elaborated on the BIOMASS approach to considering environmental change, with specific consideration of climate change, as illustrated in Figure 42. BIOCLIM explored the development of narratives of environmental change and their interpretation as sequences of biosphere states with transitions in between, including the potential use of tools such as interaction matrices and transition diagrams in characterizing the transitions. BIOCLIM included illustrative application of the methodology to five cases, covering Lowland Britain, the Meuse/Haute-Marne region of north-east France, central Spain, north Germany and the Czech Republic. For each example:

(1) narratives were provided for the present day conditions, as well as the site's evolution through one or more sequences of climate change;
(2) the narratives were interpreted as sequences of biosphere states and associated transitions; and
(3) the states and transitions were then characterized with a view to supporting subsequent radiological assessment modelling, although no modelling was undertaken.

Both BIOMASS and BIOCLIM were consistent in approach for developing 'narratives', i.e. identify mechanisms causing change, identify impacts, identify qualitatively different 'futures'. This report does not explicitly follow this terminology, but the approach adopted is consistent with it.

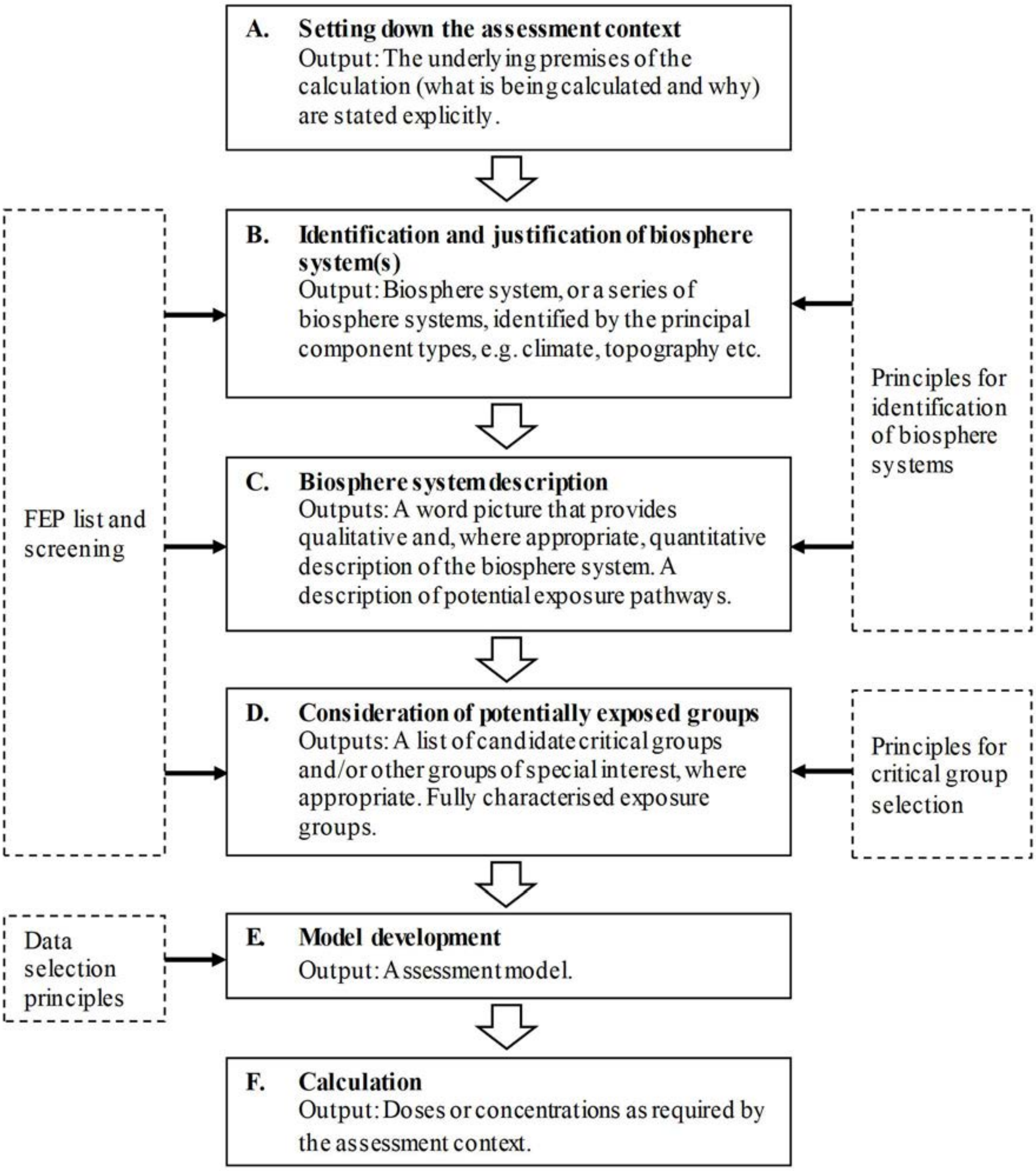


FIG. 40. The BIOMASS methodology, including route map (lettered steps) and supplementary inputs (dashed boxes), based on Figure A2 of Ref. [1].

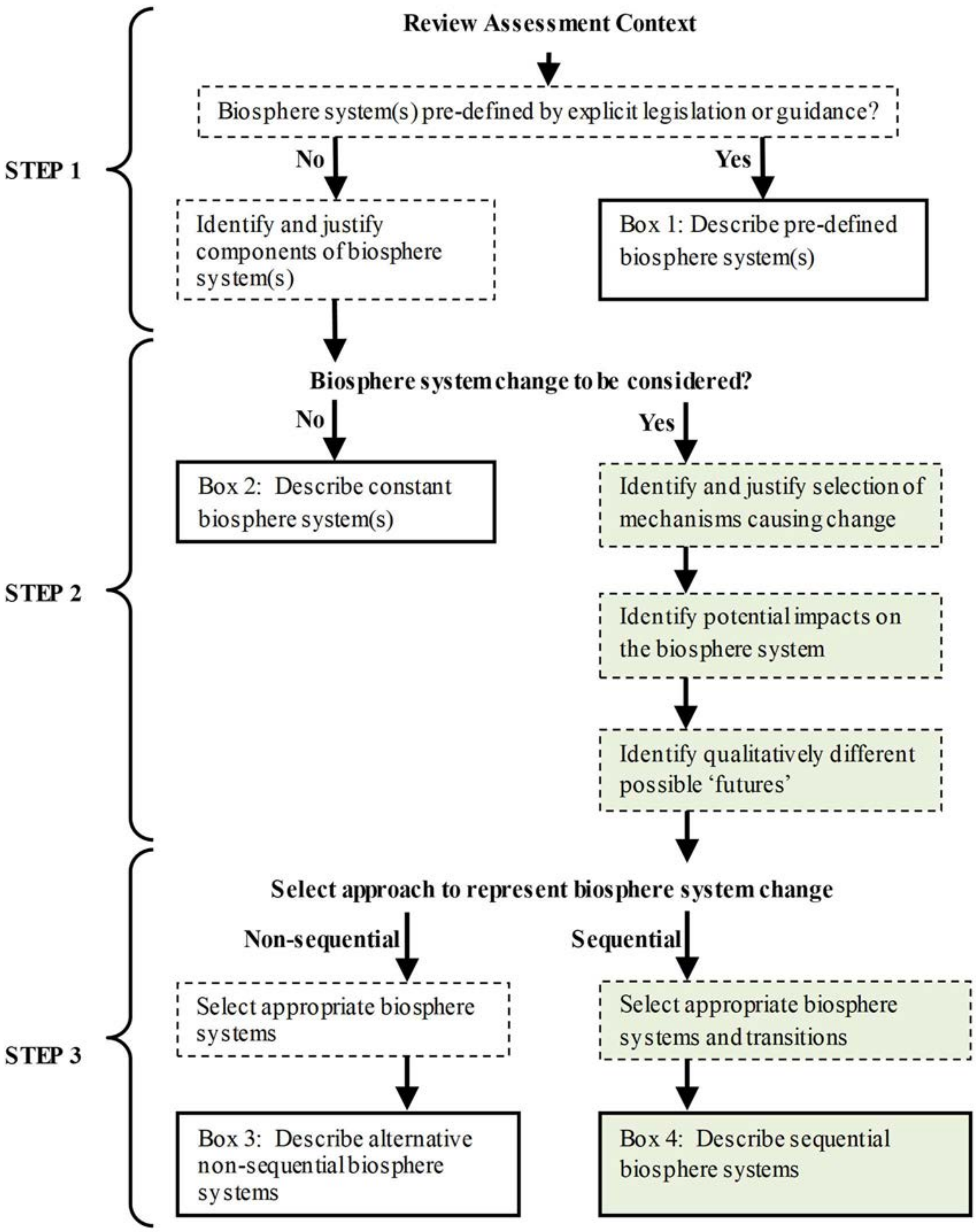


FIG. 41. Decision tree for use in identification and justification of biosphere systems (Steps B and C of the BIOMASS methodology), based on Figure A4 of Ref. [1]. Shaded boxes highlight the overlap with Figure 42.

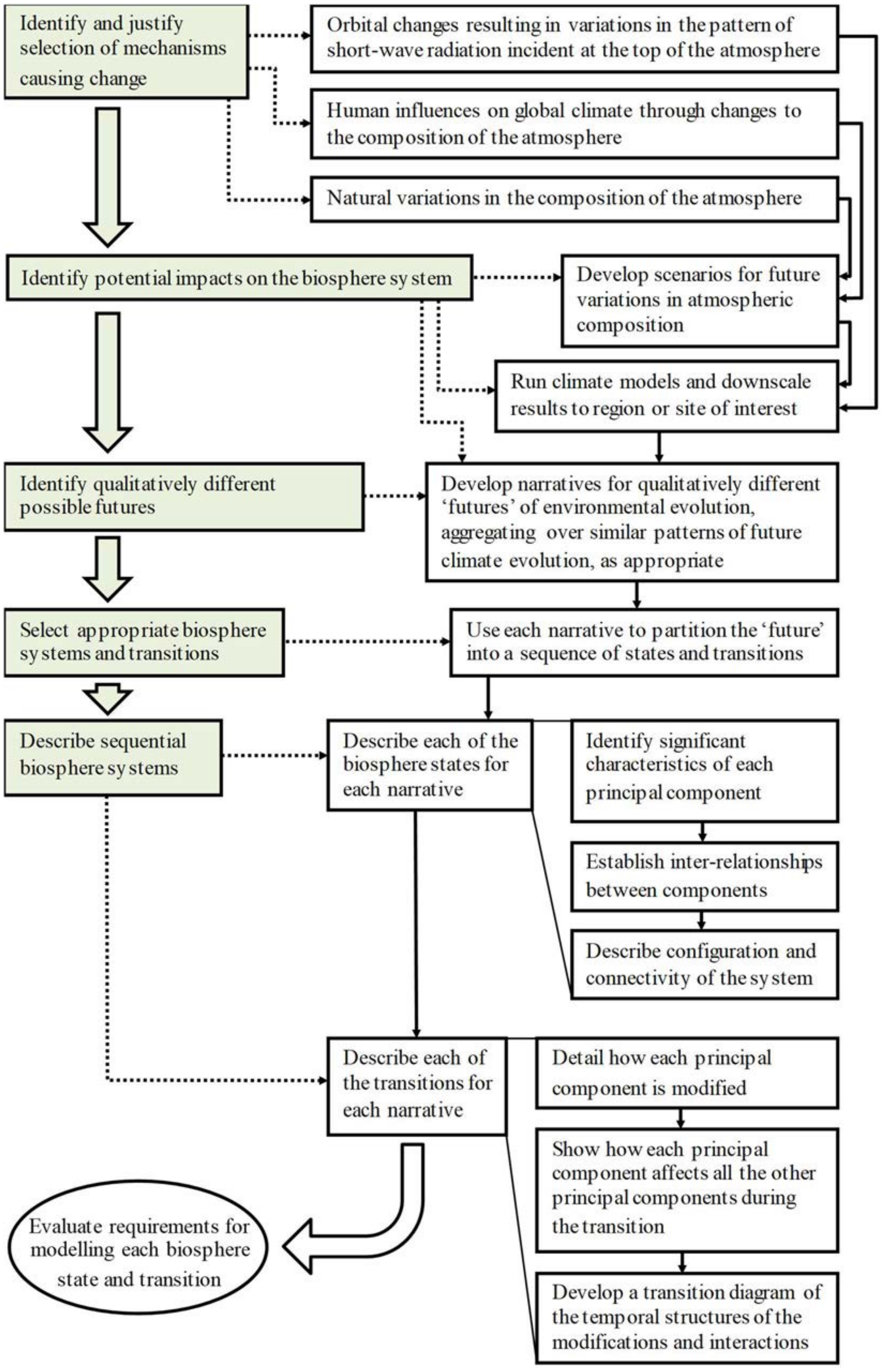


FIG. 42. BIOCLIM route map for including the effects of climate change in the representation of biosphere systems and transitions (expansion of BIOMASS Steps 2 and 3), based on Figure 3.1 of Ref. [77].

The modelling of landscape and climate evolution define boundary conditions for the geosphere and provide a basis for the development of a range of different kinds of scenarios. Therefore, the narratives of landscape and climate evolution described in previous sections are of importance to safety and performance assessments for radioactive waste disposal as a whole and not just to biosphere modelling (Figure 43). The spatial and temporal scale of the information required of the climate and landscape projections will differ for different components of an assessment, for example, geosphere assessment may require regional scale understanding of groundwater recharge and geochemistry, whereas biosphere assessment may need more localized precipitation and temperature profiles to support potential irrigation requirements. The narratives therefore provide information at a regional and local scale.

The process for moving from narratives of climate and landscape evolution to biosphere models is illustrated in Figure 44, drawing on the BIOMASS and BIOCLIM documents and using continuing assessment experience. The first step of the process is to disaggregate the narratives into sequences of biosphere states and transitions. The next step is to describe the biosphere states at the local scale. Assessment modelling typically focusses on the area within which the highest potential exposure might arise. Therefore, for assessment modelling purposes, biosphere descriptions should tend towards focusing on the local scale. To identify the spatial extent of the local scale, consideration of the location and spatial extent of radionuclide releases and human activities is needed, as well as populations of relevant non-human biota. Appropriate consideration of spatial scales in the context of solid waste disposal performance assessments was developed in the BIOPROTA programme [175]. Once the biosphere states have been described, the transitions between the states are themselves described.

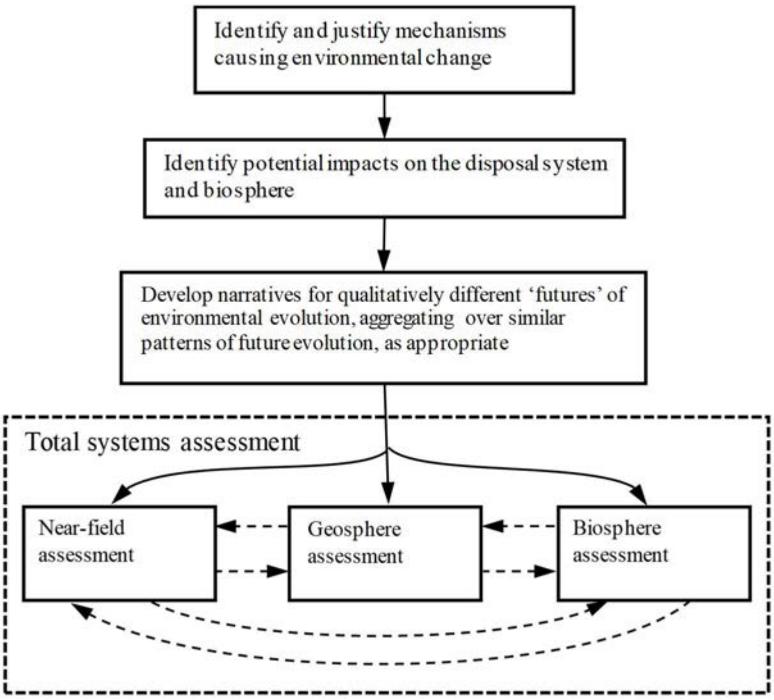


FIG. 43. The way in which narratives of environmental change are developed and how they feed into subsequent components of an assessment.

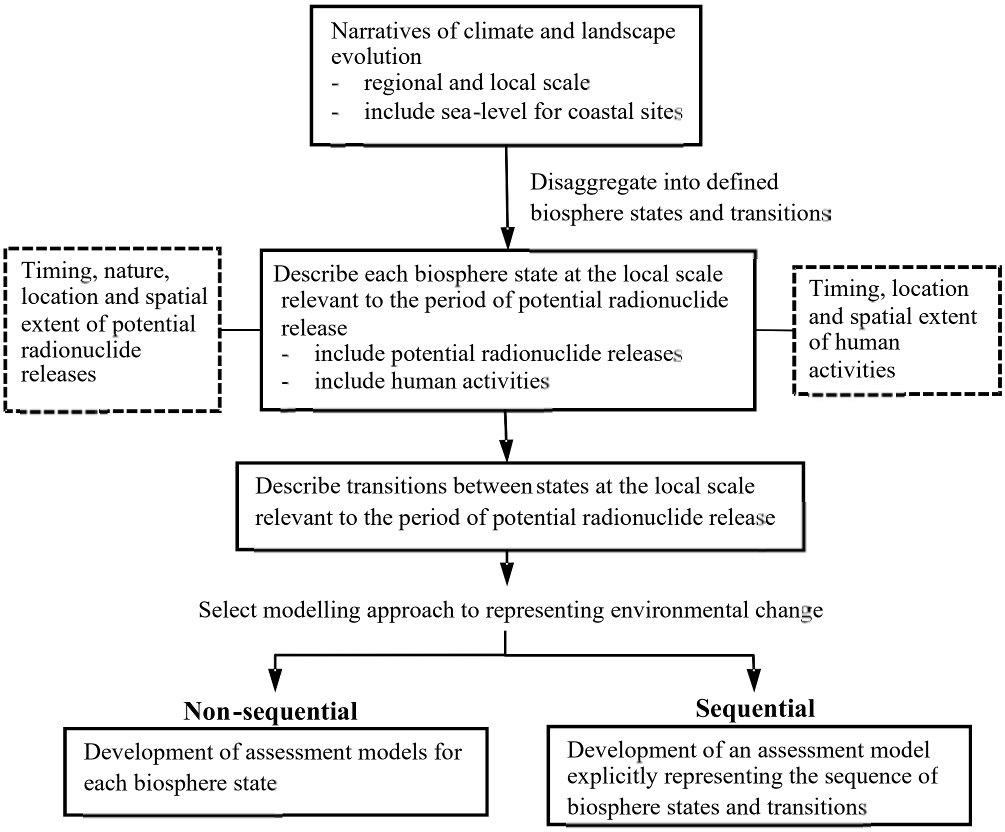


FIG. 44. Illustration of process for getting from a narrative of climate and landscape change to assessment models, based on BIOMASS and BIOCLIM results and continuing assessment experience.

A structured approach for describing biosphere systems is included in the BIOMASS methodology. Similarly, structured approaches to describing transitions between biosphere states are included in various studies [3, 4, 77].

Having described sequences of biosphere states and transitions, the next question to be addressed is whether the biosphere should be modelled as a sequence of states with explicit transitions (the sequential approach), or whether it can be adequately represented with a finite number of discrete assumed equilibrium (i.e. unchanging) biosphere states (the non-sequential approach).

This non-sequential approach involves representing one or more biosphere states independently, disregarding their projected sequence. This is appropriate where:

— potential impacts of one state are not significantly affected by radionuclide concentrations that accumulated in the previous state; and
— potential impacts during a transition do not exceed those that would occur during the preceding or subsequent states.

Only some transitions are likely to need explicit representation in an assessment, i.e. those that: (i) occur after a biosphere state within which greater accumulation occurs relative to the subsequent state; (ii) include mechanisms that can release accumulated contamination; and/or (iii) make accumulated contamination available for new exposure pathways. Scoping calculations can be used to explore transitions and then inform and justify the choice between a sequential or non-sequential approach.

Explicit representation of sequential environmental change requires greater complexity compared with the non-sequential approach. The evolution of climate, hydrology, landform, radionuclide release, radionuclide migration and accumulation and land use, need to be integrated for sequential modelling of environmental change. It can be difficult to develop coherent descriptions of biosphere states and transitions on a site generic level, not least because the approach is more data intensive. A sequential approach becomes more plausible with the support of detailed site specific characterization of the biosphere and how it is linked to the geosphere. Nonetheless, there is a challenge in maintaining transparency and therefore confidence in long term assessments as the degree of complexity increases. For this reason, it can be informative to explore both sequential and non-sequential approaches so that they become complementary [2].

The descriptions of biosphere states and, depending on the choice of approach, transitions provide the basis for subsequent development of conceptual and mathematical models. The high degree of iteration potentially required throughout the process illustrated in Figures 43 and 44 is emphasized, although it is not shown explicitly.

7.2. REPRESENTING ENVIRONMENTAL CHANGE IN DOSE MODELLING

The preceding sections of this report provide a framework within which environmental change can be considered within safety and performance assessments. The development of this framework has provided the principal focus for WG6 and is of relevance to all aspects of post-closure safety and performance assessments for radioactive waste disposal.

The methodological considerations discussed in Section 7.1 concern how the narratives of climate and environmental change provide a foundation on which conceptual and mathematical models of the biosphere can be built. Awareness of some of the challenging aspects of the development of post-closure biosphere assessments informs the methodological considerations. Further discussion of specific aspects related to the representation of environmental change in radiological assessments is given in the subsections below.

7.2.1. Simplifying assumptions

All aspects of safety assessment modelling simplify complex systems. Assessments aim to develop robust models that strike a balance between being simple enough to remain tractable and understandable, while having confidence that the array of processes with potential to affect radionuclide release, transport, accumulation and exposure are adequately represented. As a general rule, the focus needs to be on those processes that are relevant from a dosimetric point of view. Assessments can use simplifying, conservative assumptions to help provide confidence that calculated end points are not underestimated. However, the systems being modelled are complex; those conservatisms are not always obvious and what might be considered conservative from one perspective may not be conservative from another. An example of such conflicting conservatism is provided in modelling rapid transport through sediments to the surface, which is typically conservative for relatively short lived radionuclides without decay chains. However, allowing rapid transport may not be conservative for radionuclides with decays chains including radioactive progeny, where the progeny are more radiologically significant than the parent radionuclides; this is because the rapid transport might not permit sufficient time for substantial in growth of the progeny.

Justification for the balance used between simplifying, conservative assumptions and more complex modelling approaches can only be made in light of the context for a specific assessment. The significance of the assessment context in supporting biosphere modelling assumptions is recognized in previous modelling guidance, including BIOMASS (see Section 7.1). As well as documenting the justification for simplifying conservative assumptions, it is also important to justify complexity within assessment models that cover extremely long timescales [176].

A relatively simple model may be suited to a relatively simple assessment context – one in which, say, site specific details are limited, such as might be the case in scoping studies. As site understanding, including projections of landscape evolution, develops, the biosphere component of the radiological assessment may increase in complexity [68, 164] compared with earlier assessments [177, 178]. More stylized assessments that correspond to relatively simple assessment contexts can be expected to be straightforward to understand. As assessments move towards becoming more complicated, e.g. as site understanding increases, then a greater effort needs to be placed on justifying the degree of complexity and/or simplifying assumptions so that the target audience understands the approach that is used. The process for addressing climate and environmental change described in this report, coupled with methodological approaches to assessments [2, 179], provide a framework for addressing such challenges.

7.2.2. Considering uncertainty

The management of uncertainty is a key component of long term dose assessments. The framework outlined in the preceding sections of this report helps to support a transparent way in which to consider and justify the way in which uncertainty concerning environmental change is represented. Nonetheless, results must be interpreted in the context of uncertainties and the way in which they have been addressed [179]:

— Uncertainty about the future evolution of the system being modelled can be addressed by consideration of a range of different scenarios of possible future conditions (termed scenario uncertainty). Examples of uncertainties that are typically addressed through different scenarios include alternative climate sequences, e.g. covering different amounts and temporal patterns of future greenhouse gas emissions, and alternative landscape evolutions.
— Uncertainty about the way in which radionuclide migration, accumulation and potential exposures are most appropriately modelled (termed model uncertainty) can be addressed through variant calculations/side calculations with differing modelling approaches. Uncertainty about the interpretation of the scenario and process modelling can be addressed through developing assessment models by more than one researcher (or group) and establishing a consensus model afterwards [180].
— Uncertainty about the value of parameters (termed parameter uncertainty) can be addressed through probabilistic calculations and/or variant deterministic calculations based on alternative combinations of parameter values. Probability distribution functions reflecting site conditions are preferred to generic distributions, though care should be taken to ensure that they are not unduly constrained by present day site characteristics.
— While still noting the above, risk dilution or risk dispersion (an apparent lowering of the calculated risk from unduly increased input probability; e.g. Ref. [181]) should be avoided. It can be caused, for example, by event timing, spatial effects, parameter correlation, or parameter distributions assigned [182]. Unduly increased distributions of parameters may produce misleading results also in sensitivity analyses, and often it is useful to define the distributions separately for the uncertainty analysis and the sensitivity analysis.

Well-founded descriptions of future climate evolution and environmental change, together with consideration of associated uncertainties, provide a foundation for identification of scenarios and for developing conceptual models that merit quantitative evaluation. Long term assessments will typically consider a range of plausible climate and landscape evolution scenarios to help give confidence that conclusions are robust against these uncertainties. Assessments will often use a central scenario as a reference point against which other results are compared; such a central case may be termed the reference case, base case, normal evolution or expected evolution scenario. Small changes to such cases may be referred to as variants, whereas significantly differing cases may be referred to as alternative scenarios.

Central scenarios may be considered the most likely, but they remain illustrative, given the large uncertainties involved, and should not be taken as being predictions. This distinction is important, as it helps to ensure that quantitative assessment results are interpreted in light of residual uncertainties.

When evaluating the range of scenarios that warrant consideration in the dose assessment modelling, the potential for consequences arising from extreme meteorological events (e.g. intense rainfall, storms, droughts) should be borne in mind. Consideration of climate should therefore extend beyond long term averages to include magnitudes and return periods for extreme meteorological events. Such events have the potential to shape landscape development, particularly in drier climates, and should therefore already form part of the narratives of climate and landscape evolution developed for assessment purposes.

7.2.3. Present day biosphere

The present day biosphere, along with consideration of its historical evolution, provides a starting point for assessments extending into the future. In comparison with the future, there is relatively little uncertainty about the present day biosphere system and, where uncertainty arises, there is greater potential to reduce that uncertainty through research. The present day biosphere is also a more tangible system to conceptualize, both in the development of an assessment, but also among target audiences. The impact of any radionuclide releases is also likely to be greater during interglacial periods due to the potential for more intensive use of resources local to the contamination. These factors provide a driver towards a focus on the present day biosphere; this driver is, for example, reflected in some regulatory guidance[25]. Consideration of long term climate change and landscape evolution provides a framework to help identify to what extent representation of the present day biosphere remains viable. On very long timescales, the cyclic nature of glacial–interglacial variability means that conditions similar to those at the present day are likely to arise again in future.

In addition to providing information about broad glacial cycles, climate modelling will also help to inform an evaluation of the degree to which conditions will evolve within particular climate states. This is of particular interest during the current interglacial, with global warming leading to the potential for warmer climates with notably different environmental characteristics (e.g. erosion and near surface hydrogeology) compared with the present day. Such conditions can increase potential impacts in comparison to the present day, for example through increased irrigation requirements and should, therefore, be borne in mind.

If an assessment is to base its representation of the biosphere on that which exists at the site (or at an analogue site) at the present day, then this should be clearly stated when describing the scenarios to be represented. If, however, an assessment is to use present day information to provide information about the conditions that might exist in the future, then care is needed to ensure that the results are not unduly constrained by representing a specific ecosystem through very detailed modelling.

7.2.4. Supporting models

Supporting quantitative models are often used to provide plausible foundations for assumptions adopted in dose assessment models. Examples include landscape development models, catchment scale surface hydrological modelling and hydrogeological modelling with particle tracking to explore issues including well interception and groundwater discharge areas. The complexity of processes represented in supporting models, together with their associated computational solution, mean that the modelling may only represent snapshots in time and may mean that uncertainties in these supporting models are typically addressed through alternative deterministic simulations.

In making use of supporting models in dose assessment modelling, care is needed to recognize the associated uncertainties, including those assumptions that are present in those models. There is a danger that, in interpreting supporting models with deterministic representations/datasets in dose assessment models, that the associated uncertainties are somehow lost and that too much confidence is placed on the outputs (i.e. the outputs are effectively portrayed as being 'predictions' of the future). Additional uncertainties can also be introduced in interpreting the

[25] Swedish regulatory guidance states that today's biosphere conditions should be evaluated, unless it is clearly inconsistent to do so [183].

outputs of supporting models, for example, in interpolating the results from a sequence of snapshots.

Alternative scenarios and/or variant calculations, which can include both complex modelling and simple order of magnitude estimates, can be used to help build confidence that assessment results are robust against the uncertainties associated with supporting detailed modelling. Otherwise, the absence of explicit treatment of the uncertainties should be highlighted, so that it can be borne in mind when interpreting quantitative results.

7.2.5. Sequential and non-sequential modelling for dose assessment

One of the questions to be addressed in considering environmental change within the context of dose assessment models is whether the change needs to be explicitly represented or not. This issue is recognized in the BIOMASS methodology and also considered by WG3 of EMRAS II [2].

Projections of climate and landscape evolution should not be understood as the assumption of a requirement to explicitly model those changes in a radiological assessment. Consideration needs to be given to if and how the environment is changing in relation to when radionuclide releases occur (as discussed in Section 7.1). For example, should radionuclide releases be reliably expected to occur during a period of stable climate and landscape, then there is no necessity to explicitly include dynamic environmental change in the dose assessment model, even though the climate and landscape may differ from that which is present today.

Consideration should be given to the potential for radionuclide accumulation and subsequent release; examples include accumulation in sediments and subsequent availability of those sediments for exploitation. Increased availability may arise as a result of physical change, e.g. land becoming available through environmental change, or through geochemical change, e.g. a change in geochemistry leading to a change in radionuclide speciation and mobility. If potential for accumulation and subsequent availability is identified within an evolving environment, then there is a need to consider explicitly modelling the environmental change (Figure 45). If the decision is not clear cut, then there is always the option of quantitatively exploring both approaches to help justify what is ultimately carried through to the main assessment calculations. If change is explicitly represented, then it is important to ensure that the timescales of both: (i) environmental change, and (ii) radionuclide accumulation and availability are modelled appropriately.

The sorption behaviour of some elements can differ depending on redox conditions in pore water, due to differing geochemical speciation. Elements that are typically considered to exhibit redox sensitivity in the context of dose assessments include selenium, technetium, iodine and uranium. For those radionuclides, consideration needs to be given to the potential for environmental change to modify redox and therefore retention conditions within soils and sediments [184, 185]. Dose assessment models traditionally use equilibrium sorption assumptions within soil and sediments. There is potential for other modelling approaches to improve the representation of accumulation and mobilization, particularly for these redox sensitive radionuclides such as ^{79}Se [186].

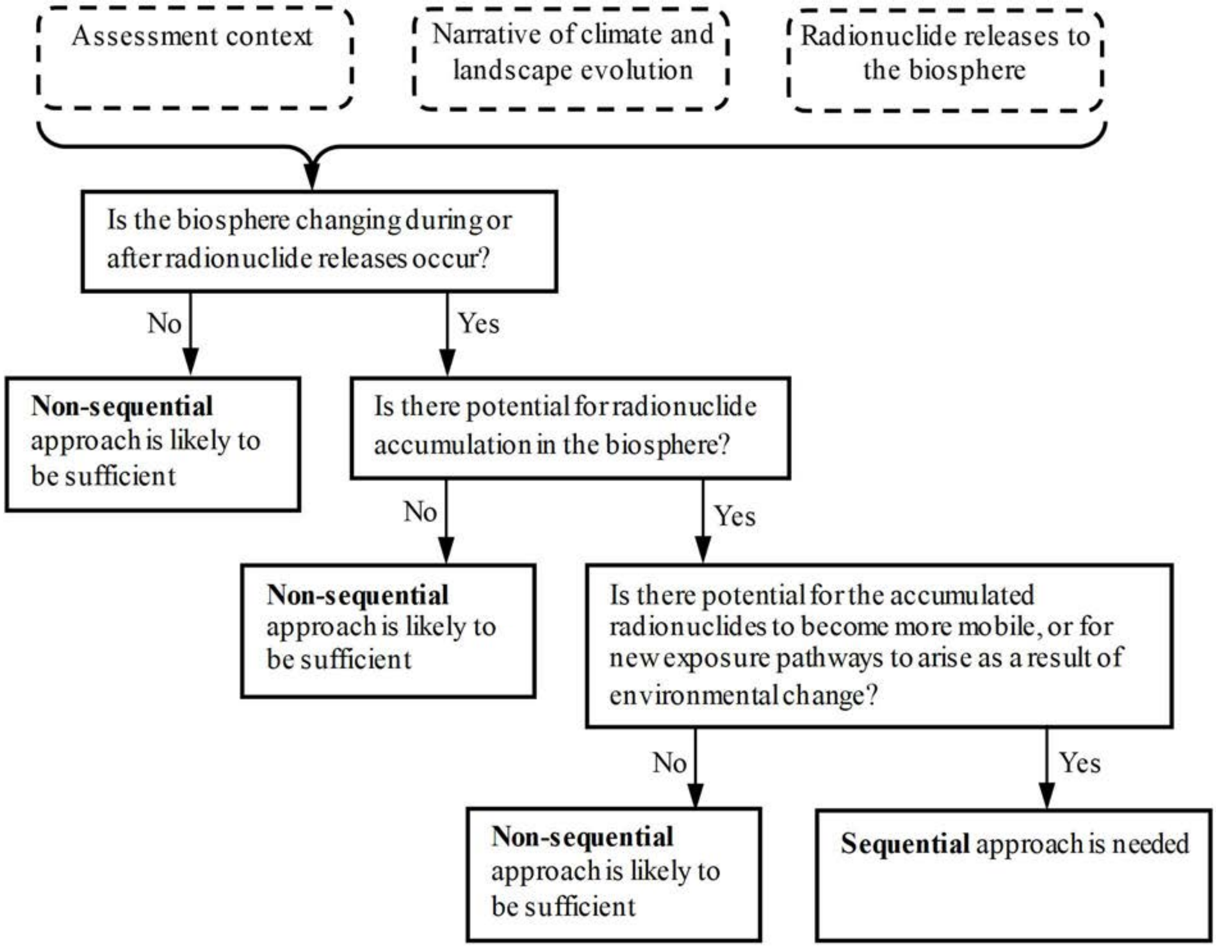


FIG. 45. Considerations for adopting a sequential or non-sequential approach to representing the biosphere for assessment modelling.

There is, inevitably, a degree of judgement relating to the way in which the biosphere is represented within the radiological assessment. As illustrated in Figure 45, any decision will be shaped by the assessment context. The decisions should reflect the above considerations and aim to create confidence in the robustness of the approach adopted to assessing and demonstrating long term safety. Even though environmental change may not be expected to give rise to an increase in calculated doses, the assessment team may still choose to explicitly represent that change within the dose assessment, for example, for consistency and coherence with other aspects of the assessment that suggest possible releases to the biosphere. In any case, it is important that the decision is explained and justified so that the audience for the assessment can follow and understand the choices made.

7.2.6. Discretization of biosphere models for contamination migration and accumulation

If environmental change is explicitly represented in assessment models, then it is particularly important that the timescales for radionuclide migration and accumulation are represented appropriately. For example, the value in developing coherent timelines for evolving biosphere systems can be undermined if the timescales for radionuclide accumulation are not represented with equal care.

Biosphere models typically adopt a linear compartment modelling approach because they are easily conceptualized as collections of distinct media or volumes of space between which radionuclide transfers can be relatively easily formulated as constant turnover/transfer rates. The identification of the number of compartments to be used when discretizing a biosphere model is a key decision that should be discussed and justified in the model formulation, in parallel with the time(s) over which the assumption of constant turnover/transfer rates is appropriate[26].

The following factors should be taken into consideration when discretizing compartment models:

— The area that might become contaminated;
— The regions within that area for which distinct environmental concentrations need to be calculated, including consideration of any averaging inherent in the behaviour of the receptors (e.g. resource area considerations);
— Regions of distinctly differing physical and chemical properties; these different environmental media should already be identified as part of the conceptual model development;
— Regions affected by differing processes and/or different process rates; these should be identified and distinguished;
— The discretization of the transport pathways; this should be chosen with due regard to numerical dispersion.

More generally, for compartment models, there is a need to ensure that the assumption of instantaneous mixing within any compartment is appropriate for the current assessment. Similar consideration applies to other modelling techniques. This is not only a function of linear donor controlled compartment models.

Numerical dispersion occurs as a result of the concept that contaminants are taken to be uniformly available throughout each compartment. If models are coarsely discretized, then this has the effect of dispersing contaminants along a transport pathway more rapidly than would be expected in practice. The number of compartments used to represent a transport pathway can therefore not be chosen arbitrarily [187, 188]. For advective/dispersive transport, the number of compartments (N) needed to provide an appropriate transport timescale is given by:

$$N = \frac{Pe}{2} \tag{7}$$

where Pe is the Peclet number, which relates advection to dispersion. The Peclet number is typically defined by:

$$Pe = \frac{L}{D_L} = \frac{L\,u}{D_c} \tag{8}$$

where L is the transport distance (m), D_L is the dispersion length, which is generally a function of the scale of the modelling and, therefore, depends on L, u is the pore water velocity (m/s) and D_c is the dispersion coefficient (m^2/s). Using a smaller number of compartments than N

[26] Some software applications allow the selection of time dependent transfer rates.

implies that the transport timescales will be affected by numerical dispersion. Using a substantially larger number of compartments than N allows explicit modelling of dispersion to be undertaken with reasonable accuracy.

7.2.7. Contaminant transport into the biosphere

One of the main inputs to take into consideration with regards to environmental change within dose assessment modelling is the way in which environmental change may affect potential radionuclide releases to the biosphere. Landscape changes and, if relevant, changes in sea level will affect near surface hydrogeology and affect potential discharge areas and locations for contaminated groundwater. Changing climate and land use will also affect near surface hydrogeology and geochemistry, which will again be reflected in differing characteristics for groundwater discharge to the surface. Issues relating to the dispersion and re-concentration of radionuclides leaving the geosphere and being transported in the biosphere are addressed in detail in a BIOPROTA report relating to the geosphere–biosphere interface zone in which dispersion and re-concentration processes mainly take place [4].

For geological disposal, potential use of groundwater for domestic and agricultural purposes is an important consideration. Groundwater wells bypass the additional dilution that occurs in the very near surface as well as bypassing additional retention in near surface strata. Groundwater wells also allow for a more stylized representation of the biosphere, as they place less reliance on characterizing near surface flow pathways, discharge locations, discharge areas, near surface hydrogeology and geochemistry. Thus, the well pathway and groundwater discharge pathway are given comparable consideration in Ref. [4].

7.3. BUILDING CONFIDENCE IN DOSE ASSESSMENTS INVOLVING ENVIRONMENTAL CHANGE

It is likely that conditions in the biosphere over the timeframe of any contaminant releases from radioactive waste disposal facilities will be different from those at the time of disposal and they may continue to evolve over the timeframe relevant to assessments. The timeframe of interest increases with the longevity of persistence of the hazard presented by the wastes and with the time and degree of isolation intended to be provided by the disposal system. Landscape evolution is typically relatively slow and/or reasonably predictable on timescales up to thousands of years [89, 95, 189] but patterns of human behaviour and land use are far less tractable, such that assumptions are needed in order to support assessments against radiation protection objectives, as discussed extensively in Refs. [1, 9].

7.3.1. Use of a systematic approach

The preceding sections describe a systematic approach to developing a set of narratives for climate and landscape evolution in support of safety and performance assessments for radioactive waste disposal. For geological disposal, this approach supports the development of a consistent set of scenarios that test the robustness of a disposal concept across the nearfield, geosphere and biosphere components of an assessment. Near surface and surface disposal facilities will be more directly impacted by climate and landscape development.

The use of a traceable and systematic approach to making projections of long term climate and landscape change, based on the latest scientific understanding, helps to build confidence in the resulting safety and performance assessments. The road map developed within WG6 has drawn on experience and expertise from a range of countries and contexts to establish an approach that may be applied consistently across different radioactive waste disposal programmes. Indeed, updated projections of global climate for a wide range of different CO_2 emission scenarios provides a suite of global climate projections that may be used as a starting point for assessments and thus encourages consistency in the treatment of long term environmental change across different radioactive waste disposal programmes.

A systematic approach to assessing safety and performance is key, in particular in ensuring that conclusions are robust with regards to key contaminants and associated FEPs. Assessments typically include sensitivity and/or uncertainty analyses to help identify those key contaminants and FEPs. From a biosphere assessment perspective, identification of critical FEPs and documentation of why other FEPs are not relevant is very important. It may be noted that the key FEPs may be different for different radionuclides, as examined within the BIOPROTA programme, e.g. for ^{14}C [190, 191], ^{79}Se [186] and ^{36}Cl [192].

7.3.2. Addressing conceptual uncertainties

The impact of conceptual model uncertainty can be addressed by alternative and/or independent formulation of the modelled system. This need not comprise a full alternate model, but can focus on the key aspects of the system. A recent example is found in the application of alternate dose models for the assessment of a deep geological repository in Sweden. Independent formulations of both evolving [193, 194] and non-evolving systems [176] have been considered. Compared with the main assessment model [195], both alternates are simpler in structure and scope, but have nevertheless been able to reproduce key results, when consistent assumptions and data are used. Confidence in the assessment results is thereby enhanced and review is then appropriately focused on the justification for the relevant assumptions and data.

7.3.3. Studying analogue sites

Study of sites representative of conditions that are projected to arise in the future can build confidence in the representation of disposal sites under different conditions compared to the present day. Use of such analogue sites is well illustrated in the recent Fennoscandian dose assessments. Following the removal of the ice loading at the end of the last glaciation, the Earth's crust is rising relative to sea level at the proposed repository locations, with land emerging from the Baltic Sea. This process has been under way for several tens of thousands of years and will continue at a decreasing rate for a similar period into the future [68]. There is a gradual succession of ecosystems at any given spatial location from marine to bay to lake, wetland and forest. This successionary path can be seen by travelling inland from the present day coast. Close to the sea, soils are young and their chemistry strongly influenced by the recent sea cover. Further inland, the soils and surface hydrology are more mature. Such a path can be used to provide suitable databases for snapshots in the model of landscape evolution. Furthermore, inland from the current Baltic coast there are, in addition to naturally evolved ecosystems, towns and farms. The agricultural areas also provide a snapshot of potential future systems, with their altered hydrology and ecological balance.

Over longer timescales, say up to 100 ka, evolution of the climate system can have a more profound effect. Analogues for site conditions at such times may nevertheless be found, albeit at a greater distance from the present day sites. For example, SKB, Posiva and the Nuclear Waste Management Organization (NWMO) have been studying how ice sheets and permafrost affect groundwater flow and chemistry in Greenland, as an analogue of conditions that may exist at their proposed repository sites in the far future [196].

For the future, there may be potential for identifying relevant analogues that have not yet been explored. For example, the Äspö site has been extensively characterized and the data that have been generated may provide potential information relevant to long term environmental change and for developing an understanding of the migration of naturally occurring radionuclides through the geosphere–biosphere interface and though the biosphere in an uplifting and changing coastal environment. Abandoned uranium mines and other legacy sites may also offer such potential.

7.3.4. Engagement with stakeholders

Description of the landscape at the present day and how it may evolve in the future is an aspect of the post-closure assessment process that is particularly accessible to, and understandable by, various stakeholder groups. In particular, descriptions of biosphere characteristics and human behaviour can appear speculative and subject to challenge. There is, therefore, a need to carefully distinguish those aspects of the assessment that are based on scientific analyses (e.g. derived from quantitative climate and landscape models), from those that are based on regulatory, or other, judgements and decisions. Engagement with all stakeholders, both technical and non-technical, is essential both to explain the basis of scientific aspects of the assessment and to support development of consensus on those aspects where judgement has the predominant role. It is recognized that, in practice, the distinction is not clear cut and that some aspects will be determined by the interplay of scientific and judgemental factors. In this context, uncertainty analyses play an important role in investigating the alternative scenarios that arise from different points of view on assessment issues, and determining the robustness of safety arguments across these alternative points of view.

7.3.5. Confidence building steps

In summary, the following steps all help to build confidence in assessments that need to consider environmental change on long timescales:

- Following a logical, transparent and systematic scientific approach to developing assessments helps to ensure that the audience has the opportunity to understand the reasoning and justification for the various assumptions that are necessarily involved;
- Models should aim to strike a balance between complexity and transparency and be as straightforward as is compatible with the context in which they are used. Furthermore they should not be more complex than can be justified against supporting data;
- FEP lists and the comprehensive and traceable auditing of how they are addressed within an assessment can to help build confidence that potentially important features, events and processes have not been overlooked;
- Assertions of conservatism should be highlighted and supported with evidence, where the conservatism is not immediately apparent; it can also be helpful to remind the audience of the conservatisms when presenting results;
- Explicit treatment of the significant uncertainties that are inherent in undertaking assessments on long timescales helps to build confidence in the interpretation of the results and their robustness:
    - The use of scenarios to assess a reasonable range to potential future conditions and ‘what if’ style situations can help to build confidence that safety is robust in spite of uncertainty about what may happen in the future;

  - The use of alternative conceptualizations and alternative mathematical representations can help to build confidence that the modelling and the inferences drawn from the results are appropriately robust;
  - Deterministic and/or probabilistic approaches can be used to help determine the sensitivity of conclusions to the different processes that are modelled;
  - Additionally, deterministic and/or probabilistic approaches can be used to assess the potential effects of parametric uncertainty on conclusions.

— Making use of the latest international consensus on long term climate change in developing and justifying scenarios to be considered;

— Consideration should be given to presenting a variety of results (e.g. calculated concentrations as well as assessed doses and risks) and to providing context to those results (e.g. by comparison to background concentrations and doses as well as comparison against other sorts of risks);

— Independent modelling, either as part of a safety assessment and/or in support of regulatory review and understanding, helps to build confidence that conclusions are robust against unintentional bias;

— Engagement with stakeholders can help to ensure that environments and/or habits of particular interest and concern are explicitly addressed within assessments; and

— Characterization of the present day biosphere, either at the site being considered and/or at locations with conditions analogous to those that might exist at the site in future, can help to build understanding of the processes that need to be represented within models as well as building confidence in the plausibility of the scenarios, descriptions, conceptualizations and data.

8. DISCUSSION AND CONCLUSIONS

An overall methodology for taking climate change and landscape development into account in post-closure radiological impact assessments of disposal facilities for solid radioactive wastes has been set out. It is intended to be applicable to a wide range of disposal facility types and provide a common and scientifically supported basis for addressing these complex issues in assessments carried out by Member States. The methodology is illustrated by a range of examples which indicate how the common approach can be applied to address locally relevant assessment specific contextual factors, such as the nature of the site and the detailed requirements for dose assessment.

The methodology builds substantially on previous work and consolidates a wide range of climate and other research. It consists of a series of sequential steps, starting with a careful examination of the context in which climate change and landscape development may need to be addressed in a specific assessment.

The next step is to define the time dependent boundary conditions to be applied to a global climate model. These are likely to comprise two areas: insolation data, determined from deterministic orbital calculations that are associated with very little uncertainty out to future times of one million years or more; and atmospheric CO_2 concentrations that are determined using a combination of a statistical regression technique, to estimate the natural contribution as a function of orbital parameters, and a model simulation of the anthropogenic contribution from fossil fuel emissions and land use changes. A simple analysis addressing the length of the present interglacial is provided in Ref. [197]. This shows clearly how the atmospheric CO_2 concentration may be calculated by this approach, including making an allowance for internal variability at suborbital timescales within the climate system. In short, it is now possible to describe in full how to solve this aspect of the problem and the method developed can be used by any organization worldwide with only small resource implications.

Investigation of the implications of these boundary conditions can be made through multiple AOGCM runs with the results made available via an emulator. Work at the University of Bristol, supported by RWM, has provided a tool that allows a user to enter any reasonable sequence of CO_2 concentrations over the next one million years. The tool then uses this sequence, combined with well defined, time dependent orbital characteristics, to give time dependent characteristics of global climate over that same period. The tool can provide results for a wide range of climatic variables at a grid scale of about 200 km at mid to high latitudes [198]. These variables include, among many others, mean monthly temperature and precipitation, which are the variables that have mainly been used in the past.

The level of ambition in detailed application of the methodology is dependent on the stage of development of the repository and proportionate to the hazard associated with the waste in question, including the timeframe over which it is hazardous and the scope for environmental change in different locations. Climate results at a 200 km scale may be sufficient for many assessment purposes. Nevertheless, there may be occasions where downscaling of these results will be appropriate. Since such downscaling depends strongly on the local geographical context, this report cannot present results that are applicable worldwide. However, it has been demonstrated how physical–statistical downscaling is a practical and effective method and can be applied to emulator results in the specific context of Great Britain. Once climate evolution data are available at appropriate spatial and temporal resolution, they can be used to drive landscape development models along with other relevant data, notably crustal uplift rates which are relevant both to shoreline regression and to river incision. Again, landscape development is strongly dependent upon local geography, so this report has discussed the relevant issues and presented an approach that, in turn, is supported with relevant illustrative examples for warm, arid and temperate conditions, periglacial conditions and glacial conditions as well as transitions between them. These indicate the construction of narratives for environmental change, based on the assumptions used in climate modelling and downscaling. Different aspects of the narratives can be developed and used differently within a single assessment but it is important that they draw on the same foundation.

The next part of the methodology concerns the use of these narratives in radiation dose assessments. The material presented in this report draws on experience of the application of biosphere assessment approaches, such as those discussed in Ref. [2], as well as ongoing project specific assessments. It is highlighted that the narratives can be used in various ways to support the assumptions for dose assessment models. The role of simplifying assumptions is discussed along with how to address uncertainties in the context of present day conditions and the sequential and non-sequential treatment of future climate states. The implications for system discretization are then considered in the context of contaminant migration and accumulation and the implications for radiation exposure.

The value of this step-by-step approach in building confidence in dose modelling results is discussed alongside the use of analogues and the role of stakeholder engagement in building trust. Description of the landscape at the present day and how it may evolve in the future is an aspect of the post-closure assessment process that is particularly accessible to, and understandable by, various stakeholder groups. In particular, descriptions of future biosphere characteristics and human behaviour can appear speculative and subject to challenge. There is, therefore, a need to carefully distinguish those aspects of the assessment that are based on scientific analyses (e.g. derived from quantitative climate and landscape models), from those that are based on regulatory requirements or other judgements and decisions. It is recognized that, in practice, the distinction is not clear cut and that some aspects will be determined by the interplay of scientific and judgmental factors. In this context, uncertainty analyses play an important role in investigating the alternative scenarios that arise from different points of view on assessment issues, and determining the robustness of safety arguments across these alternative points of view. Engagement with stakeholders is essential both to explain the basis of scientific aspects of the assessment and to support development of consensus on those aspects where judgement has the predominant role. An important example is the selection of assumptions for anthropogenic CO_2 releases that depend upon a combination of technical and political factors.

Noting these issues, it is further highlighted that the results produced through the application of the methodology are only intended as projections of possible futures based on a set of assumptions, i.e. reference futures. Uncertainty analyses may play an important role in investigating the alternative scenarios that arise from different points of view on assessment issues and determining the robustness of safety arguments across these alternative points of view. A series of steps towards building confidence in this context has been developed and presented for consideration.

Nevertheless, it is concluded that quantitative long term climate modelling is sufficiently developed and robust to define the envelope of reference futures for use in safety assessments of radioactive waste repositories, as supported by understanding of palaeo–climatic conditions. Such models have limited spatial resolution and in some cases downscaling is necessary. Physical–statistical methods exist to do this, but local statistical data are needed to apply them. Qualitative downscaling can also be used.

Quantitative modelling of landscape evolution and the linkage with climate modelling has been significantly developed in recent years but not for all potentially relevant climates and landscapes. Further work in this area may be beneficial and special attention may need to be given to more detailed understanding of the first 1000 years, which goes beyond the typical timescales focused on by the IPCC but is especially relevant to near surface disposals and the long term management of legacy sites.

Illustrative results of simulations have been prepared in the course of WG6 activities. The Working Group considers that it would be good practice that detailed results of simulations are archived for potential use in subsequent assessments. A central archive of the results of these and future simulations could be an important international resource and further thought could be given to the creation of such an archive.

It may be noted that while the focus of MODARIA is dose assessment, the methodology and results of WG6 may be valuable in a wider safety assessment context, e.g. for other types of facilities and sites.

APPENDIX I. EXAMPLE DEVELOPMENT AND APPLICATION OF ENVIRONMENTAL CHANGE NARRATIVES

A number of examples are given in this Appendix to illustrate how narratives can be developed for climate and landscape change at the site or regional level in specific assessment contexts. They illustrate the application and/or relevance of the conceptual framework discussed in the main text. The examples show how environmental change has been addressed in the past, and why the current conceptual framework is needed to support the narratives used in assessment rather than them appearing arbitrary. The support that the narratives then provide to the assessment of safety indicators [5], including radiation doses and risks, is also presented.

I.1. LOWLAND BRITAIN

RWM is an organization tasked with implementing geological disposal of the UK's higher activity radioactive wastes (principally intermediate and high level radioactive waste along with spent nuclear fuel). The process for implementing geological disposal in the UK is described in Ref. [199], with a focus on the current site selection phase. RWM maintains a generic safety case for geological disposal [200].

I.1.1. Narratives of landscape evolution used in generic studies in the UK

The geological disposal programme in the UK was in a similar position, without a specific site, at the time of the BIOCLIM project, which ran from 2000–2003. A lowland, inland site located in central England was used as the basis for exploring climatic downscaling [77]. The broad classification of the site used for downscaling increased the range of situations for which the analysis would remain relevant and avoided the potential difficulties surrounding use of a specific location.

The analysis undertaken within BIOCLIM was used to support landscape evolution studies for the same type of lowland, inland site [171]. That study used the downscaled climate results to support full narratives of landscape evolution for combinations of different:

- Climate scenarios (those considered within BIOCLIM);
- Human community types (present day and primitive); and
- Landscape contexts (e.g. small or medium catchment, reduced or maintained relief).

Refs. [77, 171] were used as the basis for a study concerning the potential requirement for explicit representation of climate and landscape transitions within post-closure assessments [201]. These studies have been used in support of the most recent generic safety assessments for geological disposal in the UK [200] and in recent biosphere modelling [202, 203].

A lowland, inland, central England location is defined as anything to the south-east of a line between the Tees Estuary and the Bristol Channel (see Figure 46). A west to east climate gradient exists within this region, which is relatively stable through different climatic periods, including both glacial and interglacial conditions [204]. The north to south gradient is relatively stable during interglacial conditions, but tends to steepen somewhat during glacial episodes [204]. Downscaling of climate at a specific location can be extrapolated to other locations within the same region using the observed gradients and taking account of the overall climatic regime[27].

A typical, inland, lowland, central England site would be characterized by unconsolidated Quaternary sediments overlying a permeable aquifer and would potentially be on the margin of ice sheets of the next significant glaciation episode. For comparison, at the LGM, ice sheets covered much of Scotland and Cumbria and laid down extensive till deposits in Northumbria, but did not extend as far south as central England or East Anglia, corresponding largely to the area marked as lowland Britain in Figure 46. In contrast, the Anglian ice at around 400 ka BP extended as far south as Suffolk and covered much of central England [101].

As noted above, in order to develop landscape change narratives for an inland, lowland, central England site, Ref. [171] considered combinations of different climate change scenarios, human community types and landscape contexts. The climate change scenarios considered were based on different assumptions regarding future variations in concentrations of atmospheric carbon CO_2. Three scenarios were selected:

- Scenario A4a: Natural variations in CO_2 concentrations only, with no post-industrial contribution from fossil fuel combustion;
- Scenario B3: Natural variations in CO_2 concentrations, plus a contribution from the fossil fuel scenario with low future utilization of fossil fuels; and
- Scenario B4: Natural variations in CO_2 concentrations, plus a contribution from the fossil fuel scenario with high future utilization of fossil fuels.

These three climate change scenarios were considered to represent a reasonably comprehensive range of scenarios, based on current knowledge. In terms of human community types, two alternative assumptions were considered [171], namely:

- Community α: A constant, present day human community; and
- Community β: Regression to a constant, primitive subsistence state.

These two contrasting human community types allow potential exposure group (PEG) situations to be considered that are due primarily to human actions, or due to natural processes. For each combination of climate change scenario and human community type, two landscape contexts were considered [171], leading to a total of 12 (3×2×2) overall landscape change scenarios.

[27] By contrast, an upland location would be more sensitive to site specific considerations and E-W and N-S gradient based downscaling would be less generally applicable as a consequence, or would need to be extended with an altitude related component. This has now been done, see Ref. [89] and Section 5 of this report.

FIG. 46. The topography of Britain.

FIG. 47. Extent of the British ice sheet at the LGM[28].

To provide a context for the discussion of landscape change, a simple model of a generic catchment, in which the evolution of the catchment landscape is determined by rates of erosion and deposition within the catchment, was developed [171]. The model is illustrated in Figure 48.

[28] from http://www.bgs.ac.uk/discoveringGeology/geologyOfBritain/iceAge/home.html

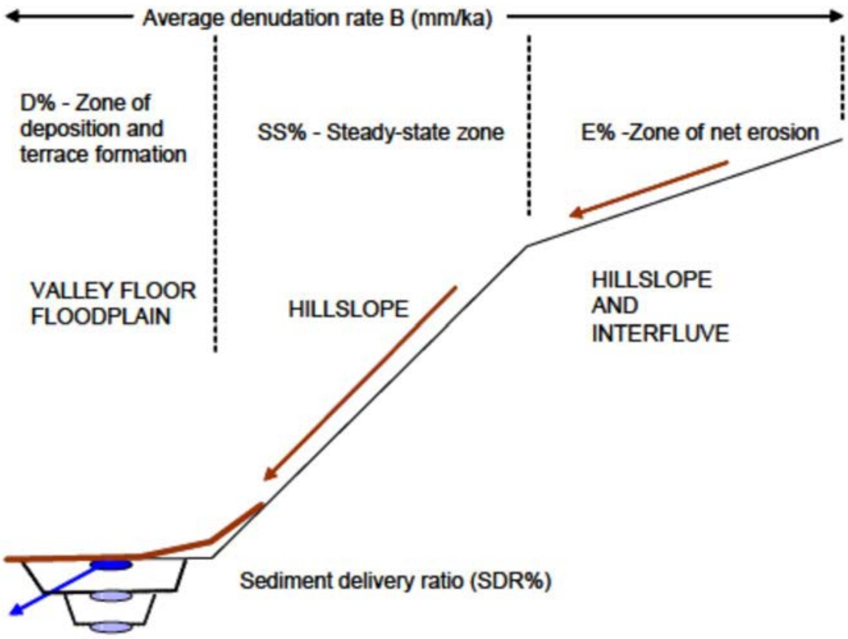


FIG. 48. 2-D section across a generic catchment showing features included in a simple model of denudation.

In this model, net erosion occurs on the upper parts of hillslopes, the lower parts of those hillslopes comprises a 'transport' domain, where erosion and deposition are in equilibrium, and the valley floor floodplain comprises a zone of deposition or aggregation.

The 12 overall landscape evolution scenarios can be related to the properties and characteristics of the model shown in Figure 48, in particular, the erosion, sedimentation and land movement regime that would be expected, given the expected climate behaviour and assumptions about human community behaviour. The net result is a change in the overall relief of the catchment, over the timescale of interest (taken to be 200 ka AP). Table 6 summarizes the landscape contexts for the 12 evolution scenarios considered [171]. Moreover, the notation is used to define the landscape evolution. Thus, scenario A4α1 refers to climate scenario A4a, community type α, landscape context 1.

Narrative descriptions for each of the landscape evolution scenarios set out in Table 6 below were developed [171]. The narratives focus on expected erosion and sedimentation characteristics, and hence changes in relief, using the hillslope regimes.

For the four A4 evolution scenarios, landscape evolution is discussed across a succession of five climate states, from the present day through to 200 ka AP. For the eight B3 and B4 evolution scenarios, only a single climate state is considered. Consequently, the narratives for the A4 evolution scenarios are somewhat more detailed than for the B3 and B4 scenarios.

TABLE 6. SUMMARY OF LANDSCAPE EVOLUTION SCENARIOS

Scenario	Catchment Description
A4α1	Small catchment, non-dynamic responses, reduced relief, agricultural
A4α2	Medium catchment, dynamic responses, river terrace formation, agricultural
A4β1	Small catchment, non-dynamic responses, reduced relief, wooded
A4β2	Medium catchment, dynamic responses, river terrace formation, wooded
B3α1	Reduced relief, agricultural
B3α2	Maintained relief, agricultural
B3β1	Reduced relief, wooded
B3β2	Maintained relief, wooded
B4α1	Reduced relief, agricultural
B4α2	Maintained relief, desertification
B4β1	Reduced relief, wooded
B4β2	Maintained relief, desertification

A significant difference between the α and β evolution scenarios is the impact that humans have on the evolution of the landscape. In the α evolution scenarios, present day human characteristics are preserved, including the facility to manage the landscape where necessary, to avoid significant disruption of its form and land use characteristics. An example of this is in the A4α1 evolution scenario, where the transition from temperate to cooler boreal climatic conditions is marked by continued intensive agriculture, albeit over a shorter growing season.

In contrast, in the β scenarios, an instant degradation of the present day community to a primitive community is assumed, with only a primitive state of technological development. Under these conditions, landscape development is assumed to be driven by natural processes only, rather than a combination of natural processes and human intervention. Thus, in the A4β1 scenario, the lack management of agricultural land results in a rapid reversion of that land, through a sequence of vegetation changes, to a wooded environment. The wooded environment results in reduced rates of erosion, compared with the present day human community cases.

For the B3 and B4 landscape evolution scenarios, only a single climate state is considered over the 200 ka timescale of interest. For the B3 evolution scenarios, the assumed climate state is Cr, which corresponds broadly to conditions in SW France, NW Spain and northern Portugal. One of the primary aspects of landscape evolution in the B3 evolution scenarios is decreased overall relief of the catchment, relative to the A4 evolution scenarios, owing to long term erosion and valley deposition/aggregation processes.

For the B4 evolution scenarios, the assumed climate state is Cs [78], which corresponds to present day conditions in the Mediterranean region. As with the B3 evolution scenarios, one of the primary aspects of landscape evolution in the B3 evolution scenarios is decreased overall relief of the catchment, owing to long term erosion and valley deposition/aggregation processes.

The overall change in relief in the 12 landscape evolution scenarios is illustrated in Table 7. This corresponds to Table 4.2 in Ref. [171]. The results in the table illustrate clearly that overall changes in relief are greater in the B3 and B4 evolution scenarios, compared with the A4 evolution scenarios. The results also indicate that overall changes in relief are lower in the scenarios that assume a primitive human community (the β evolution scenarios), compared with those that assume an agriculture based present day community.

TABLE 7. LANDSCAPE EVOLUTION SCENARIOS

Scenario	Climate Duration	Erosion (m)	Deposition (m)	Change in Relief (m)
A4α1	DO 50 ka	2.5	1	-3.5
	EO 50 ka	3.75	3	-6.75
	FT/EC 5 ka	0.38	0.6	-0.98
	Total			**-11.23**
A4α2	DO 50 ka	2.86	1	-3.86
	EO 50 ka	4.29	2.25	-6.54
	FT/EC 5 ka	0.43	0.35	-0.78
	Total			**-11.18**
A4β1	DO 50 ka	2.14	0.38	-2.52
	EO 50 ka	2.86	1.5	-4.36
	FT/EC 5 ka	0.38	0.6	-0.98
	Total			**-7.86**
A4β2	DO 50 ka	2.5	0.56	-3.06
	EO 50 ka	3.33	1.25	-4.58
	FT/EC 5 ka	0.43	0.4	-0.83
	Total			**-8.47**
B3α1	Cr 200 ka	17.78	8	-25.78
B3α2	Cr 200 ka	18.18	10	-28.18
B3β1	Cr 200 ka	14.29	5	-19.29
B3β2	Cr 200 ka	15.56	7	-22.56
B4α1	Cs 200 ka	20	10	-30
B4α2	Cs 200 ka	20	14	-34
B4β1	Cs 200 ka	20	8	-28
B4β2	Cs 200 ka	20	12	-32

I.1.2. Generic radiological assessment modelling for the UK

In the absence of a site context, the biosphere modelling undertaken in support of the post-closure safety is necessarily generic in nature, though it reflects consideration of conditions appropriate to the UK context. RWM’s approach to the biosphere is described in Ref. [205], which will be updated in support of a further iteration of the generic safety case, which is anticipated in 2016. If any activity from the disposal facility were to be released, models of transport in the geosphere would be used to calculate radionuclide fluxes through the host rock and overlying strata, leaving the biosphere modelling to encompass consideration of the near surface system, including Quaternary sediments. Potential releases to terrestrial [202] and coastal [203] environments are considered, as illustrated in Figure 49.

The biosphere model for releases to terrestrial systems is based on consideration of a lowland agricultural context, on the basis of maximizing usage of resources potentially contaminated due to releases from the geosphere. Those releases include: (i) use of contaminated groundwater via a well drilled into the near surface; and (ii) discharge of contaminated groundwater to the subsoil.

Work undertaken in support of the BIOCLIM project indicates that the climate and landscape of the UK is likely to evolve gradually over the next 100 to 200 ka, without the occurrence of a major glacial episode. This period provides the principal focus of the biosphere modelling. Greater uncertainties are associated with even longer time scales so that biosphere modelling becomes increasingly illustrative. Two sequences of climate have been considered in biosphere modelling, based on low and high fossil fuel emissions scenarios from BIOCLIM climate modelling. Both sequences show warm climate conditions persisting in central England for approaching 100 ka (see Figure 50). The research referred to in preceding sections that supports RWM’s participation in MODARIA WG6 will update this analysis.

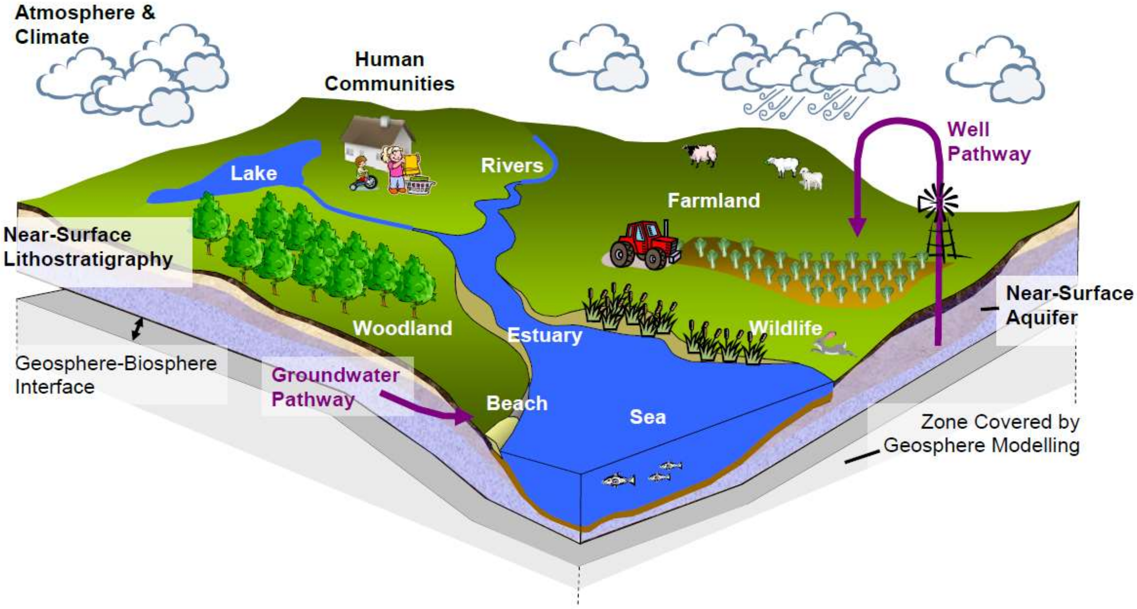


FIG. 49. RWM's conceptualization of the biosphere and its interface with geosphere modelling. Reproduced from Ref. [77] with permission courtesy of the Nuclear Decommissioning Authority.

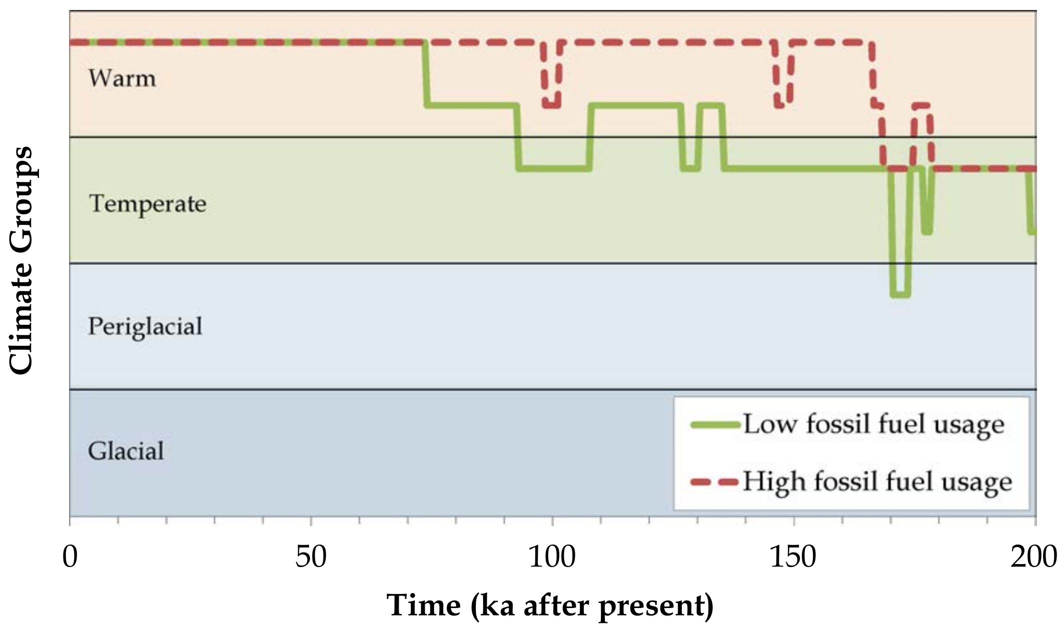


FIG. 50. Projected sequence of climate states for central England, based on Ref. [76].

In the absence of a specific geological context, retention within the near surface aquifer is currently not included in the modelling. Radionuclide releases from the geosphere are diluted in the flow rate of the near surface aquifer to provide the well water concentration and are diluted over a groundwater discharge area for the groundwater discharge pathway.

The terrestrial biosphere modelling is based on a two compartment model for the surface soil/subsoil, typically representing a depth of 2 m. Radionuclide transfers are based on consideration of soil hydrology, which is linked to climatology.

Again, in absence of a specific site, associated surface water is conservatively represented without upstream dilution. For the generic assessments, the landscape is taken to be in equilibrium, with erosion being balanced by input of uncontaminated material and the surface water course taken to be maintained. The model is parameterized for warm humid, warm dry (semi-arid), temperature, boreal and periglacial climates. The forthcoming extended, relatively stable, climate period, together with the absence of a site specific context means that a stylized approach is taken to representing the biosphere, without explicit modelling of landscape/climate evolution, i.e. a non-sequential approach [1].

The biosphere model is used to calculate biosphere dose conversion factors that convert the radionuclide flux from the geosphere (Bq/y) to potential doses (Sv/y). The results show that the well pathway dominates over the groundwater discharge pathway for the reference assumptions that are adopted. The results also demonstrate the potential importance of the irrigation, with biosphere dose conversion factors for a warm arid climate being a factor of three to four greater than those for a temperate climate principally due to a higher irrigation requirement.

The biosphere model for coastal systems is based on consideration of the coastline around the UK. The model allows potential radionuclide releases to an estuary, to the coast and/or direct releases to marine biosphere systems to be represented. The model includes consideration of potential exposures that might arise to both occupational and recreational groups.

Sediment columns within the estuarine and marine systems are represented with three compartments, plus a sink receiving net sedimentation. The model for the estuary is split into three zones, reflecting the dominance of differing processes with distance towards the sea. The model for the coast includes both beach sediments and rocky foreshores. The level of complexity is considerably larger than for the terrestrial biosphere model. This reflects the relative complexities of the systems being represented rather than their relative radiological significance[29].

The results show that radionuclide releases to upstream estuarine bed sediment typically provide higher biosphere dose conversion factors in comparison to releases direct to coastal and marine biosphere systems. This is principally due to the greater range of potential exposure pathways attributed to the estuary, which include grazing on salt marsh and bait digging on mud flats. Comparison with results for the terrestrial model show that dose factors for the coastal biosphere systems are typically more than two orders of magnitude lower for most radionuclides.

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[29] At other sites, the situation may be the opposite; that is, the terrestrial (sub)models may be more complex than those for the aquatic environments in terms of element pools and their cycling time constants e.g. in boreal forests and mires, but also for agriculture under certain assumptions on the soil management system and irrigation method.

I.2. FORSMARK, SWEDEN

SKB is responsible for the final disposal of spent nuclear fuel in Sweden. Two safety assessments (SR-Site and SR-PSU) have been performed for the Forsmark site in relation to which SKB has filed applications for constructing both the repository for spent fuel and the extension of the present low and intermediate level waste repository (SFR). In these assessments, the Forsmark site has been evaluated concerning long term environmental change. Even though safety assessments for nuclear waste storage each have their own separate lists of main questions to answer, a common strategy was used to evaluate the development of the Forsmark site. Below follows a summary of the SR-Site strategy used by SKB and the resulting landscape development variants of far future Forsmark under the influence of various climate scenarios. The strategy follows the outline method described in this report.

I.2.1. The Forsmark site

The area represents a typical coastal site at the shoreline of the Baltic Sea in northern Uppland, Sweden. Post-glacial land uplift, in combination with the flat topography, implies fast shoreline displacement that has resulted in a very young terrestrial system that contains a number of newborn shallow lakes and wetlands (Figure 51). The study area is characterized by a small scale topography with limited variations in altitude and is almost entirely located below 20 m above sea level. Till is the dominant Quaternary deposit, whereas granite is the dominant rock type. The annual precipitation and runoff are 560 and 150 mm, respectively. The latest deglaciation in Forsmark took place during the Preboreal climatic stage, circa 10 800 years ago [98]. Forsmark is situated below the highest coastline, and when the latest deglaciation took place, the area was covered by circa 150 m of water.

I.2.2. Climate cases

In the construction of a site specific landscape development, SKB has used the current site understanding to develop descriptions of possible futures of Forsmark. One main driver for site development was identified as climate change. As a main reference case for future climate in SR-Site, the last glacial cycle was used as an analogue, Figure 52 [98]. In this analogue, the reference glacial cycle starts when the Weichselian ice retreats from Forsmark around 8800 BC and continues until circa 120 000 AD when the cycle is completed. During the reference glacial cycle, a number of climate driven conditions appear, from submerged conditions directly after the ice sheet has withdrawn to recurrent temperate, periglacial and glacial domains [98]. The different environmental conditions and the transitions between them are described in the landscape development model. Although the Weichselian glacial cycle was used as an analogue for future conditions, a set of alternative climate cases was also derived to answer questions in the safety assessment, see Table 8 for all cases with a short description of each.

FIG. 51. An aerial photograph of the Forsmark site. Reproduced form Ref. [206] with permission courtesy of SKB.

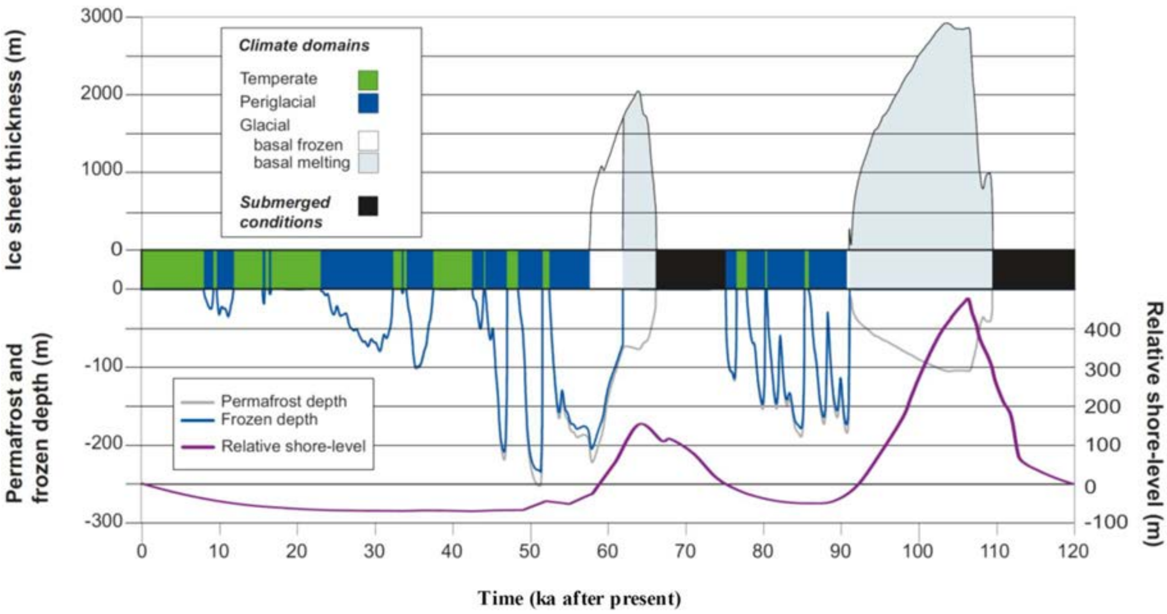

FIG. 52. Evolution of important climate related variables at Forsmark for the coming 120 000 years in the SR-Site reference glacial cycle. Reproduced from Section 4.5 of Ref. [98] with permission courtesy of SKB.

TABLE 8. CLIMATE CASES IN THE SR-SITE SAFETY ASSESSMENT [98]

Climate case		Short description
1	Reference glacial cycle	Repetition of reconstructed last glacial cycle conditions
2	Global warming	Longer period of initial temperate conditions than in case 1
3	Extended global warming	Longer period of initial temperate conditions than in case 2
4	Extended ice sheet duration	Longer duration of ice sheet coverage than in case 1
5	Maximum ice sheet configuration	Largest ice configuration in past 2 million years
6	Severe permafrost	Favourable for early and deep permafrost growth

I.2.3. Landscape development

A landscape development model was used in SR-Site to extract information for use in the radionuclide model and to function as a knowledge basis for assumptions made at landscape level in the safety assessment. The landscape model uses input from a range of discipline specific models, e.g. hydrology, chemistry, sedimentation, ecosystems, shoreline displacement and climate [89, 206, 207]. The final output is a landscape development model describing site development and the associated properties under different future conditions. The result is a synthesized description of Forsmark as it develops during a glacial cycle or under predefined climate variants. The landscape description covers therefore all potential properties of importance for the overall understanding of the site development for a safety assessment, see Figure 53. The general strategy applied in the SR-Site work was to develop discipline specific models by interpretation and analyses of the quality assured primary data stored in SKB databases, and then to integrate these discipline specific models into a unified landscape development model. The quantitative, discipline specific models are also separately reported in the SKB series of SR-Site reports.

Based on the reference or variant glacial cycles, landscape evolution models were constructed using the approach set out in simplified form in Figure 53. The overall modelling strategy was to set-up a chain of models to mimic the major processes involved in landscape development [89]. For the marine part of the landscape, the whole model area and all time steps were run in one single operation. Pre- and post-processing were done in ArcGIS 10. A marine geology map, marine regolith depths and a digital bathymetry model were the main outputs from the marine module for each time step. The outputs were then produced as raster layers that covered the marine part of the model area. These raster layers were later merged with outputs from the lake/land modelling and outputs from the sub-models to form continuous raster maps for the whole model area. In Figure 54 an example of output maps is shown for a part of the model area for a specific future climate scenario and a specific land use case.

I.2.4. Radiological assessments for SR-Site

The concept of SKB's SR-Site assessment for a proposed repository for spent nuclear fuel at the Forsmark candidate site [68] is based on the disposal of the inventory of spent nuclear fuel in 6000 high integrity copper canisters. SKB assesses that there is a low probability of a canister failing on a 1 million year timescale. This means that the supporting biosphere modelling needs to assess potential doses at an uncertain time within a time frame that will cover multiple glacial–interglacial cycles. In addition, the site has in the past been covered by ice sheets during glacial episodes and is expected to be covered by ice sheets again in the future. The landscape is currently rebounding from the last glaciation and rising up from the sea at a rate of about 6 mm per year.

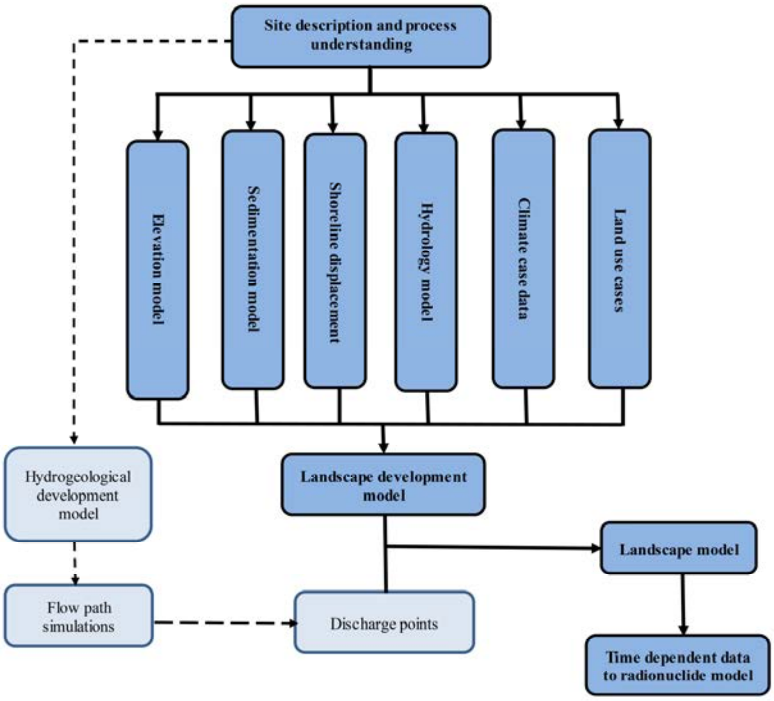

FIG. 53. Flow chart of modelling activities and inputs to obtain the biosphere characteristics within the evolving Forsmark landscape for discharge areas used in the dose calculations. Reproduced from Ref. [207] with permission courtesy of SKB.

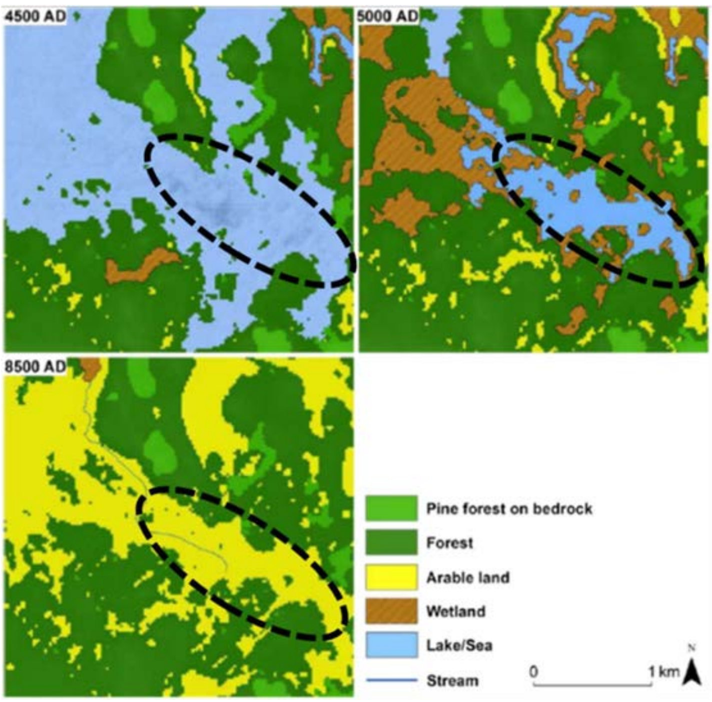

FIG. 54. The landscape development for a discharge area during an interglacial (temperate conditions) at Forsmark with time steps covering the transition from sea to arable land. Groundwater discharge area encircled in dotted black. The model version with maximum arable land cover is used. Modified after Ref. [92].

Given the uncertainty surrounding when a release may occur in the future, the last glacial cycle, the Weichselian, is adopted as a reference case. This is chosen because it includes a transition from ice sheets through to a temperate climate at the Forsmark site as well as a transition from the ice sheet, through submerged conditions to lakes, mires and potential agricultural land. The Weichselian cycle therefore includes the full range of conditions that might be expected to occur at the Forsmark site in future. The Weichselian cycle also represents the glacial–interglacial cycle that has resulted in the landscape that is present at the site today and from which projections of future landscape development can be made. The biosphere assessment undertaken in support of SR-Site therefore represents potential radionuclide releases to the Forsmark system at any time during the Weichselian cycle, as a proxy for the potential impact that might arise at an unknown time in the future.

The landscape modelling for Forsmark provides an assessment of the way in which the landscape has evolved since the last ice sheet retreated through to the present day, as well as a projection of the way in which it will evolve into the future. This provides the context within which the dose assessment modelling is undertaken. The biosphere assessment is summarized in Ref. [207] and the dose assessment model is described in Ref. [195].

Radionuclides released from the repository would reach the surface via groundwater flow in fractures within the crystalline host rock. The groundwater will discharge to the regolith, which typically comprises a sequence (from depth to surface) of till, glacial clay and post-glacial sediments.

Hydrological catchments within the landscape form the basis of the radionuclide transport modelling in SR-Site. SKB divides the landscape into seventeen distinct catchments for future lakes, described as 'biosphere objects'. Each biosphere object can typically evolve from a marine system through isolation of a lake and subsequent sedimentation to a mire. Mires are taken to receive direct groundwater discharges and are the focus of the dose assessment. Other areas within the Forsmark landscape are not explicitly modelled on the basis that they do not receive direct groundwater releases.

The evolving nature of the landscape means that SKB adopts a sequential approach to modelling radionuclide migration and accumulation in the biosphere. The model for each biosphere object includes both aquatic and terrestrial components, see Figure 55. The model allows biosphere objects to explicitly evolve from aquatic to terrestrial systems on the basis of the landscape modelling.

Given uncertainty about the exact landscape that will be present at various stages during a future glacial–interglacial cycle, potential consequences of unit releases to each of the seventeen biosphere objects are assessed. The dose assessment then uses the highest geosphere flux to dose conversion factor at any of the 17 biosphere objects for each radionuclide, termed the Landscape Dose Factor (Sv/Bq). Reference calculations are undertaken with releases from the start of the interglacial period and side calculations used to demonstrate that the potential impact would be no greater if releases were to occur midway through an interglacial period.

One of the issues highlighted in the SR-Site biosphere modelling and in its regulatory review is the need for careful consideration when discretizing compartment models [176]. Discretization needs to reflect consideration of the properties of the media and the transport processes being represented. In particular, numerical dispersion represents a key consideration when discretizing models. A coarse discretization will disperse contamination more rapidly through a sequence of compartments than would be expected for the continuous system that exists in practice. Care is therefore needed in defining compartment models at a fine enough resolution to ensure that the timescale of contaminant migration and accumulation is modelled appropriately.

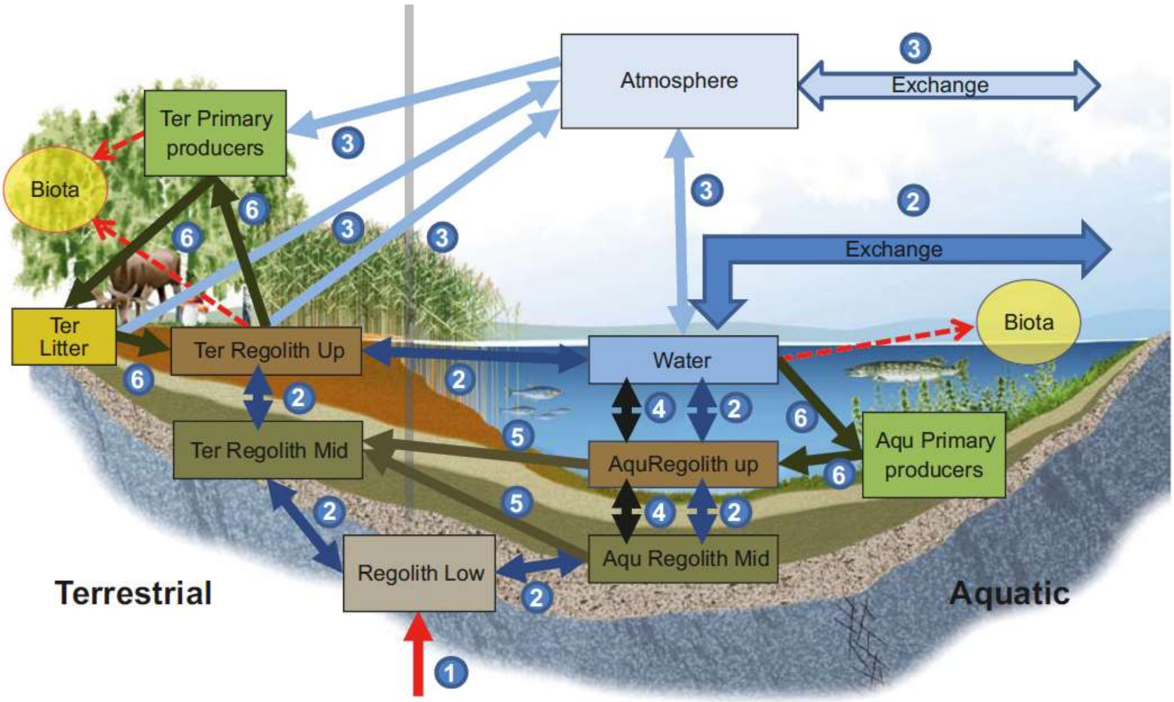

FIG. 55. SR-Site compartment model for each biosphere object; numbered processes represent (1) groundwater source term; (2) water mediated transfers; (3) gas mediated transfers; (4) sedimentation/resuspension; (5) aquatic to terrestrial evolution; (6) biological uptake/decomposition (Figure 8-1 reproduced from Ref. [207] with permission courtesy of SKB).

I.3. OLKILUOTO, FINLAND

Posiva Oy is responsible for the final disposal of spent fuel from the Loviisa and Olkiluoto power plants in Finland. In 2000, Olkiluoto Island in south-western Finland was selected as the site for final disposal. The disposal facility will be a KBS-3 type of facility, similar to that proposed by SKB in Sweden, with a depth of 400 to 450 m. A description of the biosphere at Olkiluoto at the present day is given in Ref. [164].

Currently Olkiluoto has a continental climate, with some local marine influence, due to its location on the eastern shore of the Bothnian Sea. Alternative lines of future climate evolution on a timescale of 10 000 years have been projected [208], using climate models applicable over relatively short periods and over a timescale of 120 000 years using various EMICs [209]. However, in compliance with the extant regulations (see paragraph 307 of Ref. [210]), the climate type for the next few millennia is assumed to be as at the present.

Landscape evolution at the present is mainly determined by residual glacioisostatic uplift subsequent to crustal depression during the last glaciation [211–213]. In addition to the glacioisostatic uplift, smaller differences in altitude are also caused by vertical block displacements of the crust [214].

For assessment purposes, land uplift is represented through implementation of a semi-empirical model [215–218] as interpreted in Ref. [219]. In addition, depending on the climate scenario under consideration, additional sea level changes from other causes were taken into account. Cases with alternative representations of the land uplift were also considered [168], although they were not propagated further to the dose assessment due to being readily bound by the cases that were propagated further

Present uplift rates in south-western Finland vary from 5 to 7 mm/y [220]. Due to land uplift, in coastal areas of the Bothnian Sea, bottom sediments are continuously emerging from the sea [221]. During the next several thousands of years, the bays surrounding the coastal areas of the Bothnian Sea will narrow and become isolated as lakes and further develop towards mires. The development of the shoreline will induce changes in local biosphere conditions, such as ecosystem succession, sediment redistribution and changes to groundwater flow. These will influence the areas of potential deep groundwater recharge and discharge from the repository [169, 222].

To simulate aquatic erosion and sedimentation processes, models of accumulation of organic matter in reed beds (see Section 3.5.1 of Ref. [168]) and overall sedimentation in lakes (see Section 3.5.2 of Ref. [168]) have been implemented in the Geographical Information System (GIS) based UNTAMO toolbox [168, 223]. For simulating overall erosion and sedimentation in aquatic basins, a fetch based model (physical exposure by wind induced effects, see e.g. Ref. [224] combined with consideration of shear stress conditions at the bottom [225–227] has been implemented, but requires further testing before it is considered reliable enough to use in assessments. The effect of ice cover on the sediment dynamics in the Bothnian Sea was studied [228], and was found to be insignificant, so it is neglected in the modelling.

A simple correlation model for sedimentation in lakes is presented in Refs. [229, 230] and has been adapted to the conditions at the Olkiluoto site. In the present model, gyttja accumulates at a constant rate throughout the area of the simulated reed beds. To avoid discontinuities at the reed bed boundaries, a Gaussian filter is applied.

On land, erosion is usually minor except on croplands (see Section 12.2 of Ref. [167]) but it contributes to the suspended sediment load in the streams, lakes and coastal area, making an input to the aquatic erosion and sedimentation model. To address the potential magnitude of the erosional mass transport, a stylized model assuming constant erosion rates for each combination of land use and soil type has been implemented in the UNTAMO toolbox.

On a timescale of 10 000 years, future potential sea level changes are projected to be mainly caused by non-linear or abrupt changes in the size of continental ice sheets [208, 231–233]. Modelling of the relevant processes and associated changes in sea level is subject to large uncertainties. Thus, during the next few millennia, the Bothnian Sea level rise could be 0.3 to 8 m [208]. However the mean sea level will rise only if the Bothnian Sea level rise exceeds the land uplift, which is projected to be ~0.8 m during the current century, ~8 m during the next 1500 years and ~36 m during the next 10 000 years [217]. Thus, during the next 1500 years the projected sea level rise might exceed the land uplift, whereas thereafter post-glacial crustal uplift is likely to dominate [208].

A detailed analysis of land use and its evolution at the Olkiluoto repository site and its surroundings over a time frame of 10 000 years is presented in Ref. [168]. The input data are discussed in much more detail in Ref. [167]. The results are used in the surface and near surface hydrological modelling [169] and in the biosphere radionuclide transport and dose modelling [234].

The surface environment scenarios are limited to the first ten millennia after emplacement of the first canister. In the reference case for the base scenario (see Figure 56) the coastline is projected to retreat rather fast due to the land uplift, and the deep hydrogeology at the Olkiluoto repository site reaches inland conditions within a couple of millennia.

In this scenario, the present coastal bays are taken into cultivation due to the projected presence suitable soil types and the straits between the present islands and islets, as with other depressions, form mires. The Eurajoki and Lapijoki Rivers merge north-east of the site and extend to the sea along the northern side of the site, where the shallow lakes formed by land uplift are invaded by reed beds and rather quickly filled by sedimentation. To the south of the site, there are larger lakes that remain rather stable until the end of the simulation.

Variant scenarios are formulated to take account of differences in intensity of agriculture and changes in climate, as well as combinations of these factors [168]. Disturbance scenarios are also formulated, mainly by identifying unlikely FEPs [167] or by considering unlikely deviations from the lines of evolution underpinning the base scenario. While a number of simulation cases were run for the landscape development, only a few were propagated further to the explicit radionuclide transport and dose assessment modelling due to the need to also address the uncertainties arising from these latter modelling stages (see Table 6-2 in Ref. [168]).

The most significant differences in results between the scenarios arise from factors affecting the rate of coastline retreat (i.e. land uplift and sea level changes) and the occurrence or not of croplands. Increased sedimentation into the lakes in some of the cases makes a somewhat smaller difference.

The biosphere assessment (see Ref. [166] and supporting reports]) was compiled for Okiluoto coastal site located in the boreal forest zone. The general natural conditions are similar to those in the Swedish safety case (see Section I.2 above). However, the biosphere aspects of the safety cases for the two facilities with similar surface environments show differences due to differences in regulatory requirements in the two countries and other factors, e.g. details of the underlying bedrock.

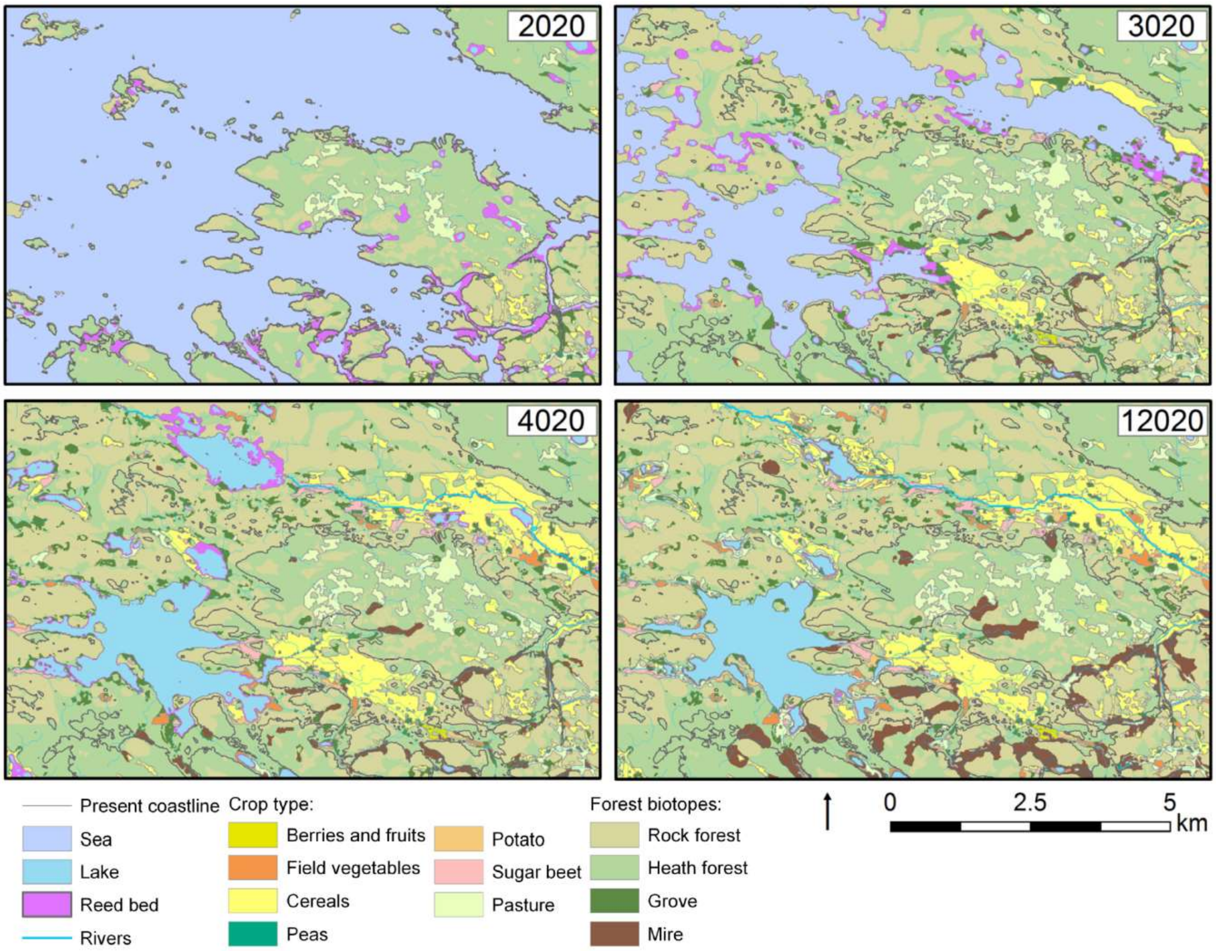

FIG. 56. Landscape evolution in the vicinity of the Olkiluoto repository site for the reference case in the base scenario of the TURVA-2012 assessment, based on Ref. [168] reproduced with permission courtesy of POSIVA.

The Finnish regulation valid for the 2012 assessment contains requirements for radiation exposures for different endpoints: the dose limit for the most exposed group of humans is 0.1 mSv/year, for other exposed humans should be insignificantly low, and for the non-human biota the radiation exposure must stay below a level which does not harm biota populations according to best knowledge. The assessment time window for human exposure is stated to be 'few thousands of years'. This is a major difference with respect to Swedish regulation, which has a longer biosphere assessment time window. Due to the time window being defined in this way, the biosphere assessment modelling is interpreted within Posiva to relate to the first 10 000 years after closure of the repository. The modelling strategy for the biosphere assessment 2012 was developed with a focus on this timescale. In particular, this timescale affects the development of terrain and ecosystem modelling with several sub-models describing e.g. land uplift, peat growth, routes of water flow and sedimentation (for more information, see Ref. [168]). The terrain and ecosystem model sub-models are justified for use in safety cases for this time window.

From a more general point of view, the surface environment over the next 10 000 years is not expected to be subject to any extreme climate conditions, e.g. ice sheet formation. However, Posiva has undertaken climate modelling over longer time scales than the biosphere assessment time window and for which extreme climate conditions can occur. The sea level may change also within this time window due to climatic reasons, but the effects are not assessed as having a major impact. These considerations underlie the Finnish regulatory text that directs that the current climate type should be assumed for the biosphere assessment time window. The surface environment during this time window is not predictable in detail, but plausible projections can be made based on the terrain and ecosystem modelling describing the development of the coastal regions of the Bothnian Bay. Due to the length of the timescale and the characteristics of the development of the surface environment, a ‘continuous style’ modelling approach has been selected for the Posiva biosphere assessment – the major transition taking place is the land rising from the sea and this process can be modelled with 500 y time steps within the regulatory biosphere assessment time window, effectively producing a continuum description of the development of the terrain and ecosystems.

The time after a few thousands of years has regulatory constraints, but on radionuclide fluxes to the biosphere rather than on the resultant radiation doses. These flux constraints are determined by the radiation authorities in Finland and their magnitude corresponds to the annual dose limit of 0.1 mSv for radionuclides originating from the repository. The background for their determination lies in the site description; in the local hydrology of the bedrock and the mixing capacity of the wells that possibly would be drilled into Olkiluoto bedrock at some future time. Different exposure scenarios in the surface environment of a coastal site were also considered (including the well scenario, fisherman, use of a large river, peat accumulation) to ensure that the geosphere fluxes are not based on overly pessimistic assumptions as to the exposure scenarios. The flux limits derived using the dose conversion factors obtained are:

- 0.03 GBq/a for long lived, alpha emitting radium, thorium, protactinium, plutonium, americium and curium isotopes;
- 0.1 GBq/a for the nuclides ^{79}Se, ^{94}Nb, ^{129}I and ^{237}Np;
- 0.3 GBq/a for the nuclides ^{14}C, ^{36}Cl and ^{135}Cs and for long lived uranium isotopes;
- 1 GBq/a for the nuclide ^{126}Sn;
- 3 GBq/a for the nuclide ^{99}Tc;
- 10 GBq/a for the nuclide ^{93}Zr;
- 30 GBq/a for the nuclide ^{59}Ni; and
- 100 GBq/a for the nuclide ^{107}Pd.

The results of safety case calculations of the geosphere transport of radionuclides are compared with these fluxes, to demonstrate compliance with the regulatory requirements on radiation exposure for the time after the first 10 000 years until one million years.

I.4. POTENTIAL CLIMATIC EVOLUTION OF CENTRAL SPAIN OVER THE NEXT 200 000 YEARS

The steps and assumptions adopted in the projections of climate and landscape evolution for central Spain have been reported in Ref. [3]. At the present day, central Spain is characterized by a Mediterranean climate, with dry warm summers and winter rain.

Geologically, as is described in Ref. [3] from south of the Sistema central range to the Campos de Calatrava area, the near surface environment is dominated by Lower Palaeozoic formations, mainly shales and sandstones, but profoundly eroded to constitute a peneplain. However, limestones dominate to the south of Badajoz. Also, intrusive granitic formations are common.

The topography comprises upland and lowland, with subdued landforms intersected by fluvially incised river valleys on the granitic zones. Surface waters are mainly flowing rivers, with some reservoirs located on them. The main soil groups are cambisols, lithosols and fluvisols. The natural climax vegetation is represented by Quercetum ilicis (holm oak forests), but today it has been substituted by bush and steppe vegetation. Agricultural land comprises 39% of the total area and just under half of this is irrigated. Grassland is 13% of the total area and about a quarter of this is irrigated. Forest comprises 32% of the total area and other uses 16%. The mean population density of rural areas is 50 persons km^{-2}.

The mean annual temperature of central Spain at the present day is around 17°C and it was around 18°C during the Holocene thermal optimum. However, under the moderate greenhouse warming scenario, B3, adopted in BIOCLIM the mean annual temperature was projected to rise over the next few hundred years to 32 to 33°C. This was projected to be followed by a slow cooling trend to about 28°C after 5 ka, about 23°C after 40 ka and about 21°C after 90 ka. Thereafter, a drop to about 13°C was projected at 100 ka AP. Subsequent to this, oscillatory warming and cooling is projected to occur out to 200 ka AP, with a particularly cold episode (mean annual temperature 8 to 9°C) at around 175 ka AP. The warmer conditions, particularly the extreme warming occurring over the first few millennia, has no analogue in terms of palaeo–climatic conditions in Spain.

During the initial warming, annual mean precipitation is projected to decrease leading to a markedly arid environment. It seems highly likely that stream and river flows would decrease, with some smaller streams becoming ephemeral. Due to the aridity, soils would be expected to lose their cohesion and aeolian weathering rates would increase. Vegetation might be mostly or entirely absent in some regions. There would likely be depletion of groundwater sources and reservoir construction for surface water storage might occur. The soil moisture deficit could be more than 1 m and there would be a greatly increased irrigation demand where agriculture or grasslands were maintained. Human community characteristics are assumed to be driven by the limited water availability, with communities being concentrated in the vicinity of sites of exploitation of deep groundwater resources and close to reservoirs on the main rivers.

The resultant warm, dry climate would then persist for a period of around 75 ka, albeit with a slow cooling trend. Over this interval, upland zones can be expected to be lowered due to prolonged and increased chemical weathering. Intense, short duration rainfall events are expected to occur and result in more active soil erosion. This is likely to be exacerbated in the early part of the period by a lack of vegetation cover. Cambisol development will be restricted and leptosol development will be enhanced. As the period progresses, vegetation cover and standing biomass will increase with the development of shrub and herb vegetation, and patches of deciduous or evergreen trees predominantly near rivers, as there is insufficient precipitation for them to flourish elsewhere. As temperatures fall and precipitation increases, groundwater resources may recover and the soil moisture deficit will decrease. Cold winters and summer drought could restrict the growing season to three to four months (April to July). Winter cereal crops and grassland might be the predominant agricultural land uses.

Over the remainder of the next 200 ka, climatic conditions would be similar to those observed in various parts of central Spain at the present day, but the landscape would have less topographic variation than at present. If climax vegetation is allowed to develop it would likely comprise holm forest, which develops on any soil type, but mainly on plains and cork trees, which develop easily on silica soils. An understorey of evergreen, small leaved shrubs and other perennial plants would also be likely to be present. Irrigation demands would be similar to those at the present day and, with irrigation, a wide range of crops could be grown. Animal husbandry practices and human community characteristics could be similar to those at the present day.

This sequence of climate and landscape characteristics provides the current context within which post-closure radiological impact assessments can be developed for existing or proposed near surface and deeper geological disposal facilities in Spain.

I.5. MOL, BELGIUM

The Belgian Agency for Radioactive Waste and Fissile Materials (NIRAS/ONDRAF) established in 1980, is responsible for the safe management of all radioactive waste on Belgian territory. NIRAS/ONDRAF's activities relating to disposal are divided into two programmes with different strategies to deal with different waste types:

- Near surface disposal of short lived low and intermediate level waste (Category A waste);
- Geological disposal of long lived and high level radioactive waste and spent fuel derived waste (category B and C wastes).

At the time of writing, the near surface facility will be located in the territory of the municipality of Dessel, in the nuclear zone of Mol/Dessel which is located in the Nete catchment. The Mol/Dessel nuclear zone is situated in the north-eastern part of Belgium, in the province of Antwerp, in a flat region known as the Campine. The name 'Campine' is derived from the Latin word Campi, which means 'flat and open territory' (see Figure 57). This clearly describes the relief of this part of Belgium. The area shows a nearly flat surface with a slope of 0.4 ‰ towards the south-west. The distance from the Mol/Dessel nuclear zone to the Belgian coastline is approximately 150 km and it is situated at 20 to 25 m above sea level.

Belgium is located in the Mid-latitude zone at 50°50' N in Western Europe. Mid-latitude climates are affected by two different air masses. These are the tropical air masses moving towards the poles and the polar air masses moving towards the equator. These two air masses are in constant conflict. Either air mass may dominate the area, but neither has exclusive control.

Depending on the reference used, the climate in Belgium can be considered as:

- Cfb type, following the Köppen classification;
- ZB VI type, following the classification of Walter.

A careful reconstruction of the landscape during the last few million years has been made [235]. It was concluded that the following events were crucial in the geomorphological evolution of the Nete basin and should be considered in explaining past and future landscape evolution of the area:

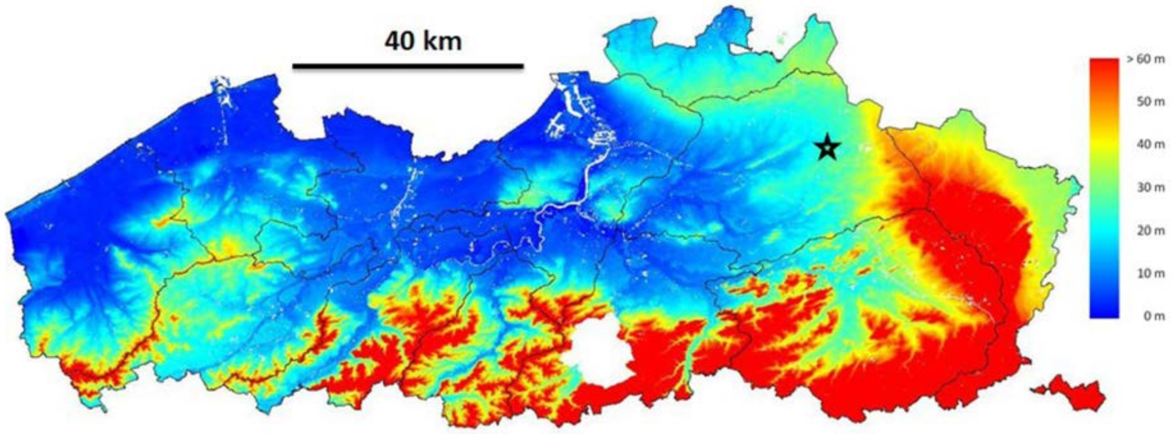

FIG. 57. Topography of Nete basin, situated in northern Belgium reproduced from Ref. [236] with permission courtesy of SCK.CEN.

(1) Mid-Pleistocene Transition: between 1.2 Ma and 0.8 Ma BP the onset of stronger glaciations and 100 ka glacial–interglacial cycles instead of 41 ka cycles, caused more intense landscape evolution in the Mol area. Certainly, after deposition of the Main Terrace deposits, erosion (fluvial erosion and denudation) became more and more important. From that time onwards, since ice volume and ice advance became prominent features in northern Europe, glacio–isostacy may have become an important element.

(2) Around 700 ka, an important uplift phase is recorded in the Ardennes and further to the north, the Maastricht area, as is attested by the Meuse terrace flight. This uplift phase may have affected the Mol area as well.

(3) Around 450 ka, an important lowering of the base level occurred together with fluvial incision in the English Channel. This was the onset for the formation of the Flemish Valley, that subsequently may have triggered fluvial erosion in the Mol area.

(4) Around 150 ka, another phase of base level lowering (drainage of a proglacial lake which occupied a large part of the southern North Sea) and fluvial incision in the English Channel may have triggered erosion in the Mol area.

(5) General lowering of the relief due to denudation processes would have been more important during intense glaciations.

(6) Very likely fluvial incision and associated denudation were most important during warm (temperate/boreal) to cold (taiga/tundra with or without permafrost conditions). and possibly also during cold to warm transitions. Incision was followed by rapid accumulation of sediments downslope.

All these processes together have caused lowering of the relief by about 30 m since the Main Terrace formation (Kempen Plateau). At present, it is not clear if this was a gradual process showing a linear relationship between forcing and response, or a sudden response to a major single event.

Fluvial erosion in the eastern Scheldt basin is thought to be an ongoing process on the scale of glacial-interglacial cycles, the current base level being the North Sea bottom at about 30 m that will emerge during future glaciations.

I.5.1. Description of assessment modelling surface disposal in Dessel

In order to be able to simulate the peak radiological impact for all radionuclides (including actinides) in the Category A waste, it is necessary to cover a time frame of 100 000 years in the performance calculations. Future climate changes were evaluated for the Mol-Dessel region over this timescale.

IPCC projections and the scenarios of the CCI-HYDR project [237], to develop a climate change tool for generating perturbed time series for the Belgian climate, were used to derive information about the future climate up to a few hundreds of years AP, whereas the BIOCLIM project was a useful source to derive climate information for longer time frames (up to 200 000 years). Expected evolution scenarios consisting of a reference case and two alternative cases were defined [238]. The scenarios are described by sequences of climate states (Figure 58). In the reference sequence of the expected evolution scenario (based on the B4 emission scenario of BIOCLIM), a subtropical climate with winter rain (Cs in the Køppen–Trewartha classification) will prevail for the majority of the assessment time frame that is most relevant for quantitative assessment. Two extreme cases ('what if' scenarios) outside the expected evolution scenarios were defined. One assumes a marine inundation of the site in the short term under a warmer climate (at between 5000 to 10 000 years) and the other includes an early glaciation (after ~53 000 years).

The future climate state Cs and the current temperate climate were considered in a non-sequential way in the safety assessments for the category A waste repository. The colder climate states were not considered further. Their radiological impact is expected to be lower than that of the current climate.

The extreme event scenarios were also not considered in the safety assessments of the repository. Although there are indications that continued sea level rise will amount to 20 to 25 m within the next 10 000 years, there are still considerable uncertainties associated with the marine inundation scenario (e.g., the assumed greenhouse gas emissions scenario, the feedback mechanisms and the assumed rates of melting and mechanical collapse of ice sheets in response to CO_2 rise). Therefore, the marine inundation scenario is taken into consideration, and is treated qualitatively as a 'what if' event. Long term sea level rise with marine inundation of the site is still too uncertain, at present, to be treated as a likely event in the expected evolution scenario. The early glaciation scenario (around 53 000 years AP) which could include the formation of periglacial (tundra) conditions with permafrost in the Dessel area and, possibly, an ice sheet covering the site is also highly uncertain and treated qualitatively as a what if scenario.

If the sea level rise is 20 m or more, the near surface repository may change from an inland site to a coastal site before being flooded completely. Once the site is flooded, the potential radiological impact is expected to be lower than for the well water scenario. However, during the transgression to a marine site, the waste disposal might become compromised by erosion processes and remnants of the waste may disperse into the coastal environment, leading to direct contact between humans and the radioactive waste.

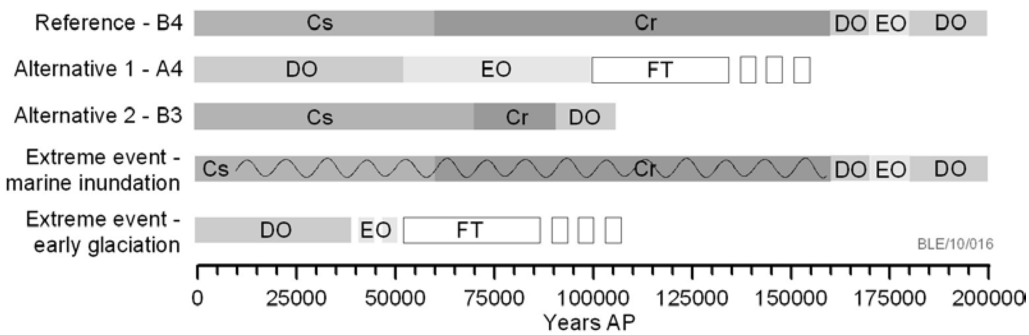

FIG. 58. Sequence of climate states in different scenarios. Year 0 corresponds to the time of closure of the facilities. The assessment time frame is limited to the first 100 000 years. Cs = subtropical climate with rainfall seasonality (dry summers); Cr = subtropical climate with no rainfall seasonality; DO = temperate climate; EO = boreal climate (cold with no permafrost); FT = tundra climate (cold with permafrost). Reproduced from Fig. [238] with permission courtesy of SKC.CEN.

I.6. CANADIAN DEEP GEOLOGICAL REPOSITORY FOR LOW AND INTERMERDIATE LEVEL WASTE

In 2011, Ontario Power Generation (OPG) submitted an Environmental Impact Statement and a Preliminary Safety Report [239, 240] to the federal authorities in Canada to support an application for a site preparation and construction license for a deep geological repository (DGR) for L&ILW. The DGR, which is proposed to be located close to the existing Western Waste Management Facility at the Bruce nuclear site (Figure 59), would receive L&ILW arising from the operation and refurbishment of OPG's nuclear reactors including wastes currently safely stored at the Facility. The proposed repository would be situated 680 m below ground surface in a competent, tight Ordovician limestone formation.

A post-closure safety assessment forms part of the application, which comprises an overall report with eight supporting documents (see Figure 60). The assessment needs to encompass the period of time when peak potential impacts may occur. Given the longevity of the radioactivity in ILW and the robustness of the geological barriers, the assessment time frame extends to a million years and beyond. The assessment therefore encompasses a time frame for which significant environmental change needs to be taken into consideration.

The current day biosphere system and its potential evolution is described in Ref. [241]. It is recognized that major changes to the surface and near surface environment are likely to occur over the timescales of interest, as a result of natural changes such as ice sheet advance/retreat and/or as a result of future human actions. Thus, in order to estimate the potential impacts in the future, a series of assumptions relating to the biosphere and its evolution are made. Although some of these assumptions are necessarily arbitrary to some extent, they are consistent with providing a reasonable level of assurance regarding the potential impact of the DGR on humans and the environment. In particular, it is noted that any description of the biosphere that is adopted for impact assessment should be considered a 'reference' or 'assessment' biosphere that acts as a 'measuring instrument' for evaluating representative indicators of the potential long term impact of the repository. A systematic process is used for establishing a logical audit trail to justify the scope, constituents and definition of such biospheres which draws directly on the BIOMASS methodology [1] and BIOCLIM project results [3, 77]. The resulting 'reference' sequence of biosphere evolution is described below.

FIG. 59. Location of the Bruce Nuclear Site, Ontario, Canada.

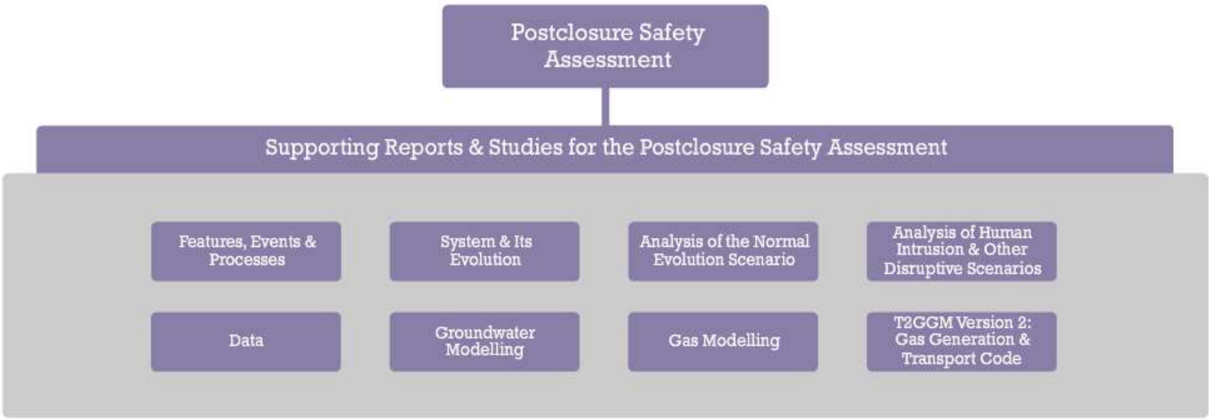

FIG. 60. Post-closure Safety Assessment Reports for the DGR.

Climate change is identified as the principal driver for environmental change, encompassing human influences on global climate. In the near term (i.e., on the scale of centuries or perhaps a thousand years), global warming is likely to cause average annual global surface temperatures to increase by several °C, with the increase being rather greater at high northern latitudes. Supporting work on long term climate change states that, if a reglaciation of the Canadian land mass should occur in the future, such an event is most likely to begin in approximately 60 000 years from present [242]. However, if at that time the concentrations of carbon dioxide and other greenhouse gases in the atmosphere were similar to the present concentrations, it is unlikely that a renewed episode of glaciation could occur as the increased surface warmth would mitigate against it. Principal conclusions for the DGR relating to cold climates are that:

- Calculated historical permafrost depths at the site have not been substantial, typically being tens of meters in depth;
- Meltwater generation is confined to temporally discrete events as the ice sheet is retreating;
- The site is likely to be covered with a proglacial lake, as the lake boundary expands and contracts following the advance and retreat of any ice sheets; and
- Crustal deflection of up to 500 m occurred at the LGM.

Qualitative assessment of the potential effect of future climate evolution on the DGR site is included in Ref. [241]. Although the DGR system will be affected by global warming in the short term (i.e., on the scale of centuries or perhaps a thousand years), the associated changes will not be significant from the perspective of the post-closure safety assessment, since they will not modify the fundamental nature of the biosphere system and its processes. However, global warming is expected to delay the onset of the next glacial cycle, so that the next ice sheet coverage of the site would not occur for at least 60 000 years.

Following the onset of climatic cooling, the climate will become drier and the present day temperate ecosystem will gradually evolve into a tundra ecosystem characterized by sparse vegetation such as lichens, grasses, sedges and arctic adapted low lying plants, and dwarf shrubs and discontinuous permafrost. The timescale over which this evolution will occur is uncertain, but previous work for a slightly more northerly latitude has suggested that it could be up to a few thousands of years. This tundra period is likely to be the predominant biosphere state at the site during a glacial cycle.

With further cooling, the land surface temperature will fluctuate around the freezing point and the amount of snow accumulation will become greater than the amount melted. An ice sheet will eventually advance over the site, developing to a maximum thickness of 3 km, resulting in the removal of unconsolidated sediments and some scouring of the underlying bedrock. As the ice provides insulation against heat loss from the earth's interior, the interface between the ice and the underlying solid earth will reach temperatures that are around freezing.

Towards the end of the glacial cycle, the ice sheet will start to retreat relatively rapidly by melting, resulting in voluminous discharges of meltwater. Regionally, this will probably lead to the formation of large proglacial lakes, the further erosion of poorly resistant rocks and sediments in some locations, and deposition of thick layers of glacially derived sediments elsewhere. Subsequently, further warming will result initially in the re-establishment of tundra conditions, and the eventual warming to present day temperatures will result in the re-establishment of a temperate ecosystem. Based on historical records, the warm conditions will persist for about 20 000 years until another cooling period initiates the next cycle of glaciation.

The 'reference' sequence of climate states for the next 120 ka is illustrated in Figure 61. Thereafter, it is assumed that the sequence of climate states will follow a repeating pattern similar to that experienced in the region in the last 120 ka years i.e. a cycle unaffected by anthropogenic influences, (see Figure 62).

Climate modelling undertaken in support of the DGR project indicates that a long period of temperate conditions of around 60 to 70 ka is likely to persist at the Bruce site before there is significant cooling. The low lying topography of the proposed site and proximity to Lake Huron mean that future landscape change will be dictated by climate change. The continental northern latitude context also means that the site will likely be again covered by an ice sheet during future glacial episodes.

Significant uncertainties surround projections of future climate and the shoreline for Lake Huron. Rather than explicitly representing evolution of the biosphere, the main calculations are based on stylized, constant climate conditions, comparable with the present day area surrounding the site, which is primarily agricultural and recreational land use [243]. The site is conservatively assumed to be occupied by a self-sufficient farming family living directly above the repository and extracting potentially contaminated well water for drinking, domestic water usage and irrigation. This approach is taken to provide an indication of potential impacts on long timescales. The biosphere system being represented is readily understandable because it aligns with current conditions. The approach is considered appropriate because it allows agriculture to form the basis of the exposure scenario, which tends to maximize doses, and because glacial cycles return periodically to temperate conditions.

For the normal evolution scenario's reference case, very little contamination is released from the geosphere, with maximum calculated doses more than ten orders of magnitude below the public dose criterion of 0.3 mSv/y, and with ^{129}I being the most important contributing radionuclide. A disruptive scenario based on severe failure of the shaft seals resulted in a maximum calculated dose of about 1 mSv/y, with ^{14}C being dominant due to the forcing of a direct gas pathway to surface. The low likelihood of the severe shaft seal failure scenario means that the resulting calculated risk was significantly lower than the associated reference health risk of 10^{-5}/y.

A variant normal evolution scenario case considering potential doses arising from radionuclide discharges to a tundra biosphere is considered in the DGR assessment. This case resulted in a limited (less than four-fold) increase in calculated doses, which therefore remained significantly below the public dose criterion. The increase is due to a lower degree of dilution in the well water, which is conservatively still assumed to be used in the tundra climate state.

A further variant explored the effect of glacial erosion removing the surficial and shallow groundwater zones, eroding to a depth of about 100 m. This resulted in a two order of magnitude increase in the maximum calculated doses, though they remained well below the dose criterion.

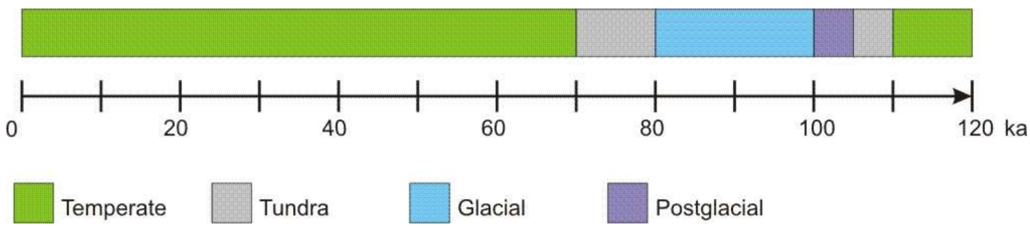

FIG. 61. Assumed 'reference' sequence of climate states for the next 120 ka.

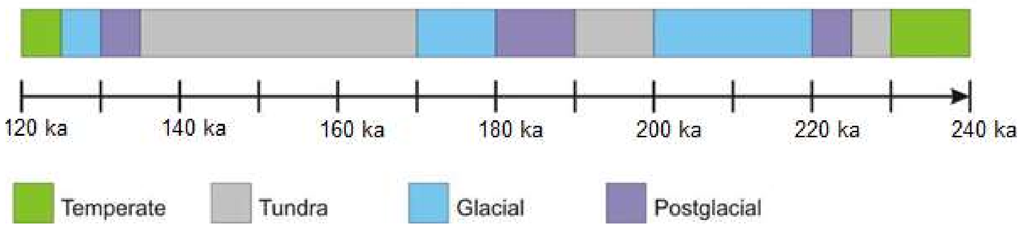

FIG. 62. Assumed repeated sequence of climate states from 120 ka onwards.

I.7. CANADIAN USED FUEL REPOSITORY

The Canadian NWMO has undertaken a study to quantitatively assess the long term safety implication of glacial cycles on a deep geological repository for used nuclear fuel located on the Canadian Shield [244]. The concept consists of a crystalline (granitic) host rock, intersected by a complex set of interconnecting fractures.

A timescale of one million years was considered, during which eight glacial cycles are postulated [244]. A timescale for a typical glacial cycle of about 120 000 years is used based on the last glacial cycle. A delay in the onset of the next glacial cycle of 50 000 years is considered based on the low amplitude of insolation variations and anthropogenic greenhouse gases. Thereafter, repetitions of the glacial cycle described in Table 9 are represented, based on continental scale modelling of glaciation and deglaciation described in Ref. [245]. The resulting sequence of permafrost depth and ice sheet height is illustrated for the first 300 000 years in Figure 63.

Transitions between the climate periods are represented by step changes in properties and no evolution of the system is represented during each period. The biosphere is therefore represented in a step wise sequential manner. This stylization is considered appropriate given the long timescale of relevance and with reference to regulatory guidance [246]. During ice sheet advance over the site, it is recognized that soil and overburden would be eroded, however, the effects of the erosion on the biosphere and geosphere are neglected.

Groundwater flow and transport results for the near field and geosphere are included in the study described in Ref. [244]. Particle tracking calculations were also undertaken, for example, illustrating the focusing of groundwater discharges at a talik during the permafrost period (see Figure 64).

TABLE 9. DURATION OF GLACIATION STATES CONSIDERED IN REF. [244], BASED ON A SIMULATION FROM REF. [245]

Glaciation period or state	Overall Duration during a Single Glacial Cycle (years)
Temperate or Interglacial Period	10 800
Permafrost Period	53 800
Ice Sheet Period	55 400
Proglacial Lake	1 200
Total duration of glacial cycle	121 200

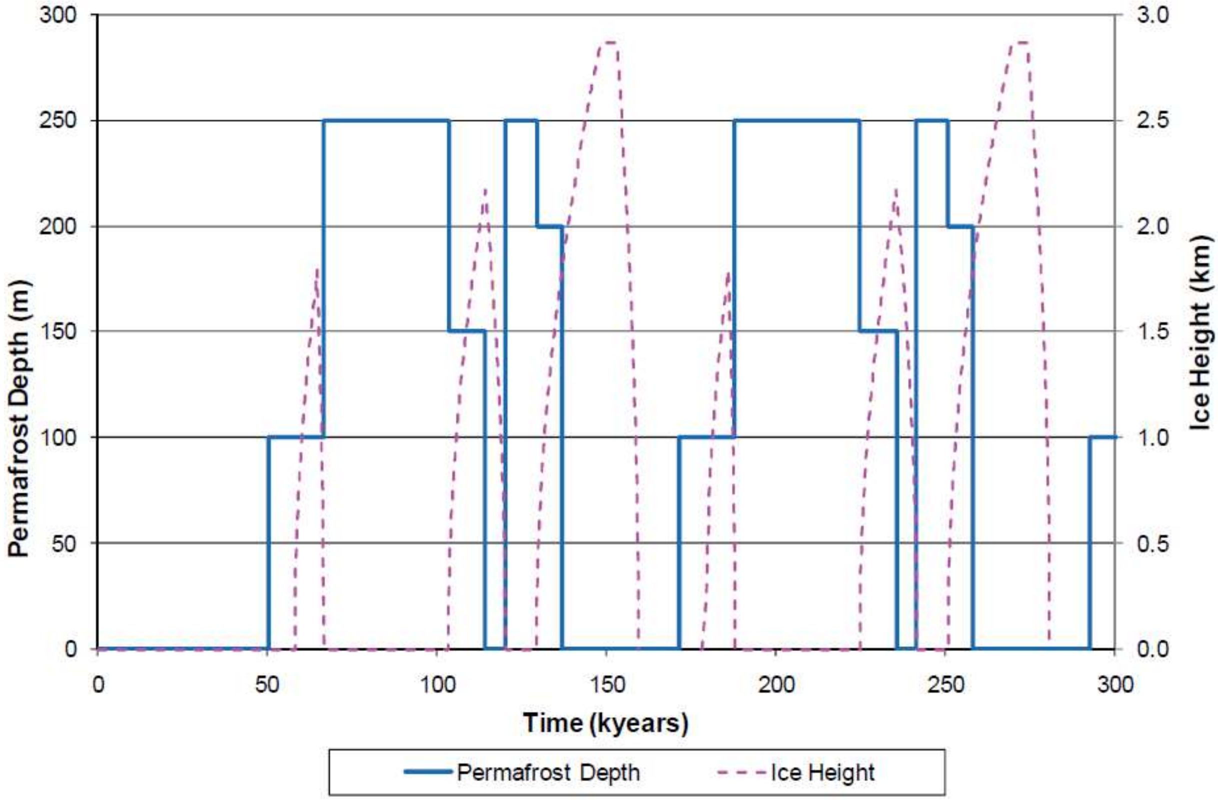

FIG. 63. Permafrost depth and ice sheet height for the glacial scenario represented in Ref. [244] up to 300 000 years AP. Reproduced from Ref. [244] with permission courtesy of NWMO.

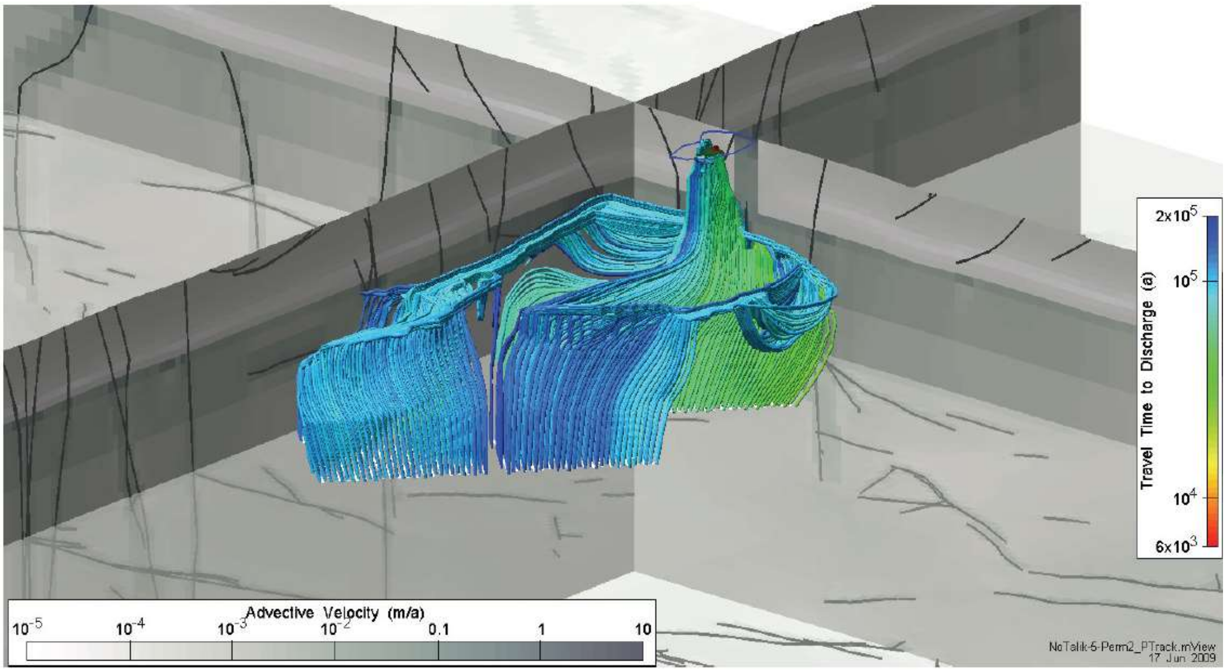

FIG. 64. 3-D visualization of particle tracks at 66 800 years, at the start of the second permafrost period. Reproduced from Ref. [244] with permission courtesy of NWMO.

Distinct biospheres are considered for each climate state:

- Temperate: Based on the current climate biosphere of a typical Canadian Shield location. Two lakes are present in the vicinity of the site. A self-sufficient farmer group is assessed and uses a groundwater well that intercepts the contaminant plume from the repository; grows its own crops and raises animals. The food ingested by this group includes plants grown in a garden, domesticated animals and fish.
- Periglacial: Two open taliks are present. A tundra hunter group is assessed and is also self-sufficient surviving mainly from hunting. Their diet consists mostly of caribou, augmented with some fish (from the lake), fowl and plants (berries). This group is assumed to use the lake at the repository site (i.e., the North Lake) for all water needs (drinking, bathing, etc.). In winter, the lake is also used for water by boring through the ice, although melted snow may also be used .
- Ice Sheet: No humans are assumed to live in the vicinity of the repository when it is covered by an ice sheet.
- Proglacial Lake: Resembles the permafrost state, although a large proglacial lake is present. A tundra hunter group is present with similar habits as in the permafrost state, except that its diet consists of much more fish (and less caribou) from the proglacial lake.

The calculated doses for the reference case are shown in Figure 65 and compared against a case in which the total system was represented with constant temperate conditions. The model showed that assessed doses are highest during temperate periods. This is attributed to the direct use of the contaminated well water by the self-sufficient farmer group. The radionuclides contributing the most to the doses are ^{129}I and ^{36}Cl, followed by ^{41}Ca, ^{208}Bi and ^{14}C.

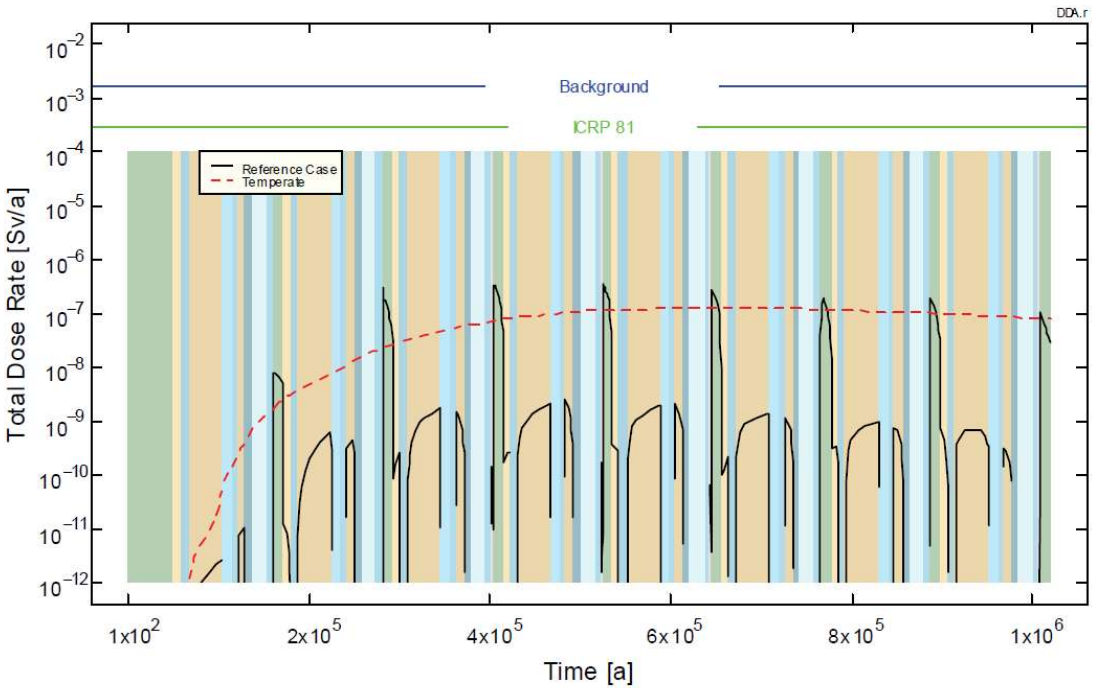

FIG. 65. Comparison of calculated doses for the glacial case (black line) against those for a constant temperate system (red dashed line); colours indicate climate periods with green being temperate, tan being permafrost, blue being ice sheet (the short proglacial lake period is not visible on this scale).

Variant calculations were undertaken in order to explore the effect of randomly varying the duration of each climate state [244]. Most of the average peak total doses from these variant calculations exceeded that of the reference case. This is attributed to the inclusion of at least one long cold based ice sheet period in each simulation. During this long period of 'frozen in' conditions, there can be an accumulation of radionuclides under the permafrost layer beneath the ice sheet (because there are no groundwater discharges to the surface). During the subsequent state, those accumulated radionuclides are effectively released as a 'pulse', leading to higher doses than in the reference case.

I.8. YUCCA MOUNTAIN, USA

In its License Application for disposal of spent fuel and high level radioactive waste at Yucca Mountain, the US Department of Energy (US DOE) [247] gives consideration to the potential for future pluvial episodes resulting in enhanced infiltration into the repository through the overlying, unsaturated volcanic tuff, which comprises a sequence of layers of varying degrees of fracturing. Glacial–interglacial cycles that are associated in more northern latitudes with the advance and retreat of continental ice sheets, are associated in the more southern latitude of Yucca Mountain with changes in overall amounts of precipitation, as well as with alterations in the frequency of storm events of different levels of intensity and duration.

The License Application assumes that projections of future climate at Yucca Mountain can be based exclusively on the interpretation of palaeo–climatic data for the area. Continuously deposited calcite at Devil's Hole, Nevada provides a precise chronology that can be used to calibrate other climate proxy data that provide estimates of the nature and magnitude of past climate events [248]. Sole reliance on palaeo–climatic data has been challenged by the State of Nevada [249], who argue that future greenhouse warming could result in no analogue climatic conditions in the south-west USA giving rise to more intense precipitation events and greater infiltration than has been estimated by the US DOE. In respect of erosion, consideration has to be given to the recent formation of the terrain at Yucca Mountain, with the landscape having largely originated about thirteen million years ago and having been subject to significant volcanic activity since that time. In particular, it has been argued that the uplifted and tilted blocks that comprise the present day landscape exhibit a significant degree of incision [15]. Using a model based on a stream power approach in which it is assumed that the rate of erosion is proportional to the size of the catchment (as a proxy for water flux) and to the square of the topographic gradient, they argue that the crest of Yucca Mountain will denude to the level of the proposed repository in between 5105 years and 5106 years. They emphasize that this prediction is based on conservative estimates for all involved parameters and that erosion may be more rapid if other processes are involved. For example, they note that their model does not consider continuing uplift or catastrophic surface processes as they have been recorded in the region.

More recently, the US Nuclear Regulatory Commission (NRC) [250] has produced a supplemental environmental impact assessment for Yucca Mountain. This addresses ways in which changes in climatic conditions may affect the regional groundwater flow regime and associated discharge locations. However, as with the US DOE License Application, it relies entirely on palaeo–environmental data. It should be noted that consultation on the report closed in November 2015 and that the US NRC has recently amended the report in the light of comments received [250]. This amended report has not been reviewed as part of this project.

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LIST OF ABBREVIATIONS

$\delta^{18}O$	Oxygen isotope anomaly relative to a modern-day standard (Standard Mean Ocean Water)
A1B	IPCC greenhouse-gas emissions scenario
AD	Anno Domini (date)
AMOC	Atlantic Meridional Overturning Circulation
ANDRA	The French National Radioactive Waste Management Agency
AOGCM	Atmosphere–Ocean General Circulation Model
AP	After present (relative to 1950 AD)
ArcGIS	A geographic information system (GIS) for working with maps and geographic information.
BIOCLIM	Modelling Sequential Biosphere Systems under Climate Change for Radioactive Waste Disposal. A project within the European Commission 5th Euratom Framework Programme Contract FIKW-CT-2000-00024s. http://www.andra.fr/bioclim/
BIOMASS	BIOsphere Modelling and ASSessment programme of the IAEA
BIOMOVS	An international modelling exercise, the BIOspheric Model Validation Study, initiated by the Swedish Radiation Protection Authority, 1985–1989
BIOMOVS II	Follow-up to BIOMOVS, 1990–1995
BIOPROTA	An international forum to address uncertainties in the assessment of the radiological impact of releases of long lived radionuclides into the biosphere (see http://www.bioprota.org).
BP	Before present (relative to 1950)
CCI-HYDR	A climate change tool for generating perturbed time series for the Belgian climate
cGENIE	University of Bristol EMIC incorporating a global carbon cycle model
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
CLIMBER	CLIMate-BiospERe
CMIP3	Coupled Model Inter-comparison Project Phase III
CMIP5	Coupled Model Inter-comparison Project Phase V
CORDEX	Globally an ongoing programme of research on climate downscaling is coordinated through CORDEX[30], which is a WCRP initiative. Sponsors include the World Meteorological Organization, the International Council for Science and the

[30] http://www.cordex.org/

DECC	UK Department of Energy and Climate Change
DGR	Deep Geological Repository (Canada)
ECA&D	European Climate Assessment and Dataset project
EMIC	Earth Model of Intermediate Complexity
EMRAS	IAEA programme Environmental Modelling for RAdiation Safety, 2003-2007
EMRAS II	Follow-up to EMRAS, 2009-2011
ENSEMBLES	The ENSEMBLES project was a five-year programme involving 66 partners from across Europe. Led by the UK Meteorological Office, and funded by the European Commission, it studied the likely effects of climate change across Europe as a whole.
E-OBS	A daily gridded observational dataset for precipitation, temperature and sea level pressure in Europe based on ECA&D information
ERB	Example Reference Biosphere 3 developed in the BIOMASS study
ESM	Earth System Model
EUR-11 and EUR-44	Gridded climatologies for Europe at 12.5 km and 50 km scales, respectively
EURO4M	European Reanalysis and Observations for Monitoring
EURO-CORDEX	European component of CORDEX[31]
EUMETNET	A grouping of 29 European National Meteorological Services that provides a framework to organize cooperative programmes between its members in basic meteorological activities
FEP	Feature, Event or Process (FEPs – Features, Events and Processes)
GIS	Geographical Information System
GRENOBLE	Grenoble Model for Land Ice in the Northern hemiSphere
HadCM3	Hadley Centre (UK Met. Office) AOGCM
HadGEM	Hadley Centre (UK Met. Office) AOGCM
HadGEM1	Hadley Centre (UK Met. Office) AOGCM
HadRM3	Hadley Centre (UK Met. Office) RCM
IAEA	International Atomic Energy Agency
IAEA-TECDOC	International Atomic Energy Agency Technical Document
ICE-5G	Ice-sheet modelling code
ILW	Intermediate Level (radioactive) Waste
IPCC	Intergovernmental Panel on Climate Change

[31] http://www.euro-cordex.net/

ka	Thousand years
KBS-3	Design of geological disposal facility for spent nuclear fuel adopted in Sweden and Finland
LGM	Last Glacial Maximum
LLWR	UK Low Level Waste Repository, West Cumbria
LOVECLIM 1.2	An EMIC that includes representations of the atmosphere, the ocean and sea ice, the land surface (including vegetation), the ice sheets, icebergs and the carbon cycle.
Ma	Million years
MIKE-SHE/MIKE11	Suite of physically based, catchment scale hydrological modelling codes
MoBiDic	A sector based EMIC originating from the University of Louvain-la-Neuve and used in BIOCLIM
MODARIA	IAEA programme MOdelling and DAta for Radiological Impact Assessments
NIRAS/ONDRAF	The Belgian Agency for Radioactive Waste and Fissile Materials established in 1980
NNL	UK National Nuclear Laboratory
NORM	Naturally Occurring Radioactive Material
NWMO	Nuclear Waste Management Organization (Canada)
OPG	Ontario Power Generation
Pg	Petagram ($1x10^{15}$ g)
PgC	Petagrams of Carbon
PMIP	Palaeo–climate Modelling Intercomparison Project
ppmv	Atmospheric concentration measured in parts per million by volume
PRUDENCE	European Union sponsored project to produce regional climate
RCM	Regional Climate Model
RCP 2.6/4.5/6.0/8.5	IPCC Representative Concentration Pathways defined by their different degrees of radiative forcing
RWM	Radioactive Waste Management Limited (UK)
SAT	Surface Air Temperature
SCM	Simple Climate Model
SFR	SKB low and intermediate level waste repository located at Forsmark
SKB	Svensk Kärnbränslehantering AB (the Swedish adioactive waste management organization)
SRES	IPC Special Report on Emissions Scenarios
SR-PSU	Safety assessment for the SKB SFR facility

SR-Site	Safety Assessment for a KBS-3 type repository published by SKB in 2011
SSMFS	Swedish Regulatory Guide
TURVA-2012	Safety assessment of a KBS-3 type repository conducted by Posiva Oy (2012)
UKCIP09	UK Climate Impacts Programme 2009
UNTAMO	GIS-based software toolbox used by Posiva Oy
US DOE	US Department of Energy
US NRC	US Nuclear Regulatory Commission
WCRP	World Climate Research Programme
WG	Working Group

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