INTERNATIONAL DEVELOPMENTS IN ADDRESSING ENVIRONMENTAL CHANGE IN POST CLOSURE SAFETY ASSESSMENTS

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Environmental change in post-closure safety assessment for radioactive waste disposal is recognised as an issue in international recommendations, national regulatory requirements and safety assessment practice. The reference biosphere's methodology, developed as part of the IAEA BIOMASS project (IAEA-BIOMASS-6), completed in 2001, considered processes relevant to environmental change, but did not take the issue very far technically. Further international work was done in the European project BIOCLIM and reported in 2004. Subsequently, a Working Group of the IAEA EMRAS II Program completed a study in 2012 of "Environmental Change in Post-Closure Safety Assessment of Solid Radioactive Waste Repositories". Following up the results of the above history of international studies, further work is in progress within the IAEA MODARIA program WG6, on "Development of a Common Framework for Addressing Climate Change in Post-Closure Radiological Assessment of Solid Waste Disposal". The key work in this project, introduced in this paper, includes: definition of the key processes that drive environmental change, describing how a relevant future may develop on a global scale; considering how that can be downscaled to provide information that is needed for site-specific assessments; and applying the conceptual framework to a number of case studies that illustrate the evolution of site characteristics and the implications for the dose assessment models.

I. INTRODUCTION

For several decades it has been recognised 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, characterisation and application of reference biospheres for use in post-closure radiological impact assessments was developed through the International Atomic Energy Agency (IAEA) in the BIOMASS project. This resulted in a comprehensive reference biospheres methodology that was fully documented in a major report arising from the project (Ref 1).

The BIOMASS methodology explicitly recognised that it might be necessary to take climate and landscape changes into account in post-closure radiological impact assessments. BIOMASS commented 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. However, BIOMASS also noted that additionally, or alternatively, one might wish to consider an inter-related sequence of biospheres, with the interest focussed on changes from one system to another. Following on from BIOMASS, the European Union (EU) 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. See Refs 2 - 5. Thereafter, the IAEA EMRAS II Program's Working Group 3 completed a study in 2012 of Environmental Change in Post-Closure Safety Assessment of Solid Radioactive Waste Repositories. A report prepared by participants, including regulators, operators and technical support organisations from many countries, provided a review of: international recommendations and guidance on the topic and how they have been applied national requirements; technical descriptions and illustrations of complementary approaches to addressing climate change based on analogues and dynamic modelling; and further illustrations of the dose assessments which take account of different environmental change effects on biosphere systems (IAEA, in publication, Ref 6).

The general aim of the IAEA MODARIA Program, which follows on from EMRAS II, is to improve 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. Within MODARIA, Working Group 6 (WG6) has the remit of developing a common framework for addressing climate change in post-closure radiological assessments of solid radioactive waste disposal. The intention is to be inclusive of a wide range of disposal facility types. More specifically the overall objective of WG6 is 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.

II. CLIMATE AND LANDSCAPE CHANGE IN SAFETY ASSESSMENTS

In general, the timescales of relevance in post-closure radiological impact assessments of geological disposal facilities for solid radioactive wastes range from a few thousand up to about one million years. 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 (Ref 1). Based on the work undertaken in MODARIA WG6, 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 provisionally summarised in the road map for assessments shown in Figure 1.

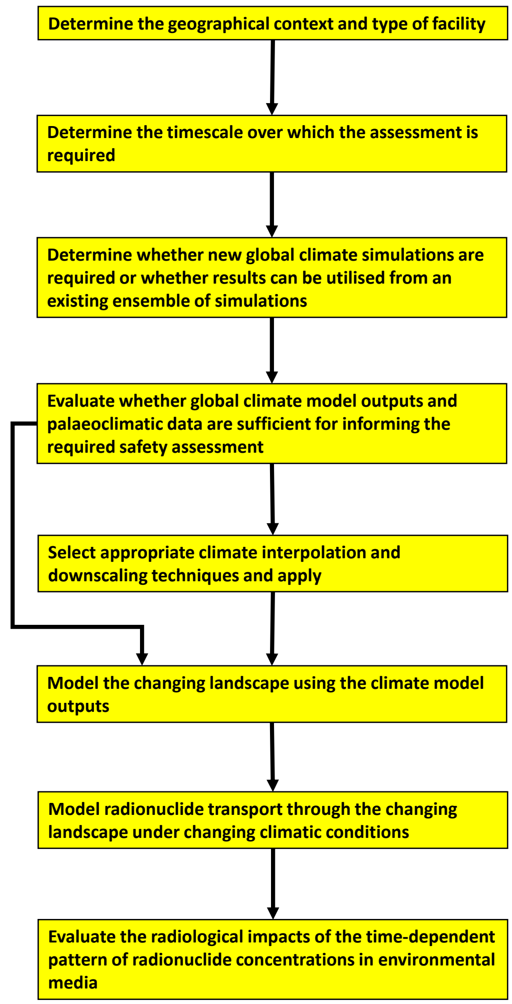

Figure 1. Provisional road map for performing an assessment taking climate change and landscape development into account.

III. FACILITY TYPE AND TIMESCALES

In order that a comprehensive common framework for addressing environmental change could be developed, the various categories of facilities needed to be identified and the different ways in which they may be impacted by environmental change, to be characterised. Different safety assessment questions emerge to be answered depending on facility context. It is emphasised that the methodological approach to developing a common framework for addressing environmental change in long-term safety assessments described in this work is intended to be applicable across a wide range of different types of facilities. Categories were identified by: mode of construction, geological- and hydrological- context, height above/below sea level (coastal context) and potential for climate extremes (historical pattern).

When describing the mode of construction, there is a distinction 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. In the geological context, the primary consideration is the host geology. For some repositories, 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. If the repository 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.

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 Fish et al., 2010, (Ref 7). 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. 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 the MODARIA scheme. With respect to climate extremes, 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 and those that were never glaciated, but experienced sub-zero 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.

The importance of various types of processes affecting a repository will differ depending on the timescale considered. In MODARIA WG6, 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 1,000 years;
- 1,000 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 1,000) 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 engineered components. 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. 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. 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.

IV. CONTROLS ON LONG TERM CLIMATE CHANGE

Geological records show that over the past 2.5 million years the Earth's climate has varied from warm (interglacial) to cold (glacial) periods characterized by extensive ice sheets in high northern latitudes. Understanding of the dynamics of past climate evolution and variability is essential to assess future climate evolution relevant for post-closure radiological impact assessments. Global climate varies on a wide range of timescales, with those variations determined by a wide range of mechanisms and processes, as illustrated in Figure 2.

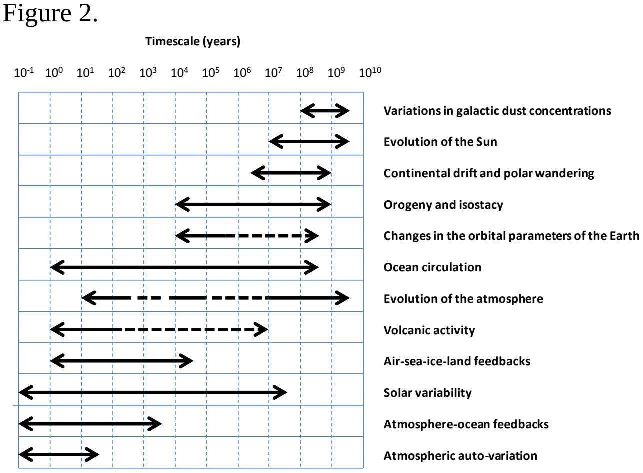

Figure 2. Major mechanisms of climate change and their timescales of operation, redrawn from Goodess et al.,1992, (Ref 8).

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 paper, 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. Thus, of the mechanisms identified in Figure 2, 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.

The latitudinal and seasonal distribution of incoming solar radiation (insolation) is the major external driver of the Earth's climate. This distribution changes over time due to 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. Statistical analyses of long climate records supported this theory. (Ref 9-12). From analyses of gas inclusions in long ice cores extracted from the Greenland and Antarctic ice sheets, it has been found that atmospheric carbon dioxide concentrations vary systemically during glacial-interglacial cycles, being low during glacial episodes and higher during interglacials. However, at the present day, the primary factor determining changes in the atmospheric concentration of carbon dioxide is the burning of fossil fuels. Human emissions have so far increased the atmospheric CO_2 concentration from 280 ppmv in 1750 AD prior to industrialisation to 394 ppmv in 2012 AD (www.esrl.noaa.gov). A continued increase in the CO_2 concentration at the same rate as during the last decade (c. 2 ppmv per year) would result in an atmospheric CO_2 concentration of c. 570 ppmv in 2100 AD.

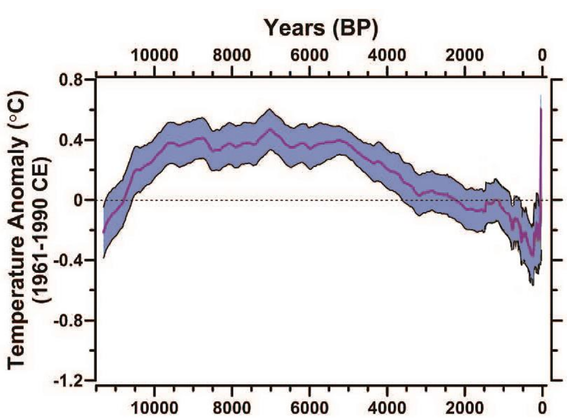

Figure 3. Globally stacked surface temperature anomalies with respect to the period 1961-1990 AD (purple line) with one standard deviation uncertainty (blue band). Modified from Marcott et al., 2013 (Ref 13).

V. MODELING OF GLOBAL CLIMATE

Due to incomplete knowledge of the dynamics and interactions of the Earth's climate system, the future evolution of Earth's climate cannot be 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. The current knowledge on the Earth's future climate evolution in the coming ~ 100 ka can be described in terms of global average evolution and large-scale patterns of climate change. Various types of computational models using the above described gas concentrations and variations in astronomical parameters can then be used in order to study the range of future climate evolutions.

For modelling short-term changes in climate, typically Atmosphere-Ocean General Circulation Models (AOGCMs) are used. These can be employed either with fixed or transient boundary conditions. Fixed conditions could, for example, include atmospheric carbon dioxide 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 carbon dioxide concentration was set at its pre-industrial level. Transient conditions might typically be an increase in atmospheric carbon dioxide concentration of 1% per year. The need to represent the whole of the Atmosphere-Ocean system on a 2D multi-layer 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 2D 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 a Regional Climate Model (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.

For longer-term projections of climate, it is necessary to use Earth Models of Intermediate Complexity (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 described in Goosse et al., 2010, (Ref 14). This includes representations of the atmosphere, the ocean and sea ice, the land surface (including vegetation), the ice sheets, icebergs and the carbon cycle. The GENIE

EMIC also includes a full representation of the carbon cycle, in which atmospheric CO_2 concentrations are predicted by the model, rather than prescribed by the user. 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., Ridgwell et al., 2007, (Ref 15). In the initial stage of the MODARIA WG6 work a flow chart was developed 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, see Figure 4. 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, use of an ensemble of AOGCMs is preferred over use of an ensemble of EMICs where this is possible.

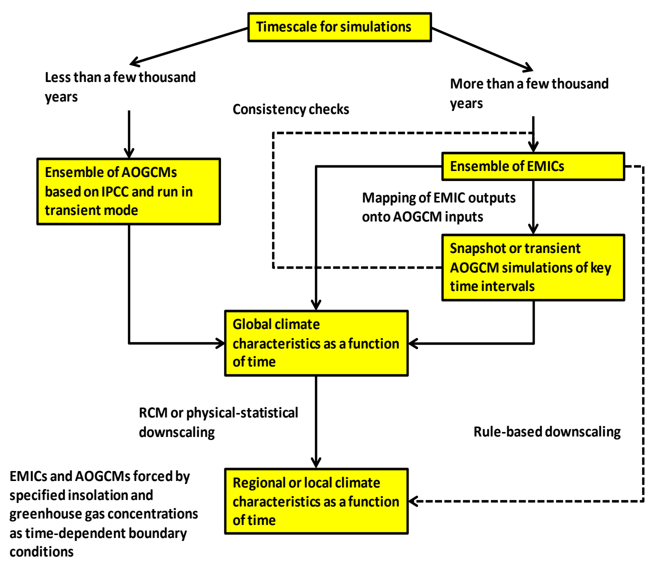

Figure 4. Selection of Climate Models for use in Post-closure Radiological Impact Assessments

VI. DOWNSCALING REQUIREMENTS AND APPROACHES

To downscale the results obtained from global climate models to be applicable to a specific site three approaches exist. These are dynamical downscaling, statistical-physical downscaling and rule-based downscaling, respectively. All three of these approaches were used in the BIOCLIM project and they are briefly discussed in general terms below, before giving consideration to more recent work on this topic.

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. Thus, dynamical downscaling can only be used for situations for which an AOGCM is to be used. Dynamical downscaling will deliver climatic results with a resolution of about 12-25 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 (Ref 16) or the more recent UKCIP09 5 km gridded climatology (Ref 17). Thus, it may be necessary to combine dynamical downscaling with physical-statistical downscaling at the smallest scales. Furthermore, physical-statistical downscaling may be used directly with AOGCM results

In physical-statistical downscaling, relationships between larger-scale climate variables (such as atmospheric circulation) and local surface climate variables (such as monthly or daily temperature and precipitation) are derived empirically using observed data and are applied to large-scale output from AOGCMs or EMICs in order to generate projections of climate at the local scale. The approach is based on two major assumptions. These are that (i) large-scale climate variables are more reliably simulated by climate models than local/regional variables, and that (ii) the relationships between the large-scale and regional/local-scale variables remain valid in a changed climate (this is often referred to as the assumption of stationarity). The alternative approaches to statistical downscaling that were available at the time of BIOCLIM (Ref 3 and 4) 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.

Although physical-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 the results from the EMIC simulations was by the use of rule-based downscaling (Ref 5 and 6). The rule-based methodology assigned a climate class from the Køppen-Trewartha scheme (Ref 18) 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 data base of present-day climate observations. Because rule-base 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 was 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 was not sufficient that they should be associated with the specific climate class. In addition, they had to be located in an appropriate geographical context. Thus, in BIOCLIM (Ref 4) only lowland (altitude less than 200 m) stations were selected as representative of Central England.

Several initiatives on downscaling have been undertaken since BIOCLIM and globally an on-going programme of research in this area is co-ordinated through CORDEX (http://wcrp-cordex.ipsl.jussieu.fr/). CORDEX is a World Climate Research Programme (WCRP) initiative. Its sponsors include the World Meteorological Organisation (WMO), the International Council for Science and the Intergovernmental Oceanographic Commission of UNESCO. The CORDEX initiative arose because it was recognized that 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 (Ref 19). Results of this work are being taken into account in MODARIA WG6.

VII. INFLUENCES OF DOWNSCALED CLIMATE AT SITE LEVEL

As discussed earlier, 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 e.g. RWMD, 2010; SKB, 2011; IAEA 2011, (Ref 20 - 22). It is not possible to accurately 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, adopted in MODARIA WG6, 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 (Refs 21, 23, 24 and 25).

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 does not provide a sufficient basis for post-closure radiological impact assessment. Rather, the narrative of projected climate change must 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 (Smith et al., 2013, Ref 26). In turn, this provides the context within which the potential radiological impacts of the repository (due to release and transport of radionuclides) can be evaluated.

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.

Outputs from climate models can then be 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. Also, at large spatial and temporal scales, climate models define input data for geomorphological models of landscape evolution, see for example, the discussion of geomorphological modelling by ANDRA provided in Appendix E of Thorne et al., 2011, (Ref 27). Permafrost development is a regional-scale phenomenon, but it can often be modelled at a local-scale, e.g. using a 1D vertical heat transfer model or a 2D model of a limited spatial domain (Ref 28; Ref 21).

In the context of modelling surface hydrology and subsurface 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. One alternative is to use long-term climate modelling with EMICs to identify situations of particular interest in an assessment context. The output from the EMIC calculations 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.

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 (e.g. Ref 29; Ref 21). 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 (Ref 29) or by determining the distribution of radionuclides released into and retained in the changing landscape in the vicinity of the facility (Ref 21).

VIII. CONCLUSIONS

The general strategy in safety assessments for handling long-term environmental change, mainly driven by climate, is constantly developing. New tools and faster computers together with a need to integrate the whole repository system in the same time-dependent context are the drivers. The MODARIA WG6 ongoing work (as of December 2014) outlined here gives an insight into the current understanding on how to handle climate-related processes affecting a site. Furthermore, work within WG6 is not restricted to a review of approaches that have been used to date. Specifically, work is included on developing a robust modelling approach to making multi-millennial projections of future atmospheric carbon dioxide concentrations for different emissions scenarios and on creating an ensemble of global climate simulations for different combinations of insolation, carbon dioxide concentrations and ice-sheet configurations that will provide insights on the range of climatic conditions that may occur worldwide over the next few hundred thousand years. It is envisaged that the methodology that is being developed, the modelling results that are being generated, and the example applications, will be of wide utility to all nations giving consideration to the geological disposal of solid radioactive wastes. We consider that by using global climate models, downscaling the information to site level and then using local-scale models of ice-sheets, permafrost development, geomorphological change, and hydrology and hydrogeology it will be possible to build ensembles of site-specific landscape narratives relevant to addressing many of the questions raised in safety assessments of repository systems.

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