Technical Report
TR-19-04
September 2019

Climate and climate-related issues for the safety evaluation SE-SFL

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ISSN 1404-0344
SKB TR-19-04
ID 1596435
September 2019

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Keywords: SFL, Long-lived low- and intermediate-level waste, Safety evaluation, Post-closure safety, Climate, Climate case, Permafrost, Ice sheet, Sea level, Laxemar.

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Preface

This report is one of the main references for the evaluation of post-closure safety for a proposed repository concept for the repository for long-lived waste (SFL) in Sweden. The report describes the climate-related issues of importance for the SFL repository concept. These are permafrost development, ice-sheet development, isostatic and eustatic changes and the resulting relative sea-level changes, as well as surface denudation. Based on the process descriptions idealised projected sequences of future climate developments are defined in support of the evaluation of post-closure safety for the proposed repository concept for SFL.

Jenny Brandefelt has been the project leader for SE-SFL and is responsible for the safety evaluation. The main contributing authors for this report have been Jens-Ove Näslund, Jenny Brandefelt and Lillemor Claesson Liljedahl (SKB). Contributions in specific subject areas have been provided by Anders Löfgren (Ecoanalytica) and Peter Saetre (SKB).

A formal review of this report was performed by Allan Hedin (SKB) and Michael Thorne (Mike Thorne and Associates Ltd, United Kingdom).

Solna, September 2019

Jenny Brandefelt
Project leader SE-SFL

Summary

The repository for long-lived waste (SFL) is planned to be constructed for the final disposal of low- and intermediate-level waste from Swedish nuclear facilities. SKB is planning to take SFL into operation around year 2045. Possible solutions for management and disposal of the Swedish long-lived low- and intermediate-level waste were examined in the SFL concept study and an approach to further assessment of post-closure safety was proposed (Elfwing et al. 2013). The next step in the development of SFL is the present safety evaluation. The purpose of this evaluation is to evaluate conditions in the waste, the barriers, and the repository environs under which the repository concept has the potential to fulfil the regulatory requirements for post-closure safety. Moreover, an objective is to provide SKB with a basis for prioritizing areas in which the level of knowledge and efficiency of methods must be improved in order to perform a full safety assessment for SFL. This report documents information on relevant climate and climate-related conditions and constitutes one of the main references supporting the **Main report**, which summarises the evaluation of post-closure safety for SFL.

Climate-related issues of importance for the SFL repository concept, identified in the processing of features, events and processes influencing post-closure safety (see the **Main report**, Chapter 3, and the **FEP report**), are briefly described. These are *i)* permafrost development, *ii)* ice-sheet development, *iii)* isostatic and eustatic changes and the resulting relative sea-level changes, and *iv)* surface denudation. For each process, references are also given to in-depth process descriptions presented in previous SKB safety assessment Climate reports.

Furthermore, climate-related information needed as input to other modelling activities in SE-SFL is described. This includes information on relative sea-level for the Laxemar site from early Holocene submerged conditions to present-day and projected future terrestrial conditions, as well as present-day climate conditions in Laxemar and at a few other locations in Sweden.

Finally, idealised projected sequences of future climate developments are defined and described to support the evaluation of post-closure safety for the proposed repository concept for SFL. The scientific basis for the selection and definition of these climate cases is given in the Climate reports produced for both the SR-PSU safety assessment performed for the extended SFR repository, and for the planned Spent Fuel Repository within the SR-Can and SR-Site safety assessments. In those reports, current knowledge on past and future climate evolution is described in detail, including detailed process descriptions, based both on reviews of international scientific literature and on studies performed for SKB to extend current knowledge in areas of major interest for the safety assessment. That information is not repeated in the present report.

The set of climate cases for a specific safety assessment is chosen to represent conditions covering the range of possible future climate development at the repository site that may influence post-closure safety for the specific repository. The strategy for selection and description of climate cases in SE-SFL is the same as in SR-Site and SR-PSU. However, since SE-SFL constitutes a first evaluation of post-closure safety for a proposed repository concept, located at an example site, the future climate developments chosen are intentionally simplified and limited in number as compared with the ones presented and used in a full safety assessment (e.g. SR-Site). The climate cases included in SE-SFL allow a first evaluation of how the properties of the proposed repository concept evolve over time under relevant future climate developments. In a full safety assessment for SFL, the results of the SE-SFL evaluation will serve as basis for the definition of a sufficient set of future climate developments that together illustrates the most important and reasonably foreseeable sequences of future climate states and their impact on the protective capability of the repository and their environmental consequences.

Two simplified developments of climate and climate-related processes are defined and presented for the Laxemar example site from the last deglaciation and over the next 100 000 and one million years. These include one climate case with warm temperate climate conditions, initially dominated by an increased greenhouse effect. The other case describes colder climate conditions with, at times, permafrost development and with an ice sheet overriding the repository site. In this simplified glacial cycle case, the site is covered by the sea following deglaciation.

Sammanfattning

Slutförvaret för långlivat avfall (SFL) planeras att uppföras för slutförvaring av långlivat låg- och medelaktivt avfall från svenska kärntekniska anläggningar. SKB planerar att ta SFL i drift runt år 2045. Elfwing et al. (2013) undersökte möjliga lösningar för slutligt omhändertagande av det svenska långlivade låg- och medelaktiva avfallet och föreslog ett system att analysera vidare med avseende på säkerheten efter förslutning. Föreliggande säkerhetsvärdering utgör nästa steg i utvecklingen av SFL. Syftet med utvärderingen är att undersöka under vilka betingelser med avseende på säkerhet efter förslutning, förvarets omgivningar, avfall, och barriärer som föreslaget koncept har möjlighet att uppfylla myndighetskraven. Denna rapport dokumenterar information om relevanta klimatförhållanden och klimatrelaterade betingelser och utgör en av huvudreferenserna till **huvudrapporten** som summerar utvärderingen av säkerheten efter förslutning för SFL.

Klimatrelaterade processer av betydelse för det föreslagna förvarskonceptet för SFL, vilka identifierats i genomgången av egenskaper, händelser och processer som påverkar säkerheten efter förslutning (se **Huvudrapporten**, kapitel 3, samt **FEP-rapporten**), beskrivs kortfattat. Dessa inkluderar i) utveckling av permafrost och frusen mark, ii) utveckling av inlandsisar, iii) isostatiska och eustatiska förändringar vilka resulterar i förändringar av den relativa havsnivån, och, iv) denudation vid markytan. För varje process ges också referenser till detaljerade processbeskrivningar som presenterats i klimatrapporter i SKB:s tidigare säkerhetsanalyser.

Vidare beskrivs klimatrelaterad information som behövs som input till andra modelleringsaktiviteter i SE-SFL. Detta inbegriper information om relativ havsnivå för Laxemar från tidig holocen då området var havstäckt till nutida och projicerade framtida terrestra förhållanden. Därutöver beskrivs dagens klimatförhållanden i Laxemar och på några utvalda andra platser i Sverige.

Slutligen definieras och presenteras idealiserade projicerade sekvenser av framtida klimatutvecklingar som underlag för utvärderingen av säkerhet efter förslutning för det föreslagna förvarskonceptet för SFL. Den vetenskapliga basen för val och definition av dessa klimatfall ges i Klimatrapporterna för säkerhetsanalysen för utbyggt SFR (SR-PSU), och säkerhetsanalysen för Kärnbränsleförvaret (SR-Site). Nuvarande kunskap om forntida och framtida klimatutveckling, inklusive detaljerade processbeskrivningar, redogörs för i detalj, baserat på internationell vetenskaplig litteratur samt SKB:s egna studier som genomförts för att utvidga nuvarande kunskap i områden av stor betydelse för säkerhetsanalyserna. Information som har sammanställts i SR-PSU och SR-Site upprepas inte i föreliggande rapport.

Uppsättningen klimatfall för en specifik säkerhetsanalys väljs för att representera förhållanden inom det spann av möjliga framtida klimatutvecklingar på anläggningsplatsen som kan påverka säkerheten efter förslutning för det specifika förvaret. Strategin för val och beskrivning av klimatfallen i SE-SFL är densamma som i SR-Site och SR-PSU. Eftersom SE-SFL utgör en första utvärdering av säkerhet efter förslutning för ett föreslaget förvarskoncept, på en exempelplats, är de framtida klimatutvecklingar som valts avsiktligt förenklade och färre än de som tillämpas i en fullständig säkerhetsanalys (t ex SR-Site). De klimatfall som ingår i SE-SFL tillåter en första utvärdering av hur det föreslagna förvarskonceptets egenskaper utvecklas med tiden under relevanta framtida klimatutvecklingar. I en fullständig säkerhetsanalys för SFL kommer resultaten av säkerhetsvärderingen SE-SFL att utgöra grunden för definitionen av en tillräcklig uppsättning av framtida klimatutvecklingar som tillsammans belyser de mest betydelsefulla och rimligt förutsägbara sekvenserna av framtida klimattillstånd och deras påverkan på slutförvarets skyddsförmåga och omgivningskonsekvenser.

Två förenklade utvecklingar av klimat och klimatrelaterade processer definieras för exempelplatsen Laxemar för tiden från den senaste deglaciationen och över de kommande 100 000 åren till en miljon år. Det ena klimatfallet utgår ifrån varma tempererade klimatförhållanden som initialt domineras av en ökad växthuseffekt. Det andra fallet beskriver kallare klimatförhållanden med perioder av permafrostutveckling och en inlandsis som växer in över anläggningsplatsen. I detta fall med en förenklad glacial cykel är platsen havstäckt under en period efter att inlandsisen dragit sig tillbaka.

Contents

1 Introduction

This report constitutes one of the main references supporting the safety evaluation for a proposed repository concept for the repository for long-lived waste (SFL) in Sweden. The purpose of the SFL safety evaluation (SE-SFL) is to provide input to the subsequent, consecutive steps in the development of SFL. These consecutive steps include further development of the design of the engineered barriers and the site-selection process for SFL. Further, the outcomes of SE-SFL can be used to prioritize areas in which the level of knowledge must be improved in order to perform a subsequent, full safety assessment for SFL. This chapter gives the background to the project and an overview of the safety evaluation. Moreover, the role of this report is described in the context of the evaluation.

1.1 Background

The Swedish power industry has been generating electricity by means of nuclear power for more than 40 years. The Swedish system for managing and disposal of the waste from operation of the reactors has been developed over that period. When finalised, this system will comprise three repositories: the repository for short-lived radioactive waste (SFR), the repository for long-lived waste (SFL), and the Spent Fuel Repository.

The system for managing radioactive waste is schematically depicted in Figure 1-1. SKB currently operates SFR at Forsmark in Östhammar municipality to dispose of low- and intermediate-level waste produced during operation of the various nuclear power plants, as well as to dispose waste generated during applications of radioisotopes in medicine, industry, and research. Further, SFR is planned to be extended to permit the disposal of waste from decommissioning of nuclear facilities in Sweden. The spent nuclear fuel is presently stored in the interim storage facility for spent nuclear fuel (Clab) in Oskarshamn municipality. Clab will be complemented by the Encapsulation Plant, together forming Clink. SKB has also applied to construct, possess and operate the Spent Fuel Repository at Forsmark in Östhammar municipality. The current Swedish radioactive waste management system also includes a ship and different types of casks for transport of spent nuclear fuel and other radioactive waste.

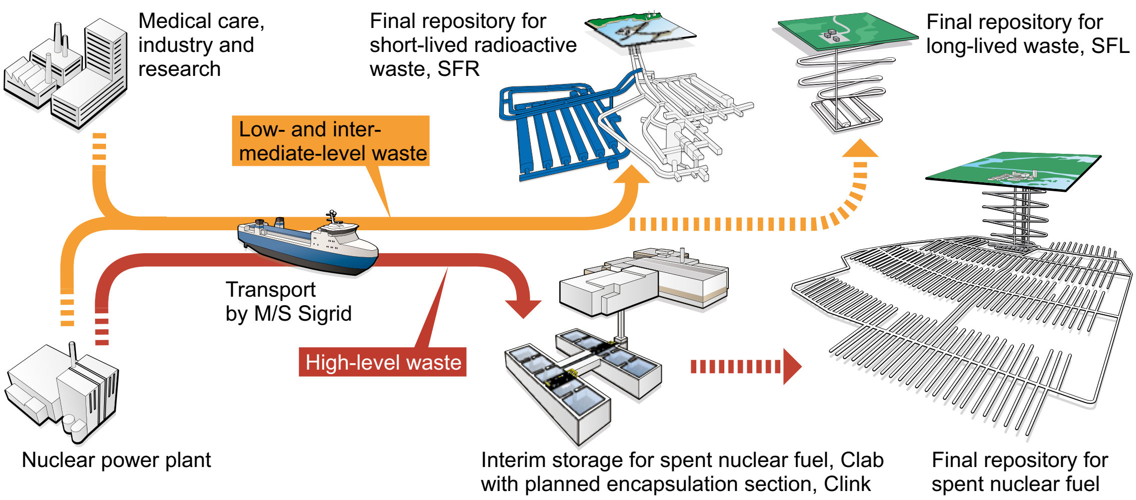

Figure 1-1. *The Swedish system for radioactive-waste management. Dashed arrows indicate future waste streams to facilities planned for construction.*

SFL will be used for disposal of the Swedish long-lived low- and intermediate-level waste. This comprises long-lived waste from the operation and decommissioning of the Swedish nuclear power plants, from early research in the Swedish nuclear programmes (legacy waste), from medicine, industry, and from research which includes the European Spallation Source (ESS) research facility. The long-lived low- and intermediate-level waste from the nuclear power plants consists of neutron-activated components and control rods and constitutes about one third of the waste planned for SFL. The rest originates mainly from the Studsvik site, where Studsvik Nuclear AB and Cyclife Sweden AB both produce and manage radioactive waste from medicine, industry and research. The legacy waste to be disposed of in SFL is currently managed by the company AB SVAFO.

In 1999, a preliminary safety assessment for SFL was presented (SKB 1999). Reflecting the comments from the authorities on the preliminary safety assessment, possible solutions for management and disposal of the Swedish long-lived low- and intermediate-level waste were examined in the SFL concept study (Elfwing et al. 2013). Among the considered alternatives a system was proposed as a basis for further assessment of post-closure safety. According to this concept, SFL is designed as a deep geological repository with two different sections:

- one waste vault, designed with a concrete barrier, BHK, for metallic waste from the nuclear power plants, and
- one waste vault, designed with a bentonite barrier, BHA, for the waste from Studsvik Nuclear AB, Cyclife Sweden AB and AB SVAFO.

A schematic illustration of SFL is displayed in Figure 1-2. In SE-SFL, it is assumed that the waste vaults are located at 500 m depth. BHK is approximately 135 m long and BHA is approximately 170 m long. Both vaults have a cross sectional area of approximately 20×20 m^2. An important assumption for the present report is that the repository needs to be established at a depth where it will not be adversely affected by permafrost during future glacial cycles, i.e. at a depth sufficient to exclude the possibility of freezing of the repository.

1.2 The SE-SFL safety evaluation

There are two main objectives for SE-SFL. The first is to evaluate conditions in the waste, the barriers, and the repository environs under which the repository concept has the potential to fulfil the regulatory requirements for post-closure safety. The second is to provide SKB with a basis for prioritizing areas in which the level of knowledge and adequacy of methods must be improved in order to perform a full safety assessment for SFL. This is in line with the iterative safety analysis process that the SFL repository program follows, in which the results from post-closure safety analyses and related activities (e.g. information from a site selection process and development of numerical methods) are used to successively inform and improve the analysis. In accordance with the Nuclear Activities Act (1984:3), important research needs for the SFL programme that emerge as a result of SE-SFL will be reported in the research development and demonstration (RD&D) programme. An important aspect of this is to ensure that the industry has well founded information to support long-term planning.

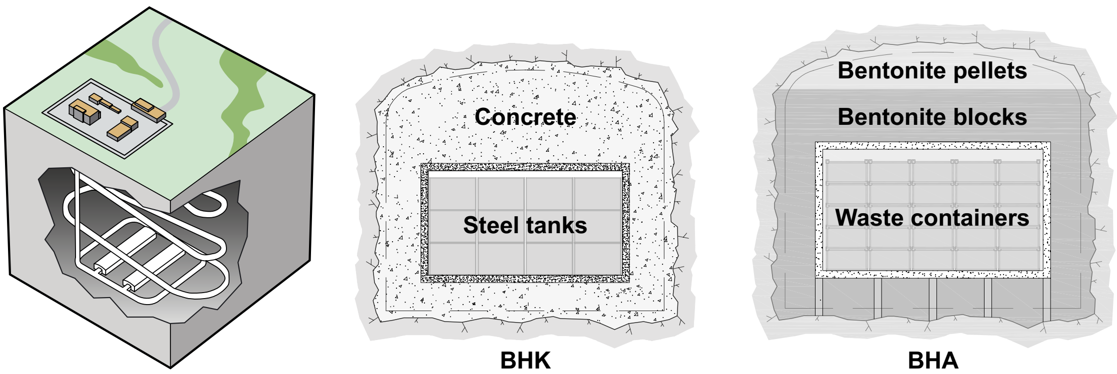

Figure 1-2. *Preliminary facility layout and the proposed repository concept for SFL (left), one waste vault for metallic waste from the nuclear power plants (BHK, centre) and one waste vault for waste from Studsvik Nuclear AB, Cyclife Sweden AB and AB SVAFO (BHA, right).*

The safety analysis methodology as applied in SE-SFL is a first evaluation of post-closure safety for the repository concept proposed by Elfwing et al. (2013) and is not part of a license application. As such, the methodology has been adapted to suit the needs of SE-SFL and thus differs from the methodology established by SKB for the most recent safety assessments for the extended SFR (SR-PSU; SKB 2015) and for the Spent Fuel Repository (SR-Site; SKB 2011a). This also implies that the regulatory requirements on the methodology have not been applied rigorously, which would be needed for a safety analysis that is part of a license application. The evaluation is intentionally simplified as compared with SR-Site and SR-PSU, and more focus is given to aspects connected to the further development of the repository concept and related analyses. This is also reflected in using the term safety evaluation in contrast to safety assessment. The differences between SE-SFL and a full safety assessment are described in more detail in Section 2.1 of the **Main report**. The adaption of the methodology for the purposes of SE-SFL is described in Section 2.5 of the **Main report**.

To the extent applicable, SE-SFL builds on knowledge from SR-PSU and SR-Site. There are commonalities regarding the waste, engineered barriers, bedrock, surface ecosystems and external conditions relevant to post-closure safety. For instance, SE-SFL and SR-Site both address timescales of one million years (see Section 2.3 of the **Main report**). A further similarity is the proposed depth of 300–500 m. There are similarities between SFR and SFL regarding the waste and waste packaging and the proposed engineered barriers.

In SE-SFL, a first evaluation of a suitable repository design for disposal of the ESS waste is carried out. Since the information regarding the ESS inventory is not yet as well defined as for the other waste streams, the protective capability of the different waste vaults in relation to this waste is analysed separately.

No site has yet been selected for SFL and therefore data from SKB's site investigation programmes for the Spent Fuel Repository and for the extension of SFR have been utilized in SE-SFL. In order to have a realistic and consistent description of a site for geological disposal of radioactive waste, data from the Laxemar site in Oskarshamn municipality (see Figure 1-3), for which a detailed and coherent dataset exists, are used. Based on an initial hydrogeological analysis for SE-SFL, the example location for the SFL repository was selected to be a part of the rock volume that was earlier found most suitable for a potential Spent Fuel Repository within the Laxemar site (SKB 2011b).

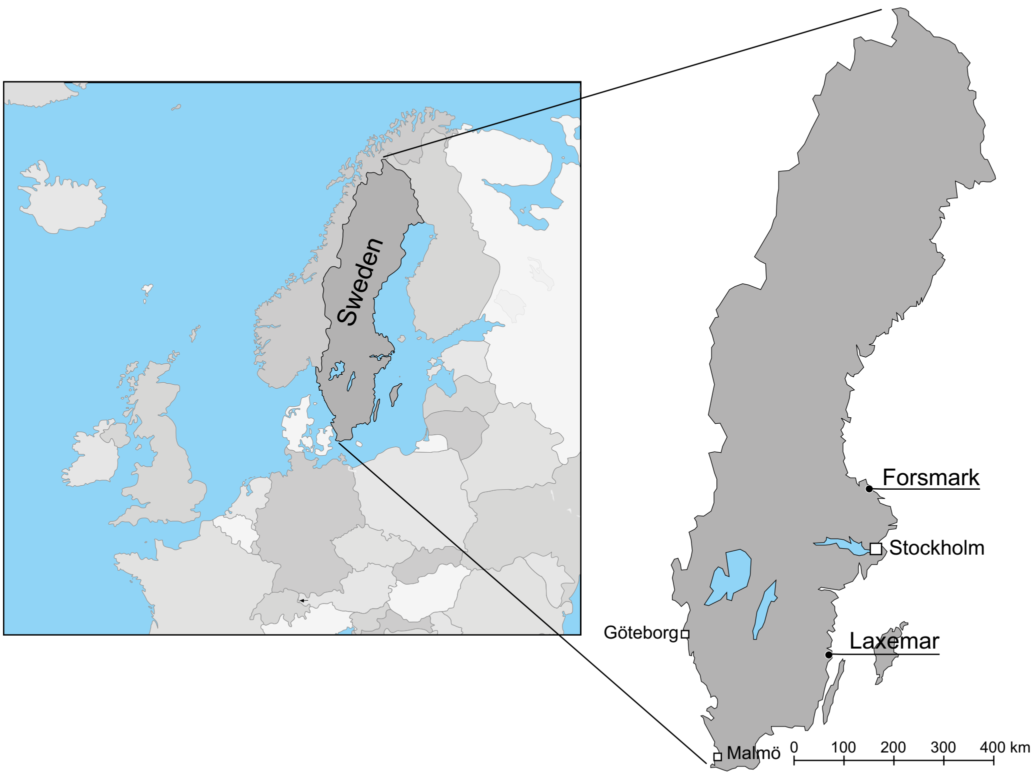

Figure 1-3. *Map showing the location of Laxemar and Forsmark. Data from the site investigations in Laxemar, along with the data from the SR-Site and SR-PSU assessments from Forsmark, are used in SE-SFL in order to have a realistic and consistent description of a site for geological disposal of radioactive waste, for which a detailed and coherent dataset exists.*

SE-SFL is further developed in comparison to the previous assessments, which were mentioned in Section 1.1. Important improvements are an updated inventory and more elaborate account of internal and external processes. Moreover, the biosphere was in the preliminary assessment handled in a simplified manner, whereas it is handled in a more realistic way in SE-SFL. The availability of data from the Spent Fuel Repository site investigations also allows for more detailed representations of the geosphere. In general, SKB's experiences with safety analysis work have led to many developments since the late 1990s.

1.2.1 The SE-SFL report hierarchy

The **Main report** and main references in SE-SFL are listed in Table 1-1, also including the abbreviations by which they are identified in the text (abbreviated names in bold text). It can be noted that there are no dedicated process reports for SE-SFL. The SFR and SFL waste and repository concepts have many similarities, for instance the use of similar barrier materials and thus similar process interactions with the surrounding bedrock environment (Section 2.5.4 of the **Main report**). Therefore, the descriptions of internal processes for the waste (SKB 2014c) and the barriers (SKB 2014d) in SR-PSU are used in SE-SFL. For the bedrock system, the descriptions of internal processes for the geosphere in SR-Site (SKB 2010f) and SR-PSU (SKB 2014e) are used. There are also several additional references, which include documents compiled within SE-SFL. But there are also references to documents that have been compiled outside of the project, either by SKB or other similar organisations, or are available in the scientific literature. In Figure 1-4, the hierarchy of the **Main report**, main references and additional references within SE-SFL is shown.

Table 1-1. Main references in SE-SFL and their abbreviations used in this report.

Abbreviation used when referenced in this report	Text in reference list
Main report	**Main report, 2019.** Post-closure safety for a proposed repository concept for SFL. Main report for the safety evaluation SE-SFL. SKB TR-19-01, Svensk Kärnbränslehantering AB.
Biosphere synthesis report	**Biosphere synthesis report, 2019.** Biosphere synthesis for the safety evaluation SE-SFL. SKB TR-19-05, Svensk Kärnbränslehantering AB.
Climate report	**Climate report, 2019.** Climate and climate-related issues for the safety evaluation SE-SFL. SKB TR-19-04, Svensk Kärnbränslehantering AB.
FEP report	**FEP report, 2019.** Features, events and processes for the safety evaluation SE-SFL. SKB TR-19-02, Svensk Kärnbränslehantering AB.
Initial state report	**Initial state report, 2019.** Initial state for the repository for the safety evaluation SE-SFL. SKB TR-19-03, Svensk Kärnbränslehantering AB.
Radionuclide transport report	**Radionuclide transport report, 2019.** Radionuclide transport and dose calculations for the safety evaluation SE-SFL. SKB TR-19-06, Svensk Kärnbränslehantering AB.

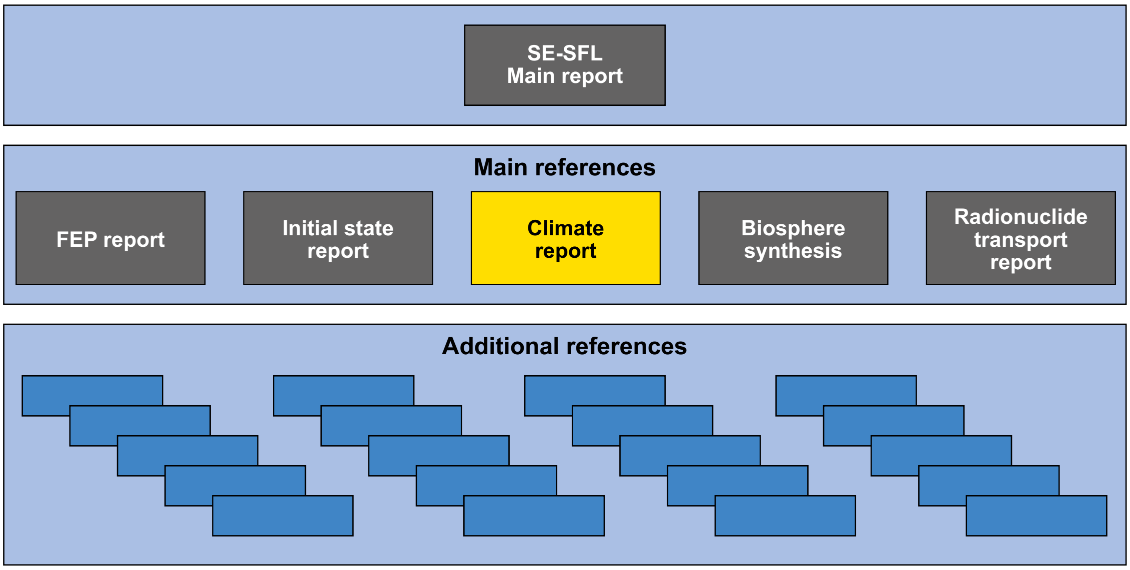

Figure 1-4. *The hierarchy of the Main report, main references and additional references in the safety evaluation of post-closure safety SE-SFL. The additional references either support the Main report or one or more of the main references.*

1.3 The role of this report in SE-SFL

This report documents information on climate and climate-related issues relevant for the evaluation of post-closure safety for the proposed repository concept for SFL.

Information on climate and climate-related issues is needed for the following steps of the methodology for the safety evaluation SE-SFL (see the **Main report**, Section 2.5)[1]:

1. Identification of all factors potentially influencing post-closure safety for the proposed repository concept for SFL, which need to be considered in the safety evaluation SE-SFL.
2. Description of the initial state for the analysis, defined as the expected state of the repository and its environment at closure.
3. Definition and description of idealised future developments (*climate cases*) of climate and relevant climate-related issues.
7. Description of a reference evolution for the repository and its environment, i.e. the bedrock and surface systems surrounding the repository.
8. Selection of *evaluation cases* designed to evaluate post-closure safety for the proposed repository concept.

Step 1 is done in a screening of potentially important features, events and processes (FEPs) influencing post-closure safety (see the **FEP report** and Chapter 3 in the **Main report)**. Experience gained from previous safety assessments for the Spent Fuel Repository and for the SFR, and international databases of relevant FEPs that affect post-closure safety are utilised. The handling in SE-SFL of each FEP thus identified is described in the FEP database summarizing this step. Since the safety evaluation constitutes a first evaluation of post-closure safety for a proposed repository concept, not all potentially important FEPs are handled. The climate-related issues thus identified are briefly described in Chapter 2.

Step 2 includes a description of the climate state at closure. A main assumption in the SE-SFL safety evaluation is that the initial state conditions for the bedrock and surface systems, at repository closure at 2075 AD, constitute present-day conditions. For consistency the same assumption is made for the

[1] Note that the steps are numbered according to the SE-SFL methodology, described in Section 2.5 in the **Main report.** Only steps that need information on climate and climate-related issues are described here.

climate. To this end, a description of present-day climate conditions in Laxemar and at a few other locations in Sweden is given in Chapter 3. Further, information needed as input to modelling of hydrogeological and surface ecosystem development from early Holocene submerged conditions to the present day are also described.

Step 3 consists of selection and description of idealised future developments of climate and relevant climate-related issues. The selection and description of these *climate cases* are given in Chapter 4.

Step 7 includes description of a reference evolution for the bedrock and surface systems surrounding the repository. Information on relative sea-level, needed as input to modelling of future hydrogeological and surface ecosystem developments, is provided in Chapter 3.

Step 8 consists of definitions and descriptions of evaluation cases designed to evaluate post-closure safety for the proposed repository concept. To complement the data from Laxemar, present-day climate conditions in a few other locations in Sweden are quantified in Chapter 3.

1.4 Strategy for managing climate and climate-related issues in safety assessments

Climate-related changes such as variations in relative sea-level and the development of permafrost and ice sheets are the most important naturally occurring external factors affecting a nuclear waste repository in Fennoscandia in a time perspective of hundreds of thousands of years up to one million years (e.g. SKB 2010a, 2014a). Most of the processes occurring in the geosphere, hydrosphere and biosphere are affected by climate and climate-related changes in one way or another (see also Section 2.2). For instance, freezing of groundwater, changes in relative sea-level and the presence of an ice sheet influence permeability, water turnover, hydrostatic pressure at repository depth, groundwater flow and chemical composition. Furthermore, the presence of an ice sheet influences rock stresses during different phases of a glaciation.

The methodology for handling future evolution of climate and climate-related issues in SKB's assessments of post-closure safety for repositories for radioactive waste involves:

- Identifying and describing a range within which future climatic conditions and climate-related processes may vary at the repository site. Within these limits, characteristic climate-related conditions of importance for repository safety can be identified. The conceivable climate-related conditions can be represented as climate-driven process domains (Boulton et al. 2001), where such a domain is defined as "a climatically determined environment in which a set of characteristic processes of importance for repository safety appear". In the following parts of this report these climate-driven process domains are referred to as *climate domains*.
- Identifying and describing several future potential climate evolutions, here called *climate cases*, based on information from climate modelling, natural palaeo-climate archives and process understanding. The climate cases shall together cover the wide range of possible future climate developments on the time-scale of the safety assessment at hand.

The set of climate cases for a specific safety assessment are chosen to represent conditions covering the range of possible future climate development at the repository site that may influence post-closure safety for the specific repository. Thus, the set of climate cases that is included in a particular safety assessment is dependent both on the geographic location of the repository site and characteristics of the repository concept and waste type analysed, see Näslund et al. (2013).

The strategy for selection and description of climate cases in SE-SFL is the same as in SR-Site (SKB 2010a) and SR-PSU (SKB 2014a). However, since SE-SFL constitutes a first evaluation of post-closure safety for a proposed repository concept, located at an example coastal site, the future climate developments chosen are intentionally simplified and limited in number as compared with the ones presented and used in a full safety assessment (e.g. SR-Site). The climate cases included in SE-SFL allow a first evaluation of how the properties of the proposed repository concept evolve over time under relevant future climate developments. In a full safety assessment for SFL, the results of the SE-SFL evaluation will serve as basis for the definition of a sufficient set of future climate developments that together illustrates the most important and reasonably foreseeable sequences of future climate states and their impact on the protective capability of the repository and their environmental consequences.

The selection of climate cases in SE-SFL is described in Section 4.1 and, the climate cases selected are described in Sections 4.2–4.6.

1.5 Publications supporting the selection of climate cases for SE-SFL

As previously mentioned, the selection of climate cases for SE-SFL is based on information and data for the Laxemar and Forsmark sites from the SR-Can and SR-Site Climate reports (SKB 2006, 2010a) produced for the Spent Fuel Repository, and from the SR-PSU Climate report (SKB 2014a) produced for the SFR repository. For the latest safety assessment performed for the Spent Fuel repository (SR-Site), twelve reports were produced on various climate-related topics to support the SR-Site Climate report, see SKB (2010a) and references therein. Likewise, for the latest safety assessment performed for SFR, three reports were produced to support the SR-PSU Climate report, see SKB (2014a) and references therein. Hence, even though no dedicated reports have been produced to support the SE-SFL Climate report, an ample basis of knowledge for the Forsmark and Laxemar sites has been available from previous safety assessments for the production of the present report. In addition to the studies performed for SR-Can, SR-Site and SR-PSU, papers from the general scientific literature have been used as input to the SE-SFL **Climate report**.

1.6 Structure of the report

Following this introductory chapter, the present report includes three main chapters:

- Chapter 2 with brief descriptions of the climate and relevant climate-related processes for safety assessments of Baltic Sea coastal sites in Sweden.
- Chapter 3 with descriptions of relative sea-level for Laxemar from early Holocene submerged conditions to present-day and future terrestrial conditions, and of present-day climate conditions in Laxemar and at a few other locations in Sweden.
- Chapter 4 with descriptions of the selection of climate cases, as well as descriptions of climate and relevant climate-related conditions for the two climate cases defined for the safety evaluation SE-SFL.

A list of abbreviations is found in Appendix A. A detailed description of the relative sea-level described in Chapter 3 is given in Appendix B. Appendix C presents additional climate information used for describing the *increased greenhouse effect climate case*.

The report was written and edited by Jens-Ove Näslund, Jenny Brandefelt and Lillemor Claesson Liljedahl, SKB. Textual input to the report was also provided by Anders Löfgren, Ecoanalytica, and Peter Saetre, SKB.

2 Climate and climate-related issues

Climate and climate-related conditions of relevance for the future evolution of the repository and its environs, identified in the screening of features, events and processes influencing post-closure safety (see Section 1.3), are briefly described here.

As a first evaluation of the performance of the proposed repository concept, SE-SFL evaluates which climate-related issues can significantly influence post-closure safety for SFL. The identification of climate-related issues to evaluate in SE-SFL is based on the corresponding identification performed in SR-Site (see SKB 2010a, Section 1.2) and SR-PSU (see SKB 2014a, Section 1.2). The motivation for this procedure is the commonality with the Spent Fuel repository in terms of repository depth and analysis period and with SFR in terms of technical barriers, waste packaging and radionuclide inventory.

The following climate-related issues have been identified in SE-SFL as potentially having an impact on repository safety (see the **FEP report**, Section 4.2.5):

- The development of hydrostatic pressures, including pressure gradients, associated with ice-sheet development affecting repository structures.
- The maximum permafrost and ground freezing depths.
- Variations in groundwater fluxes during glacial cycles affecting the transport of radionuclides to the surface.
- The possible penetration of dilute groundwater to repository depth during glacial phases and extended periods of temperate climate conditions, potentially causing erosion of bentonite backfill.
- The potential for glacially induced faulting affecting repository structures.
- The potential impacts of global warming on the surface ecosystems.

Brief descriptions of the climate domains and the associated identified climate-related issues are given in this chapter. The descriptions are based on existing knowledge of the range over which climate and climate-related issues may vary at coastal sites such as Laxemar and Forsmark in a one-million-year time perspective. The existing knowledge is, to a large extent, based on information from previous safety assessments performed for the planned Spent Fuel Repository in Forsmark and for the existing, and planned extension of the SFR repository for short-lived low- and intermediate-level radioactive waste in Forsmark. References to more detailed information on the climate-related processes are given within each section. As an introduction, the concept of climate domains is further explained, and the definition of each climate domain is given.

2.1 Climate domains

SFL is designed for long-lived radioactive waste and assessments of post-closure safety must therefore address timescales up to one million years, i.e. the same timescale addressed in safety assessments for the Spent Fuel Repository (see e.g. SKB 2011a). Climate is not predictable on this time-scale and therefore a single most likely climate evolution cannot be provided for the evaluation of post-closure safety for SFL. In SE-SFL, the range within which future climatic conditions and climate-related processes may vary at a coastal repository site in Sweden is represented by a similar range to the one included in SR-Site (SKB 2011a). As described in Section 1.3, the set of future climate developments (*climate cases*) for a specific safety assessment are chosen to represent conditions covering the range of possible future climate development at the repository site that may influence post-closure safety for the specific repository. However, since SE-SFL constitutes a first evaluation of the proposed repository concept, the climate cases included in SE-SFL do not include bounding cases. Rather, the climate cases included allow a first evaluation of how the properties of the proposed repository concept evolve over time under relevant future climate developments. In a full safety assessment for SFL, the results of the SE-SFL evaluation will serve as basis for the definition of a sufficient set of realistic future climate developments that include the climate domains and sequences that have the greatest impact on repository safety.

The definition and construction of climate cases can be based on knowledge of climate variations in the past, on the same time-scales and even longer, and on inferred future climate change taking e.g. human influences on climate into account. Within the uncertainty range of future climate change, characteristic climate-related conditions of importance for repository safety can be identified. In SKB safety assessments, these conditions are described as *climate-driven process domains,* or simply *climate domains* (e.g. SKB 2010a). In each of these climate domains, a set of characteristic climate-related processes of importance for repository safety occur. For a more detailed description of the climate domain concept, see SKB (2010a). Three relevant climate domains have previously been identified for Swedish Baltic Sea coastal sites:

- The temperate climate domain.
- The periglacial climate domain.
- The glacial climate domain.

Each of the climate cases (climate developments) that is included and analysed in SKB's assessments of post-closure safety is constructed, for a specific site, by assembling different temporal successions of the three climate domains. Below is a short description of the climate domains. For more detailed descriptions, see e.g. SKB (2010a).

The *temperate climate domain* is defined as regions without permafrost or the presence of ice sheets. It is dominated by a temperate Baltic Sea coastal climate in a broad sense, with cold winters and either cold or warm summers. Precipitation may fall at any time of the year, either as rain or snow. The temperate climate domain has the warmest climate of the three climate domains. However, the temperate climate domain includes both warmer and colder climates as compared with the present climate. Within the temperate climate domain, a site may also at times be submerged by the sea. Climates dominated by global warming due to enhanced atmospheric greenhouse gas concentrations are also included in the temperate climate domain.

The *periglacial climate domain* is defined as regions that contain permafrost. The permafrost coverage may be restricted or extensive. Furthermore, the periglacial climate domain is a cold region but without the presence of an ice sheet. In general, the periglacial climate domain has a colder climate than the temperate climate domain and warmer than the glacial climate domain. Precipitation may fall either as snow or rain. Within the periglacial climate domain, a site may also at times be submerged by the sea.

The *glacial climate domain* is defined as regions that are covered by glaciers or ice sheets. Within the glacial climate domain, the ice sheet may in some cases be underlain by sub-glacial permafrost. In general, the glacial climate domain has the coldest climate of the three climate domains. Precipitation normally falls as snow in this climate domain.

A simplified glacial cycle constructed, for a coastal site impacted by major ice sheets, using the above climate domains is presented in Figure 1-2.

2.2 Climate-related processes

2.2.1 Permafrost

Permafrost is defined as ground that remains at or below a temperature of 0°C for at least two consecutive years. Freezing of water in the ground is governed by the thermal, hydraulic, mechanical, and chemical processes in the ground and on the ground surface. In addition, freezing of water influences the thermal, hydraulic, mechanical, and chemical properties of the ground, see e.g. Hartikainen et al. (2010).

This definition of permafrost is based exclusively on temperature. Therefore, in reality, *permafrost* is not necessarily the same as *perennially frozen ground.* Depending on the pressure and salinity of groundwater, and on the adsorptive and capillary properties of ground matter, water in the ground may freeze at temperatures below 0°C. However, for the SE-SFL safety evaluation, the term *permafrost* is taken to be equivalent to *perennially frozen ground*.

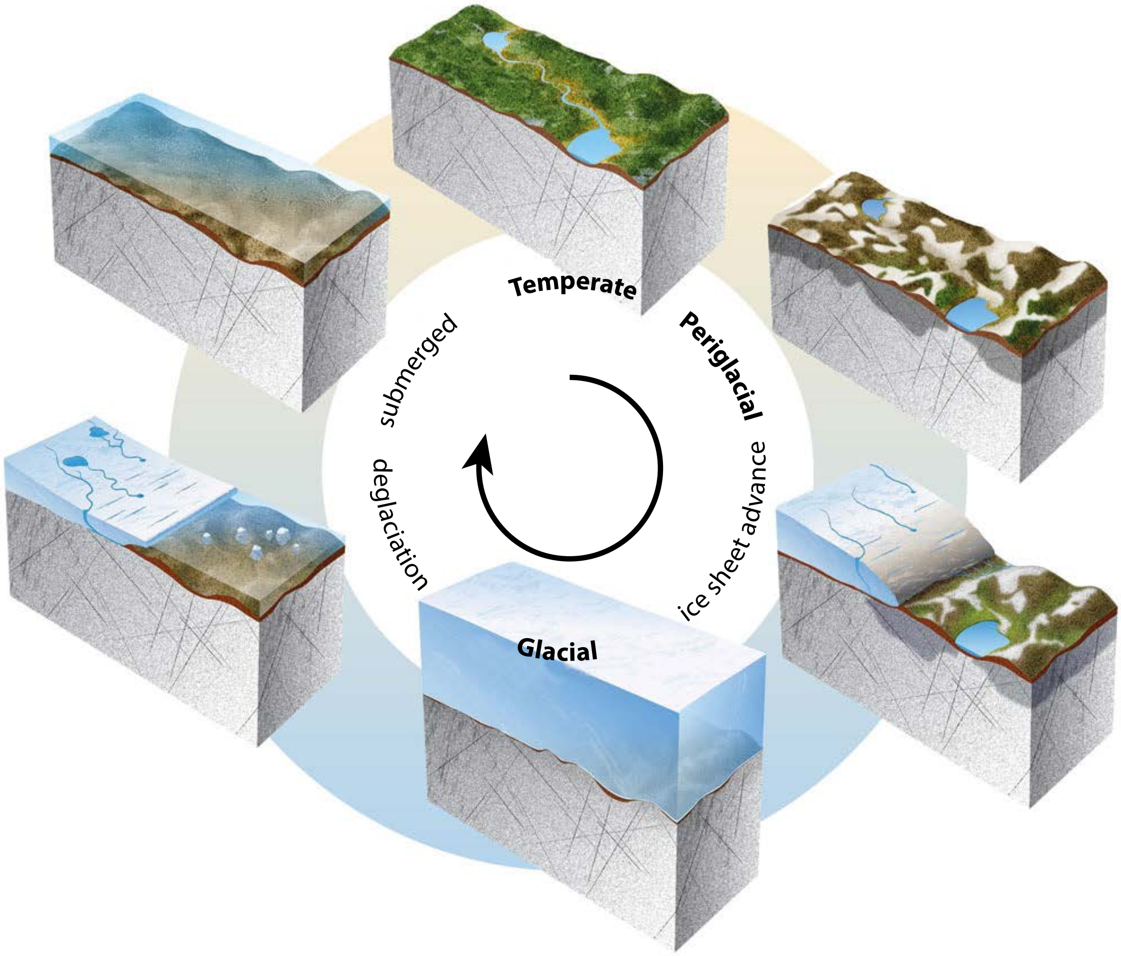

Figure 2-1. Simplified glacial cycle constructed from the three climate domains (bold text) relevant for assessments of post-closure repository safety at coastal sites in Sweden, such as Laxemar and Forsmark (Figure 1-2). In addition to depicting the climate domains, the illustration also shows an ice sheet advance and deglaciation followed by submerged conditions.

Water bodies, i.e. the sea, lakes and watercourses, as well as wetland types with a high water content (such as mires), influence permafrost creation and distribution considerably since water has a high specific heat value. A talik, i.e. unfrozen ground located within permafrost, can exist beneath water bodies that do not freeze to their bottom in winter. A talik extending through the entire thickness of permafrost is called a through talik (Yershov 1998). Because extensive permafrost generally acts as an impermeable layer, groundwater recharge and discharge are reduced relative to unfrozen soil conditions, and, in areas with continuous permafrost, groundwater recharge and discharge are restricted to taliks (e.g. Bosson et al. 2012, Kane et al. 2013). Observational and numerical studies indicate that through taliks, can act as either recharge or discharge pathways for deep groundwater flow (e.g. Vidstrand et al. 2013, Bosson et al. 2013).

Past and future site-specific permafrost growth and degradation has been modelled in 1D and 2D for the Forsmark and Laxemar sites within the SR-Can, SR-Site and SR-PSU safety assessments (SKB 2006, Hartikainen et al. 2010, Brandefelt et al. 2013), as summarised in the respective safety assessment climate reports (SKB 2006, 2010a, 2014a). One of the main results of the permafrost studies performed for SR-Site was that, under the most pessimistic assumptions, perennially frozen ground could reach the 450 m repository depth in Forsmark. However, in this pessimistic case there was still a wide margin to freezing of the buffer clay at repository depth (SKB 2011a), since the buffer clay freezes at a lower temperature than water.

The results from these previous studies form the basis for the selections and assumptions regarding the absence or presence of permafrost in the SE-SFL climate cases. Detailed accounts of all the processes associated with permafrost development and decay are given in SKB (2010a) and Hartikainen et al. (2010).

2.2.2 Ice sheets

A glacier is an ice mass that has been formed by successive local accumulation of snow, and where the resulting ice has started to move due to the ice deforming under its own weight. An *ice sheet* is defined as a glacier in which the general ice movement is not governed by the topography of the underlying landscape, but instead is directed outwards in all directions from central ice divide areas.

Ice sheets form at mid- to high latitudes during so-called glacial periods when the climate is generally cold and favourable for ice-sheet growth. Conversely, ice sheets decay during subsequent periods when the climate becomes warmer. The last ~800 000 years have been dominated by glacial-interglacial cycles of ~100 000 years duration, with cold climate conditions periods prevailing for a substantial fraction of each cycle. The ice sheets during these glacial periods have however been highly dynamic in their extents and volumes, resulting in a number of glaciated and less glaciated phases during each glacial phase, see e.g. SKB (2010a). This, in turn, has resulted in significant differences in the impacts of the individual glaciated phases. For example, during the last glacial cycle, the Weichselian, the ice sheet did not reach the Forsmark and Laxemar sites for the major part of the time, but only during the major phases of the glaciation (e.g. SKB 2010a and references therein).

The presence of an ice sheet influences the geosphere and hydrosphere in several ways, such as in changes in i) the stress field in the Earth's crust, which may result in glacially induced faulting, ii) vertical isostatic changes of the crust and associated changes in relative sea-level, iii) the magnitude and direction of groundwater flow during ice sheet overriding, and iv) the chemical composition of groundwater through infiltration by dilute but oxygen-rich meltwater at the ice-sheet base/substrate interface.

The ice-sheet history of the last glacial cycle was reconstructed by means of numerical modelling for the SR-Can safety assessment (SKB 2006), for which data on ice-sheet thickness and duration of ice coverage were extracted for the Forsmark and Laxemar sites. The simulated reconstruction has been complemented by several geological studies of the Fennoscandian glacial history, performed both by SKB and others, see SKB (2010a, 2014a) and references therein. In SR-Can, and subsequently also in SR-Site and SR-PSU, the Weichselian ice-sheet reconstruction was used for constructing a climate case comprising a future glacial reference scenario. This was done by assuming a future glacial cycle identical to the Weichselian reconstruction. More extreme Eurasian ice-sheet configurations, with larger ice thicknesses than during the last glacial cycle, have also been modelled and studied in detail (Colleoni et al. 2014, Quiquet et al. 2016).

The Weichselian ice-sheet reconstruction made for Forsmark and Laxemar within SR-Can has been used as a basis for the construction of the SE-SFL climate cases that include glacial conditions. The more extreme ice-sheet configurations reconstructed by Colleoni et al. (2014) and Quiquet et al. (2016) are not included in SE-SFL. In-depth descriptions of the glacial processes associated with ice sheets are given in SKB (2010a) and Jansson (2010).

2.2.3 Isostatic adjustment and shoreline displacement

The redistribution of mass associated with the growth and decay of continental ice sheets gives rise to major global loading and unloading effects over time-scales of several tens of thousands of years. For instance, when an ice sheet develops, the mass of the ice results in isostatic depression of the Earth's crust under, and to some extent also in front of, the ice sheet. Further from the ice margin, there is compensating uplift of the crust due to viscous flow of underlying asthenospheric material, forming a so-called forebulge. During the subsequent ice sheet retreat, the unloading of mass also results in a flow of the asthenospheric material, in turn giving rise to a slow post-glacial rebound of the crust, which continues long after the disappearance of the ice. In previously glaciated terrain such as Fennoscandia, this process is still active today, some 10 000–15 000 years after the last deglaciation. This response of the Earth's crust, mantle and gravitational field to the redistribution of water and ice-sheet mass is referred to as Glacial Isostatic Adjustment (GIA).

Changes in relative sea-level are the net result of isostatic changes, such as those described above, and eustatic changes, that is sea-level changes. Changes in sea-level, in turn, arise from changes in ocean water volume, due to mass exchange between continental ice masses and the oceans, and density changes associated with alterations in ocean temperature and salinity. The sea-level changes are not identical throughout the oceans, but are regionally modified by alterations in the Earth's gravitational field due mainly to changes in continental ice mass. In order to describe if and for how long coastal sites such as Forsmark and Laxemar are subject to submerged conditions following a glacial period, GIA modelling needs to be performed.

Results of the GIA modelling undertaken for the SR-Can safety assessment (SKB 2006, Whitehouse 2009), and also used in SR-Site (SKB 2010a) and SR-PSU (SKB 2014a), have been used for assumptions relating to the occurrence and characteristics of submerged or non-submerged conditions following deglaciation in the SE-SFL climate cases that contain periods with ice-sheet coverage.

A detailed in-depth description of the physics of GIA, how it affects the relative sea-level, and the methods that have been used to make site-specific studies of long-term relative sea-level changes for Forsmark and Laxemar are presented in SKB (2006) and Whitehouse (2009).

2.2.4 Surface denudation and maximum freezing depth

Surface denudation is a term that includes all erosional and weathering processes that result in a long-term lowering of the ground surface (see e.g. SKB 2010a, 2014a, Olvmo 2010). These processes are mainly glacial, fluvial, and eolian erosion, and chemical and physical weathering of the bedrock. Long-term surface denudation has been studied and described for the Forsmark and Laxemar sites (Olvmo 2010, SKB 2010a). These references also include detailed descriptions of this process.

In SR-Site, the long-term lowering of the ground surface through denudation was assessed not to influence the safety of the planned Spent Fuel Repository in Forsmark (SKB 2010a, 2011a, SR-Site complementation[2]). This analysis included the associated effect of permafrost penetrating deeper after surface denudation. The proposed repository concept for SFL constitutes a geological repository with two repository sections at sufficient depth to avoid e.g. adverse effects of permafrost on the repository (Elfwing et al. 2013). In Forsmark, the maximum freezing depth is around 450 m (SKB 2010a, b), and at Laxemar about 100 m shallower (SKB 2010c), indicating that a repository depth of 350–500 m would be sufficient if SFL was to be placed at either of these sites or at a site with a similar climate.

Just as for permafrost- and freezing processes, surface denudation processes are highly site-dependent. At the Forsmark and Laxemar sites, surface denudation processes have been assessed as resulting in a very small amount of general bedrock surface lowering (Olvmo 2010, SKB 2010a), in the order of up to 20 m at Forsmark over the coming one million years (SKB 2011a). However, at other sites, and locally, the lowering might be considerably larger, depending on e.g. local topographic conditions, bedrock type, and on how effective the erosional and weathering processes are at the site over time. In a full safety assessment for SFL, for a chosen repository site or a few alternative sites, detailed studies of potential surface denudation and permafrost development will be performed.

[2] SR-Site complementation found in **Åhsberg H, 2013.** Granskningssammanställning, kompletteringar till SSM 2013 – mars 2015. SKBdoc 1387259 ver 2.13, Svensk Kärnbränslehantering AB. Internal document.

3 Holocene and present-day climate and relative sea-level change

The information included in this chapter comprises a description of present-day climate conditions in Laxemar and at a few other locations in Sweden, to support the definition of evaluation cases in the SE-SFL safety evaluation (see the **Main report**, Section 2.5). Further, a description of relative sea-level in Laxemar from early Holocene submerged conditions to present-day and future terrestrial conditions is included. This information is needed as input to modelling of hydrogeological and surface ecosystem development for SE-SFL.

3.1 Alternative climate sites along the Swedish coast

The regional climate may influence several different parameters used as input in the radionuclide transport model for surface ecosystems and consequently may affect the potential dose to humans. To evaluate these consequences, four hypothetical sites were chosen to represent different regional coastal climate types in Sweden. The three parameters mean annual air temperature, precipitation (adjusted for evaporation) and the length of the vegetation period were used to characterise the climate of the sites (Table 3-1). The Laxemar and "Central" (i.e. Forsmark) sites, together with the northernmost site "North" (Örnsköldsvik municipality) represent a north-south climate gradient in temperature and length of the vegetation period (Figure 3-1, Table 3-1). The North, Central and Laxemar sites were described by Lindborg and Schüldt (1998) during the siting process for the Spent Fuel Repository. The fourth location "Southwest" (Varberg municipality), represents the maritime climate found in the westernmost part of southern Sweden, having a relative high mean annual air temperature and a high annual precipitation (Table 3-1). In order to describe the relative difference between the sites in a systematic way, temperature and precipitation data was taken from the reference period 1961–1990 (Alexandersson and Eggertsson Karlström 2001).

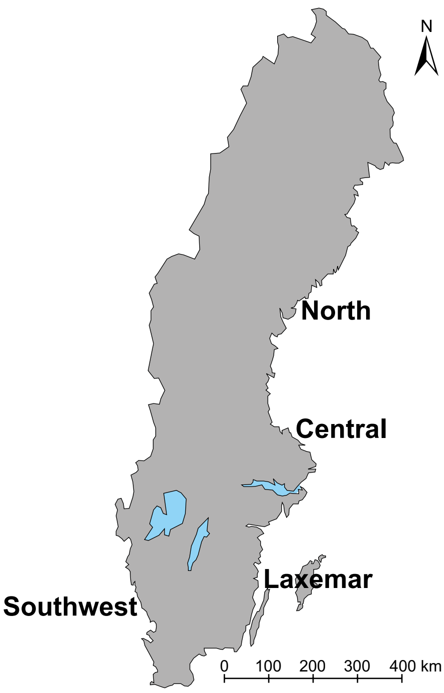

__Figure 3-1.__ Map showing the locations of the Laxemar site and the three alternative locations chosen to represent four coastal regional climates in Sweden.

Table 3-1. Present-day climate conditions for Laxemar and three other sites along the Swedish coast chosen to represent different regional coastal climate types in Sweden. The location of the sites is shown in Figure 3-1. All values are for the reference period 1961–1990 (Alexandersson and Eggertsson Karlström 2001), unless otherwise indicated.

Climate- or climate-dependent parameter	North	Central (Forsmark)	Laxemar	Southwest
Mean annual air temperature (°C)	2.6	5.0	6.4	7.3
Annual precipitation (mm)	654	606	553	738
Length of vegetation period (> 5 successive days with +5°C or higher)	160[1)]	195[2)]	224[2)]	240[1)]

[1)] SLU (http://www-markinfo.slu.se/eng/climate/vegper.html; accessed 2013-02-19)

[2)] Löfgren (2010, Table 3.5)

3.2 Relative sea-level

Relative sea-level change is the net result of isostatic changes (vertical crustal movement, in Fennoscandia, at present typically dominated by post-glacial uplift) and eustatic changes (sea-level changes). Påsse (2001) compiled information on shoreline displacement for Fennoscandia, including a station in Oskarshamn. Påsse (2001) also gave a method for transforming relative sea-level (rsl) data (altitude and age) into an equation that simplifies the use in mathematical models.

To analyse and illustrate the development of biosphere objects after the last deglaciation in the Laxemar area, the time frame for development from a marine stage to a mire stage covers the period from 10 000 BC to 20 000 AD. In SE-SFL, the rsl was modelled over this period using rsl equations based on Påsse (2001), see Appendix B. The resulting development is shown in Figure 3-2.

In SE-SFL it was decided to use a simplified development of rsl in Laxemar to facilitate the mathematical handling of the development in the modelling of landscape development. The simplified development, also based on Påsse (2001), excludes the Ancylus transgression, see Figure 3-2. The well-documented Ancylus transgression and associated Ancylus Lake constitute a freshwater stage in the post-glacial Baltic development, at a time when the Baltic temporarily was cut-off from the Atlantic. The Ancylus transgression only affected the Laxemar area early in the landscape development, justifying the assumption of not implementing it in the SE-SFL calculations of biosphere object development.

For a detailed description of the construction of the Holocene rsl development, see Appendix B.

In SE-SFL, the Holocene rsl development described here is taken to represent a typical rsl development after deglaciation at Laxemar. As such it is used as boundary conditions in simulations of groundwater flow and geochemistry in Laxemar from the last glaciation up to 60 000 AD (Joyce et al. 2019). It is also used to represent the deglaciation after a future glaciation in the *simplified glacial cycle climate case* (Section 4.3).

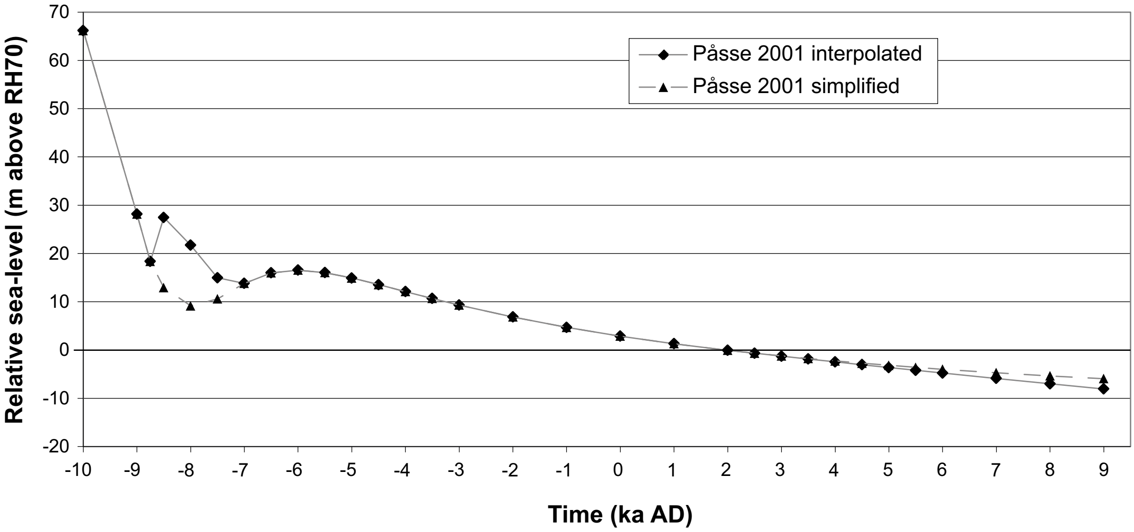

Figure 3-2. *Holocene relative sea-level for Laxemar based on Påsse (2001). The solid line ("Påsse 2001 interpolated") includes the Ancylus transgression at around 8000 BC and also an adaptation (lowering of the last part of the curve) to data from GIA modelling used further into the future (see Section B2.3 in Appendix B). The dashed curve ("Påsse 2001 simplified") describes a simplified relative sea-level development, also based on Påsse (2001), but excluding the Ancylus transgression and excluding the interpolation with GIA data. The solid curve is the more realistic of the two. In order to use a simple mathematical expression for rsl, the dashed curve was used for the description of the development of the biosphere objects (4700 BC to 6800 AD), whereas the solid curve was used for the description of long-term land/sea water development in SE-SFL.*

4 Climate cases for the safety evaluation SE-SFL

4.1 Selection of climate cases in SE-SFL

In SE-SFL, two climate cases are defined. These are highly simplified as compared with the ones used in full safety assessments such as SR-Site (SKB 2010a, 2011a) and SR-PSU (SKB 2014a, 2015). As described in Section 1.4, the strategy for selection and description of climate cases in SE-SFL is the same as in SR-Site (SKB 2010a) and SR-PSU (SKB 2014a). However, since SE-SFL constitutes a first evaluation of post-closure safety for a proposed repository concept, located at an example coastal site, the future climate developments chosen are intentionally simplified and limited in number as compared with the ones presented and used in a full safety assessment (e.g. SR-Site). The climate cases included in SE-SFL allow a first evaluation of how the properties of the proposed repository concept evolve over time under relevant future climate developments. In a full safety assessment for SFL, the results of the SE-SFL evaluation will serve as basis for the definition of a sufficient set of future climate developments that together illustrates the most important and reasonably foreseeable sequences of future climate states and their impact on the protective capability of the repository and their environmental consequences.

The identification and definition of the climate cases is based on existing knowledge on the range over which climate and climate-related issues may vary at Swedish coastal sites such as Laxemar and Forsmark in a one-million-year time perspective:

- Characteristic climate-related conditions of importance for repository safety at a Swedish Baltic coastal site can be represented by the temperate, periglacial and glacial climate domains described in Section 2.1.
- The reconstruction of the last glacial-interglacial cycle, utilised in previous safety assessments, e.g. in SR-Site (SKB 2010a, 2011a), provides a relevant example of a reasonable succession of climate domains during a glacial-interglacial cycle.
- It is highly likely that the current interglacial, the Holocene, will be significantly longer than previous interglacials. It may last for 50 000, 100 000 years, or even longer, because of limited future variations in insolation and as a consequence of human emissions of atmospheric greenhouse gases such as CO_2 (see e.g. Berger and Loutre (2002), Ganopolski et al. 2016, SKB 2014a, Section 3.3.5).

This existing knowledge is, to a large extent, based on information from previous safety assessments performed for the planned Spent Fuel Repository in Forsmark and for the existing, and planned extension of the SFR repository for short-lived low- and intermediate-level radioactive waste in Forsmark. In this way, the idealised future climate developments presented in the present report are based on research conducted and published by SKB as well as on research presented in the general scientific literature, see Section 1.5.

SFL is designed for long-lived radioactive waste and assessments of post-closure safety must therefore address timescales up to one million years (see the **Main report**, Section 2.3). This is the same timescale addressed in safety assessments for the Spent Fuel Repository (see e.g. SKB 2011a). Therefore, in SE-SFL, the range within which future climatic conditions and climate-related processes may vary at a coastal repository site in Sweden is represented by a similar range to the one included in SR-Site (SKB 2011a). In SR-Site, a *reference glacial cycle* for the coming 120 ka, comprising a repetition of conditions reconstructed for the last glacial cycle, was described and used as *an example* of a conceivable future evolution that covers climate-related conditions and sequences that could be expected in a 100 ka time perspective. The *reference glacial cycle* was supplemented five additional climate cases that describe alternative possible future developments of climate and climate-related issues at Forsmark. The selection and description of these climate cases were based on i) knowledge on past changes in climate and environmental parameters, ii) anticipated future climate change affected by anthropogenic actions, and iii) knowledge as to which processes are of importance for post-closure safety for a repository using the KBS-3 concept. The overall climate development in the reconstruction of the last glacial cycle, with periods of temperate climate, periglacial conditions with permafrost, ice-sheet development and variations in relative sea-level, is described in the

SE-SFL *simplified glacial cycle climate case* (see Section 4.3), whereas a future climate affected by anthropogenic actions is described in the *increased greenhouse effect climate case* (see Section 4.2). The climate cases considered in SE-SFL are listed in Table 4-1.

In SR-Site, some of the five additional climate cases, e.g. *extended global warming* and *severe permafrost*, were included in order to evaluate realistic, but more extreme, future climate evolutions than that represented by the *reference glacial cycle*. Since SE-SFL constitutes a first evaluation of the proposed repository concept, no such bounding climate cases have been defined in SE-SFL. Instead, some aspects related to climate development, such as the potential effects of groundwater chemistry variations during glacial cycles on the bentonite backfill are discussed based on existing knowledge (see the **Main report**, Section 6.4). In a full safety assessment for SFL, the results of the SE-SFL evaluation will serve as basis for the definition also of bounding climate cases, representing more extreme, future climate evolutions than those represented in SE-SFL.

Since SE-SFL does not evaluate a specific repository site for SFL, no new detailed investigations of the maximum permafrost and ground freezing depth has been performed. Rather, in SE-SFL, a main assumption is that the repository is located at a depth where permafrost and frozen conditions will not form during future periods of cold climate. The repository depth chosen for the SE-SFL evaluation, 500 m, is based on the detailed investigations of the maximum permafrost and ground freezing depth at Forsmark performed in the safety assessments for the Spent Fuel Repository (SKB 2010b, 2011a) and on similar investigations made for the Laxemar site (SKB 2006). The maximum permafrost depth at the Spent Fuel Repository site in Forsmark is approximately 460 m taking the full range of uncertainties into account. At Laxemar, the maximum permafrost depth is shallower, see Section 2.2.4. The maximum permafrost depth is site-specific and depends on a number of factors. In a full safety assessment for SFL, with one or a few potential repository sites chosen, the depth required to meet the criteria for non-freezing conditions during future glacial cycles will be evaluated.

Table 4-1. Selected climate cases for the SE-SFL.

Climate case number (section in present report)	Climate case name	Description
1 (Section 4.2)	*Increased greenhouse effect*	Initial period of with warmer and wetter climate than at present, followed by present-day temperature conditions.
2 (Section 4.3)	*Simplified glacial cycle*	Simplified glacial cycle, early permafrost development, ice-sheet overriding, and subsequent submerged conditions.

4.2 Increased greenhouse effect climate case

The *increased greenhouse effect climate case* assumes temperate climate conditions for the complete analysis period of one million years, with a considerably warmer and wetter climate than at present during the first 23 000 years of the period. The development of climate domains for the *increased greenhouse effect climate case* is shown in Figure 4-1. The temperate climate domain completely dominates this climate case.

The temperature and precipitation increase due to the increased greenhouse effect is here implemented as a simplified step-function. The conditions during the warmer and wetter period are chosen based on climate projections for 2100 AD for the IPCC intermediate emissions scenario RCP4.5 (see Appendix C). Thus, from repository closure (2075 AD) to 25 075 AD, the annual near-surface air temperature and precipitation are assumed to be 2.6 °C and 12 % higher than present-day respectively (Table 4-2 and Figure 4-2). After 25 075 AD, and for the remaining part of the analysis period of one million years, present-day temperate climate conditions are assumed.

Also the atmospheric CO_2 concentration, which is the main driver for the increased annual near-surface temperature and precipitation, is represented by a simplified step-function, based on the RCP 4.5 emissions scenario. Thus, the atmospheric CO_2 concentration of 528 ppm, corresponding to the atmospheric CO_2 concentration at 2100 AD in the IPCC RCP 4.5 emission scenario (Collins et al. (2013), is assumed during the warmer and wetter period from repository closure to 25 075 AD. Thereafter, present-day conditions are assumed.

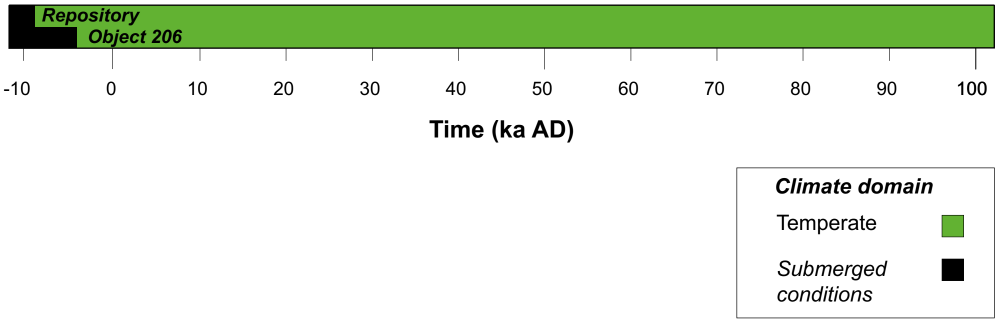

Figure 4-1. Evolution of climate and climate-related conditions for the SE-SFL increased greenhouse effect climate case for Laxemar, from the last deglaciation and for the first 100 000 years after repository closure. This climate case only contains the temperate climate domain and, during early Holocene, submerged conditions. Note that the submerged period following deglaciations (black) shows the duration of sea water-covered conditions specifically for the locally elevated (21.5 m above present sea level) area immediately above the repository and for biosphere object 206, see the text. After the first 23 000 years, present-day temperate climate conditions are assumed for the remaining part of the analysis period of one million years.

Table 4-2. Timing and duration of climate domains and the associated air temperature development at Laxemar from the last deglaciation and for first 100 000 years after repository closure of the SE-SFL *increased greenhouse effect climate case*. See also Figures 4-1 and 4-5. For a description of the estimates of the increase in air temperature after repository closure, see SKB (2014b). For the initial period dominated by anthropogenic warming, the estimated temperature increase has been added to the present-day Laxemar near surface air temperature (Table 3-1). The submerged period is given both for the area above the repository and for biosphere object 206 (the latter within brackets), see the text.

Time AD (years)	Climate domain	Annual near-surface air temperature (°C)	Source of temperature information
−12 000 – −8800 (−12 000 – −4100)	submerged	+4	Estimated water temperature
−8800–2075 (4100–2075)	temperate	+6.4	Present-day near-surface air temperature Laxemar (Table 3-1)
2075–25 075	temperate	+9.0	Estimate of increase in air temperature (see SKB 2014b) added to the present-day Laxemar air temperature (Table 3-1)
25 075–102 000	temperate	+6.4	Present-day near-surface air temperature Laxemar (Table 3-1)

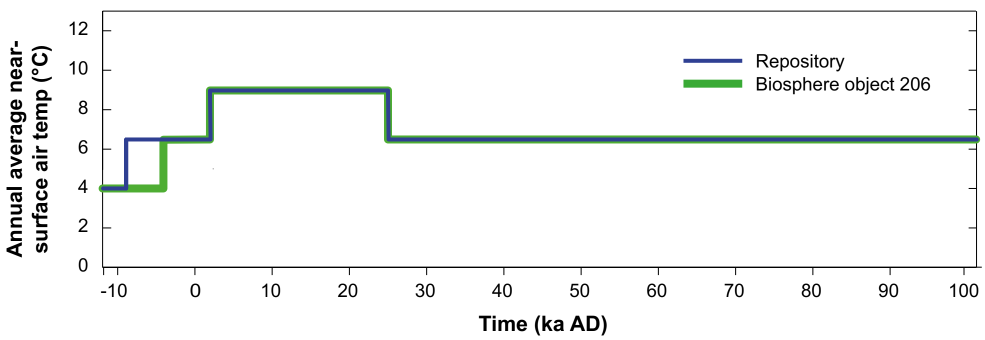

Figure 4-2. Evolution of annual average air temperature from the last deglaciation and for the first 100 000 years after repository closure of the SE-SFL increased greenhouse effect climate case. The temperature is given both for the area above the repository and for biosphere object 206, see the text.

The simplistic step-wise climate description for the period with increased greenhouse effect is chosen in order to match the simplistic assumptions regarding air temperature and precipitation that are made in the calculations of landscape development (see the **Biosphere synthesis report**). In reality, the air temperature at Laxemar is likely to increase with a maximum occurring around 3000 AD, when the temperature, over a shorter period of time, could get higher than envisaged above. After that, the temperature is likely to slowly, over many millennia, return to lower values (see SKB 2014a, Figure 3-28). The simplistic approach above instead means a somewhat lower maximum temperature but extended over a longer period of time. Due to this simplistic approach, one must take care when comparing the step-wise development in the SE-SFL *increased greenhouse effect climate case* (Table 4-2 and Figure 4-2) to the continuous development in the IPCC RCP4.5 scenarios (see e.g. Appendix C, Table C-1).

The *increased greenhouse effect climate case* is included in the analysis to i) cover the uncertainty associated with the projected climate change due to human activities (see e.g. SKB 2010a, 2014a and references therein), and ii) facilitate evaluation of the importance of potential effects of warmer and wetter temperate conditions for post-closure safety.

For the first 50 000 years, this climate case is similar to the *global warming climate cases* of SR-Site (SKB 2010a) and SR-PSU (SKB 2014a). In those climate cases, the initial ~50 000 years of temperate conditions is followed by an overall development towards colder climate conditions including periglacial periods. As described in Section 1.4, the climate cases in SE-SFL are kept simple and therefore the initial period of an increased greenhouse effect is here followed by a period of constant present-day temperate conditions extending to one million years after closure. A climate evolution with temperate, albeit varying, climate conditions for the coming one million years, as in this climate case, is considered unrealistic from a climate perspective. However, there are a few studies suggesting that, due to human activities, the present interglacial may be considerably longer than one hundred thousand years (Archer and Ganopolski 2005).

In the SR-PSU *global warming climate case*, an initial submerged period is included motivated by the fact that the existing and planned extension of SFR is located below present-day sea level. Since SFL in the present safety evaluation is assumed to be located above the present-day shoreline, submerged conditions are only included for the early Holocene in the *increased greenhouse effect climate case*. Potential effects of post-glacial submerged conditions are included in the *simplified glacial cycle climate case* in SE-SFL (see Section 4.3).

The surface above the SE-SFL repository location is located at an average elevation of 21.5 m above present mean sea level. According to the reconstructed Holocene relative sea-level development at Laxemar (Figure 3-2), the surface above the repository location became terrestrial around 8800 BC, as illustrated in Figure 4-1 (for details, see Appendix B, Table B1-1). The SFL repository is located below a local hill in the landscape. Because of this, radionuclides potentially released from the repository are expected to be transported to more lowland areas in the surrounding landscape (Joyce et al. 2019). The area chosen for the base evaluation case in SE-SFL, biosphere object 206 (see the **Biosphere synthesis report**), is at present located at an altitude of 12.3 m above sea level and it became isolated as a lake at around 4100 BC, as illustrated in Figure 4-1 (see also Appendix B, Table B1-1).

The future climate evolution in the *increased greenhouse effect climate case* has potential effects on the surface systems (see the **Main report**, Section 6.3). To facilitate analysis of these potential effects, regions with present-day conditions similar to the projected future near-surface air temperature and precipitation in Laxemar are identified and described in Appendix C.

4.3 Simplified glacial cycle climate case

The *simplified glacial cycle climate case* assumes that an early period of periglacial climate domain, with permafrost at the site, occurs ~17 000 years after repository closure. This corresponds to the next future period with a minimum in incoming summer solar radiation at high northern latitudes (cf. SKB 2014a, Brandefelt et al. 2013, and references therein). A second period of periglacial conditions starts ~50 000 years after repository closure and is followed by a period of glacial climate domain, with an ice sheet overriding the repository site. This second cold period also corresponds to a known future time interval of low solar insolation. During the glacial period, the ice sheet is assumed to grow thick enough as to result in substantial isostatic bedrock depression, identical to the situation reconstructed for the Laxemar site for the last stadial of the Weichselian glacial cycle at around 20 ka BP (during Marine Isotope Stage 2) in SR-Can (SKB 2006). The reconstructed maximum ice-sheet thickness over Laxemar during this period is almost 2 500 m, resulting in isostatic depression and associated submerged conditions following deglaciation of the site. This sequence of events is illustrated in Figure 4-3, including the relative sea-level and ice-sheet thickness. The relative sea-level development was constructed by combining Holocene data based on Påsse (2001) and data from Glacial Isostatic Adjustment (GIA) simulations for the glaciated phase. For a detailed description of the methods and data used for constructing the relative sea-level development, see Appendix B. The timing and duration of periods with different climate domains, as well as the air temperatures of these periods, are given in Table 4-3. The air temperature evolution of this climate case is illustrated in Figure 4-4.

Also in the *simplified glacial cycle climate case*, the changes in annual mean temperature are implemented as a simplified step-function. The simplistic step-wise climate description is chosen in order to match the simplistic assumptions regarding air temperature and precipitation that are made in the calculations of landscape development (see the **Biosphere synthesis report**).

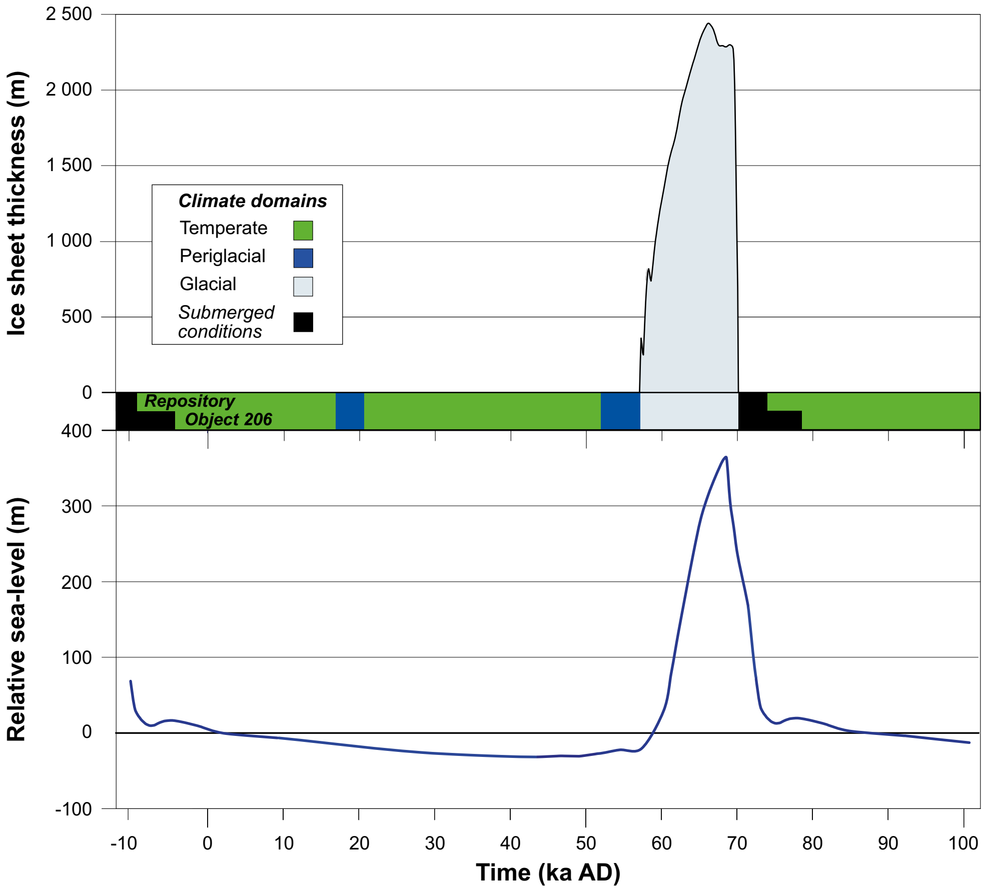

Figure 4-3. *Evolution of climate and climate-related conditions for the simplified glacial cycle climate case for Laxemar, from the last deglaciation and for the first 100 000 years after repository closure. The climate development is shown as a succession of climate domains and submerged periods. The duration of the glacial climate domain and the subsequent submerged conditions are derived from the glacial maximum stadial (corresponding to MIS 2) in the Laxemar Reference glacial cycle of SR-Can (SKB 2006). For a description of the construction of the relative sea-level development, see Appendix B. Note that the submerged period following deglaciations (black) shows the duration of sea water-covered conditions specifically for the locally elevated (21.5 m above present sea level) area immediately above the repository and for biosphere object 206, whereas the relative sea-level has its zero line at the present sea level.*

Table 4-3.Timing and duration of periods with different climate domains, as well as air temperature development, from the last deglaciation and for the first 100 000 years after repository closure of the *simplified glacial cycle climate case*. See also Figure 4-4. The duration of the glacial climate domain and the subsequent submerged conditions are derived from the Laxemar glacial maximum stadial (corresponding to MIS 2) in the Reference glacial cycle of SR-Can (SKB 2006). The submerged periods are given both for the area above the repository and for biosphere object 206 (the latter within brackets), see the text.

Time AD (years)	Climate domain	Annual near-surface air temperature, water temperature and basal ice temperature (°C)	Source of temperature information
−12 000 – −8800- (12 000 – −4100)	submerged	+4	Estimated water temperature
−8800 – 17 500 (−4100 – 17 500)	temperate	+6.4	Present-day near-surface air temperature Laxemar
17 500–20 500	periglacial	-1	From Early periglacial climate case SR-PSU Forsmark
20 500–52 000	temperate	+6.4	Present-day near-surface air temperature Laxemar
52 000–57 000	periglacial	-4	Simplified from early periglacial climate case SR-PSU Forsmark
57 000–70 000	Glacial (cold-based conditions during the first 100 years, then warm-based until deglaciation)	-1	Approximate basal ice temperature (pressure melting point temperature based on an approximate 1 700 m average ice thickness over Laxemar)
70 000–74 000 (70 000–78 700)	submerged	+4	Reference glacial cycle SR-Site Forsmark
74 000–102 000 (78 700–102 000)	temperate	+6.4	Present-day near-surface air temperature Laxemar

As previously noted (Section 4.2), the surface above the repository was submerged until c. 8800 BC (illustrated in Figure 4-3. See also Appendix B, Table B1-1), and radionuclides from the repository are expected to be transported to lowland areas in the surrounding landscape which became isolated as lakes around 4100 BC (See also Appendix B, Table B1-1).

The *simplified glacial cycle climate case* is included in the analysis to *i)* cover the colder end of the range within which future climate may vary, and *ii)* facilitate evaluation of the importance of effects of periglacial, glacial, and submerged conditions, and the transitions between these states, on internal FEPs for post-closure safety.

This climate case contains selected key elements (the maximum stadial of the glacial cycle followed by submerged conditions) from the *reference glacial cycle climate case* of SR-Can for the Laxemar site (SKB 2006), combined with the first realistic period of periglacial conditions at Forsmark from the *early periglacial climate case* of SR-PSU (SKB 2014a). Since this climate case intentionally is meant to be simplified, it does not contain the full climate variability expected at a coastal site in Sweden during a glacial cycle (cf. SKB 2006, 2010a).

In the evaluation of post-closure safety, the evolution from 2000 AD to 102 000 AD in the *simplified glacial cycle climate case* is repeated every 100 000 years until one million years after repository closure to represent the effects of repeated Late Quaternary glacial-interglacial cycles. Since the *simplified glacial cycle climate case* does not include a complete reconstruction of last glacial cycle conditions, the relative sea-level is not identical at 102 000 AD and 2000 AD (see Figure 4-3). However, since the distance to the shoreline is large at both times, the conditions in the repository and its environs are assumed to be identical at 102 000 AD and 2000 AD (see the **Radionuclide transport report**, Section 5.4).

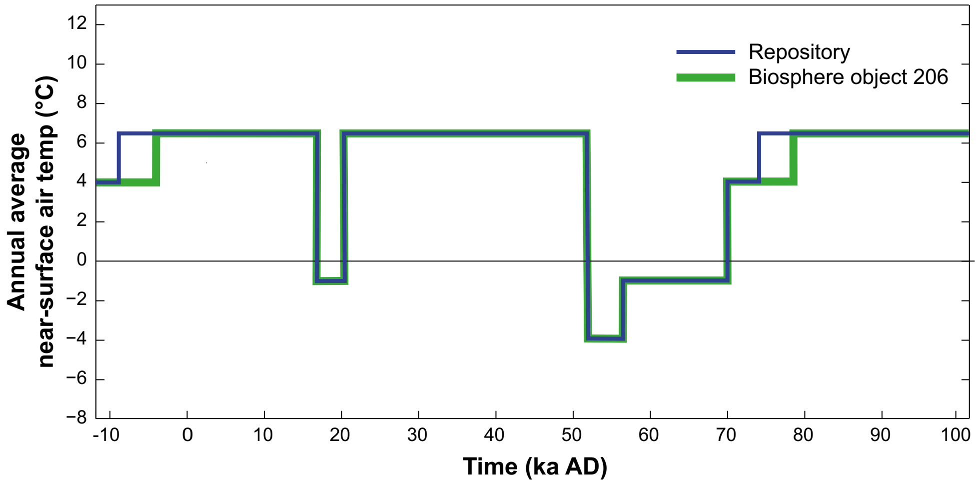

Figure 4-4. *Evolution of annual average air temperature from the last deglaciation and for the first 100 000 years after repository closure of the SE-SFL simplified glacial cycle climate case. The temperature is given both for the area above the repository and for biosphere object 206, see the text.*

4.4 Transitions between climate domains

Depending on what spatial scale is considered, the transitions between climate domains may need to be described differently. For example, if considering the area of the SFL repository footprint only, the transitions between climate domains (temperate, periglacial, glacial and submerged conditions) may be described as more or less instantaneous in time, in line with how the way the succession of climate domains is depicted and perceived in Figures 4-1 and 4-3. However, if looking at Laxemar on a site-scale, i.e. several tens/hundreds of square km, the transition between climate domains is of a gradual nature, both spatially and temporally. Depending on the context in which the climate development is employed, for instance in landscape development or in modelling of some process within the repository itself, different assumptions should be made on the duration of the climate domain transitions. The transitions occur when the site goes from i) temperate climate domain to periglacial climate domain, ii) periglacial climate domain to glacial climate domain, iii) glacial domain to submerged conditions, and finally iv) from submerged conditions back to temperate climate domain.

The transient nature of the change from temperate climate domain to periglacial climate domain includes the development of sporadic permafrost. Subsequently, if the climate cools further, the permafrost may develop to discontinuous or continuous spatial coverage.

The transition from periglacial to glacial climate domain manifests itself as an ice sheet margin that advances over the site. A spatially transient change takes place in one specific direction over the site, by which the periglacial climate domain is replaced with glacial climate domain behind the advancing ice sheet front, under the ice. In the *simplified glacial cycle climate case* the ice-sheet margin advances over the site at a speed of ~50 m/year, based on the Weichselian ice-sheet model reconstruction used in SR-Can (SKB 2006). Note that permafrost may still exist under the ice sheet for an initial period when the site is assigned to the glacial climate domain. The duration of this phase is affected by several factors, such as the temperature of the permafrost, the geothermal heat flux at the site and the heat from the ice deformation and sliding and from the subglacial hydrological system. One first coarse estimate of this duration could be that is roughly equals the period for which the ice sheet is cold based (see Table 4-3 and 4-4).

The ice-sheet margin retreat rate during deglaciation of the Laxemar site is ~200 m/year, estimated from the last deglaciation of this region. In the *simplified glacial cycle climate case*, the deglaciation results in a transition from glacial to submerged conditions. In this climate case, the relative sea-level development, caused by isostatic rebound following deglaciation, subsequently results in the submerged conditions being followed by terrestrial conditions and the temperate climate domain.

4.5 Ice-sheet profiles

The longitudinal shape and steepness of the ice-sheet surface is of importance for the pressure gradients that drive groundwater flow, and longitudinal ice-sheet profiles are therefore used as input to simulations of groundwater flow during glacial conditions (SKB 2010d, e, Vidstrand et al. 2013). In line with what was assumed for the Forsmark site in the SR-Site safety assessment (SKB 2010a, Appendix 2), a relatively steep theoretical profile (based on Equation A2-2 in SKB 2010a) is selected as an adequate representation of an advancing ice sheet profile. Also in line with the handling in SR-Site, a modelled ice-sheet profile over the Forsmark site is selected as an adequate representation of an ice-surface profile during the deglaciation phase. The transect from which this simulated ice-surface profile is extracted is located close to both the Forsmark and Laxemar sites, and this profile is therefore considered appropriate for representing deglaciation conditions also for the present safety evaluation. For a detailed discussion of the origin, characteristics, and selection of the two ice-surface profiles, as well as plots of them, see SKB (2010a, Appendix 2).

4.6 Summary of climate cases for the safety evaluation SE-SFL

A summary of the evolution of climate and climate-related conditions from the last deglaciation and for the first 100 000 years after closure for the two simplified climate cases for SE-SFL is shown in Figure 4-5.

To assess the doses to humans for the complete analysis period, the simplified evolution of climate and climate-related conditions of the climate cases depicted in Figure 4-5 is extended to one million years after closure. For the *increased greenhouse effect climate case,* the conditions at 102 000 AD are assumed to prevail until one million years after closure. For the *simplified glacial cycle climate case*, the evolution from 2 000 AD to 102 000 AD is repeated every 100 000 years until one million years after repository closure to represent the effects of repeated glacial-interglacial cycles.

The evolution of annual average air temperature of the SE-SFL climate cases is illustrated in Figure 4-6.

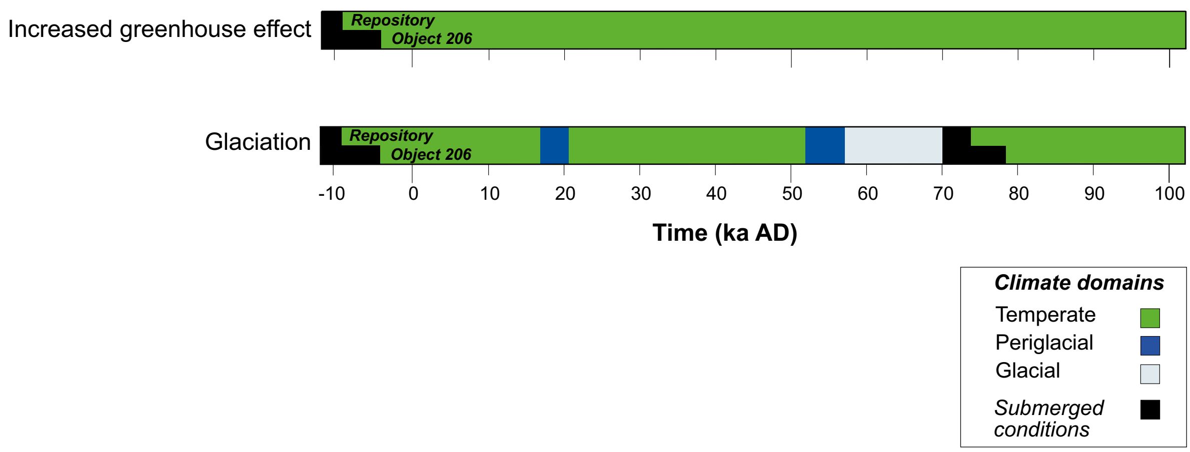

***Figure 4-5.** Evolution of climate and climate-related conditions as a succession of climate domains and submerged periods from the last deglaciation and for the first 100 000 years after repository closure of the simplified climate cases identified and selected for further analyses in SE-SFL. The submerged periods are given both for the area above the repository and for biosphere object 206, see the text.*

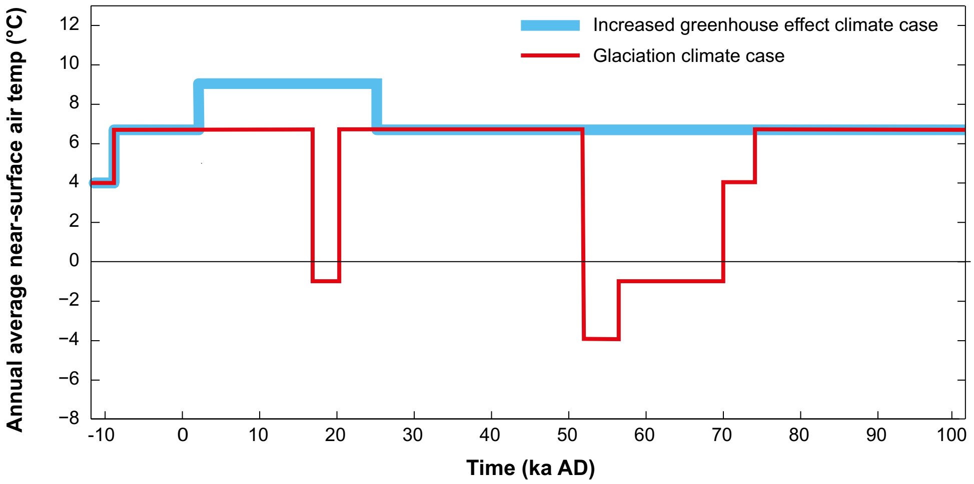

Figure 4-6. *Evolution of annual average air temperature for the repository location from the last deglaciation and for the first 100 000 years after repository closure of the simplified climate cases identified and selected for further analyses in SE-SFL.*

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Appendix A

List of abbreviations

AD	Anno Domini
BC	Before Christ
BHA	SFL section with bentonite barrier
BHK	SFL section with concrete barrier
FEPs	Features, events, and processes
GIA	Glacial Isostatic Adjustment
ka	thousand years
SE-SFL	Safety evaluation for the SFL repository
SFL	Planned repository for long-lived radioactive waste
SFR	Existing repository for short-lived radioactive waste
SR-Can	Safety assessment performed for the planned Spent Fuel Repository
SR-PSU	Safety assessment performed for the extended SFR
SR-Site	Safety assessment performed for the planned Spent Fuel Repository

Appendix B

Relative sea-level development at Laxemar

SKB has done an extensive amount of work on relative sea level (rsl) and shoreline displacement at the Forsmark and Laxemar sites, and also made many additional studies based on other types of analyses of these data, such as landscape development and groundwater flow modelling. The rsl for the Laxemar site, used for SE-SFL, is described below. The construction of the Holocene rsl development, based on rsl data (Påsse 2001), is described first. This is followed by the construction of the rsl development for the next glacial cycle (~100 ka) where the Holocene reconstruction is combined with rsl data from Glacial Isostatic Adjustment (GIA) modelling.

B1 Holocene relative sea-level development

In order to describe the long-term development of the landscape in general and biosphere objects in particular the landscape development needs to be modelled continuously based on a rsl development covering the appropriate time period. The present rsl rate in Laxemar is ~ 1 mm/year (Ågren and Svensson 2007). In Påsse (2001) there is a compilation of rsl data for Fennoscandia and one of the stations is in Oskarshamn. Påsse (2001) also gives an empirical method for transforming rsl data (altitude and age) into an equation that simplifies the use of the rsl in mathematical models.

To illustrate the development of biosphere objects after the last deglaciation in the Laxemar area, the time frame for development from a marine stage to a mire stage covers −10 000 to 20 000 AD. In SE-SFL, the rsl development was modelled during this time frame using SKB's rsl development equations based on Påsse (2001). The site-specific parameters for the functions were taken from Påsse (2001).

The rsl development constitute the net result of the land uplift after unloading of ice (the glacio-isostatic uplift U) and changes in sea level (eustacy E). In Påsse (2001), the glacio-isostatic uplift is divided into a slow (U_s) component representing the main uplift, and a fast (U_f) component, which was included to capture the relatively fast uplift rates in the early Holocene. The slow component is described by the function:

$$U_s = \frac{2}{\pi} A_s \left[arctan\left(\frac{T_s}{B_s}\right) - arctan\left(\frac{T_s - t}{B_s}\right)\right]$$

where A_s (m) is a download factor, T_s (years) is the time for the maximal uplift rate, t (year) is the time and B_s (y^{-1}) is an inertia factor. A_s and B_s are site specific parameters [163, 2600][3], whereas T_s is a constant [12 000] (Påsse 2001). The fast uplift component is defined as:

$$U_f = A_f e^{\left[-0.5\left(\frac{t - T_f}{B_f}\right)^2\right]}$$

where A_f (m) is the total subsidence or uplift (m), B_f is the inertia factor (y^{-1}) and T_f (y) is the time for the maximal subsidence/uplift. A_f and B_f are site specific parameters [24, 400][3], and T_f has a small regional variation, and was given a specific value for the Oskarshamn region [11 600] [3] (Påsse 2001).

The function for the global sea-level rise was calculated as the difference between hypothetical uplift curves and the empirical relative sea-level, and was described by the function (Påsse 2001):

$$E = \frac{2}{\pi} 56 \left[\arctan\left(\frac{a}{b}\right) - \arctan\left(\frac{a - t}{b}\right)\right]$$

where a and b (year) are empirical constants [9500, 1350].

Påsse (2001) also described a fast transgression and regression during the Ancylus lake stage (8700–6500 BC). The water-level changes during the Ancylus transgression can be calculated by combining the shoreline displacements at the outlets at Degerfors and at Darss Sill (Påsse 2001).

[3] Parameter values for Oskarshamn, Table 3-1 in Påsse (2001). The original reference for the site is Svensson (1989).

This was described in the SDM-Laxemar (SKB 2009) as a more detailed description of the shoreline displacement in the area.

Figure B-1 (solid line) shows the resulting Holocene rsl development for Laxemar based on Påsse (2001). This development was used together with simulated Glacial Isostatic Adjustment (GIA) data on rsl development to produce the full glacial cycle rsl scenario described in Section 4.3, see the following sub-section below.

The Holocene post-glacial emergence of the ground surface above SFL has been calculated using the Påsse (2001) equations (Table B-1). In addition, the timing of the emergence of the area chosen for the base evaluation case in SE-SFL, biosphere object 206 (see the **Biosphere synthesis report**) has been calculated in the same way (Table B-1).

Table B-1. Timing of Holocene post-glacial emergence of the ground surface above SFL and of biosphere object 206, based on Påsse (2001). The emergence of the area above the repository coincides with a time period where the relative sea-level development goes very fast (see Figure B-1).

SFL ground surface elevation and biosphere object 206	Elevation (m above present mean sea level. RH70 height reference system.)	Timing of emergence (AD)
Minimum elevation	18.71	−8800
Maximum elevation	26.46	−9000
Mean elevation	21.50	−8800
25 % percentile (25 % of area raised above sea level)	20.10	−8800
75 % percentile (75 % of area raised above sea level)	22.68	−8900
Biosphere object 206	12.3	−4100

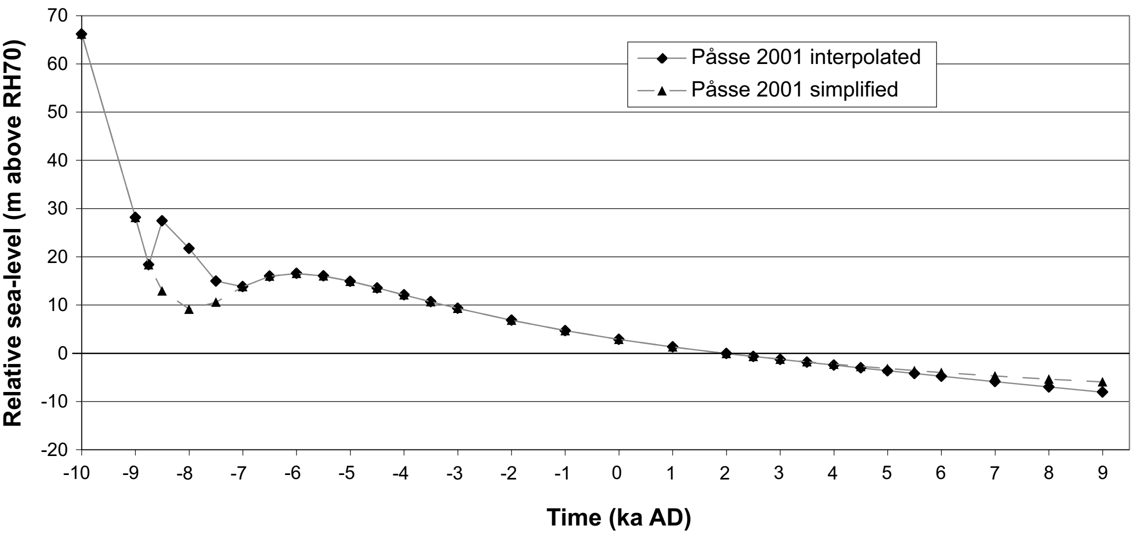

Figure B-1. *Holocene relative sea-level for Laxemar based on Påsse (2001). The solid curve ("Påsse 2001 interpolated") includes the Ancylus transgression at around −8000 AD and also an adaptation to GIA data. The method to produce the relative sea-level development for the coming 100 ka by combining the Holocene reconstruction with GIA data (see the text) results in a slight increase in the Holocene relative sea-level rate of change from around 4000 AD, here seen as a lowering of the last part of the solid curve. The dashed curve ("Påsse 2001 simplified") describes a relative sea-level development, also based on Påsse (2001), but excluding the Ancylus transgression and excluding the interpolation with GIA data. The solid curve is the more realistic of the two. In order to use a simple mathematical expression for rsl development, the dashed curve was used for the description of the development of the biosphere objects (−4700 to 6800 AD), whereas the solid curve was used for the description of long-term land/sea water development in SE-SFL.*

In SE-SFL it was decided to use a simplified rsl development for Laxemar to facilitate the mathematical handling in the modelling of landscape development. The simplified development of the Laxemar rsl, also based on Påsse (2001), excludes the Ancylus transgression (Figure B-1, dashed line). The Ancylus transgression only affected the Laxemar area early in the landscape development, and was not implemented in the SE-SFL calculations describing the development of biosphere objects. Also, the simplified curve is not connected to the full glacial cycle GIA rsl data (see section below), but ends at −9000 AD. The simplification of the rsl function presented by Påsse (2001) thus excludes the transgression and regression associated with the Ancylus lake phase at around −8000 AD (Figure B-1). This event has effects on the marine basins alone, where they would be reduced in area before becoming larger again.

Påsse's (2001) function can be used to model the time period from the last deglaciation until today. In previous safety assessment work it has been judged that it also can be extended some thousands of years further into the future by extrapolation. To achieve approximations further into the future, when new ice-sheet formation in the *simplified glacial cycle climate case* affects rsl development, it is necessary to include the effects of Glacial Isostatic Adjustment (GIA), see the section below. The method to produce a rsl development for the coming 100 ka for a case without global warming by combining GIA data with the Holocene reconstruction (Figure B-1) is described in the following section. Combining the two data sets results in a slight increase in the Holocene rsl rate of change from around 4000 AD, seen as a lowering of the solid curve in Figure B-1. This correction against GIA data has been disregarded in the SE-SFL modelling of the biosphere objects, using the dashed rsl curve in Figure B-1. However, this is regarded to be of minor importance as most of the biosphere objects reach their final stage (the mire) before this correction becomes significant.

B2 Relative sea-level development for the next 100 ka

The first two sub-sections below constitute rewritten extracts from text describing the Laxemar relative sea-level development for the coming ~100 ka originally presented in SKB (2010c, Appendix A10). The original text in SKB (2010c) contains several errors in the descriptions and in the references, which have been corrected and clarified here.

The first sub-section below gives a brief account of the rsl reconstruction for the last glacial cycle (the Weichselian) using GIA modelling. The second sub-section describes how these results previously, for the SR-Can safety assessment and for the site selection process for the Spent Fuel Repository, were used to construct a glacial rsl scenario for the coming 100 ka by combining them with the Holocene rsl curve. Finally, the third sub-section describes the similar construction of a future 100 ka rsl scenario made specifically for the SE-SFL *simplified glacial cycle climate case*.

B2.1 Modelling of Glacial isostatic adjustment for the last glacial cycle

GIA is the response of the solid earth to the mass redistribution of water and ice associated with glacial cycles, see e.g. Whitehouse (2009). The relative sea level (rsl) is defined as the elevation of the contact between the ocean surface and land. GIA development, including site-specific changes in rsl, has been modelled for the last glacial cycle, the Weichselian, for the SR-Can safety assessment for the Spent Fuel Repository (SKB 2006, Whitehouse 2009), with the aim of using the results for a future glacial cycle scenario. Given that these results were to be used for a future scenario without global warming, eustatic changes caused by ice-sheet melting and thermal expansion of seawater under global warming conditions were not included in this specific GIA simulation. A total melting of the Greenland ice sheet is however included in other GIA simulations (for e.g. the Global warming climate cases of SR-Can and SR-Site (SKB 2006, 2010a)).

B2.2 Previous construction of relative sea-level development from the last deglaciation to 120 ka AD

For the SR-Can safety assessment and the site selection process for the Spent Fuel Repository, a rsl curve for the coming 120 ka were produced for the Laxemar site (SKB 2006, SKB 2010c, Appendix A10) using the reconstructed Weichselian rsl from the GIA simulations described above. The Weichselian GIA reconstruction starts at the penultimate interglacial, the Eemian. When using this GIA reconstruction for a future glacial cycle scenario, the results from the Eemian interglacial are not suitable for describing Holocene conditions. Therefore, in order to produce a well-founded rsl development for the initial period (the Holocene) of the future 120 ka scenario, the first few thousands of years of future rsl development were based on an extrapolation of the Holocene rsl development by Påsse (2001) (Figure B-1 solid line). As previously mentioned, it has been judged that the Holocene rsl development based on Påsse (2001) can be extended into the future for a period of some thousands of years. However, it would certainly not be justified to extend it longer than to the beginning of next future glacial phase since renewed glacial isostatic changes will occur in association with future ice sheet growth.

The initial future rsl development based on Påsse (2001) was therefore combined with the rsl development from the GIA simulations (SKB 2006, Whitehouse 2009) to make a rsl scenario covering the period from the last deglaciation up to 120 ka AD. The resulting development was presented in the SR-Can Climate report (SKB 2006, Figure 4-5). In 2009, an improvement was made of the mathematical connection between the initial part of the Laxemar rsl curve based on Påsse (2001) and the latter part of the development based on the GIA simulations. This was made to better merge the two developments and it was achieved by adjusting a merging level from an altitude of −50 to −30 m. The new revised rsl curve for Laxemar was presented in the documentation for the site-selection process for the Spent Fuel Repository, in SKB (2010c), Appendix A10, Figure A10-1. The figure is here reproduced in Figure B-2. This improved development differs considerably from the original development used in SR-Can (SKB 2006, Figure 4-5).

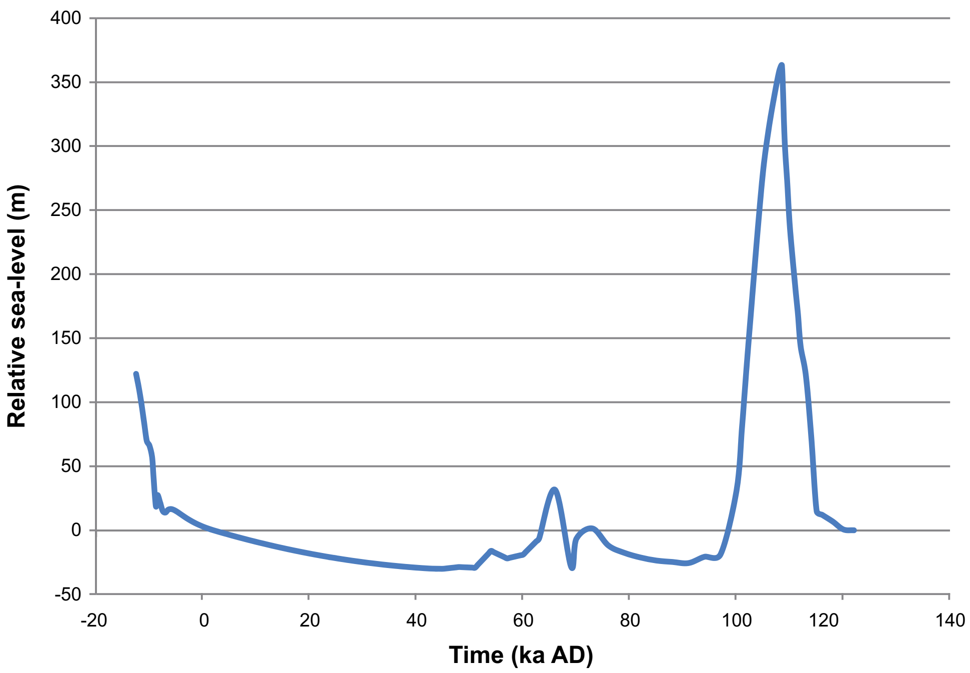

Figure B-2. The improved relative sea-level development for Laxemar (see the text), from the last deglaciation to 120 ka AD, constituting a scenario based on a reconstruction of the last glacial cycle. The first part of the development is based on Påsse (2001), whereas the latter part is based on relative sea-level development from GIA simulations (SKB 2006, Whitehouse 2009). The figure is reproduced from SKB (2010c, Appendix A10).

B2.3 Construction of relative sea-level development for the SE-SFL *simplified glacial cycle climate case*

For the SE-SFL safety evaluation, a Laxemar rsl develoment matching the simplified climate development of the *simplified glacial cycle climate case* (Section 4.3) was constructed (Figure B-3) based on the Holocene rsl development seen in Figure B-1 and rsl data from the GIA simulations in Figure B-2. The initial period, from the deglaciation, was hence based on Påsse (2001) (Figure B-1, dashed line).

The glaciated period in the *simplified glacial cycle climate case* corresponds to the last glacial period of the Weichselian glaciation (SKB 2006, 2010a), i.e. the so-called MIS2 stadial. This period includes the peak glacial conditions of the Weichselian (the Last Glacial Maximum (LGM)). The rsl for the glacial period of the SE-SFL *simplified glacial cycle climate case* was therefore copied from the reconstructed rsl of the major phase of glaciation in Figure B-2 occurring around 100–120 ka AP (after present). Data for the periods between those based on Påsse (2001) and GIA modelling were obtained by interpolation. The post-glacial rsl development, following the glaciated period at around 60–70 ka AD, is assumed to be identical to that during the Holocene (in line with the assumption that the ice sheet during this phase corresponds to the last phase of the Weichselian). The data used for different periods are summarized in Table B-2.

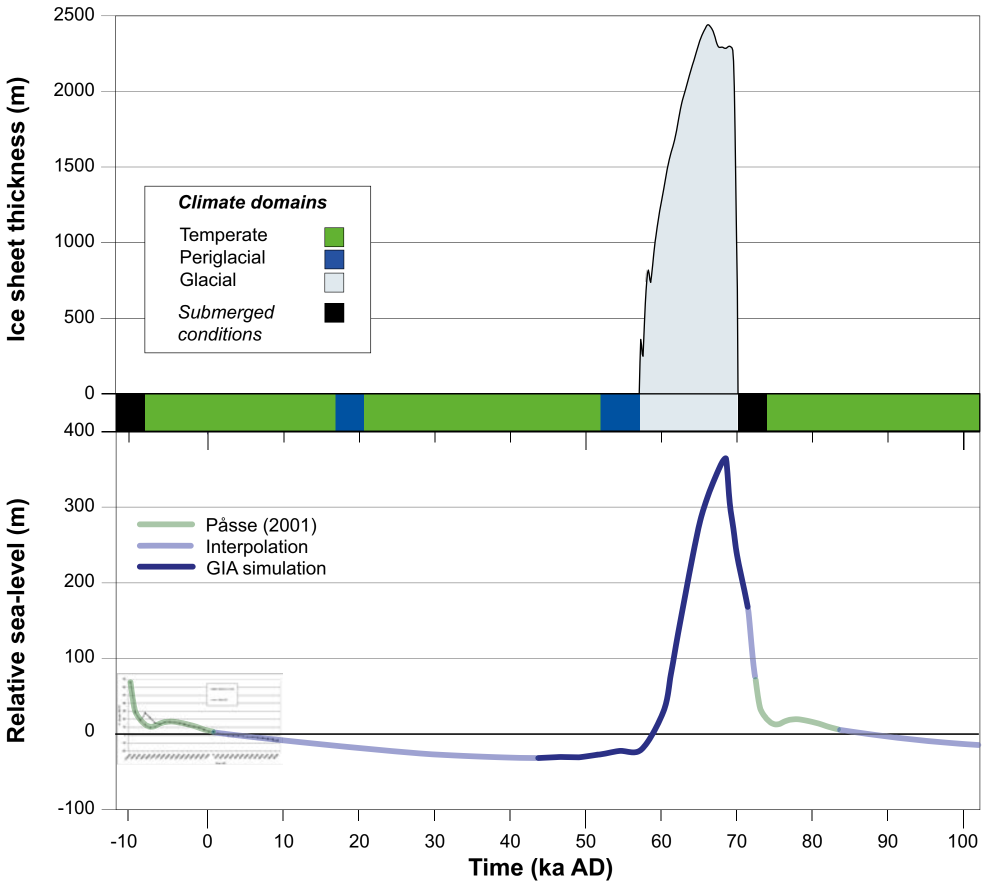

***Figure B-3.** Relative sea-level constructed for the SE-SFL simplified glacial cycle climate case. This figure corresponds to Figure 4-3 in Section 4.3. The green parts of the curve, including the first period following the last deglaciation, is constructed from Laxemar rsl data based on Påsse (2001) (Figure B-1, dashed line). The rsl for the glaciated period (dark blue) constitute the revised relative sea-level development for Laxemar (Figure B-2) for the major glacial phase, originating from the last glacial cycle GIA reconstruction (SKB 2006, Whitehouse 2009), see the text. The periods between the ones based on Påsse (2001) and GIA (grey) have been constructed by interpolation. The post-glacial rsl development is assumed to be similar to that during the Holocene. Note that the submerged period following deglaciation (black) shows the duration of sea water-covered conditions for the locally elevated area (~20 m above present sea level) immediately above the repository, whereas the rsl curve has its zero line at the present sea level.*

Table B-2. Data used for the construction of the relative sea-level development for the *simplified glacial cycle climate case*.

Time period (ka AD)	Data used
−10–0	From equation based on Påsse (2001)
0–43	Interpolation
43–71.5	Glacial Isostatic Adjustment (GIA) modelling
71.5–73	Interpolation
73–83	From equation based on Påsse (2001)
83–102	Interpolation

B3 Relative sea-level development used for the SE-SFL hydrogeology simulations

In SE-SFL, the hydrogeological simulations used parts of the improved rsl development seen in Figure B-2 (SKB 2010c, Appendix A10). However, these data were used only up to 20 ka AD. After that, a constant rsl value of −18 m (the 20 ka value) was used, see Figure B-4. The development in Figure B-4 covers the initial temperate and periglacial climate periods of the *simplified glacial cycle climate case*, prior to glacial conditions occurring at Laxemar. The development constitutes a simplified yet reasonable approximation for this pre-glacial period. Hydrogeological simulations that are to be made within future SFL safety assessments may also cover the glacial period, and therefore also need to consider e.g. rsl changes associated with the ice sheet growth and decay, as seen in Figure B-3.

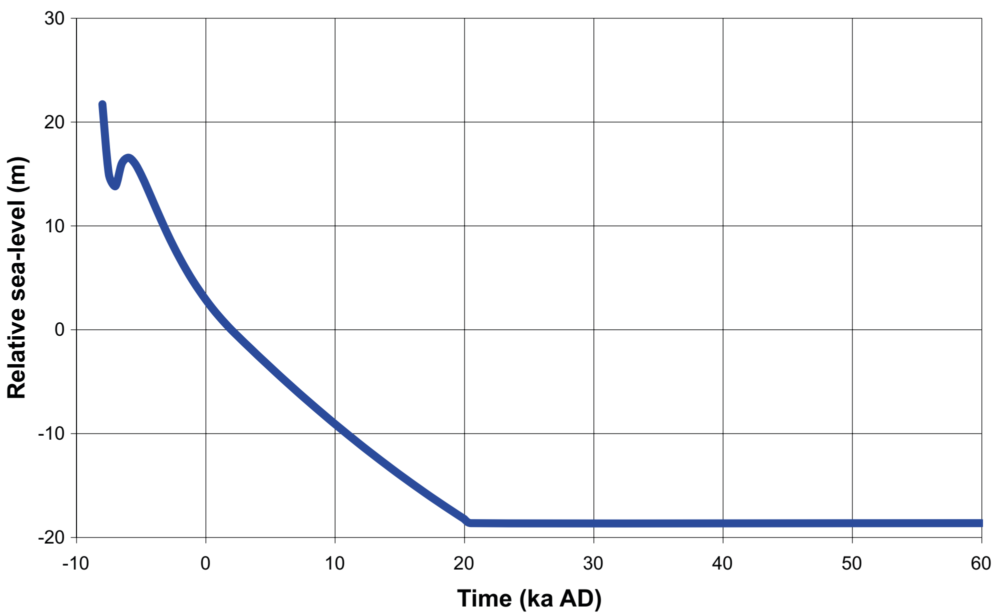

***Figure B-4.** Relative sea-level used in the SE-SFL hydrogeological simulations. The first part of the development constitutes parts of the improved Laxemar rsl curve seen in Figure B-2. After 20 ka AD, a constant value of −18 m was used.*

Appendix C

Identification and description of regions with present-day conditions similar to the future projected near-surface air temperature and precipitation in Laxemar

The future climate evolution in the *increased greenhouse effect climate case* has potential effects on the surface systems (see the **Main report**, Section 5.3). To facilitate analysis of these potential effects, regions with present-day conditions similar to the future projected near-surface air temperature and precipitation in Laxemar are identified.

C1 Future projected climate in Kalmar Län

A set of future climate projections for Sweden, performed with the Rossby Centre Regional Climate Model RCA4 (Persson et al. 2015), was utilised to estimate relevant near-surface temperature and precipitation changes for the *increased greenhouse effect climate case*. The results are available as seasonal and annual averages for different regions in Sweden and the future projected changes presented for Kalmar Län are chosen here to represent the future projected change in Laxemar. The results presented by Persson et al. (2015) were obtained using boundary conditions from nine different global climate models and for two different Representative Concentration Pathways (RCPs)[4], representing greenhouse-gas emissions partly moderated by political decisions (RCP4.5) and increasing greenhouse-gas emissions to three times the present emissions at 2100 AD (RCP8.5). The response of the simulated climate to the imposed greenhouse-gas emissions varies due to model-differences and natural variability. The range resulting from using boundary conditions from different global climate models is taken here to represent the uncertainty in the future projected climate.

In order to represent present-day climate, the 30-year average for the normal reference period (1961–1990) for the CRU CL 2.0 monthly gridded global land dataset from the Climate Research Unit (CRU) at the University of East Anglia (New et al. 2002) was used. For internal consistency in the present identification of regions with a representative climate , this dataset is also used to represent present-day climate in Laxemar. Thus Laxemar is represented by the grid point closest to Laxemar. Since the temperature and precipitation for this grid point represents a considerably larger area than the Laxemar site, the annual mean temperatures and precipitation rates given in C-1 and C-2 differ from those presented in Table 3-1 based on Alexandersson and Eggertsson Karlström (2001).

The seasonal average projected near-surface temperature and precipitation change in Kalmar Län by the end of this century (2069–2098) as compared with the average for Laxemar for the normal period is given in Table C-1 and C-2 respectively. The projected climate for this time period (2069–2098) under RCP4.5 is here chosen to represent the initial 25 000 year period of elevated temperature and precipitation in the of the *increased greenhouse effect climate case*. This choice is motivated by the availability of projections for Sweden performed with a set of state-of-the-art climate models which gives a measure of the uncertainty in the projected climate for this period. The future projected annual average near-surface temperature and precipitation increases by 2069–2098 in the RCP4.5 scenario vary in the range 1.7–3.1 °C and 3.5–20 %, respectively.

In agreement with all other regions of Sweden, the projected near-surface temperature in Kalmar Län increases for all seasons and in all model simulations for the two RCP's included by Persson et al. (2015). This is however not the case for the projected change in the seasonal precipitation in Kalmar Län for which some model simulations give decreased precipitation in summer (June–August) and autumn (September–November). For the summer season 4 (3) out of nine model simulations give decreased precipitation for RCP8.5 (RCP4.5). For the autumn season, 1 (2) out of nine model simulations give decreased precipitation for RCP8.5 (RCP4.5). For winter (December–February), spring (March–May) and the annual average, all model simulations give increased precipitation in Kalmar Län.

[4] See Section 3.3.1 in SKB (2014) for a description of the use of emission scenarios or scenarios for atmospheric concentrations of greenhouse gases consistent with RCPs.

Table C-1. The seasonal and annual average projected near-surface temperature change by the end of this century for Kalmar Län (2069–2098; Persson et al. 2015) as compared with the average for the observed reference period (1961–1990 for the grid point closest to Laxemar (New et al. 2002). For each season and each RCP, the minimum and maximum values from the set of nine climate model simulations are also given. Given that these CRU CL 2.0 data consist of interpolated gridded data, there is a discrepancy when compared to corresponding data from the individual observational station of Laxemar (Table 3-1).

Season	RCP4.5 mean change (°C)	RCP4.5 minimum and maximum values of change (°C)	RCP8.5 mean change(°C)	RCP8.5 minimum and maximum values of change (°C)	Observed Laxemar 1961–1990 (°C)
December–February	2.9	2.1–3.8	4.5	3.2–5.8	−1.4
March–May	2.6	1.8–3.3	4.0	3.4–4.7	5.1
June–August	2.3	1.4–3.4	3.8	2.6–5.0	15.8
September–November	2.5	1.6–3.2	4.0	2.8–5.3	7.9
Annual average	2.6	1.7–3.1	4.1	3.4–4.8	6.8

Table C-2. The seasonal and annual average projected precipitation change by the end of this century for Kalmar Län (2069–2098; Persson et al. 2015) as compared to the average for the observed reference period (1961–1990) for the grid point closest to Laxemar (New et al. 2002). For each season and each RCP, the minimum and maximum values from the set of nine climate model simulations are also given. Given that these CRU CL 2.0 data consist of interpolated gridded data, there is a discrepancy when compared to corresponding data from the individual observational station of Laxemar (Table 3-1).

Season	RCP4.5 mean change (%)	RCP4.5 minimum and maximum values of change (%)	RCP8.5 mean change (%)	RCP8.5 minimum and maximum values of change (%)	Observed Laxemar 1961–1990 (mm)
December–February	15	6.4 – 27	23	13–36	111
March–May	17	6.4 – 27	24	13–39	94
June–August	12	−6.5 – 38	12	−6.4–46	152
September–November	5.8	−5.9 – 16	12	−0.7–21	147
Annual average	12	3.5–20	17	8.3–26	504

C2 Regions with analogous climate

A potential effect of the climate conditions assumed during the initial 25 000 years (2075–25 075 AD) of the *increased greenhouse effect climate case* is an increased need for irrigation of crops. To provide input to the evaluation of this potential effect, regions with present-day climate analogous to the future climate in Laxemar have been identified for the summer season (June–August). To represent the present-day climate in other regions on Earth, the 30-year average for the normal reference period (1961–1990) for the CRU CL 2.0 monthly gridded global land dataset from the Climate Research Unit (CRU) at the University of East Anglia (New et al. 2002) was used. Regions with present-day conditions similar to the future projected near-surface air temperature and precipitation in Laxemar can be identified in Figures C-1 and C-2, which display the difference in the 30-year average for the normal reference period and the corresponding near-surface temperature/ precipitation rate in Laxemar for the same period. Taking the projected change in near-surface temperature for RCP8.5 (see Table C-2) as an example, regions in Figure C-1 that are approximately 4 °C warmer than Laxemar at present day are analogous to the future projected Laxemar in terms of temperature. Similarly, for the precipitation rate, regions in Figure C-2 which have approximately 12 % more precipitation than in Laxemar at present day are analogous to the future projected Laxemar for RCP8.5 in terms of precipitation.

To facilitate the identification of regions which are analogous to the future projections for Kalmar Län both in terms of temperature and precipitation, a complementary set of maps were produced. In these, analogous climate is defined by requiring that the near-surface temperature is within ± 1 °C *and* that the precipitation rate is within ± 10 % of the future climate projected for Laxemar. Thus, defined regions with analogous summer climate to the future projected climate in Laxemar for the RCP4.5 and RCP8.5 scenarios are displayed in Figures C-3 and C-4, respectively.

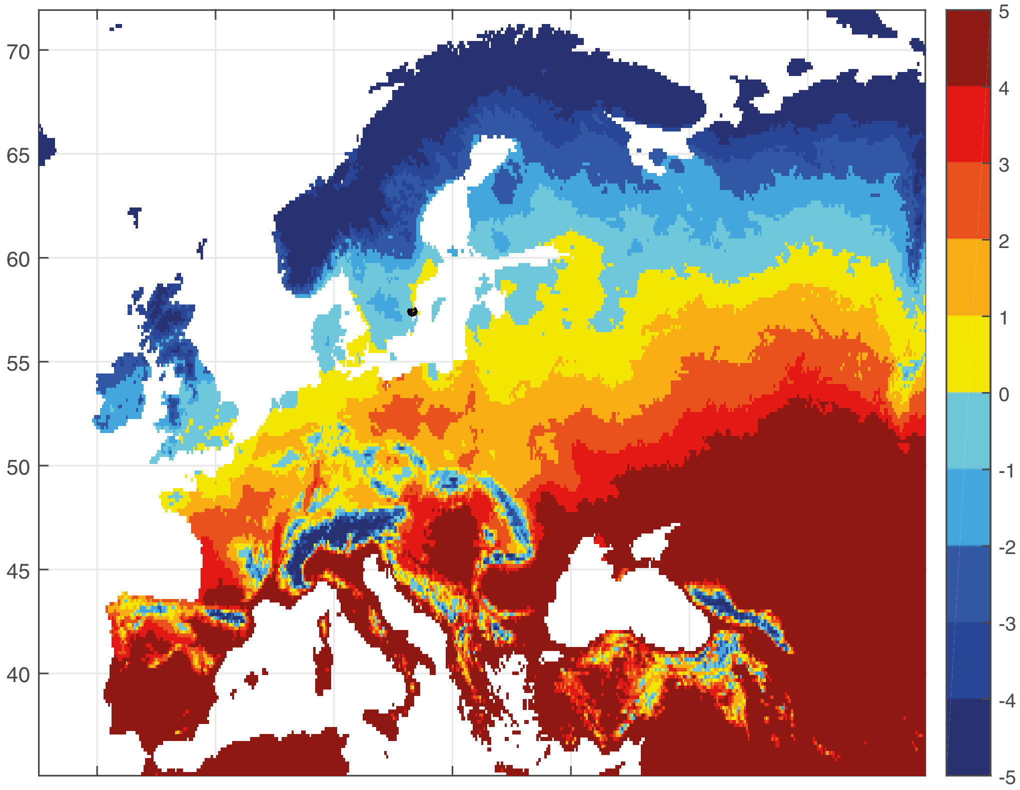

Figure C-1. *The difference in the 30-year summer (June–August) average near-surface temperature (°C) for the normal reference period (1961–1990) and the corresponding value for the gridpoint closest to Laxemar for the same period.*

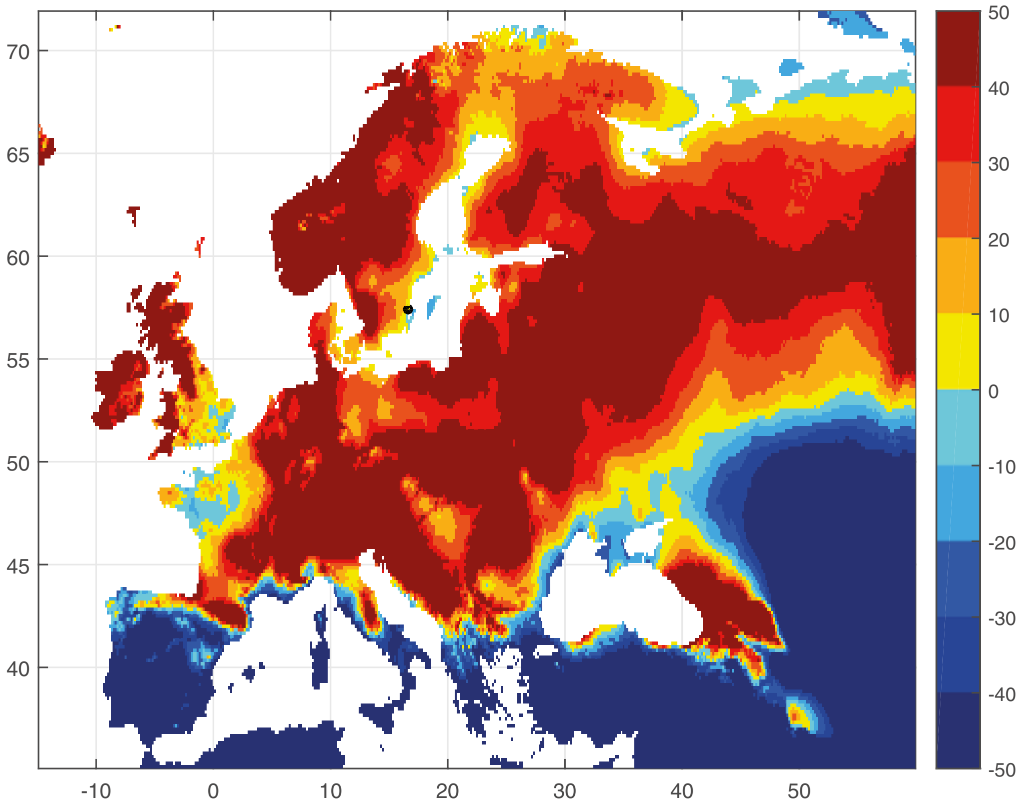

Figure C-2. *The difference in the 30-year summer (June–August) average precipitation (%) for the normal period (1961–1990) and the corresponding value for the gridpoint closest to Laxemar for the same period.*

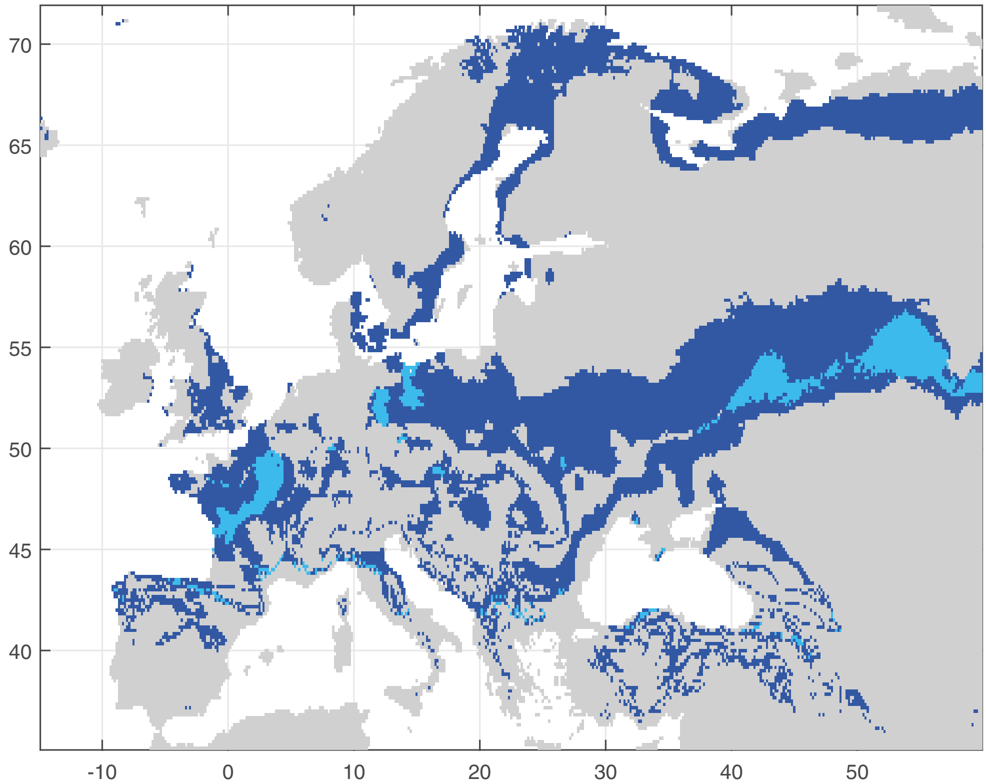

Figure C-3. *Regions with a present-day near-surface summer (June–August) temperature within ± 1 °C and precipitation rate within ± 10 % of the future projected in Kalmar Län for RCP4.5 (light blue). Regions that are within the defined range for either temperature or precipitation are also shown (dark blue).*

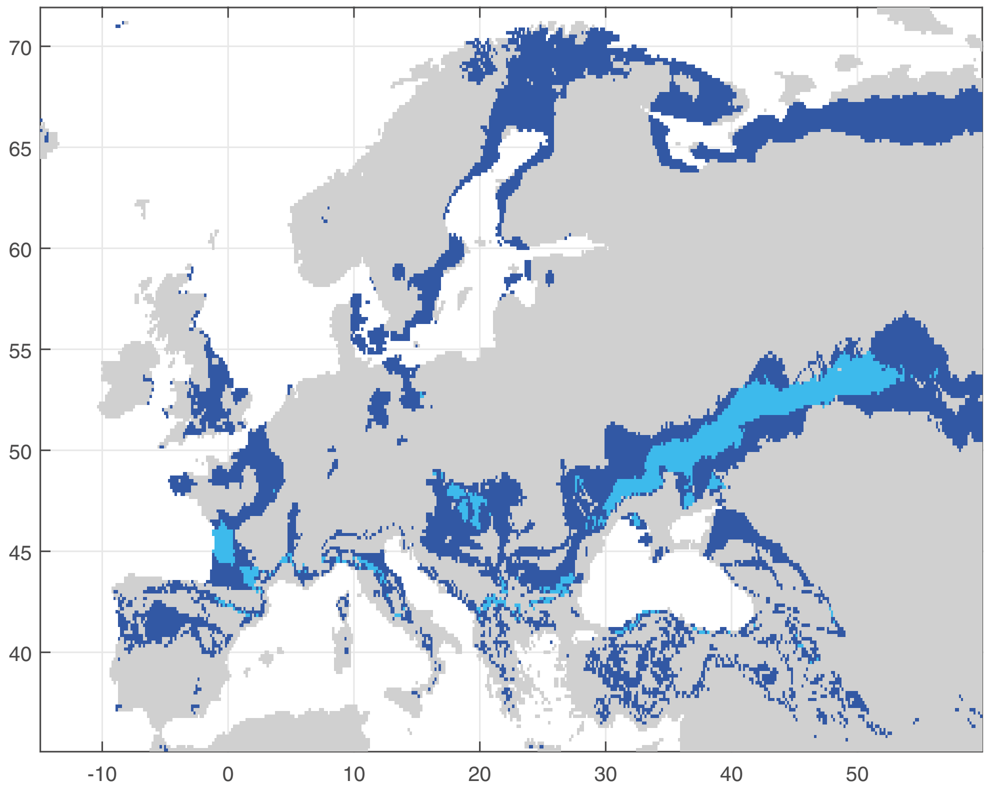

Figure C-4. *Regions with a present-day near-surface summer (June–August) temperature within ± 1 °C and precipitation rate within ± 10 % of the future projected in Kalmar Län for RCP8.5 (light blue). Regions that are within the defined range for either temperature or precipitation are also shown (dark blue).*

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SKB is responsible for managing spent nuclear fuel and radioactive waste produced by the Swedish nuclear power plants such that man and the environment are protected in the near and distant future.

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