

Application of Climate Modelling to Assess the Robustness of Safety Statements and Scenario Uncertainties for the Disposal of High-Level Radioactive Waste



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Application of Climate Modelling to Assess the Robustness of Safety Statements and Scenario Uncertainties for the Disposal of High-Level Radioactive Waste

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Abstract

This final report presents the results of the REDUKLIM project, which investigated the influence of future climate developments on the long-term safety of a deep geological repository for high-level radioactive waste. The project aimed to identify and reduce uncertainties in safety assessments by combining global climate modelling, regional groundwater simulations, and sensitivity analyses.

Key objectives and findings:

- Climate Modelling: Using the Earth system model CLIMBER-X, plausible climate scenarios for the next one million years were constructed, considering both natural evolution and anthropogenic emission scenarios. Results suggest that intermediate emission scenarios could delay the onset of the next glaciation to 100,000 years, while high cumulative CO₂ emissions may postpone it for nearly 200,000 years.
- Impact on Biosphere Dose: Climate conditions strongly affect agricultural irrigation needs and, consequently, the mean additional effective annual dose for a representative person of the population. Warmer scenarios increase irrigation deficits and potential radiation doses, whereas colder scenarios significantly reduce radiation exposure.
- Stylised Climate States: Derived from model outputs, six representative climate states (temperate, permafrost, glaciation, glaciation with permafrost, erosion valleys, and sea level rise) were implemented in groundwater models to assess their impact on repository safety.
- Groundwater Modelling: Long-term simulations show that glaciation can increase hydraulic gradients and therefore accelerate the radionuclide transport from the repository and the host rock. Other climate states, such as permafrost or sea level rise, have comparatively minor effects.
- Sensitivity Analysis: Among all parameters in the groundwater models, sorption and diffusion coefficients exert the greatest influence on radionuclide transport. With the sensitivity analysis it can be said that climate states play a secondary role compared to these material properties.

Climate evolution is relevant for long-term safety but less critical than uncertainties in host rock properties. The results provide valuable input for site selection and safety case development by illustrating extreme conditions and their potential impact. Sensitivity analysis proved to be an effective tool for uncertainty quantification and prioritisation of research needs. In this final report, the results from all work packages (WP) are presented in a short form of the interim reports.

Preface

As part of REDUKLIM, two doctoral students were funded to work on topics related to the research questions. This report was mainly written by the two PhD students Christine Kaufhold and Marc Johnen and contains results that are part of their dissertations. As this report is being published prior to the submission of the corresponding dissertations, the chapters primarily authored by the dissertation's contributor are listed below. These chapters may also appear in a forthcoming monograph. This approach ensures that copyright for the written sections are attributed to the respective authors, allowing the texts to be incorporated into the dissertation. The chapters in question and written by Marc Johnen are: 2.1, 2.2, 2.3, 3, 5, 6, 7.3, and 7.4. The chapters in question and written by Christine Kaufhold are: 4.1, 4.2, 4.3, 4.4, and 7.1.

Kurzfassung

Der Abschlussbericht fasst die Ergebnisse des Projekts REDUKLIM zusammen, das den Einfluss zukünftiger Klimaentwicklungen auf die Langzeitsicherheit eines Endlagers für hochradioaktive Abfälle untersucht. Ziel war es, Unsicherheiten in der Sicherheitsbewertung zu identifizieren und zu reduzieren, indem globale Klimamodelle, regionale Grundwassermodelle und Sensitivitätsanalysen kombiniert wurden.

Schwerpunkte des Projekts:

- Klimamodellierung: Mit dem Erdsystemmodell CLIMBER-X wurden Szenarien für die nächsten 1 Mio. Jahre berechnet. Dabei wurden natürliche Entwicklungen und anthropogene Emissionsszenarien berücksichtigt. Die Ergebnisse deuten darauf hin, dass mittlere Emissionsszenarien den Beginn der nächsten Glazial auf etwa 100.000 Jahre verzögern könnten, während hohe kumulative CO₂-Emissionen diese um nahezu 200.000 Jahre verzögern könnten.
- Auswirkungen auf die Biosphäre: Klimatische Bedingungen beeinflussen maßgeblich den landwirtschaftlichen Bewässerungsbedarf und damit die mittlere zusätzliche effektive Jahresdosis einer repräsentativen Person der Bevölkerung. Wärmere Szenarien erhöhen die Bewässerungsdefizite und potenzielle Strahlendosen, während kältere Szenarien die Strahlenexposition deutlich verringern.
- Ableitung von Klimazuständen: Aus den Modellierungen wurden stilisierte Klimazustände (Permafrost, Vergletscherung, Meeresspiegelanstieg, Erosion) für die Sicherheitsanalyse abgeleitet.
- Numerische Grundwassermodelle: Simulationen über 1 Mio. Jahre zeigen, dass Vergletscherungen den hydraulischen Gradienten und damit den Transport aus dem Wirtsgestein erhöhen können. Die Klimazustände Meeresspiegelanstieg und Permafrost zeigen vernachlässigbar geringe Effekte auf den Radionuklidaustrag aus dem Wirtsgestein.
- Sensitivitätsanalyse: Den größten Einfluss auf den Radionuklidtransport aus dem Wirtsgestein haben Sorptions- und Diffusionskoeffizienten. Der Einfluss der Klimazustände ist gegenüber den Parameterungewissheiten in Bezug auf den Radionuklidaustrag gering.

Klimatische Entwicklungen sind für die Langzeitsicherheit relevant, aber ihre Auswirkungen auf den Radionuklidtransport sind geringer als die Parameterunsicherheiten im Wirtsgestein. Die Ergebnisse unterstützen die Standortauswahl, indem sie zukünftige Klimaentwicklungen und deren Einfluss auf die Sicherheitsnachweise quantifizieren. Sensitivitätsanalysen zeigten sich als ein wirksames Instrument zur Bewertung von Unsicherheiten und zur Priorisierung weiterer Forschung in Bezug auf bestimmte Parameter im Wirtsgestein.

In diesem Abschlussbericht werden die Ergebnisse aller Arbeitspakete (WP) in einer Kurzfassung der Zwischenberichte vorgestellt. Teilweise sind die Arbeitspakete ausführlicher in den entsprechenden Zwischenberichten beschrieben, sodass das vorliegende Dokument als Synthesebericht aller Arbeiten im REDUKLIM Projekt angesehen werden kann.

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1 Purpose of the report

The Ordinance on Safety Requirements on the final disposal of highly radioactive waste in Germany (Endlagersicherheitsanforderungsverordnung) defines the safety requirements of the deep geological final repository (EndlSiAnfV 2020). The assessment period for the safety requirements is set up to 1 million years after § 3 EndlSiAnfV 2020 and all future evolutions with relevance to the geological situation and the long-term safety case must be depicted in expected or deviating evolutions. The radioactive waste to be stored shall be concentrated and safely contained in the repository system with the aim of keeping the radionuclides away from the biosphere for at least the assessment period. The design of the containers and the repository must therefore ensure safe containment for a period during which a multitude of endogenous and exogenous processes can affect the Earth and the repository system. The EndlSiAnfV defines further requirements for the repository, non-compliance with which will result in exclusion of the site in the site selection process. In order to accept these requirements for individual sites as given, sufficient knowledge must be gained about the site as well as about the impacts of the respective processes. Regarding safety requirements, no absolute certainty can be predicted about single climate evolutions over a period of one million years. But on the basis of the current state of knowledge on climate variations in the past, predictions with varying degrees of uncertainty can also be made for individual climate scenarios, even for the long periods of time required by the safety requirements (Näslund et al. 2020).

A broad range of processes can influence the integrity of a final repository system within a period of one million years. On this time scale, there are several different drivers of climate change. The main drivers are changes in Earth's orbital parameters, solar radiation, plate tectonics, volcanism, atmospheric parameters and other biogeochemical or nutrient cycles which affect the climate. These can be affected by anthropogenic factors like elevated carbon emissions (Archer & Ganopolski 2005; Lord, Lunt & Thorne 2019), which can then cause changes in the climate domains over different timescales. The most important naturally occurring external factors affecting a repository system over thousands of years appear to be permafrost, ice sheets, glaciations and change in relative sea level (Näslund et al. 2020).

The main focus of the URS research cluster and the REDUKLIM project was the identification and quantification of uncertainties. The uncertainties surrounding the influence of processes and parameters were addressed and partially quantified in the global climate and regional generic groundwater models.

The publications and reports describe the different aspects of the respective models and answer the following research questions:

1. When will the next glacial period begin, and how does the timing of the next glacial advance depend on cumulative anthropogenic CO₂ emissions? Which regions of Germany will be affected, and to what extent? How great are the uncertainties?

2. Will the glacial cycles within the next million years differ significantly from those of the last million years? Is it possible that instead of regular 100,000-year cycles, much longer glacial cycles with more extensive ice advances will occur?
3. How can the results from climate modelling be converted into stylised climatic conditions that need to be considered when assessing the dose estimate?
4. What implications do the results of the climatic model calculations have for the uncertainties regarding the safe confinement of radionuclides in a repository for high-level radioactive waste?

The report is organised into several chapters. Chapter 2 describes the factors that influence the Earth's climate, explains the basic mechanisms behind these processes, and considers the different time scales relevant to climate scenarios. Chapter 3 discusses possible climate developments that may be caused or reduced by the factors described above. Chapter 4 presents the results of climate modelling using the CLIMBER-X model, together with the outcomes of dose calculations, where specific parameters from CLIMBER-X were used as input. Chapter 5 outlines the structure and presentation of climate developments, as well as the calculation results of the regional groundwater model. Finally, Chapter 6 examines the uncertainties and sensitivities of selected model parameters using different evaluation methods.

This report synthesises research on potential future climate impacts on nuclear waste repository systems performed in the REDUKLIM project. Climate developments are key factors in site selection, requiring a broad understanding of possible scenarios. Although precise predictions are impossible, data from research projects, experiments, and modelling approaches help constrain uncertainties and estimate scenario probabilities. By integrating findings into models such as Earth system models of intermediate complexity (EMICs) and regional groundwater simulations, the range of uncertainties can be reduced. The report consolidates all results from the REDUKLIM project, providing a comprehensive basis for assessing long-term climate influences on repository safety.

In order to address these and several other objectives, the Bundesgesellschaft für Endlagerung (BGE) established the “Uncertainties and Robustness with regard to the Safety of a repository for high-level radioactive waste (URS)” research cluster dedicated to investigating various aspects of uncertainty and funded it, with the overarching aim of enhancing the robustness and, consequently, the safety of a repository. This initiative encompasses both the advancement of the current understanding of uncertainties and the development of methodologies for their systematic management. The research cluster comprises six research consortia, each focusing on distinct questions related to the treatment and mitigation of uncertainties.

Interaction between the URS projects

During the duration of the URS project, connections were established with the other project partners in various ways. Personal meetings at different technical and organizational levels led to a constructive dialogue. At the URS Cluster Retreat, the objectives for the URS Cluster were further defined and the idea for a joint publication was discussed. The URS workshops led to a scientific and personal exchange between the project members. In the course of these meetings and conferences, individual exchanges on the possible implementation of methods and applications of other URS project partners were encouraged, even if the attempts to implement the methods did not always lead to the use of the application in the project itself. At various conferences (Site selection days, SafeND, EGU General Assembly), the research cluster was able to meet and address the topic of uncertainties related to the final repository research, and to present results thanks to the large number of employees involved. In the course of the REDUKLIM project, questionnaires from the ENSURE research network were repeatedly answered, investigating the uncertainties of human action.

2 Impact of climate modelling and uncertainties on the development of a final repository system

2.1 Compilation of the important impacts of climate change on long-term safety

Climate is defined as the mean and variability of certain variables like temperature, precipitation and wind over a period of time ranging from month to millions of years (WMO 2021). Climate is variable, and changes over millions of years. Typically, climate changes are assessed over a 30-year period set by the World Meteorological Organisation (WMO) to map a "normal state" and identify trends (WMO 2017). However, these time periods are too short for this report, so climate evolutions must be considered on larger time scales. The changes are driven by different factors which are influenced by orbital parameters, endogenous processes on the Earth and partly anthropogenic influences. While the climate evolution is critical for the safety assessment of deep geological repositories (Lord, Lunt & Thorne 2019), the driving factors and their periodicity are described below. These driving factors affect the climate on different timescales (Table 1).

Table 1: Important factors of climate formation and their effective time span taken from Noseck et al. 2008.

Time [a]	10 ⁻¹	10 ⁰	10 ¹	10 ²	10 ³	10 ⁴	10 ⁵	10 ⁶	10 ⁷	10 ⁸	10 ⁹
Extraterrestrial											
Galactic dust											
Solar activity											
Earth orbit parameter											
Terrestrial											
Plate tectonics											
Isostasy											
Ocean circulation											
Atmosp., ocean, ice, land feedback loops											
Atmospheric dust/ Aerosols											

In this chapter the driving factors of climate will be described. Some issues and their associated processes have a significant impact on the long-term safety of a final repository system, whereas others are negligible, but all are nevertheless explained.

All of what is presented in this work is an attempt to describe the state of climate science and research, and to give possible future scenarios within the large range of uncertainties. All mentioned scenarios and assumptions are more or less likely scenarios, and

cannot be seen as a forecast for the future climate. The system is highly complex, and some processes are well understood, whereas others are not (or poorly) understood with low reliability on the data or high uncertainties. Therefore, it is currently not possible to construct a precise model with all processes. Furthermore, there can be more correlations between different climate drivers which are not possible to model with the actual knowledge, are not described as equations by now or as numerical models considering actual CPU capacities. On the other hand, the knowledge of the past and today can be used to give good estimates to possible future evolutions, also over long time periods (Näslund et al. 2020).

2.2 Extraterrestrial factors

2.2.1 Solar radiation

The solar radiation (insolation) is conditioned by the orbital parameters (Milankovitch cycles) which can be described by a solar constant. Currently the solar constant is between $1,325 \text{ W m}^{-2}$ and $1,420 \text{ W m}^{-2}$, with the average value being $1,361 \text{ W m}^{-2}$ since 2015 (Mamajek et al. 2015; Prša et al. 2016). This solar energy decreases with lower incidence angles, and with more higher cloud cover in the Earth's atmosphere (Quaschnig 2003). On average the albedo effect reflects around 20 % of the global irradiance (Quaschnig 2003). The 11 years sunspot cycle has a very low impact on the long-term climate ($<0,1 \%$) (Schurer, Tett & Hegerl 2014).

2.2.2 Earth's orbital parameters

According to the safety requirements and the associated assessment period of one million years, astronomical influences (i.e., orbital parameters) also have to be considered, as they have influenced the past climate and will therefore very likely the future climate (Rahmstorf & Schellnhuber 2019; Lord, Lunt & Thorne 2019). The relevant astronomical influences can be divided into three processes: eccentricity of the Earth's orbit, the precession, and the obliquity (Milankovitch 1941; Berger 1988; Barker et al. 2025). Together, they influence the strength of solar radiation and show a clear cyclicity that was first described by Milutin Milankovitch (Milankovitch 1941; Berger 1988). The three parameters and their influence on the climate will be described further below.

Eccentricity describes the extent of the elliptical orbit around the sun (Lord, Lunt & Thorne 2019). The Earth's eccentricity over time varies between 0.054 and 0.001 (Imbrie & Imbrie 1980). Presently, the eccentricity of the orbit is 0.017 so that the distance between the Sun and Earth varies between 147.1 million km at the perihelion (shortest distance to Sun) in January and 152.1 million km at the aphelion (longest distance to Sun) in July (Boblest, Müller & Wunner 2016). This distance differences lead to a about 6.8 % stronger incoming solar radiation in January in comparison with July (Buis 2020). The cycle time is around 95,000 and 125,000 years (Zachos et al. 2001). There is also

another 400,000-year cycle in eccentricity, which is thought to have contributed to the unusually long interglacial period around 400,000 years ago and may also explain the extended interglacial conditions observed today.

Precession is the gyroscopic motion of the Earth due to the gravitational forces of the Moon and Sun which influence the tidal forces. One cycle takes about 25,771 years and has impact on the seasonal contrast in the Northern and Southern Hemisphere (Buis 2020). Currently perihelion is during winter in the Northern Hemisphere (NH) and moderates the seasonal variations there (Buis 2020).

Obliquity describes the angle of the rotation axis which differs from the plane of the Earth orbit around the Sun (Lord, Lunt & Thorne 2019). The cyclicity of the obliquity is about a period of 40,000 years and an angle between $24^{\circ}36'$ and $21^{\circ}55'$. Similar to eccentricity, also the obliquity influences the strength of the seasons. A greater angle in obliquity leads to a larger contrast between seasons. When obliquity is small, the probability for an glaciation is larger because summer solar radiation in high northern latitudes is smaller (Lourens et al. 2010).

While eccentricity affects the total incoming radiation (to a small degree), radiation distribution and has impact on the precession parameter, it is the precession and obliquity parameters that modify the latitudinal and seasonal distribution of radiation (Lord, Lunt & Thorne 2019).

In the next 100,000 years, there will be a low summer insolation at 65° N at about 16,000, 53,000, 77,000 and 97,000 years after present (AP). These insolation minima increase the probability for a glacial cycle to begin (i.e. glacial inception). On the other hand, increased radiative forcing at other times leads to higher CO_2 concentrations, which can potentially delay one or more glacial cycles (Lord, Lunt & Thorne 2019).

2.3 Terrestrial factors

2.3.1 Plate tectonics, ocean circulations and isostatic adjustment

Plate tectonics is responsible for the land ocean distribution and formation of mountains. These impacts can help to provide conditions which is favourable for the growth of ice sheets and glaciations due to changes in the air and ocean streams as well as the moisture supply to these regions (Noseck et al. 2008). Due to the long timescales on which plate tectonics changes, it is not included in the safety assessment and can be neglected unless there is a significant change in ocean stream like the Panama Isthmus closure around 2.7 million years ago (Noseck et al. 2008; Lord, Lunt & Thorne 2019).

Glacial isostatic adjustment, as a result of the pressure from forming or melting ice sheets, and sea level changes can change the environmental condition of a potential

repository. Falling sea level or a region with positive uplift rate can lead to another land use (e.g. agriculture, urban use etc.) which can have negative effects on repository safety. Positive uplift rates can cause higher erosion rates and affect the containment-providing rock zone (CRZ) on long timescales.

2.3.2 Volcanism

Volcanism can have different kind of impacts to a final repository or to the safety assessment. Magma plumes in the Earth's crust can influence heat conditions in a repository. Additionally, volcanic eruptions and the formation of caldera can have direct consequences to the region. These regional consequences can be excluded by the regulations from the site selection process in Germany (Standortauswahlgesetz – StandAG 2020). However, the short term climate impact of an erupting super volcano cannot be ruled out (Lord, Lunt & Thorne 2019), and ash and soot from an eruption can lead to a cooler climate for decades. Additionally there is a diffuse influence through volcanic outgassing all around the world where greenhouse gases (GHGs) can be emitted into the atmosphere (Bebbington 2020). While this is often regarded as the “background” state that holds the climate system in equilibrium, it nevertheless has the potential to affect the future climate if a disequilibrium develops.

Volcanic eruptions cannot be predicted. This results in the problem that volcanism cannot be adequately represented in climate models using current methods. Thus, volcanic eruptions are not considered in climate models with long simulation periods until now. So, the question remains what impact the frequency of future volcanic eruptions will have (Ribbert et al. 2012).

2.3.3 Atmospheric parameters

Astronomical forcing determines the average climate conditions, although the yearly average radiation is can be different due to internal variability (Lord, Lunt & Thorne 2019). This variability is due to seasonal orbital forcing, and the feedback of this orbital forcing on the carbon and other cycles, however, it is not fully understood due to several competing factors (Lüthi et al. 2008). Glacial periods correlates with low CO₂ and CH₄ concentrations, however, the processes and mechanisms are not fully understood (Lüthi et al. 2008). In Ciais et al. 2013, different mechanisms and processes such as temperature, iron fertilisation, ocean circulations, solubility boundaries or biochemical processes are also mentioned to contribute to the impact on the climate.

Human civilisation affects CO₂ and other GHG concentrations in the atmosphere by land use change, an increasing construction industry and reliance on fossil fuels (Lord, Lunt & Thorne 2019; Friedlingstein et al. 2021). There is also an uncertainty in future climate change due to the relative partitioning of anthropogenic CO₂ in the atmosphere, ocean and land that has been seen over the last decades (Friedlingstein et al. 2021).

Furthermore, models show a long lifetime of CO₂ in the atmosphere (Lord, Lunt & Thorne 2019) and impacts cannot clearly be described because there is no comparable GHG increase in climate archives (Committee on Radiative Forcing Effects on Climate 2005).

Following Lenton & Britton 2006 and Colbourn, Ridgwell & Lenton 2015, a period of up to around 1 million years is needed to return to the pre-industrial (PI) CO₂ concentration depending on the future anthropogenic emissions. It's important to note that the cumulative emission is relevant for the resulting climate impact, not the emission rate (Eby et al. 2009). Besides an increase of CO₂ in the atmosphere, it is possible that in the future, there is widespread carbon reducing geoengineering which can have an impact on the climate (UBA 2011; Lord, Lunt & Thorne 2019).

2.4 Anthropogenic scenarios for the deep future

In recent decades, however, the influence of human activity on the climate, mainly through the emission of CO₂ and other well-mixed GHGs, has become the dominant climate forcing. As a result, it has been proposed to introduce a new geological epoch, the Anthropocene, which began after the Holocene around 1950 CE (Steffen et al. 2011; Summerhayes et al. 2024). Although this proposal has not yet been accepted by the geological community (e.g., Carrington 2024), the result of model simulations suggests that, due to a very long residence time of anthropogenic CO₂ (Archer, Kheshgi & Maier-Reimer 1997), the Anthropocene may last much longer than the Holocene, which would naturally end in about 50,000 years (Loutre & Berger 2000; Paillard 2001; Archer & Ganopolski 2005; Cochelin, Mysak & Wang 2006; Mysak 2008; Crucifix & Rougier 2009; Herrero, García-Olivares & Pelegrí 2014; Haqq-Misra 2014; Ganopolski, Winkelmann & Schellnhuber 2016; Talento & Ganopolski 2021). Therefore, making plausible projections for the deep future¹ requires making assumptions about the possible duration of the Anthropocene, which is primarily controlled by future human CO₂ emissions and the potential removal of such emissions. Such a prominent role of CO₂ in the long-term future is primarily explained by its very long residence time in the atmosphere compared to other anthropogenic forcings.

Future emissions of CO₂ and other GHGs cannot be accurately predicted, even over a few decades. Due to the increasing role of carbon dioxide removal technologies, the cumulative amount of future emissions cannot be predicted. Therefore, the full diversity of possible future emission scenarios can be grouped into three distinct types of long-term scenarios.

¹ Long timescales from 1,000-100,000 years

2.4.1 Short Anthropocene

The first is the so-called “Short Anthropocene”. This scenario assumes that, after a period of positive CO₂ emissions, humans will introduce massive carbon sequestration technologies, and the net CO₂ emissions will become negative and, after a period of time, most of the anthropogenically emitted CO₂ will be permanently stored in one form or another (Brunner, Hausfather & Knutti 2024). In this case, the future climate trajectory will gradually converge to the natural one. Based on modelling studies, this scenario requires that the amount of anthropogenic CO₂ remaining in the atmosphere–ocean–biosphere system should not exceed the amount already emitted of about 500 PgC (490 ± 25 PgC; Friedlingstein et al. 2025). If such a reduction is achieved within a relatively short period of time (i.e., <1,000 years), the long-term trajectory of the Short Anthropocene would not differ significantly from the natural scenario. In this case, the Short Anthropocene is closer to the definition of a “event” rather than an “epoch”, since even the shortest geological epoch, the Holocene, lasted already more than 10,000 years. Should carbon sequestration technologies fail to be implemented, or prove to be ineffective, it could mean certain temperature commitment which would lead to the following case (Anderson & Peters 2016).

2.4.2 Long Anthropocene

The second option is the “Long Anthropocene”. Like most studies of the deep future, this scenario assumes that emissions of all climate-relevant substances and massive land-use changes will cease completely within a one or several centuries, and that some (but not all) of the emitted CO₂ will be permanently stored. If all anthropogenic activities that can change the atmospheric CO₂ concentration cease at some point, the future evolution of the Earth system can be predicted considering only natural processes, but if the remaining cumulative amount of CO₂ (defined as cumulative CO₂ emissions minus permanently stored carbon) is of the order of 103 PgC or more, an extremely long deviation of the Earth system trajectory from a natural one can be expected. Previous modelling studies (Archer & Ganopolski 2005; Ganopolski, Winkelmann & Schellnhuber 2016) indicate that the next glacial cycle can be delayed by 50,000 years or more (compared to the natural scenario), depending on the cumulative CO₂ emission. Such studies utilise an ensemble of idealised cumulative CO₂ emission scenarios, ranging from historical carbon emissions (500 PgC) to the total estimated fossil fuel reserves (~5,000 PgC, Lal 2008; McGlade & Ekins 2015). Our recent work (Kaufhold et al. 2025b) also shows that the timing of the next glacial cycles depends not only on cumulative CO₂ emissions, but also on the way the carbon cycle model is initialised, which introduces additional significant uncertainties. In any case, the duration of the Anthropocene of 100,000 years or much longer would qualify the Anthropocene not just as an Epoch of the Quaternary Period, but rather as a significant hiatus in the Quaternary Period, since the only climatologically meaningful definition of the Quaternary is the period of regular glacial cycles, and there is no evidence that interglacial conditions lasted anywhere near 100,000 years

during the entire Quaternary. More importantly, the resumption of glacial cycles after a certain period of time does not imply a rapid return to the pre-Anthropocene mode of climate variability, since the influence of elevated CO₂ levels will affect the climate variability at least during several glacial cycles, which are expected to be weaker and possibly shorter than the glacial cycles of the late Quaternary. Because of all the uncertainties involved, the Long Anthropocene is only qualitatively predictable, but the most likely scenario is a (nearly) ice-free NH for the next 100,000 years and a gradual return to the Late Quaternary mode of climate variability during the next 500,000 to 1,000,000 years.

2.4.3 Permanent Anthropocene

The third scenario is the “Permanent Anthropocene”. This scenario can be interpreted in two ways. Firstly, there is the potential prospect of runaway warming. In Steffen et al. 2018, it was highlighted that even relatively modest anthropogenic emissions may destabilise the climate system by amplifying strongly nonlinear positive feedbacks (such as permafrost thaw, land biosphere degradation, and declining Arctic albedo). The interaction of these processes could set off a cascade of self-reinforcing feedbacks, ultimately driving the Earth system toward a “Hothouse” state. So far, there is no modelled evidence that a Hothouse Earth could happen under present-day boundary conditions – even under an excess of 15,000–20,000 PgC in the atmosphere (approximately 3–4 times our current estimated fossil fuel reserves; Lenton & Britton 2006; Lord et al. 2016).

A second pathway toward a permanent Anthropocene is the idea that future humans will take full control of climate evolution, and the Earth system will never return to its natural trajectory; implying that massive NH glaciations will never occur again. In this case, the Anthropocene cannot be considered an epoch, but rather a period or even a larger geological unit. While this scenario may appear implausible, it remains technologically viable even with present-day capabilities. According to the critical insolation – CO₂ relation (Ganopolski, Winkelmann & Schellnhuber 2016; Talento, Willeit & Ganopolski 2024), the prevention of future glaciations would necessitate maintaining CO₂ concentrations at approximately 350–400 ppm, i.e., lower than current levels. Achieving such stabilisation would require CO₂ emissions amounting to only a fraction of present-day values, a quantity comparable to emissions from cement production alone (5–8%; Ige, Kallon & Desai 2024). However, the long-term persistence of human habitation on Earth and sustained commitment to climate stabilisation are questions beyond the scope of natural science, and therefore, will not be discussed here.

3 Possible climatic geomorphological processes

The aforementioned factors influencing the climate lead to different climatic conditions, which are reflected by cold or warm periods and their associated global or regional processes. Temperature and pressure play fundamental roles in this context, and can either be independent factors or driving forces for the development of, for example, permafrost, glaciers, sea level fluctuations, changes in permeability, groundwater flow or chemical conditions. These factors and the associated processes can have an impact on the long-term safety of a final repository system. All these processes have been observed during the Quaternary glacial and interglacial phases based on various research studies (Cohen et al. 2022; Oliva, Nývlt & Fernández-Fernández 2022; Fraedrich 2023; Palacios et al. 2023b; Palacios et al. 2023a). Although the observation of the past cannot be used to make clear predictions for the future, especially regarding anthropogenic influence, assumptions and scenarios with different probabilities can be derived. After a description of the processes, their influence on the geosphere is summarised in *Table 2*.

3.1 Glaciers and ice sheets

Glaciers and ice sheets are accumulations of snow with different characterizations (Näslund et al. 2020). In general, ice sheets have bigger spatial extents and spread to all directions from higher elevations. Glaciers grow in their extent up to 100 km², but they are often confined by the topography. The growth of glaciers and ice sheets occurs when the accumulation of snow is higher than the melting rate. The melting of glaciers and ice sheets (~10,000 years) can occur faster than the growth (~100,000 years).

As glaciers and ice sheets grow from higher elevations, and generally melt at lower elevations, there naturally arises a line between the area where it grows and where it shrinks. This is known as the equilibrium line, with the melting area called the ablation zone, and the growing area called accumulation zone. The borders of glaciers and ice sheets are always changing and never in a steady state since the climate is constantly changing. The temperature has fundamental importance for the ice dynamics. Within the ice, different temperature and pressure conditions can occur and glaciers/ice sheets can be classified accordingly. While glaciers with temperatures at the pressure melting point throughout the year are considered as temperate/warm ice glaciers, glaciers with temperatures below the pressure points throughout the year are called polar/cold ice glaciers, and have harder and less permeable ice. At the glacier bed there can be cold based conditions with no free water and without movement or sliding of the ice. This situation is mostly found in areas with higher ice thickness in the accumulation zone. Warm based conditions are found around the pressure melting point at the glacier/ice sheet bed with free water so there can be sliding over substrate. In melting areas, the surface runoff and the groundwater recharge rate increase and are accompanied by strong morphological changes around the glacier front. These characteristics are important for deep geological

repositories because they have an impact on the interaction with the underlying rock and thus for the repository safety.

Glaciers and ice sheets always result in a mechanical load for the underlying rock. With increasing ice thickness and spatial extent this mechanical load increases and influences the underlying rock in different ways. For sediments, there can be a possible reduction in pore space, or the ice load can cause fractures in the subsurface. Due to higher pressure at the rock surface, temperature and pressure conditions can be above the pressure melting point and no permafrost could be under the ice sheet. Also, the advance and retreat of the glacier can have an influence on the mechanical stability of the underlying rock units and the shape of the relief, for example, the formation of glacial valleys.

3.2 Glacial hydrogeology

Glacial hydrogeology describes the storage and transport of water, snow, or ice on the glacier surface, or in englacial and basal glacier areas. Numerous processes influence the hydrogeology in a glacier at several spatial and time dependent scales (Näslund et al. 2020). The progression of the solidus in the pressure-temperature phase diagram has a negative nonlinear slope, so freezing and thawing processes can occur at different temperature or pressure conditions (Figure 1) (Wagner & Pruß 2002; IAPWS 2018). The highest discharge rates of glaciers and ice sheets are measured after “warm rain”, as cold weather periods in summer lead to a decrease in discharge (Krainer & Mostler 2002). On the ice surface, the melting rates can reach several metres per year depending on the debris thickness on the ice surface, whereas the basal melt rates reach just some mm year⁻¹ (Reznichenko et al. 2010; Pratap et al. 2015; Näslund et al. 2020). High melting rates have strong influence on the basal sliding speed due to the higher pressure conditions through high meltwater supply (Benn et al. 2009).

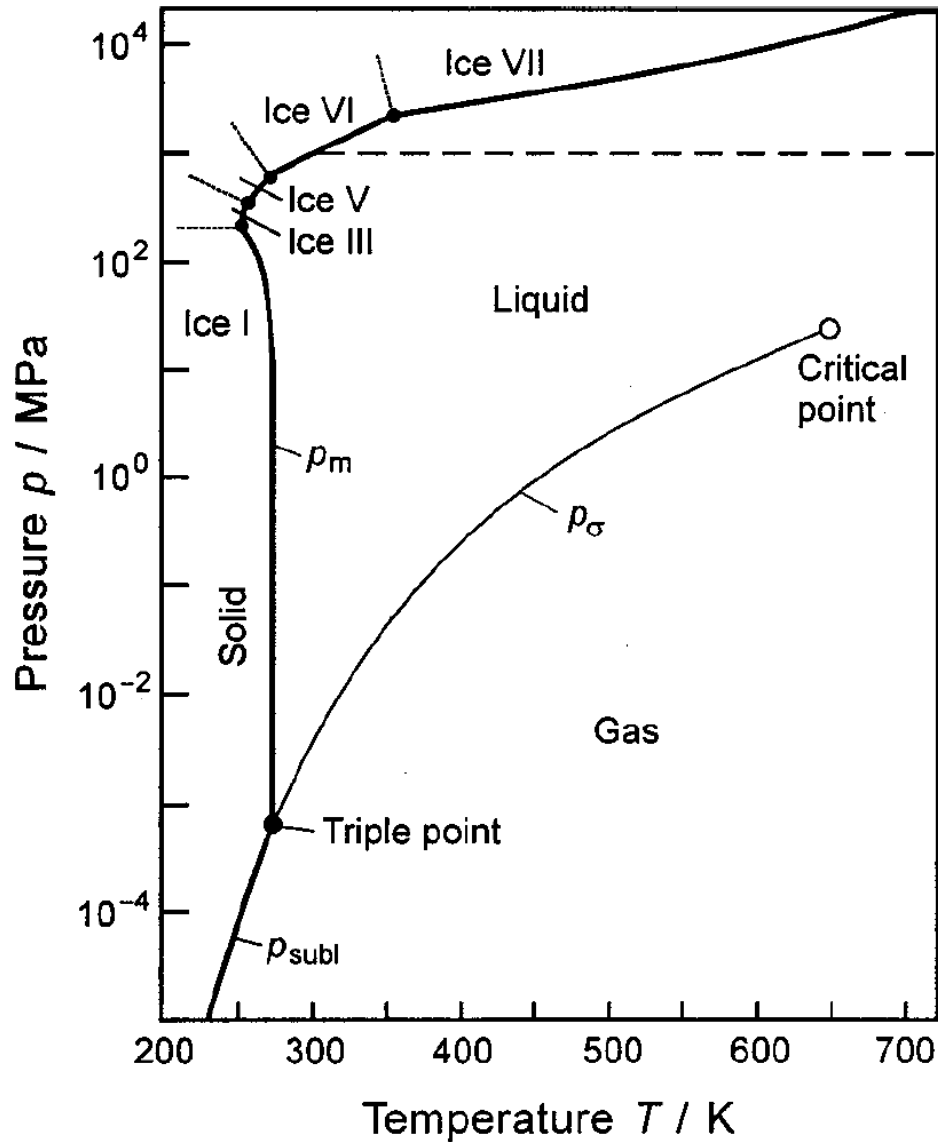


Figure 1: The phase-boundary curves of water in a p – T diagram taken from Wagner & Pruß 2002.

3.2.1 Conduits and crevasses

In Antarctica and Greenland, subglacial lakes have been found inside the ice sheets. In contrast, the existence of subglacial lakes beneath the former Fennoscandian ice sheet is not proven (Näslund et al. 2020). This additional storage of water increases the complexity of the glacial system. The conduits and crevasses can be compared to a karst groundwater system, with a fast response of the ice to the water fluxes and pressure conditions. High water pressures lead to an opening of conduits, whereas low water pressures let open conduits decrease in their size through creeping processes. The propagation depth of water filled cracks are dependent on the lake size diameter and the water pressure (Krawczynski et al. 2009).

3.3 Permafrost

Permafrost can be described as subsoil whose temperature is continuously below 0 °C for at least two years (French 2007; IPA 2022). In contrast to permafrost, perennial frozen ground does not have to be under 0 °C the whole time because the texture, degree of compaction, water content and lithologic character of the material also have an influence on freezing and thawing temperatures (Näslund et al. 2020). The surface temperature presupposes the development of the permafrost depth where the pore water is frozen. Frozen pore water leads to a reduction of permeability and porosity without groundwater recharge. Permafrost is influenced by several parameters and increases the complexity of the system. Like glaciers and ice sheets, permafrost can aggregate centi- to some decimetres a year under periglacial conditions. The degradation of permafrost can be significantly faster than aggregation, especially under warmer conditions above 0 °C (Näslund et al. 2020).

3.3.1 Taliks

A talik is an unfrozen body or layer in a region of permafrost due to thermal, hydrological, hydrogeological, or hydro-chemical anomaly. Due to the dynamic temperature/pressure conditions, there can be taliks with temperatures above 0 °C, so called non-cryotic taliks, or cryotic taliks with temperatures below 0 °C. Depending on their location they can be divided into isolated/open, closed or open/through taliks depending on the literature (Figure 2). **Isolated/open taliks** are often located under a lake surrounded by permafrost. The wording “isolated” is due to the fact that the Talik is cut off from other unfrozen areas. It is considered an open talik because it has a connection to the lake and therefore to the ground surface. **Closed taliks** do not reach the surface and are completely surrounded by permafrost. They can arise from supraglacial lakes with higher temperatures than their surroundings. **Open/through taliks** are connected from an unfrozen area under the permafrost to the surface or a lake. Here, the “open” is described by the connection to the surface and to the unfrozen area below the permafrost. According to the use of the term “open talik”, “through talik” is also an open talik, but it also has a connection to the unfrozen area below the permafrost. Taliks can have strong influence on the hydraulic interaction with nearby glacier fronts and the groundwater flow.

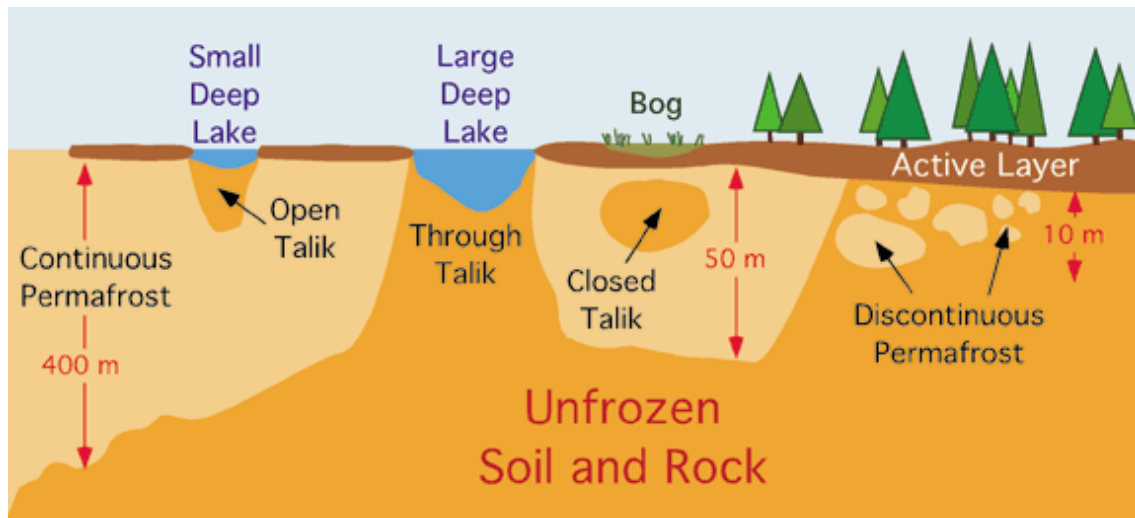


Figure 2: Schematic illustration of different types of taliks in a cross section (Pidwirny 2006).

3.4 Sea level changes

The growth and melt of global ice sheets are the primary processes responsible for sea level changes. With rising temperatures on Earth, it is expected that ice sheets will melt, and sea level will rise. In turn, growing ice sheets lead to a lower sea level. The change of the sea level has influence on the groundwater flow conditions by the trans- or regression of the shoreline. When land is above the groundwater level, the hydraulic pressures are determined by topography and groundwater recharge rates. When the land is submerged the groundwater pressure conditions are determined by the overlying water column height and might also be influenced by the density distribution of the fluids. The higher salinity of sea water can change flow directions and watersheds on large scales. In recent decades, the primary process responsible for sea level rise has been ocean thermal expansion and the melting of mountain glaciers (Palmer et al. 2020). However, in the long-term, the contribution from global ice masses will dominate, and with present climate developments there is a high probability for changing sea levels in the future.

3.5 Glacial isostatic adjustment

Distribution of mass on the planet can cause uplifts and subsidence over time scales of several tens of thousands of years. The increased or decreased loading of glaciers and ice sheets are related to glacial isostatic adjustments (GIA). The glaciers' load results in an outflow of underlying mantle material towards the glacier edge. In the process, crustal material is submerged and in the front of the glacier this shift leads to the upward movements of the mantle. The process can generally take more than 10,000 years, meaning that changes due to the loading of glaciers and ice sheets are still undergoing changes from the last deglaciation. The rebound velocity is related to the ice load and the mantle viscosity. Lower viscosity can lead to higher uplift rates despite smaller ice loss volumes.

Next to ice sheet related GIA, there is also erosion and the associated sediment transfer over time has impact on the mass distribution, but the up- or downlift rates are negligible compared to the glacial processes.

3.6 Erosion

Erosion is part of the process of surface denudation and describes the removal and transport of material by shear stress from flowing air, water or ice that initiates particle movement (Collinson 2005; Näslund et al. 2020). The moved particles can accumulate or enhance the effect of erosion by abrasion. Erosion and the resulting structures can only take place in connection with transport, and can be divided into aeolian, marine, fluvial, and glacial erosion. The type of glacial erosion depends on the ice and rock properties, thermodynamics, friction and lubrication, chemical effects and subglacial hydrology and can result in two types of glacial erosion: plucking and abrasion. Plucking is responsible for loosening, entraining, and transporting whole rock fragments of various sizes. Abrasion leads to polished rocks caused by rock fragments in the basal ice grinding over the substrate. Another erosion type is glacial ripping. In this case, the bedrock fractures get widened under a high hydrostatic pressure which leads to disruption and transport of surficial rocks (Hall & Krabbendam 2019; Hall et al. 2020).

Erosion rates vary by several orders of magnitude. Plateau glaciers on crystalline bedrock have low rates around $0.01 \text{ mm year}^{-1}$ while temperate valley glaciers can reach erosion rates around 100 mm year^{-1} . Next to the rock characteristics, the thermal regime of the glacier bed is also an important factor. During a full glacial period, the glacial erosion is estimated to be between 0.2 and 4 m depending on the duration of the glacial period and the aforementioned factors like rock characteristics (Påsse 2004). Without glacial periods, the erosion rate has been between 0 and 5 m over the last one million years (Olvmo 2010).

3.7 Subrosion

Subrosion is the leaching of soluble rocks induced below the Earth's surface by contact with underground waters. Subrosion or leaching takes place on saline rocks under the influence of slightly mineralised groundwater or groundwater undersaturated with the salts under consideration. Next to chlorides, carbonates can also be dissolved by fluids which can lead to karst structures (Jeannin et al. 2015). The leaching of carbonates on the surfaces can be subrosion by definition. The general hydrogeological conditions and properties also have an influence on the subrosion rate. Pathways with a higher freshwater inflow in the direction of a salt formation can lead to increased leaching, as the salt concentration in the inflowing water is lower. Groundwater chemistry and temperature are one of the main drivers for subrosion but also the CO_2 -content has impact on the reactivity of the rock (Mujalli 2019). In salt rocks and sulphate rocks, hydration takes place during which ions are removed from the crystal structure, thereby loosening it. In

general, the solubility of salt rocks increases with higher temperatures, and the less mineralised the water is at the contact surface with the rock.

Subrosion in the salt rock leads to a strong increase in groundwater salinity in the area of the salt formation. The resulting density stratification has an effect on the groundwater flow and direction (OECD NEA 2019). The different properties of salt rocks also vary the solubility properties, such that the subrosion does not proceed uniformly. This leads to recrystallization and crystallisation, new formation of minerals and volume changes (Mrugalla 2011). These changes can lead to cavities with increased water permeability, such as fractures. The subrosion rate decreases with increasing depth. Salt uplift or epeirogenic uplift with erosion of the overburden increase the rate of subrosion (Bornemann et al. 2008). Depending on the depth and extent of the subrosion processes, the loss of mass is reflected on the surface in the form of depressions, sinkholes and dolines.

Consequently, subrosion processes do not only directly influence rock salt as a potential host rock or a confining rock mass, but can also have an effect on the underlying geological units of the host rock or the groundwater body. This can indirectly have a negative influence on the overlying host rocks or groundwater bodies due to the resulting fracture. The dissolution can have influence on the mechanical stability or the rock thickness up to the surface (Stück et al. 2020).

3.8 Summary of possible climatic geomorphological processes

The results from *Table 2* are a brief compilation of the summaries from described processes in Näslund et al. 2020 with very reduced and abstracted statements which can be used to derive the climate states into boundary conditions in a numerical model.

Table 2: Overview over the Influence of climate factors on the geosphere modified after Näslund et al. 2020

Geosphere variable	Climate factor	Impact
Ice sheets/ glaciers		
Ground temperature	Basal ice temperature	Cold based ice → low ice temperature → forming permafrost Warm based ice → pressure melting point temperature → permafrost degradation
Groundwater flow	Basal thermal condition Basal melt rate Supply of surface melt water	Cold based → no free water, no groundwater recharge Warm based → meltwater, groundwater recharge Recharge and flow determined by ice sheet
Groundwater pressure	Basal thermal condition Ice sheet thickness Basal melt rate Supply of surface melt water	Warm based ice → water pressure corresponding to overburden ice sheet pressure Groundwater pressure depends on melt water supply and hydrological system Bedrock pores and fractures are compressed and influence groundwater pressure
Rock stresses	Basal condition Englacial ice temperatures Ice sheet thickness	Ice load and hydrostatic pressure affects rock stresses Increase of vertical stress corresponding to ice thickness Warm based ice affects rock stress at ice bed

Geosphere variable	Climate factor	Impact
Ice sheets/ glaciers		
Groundwater composition	Glacial melt water composition Underlying rock composition	Meltwater is oxygen rich and reach larger depth Consumption of oxygen limited to less organic matter
Glacial hydrology		
Groundwater pressure and flow	Subglacial hydrological system Melt-water supply	Groundwater recharge, pressure and flow determined by temperature regime, melt water supply, ice thickness and conductivity and distribution of the ice
Glacial isostatic adjustment (GIA)		
Rock stresses	Isostatic depression/rebound	Deformation of Earth's crust leads to altered rock stresses and higher erosion rates
Sea level change		
Groundwater pressure	Relative sea level	Groundwater pressure determined by depth of sea if the site is flooded
Permafrost		
Groundwater flow	Frozen/unfrozen fraction of groundwater	Permafrost leads to less permeable bedrock and soil
Groundwater pressure	Frozen/unfrozen fraction of groundwater	Volume changes by phase changes lead to changes in groundwater pressures
Groundwater composition	Frozen/unfrozen fraction of groundwater	Salt crystals get transferred to liquid phase while water is freezing, leading to an increase of salinity in unfrozen fraction

Geosphere variable	Climate factor	Impact
Ice sheets/ glaciers		
Rock stresses	Frozen fraction of groundwater	Deformations due to ice formation change rock stresses
Fracture geometry	Frozen fraction of groundwater	Permafrost processes can lead to fracture geometry changes like widening of fractures
Surface denudation		
Rock stresses	Stress field	Removal, transport, or sedimentation of bedrock changes the stress field
Fracture geometry	Fractures	Weathering can lead to freezing cracks and widening of fractures

3.9 Climate scenarios in the literature

A climate scenario is a plausible and simplified representation of the future climate based on the knowledge of climatological relationships and couplings (IPCC 2012). Such scenarios are developed to investigate potential changes of the climate in the future, often with respect to anthropogenic influences, and are used as input for impact models. For the development of climate scenarios, data from climate archives and present-day data is used to calibrate and increase the robustness of the scenario (IPCC 2012). Climate scenarios can extend millions of years into the future, but most of the projections are limited to this century. In Germany, the assessment period for the site selection of a deep geological repository is one million years, so this time period also has to describe possible climate scenarios. In other countries like Sweden or Finland, the climate scenarios based on the results from the Bioclim project (Calvez et al. 2001). The Bioclim data later was used and adapted to the Scandinavian region from the Swedish Atomic Energy and Waste Management Company Svensk Kärnbränslehantering AB (SKB) (Cedercreutz 2004; SKB & Svensk Kärnbränslehantering AB 2011). In the following different climate scenarios from literature are described.

The Bioclim project developed three future scenarios for the next 125,000 years (Figure 3). All three Bioclim scenarios assume a continuing warm period lasting until 90,000 years from now. The first scenario assumes the formation of permafrost approximately 90,000 years from today for a period of around 15,000 years. This is followed by a glacial period lasting around 5,000 years, with flooding at the Swedish final repository site after the glaciation. In this scenario, the next glacial period is estimated to occur after 175,000 years. The second scenario assumes warmer conditions, so that after 90,000 years, sporadic permafrost may occur during the warm period. From about 110,000 years from now, a warm climate will prevail until a possible glacial period after 200,000 years. In the Bioclim 3 scenario, warm conditions will prevail until the next glacial period after 200,000 years, without permafrost, glaciation, or flooding.

The other models shown in Figure 3 are older, and extrapolated the orbital cycles of the past into the future and additionally calculated the ice volume based on this cyclicity (Imbrie & Imbrie 1980). The ice volume was calculated on the basis of $\delta^{18}\text{O}$ ratios. The aim of the ACLIN model was to investigate the extent of orbital or terrestrial influences on the cold and warm periods. In Kukla et al. 1981, it is assumed that the cyclicity of 100,000 years is primarily characterised by orbital influences, but that ice dynamics in the Northern and Southern Hemispheres also play a key role. In addition to the orbital parameters, the LLN 2D model also takes into account CO_2 concentration in the atmosphere (Berger, Loutre & Gallée 1998). In this model, however, a constant CO_2 concentration was assumed, such that there was no increase in CO_2 emissions for simulation cases with different CO_2 concentrations.

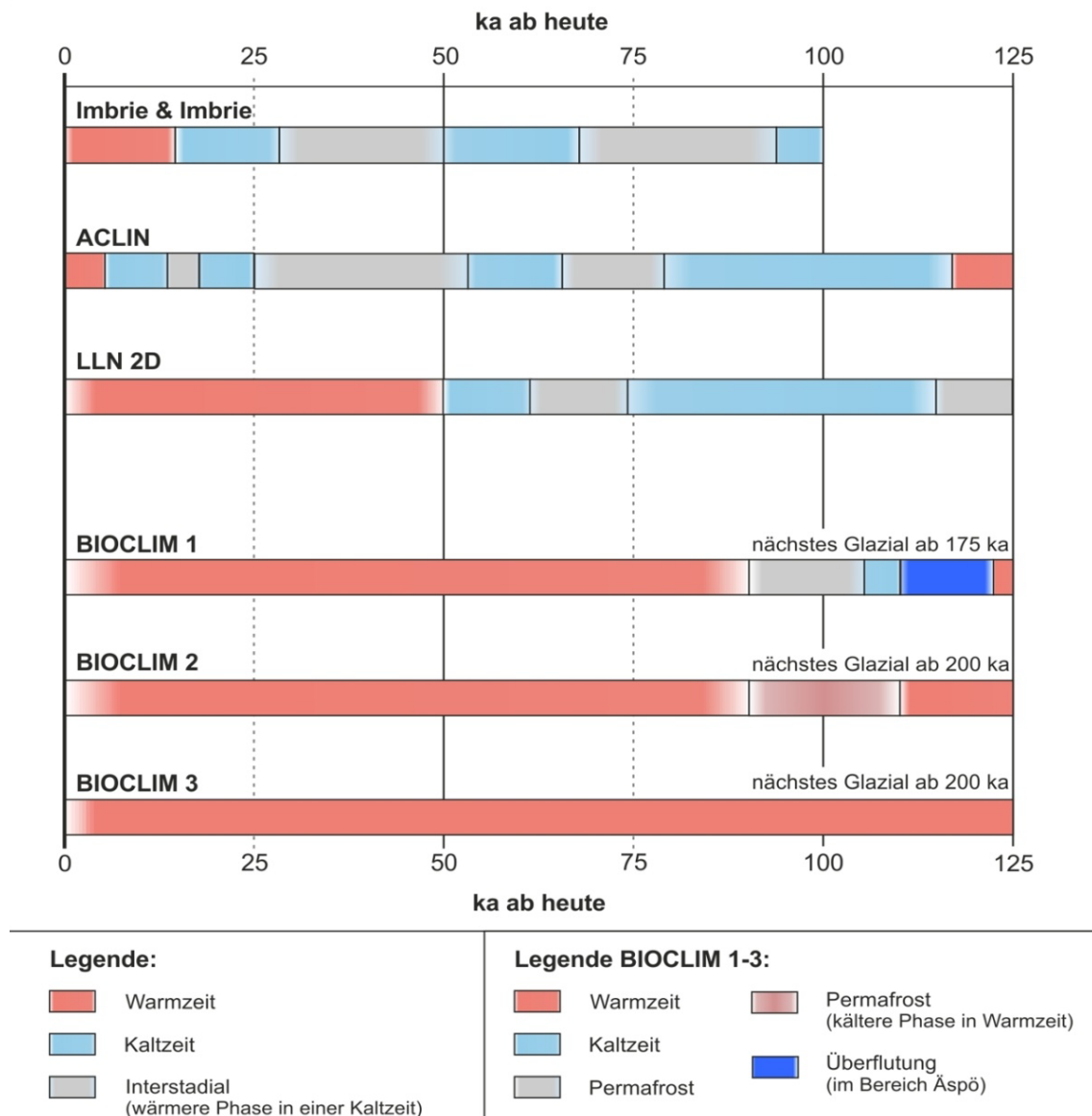


Figure 3: *Climate developments with warm, cold, interstadial stages from different climate models taken from Mrugalla 2011.*

Most of the climate models which are mentioned before are used for site specific climate scenarios (Cedercreutz 2004). For example, Posiva Oy cited all of the aforementioned models, and fit them for a possible repository site in Finland. Two climate scenarios for a “global warming” and an “extended global warming” are mentioned in a report from Posiva Oy (Figure 4) (Marcos et al. 2021). These scenarios cover a time span of 1 million years and do not differ from each other after 400,000 years. During the first 400,000 years in the Finnish global warming scenario, eight glacial cycles with time spans between around 8,000 and 61,000 years. The longest glacial period starts at 362,000 years and lasts until 429,000 years into the future (Figure 4). In between there are warm, submerged, permafrost and deglaciation phases in different sequences fitted to the repository site in Finland. In the extended global warming scenario, glaciation will not occur before 380,000 years in the future. From today until 210,000 years into the future, warm

conditions are assumed, followed by cycles of permafrost conditions and warm climates until glaciation at around 380,000 years.

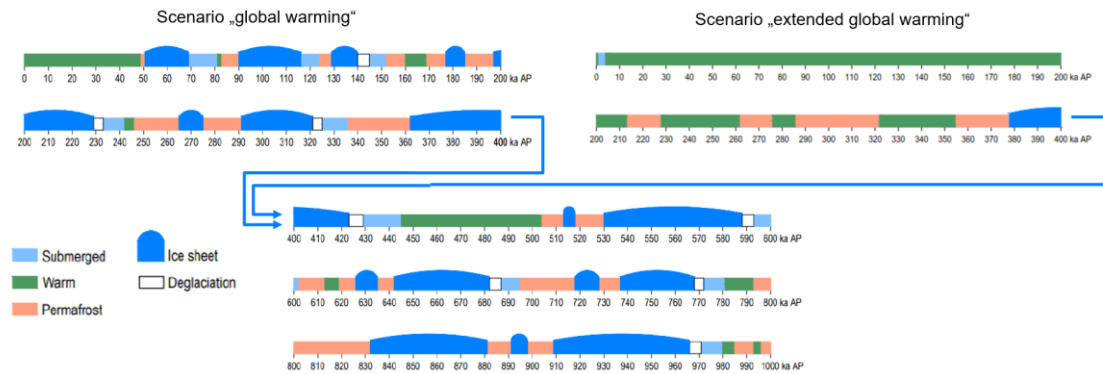


Figure 4: Climate scenarios for the Finnish Safety case with a “global warming” and an “extended global warming” scenario at the repository site modified after (Marcos et al. 2021).

SKB used the Bioclim models and fit them to their repository site with several climate scenarios (Näslund et al. 2020). For the Swedish Preliminary Safety Assessment Report (PSAR) the two climate scenarios “reference glacial cycle” and “global warming” are used. Based on the safety functions of the repository, additional less likely but also possible climate scenarios were created. The additional safety assessment scenarios are “extended global warming”, “extended ice sheet”, “maximum ice sheet configuration” and “severe permafrost” (Figure 5).

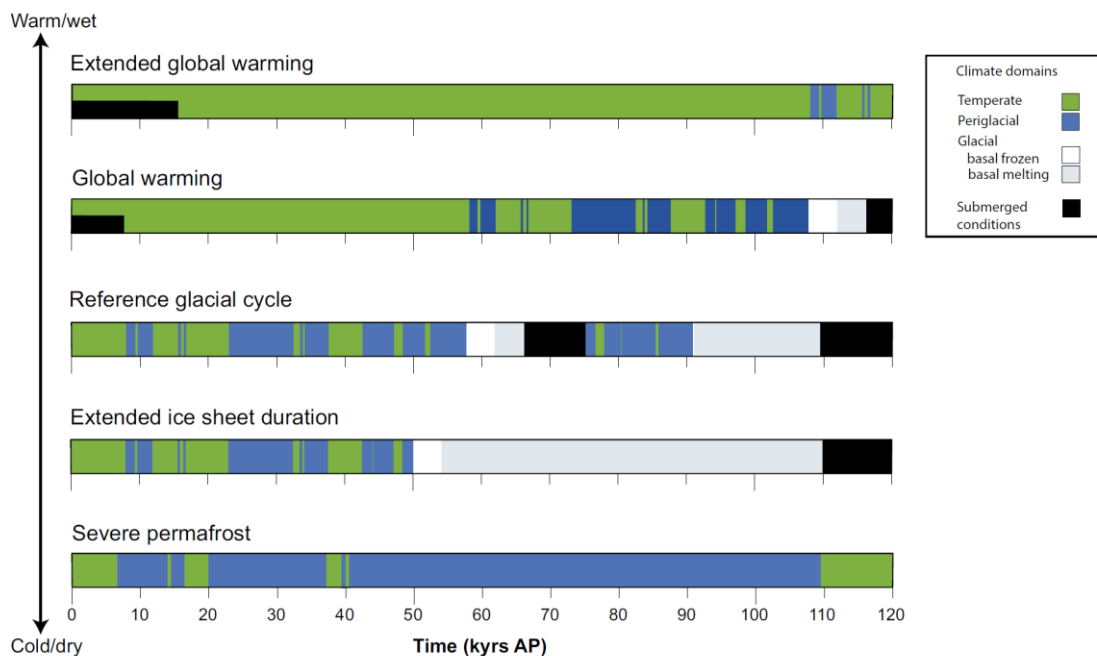


Figure 5: Climate scenarios for the Swedish Preliminary Safety Assessment Report (PSAR) (Main and additional scenarios) at the repository site taken from Näslund et al. 2020.

These climate models have been used to derive scenarios for the future climate on time scales of several hundred thousand years for the safety assessment for radioactive waste repositories. While the scientific basis and extraterrestrial processes are considered equally, not all terrestrial processes are always represented equally in the models, leading to different model results in which glacial cycles can differ by several tens of thousands of years. The influence of anthropogenic CO₂ emissions is also an important aspect which is considered differently by scientific studies, and is one additional reason for the different time sequences. Another important point is the regional validity, which in the case of global models does not have to be directly valid for the site-specific condition. Nevertheless, the chapter provides a good overview of the climate developments to be expected in the safety assessments in other countries. In following chapters, possible climate scenarios for Germany will be described.

3.10 Relevance for long-term safety in Germany

The relevance of climate factors like future ice sheets or permafrost for the long-term safety of a deep geological repository in Germany must be considered with regards to possible future climate evolutions. In Northern Germany, there were the Elsterian (400,000 years to 320,000 years before present, BP), the Saalian (300,000 years to 126,000 years BP) and the Weichselian (115,000 years to 11,600 years BP) glacial periods as three large-scale glaciations within the last 400,000 years (Menning & Hendrich 2016) (Figure 6). In Southern Germany, glaciations from the alps reached to the river Rhine (Rhein) and partly to the river Danube (Donau) during their maximum ice advance in the Pleistocene (Stark 2014). Extrapolating these past glaciations into the future, Northern and Southern Germany could be covered by ice depending on the climate conditions in the future. (Figure 6 and Figure 7). For example, it can be reasonably assumed that ice thickness in Germany will be thinner compared to the ice thicknesses in Scandinavia. During the Saale glacial, the ice thickness in the Gorleben area in Northern Germany is assumed to have been around 700 m, with high variation specifically at the ice margin area (Skupin, Speetzen & Zandstra 2003; Köthe et al. 2007; Mrugalla 2011). Beuth et al. 2012 provides a qualitative estimate that the ice thickness in the Gorleben area could have been up to 1,500 m. The advance of ice sheets to Germany occurred several thousand years after that in Scandinavia, and retreated in a shorter time period.

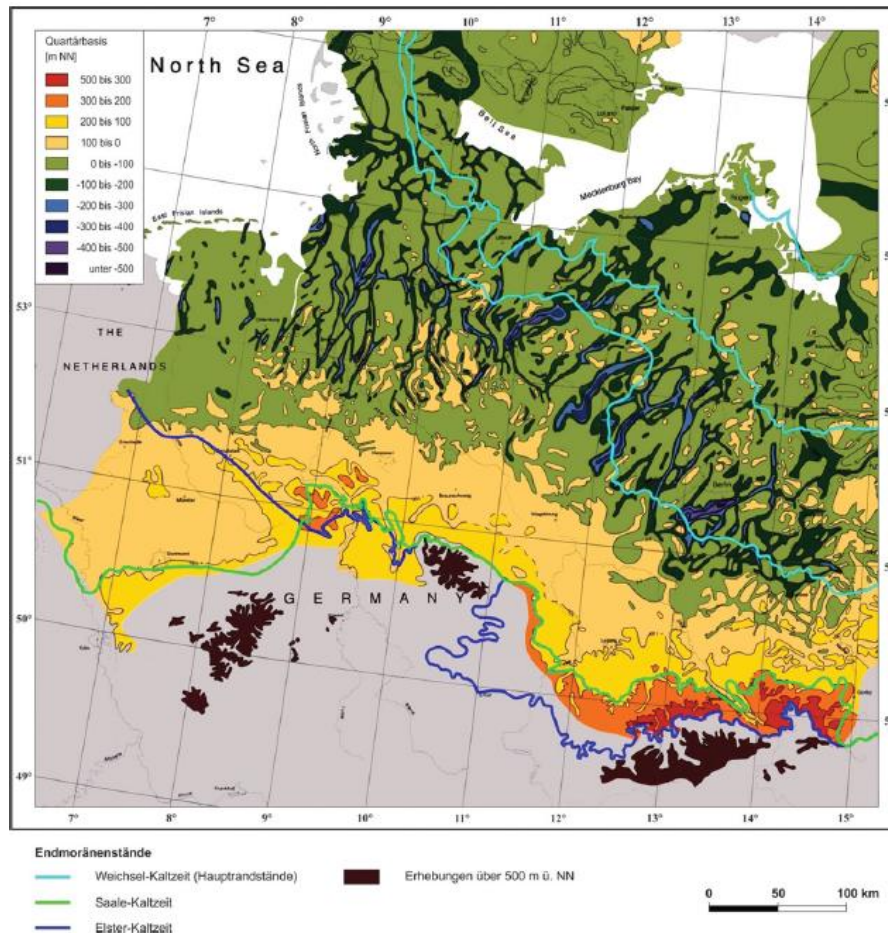


Figure 6: Ice margins of the last three glaciations after Mrugalla 2011 and distribution of glacial valleys in Northern Germany taken from Weitkamp & Bebiolka 2017.



Figure 7: Map of the alps with overdeepened valleys (red areas), the maximum ice extend in the Pleistocene (black line) and the ice margin of the last ice advantage (red line) taken from Stark 2014 referenced to Preusser et al. 2011.

Although the assumed ice loads can cause fractures and denudation, the possibility for glacial induced crust deformation with high uplift rates is low (Forsström 1999; Mrugalla

2011). BGE and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) do not see arguments for an average vertical movement rate of more than 1 mm year⁻¹ in any region of Germany for the next one million years (Jähne-Klingberg et al. 2019; BGE 2020a; BGE 2020b). An uplift rate above 1 mm year⁻¹ is an exclusion criterion after the German law, because of the potential of higher erosion rates by the uplift (StandAG 2023). Erosion depends on various factors like topography, temperature, sediment, bedrock, and wind conditions. In many parts of Germany, the topography is flat and the erosion rates are low, but sediments can be eroded over short time periods by a glacier and form glacial valleys (Lang 2022). Erosion rates of around 1.5 mm year⁻¹ in high alpine areas have been estimated using ¹⁰Be dating (Delunel et al. 2020). Data on bedrock erosion rates in Germany are limited, but the work from Delunel et al. can provide a first estimation. In lower altitudes, erosion rates generally decrease in most cases. Most of the erosion rates in less mountainous regions do not exceed 0.25 mm year⁻¹.

Permafrost also has an influence on the long-term safety through changing the conditions for groundwater flow. Currently there is no permafrost in Germany (Obu et al. 2019). In the past, permafrost depth in Northern Germany was around 120 m to 200 m, meaning that comparable permafrost depths could be possible in the future (Delisle 1998; Delisle et al. 2007; Beuth et al. 2012). Govaerts, Beerten & Veen 2016 estimated permafrost depth between 155 to 195 m with higher probability, with a maximum depth up to 280 with unrealistic climate conditions in their models.

Depending on the assumed climate scenario, different levels of sea level rise can be expected in the future. The melting of the Greenland ice sheet would lead to a sea level rise of about 7 m, while a complete melting of the Antarctic and Greenland ice sheets would raise sea level to about 65 m. In this case, a large part of Germany would be flooded (Allison et al. 2009). The repository design should be adapted to this scenario, where there is a higher hydraulic pressure, density driven flow and higher salinity of the surrounding water.

The aforementioned described climate scenarios use different approaches, assumptions and processes into account. For the simulation of future climate scenarios several input parameters have to be chosen from a parameter range and for the specific regional conditions. Global climate models provide a good overview of future climate developments. These climate scenarios should be adapted to local or regional conditions for a safety assessment of a potential final repository site in order to provide robust statements on climate developments at the site. In the end, it is important for the search of a repository to validate the factors mentioned here with site-specific data and an appropriate set of climate scenarios.

4 Climate modelling

The long-term climate contains many uncertainties. These arise from limited constraints on future feedback processes, the range of possible equilibrium climate sensitivity, and the long timescales over which anthropogenic perturbations interact with natural variability. Geological evidence provides important boundary conditions for assessing these processes, but projections require modelling techniques. By employing an EMIC, it is possible to systematically investigate the influence of GHG concentrations, orbital forcing, and carbon cycle feedbacks on long-term climate evolution.

4.1 Earth system model CLIMBER-X

To perform such investigations, we use the newly developed fast Earth system model CLIMBER-X. CLIMBER-X comprises several model components: the statistical–dynamical semi-empirical atmosphere model SESAM; the 3D frictional–geostrophic ocean model GOLDSTEIN; the dynamic–thermodynamic sea ice model SISIM; the land surface and dynamic vegetation model PALADYN; the biogeochemistry and marine sediments model HAMOCC; the ice sheet model SICOPOLIS; the surface mass balance model SEMIX; and the viscoelastic solid Earth model VILMA. The statistical-dynamical atmospheric model, SESAM, is regarded as 2.5 dimensional, as variables which operate in 2-D (latitude and longitude) make use of the 3D structure of the atmosphere. This goes back to CLIMBER-2, as a number of empirically based modifications were made to match with general circulation model (GCM) performance.

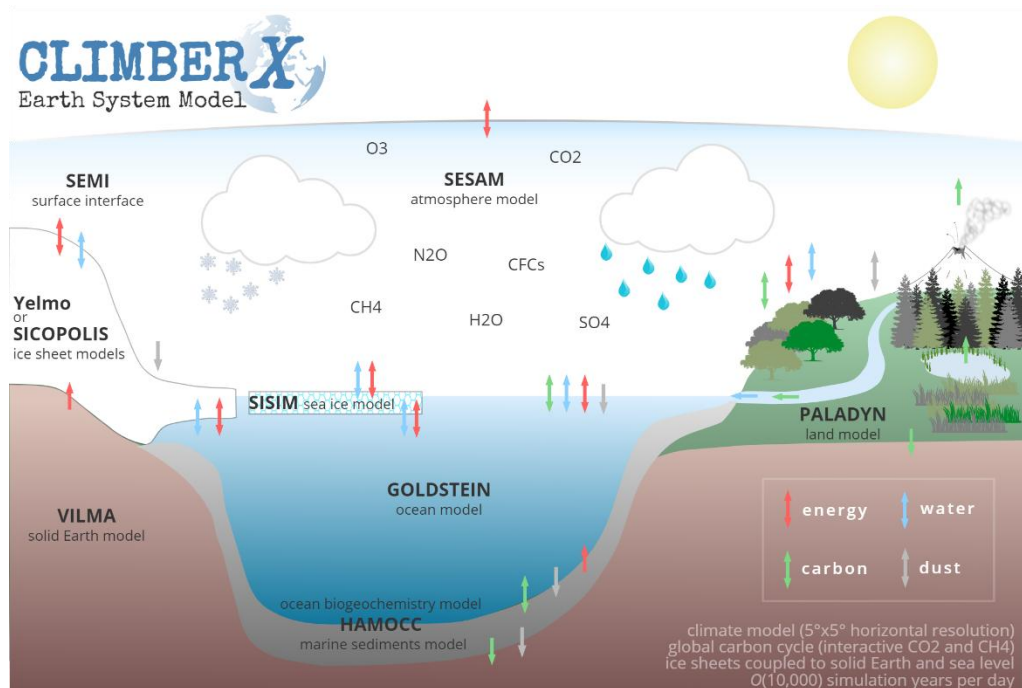


Figure 8: A schematic of CLIMBER-X taken from Willeit et al. 2022.

The ocean component in CLIMBER-X is based off of the 3-dimensional frictional geostrophic model GOLDSTEIN. This is effectively an upgrade from previous CLIMBER series, as GOLDSTEIN is dynamically similar to GCMs and is employed in a number of other EMICS (e.g., cGENIE in Lord et al. 2016). In CLIMBER-X, the ocean is discretised into 23 vertical layers, with increasing layer thickness with decreasing depth. SISIM, the dynamic–thermodynamic sea ice model, works as a coupler between the atmosphere and ocean models as it computes energy fluxes ice/ocean. It describes a single ice layer with a snow layer on top. Finally, the land surface-vegetation model PALADYN is a 5-layer soil model, which describes 8 different surfaces: water (i.e., lakes), land ice, bare soil, and five plant functional types (C3 grass, C4 grass, shrubs, needleleaf trees, and broadleaf trees). CLIMBER-X can be run with two different ice sheet models, Yelmo or SICOPOLIS, with variable resolution (typically 32 km, see Figure 9). The viscoelastic solid-Earth model VILMA accounts for changes via GIA, thereby controlling surface displacement and sea level. Experiments requiring VILMA are run using the 3-D mantle viscosity described in Bagge et al. 2021, providing a more realistic representation as ice loads interact with the upper mantle in the vertical.

Most relevant for our investigations is that CLIMBER-X can simulate interactive ice sheets and contains a comprehensive representation of the global carbon cycle. In the simplest configuration, CLIMBER-X can generate up to 10,000 simulation years per day, making it an excellent tool for providing many realisations on long timescales. As a consequence, some processes have been parameterised for reducing large computational costs. For example, short term processes (e.g., weather, diurnal cycles) are generally not resolved. All components in CLIMBER-X (except for the ice sheets) have comparable complexity, and a common $5^\circ \times 5^\circ$ grid resolution. In our simulations, Germany effectively takes up 2 of the 72×36 grid cells in CLIMBER-X, see Figure 9.

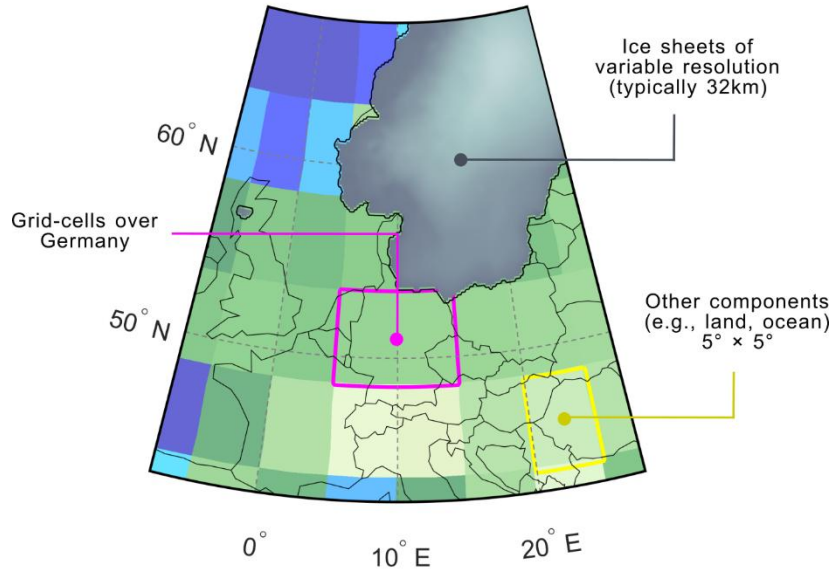


Figure 9: Grid-cells used for ice sheets and the broader climate in CLIMBER-X. The grid-cells comprising of Germany is also highlighted here.

4.2 The timing of the next glaciation

Due to the exceptionally long atmospheric lifetime of anthropogenic CO_2 (Kaufhold et al. 2025a), anthropogenic emissions are expected to affect the timing of the next glacial cycle (Archer & Ganopolski 2005; Ganopolski, Winkelmann & Schellnhuber 2016; Talento & Ganopolski 2021). This is because glacial inception depends not only on changes in solar insolation, but also on CO_2 concentration (Calov et al. 2005; Mysak 2008; Ganopolski, Winkelmann & Schellnhuber 2016). As a result, there is a fundamental relationship between critical value of summer insolation leading to glacial inception and CO_2 concentration (i.e., the critical insolation– CO_2 relation; Talento, Willeit & Ganopolski 2024; Ganopolski, Winkelmann & Schellnhuber 2016). Given that the Earth’s orbital configuration, and therefore, solar insolation, is known for the next 50 million years (Laskar et al. 2004), it is generally known at which level of CO_2 concentration in the future will lead to glacial inception. If simulated CO_2 concentration falls below the inception threshold ($\text{CO}_{2,\text{cr}}$, see Figure 11), it is likely that glacial inception will occur as conditions are favourable.

Complicating this is the initialisation of the carbon cycle (forming the equilibrium condition) in CLIMBER-X. If all biogeochemical processes continuously removed carbon from the atmosphere (without any being returned), eventually all atmospheric CO_2 would disappear. Therefore, carbon must also be returned to the Earth system to maintain a balance. In CLIMBER-X, an equilibrium condition of the carbon cycle requires volcanic outgassing to provide half of the global CO_2 consumption from silicate weathering. This equilibrium condition can be adjusted in CLIMBER-X by changing the prescribed value

of volcanic outgassing. Previous studies, such as Liakka et al. 2024, have assumed volcanic outgassing and silicate weathering were perfectly balanced during the PI, given the relatively long and stable conditions over the Holocene. Silicate weathering is typically assumed to be the biogeochemical process balancing carbon released from geological reservoirs over long periods of time. Carbonate weathering, although explicitly simulated in CLIMBER-X, mainly only recycles carbon within the atmosphere—ocean system and therefore does not affect long-term evolution of atmospheric CO₂. Furthermore, it has been suggested that organic carbon burial may constitute an additional factor affecting the long-term balance of carbon (Hülse & Ridgwell 2025), although this remains a relatively new and still developing area of research.

On sub-millennial timescales, it is typically sufficient to consider only carbon exchange between the atmosphere, ocean, and land. However, as we have already demonstrated in Kaufhold et al. 2025a, the marine sediment response and geological sources and sinks of carbon from sediment burial and chemical weathering becomes important on long timescales. Since these processes are not necessarily in equilibrium during the Holocene, we consider an alternative assumption – namely, that they were in equilibrium during the entire glacial cycle. As such, a more realistic assumption, given that CO₂ concentrations have remained relatively stable over glacial cycles, is to balance volcanic outgassing with the average weathering rate over the last glacial cycle (LGC). This leads to a significant CO₂ decreasing trend over time even under interglacial conditions. Due to limited constraints on present-day values of silicate weathering and volcanic outgassing, we ran experiments under both assumptions (Pleq and LGCeq) and consider these two configurations as “end members” of what we consider plausible (Figure 10).

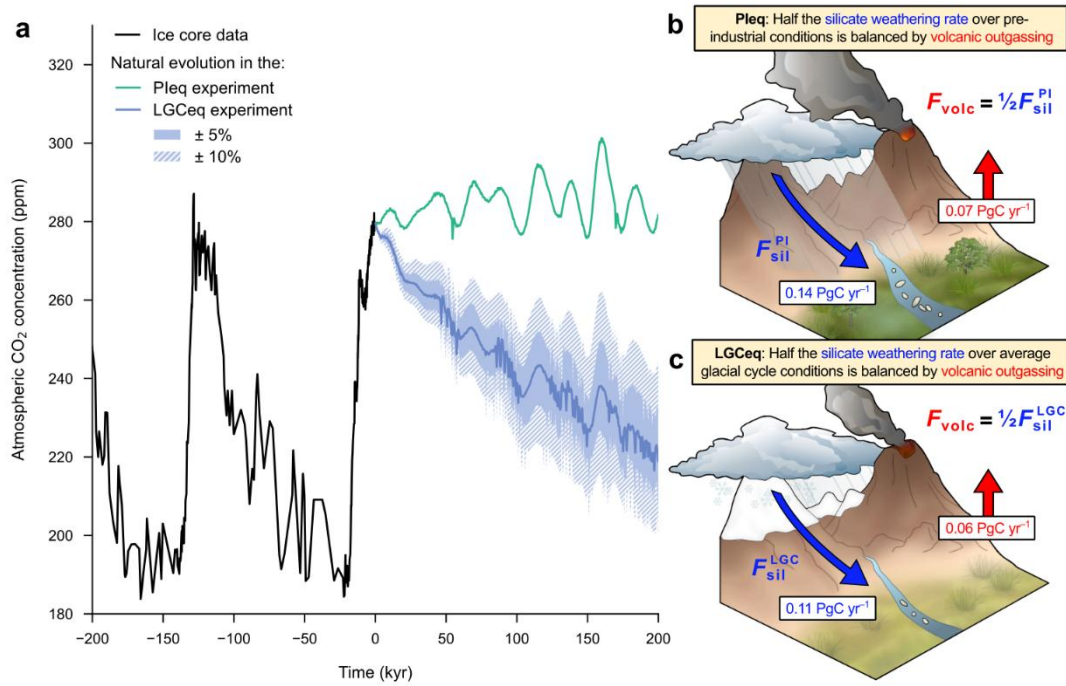


Figure 10: *The past and future natural evolution of atmospheric CO₂ concentration. Here, we demonstrate the impact of the carbon cycle initialization (Pleq vs. LGCeq). This image was taken from Kaufhold et al. 2025b, and more details can be found there.*

In Kaufhold et al. 2025b, we present the first Earth system model simulations under an ensemble of different emission scenarios (natural evolution to 5,000 PgC) for the next 200,000 years with dynamic ice sheets and interactive atmospheric CO₂. Using these simulations, we investigated how different emission scenarios will affect future glacial inception by determining when simulated atmospheric CO₂ concentration fall below CO_{2,cr}. In this work, we address both the Short (e.g., natural evolution of the Earth system) and the Long (e.g., evolution of the Earth system under different emission scenarios) Anthropocene. As uncertainties related to the carbon cycle were already examined in Kaufhold et al. 2025a, we focus on uncertainties related to the carbon cycle initialisation in Kaufhold et al. 2025b.

We find that the natural timing of the next glacial inception would occur between approximately 50,000–125,000 years; the former when we account for a CO₂ decreasing trend (LGCeq), and the latter when this trend is not accounted for (Pleq). However, we consider the 50,000 year estimate more realistic, considering CO₂ variability and the steady decrease in atmospheric CO₂ observed over previous glacial cycles and throughout the Pleistocene. With the assumption used in the LGCeq experiment, a rapid increase in ice coverage is simulated around 50,000 years across the Canadian Arctic Archipelago and Scandinavian Mountains under the natural evolution. Our results show that ice sheet growth begins at nucleation sites in the Pacific and Arctic Cordillera, leading to the formation of the Cordilleran, Innuitian, and Foxe–Baffin ice sheets around 52,000 years.

This closely matches the ice sheet progression observed in the last glacial cycle (Batchelor et al. 2019; Dalton, Stokes & Batchelor 2022).

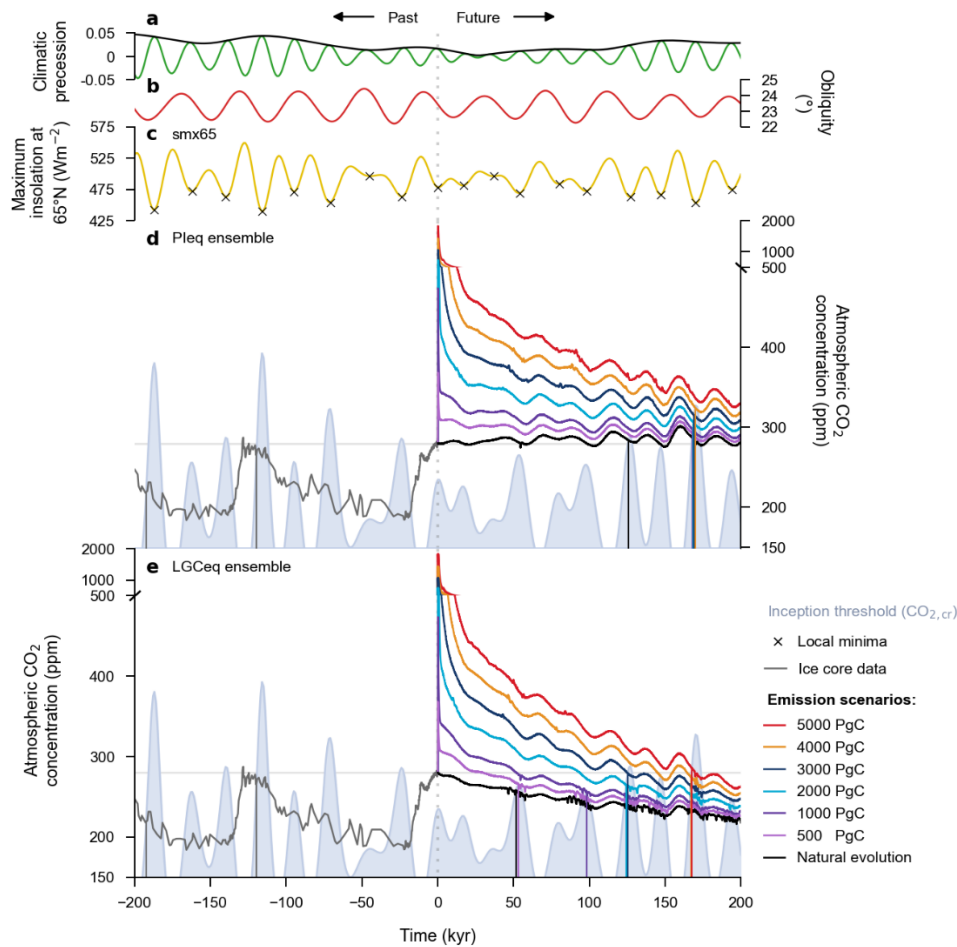


Figure 11: *Orbital forcing and CO₂ concentration over the last 200,000 and the next 200,000 years. Simulated future atmospheric CO₂ concentrations is also plotted here in Panels (d) and (e). This image was taken from Kaufhold et al. 2025b, and more details can be found there.*

4.3 Plausible future climate developments

Using our modelling results, we generated a set of plausible future scenarios based on the magnitude of cumulative emissions. Until anthropogenic emissions return to near pre-industrial levels (“Interglacial”), and in the absence of human engineering (as with the “Short” and “Permanent” Anthropocene), we assume that the dominant climate state for different emission scenarios will be the “Long Anthropocene”. Global temperatures are expected to remain elevated depending on the magnitude of cumulative emissions. Permafrost extent, which currently does not cover Germany (in either observations or our model), would consequently decline.

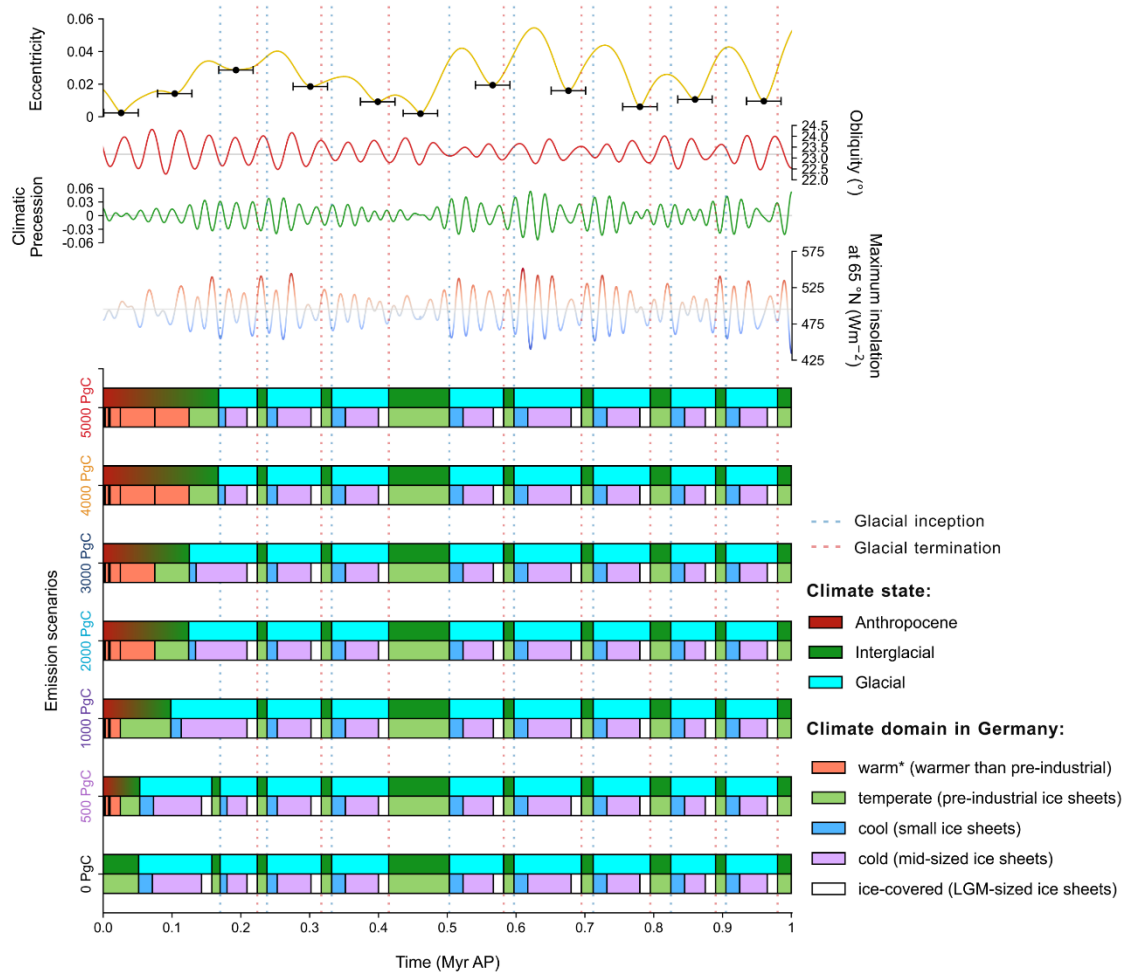


Figure 12: A set of plausible climate states (and climate domains for Germany) for different levels of cumulative emissions over the next 1 million years.

Before moving into a future “Glacial” climate state, the Earth system is first assumed to leave the “Anthropocene” climate state, and return to a natural “Interglacial” state. We used simulations from Kaufhold et al. 2025b to provide a best estimate on the timing of the next glacial inception (based on the predicted timing in the LGCEq experiments). After the climate state changes to a “Glacial” state, it remains there until glacial termination. To determine when glacial termination could plausibly occur in the future, we used a simple rule from Generalized Milankovitch Theory (Ganopolski 2024) that has been able to capture 9 of the 10 last glacial terminations of the last 1 million years. The rule states that glacial terminations occur during rising boreal summer insolation if the previous precession maximum was at low eccentricity and anti-phase with obliquity. Following glacial termination, the next glacial inception was determined from the next significant minima in insolation. Based on palaeo-data, the “Interglacial” state should ideally persist for around ~10,000 years.

Under this constructed timeline, glacial inception is projected to occur at least 8 times over the next 1 million years. These generated future scenarios assume that, after an

anthropogenic perturbation in the carbon cycle, glacial cycles will eventually return to their natural frequency of ~100,000-year cycles. This assumption relies on the idea that the carbon cycle, despite being significantly altered by human activities, will stabilise over time and resume its typical feedback mechanisms. It is important to note, however, that in reality this assumption may not hold, and some deviations from the constructed timeline can reasonably be expected.

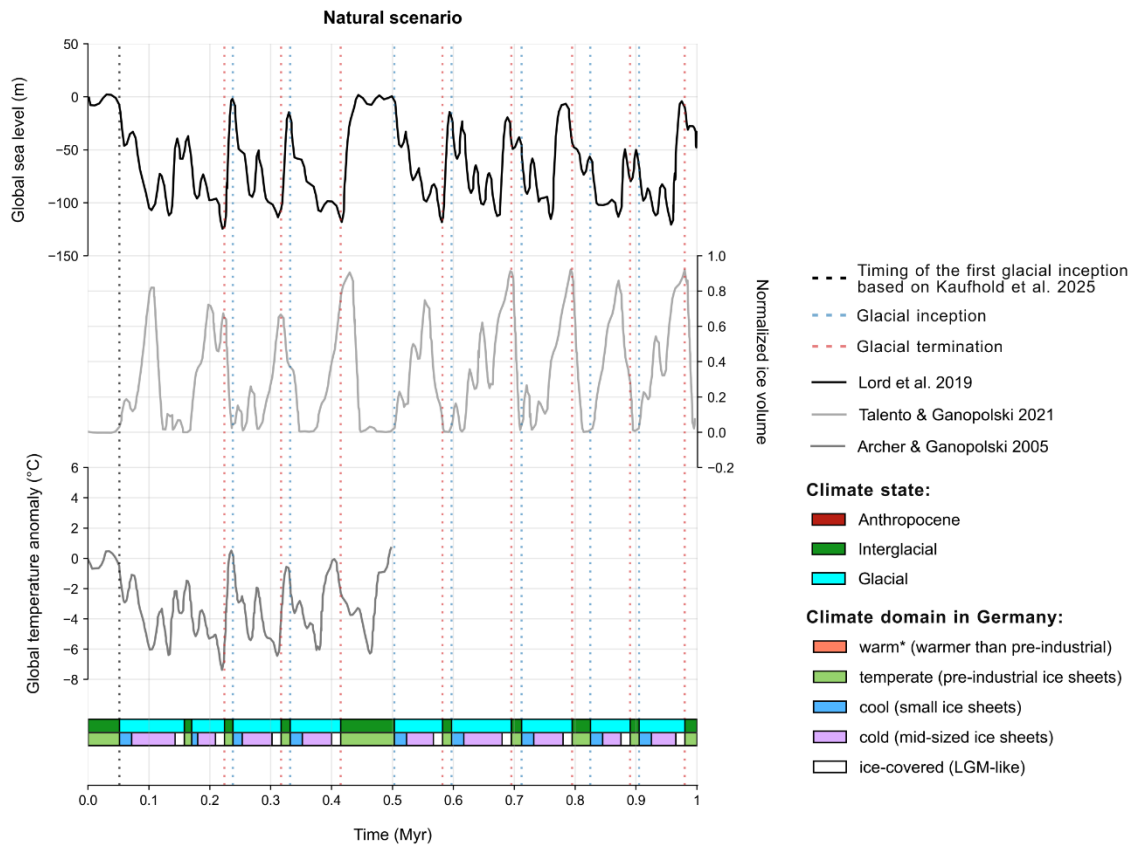


Figure 13: *The constructed timeline of future climate developments for the 0 PgC (“natural”) scenario. A comparison with Archer & Ganopolski 2005; Lord, Lunt & Thorne 2019; Talento & Ganopolski 2021 has been additionally plotted. Ice volume, as reported by Talento & Ganopolski 2021, is normalized between 0.0 and 1.0, where 1.0 roughly correspond to 120 metres sea level equivalent (msle).*

To assess the robustness of our constructed future timelines, we compare our natural, 500 PgC, 1,000 PgC, and 5,000 PgC scenarios with projections from Archer & Ganopolski 2005, the Swedish Nuclear Fuel and Waste Management Company (SKB) as reported in Lord, Lunt & Thorne 2019, and Talento & Ganopolski 2021. Figure 13 shows a comparison for the natural scenario, Figure 14 for the 500 PgC scenario, Figure 15 for the 1,000 PgC scenario and Figure 16 for the 5,000 PgC scenario. These studies, which span decades and employ a variety of modelling approaches, provide sufficient diversity for comparison. Notably, the timing of glacial inception and termination in our scenarios

aligns well with the previous studies, with at least one model in each case matching our timelines. We further assume that a long interglacial will occur within the next 400,000 years due to an upcoming minimum in eccentricity, a pattern also observed in Lord, Lunt & Thorne 2019; Talento & Ganopolski 2021.

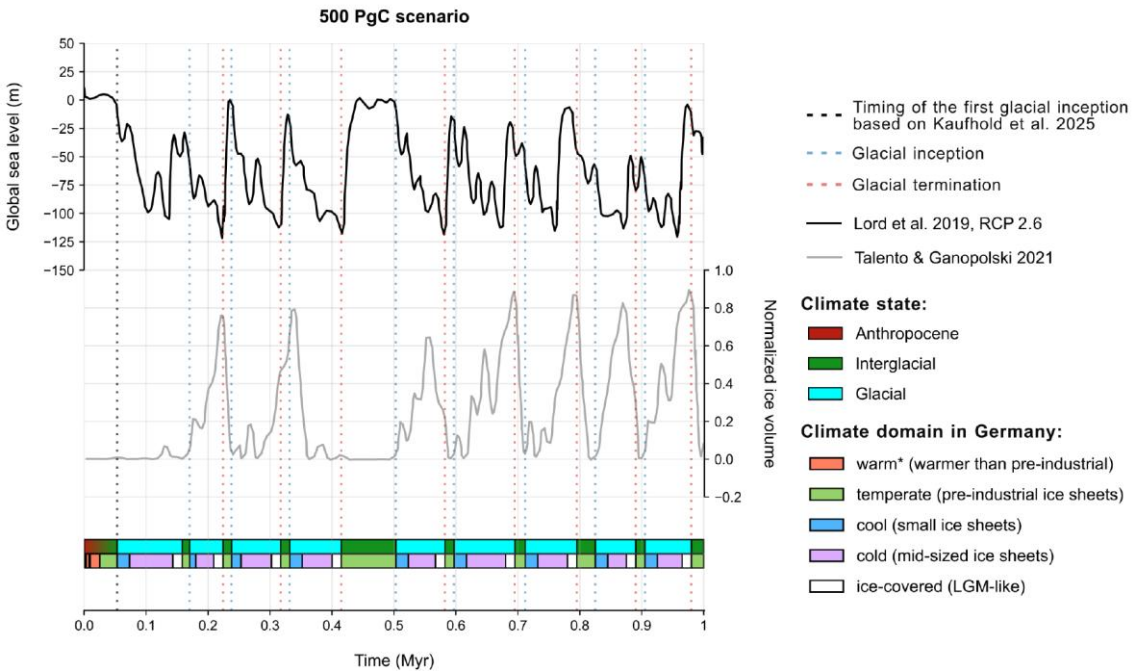


Figure 14: The constructed timeline of future climate developments for the 500 PgC scenario. Ice volume, as reported by Talento & Ganopolski 2021, is normalized between 0.0 and 1.0, where 1.0 roughly correspond to 120 msle.

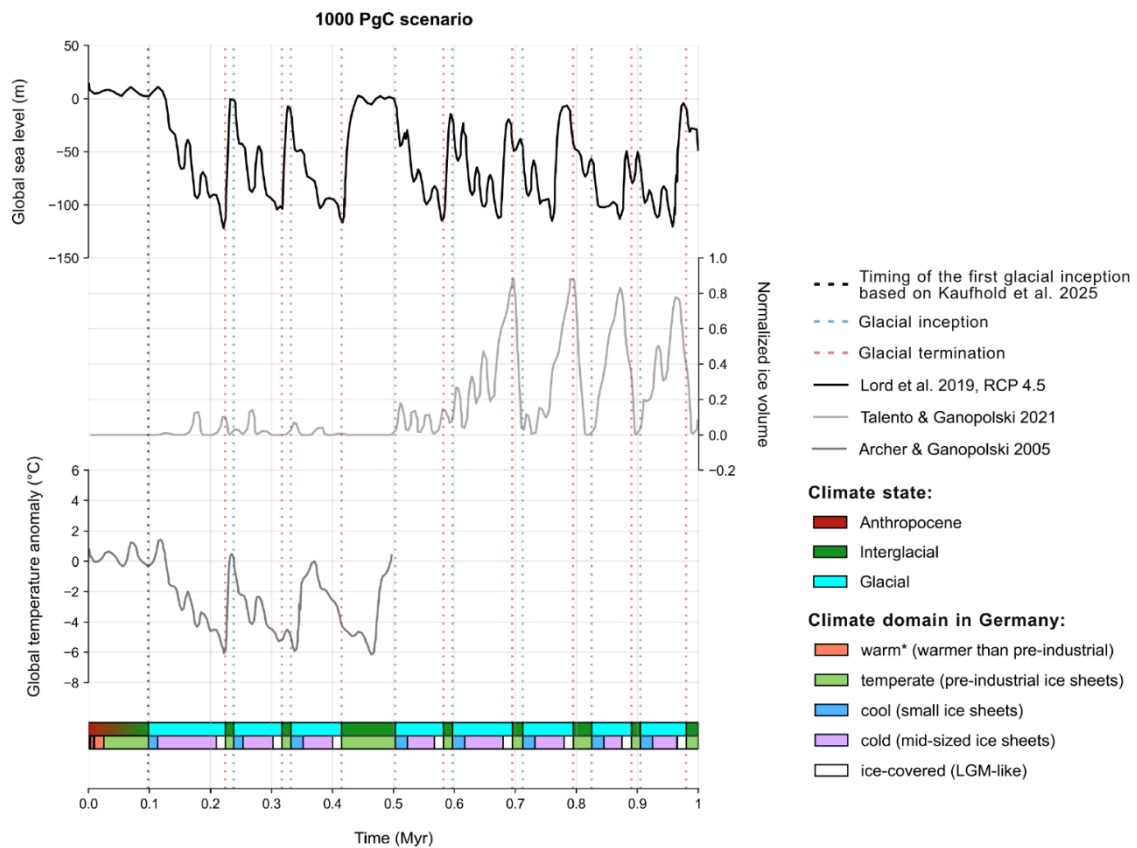


Figure 15: *The constructed timeline of future climate developments for the 1,000 PgC scenario. Ice volume, as reported by Talento & Ganopolski 2021, is normalized between 0.0 and 1.0, where 1.0 roughly correspond to 120 msle.*

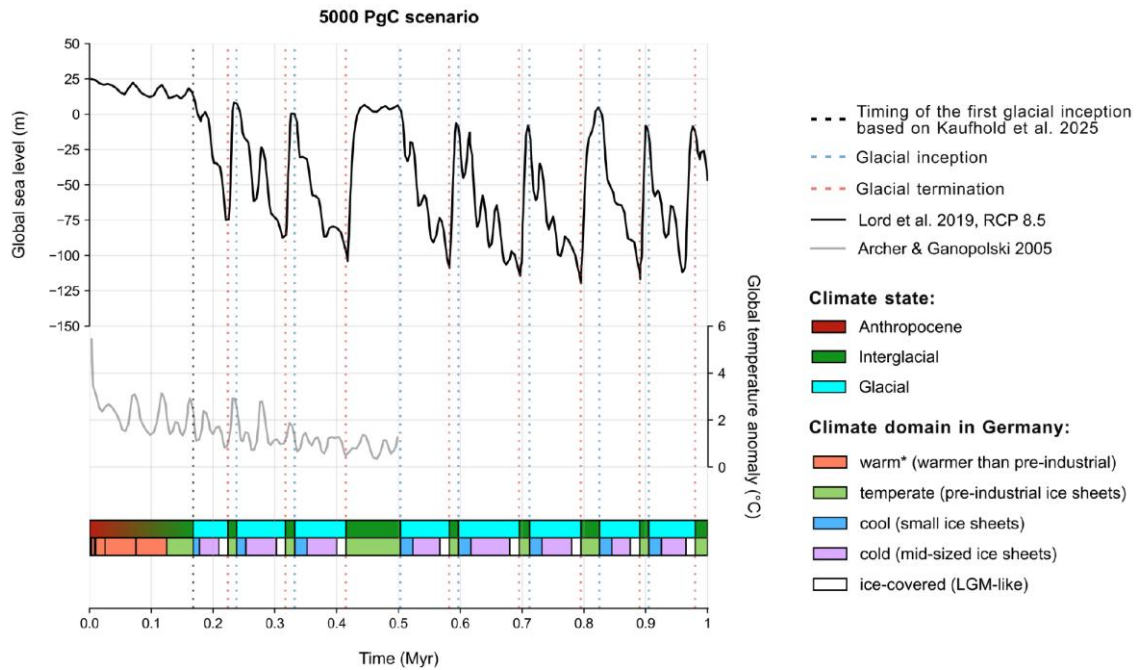


Figure 16: *The constructed timeline of future climate developments for the 5,000 PgC scenario.*

Complicating these results is the potential effect of the Atlantic Meridional Overturning Circulation (AMOC). In our simulations, CO₂ was added to the atmosphere through idealised scenarios, reflecting the fact that cumulative emissions control the long-term climate. However, the rate of CO₂ emissions is crucial for AMOC stability. The AMOC transports warm, salty water from equatorial regions toward the Arctic and helps maintain Europe's relatively mild climate compared with regions at similar latitudes such as Russia or Canada. Studies indicate that the AMOC could collapse within the next few centuries if emissions rise rapidly enough (McCarthy et al. 2017; Rahmstorf 2024). If such a collapse were to occur (and potentially persist for several millennia), it would lead to substantially cooler conditions over Europe than those represented in our simulations. This could influence the timing of the next glaciation, potentially triggering glacial inception at an earlier insolation minimum, for example at around 17,000 years or 37,000 years AP. However, an earlier glacial inception would not necessarily result in a substantially longer glacial state. Given the approximately 100-kyr cyclicality of past glacial cycles, and assuming that termination occurs once a critical ice-sheet volume is reached, an earlier onset could instead lead to an earlier attainment of this threshold. Moreover, the extent of the ice sheet over Germany has been relatively similar during the last three glacial cycles, suggesting that an earlier inception would not necessarily imply substantially greater southward ice-sheet expansion over Germany. In this way, we assume that, while the timing of glacial inception could shift, the overall duration and maximum extent of the subsequent glacial state would remain broadly similar.

4.4 A set of climate domains focused on Germany

Using the timeline of future climate states, plausible future climate domains for Germany were generated. The term “domain” is used to differentiate from “climate state”, and is intended to represent a distinct set of environmental conditions defined by specific climatic variables, such as temperature and precipitation, that influence ecological and geophysical processes. During an extended “Long Anthropocene,” Germany is expected to remain in a climate state warmer than PI conditions, with the potential for local inundation due to sea level rise (for at least 10,000 years; see Clark et al. 2016).

Following the eventual sequestration of anthropogenic CO₂ via natural carbon sinks and silicate weathering, Germany’s climate is eventually expected to return to a “temperate” state. In the case of a “Short Anthropocene,” where anthropogenic influence on the climate is minimal or short-lived (e.g., humanity returns to the natural evolution, or in other words, emission scenarios 500 PgC and lower), Germany would not experience a prolonged warm phase and would remain in or return to a temperate climate state in the coming multi-millennia. Assuming that future glacial cycles, once resumed, will follow the patterns of past cycles, ice sheets are expected to gradually expand over a 100,000-year period, ultimately reaching an extent similar to that of the last glacial maximum (LGM). During the transition from “Interglacial” to “Glacial”, small ice sheets are expected to form, contributing to a decrease in NH temperatures which would place Germany in a “cool” climate domain (see Figure 17i, Figure 19i). Palaeoclimate evidence suggests that ice sheets in past glacial cycles spent the majority of their time in an intermediate (“mid-sized”) configuration before advancing to their maximum extent. By analogy, future ice sheets are expected to exhibit similar behaviour, and Germany is projected to remain predominantly in a “cold” climate domain for much of a glacial cycle, with some permafrost present (see Figure 17ii, Figure 19ii). Once ice sheets reach their maximum extent, Germany will transition to an “ice-covered” domain with nearly full coverage of permafrost (see Figure 17iii, Figure 19iii). On average this permafrost is 1 m thick.

It’s important to note that the designation of “ice-covered” does not imply complete ice coverage of the region. Reconstructions of the last three glacial cycles indicate that only Northern Germany and some areas of Southern Germany (from the Alpine ice sheet) was glaciated at their maximum extent. After glacial termination occurs, we assume Germany would again return to a “temperate” interglacial climate domain.

Based on the experiments conducted by Kaufhold et al. (2025b) and the projections outlined by Archer & Ganopolski (2005) and Lord, Lunt & Thorne (2019), Germany is expected to remain largely ice-free for the next 150,000 years. This is because, under the natural climate evolution and low-emission scenarios, NH ice sheets will generally remain small due to the weak insolation minima. For cumulative carbon emissions larger than 1,000 PgC, glacial inception is unlikely to occur within the next 100,000 years. Given that the insolation minimum at ~175,000 years in the future is particularly low (3rd lowest

minimum, Figure 11d), it is likely that Germany will move into an “ice-covered” domain for emission scenarios 1,000 PgC and lower at that time. This assumption that all scenarios (regardless of cumulative emission) will begin a “proper” glacial inception (i.e., one not weakened by low orbital forcing) after 170,000 years is backed by Lord, Lunt & Thorne (2019) and Archer & Ganopolski (2005); see Figure 13.

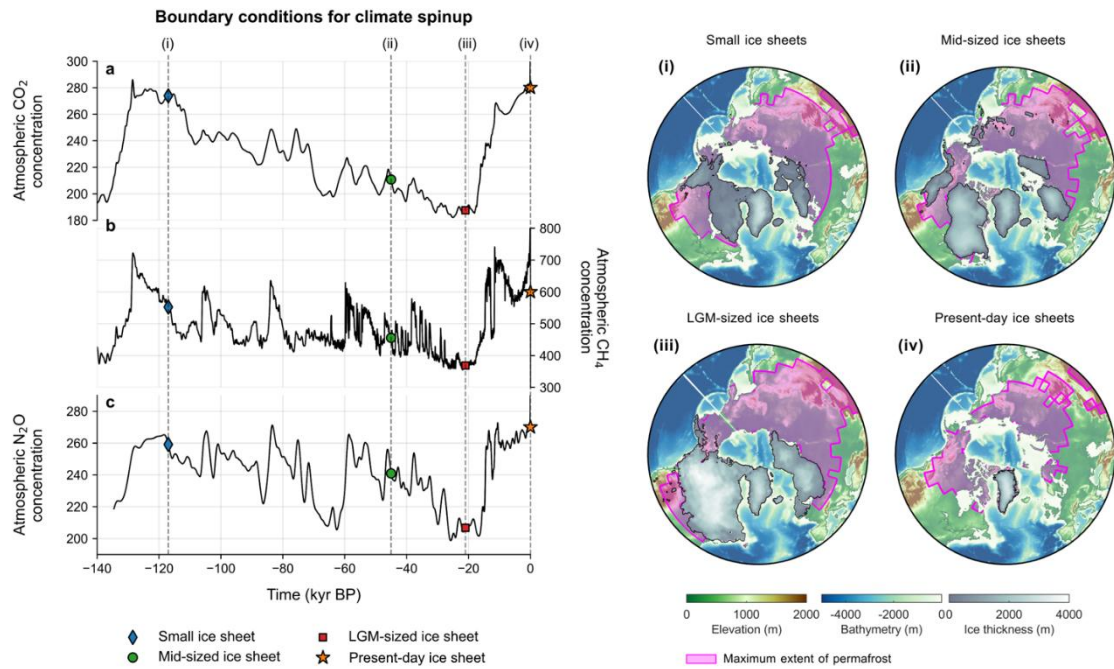


Figure 17: *Boundary conditions used for the climate spin-up for small, mid-sized, LGM-sized, and present-day ice sheets. The resulting spun-up climate corresponds to the cool, cold, ice-covered, and temperate domains. Panels (a–c) show the sampled GHG configuration, with the appropriate orbital forcing for the chosen timestep also applied. Panels (i–iv) show the corresponding ice sheet configurations. Note that permafrost extent was not prescribed in the model; it is included here only to illustrate the maximum extent of permafrost possible for a given ice sheet geometry.*

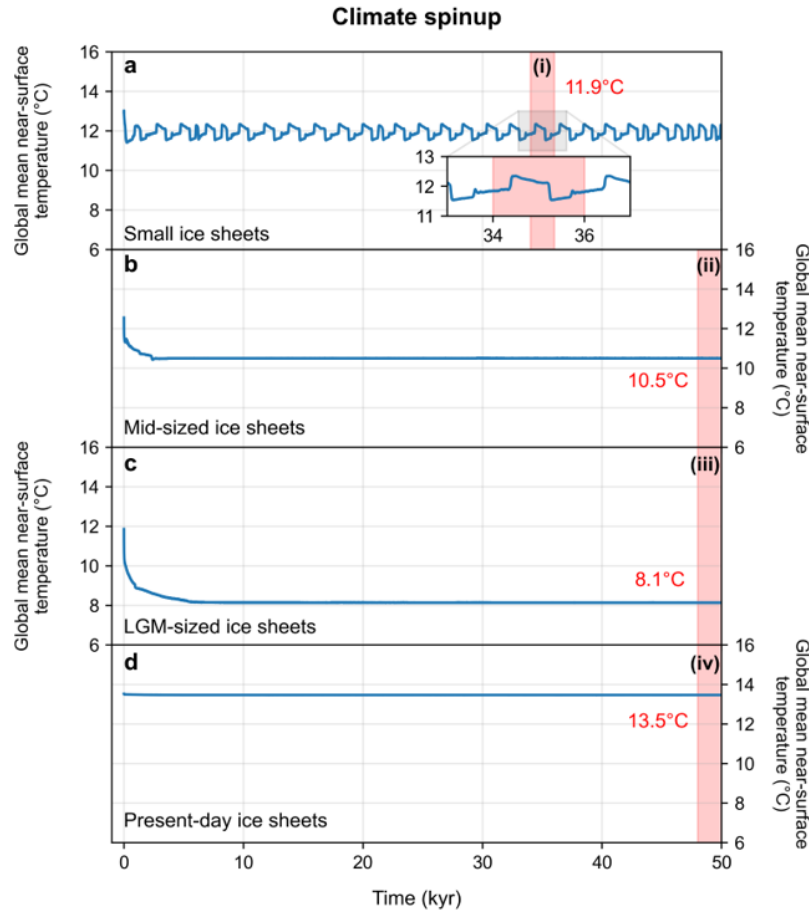


Figure 18: Climate spin-up for (i) small, (ii) mid-sized, (iii) LGM-sized, and (iv) present-day ice sheets. The resulting spun-up climate was averaged over the red shaded area to represent the cool, cold, ice-covered, and temperate climate domains.

Data on the climate in Germany over the coming 50,000-170,000 years can be directly pulled from the archived repository for Kaufhold et al. (2025b) in Kaufhold & Ganopolski 2025. To provide data on future glacial climate states, we conducted a set of four equilibrium experiments over a time span of 50,000 years representing four time periods from the last glacial cycle: 117,000 years BP, 45,000 years BP, 21,000 years BP, and 0 years BP (see Figure 17a-c). Since the last glacial inception began around 120,000 years BP, these periods correspond broadly to times with small ice sheets, mid-sized ice sheets, large ice sheets (i.e., LGM), and present-day ice sheets. The ice sheet configuration for present-day ice sheets was the RTopo dataset (Schaffer et al. 2016), for small ice sheets was from Willeit et al. (2024), for mid-sized ice sheets was the 45,000 year “max” estimate from Batchelor et al. (2019), and the LGM-sized ice sheet was the ICE-6G_C reconstruction. By running equilibrium experiments with boundary conditions defined by the orbital forcing, GHG concentrations, and the ice sheet configuration of each period, we were able to spin up the climate (see Figure 18) and assess what conditions in Germany could plausibly have looked like under these scenario, and would effectively generate the cool, cold, and ice-covered climate domains. The equilibrium experiments and

spun-up climate can be seen in Figure 17 and Figure 19. For mid-sized ice sheets, LGM-sized ice sheets, and present-day ice sheets, data was generally averaged over the last 2000 years of the experiment. As the equilibrium experiments with small ice sheets exhibited internal variability (i.e., meaning that there is no true “equilibrium” under such conditions), we instead averaged over years 34,000-36,000 in the experiment, which more or less corresponded to one complete cycle of the variability; see Figure 18. Data corresponding to these climate domains can be found in Kaufhold & Ganopolski (2025).

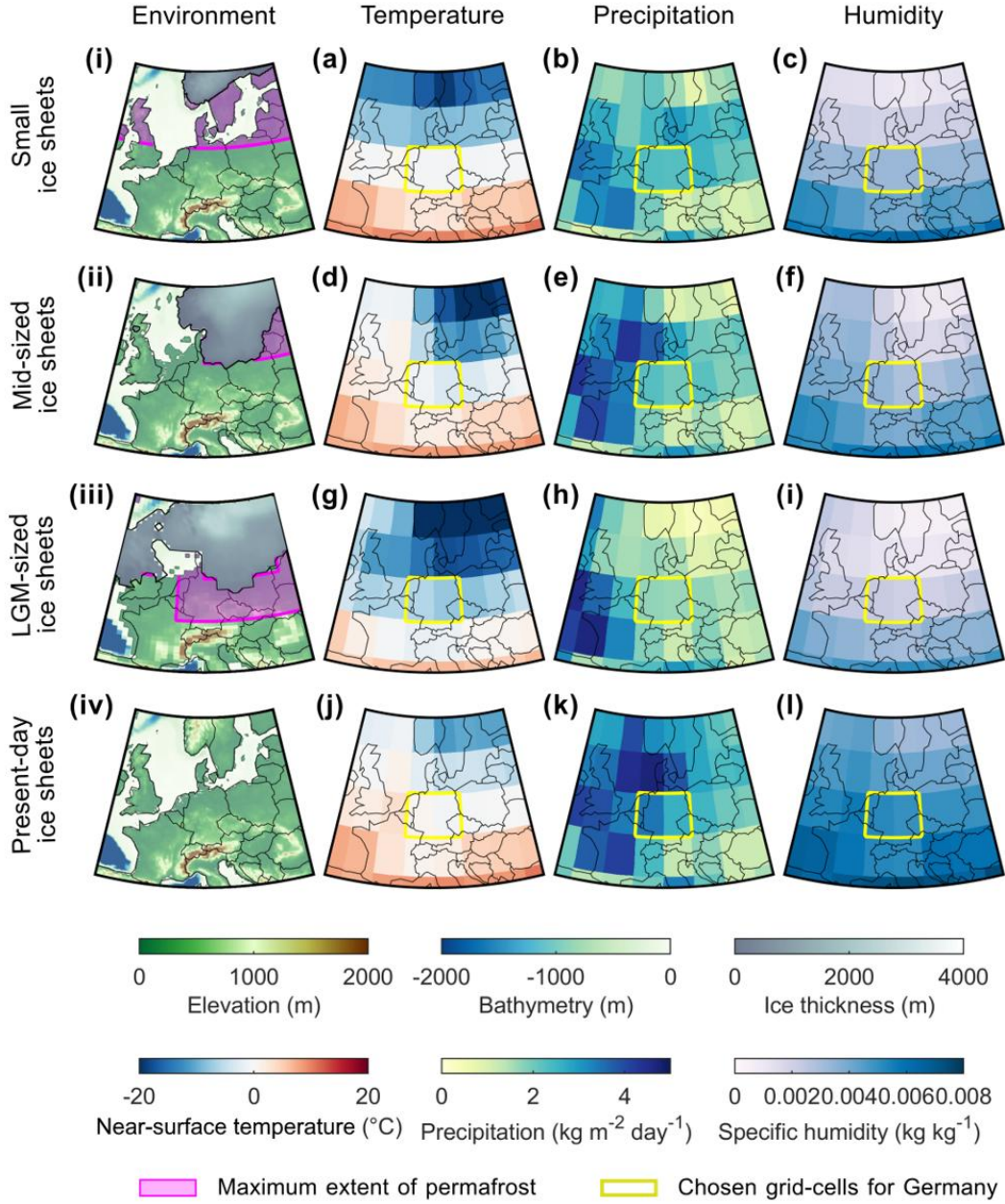


Figure 19: Resulting (a,d,g,j) near-surface temperature, (b,e,h,k) precipitation, and (c,f,i,l) near-surface specific humidity for the four climate spin-ups. Ice sheet data was taken from Schaffer et al. (2016), Willeit et al. (2024), Batchelor et al. (2019), and ICE-6G_C reconstruction.

4.5 Impact on biosphere dose estimation

As stipulated by § 7 of the EndlSiAnfV (2020), the radiation dose to which individual members of the population (representative person) are exposed needs to be estimated. The calculation basis and relevant exposure pathways (Figure 20) are defined by (BASE 2022). Given that the assessment period for the final repository spans $1 \cdot 10^6$ years, the biosphere will be subject to various climatic states, which influence exposure pathways and, consequently, the estimated radiation dose for a representative person. More specifically, climatic conditions primarily affect water availability for agricultural purposes. Depending on air temperature, precipitation, and relative humidity, irrigation using contaminated groundwater may become necessary to meet the water demand of agricultural produce. This constitutes a crucial transport pathway of radionuclides into the biosphere, leading to contamination of food and environmental media and contributing to the additional mean additional effective annual dose for the representative person.

To analyse the impact of different climatic states on biosphere dose estimation, dose calculations were performed using climate parameters derived from CLIMBER-X simulations. The PI cool-temperate served as the reference state. Parameters for distinct climate states (cool, cold, ice-covered) were obtained from equilibrium simulations, whereas parameters for six carbon emission scenarios, representing the active Anthropocene, were taken from transient simulations (Kaufhold et al. 2025b) sampled 1,000 years after present. Dose calculations were performed for six age groups and averaged over a lifetime of 70 years in accordance with the guidelines, equations and calculation methods described in BASE (2022). A well scenario with agricultural irrigation using contaminated groundwater was assumed, leading to contamination of:

- drinking water for humans and livestock,
- upper soil layers (field, pasture),
- shore sediments,
- plants (leafy vegetables, pasture plants, other plant products),
- animal products (cow's milk, meat, fish),

consistent with the external and internal exposure pathways defined in BASE (2022). The contamination depends strongly on the irrigation deficit and is therefore influenced by climatic conditions. Resulting doses were derived from the calculated contamination of the pathways listed above. Internal exposure via inhalation was taken into account for dust-bound radionuclides. Contamination scenarios other than well extraction (e. g. surface waters, gas path, or groundwater rise) were not considered. In cases of ambiguous specifications or parameter sets in BASE (2022), pessimistic assumptions were adopted, resulting in higher radiation doses. The ordinary differential equations in BASE (2022), describing the contamination of soil and shore sediments, were solved analytically, conservatively assuming long-term equilibrium conditions and neglecting the exponentially attenuated accumulation term in the solution. This approach yields the maximum

contamination of soil and shore sediments. To ensure comparable conditions with respect to the biosphere, transport within the geosphere was excluded from all considerations, and constant living conditions, agricultural practices, and dietary habits were assumed. Neglecting geosphere transport effectively implies that, instead of using specific radionuclide activity concentrations in groundwater, unity concentration (1 Bq L^{-1}) is used for all radionuclides when computing the equations in BASE (2022). Consequently, rather than absolute doses, radionuclide-specific dose conversion factors (DCF) were derived, representing the estimated dose per unity concentration ($\text{Sv L Bq}^{-1} \text{ a}^{-1}$) groundwater. Actual doses can easily be calculated by multiplying the DCF by groundwater activity concentration. All calculations were performed for a selection of radionuclides representative of intermediate-level waste, following Storck et al. 1986. The calculations were performed using a set of radionuclides that have proven to be relevant in past safety assessments (Storck et al. 1986 and Pröhl 1991). This selection comprises radionuclides that can be expected to be transported into the biosphere and includes members of all four decay chains as well as long-lived fission and activation products, especially highly mobile species such as I-129, Tc-99, and Cl-36.

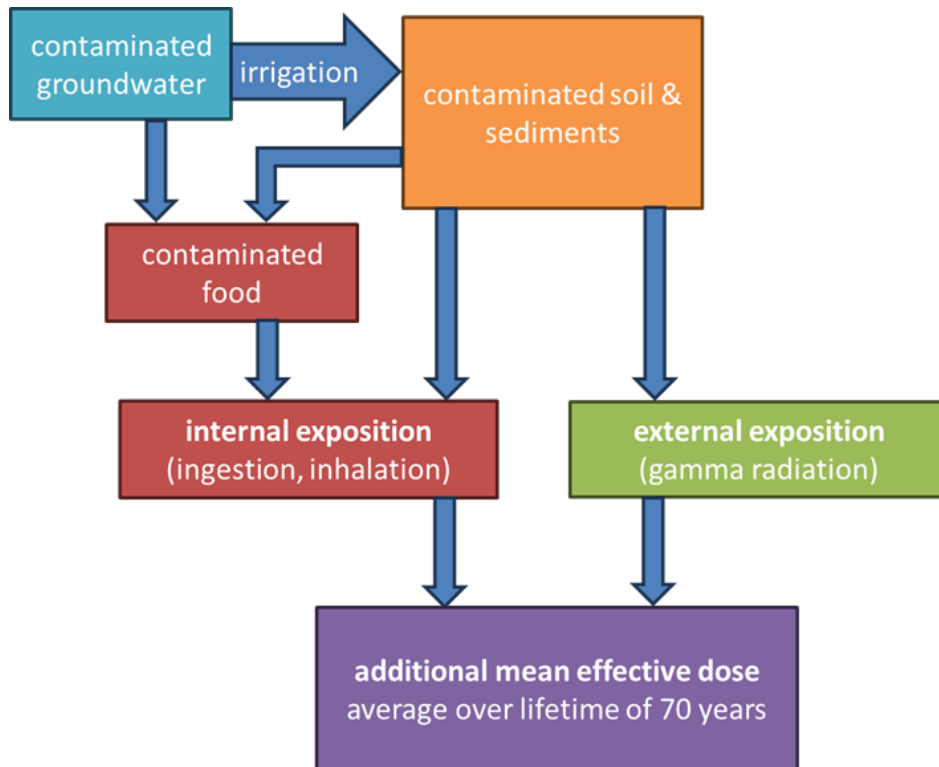


Figure 20: Overview of exposure pathways in the biosphere.

The annual cycle of the air temperature determines the onset, end, and overall duration of the vegetation as well as the water demand of agricultural plants. Figure 21 illustrates the annual cycle of the mean monthly air temperature for various distinct climate states and carbon emission scenarios. Compared to the reference cool-temperate climate (black squares in Figure 21) with a vegetation period of six months, the cool and cold climatic states (blue circles and upright triangles) exhibit shortened vegetation periods of

only four and three months, respectively. In contrast, the ice-covered scenario (purple inverted triangles) shows mean monthly air temperatures remaining below 5 °C even during summer, indicating the complete absence of vegetation. Conversely, for the active Anthropocene (red, orange, green, yellow, and green symbols), elevated mean monthly air temperatures throughout the year reflect an increase proportional to the total cumulative carbon emissions. This results in an extended vegetation period of seven months for scenarios with 2,000 PgC to 4,000 PgC emissions and eight months for 5,000 PgC emissions.

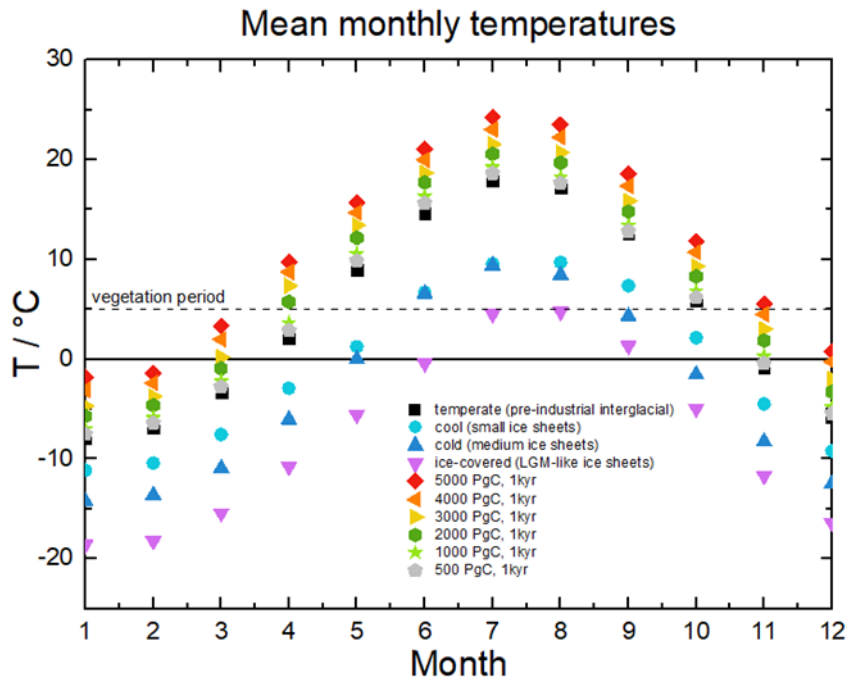


Figure 21: Annual cycle of mean monthly air temperature for different climatic conditions and carbon emission scenarios.

The second climate parameter of interest is mean monthly precipitation as it fully or partially meets the water demand of agricultural plants. Compared to the reference cool-temperate climate, the cool, cold, and ice-covered states exhibit a significant decrease of mean monthly precipitation, particularly during the summer months. In contrast, scenarios with total cumulative carbon emissions of 1,000 PgC and above show consistently higher mean monthly precipitations throughout the year, with the most pronounced increases occurring during autumn.

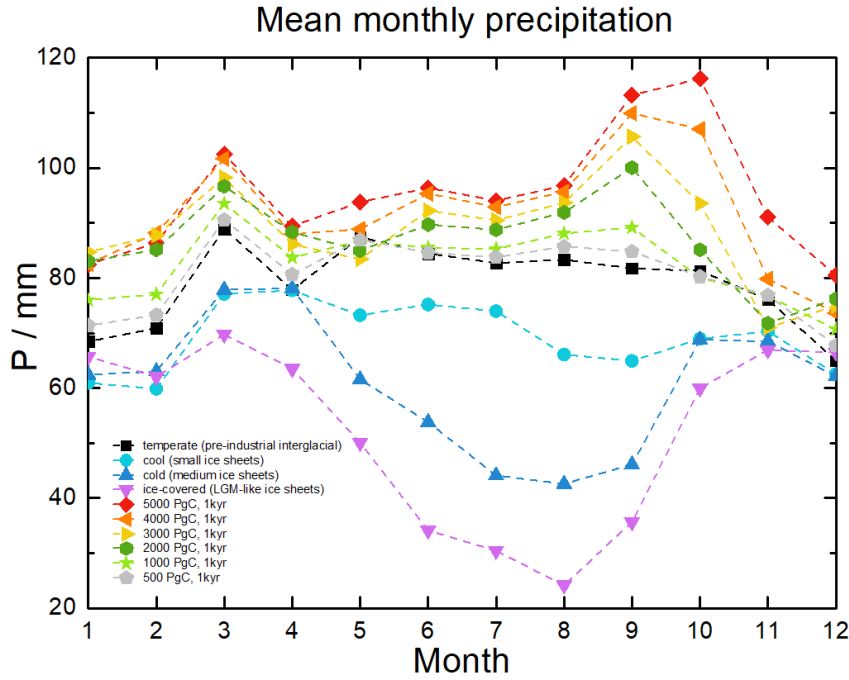


Figure 22: Annual cycle of mean monthly precipitation for different climatic conditions and carbon emission scenarios.

From the mean monthly climate parameters, the irrigation deficit is calculated according to BASE (2022). The annual cycle of the monthly irrigation deficit is shown in Figure 23. For the reference cool-temperate climate, an irrigation deficit occurs only in July and August, as precipitation meets the water demand during the remaining months of the vegetation period. For the cool, cold and ice-covered states, no irrigation deficit occurs throughout the year, as the vegetation period is shortened (or absent in the latter case) and prevailing precipitation fully satisfies the water requirements of agricultural plants. Consequently, the use of contaminated groundwater for irrigation is not necessary, leaving two substantial exposure paths (consumption of plants and external radiation) inactive. Moreover, all three climate states become indistinguishable in terms of dose estimation. In contrast, all emission scenarios for the active Anthropocene exhibit a three-month irrigation deficit during summer, with its magnitude increasing proportionally to total cumulative carbon emissions.

The annual irrigation deficits, defined as the sum over all monthly irrigation deficits for a given climate state, are presented in Figure 24 for all emission scenarios. The annual irrigation deficit exhibits a strictly monotonic increase with total cumulative carbon emissions, reaching up to an increase by a factor of five for the 5,000 PgC emission scenario compared to the PI reference. Assuming a linear dependency, the slope corresponds to approximately 32 mm of additional irrigation demand per 1,000 PgC emitted.

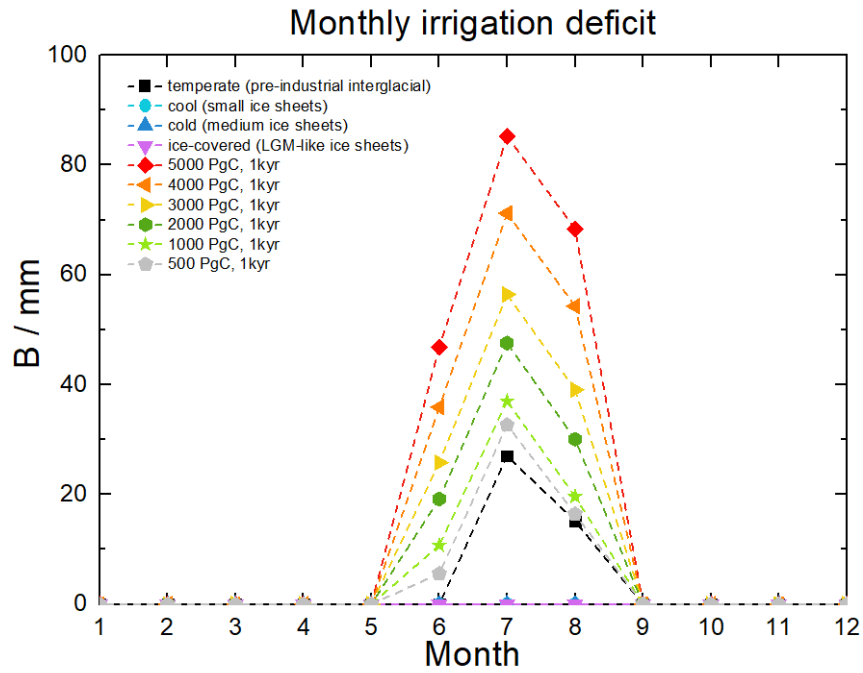


Figure 23: Annual cycle of monthly irrigation deficit for different climatic conditions and carbon emission scenarios.

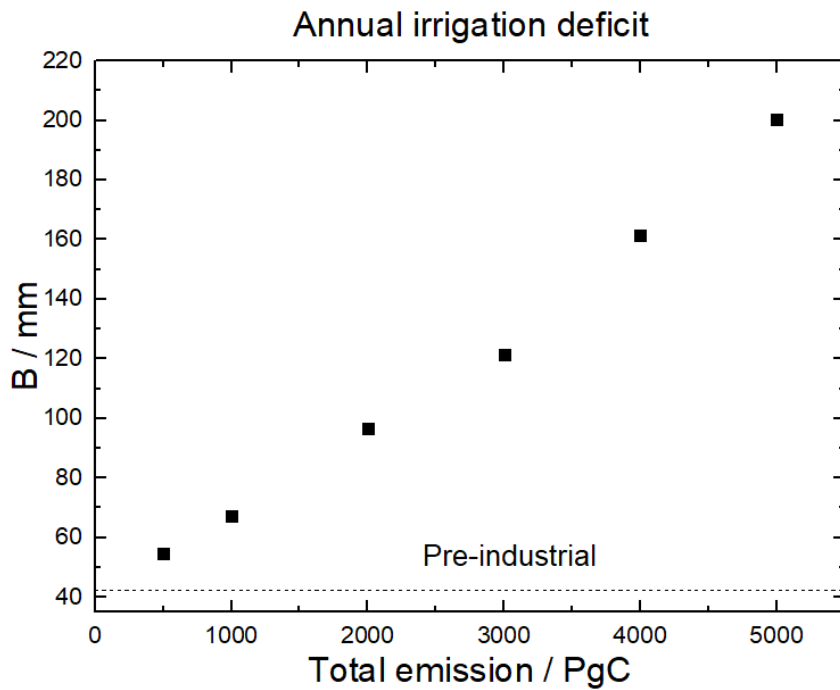


Figure 24: Annual irrigation deficit as a function of total cumulative carbon emission.

Next, DCF for the reference PI cool-temperate climate are derived following the computational framework described in BASE (2022) for a set of 27 radionuclides potentially relevant for long-term safety (Figure 25).

Naturally, radionuclides and their associated chemical species exhibit substantial variability with respect to coefficients reflecting transfer to and accumulation in soil, plants, and animal products as well as in their radiotoxic impact on the human body through both external and internal exposure pathways. This variability is reflected in the resulting DCF distribution, which spans several orders of magnitude from approximately $1 \cdot 10^{-7}$ to $1 \cdot 10^{-2}$ Sv·L·Bq⁻¹ (Figure 25). For the majority of radionuclides considered, ingestion of contaminated foods constitutes the dominant exposure pathway. Only for Thorium and Radium isotopes, external exposure pathways become significant.

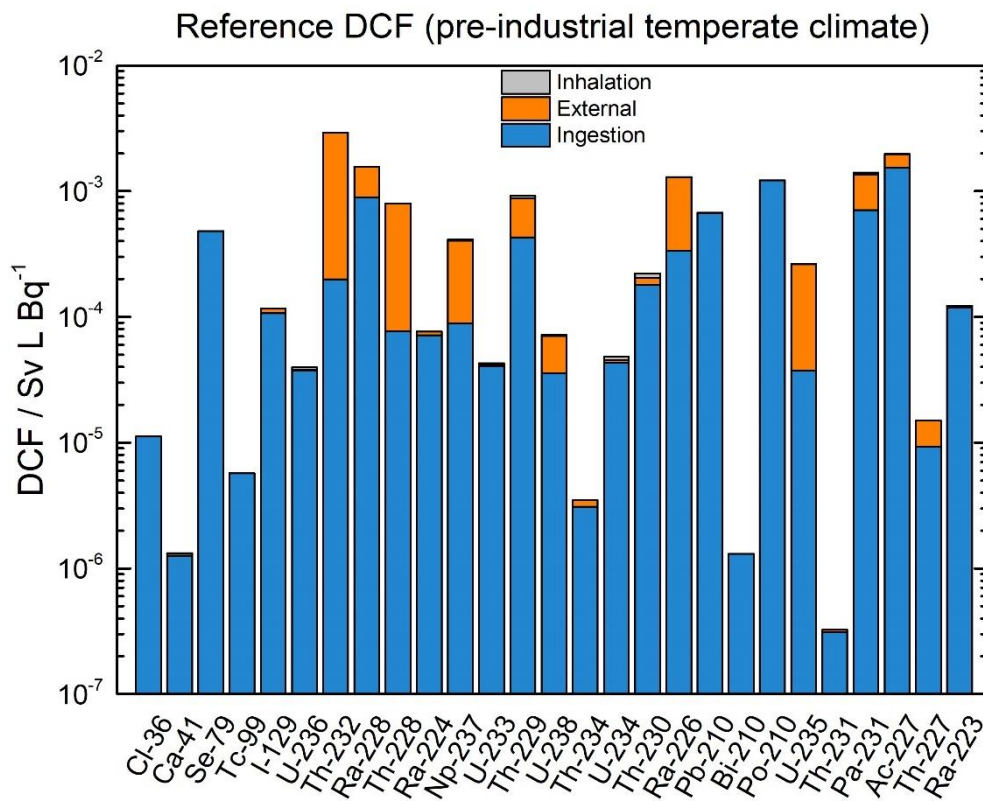


Figure 25: Radionuclide-specific dose conversion factors for PI cool-temperate climate.

Finally, the DCF of all 27 radionuclides were calculated across all climate states considered. To enable direct comparison, the values were normalised to their respective DCF under the reference PI cool-temperate climate. An increase relative to the reference climate is indicated by normalised DCF > 1, represented by upright bars in Figure 26, whereas reductions (normalised DCF < 1) are indicated by downward bars. Across all carbon emission scenarios and radionuclides, the normalised DCF increase by up to a factor of four compared to the reference climate. For most radionuclides, this increase is

proportional to the total amount of carbon emissions. The sole exception is Se-79, which shows a decrease in normalised DCF between 3,000 and 4,000 PgC emissions. This non-monotonic behaviour can be attributed to a shift in the dominant food group contributing to the ingestion dose, combined with individual weighting factors applied to individual food categories. In contrast, colder climate states, characterised by the absence of irrigation deficits (Figure 23) and indistinguishability in dose estimation as previously discussed, show a reduction in DCF by up to an order of magnitude, as most exposure pathways are eliminated in these scenarios.

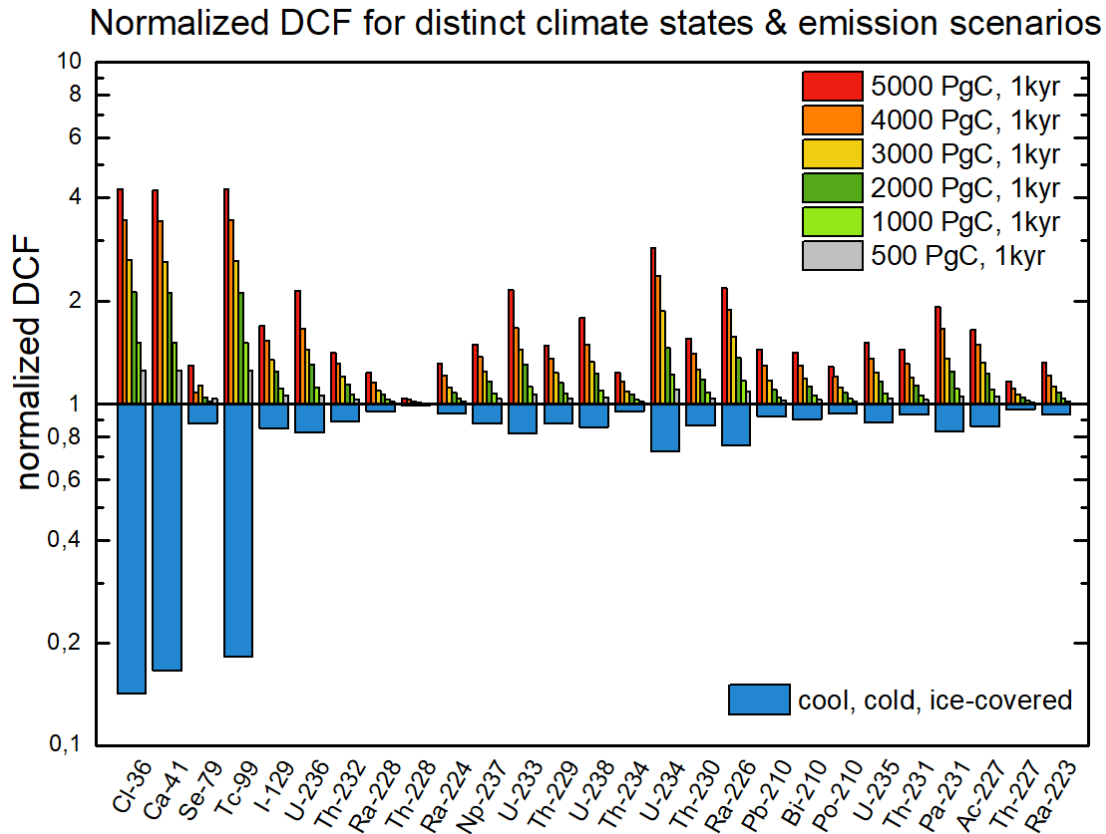


Figure 26: Normalised dose conversion factors for 27 radionuclides and all considered climate states.

In conclusion, climatic conditions exert a decisive influence on irrigation requirements and, consequently, on estimated radiation dose from contaminated groundwater. Warmer climate states are associated with increased irrigation deficits, leading to higher potential radiation exposure, whereas cooler climates, without irrigation needs due to shortened or absent vegetation periods, result in significantly lower DCF. In the ice-covered scenario, the residual finite DCF arise from the application of formalised dose calculation methodologies. Nevertheless, the extent to which substantial ice coverage fulfils the essential criteria for sustaining a viable population remains highly questionable. Overall, warmer climatic conditions are more likely to increase radiation exposure compared to cooler states. The effects discussed are exclusively related to processes within

the biosphere. Potential reinforcing or counteracting influences from radionuclide transport in the geosphere have not been considered.

5 Numerical groundwater models

The generic model from the „Method development and application of a safety assessment concept for a generic HAW repository site in claystone“ (AnSichT) project (Reinhold et al. 2013; Jobmann et al. 2017; Rübel & Gehrke 2022), which was also used in the RESUS project (Alfarra et al. 2020) as the model basis. The model area, parameters, initial (IC) and boundary conditions (BC), and the implementation of future climate developments as stylised states in the groundwater model are described below.

The density-driven groundwater flow simulations are carried out with the code "distributed density-driven flow" (d³f++). This is a finite volume code that was developed under the auspices of GRS in cooperation with various universities in order to be able to handle specific questions on groundwater flow with a focus on density-driven flow, which also is used for complex transport models (Fein & Schneider 1999; Schneider et al. 2020; Rübel & Gehrke 2022).

As part of the RESUS project, a model of a generic repository site in the host rock claystone was created (repository system T1 after Alfarra et al. 2020, based on Reinhold et al. 2013). This model is used as the basis for simulations assuming a typical layer sequence of clay rock formation in Germany. The generic repository system T1 consists of a shallow dipping layer sequence of 17 stratigraphic units of the Zechstein, Buntsandstein, Muschelkalk, Keuper, Lower Jurassic, Middle Jurassic, Upper Jurassic, Lower Cretaceous and Quaternary. The units are understood to be homogeneously formed and easy to characterise (Alfarra et al. 2020).

Contrary to the RESUS/AnSichT model geometry, the stratigraphic units below the Upper Jurassic were neglected, as they offer no added value in the model for the dispersal paths from the host rock (Rübel & Gehrke 2022).. The Hauterivian (krh) and Barremian (krb) clay represent the host rocks for the repository. Below the host rocks the Wealden Group can have an effect on the transport paths as an aquifer. The geometry of this model has dimensions of approximately 10 km in a N-S direction, and a maximum depth of approximately 1,400 metres (Figure 27).

At the model base, the Upper Jurassic with thicknesses of approximately 70 m to 250 m is located in the southern model area and consists of limestones. This formation is superimposed by the Wealden formation (wd) with alternating layers of claystone and sandstone, which have a relatively high permeability in relation to the surrounding layers and acts as an aquifer. The thickness is between 100 and 200 m. Above the Wealden is the thin Valanginian (krv) with up to 50 m of clay stone and clay marl stone. The two very low-permeable clay and clay marl layers of the Hauterivian (krh) and Barremian (krb) with total thicknesses of 500 to 600 m form the host rock. The barrier rock consists of claystone, which is partly characterised by silty fine sand and clay marl. The carbonate

content decreases from the Lower Hauterivian to the Upper Barremian, while the clay mineral content increases.

The Aptian (krp) is lithological connected to the host rock with clay rock, clay marl and marl rock. The higher marl contents lead to higher permeabilities compared to the host rocks from the Hauterivian and Barremian. The thicknesses range from around 50 to 120 m. Another aquifer next to the Wealden formation in the model area is the Hils-sandstein (s3) with sandy facies and a relatively uniform thickness of around 50 m. The Albian (krl) forms the end of the Mesozoic layer sequence with low-permeability clay and marl rock and a thickness of 120 to 260 m. The Cenozoic is represented by up to 100 m thick Quaternary sediments (q), which can be regarded as aquifers.

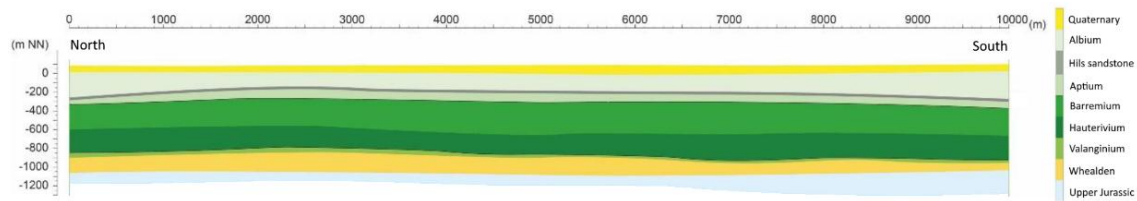


Figure 27: Cross section through the generic geological model with clay rocks as host rock based on the RESUS project taken from Alfarrá et al. 2020.

After working out the possible climate developments, the climate states “temperate climate”, “permafrost”, “permafrost with glaciation”, “glaciation”, “erosion valleys” and “sea level rise” are to be modelled. The climate states are represented by modified parameterizations, IC and BC.

5.1.1 General flow and transport parameters

In this Chapter the necessary model assumptions and parameters are described. In the numerical groundwater model, the following parameters were used for the hydrogeological units:

- Permeability,
- Porosity,
- Dispersion length,
- Diffusion coefficient,
- Sorption coefficient,
- Fluid density, and
- Fluid viscosity.

From the described climate states and developments, the BC and parameters for the numerical model were derived and described in the following. The parameters fluid density and fluid viscosity were only regarded for the climate state “sea level rise”.

The **permeability** [m²] differs significantly in aquifers and aquitards. The permeabilities of the hydrogeological units are used according to the data from Alfarrar et al. 2020. The conversion of permeabilities (hydraulic conductivity in metres per second) to k_f -values K [m²] is carried out according to

$$k_f = \frac{K \cdot \rho \cdot g}{\eta} \quad (1)$$

with

k_f = Permeability coefficient [m s⁻¹],

K = Permeability [m²],

ρ = Density of fluid, for water 998.2 at 20 °C [kg m⁻³],

g = Gravitational acceleration 9.81 [m s⁻²],

η = Dynamic viscosity of fluid, for water 1·10⁻³ at 20 °C [kg m⁻¹ s⁻¹].

The conversion was carried out manually for all model units before the simulation.

The total porosity is the quotient of the volume of all cavities in the rock body and its total volume. The **effective porosity** [-] describes the effective usable proportion of pore space in the rock and is lower than the total porosity (Bernhardt et al. 2008). Representative values for different grain sizes reach from a porosity smaller than 5 % up to values of around 35 % (Table 3).

Table 3: Grain sizes, total and effective porosity corresponding to different material types according to Bernhardt et al. 2008.

Material type	Grain sizes [mm]	Total porosity [%]	Eff. porosity [%]
Clay	≤ 0.002	> 50	< 5
Silt	0.002 – 0.063	50 - 45	5 - 15
Sand	0.063 – 2.0	45 - 40	15 - 35
Gravel	2.0 – 63.0	40 - 30	35 - 20
Stones	> 63	< 30	< 20

The **dispersivity** or **dispersion length** [m] describes the distribution and mixing of a substance due to heterogeneity on different scales for the longitudinal (D_L) and transverse (D_T) directions. On a microscopic scale, the dispersion is caused by the parabolic velocity distribution in the pore space between two grains, on larger scales by the different flow paths through the porous medium. In numerical modelling, the parameter should be chosen according to the model scale (Figure 28). In comparable models, the transverse dispersion length is assumed to be one tenth of the longitudinal dispersion length, unless a different ratio can be assumed on the basis of the geological data (König et al. 2023).

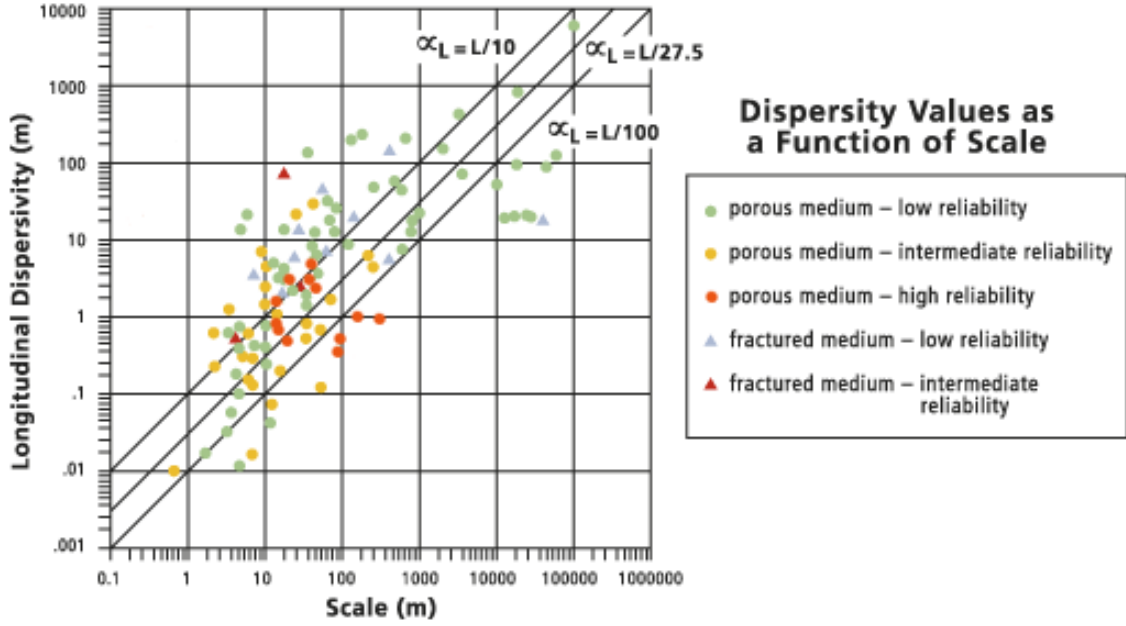


Figure 28: Scale-dependent longitudinal dispersivity relative to the scale of the considered test area (according to Gelhar, Welty & Rehfeldt 1992, revised in colour by ESRI 2023).

Diffusion is the ability of molecules to balance out a concentration gradient leading to a homogeneous distribution in the long-term (Wienberg 1998). Diffusion is represented by using the molecular **diffusion coefficient** [$\text{m}^2 \text{s}^{-1}$] in d³f++. The effective or molecular diffusion coefficient can be used in the numerical codes. This can be calculated using the following formula

$$D_m = \frac{D_{eff}}{\frac{\phi_{dif}}{\phi_{adv}} \cdot \tau} \quad (2)$$

with

D_m = Molecular diffusion coefficient [$\text{m}^2 \text{s}^{-2}$],

D_{eff} = effective diffusion coefficient [$\text{m}^2 \text{s}^{-2}$],

ϕ_{adv} = advective porosity [-],

ϕ_{dif} = diffusive porosity [-],

τ = Tortuosity [-].

The effective diffusion coefficients consider molecular diffusion, porosity and tortuosity. In d³f++, advection porosity and the molecular diffusion coefficient are input parameters for the simulations. In this case, a factor of 4.8 between diffusive and advective porosity was assumed in order to calculate the molecular diffusion coefficient for parameter calculation in the sensitivity analysis. In the calculations of climate conditions, the values mentioned were assumed to be molecular diffusion without conversion.

The **salt concentration** is specified in the groundwater flow and transport code d^{3f++} as a salt mass fraction. The relative salt concentration of 0 corresponds to a salt concentration of 0 kg kg⁻¹, and the relative salt concentration of 1 corresponds to a saturated salt solution at 20 °C. **Density [kg m⁻³]** and **viscosity [kg (m⁻¹ s⁻¹)]** of the groundwater are specified as a function of the salt concentration (Fein & Schneider 1999). The fluid density depends on the amount of dissolved substances in the water (e.g. rock salt, NaCl). Generally, fluid density increases with increasing proportions of dissolved substances. Dynamic viscosity is a measure of a fluid's internal resistance to flow under shear stress. It is a key parameter in hydrodynamic modelling because it influences momentum transfer and the overall behaviour of fluid motion, especially in systems with varying salinity. For models without density variations, a constant dynamic viscosity of 0.001 kg m⁻¹ s⁻¹ was assumed. In simulations that include density differences, viscosity values ranged from 0.001 to 0.002 kg m⁻¹ s⁻¹, depending on the salt concentration. These values are consistent with typical ranges for saline water. The salt concentration only plays a role in the “sea level rise” climate state, otherwise the concentration of the groundwater and inflows at the model boundaries is set to $c_{rel} = 0$. Jobmann et al. 2017 assume a fluid density of 1,095 kg m⁻³ in the AnSichT model.

Sorption is the interaction of a substance between a medium and a fluid. It is an important process at the interface between the solid, gas and solution phase and is differentiated between adsorption (adhesion) and desorption (detachment) from the medium (Amelung et al. 2018). The adsorption can be of chemical or physical origin, and is influenced by material properties such as charge density, reactivity, hydrophobicity, surface area and surface roughness (Amelung et al. 2018). Sorption generally describes the processes of distribution between a solution and the solid phase (sorbent). Within heterogeneous material, the processes appear very complex and abstract (McKinley & Scholits 1993). Thus, a sorption coefficient is used to model the process of adsorption, which represents the state of equilibrium between the solid and liquid phases with a specific distribution sorption coefficient (K_d -value).

In general, the rock or radionuclide properties also have an influence on transport behaviour. Negatively charged clay mineral surfaces repel anions thereby reducing the accessible proportion of the pore space. The size of radionuclides also plays a role, and a distinction is made between cations, anions and neutral substances (NAGRA 2002). The parameterisations for anions were primarily used for the simulations.

5.1.2 Flow boundary conditions and parameters

The base case represents the climate state “temperate climate”, where the fluid density and viscosity have a fixed value, as for most other climate conditions (Table 4). The base case of groundwater modelling differs from the definitions, initial conditions and boundary conditions of climate and dose calculations due to the different initial and boundary conditions, as the approaches of the models differ from one another. The parameters do not

correspond between the “temperate climate” state in groundwater modelling and the parameterisation from the “temperate climate” in climate modelling. The longitudinal and transverse dispersion length depend on the scale and the model area, and is set to 10 and 1 m in the longitudinal and transverse directions. Similar parameterizations can also be found in other models (Flügge 2009; Larue & Weyand 2018; Rübel & Gehrke 2022). The diffusion coefficient was set to $1.0 \cdot 10^{-9} \text{ m}^2 \text{ s}^{-1}$ for first simulations but is also varied for the parameter variation and sensitivity study.

Table 4: Overall model parameters for all climate states

Parameters	Unit	Reference values
Dispersion length D_L / D_T (longitud. / transv.)	[m]	1/0.1, 10/1, 100/10
Diffusion coefficient (water)	$[\text{m}^2 \text{ s}^{-1}]$	$1.0 \cdot 10^{-9} - 1.0 \cdot 10^{-11}$
Fluid density ρ^*	$[\text{kg m}^{-3}]$	998.2 - 1,197.2
Fluid viscosity η	$[\text{kg m}^{-1} \text{ s}^{-1}]$	$1.0 \cdot 10^{-3} - 2.0 \cdot 10^{-3}$

* after Jobmann et al. 2017

The model described is implemented in ProMesh and the various lithostratigraphic units were defined as individual units. The model grid was discretised finer in the repository area to enable a better numerical resolution of the mass transport and less numerical error.

The parameterization is based on the data from Jobmann et al. 2017; Alfarra et al. 2020; Rübel & Gehrke 2022. The permeability and porosity values for the layers represented in the model are compiled in Table 5. The longitudinal and transverse dispersion lengths and the value range of the fluid density and viscosity are shown in Table 4. For the variation simulations also the diffusion coefficients from for anions and cations after Nowak & Maßmann 2013 were used (Table 6).

Table 5: *Parameters for the model simulations according to Nowak & Maßmann 2013, Alfarra et al. 2020 and Rübel & Gehrke 2022.*

Lithostratigraphic unit	Permeability [m ²]	Effective porosity [-]
Quaternary (q)	$1.19 \cdot 10^{-14}$	0.2
Albian (krl)	$1.19 \cdot 10^{-18}$	0.05
Hilssandstein (s3)	$1.19 \cdot 10^{-14}$	0.1
Aptian (krp)	$1.19 \cdot 10^{-18}$	0.05
Barremian (krb)*	$1.19 \cdot 10^{-19**}$	0.05
Hauterivian (krh)*	$1.19 \cdot 10^{-19**}$	0.05
Valanginian (krv)	$1.19 \cdot 10^{-16}$	0.05
Wealden (wd)	$1.19 \cdot 10^{-14}$	0.075
Upper Jurassic (jo)	$1.19 \cdot 10^{-15}$	0.01

* Host rock; ** Vertical $1 \cdot 10^{-20}$ [m²]

5.1.3 Transport boundary conditions and parameters

For the transport simulation of a tracer from the potential repository some additional IC, BC and parameters must be defined. Like flow models, transport models are defined by differential equations. In addition to advection, other processes also influence mass transport. In order to calculate the concentration distribution of a substance, the processes of dispersion, diffusion, retardation by sorption and radioactive decay must also be considered. Either one constant value or stratigraphical unit dependent diffusion coefficient was used for the transport simulations. Additionally, the diffusion coefficient for cations and anions differ from each other because of their molecular size. The varying diffusion coefficients are based on the approach, that cations and anions have a defined size which influences the transport in the fine-grained clays. The rock density varies by the unique characteristics of the lithological unit, which was taken from Nowak & Maßmann 2013. Different sorption coefficients were used in the sensitivity analysis. The tracer provided to the model as an initial concentration at a defined straight line of 5 km in length and 700m depth (under the model surface). This broadly represents the location of a repository. The initial concentration is assumed to be 100 kg m^{-3} for the repository area. No additional tracer is given into the model afterwards.

Table 6: *Rock density, rock dependent molecular diffusion coefficients for anions and cations according to Nowak & Maßmann 2013 and Rübél & Gehrke 2022.*

Lithostratigraphic unit	Rock density [kg m⁻³]	Diffusion coefficient anions [m² s⁻¹]	Diffusion coefficient cations [m² s⁻¹]
Quaternary (q)	2,620	$7.05 \cdot 10^{-11}$	$1.41 \cdot 10^{-10}$
Albian (krl)	2,620	$8.81 \cdot 10^{-11}$	$1.76 \cdot 10^{-10}$
Hilssandstein (s3)	2,640	$2.82 \cdot 10^{-10}$	$5.64 \cdot 10^{-10}$
Aptian (krp)	2,650	$9.40 \cdot 10^{-11}$	$1.88 \cdot 10^{-10}$
Barremian (krb)*	2,685	$1.18 \cdot 10^{-11}$	$2.35 \cdot 10^{-10}$
Hauterivian (krh)*	2,685	$1.18 \cdot 10^{-11}$	$2.35 \cdot 10^{-10}$
Valanginian (krv)	2,700	$1.41 \cdot 10^{-10}$	$2.69 \cdot 10^{-10}$
Wealden (wd)	2,700	$2.35 \cdot 10^{-10}$	$4.34 \cdot 10^{-10}$
Upper Jurassic (jo)	2,730	$2.01 \cdot 10^{-10}$	$3.76 \cdot 10^{-10}$

* Host rock

5.1.4 Model assumptions and simplifications

Due to the long assessment period of one million years, short-term processes associated with the construction of the repository and the emplacement of the waste, which only has an effect at the beginning of the simulation period, were neglected. The following additional simplifications and assumptions were made:

- The failure of casks and the distribution of tracers within the repository were not considered. For simplification, the tracer was given into the model evenly distributed as a line source.
- The geometry of the repository was not realised with shafts and drifts and was simplified as a line under the assumption that the permeability in the repository area corresponds to the permeability of the host rock. This was considered acceptable as the transport processes within the repository were neglected and only the tracer flow into the surrounding host rock was regarded.
- The (re-)saturation of the (geo-)technical barriers and the neighbouring host rock is completed after a few hundred to a few thousand years after closure of the repository (Jobmann et al. 2016) to such an extent that the influence on the long-term transport of tracers is estimated to be small. The saturation process was neglected, and the repository was assumed to be saturated throughout the simulation.

- The influence of the temperature increase in the repository area due to heat-generating waste on the flow field is estimated to last a few thousand years and was not taken into account (Jobmann et al. 2016).
- The area between the permafrost and a glacier is volatile and the conditions change within a short period of time, just as glacial moraines and glacial lakes were not represented in the model.

5.2 Realisation of the climate states

In this chapter, the realisation of the different climate states with the change of parameters, initial and boundary conditions are described.

5.2.1 Realisation of the climate state “temperate climate”

The “temperate climate” climate state should represent the recent climate conditions and was used as a base case, against which the other climate state simulations were compared with. The focus of the work in Alfarra et al. 2020 was not the flow simulation, so the report does not provide information on pressure boundary conditions, flow direction or gradient of the groundwater level. For the model simulations, a low gradient of 0.002 was initially applied as of a depth dependent Dirichlet boundary condition, in accordance with Rübel & Gehrke 2022. The “temperate climate” climate state should represent the present-day climate conditions. This simulation was used as a base case, against which the other climate state simulations could be compared with. The geological model description in the report from Alfarra et al. 2020 do not provide information on pressure boundary conditions, flow direction or hydraulic gradient. For the these model simulations, a low gradient of 0.002 was initially applied as of a depth dependent Dirichlet boundary condition, in accordance with Rübel & Gehrke 2022 (Figure 29). On the northern model boundary an additional pressure (green box) was provided to represent the hydraulic gradient in addition to the depth depended hydrostatic pressure. The model base was regarded as an impermeable layer. A constant groundwater recharge rate of 0.2 m year^{-1} was assumed at the model surface as a Neumann boundary condition (Figure 29).

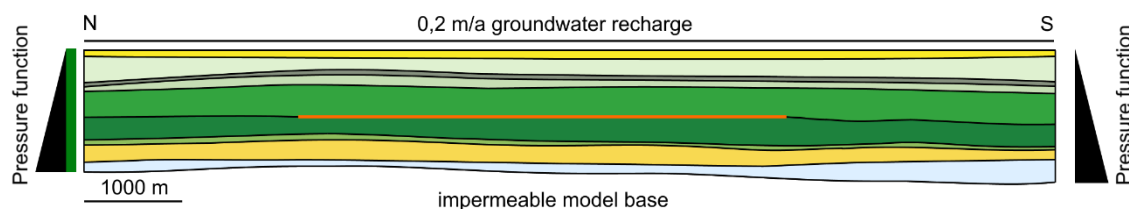


Figure 29: BC for the climate state “temperate climate”. The orange line represents the repository, while the green box represents the additional pressure for the hydraulic gradient.

5.2.2 Realisation of the climate state “permafrost”

As the water freezes in the layers near the surface, the permeability in the affected areas was reduced. At the model surface, a pressure potential corresponding to the elevation was applied without groundwater recharge. The pressure boundary conditions remain the same at the lateral edges. The model base is impermeable.

Permafrost was implemented in the Quaternary and the Albian lithologies up to a depth of maximum 330 m, with an average depth of around 200 and 250 m below the surface. This depth is also mentioned in Govaerts, Beerten & Veen 2016 for possible permafrost depths. The freezing of the water in the pore spaces and the associated reduction in permeability and effective pore space were considered by changes in permeability and porosity, as well as a change in the groundwater recharge rate in the groundwater model. Water from thawing permafrost and precipitation does not percolate into the ground, but is instead drained off on the surface. Surface runoff was not considered in this model. Under permafrost conditions, the lateral boundaries were still open for inflow and outflow, implemented by a Dirichlet-BC. Due to numerical aspects, the porosity and permeability in the permafrost area were set to 1 % and $1.19 \cdot 10^{-19} \text{ m}^2$.

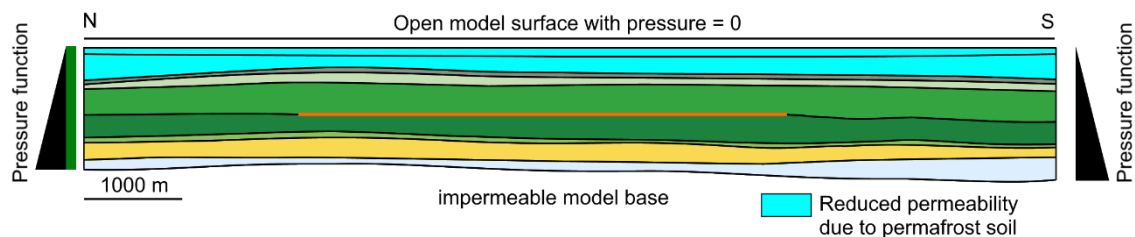


Figure 30: BC for the climate state “permafrost”. The orange line represents the repository, while the green box represents the additional pressure for the hydraulic gradient.

The salt concentration remains the same as in the “temperate climate” climate state in the whole model. A relative salt concentration of 0 was assumed at the top of the model, as well as at the lateral sides of the model, so no salt influence was considered in this climate state.

5.2.3 Realisation of the climate state “glaciation”

The presence of an ice sheet increases the load on the underlying rock. This load was represented by higher pressure boundary conditions at the model surface and sides (Figure 31). For this purpose, the pressure of a water column ($9,810 \text{ Pa m}^{-1}$) is multiplied by 92 % of the thickness of the glacier according to Näslund et al. 2020. The factor results from the lower density of ice compared to water. The maximum ice sheet thickness was assumed to be 1,000 m at the northern boundary, which was gradually reduced to 0 m at the southern boundary of the model using a linear function (Beuth et al. 2012).

The glacier thickness function was considered as constant over time. No transient movement of the glacier was modelled. A Dirichlet boundary condition with a fixed pressure potential below the glacier was assumed at the northern and southern boundaries of the model. The model base is impermeable. The permeability and porosity values for the "glaciation" climate state are listed in Table 5. In this climate state, the salt concentration on all model sides is $c_{rel} = 0$.

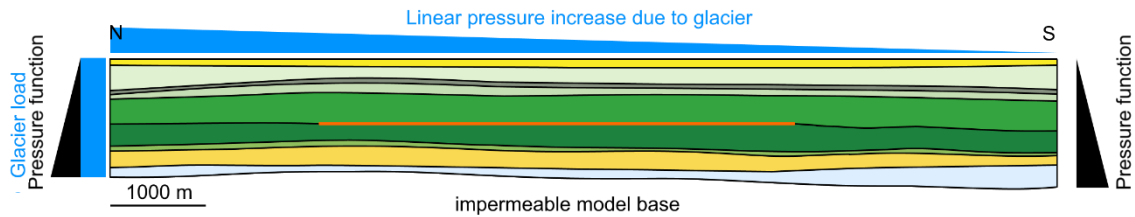


Figure 31: BC for the climate state "glaciation". The orange line represents the repository, while the blue box and triangle represent the additional pressure from the glacier.

5.2.4 Realisation of the climate state "glaciation and permafrost"

An additional climate state is a partial glaciation combined with permafrost conditions. The higher pressure below the ice sheet and the reduced permeability of the subsurface due to the permafrost influences the groundwater flow with a higher hydraulic gradient and the impermeable permafrost. This model was used to analyse the effect of the two combined processes in more detail.

The "glaciation and permafrost" climate state was intended to represent both processes in one model. For this purpose, an increased pressure at the model surface was assumed at the northern model boundary. The ice sheet thickness was halved to 500 m at the northern boundary and in the centre of the model, and no additional pressure was given due to the absence of the glacier there (Figure 32). The pressure is represented by a linear function from the south to the centre of the model. The pressure boundary conditions from the "permafrost" climate state were used in the southern model area. The model base is impermeable. The permafrost reaches 100 m under the glacier due to the thawing processes under the higher-pressure conditions under the glacier. The glacier and permafrost areas were constant and did not change their position. In reality, the area between permafrost and ice sheet is volatile and the conditions change within a short period of time. Structures such as moraines and glacial lakes were not depicted in the model.

The permeabilities were changed in the southern model area for the permafrost according to the simulation case "permafrost" with a porosity of 1 % and permeability of $1.19 \cdot 10^{-19} \text{ m}^2$. Otherwise, the permeabilities were set as in the "temperate climate" state. As in the other climate states, a relative salt concentration of $c_{rel} = 0$ was assumed at all model sides.

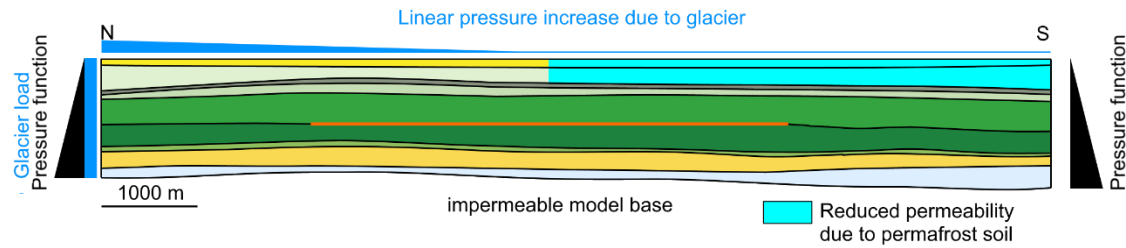


Figure 32: BC for the climate state “glaciation and permafrost”. The orange line represents the repository, while the blue box and triangle represent the additional pressure from the glacier.

5.2.5 Realisation of the climate state “erosion valleys”

During glacial cycles, ice sheets may advance and retreat, leading to glacial overriding and erosion. As a result, erosion valleys can be formed by glacial meltwater with high flow velocities under the ice sheet, especially for unconsolidated rocks. These can also be of other origins and are usually a few metres up to 300 m deep (Flügge & Rübel 2010; Mrugalla 2011; Lang 2023). Channel depths of over 500 m are possible, but rare (Weitkamp & Bebiolka 2017). Erosion and subsequent backfilling are usually accompanied by a change in permeability. After backfilling, the permeability of the sediments is usually higher than the permeability of previously existent sediments. Erosion valleys are often backfilled with sediments of a sandy facies whose permeabilities can be classified as aquifer and are therefore in the range of $1 \cdot 10^{-5} - 1 \cdot 10^{-3} \text{ m s}^{-1}$ (Hölting & Coldewey 2005). The permeability in the model was set to values typical for erosion valleys in previously defined model areas (Table 7). Two different directions of erosion valleys were analysed. One generic erosion valley is assumed in the north-south direction and cuts through the whole model area with a depth of up to 330 m, in average of around 200 to 300 m in depth (Figure 33). Another model version has a west-east directed channel (Figure 34). The west-east directed channel can vary in position to analyse if the position of the channel has an influence on the potential transport path.

The IC, BC and parameters stay the same as in the climate state “temperate climate” with Dirichlet-boundary conditions at the lateral sides, a groundwater recharge at the model surface of 0.2 m year^{-1} , and an impermeable model base. The permeability and porosity values for the “erosion valleys” climate state remain as that listed in Table 5, except for the values for the erosion valleys (Table 7). In this climate state, the salt concentration was set to $c_{\text{rel}} = 0$ at every model boundary.

Table 7: Parameters for the climate state “erosion valleys”

Parameter	Unit	Reference value
Permeability in areas affected by erosion valleys	$[\text{m}^2]$	$1.19 \cdot 10^{-12}$
Effective porosity in areas affected by erosion valleys	$[-]$	0.3

In one model configuration, a channel in an west-east direction is represented in a small defined area of the model in the Southern part (Figure 34) and in another model configuration, a channel in a north-south direction was realised along the entire model (Figure 33). It is not possible to regard transient erosion processes by meltwater with changing geometry in the simulations, so the erosion valleys are regarded to be constant in geometry during simulation.

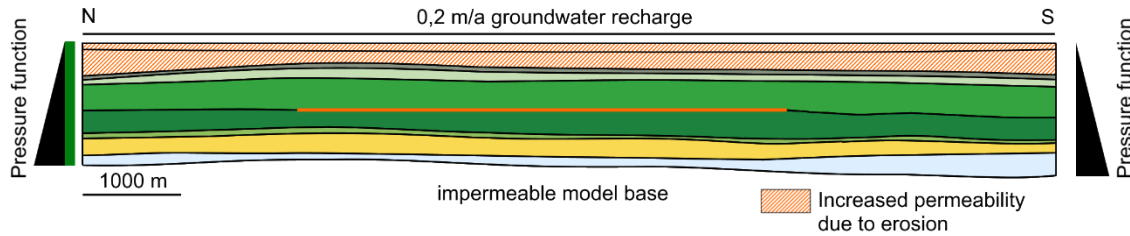


Figure 33: BC for the climate state “erosion valleys” with a channel in W-E direction (orange line represents the repository; green bar represents the additional pressure for the hydraulic gradient).

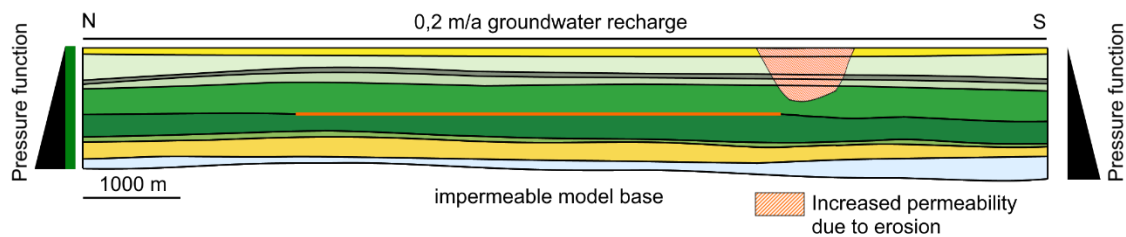


Figure 34: BC for the climate state “erosion valleys south” with a channel in N-S direction (orange line represents the repository; green bar represents the additional pressure for the hydraulic gradient).

5.2.6 Realisation of the climate state “sea level rise”

Over the last 700,000 years, variation in sea level has amounted to fluctuations of up to almost 140 m. At LGM approximately 20,000 years ago, sea level was approximately 120 m below today's sea level (Bradley, Alverson & Pedersen 2001). Due to the changing climate and the melting of the ice sheets, a higher sea level can be expected in the future. With the melting of the Antarctic and Greenland ice sheets, a sea level rise of approximately 65 m can be achieved (Beuth et al. 2012). A water column of 65 m would result in a maximum additional pressure of 637,650 Pa or 9,810 Pa m⁻¹. This maximum extreme case is then assumed for the “sea level rise” climate state.

Like the “glaciation” climate state, the “sea level rise” climate state was modelled with increased pressure at the model surface. However, in contrary to the “glaciation” climate state, the pressure was assumed to be constant at the surface. The lateral sides and the model base are impermeable for fluid flow. The permeability and porosity values remain the same climate state as in Table 5. A salt concentration boundary condition with

$c_{rel} = 0.13$ was applied to the model surface, corresponding to the salt concentration of seawater of 3.4 % (Schmitt 2008). The lateral sides are open for the outflow of tracer and salt, but no tracer and salt concentration are assumed to enter over the lateral sides.

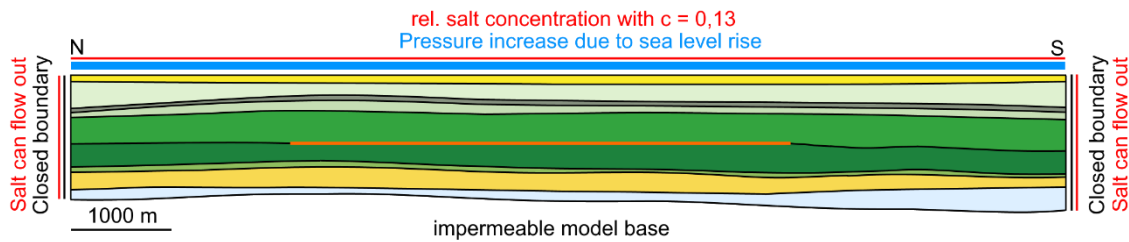


Figure 35: BC for the climate state “sea level rise” with salt boundary conditions. The orange line represents the repository, while the blue bar represents the additional pressure for the sea water at the model surface. Red lines represent the implemented salt boundary conditions.

5.3 Model results for the different climate states

This chapter presents the results of the groundwater flow and transport models for the different climate states and parameter variations. It should be mentioned that every climate state was simulated for the whole assessment period without a change in boundary conditions, so that possible differences between the climate states could be identified. With this method, the influence of the climate states could be quantified in order to identify the most important climate states, with regards to safety assessment of a deep geological repository and a favourable host rock.

5.3.1 Flow directions and velocities for different climate states

The climate states stylised by boundary conditions were simulated over a period of one million years for each climate state. An initial comparison of the results for the different climate states was carried out by analysing the flow velocity. A profile at the X-coordinate 5,040 m, which extends from 1,200 m below sea level to 70 m above sea level (blue line in Figure 36), was used to analyse the flow velocities. Significant differences in the velocities could be observed across the different permeable geological units. Depending on the lithological properties, the groundwater reached higher flow velocities in sandier units, such as in the Quaternary, Hilssandstein or Wealden (Figure 36).

It is important to note that the flow velocity in all simulations with different climate states are favourable in the host rock with the used boundary conditions. The transition from favourable to conditionally favourable is at a velocity of 0.1 mm year^{-1} and from conditionally favourable to less favourable at 1 mm year^{-1} (StandAG 2023). The highest velocities in the host rock have been calculated for the climate states “glaciation” and “permafrost with glaciation” with $3.7 \cdot 10^{-3}$ and $1.9 \cdot 10^{-3} \text{ mm year}^{-1}$ respectfully. The higher velocities are due to the higher hydraulic gradient caused by the loading of the ice sheet.

Velocities of $7.3 \cdot 10^{-5}$ to $1.35 \cdot 10^{-4}$ mm year⁻¹ were calculated for the climate states “temperate climate”, “erosion” and “permafrost”. The lowest velocities in the host rock were found for the climate state of “sea level rise” ($1.5 \cdot 10^{-7}$ mm year⁻¹). The flow velocities plotted for the “sea level rise” climate state show oscillations, especially at depths of 200 and 300 metres (Figure 36). These oscillations are caused by density-driven flow and are not unusual. In the calculations for the other climate states, the constant density and viscosity prevent any oscillations in the flow velocities. The highest velocities of all climate states and model units could be found in the Quaternary layers and the climate state “erosion”. All in all, the velocities in this profile section of the model vary between $8.1 \cdot 10^3$ mm year⁻¹ and $1.5 \cdot 10^{-7}$ mm year⁻¹ for all stratigraphical units.

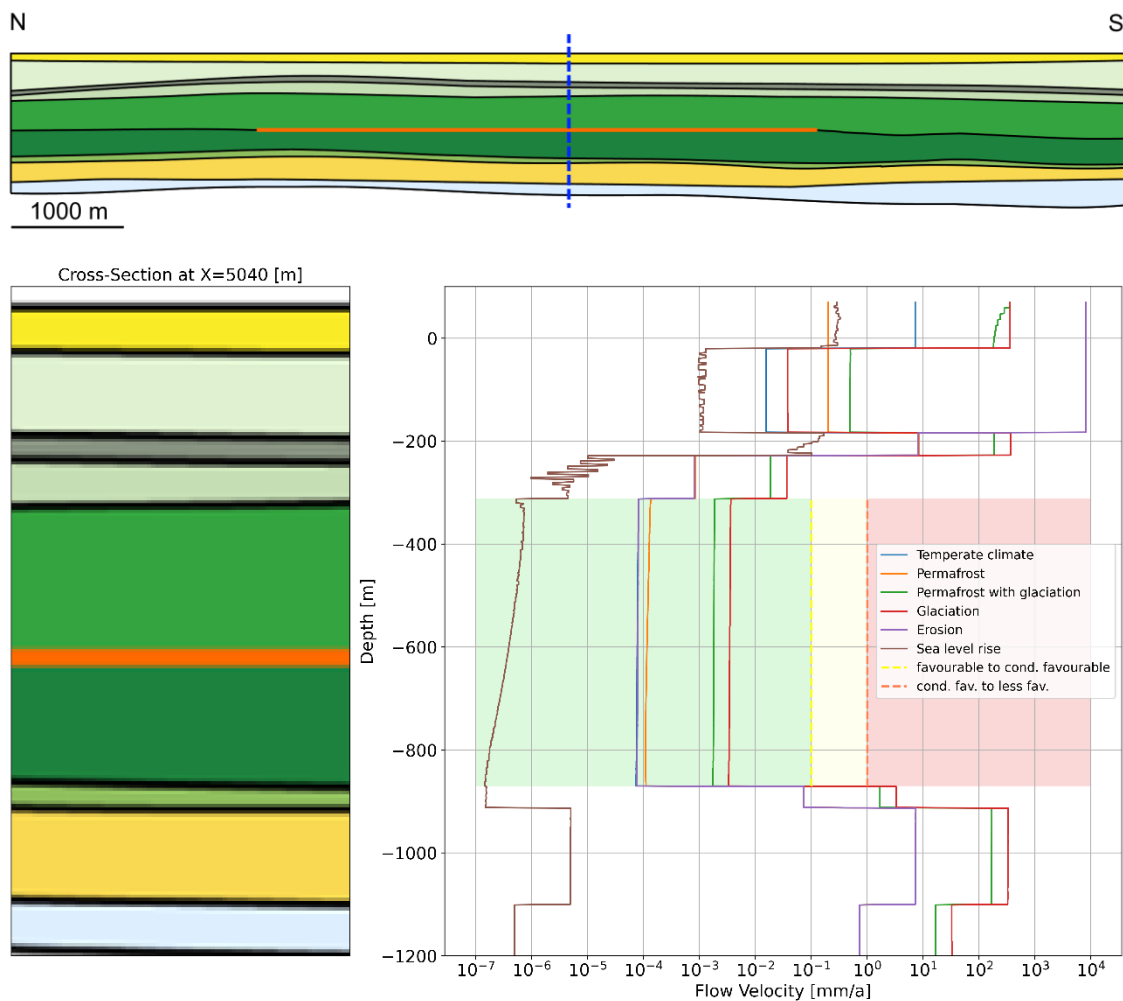


Figure 36: *Velocity profile at the X-coordinate at 5,040 m (blue line in top figure) in the middle of the model for the different climate states with the host rock area between -310 and -870 m below surface. All velocities are in the “favourable” rating group for the groundwater flow indicator of the geological assessment criteria of 0.1 mm year⁻¹ of the StandAG 2023.*

In addition to a comparative profile with the flow velocities plotted over the depth, differences in the flow direction and velocity could also be observed over the entire model

area (Figure 37). The steady state velocities are shown for all climate states. Figure 37 shows the pressure in Pa as area distribution in the background in the colours blue to red. The arrows indicate the flow directions, and the colours reflects the flow velocities on a logarithmic scale. Due to the wide range of flow velocities from the more permeable layers (e.g. Quaternary and Hilssandstein) to the less permeable clays of the host rock, a velocity scaled size representation of the arrows was avoided. The scalar range in all figures extends from $2 \cdot 10^{-15} \text{ m s}^{-1}$ to $2 \cdot 10^{-8} \text{ m s}^{-1}$. In the case of the climate state “sea level rise”, the lowest velocities are lower than the shown scalar range (to $1 \cdot 10^{-18} \text{ m s}^{-1}$), a representation of an even wider range would make it more difficult to distinguish the velocities for all other climate states.

In the “temperate climate” state, the flow direction is directed from north to south according to the boundary conditions. In the low-permeable Albion, the flow direction is directed from the model surface towards the Hilssandstein due to the groundwater recharge ; the proportion of vertical flow is low in relation to the flow velocities in the horizontal direction. Otherwise, the flow velocities correspond to the permeabilities, with the lowest velocities in the host rock.

The pressure distribution in the “permafrost” climate states is equal to that of the “temperate climate” state, except for the limited groundwater flow and the lower velocities in the Quaternary due to permafrost. The deeper layers are not strongly influenced by the permafrost and there is a continuous south-facing flow regime.

For the case “glaciation and permafrost”, the higher hydraulic gradient characterises the flow regime. The more permeable layers of the Quaternary, Hilssandstein and Wealden show higher flow velocities. In the Quaternary, groundwater flows to the centre of the model, where it then meets the frozen permafrost areas and subsequently flows to the surface due to the pressure conditions. The direction of flow in the host rock is also directed slightly towards the model surface, but with significantly lower flow velocities. In the southern part, groundwater in the Quaternary and Albion pushes further towards the model surface. In the Hilssandstein and the underlying layers, the flow points southwards.

In the “glaciation” climate state, the flow environment is similar to that of the “temperate climate”, but with higher flow velocities. In the Albion, the water flows stronger in southern direction than in the “temperate climate” state, resulting in a higher discharge at the southern model boundary. The boundary conditions used, with a steeper gradient between the model surface and the lower edge of the model, result in a slightly upward-directed flow in the host rock. In addition, the steeper gradient between the northern and southern edges of the model, as well as throughout the entire model area, leads to higher flow velocities. The higher pressure due to the glacier load is visible in Figure 37 by the red colour in the northern part of the model area.

If erosion valleys are present (as in the climate state “erosion”), high flow velocities can be observed due to higher permeabilities in the backfilled valleys. The entire upper third of the model shows high flow velocities, however, the host rock remains unaffected, as do the layers at the base of the model. The flow velocities in the host rock point slightly towards the model surface in the southern part of the model, similar to the “glaciation” climate state, but are lower due to the lower hydraulic pressure gradient. With the “sea level rise” climate state, there is no directional flow according to the boundary conditions. The flow directions are driven by the differences in density and are low in relation to the flow velocities of the other climate states (around $1 \cdot 10^{-18} \text{ m s}^{-1}$).

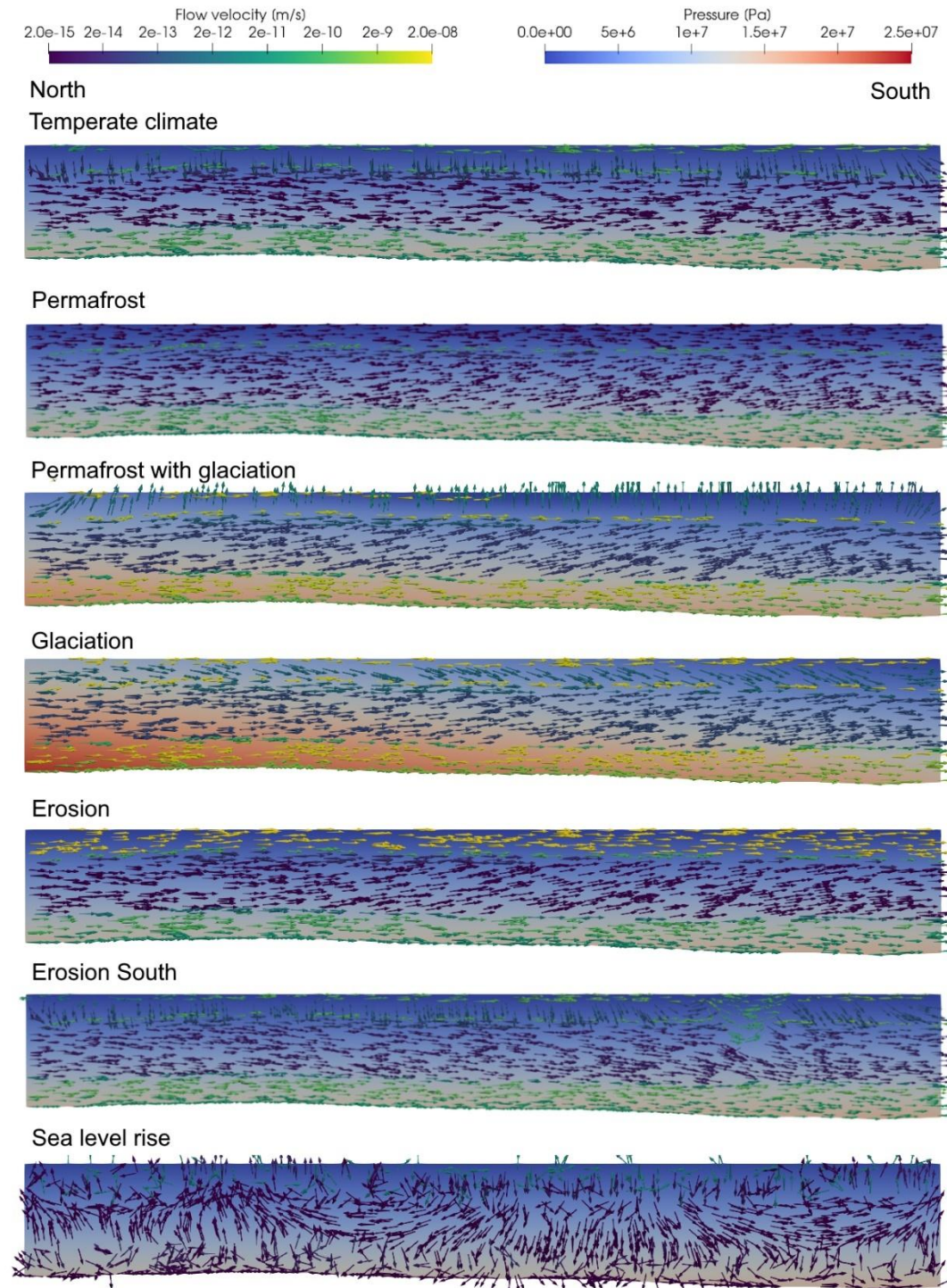


Figure 37: Pressure distribution and flow velocity for the different climate states after one million years.

5.3.2 Evaluation of the concentration distribution

The radionuclide mass was integrated every timestep for every stratigraphical model unit. With this integration, the criterion of safe containment according to EndISiAnfV 2020 § 4 could be evaluated. In the future of the site selection process, this criterion will be

used to define the contaminant providing rock zone (CRZ). In this model, fulfilment or non-fulfilment of the criterion is considered over the entire host rock, and no designation of a CRZ is aimed at. The stratigraphic units of the Barremian and the Hauterivian were therefore to be regarded as CRZ, no calculations were done to estimate the size of the CRZ within the Barremian and Hauterivian host rock. To evaluate the radionuclide mass transported out of the host rock, the radionuclide mass over time is divided by the initial mass in the host rock resulting in the normalised mass fractions (M_{norm}) shown in the different plots.

Within various simulation runs with changed diffusion and sorption coefficients for the “temperate climate”, significant differences in the amount of mass transported out of the host rock were identified (Figure 38). In the simulation cases with a diffusion coefficient of $1 \cdot 10^{-9} \text{ m}^2 \text{ s}^{-1}$, only 60% of the initial mass remains in the host rock after 1 million years. At this time, about 40% of the initial mass had primarily entered the surrounding layers of the host rock (with diffusion as the main transport process). The radionuclides then were transported out of the model due to the higher flow velocities in the surrounding layers. Such a diffusion coefficient describes diffusion in free water and can therefore be considered (to some extent) the maximum diffusion coefficient, which is less favourable for the host rock according to the StandAG. This diffusion coefficient was used as a generic value for exploring parameter space, and does not represent a real repository system. Instead, it provides a better understanding of the model and to classify the influence of parameter variations.

By reducing the diffusion coefficient to $1 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}$, the proportion of mass transported out of the host rock over one million years is less than 0.3 %. According to StandAG, the applied diffusion coefficient corresponds to the boundary from less favourable to conditionally favourable. By reducing the molecular diffusion coefficient to a value of $1 \cdot 10^{-11} \text{ m}^2 \text{ s}^{-1}$, the curve runs below the scales shown here and does not violate the mass criterion according to EndlSiAnfV. No fractions more than $1 \cdot 10^{-6}$ could be found in units other than the host rock. These results show that the diffusion coefficient is an important transport parameter in this model set up.

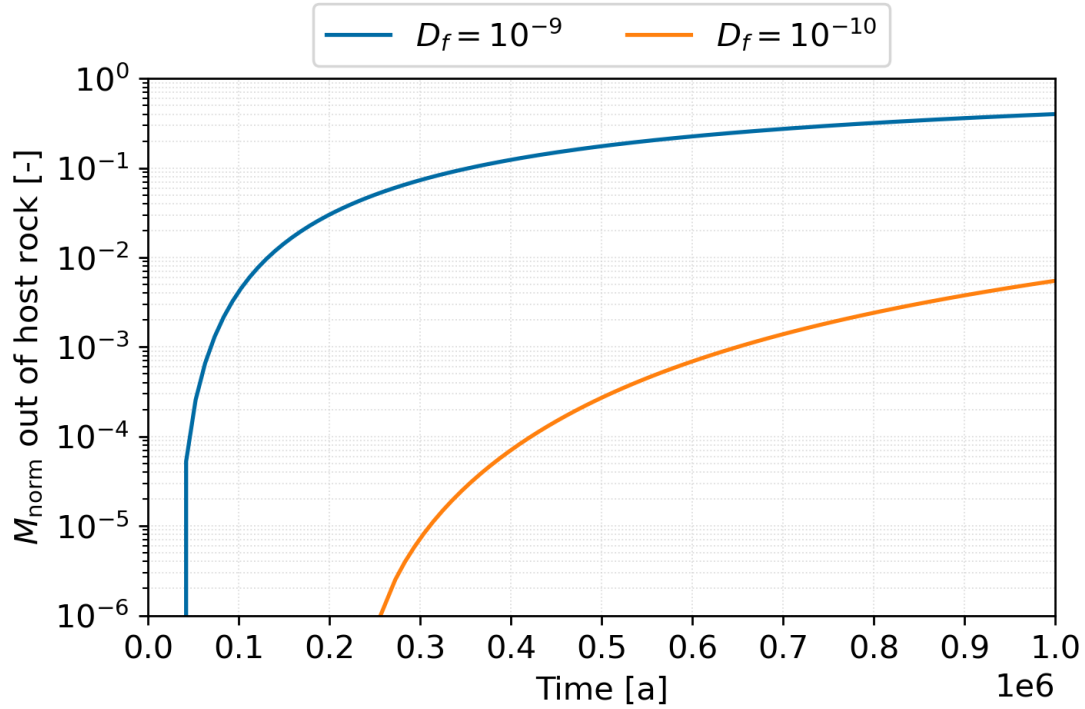


Figure 38: Normalised mass fractions of the radionuclides out of the host rock for temperate climate with diffusion coefficients of $1 \cdot 10^{-9} \text{ m}^2 \text{ s}^{-1}$ and $1 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}$.

A comparison of the three aforementioned diffusion coefficients could be made by plotting the concentration distribution after one million years. This shows a radial concentration distribution in all cases (Figure 39). The radial shape around the line shaped repository structure suggest that diffusion contributes a larger proportion to transport than advection. For the simulation case with $1 \cdot 10^{-11} \text{ m}^2 \text{ s}^{-1}$ as the diffusion coefficient, the transport length from the repository is around 40 metres for 0.1 % of the initial radionuclide repository concentration without considering sorption as retardation process. For higher diffusion coefficients, the distribution in the host rock is visibly stronger. In the northern part of the model, the final repository is located closer to the Valanginian underlying the host rock. With high diffusion coefficients, the radionuclides reach this layer boundary and are transported at higher flow velocities in the direction of flow. Along the host rock and the Valanginian, a stronger concentration gradient develops there compared to other model areas.

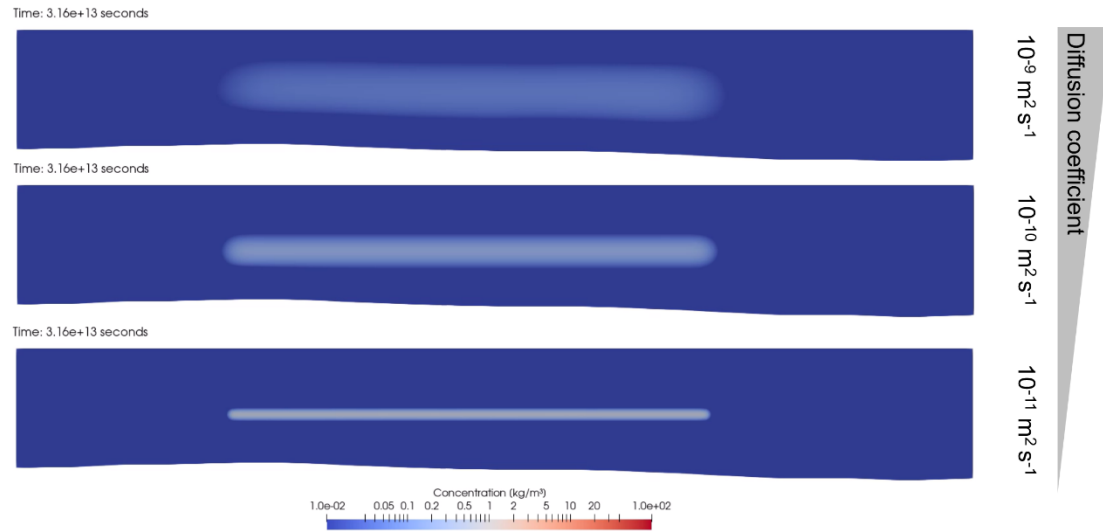


Figure 39: Concentration distribution for three different diffusion coefficients ($1 \cdot 10^{-9}$, $1 \cdot 10^{-10}$, $1 \cdot 10^{-11} \text{ m}^2 \text{ s}^{-1}$) after 1 million years.

Besides the comparison of different diffusion coefficients for the “temperate climate”, other climate states were also simulated with different diffusion coefficients. The climate states were stationary over the whole simulation time and no change in climate was considered in these simulations. As a result, the differences in the transported mass from the host rock are potentially the maximum change of mass fraction occurring due to different climate states. With higher diffusion coefficients, the mass fraction transported out of the host rock is higher in each simulation case compared to the lower diffusion coefficients (Figure 40). For all climate states with the same diffusion coefficient, the mass fraction transported out of the host rock is within a range of a factor 2.

The lowest discharge from the host rock is observed for the climate state “sea level rise”. The climate states “temperate climate”, “permafrost” and “erosion” show nearly the same results. The changes of the boundary conditions in the Quaternary with lower (“permafrost”) and higher permeabilities (“erosion”) do not affect the discharge compared to the “temperate climate” state and the generic model set up. The results from the generic model cannot be directly transferred to other model areas. The common aspect of the three climate states is the constant hydraulic gradient. For the other climate conditions, the hydraulic gradient changes due to the different model boundary conditions. These results show that the hydraulic gradient also has an influence on the radionuclide transport from the host rock. The climate state “glaciation” has the highest hydraulic gradient and in both diffusion coefficient simulations has the highest discharge from the host rock. Again, no significant transport from the host rock was observed for a diffusion coefficient of $1 \cdot 10^{-11} \text{ m}^2 \text{ s}^{-1}$.

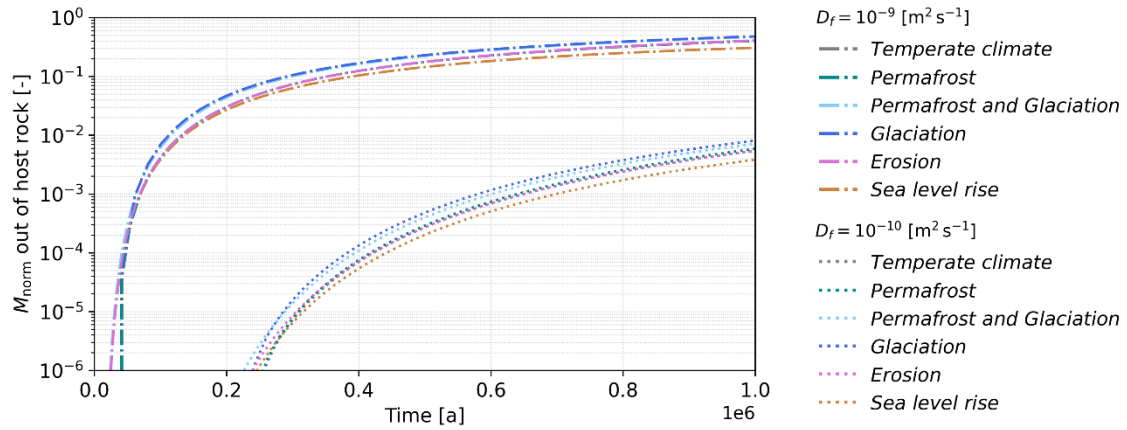


Figure 40: Normalised mass fractions of the tracer in the model units, the mass fraction out of the host rock for different climate states with diffusion coefficients of $1 \cdot 10^{-9}$ and $1 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}$.

5.3.3 Effect of sorption coefficients on transport behaviour

Sorption is the accumulation of substances on the solid phase, which varies depending on the properties of the rock and the charge of the surfaces and the substance. The K_d -value indicates the ratio of the substance concentration in the solid phase to the dissolved phase under equilibrium conditions. Simulation cases were set up to variate different diffusion and sorption coefficients with each other, and compare the influence on the discharge from the host rock. A diffusion coefficient of $1 \cdot 10^{-9} \text{ m}^2 \text{ s}^{-1}$ and no assumed sorption leads to a rapid discharge of the mass from the host rock. After one million years, only around 60 % of the mass remained in the host rock and 40 % was transported from the host rock into surrounding layers or out of the model area at the southern edge of the model (Figure 41). With a sorption coefficient of $1 \cdot 10^{-5} \text{ m}^3 \text{ kg}^{-1}$ and the same diffusion coefficient, around 27 % was transported out of the host rock at the end of the assessment period. With a diffusion coefficient of $1 \cdot 10^{-9} \text{ m}^2 \text{ s}^{-1}$ and a higher sorption coefficient of $1 \cdot 10^{-4} \text{ m}^3 \text{ kg}^{-1}$, the discharged mass from the host rock was reduced to 2 %. With a reduced diffusion coefficient of $1 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}$ and no assumed sorption, 0.55 % of the tracer was transported out of the host rock at the end of the assessment period, and with a sorption coefficient of $1 \cdot 10^{-5} \text{ m}^3 \text{ kg}^{-1}$, only 0.1 % was transported out of the host rock. For the simulation cases with a diffusion coefficient of $1 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}$ and a sorption coefficient of $1 \cdot 10^{-4} \text{ m}^3 \text{ kg}^{-1}$ and $1 \cdot 10^{-3} \text{ m}^3 \text{ kg}^{-1}$, a mass fraction of $1 \cdot 10^{-8}$ is reached within 800,000 years.

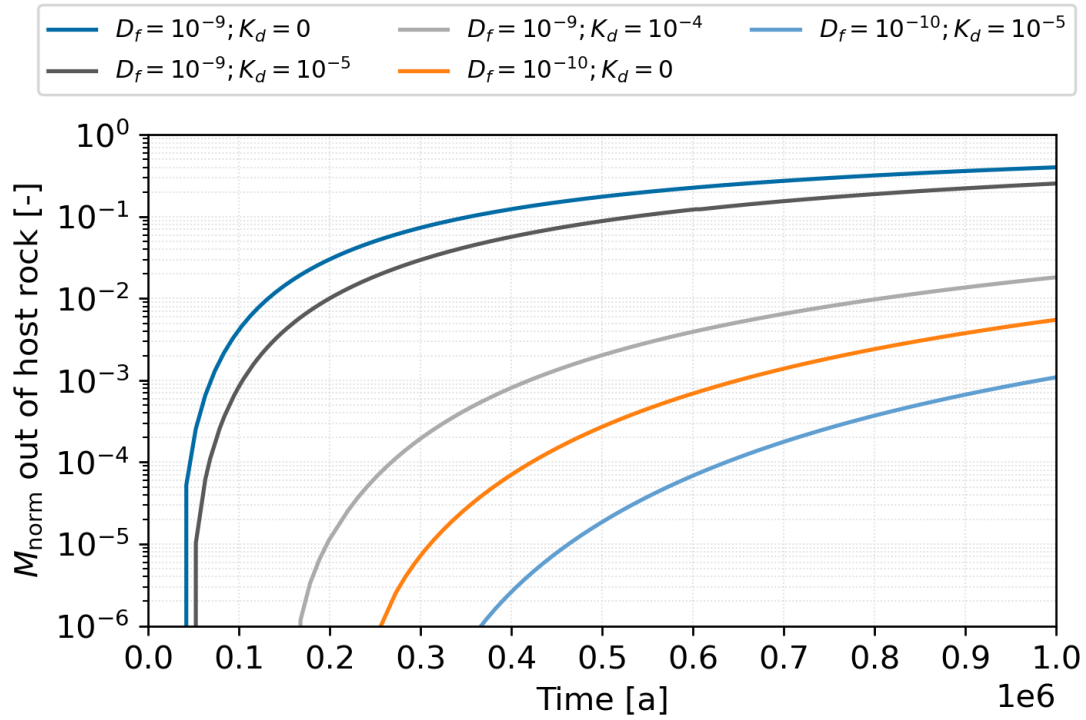


Figure 41: Mass fraction for the transport of the tracer out of the host rock for several simulation cases for different diffusion coefficients ($1 \cdot 10^{-9}, 1 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}$) and sorption coefficients (0, $1 \cdot 10^{-5}, 1 \cdot 10^{-4} \text{ m}^3 \text{ kg}^{-1}$).

The simulation cases shown in Figure 41 are shown in Figure 42 after one million years. In some cases, there is no significant amount of radionuclides transported out of the host rock. This applies to simulation cases with low diffusion coefficients and high sorption coefficients. These simulation cases were not shown in the diagrams (Figure 41) but are shown in the concentration plot in Figure 42. The simulation case $D_f = 1 \cdot 10^{-9} \text{ m}^2 \text{ s}^{-1} / K_d = 1 \cdot 10^{-4} \text{ m}^3 \text{ kg}^{-1}$ show slightly longer transport lengths compared to the $D_f = 1 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1} / K_d = 1 \cdot 10^{-5} \text{ m}^3 \text{ kg}^{-1}$ case. No difference could be visually observed between the simulation cases $D_f = 1 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1} / K_d = 1 \cdot 10^{-4} \text{ m}^3 \text{ kg}^{-1}$ and $D_f = 1 \cdot 10^{-9} \text{ m}^2 \text{ s}^{-1} / K_d = 1 \cdot 10^{-3} \text{ m}^3 \text{ kg}^{-1}$.



Figure 42: Concentration distribution for different diffusion coefficients ($1 \cdot 10^{-9}, 1 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}$) and different sorption coefficients (K_d -value: $1 \cdot 10^{-5}, 1 \cdot 10^{-4}, 1 \cdot 10^{-3} \text{ m}^3 \text{ kg}^{-1}$) after 1 million years.

Diffusion and sorption were thus identified as the most important parameter for the transport of tracer from the host rock under the given assumptions. Although the parameters used remain generic in origin, they illustrate the influence of the site-specific parameters and their relevance.

6 Strategies for dealing with uncertainties regarding the long-term safety of a final repository for high-level radioactive waste

6.1 Uncertainty quantification (UQ)

There are different aspects in the definition of uncertainties. A general definition is that “uncertainty is understood as a lack of certainty in describing and modelling a system” (Nummi 2019). Funtowicz & Ravetz 1990 describe that there can be three sorts of uncertainty: inexactness, unreliability, and border with ignorance. All these aspects can also be projected onto modelling. Errors in the simulation, unreliable input data or black box models can be examples for the different sorts of uncertainty. While additional research should ideally lead to a reduction of the overall uncertainty, it often happens that it raises new questions, resulting in apparently larger instead of smaller uncertainty ranges. In such cases, uncertainty has been underestimated originally, which should be avoided as far as possible. When defining uncertainty ranges, it is always advisable to consider that there may be “unknown unknowns”.

Numerical methods are used in long-term safety assessments to describe different effects and processes like, in this model, fluid flow and radionuclide transport. The results depend on the initial, boundary conditions and input parameters. The parameters describe data from the real world, which are implemented in the model in a more or less simplified form, but the model never can describe the real evolution of the system. Often one parameter represents complex physical or chemical influences which cannot be quantified exactly. Those parameters can then be measured or estimated by experts, but are always subject to a range of uncertainty (Spießl & Becker 2017). With reliable data and a thorough model set-up, it should at least be possible to yield results that allow an assessment of the long-term safety of the system. To derive reliable safety statements, it is necessary to take the uncertainty ranges into account in the safety assessment. Some uncertainties can be ruled out due to low relevance for the results. For an uncertainty or sensitivity analysis, a reduction from many model parameters to a lower number is needed to keep it manageable. The process of sorting out processes and parameters for the uncertainty analysis, however, is often subjective and should be based on substantiated expert knowledge.

There are two different types of uncertainties. On one hand there is the aleatory uncertainty (i.e., stochastic uncertainty, type A uncertainty, variation, variability, stochastic variation, statistical inexactness, part of the risk under consideration) caused by the stochastic nature of a phenomena (Röhlig & Plischke 2009; IAEA 2012). On the other hand there is the epistemic uncertainty (i.e., subjective uncertainty, type B uncertainty, imprecise knowledge/ignorance, inexactness due to human judgement, uncertainty in the determination of risk) caused by the lack of knowledge about a phenomena (Walker et al. 2003; Röhlig & Plischke 2009). A straight classification between aleatory and epistemic

uncertainties is difficult and not always relevant and/or helpful (Walker et al. 2003; Röhlig & Plischke 2009). It can also be a matter of the detail scale, whether an uncertainty appears epistemic or aleatory (Spießl & Becker 2017). In the case of uncertainty, the goal is to reduce the epistemic uncertainty with information, knowledge, and data so that ideally just aleatory uncertainties remain (Ebengué 2016).

Uncertainties are classified into three categories in the final repository safety assessment: parameter (data), model and the scenario uncertainty (IAEA 2012; Nummi 2019). The sources of uncertainties cannot always be clearly assigned to one type because they are often linked to each other (Nummi 2019). Parameter uncertainties can arise from measurement errors, limited measurement availability or spatial or temporal variability and refer to the numerical input data of models (Spießl & Becker 2017; Nummi 2019). Model uncertainties emerge from lack of knowledge of processes of the modelled system and the abstraction and simplification of the reality by using mathematical and computational models (Nummi 2019). Scenario uncertainty reflects the range of possible evolution of the system over time. It arises from the limited understanding of the system, lack of knowledge and “the factors governing its evolution as well as from the inherent uncertainty regarding the future” (Nummi 2019). Walker et al. 2003 define scenarios as “a plausible description of how the system and/or its driving forces may develop in the future” and mention that scenarios are no forecasts for the future and that they more indicate what could happen in the future.

In the case of repository safety, Röhlig & Plischke 2009 mention the importance of uncertainties, stating that “Addressing uncertainties in safety cases and in particular in safety and performance assessments for radioactive waste disposal facilities is an issue of utmost importance” (after Galson & Khursheed 2007). Furthermore uncertainties “are unavoidable due to the complexity of the phenomena of concern and the scales in time and space under consideration, and their management is central when developing a repository system and assessing its safety” (from Röhlig & Plischke 2009 after Vigfusson et al. 2007).

6.1.1 Probability density functions (pdf)

Numerical uncertainties are commonly characterised using probability density functions (pdf). The integral of a pdf over a finite interval yields the probability that the true, but unknown, value of a parameter lies within that range for epistemic uncertainties. By definition, the integral of a pdf over the entire domain of the parameter equals one, ensuring a complete probabilistic description.

The accurate identification, evaluation, and quantification of such uncertainties represent a highly complex and resource-intensive component of the safety case. This process demands interdisciplinary expertise spanning physics, chemistry, hydrodynamics, geology, climatology, biology, and other natural sciences, as well as advanced mathematical

proficiency. The selection of appropriate pdf types is contingent upon the extent and quality of available knowledge regarding the parameter in question, necessitating thorough analysis.

Inherent uncertainties may exhibit interdependencies. For instance, a low porosity in a porous medium often suggests low permeability, although this relationship is not deterministic and cannot be captured by a strict analytical expression. Such statistical dependencies frequently arise when the underlying physical mechanisms are not fully understood or are difficult to model in detail. In practice, these interdependencies are typically represented through statistical correlations, although this approach may not encompass all forms of dependency.

For the numerical evaluation of long-term safety, a model is required that is assumed to adequately represent the evolution of the actual system over time. Such a model incorporates a range of input parameters and generates one or more output variables. Any safety-related conclusion derived from such a model is inherently subject to uncertainty, which originates from the uncertainties embedded in the input parameters. To quantify the uncertainty associated with the model output, the model must be executed multiple times, with input parameters varied according to their respective uncertainty distributions. The resulting outputs are then subjected to statistical evaluation – a process known as uncertainty analysis. This type of analysis focuses solely on the variability in the model outputs, without directly attributing it to specific sources of uncertainty.

A more advanced question concerns the extent to which individual or grouped inherent uncertainties influence the overall uncertainty in the safety assessment. Various mathematical techniques have been developed to address this issue, each emphasizing different aspects and based on distinct conceptual frameworks. This process is referred to as sensitivity analysis. It is important to emphasise that both uncertainty and sensitivity analyses are purely mathematical procedures applied to the model outputs. Consequently, any conclusions drawn from these analyses relate strictly to the model itself and should not be interpreted as direct statements about the real-world system it aims to represent (Loucks & van Beek 2017).

6.2 Sensitivity analysis (SA)

One way to handle uncertainties is to use sensitivity analysis, where the relative importance and impact of different input parameters to the results can be identified (IAEA 2012). Sensitivity analysis can be interpreted variously in different communities and problem settings (Saltelli et al. 2004). In general, sensitivity analysis can be understood as a local measure of the effect of a given input on a given output (Saltelli et al. 2004). Sensitivity analyses are often used in mathematical models which aim to represent real systems with the help of complex equation systems and different input variables (physical, chemical, biological and other) (Siebertz 2010). Sensitivity analysis is a procedure

in which the relationship between the variance of the input variable and the variance of the output variable is determined (Siebertz 2010). The method is used to identify variables that have no, moderate or a significant influence on the final result and can be considered rather unimportant for the modelling. If such variables are identified, the model can possibly be simplified under this aspect without loss of information (Saltelli et al. 2004).

"The global sensitivity analysis determines the influence of factors with variation over their entire definition range" (Siebertz 2010). This method is used to evaluate the relevance of the factors in a model and to compare them with each other. Different factors flow into the model in different ways. They can be equal or fixed value distributions and the variables have different effects on the model result due to the equation systems of the model (Figure 43) (Siebertz 2010).

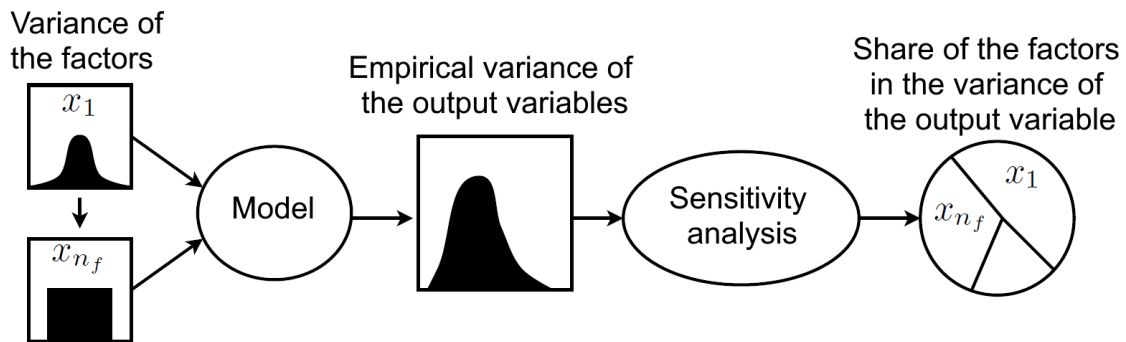


Figure 43: Schematic variance-based global sensitivity analysis, modified and taken from Siebertz 2010.

6.2.1 Evaluation of sensitivities

In the context of repository safety assessments, it is often of greater interest to determine the maximum potential environmental impact of a given – real or hypothetical – system, regardless of when this maximum occurs, rather than to focus on contaminant releases or doses at a specific point in time. Consequently, uncertainty and sensitivity analyses can be conducted either for calculated contaminant releases or annual dose rates at selected time points, or for the maximum values observed over the entire simulation period. These two approaches address fundamentally different questions and may yield significantly different results. In the following just maxima values are compared.

In extreme cases, the maximum impact may manifest as a sharp, isolated peak. In such scenarios, a particular parameter might strongly influence the timing of the peak, while having little or no effect on its magnitude. This parameter would not be identified as influential in a sensitivity analysis focused on the maximum value itself, but could instead emerge as highly significant in a time-specific analysis (OECD 2005). This highlights the

importance of carefully selecting the analytical approach based on the specific objectives of the safety assessment.

Due to the criterion of § 4 EndlSiAnfV, the sensitivities of the model parameters are evaluated on the basis of the proportion of the radionuclide mass being released from the host rock over one million years. In the applied model, no inflection points or short-term effects – on the timescale of one million years – are present that would be expected to cause significant impacts on the results due to parameter variations, as described in the previous section.

6.2.1.1 Graphical methods for sensitivity analysis

Graphical approaches to sensitivity analysis offer an effective way to rapidly obtaining a visual overview of a system's sensitivities. In many cases, such methods are particularly well-suited for conveying the fundamental insights related to sensitivity. Furthermore, graphical representations can reveal qualitative aspects that may not be captured by purely numerical sensitivity evaluation. Sensitivity graphs are generally intuitive and accessible, and their generation typically requires minimal computational resources.

6.2.1.1.1 Scatterplots

A scatterplot is a graphical representation consisting of discrete, unconnected data points plotted within a two-dimensional space. This technique is particularly useful for visualizing statistically distributed data. When plotting model outputs against the values of a specific parameter, scatterplots provide an immediate and intuitive way to assess the parameter's impact on the results. Such visualizations can convey nuanced information that may not be accessible through other types of plots. However, scatterplots are generally less effective for analysing multiple parameters simultaneously or illustrating the temporal evolution of system sensitivities.

6.2.1.1.2 Contribution to the sample mean (CSM)

The Contribution to the Sample Mean (CSM) plot is a specialised two-dimensional visualization tool used to quickly assess and compare how sensitive a system is to variations in different parameters (Saltelli et al. 1993; Bolado-Lavin, Castaings & Tarantola 2009; Spießl & Becker 2017). For each parameter, a curve is plotted within a unit square, starting at point (0,0) and ending at point (1,1), following a specific procedure. First, a probabilistic set of simulation runs is performed. For each run, the model output – either at a specific point in time or the maximum value during the run – is paired with the corresponding value of the parameter being analysed. These pairs are then sorted in ascending order based on the parameter values. Next, the cumulative contribution of each pair to the sample mean is calculated. This involves summing the model outputs up to each pair, dividing by the total number of runs, and normalizing by the overall mean of all

outputs. By design, the final value of the curve (corresponding to the highest parameter value) is always 1. The horizontal axis represents the fraction of the total number of runs.

If the model output is independent of the parameter, the cumulative sum increases uniformly across the interval, resulting in a curve close to the diagonal. In contrast, if lower parameter values tend to produce lower model outputs, the curve rises slowly at first and more steeply toward the end. A strong sensitivity is indicated by a curve that significantly deviates from the diagonal. However, the key indicator of sensitivity is not the deviation itself, but the curvature of the curve. A negative curvature suggests an inverse relationship – higher parameter values lead to lower model outputs. If the relationship is non-monotonic, the curve will show an inflection point. CSM plots are useful for comparing the effects of multiple parameters. They also help identify parameter ranges with higher or lower sensitivity by analysing the shape of the curve. CSM plots are easy to understand, but subject to some drawbacks like dependency on a constant offset and non-scalability.

6.2.1.1.3 Cumulated sums of normalised reordered output (CUSUNORO)

The CUmulated SUms of NOrmalised Reordered Output (CUSUNORO) plot is an enhancement of the CSM plot that avoids the mentioned drawbacks (Plischke 2012). Instead of summing the output values directly, CUSUNORO computes the sum of their deviations from the mean, which is then normalised by the square root of the sum of squared deviations. This transformation yields a curve that begins at the origin (0, 0) and ends at the point (1, 0). A pronounced deviation of the curve from the x-axis indicates high sensitivity. As with the CSM plot, the extent of sensitivity is expressed through the graph's curvature.

6.2.1.2 Correlation- and regression-based methods

For the numerical assessment of model sensitivities based on a probabilistic ensemble of simulations, various methodological approaches have been developed. A commonly used classical technique involves approximating the effect of an input parameter on the model output through a linear relationship. This approximation then serves as the basis for deriving a quantitative measure of sensitivity, which can be calculated on the basis of regression or correlation. In the case of independent inputs, both approaches are equivalent.

6.2.1.2.1 Standardised regression coefficients (SRC)

Linear regression aims to approximate the relationship between the statistical variables X and Y as accurately as possible using a linear function:

$$\hat{Y} = b_0 + \sum_{j=1}^k b_j X_j \quad (3)$$

For each set of input parameter values x_{ji} , where $i = 1, \dots, n$, an absolute error ε_i arises:

$$y_i = b_0 + \sum_{j=1}^k b_j x_{ji} + \varepsilon_i = \hat{y}_i + \varepsilon_i \quad (4)$$

The regression coefficients b_j , for $j = 1, \dots, k$, are determined by minimising the total squared error according to the least squares criterion:

$$\sum_{i=1}^n \varepsilon_i^2 = \min \quad (5)$$

Once estimated, the coefficients $b_1, \dots, b_k$ serve as indicators of the sensitivity of the model output Y with respect to variations in the input parameters $X_1, \dots, X_k$. To enable a standardised interpretation of these coefficients, the variables are transformed to have zero mean and unit standard deviation:

$$\frac{\hat{Y} - \bar{Y}}{\hat{s}} = \sum_{j=1}^k \frac{b_j \hat{s}}{\hat{s}_j} b_j \cdot \frac{X_j - \bar{X}_j}{\hat{s}_j} \quad (6)$$

With the mean value defined as:

$$\bar{Y} = \frac{1}{n} \sum_{i=1}^n \hat{y}_i, \bar{X} = \frac{1}{n} \sum_{i=1}^n x_{ji} \quad (7)$$

And the standard deviations given by:

$$\hat{s} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\hat{y}_i - \bar{Y})^2}, \hat{s}_j = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_{ji} - \bar{X}_j)^2} \quad (8)$$

The coefficients $(b_j \hat{s}_j) / \hat{s}$ are referred to as standardised regression coefficients (SRCs). Their values always lie within the range of -1 to 1, where negative values indicate an inverse relationship between the input variable and the model output.

6.2.1.2.2 Standardised Rank Regression Coefficient (SRRC)

As previously mentioned, correlation- and regression-based methods for sensitivity analysis rely on the assumption that the relationship between input parameters and model output is approximately linear. However, this assumption often does not hold for complex models. In many cases, the relationship is at least monotonic, meaning that the output consistently increases or decreases with changes in the input. A monotonic relationship can be transformed into a linear one by applying a rank transformation. This involves sorting the values of each input parameter and the model output in ascending order and replacing each value with its corresponding rank in the sorted list. This transformation preserves the order of the data while enabling the use of linear methods for sensitivity analysis. In the equations above, the original X and Y values are replaced by the ranks of the input and output variables, respectively. Apart from this transformation, the mathematical formulation remains unchanged.

6.3 Parameter distributions and sampling

In a sensitivity analysis, the selection of appropriate probability distributions for uncertain input parameters is a critical step that significantly influences the robustness and interpretability of the results. The choice of distribution should reflect the nature of the available data and the underlying physical or empirical understanding of the parameter. Uniform distributions are often employed when only the minimum and maximum bounds of a parameter are known, assuming equal likelihood across the range. Log-uniform distributions are suitable when the parameter spans several orders of magnitude and no particular scale is favoured, which is common in environmental modelling. Normal distributions are appropriate when the parameter is symmetrically distributed around a mean value with known variability. The log-normal distribution is characterised by a positively skewed shape, arising when the logarithm of a variable follows a normal distribution. This implies that the variable itself is constrained to positive values and tends to exhibit a long right tail.

The selection process should also consider the sensitivity of the model outputs to the tails of the distributions, especially in non-linear systems. To ensure a comprehensive exploration of the input space, sampling methods must be carefully chosen. In this study, quasi-random sampling was employed to generate input parameter sets. This method provides a more uniform coverage of the multidimensional input space compared to purely random or Latin hypercube sampling. According to Spießl & Becker 2017, quasi-random sampling is particularly well-suited for sensitivity analyses involving a mix of distribution types, as it enhances convergence and reduces sampling bias.

Based on expert knowledge from multiple geologists and modelers, probability distribution functions were selected for six key parameters: permeability in the host rock, porosity in the host rock, the sorption coefficient in the host rock, the hydraulic gradient, the

effective diffusion coefficient in the host rock, and the dispersivity length (Table 6, Figure 44).

Permeability in claystone can vary across several orders of magnitude. At very low permeabilities, only minimal radionuclide release is expected. Therefore, values below $1 \cdot 10^{-19} \text{ m}^2$ were excluded from the distribution. Higher permeabilities, which are classified as less favourable according to the German Site Selection Act (StandAG 2023), were included in the sensitivity analysis using a log-normal distribution with a mean of $3.16 \cdot 10^{-18} \text{ m}^2$ with a ± 3 -sigma range from $1 \cdot 10^{-19} \text{ m}^2$ to $1 \cdot 10^{-16} \text{ m}^2$.

Porosity in the host rock, which is the only porosity value which is included in the sensitivity analysis refers to the effective advective porosity and is varied uniformly between 1 % and 10 %. In claystone, effective porosity is typically low, whereby the total porosity can be significantly higher, depending on the specific clay formation. In the AnSichT models the effective porosity is mentioned as 5 % and the absolute porosity as 24 %.

The sorption coefficient depends on the radionuclides. Since no specific radionuclide is analysed in this sensitivity study, the sorption coefficient spans several orders of magnitude. Previous modelling studies have shown that for values below $1 \cdot 10^{-6} \text{ m}^3 \text{ kg}^{-1}$, radionuclide retention is negligible. At $1 \cdot 10^{-3} \text{ m}^3 \text{ kg}^{-1}$, significant retention occurs, although releases from the repository are still observed over a timescale of one million years. While higher sorption coefficients are plausible, they would imply nearly complete retention within the host rock. Consequently, a log-uniform distribution ranging from $1 \cdot 10^{-6} - 1 \cdot 10^{-3} \text{ m}^3 \text{ kg}^{-1}$ was assumed.

The hydraulic gradient is influenced by the properties of geological units and topography. In the generic model used here, the hydraulic gradient is implemented as a model function and included in the sensitivity analysis to assess its impact on radionuclide transport. A log-normal distribution with mean value of $7.07 \cdot 10^{-3} \text{ m m}^{-1}$ with a ± 3 -sigma range was applied to represent various flow regimes with a value range from $1 \cdot 10^{-4} - 5 \cdot 10^{-1} \text{ m m}^{-1}$.

For the scale-dependent dispersivity, a uniform distribution between $1 \cdot 10^0 - 1 \cdot 10^1 \text{ m}$ was assumed.

The diffusion coefficient here is understood as the effective diffusion coefficient relevant for advective transport. To derive the molecular diffusion coefficient which is used by d^{3f++}, the effective diffusion coefficient is divided by the product of the porosity and the ratio of total to effective porosity for the host rock unit. In this analysis, porosity is varied, and the ratio is simplified to a constant factor of 4.8, derived from the ratio between effective and absolute porosity, based on values from the AnSichT models. As a result, the molecular diffusion coefficients are higher than the values defined in the probability distribution functions resulting in values between $2 \cdot 10^{-12} - 8 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}$ (Figure 45).

Following the definition of the parameter distributions, a quasi-random sampling method was employed to generate 1,000 data points.

Table 8: pdf functions for different parameters with range for the pdf and standard values.

Parameter	Type of pdf	Range or pdf parameter	Unit
Permeability	Log-normal ²	$1 \cdot 10^{-19} - 1 \cdot 10^{-16}$	m ²
Porosity	Uniform	$1 \cdot 10^{-2} - 1 \cdot 10^{-1}$	-
Sorption coefficient	Log-uniform	$1 \cdot 10^{-6} - 1 \cdot 10^{-3}$	m ³ kg ⁻¹
Hydraulic gradient	Log-normal ¹	$1 \cdot 10^{-4} - 5 \cdot 10^{-1}$	m m ⁻¹
Dispersion length	Uniform	$1 \cdot 10^0 - 1 \cdot 10^1$	m
Diffusion coefficient	Uniform	$1 \cdot 10^{-12} - 5 \cdot 10^{-11}$	m ² s ⁻¹

² The range refers to the $[\mu - 3\sigma, \mu + 3\sigma]$ -interval on the logarithmic scale. μ is the geometric mean of the upper and lower limits of the range.

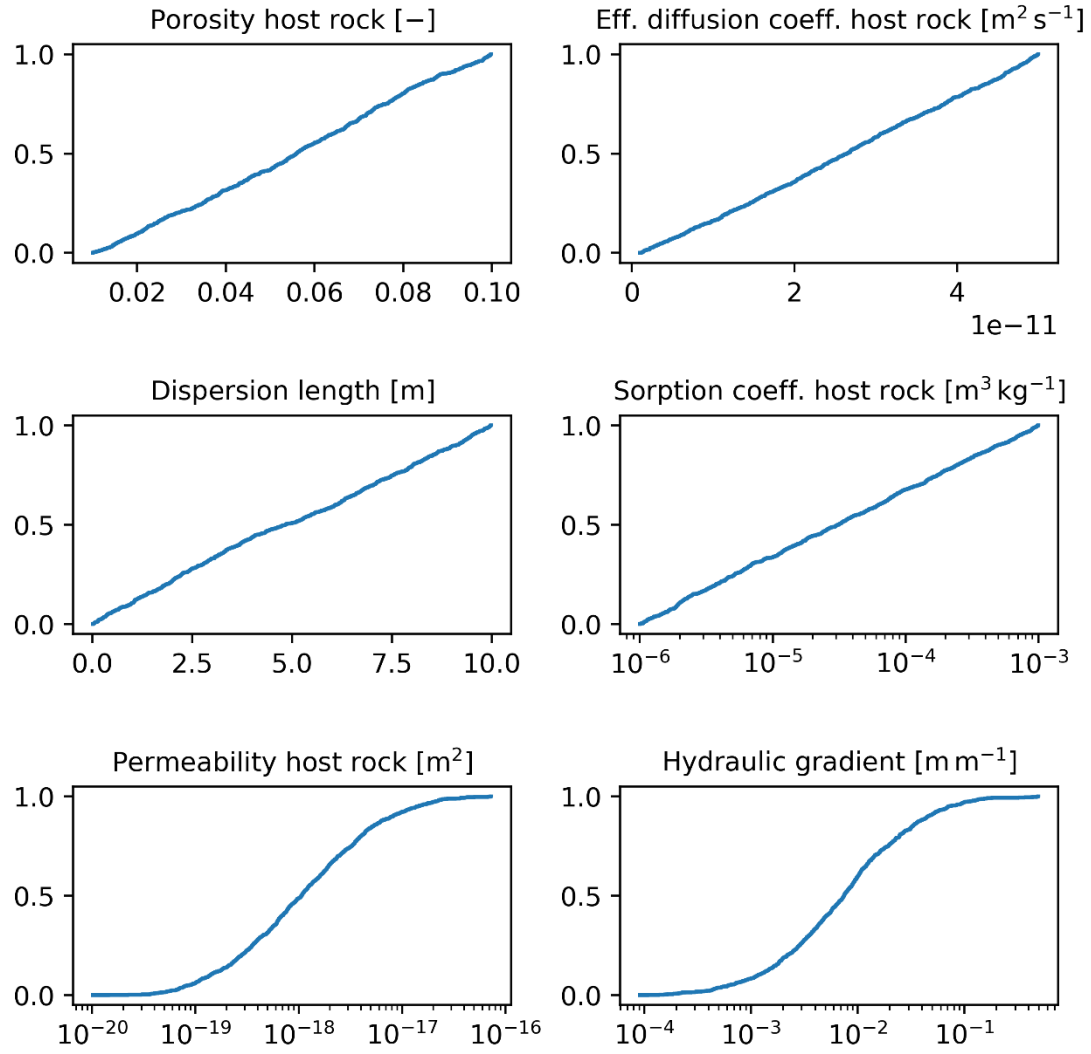


Figure 44: Probability density functions of the sensitivity analysis for the six varied key parameters.

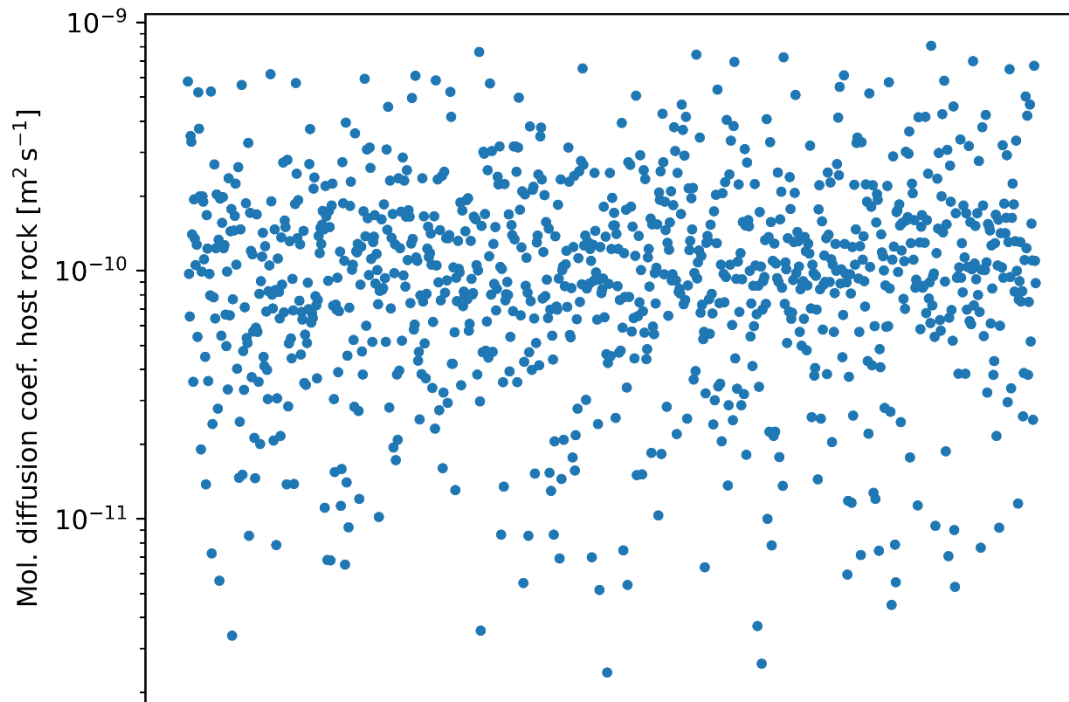


Figure 45: *Parameter distribution for the calculated molecular diffusion coefficient of the host rock for 1,000 simulation cases.*

6.4 Results from the sensitivity analysis of the groundwater model

There are various methods for presenting and interpreting the results. These evaluation methods were briefly explained in Chapter 6.2.1. This chapter describes the results of the evaluations. From the 1,000 simulations, 940 finished, and 60 simulations did not reach the aimed simulation time of 1 million years due to unfavourable numerical parameter variations in the samplings. An initial screening of the non-converging simulation cases was done but did not reveal any trend in parameter configuration where the solutions did not converge or converged poorly. No trends were visible in the correlation between the parameters.

6.4.1 Evaluation of the scatterplots

Scatterplots showing the model output against individual parameter values can be easily generated from the results of probabilistic simulations. These plots offer a direct and intuitive way to assess the influence of a parameter on the model output, even when the number of simulations is relatively small. Because of their simplicity, scatterplots are well-suited as an initial step in sensitivity analysis. In this case the scatterplots are based on the ratio between maximum mass transported out of the host rock versus the mass in the host rock at the simulation start (M_{norm}). This ratio is plotted against the six selected parameters for the sensitivity analysis.

Several M_{norm} values are 0 (no outflow out of the host rock) or $6.41 \cdot 10^{-14}$ which represents changes of the last digit in the written-out mass in the host rock, like a kind of rounding error or oscillation. This value also can be seen as no outflow of the model. If no radionuclide discharge from the host rock is computed, these simulation cases are not shown in the scatterplot, since the ratio between initial mass and remaining mass after 1 million years is 0.

For the range of **dispersion lengths** between 0 and 10 metres, the scatterplots (Figure 46) do not reveal any visual sensitivities. Consequently, the mass release from the host rock appears to be independent of the dispersion length. The distribution of the scatterplots resembles the random pattern observed during parameter sampling.

Similarly, no distinct trends are observable for the **permeability** in the host rock. Within this range, mass fractions released from the host rock tend to cluster around $1 \cdot 10^{-2}$ and $1 \cdot 10^{-3}$. In individual simulation cases, high permeabilities result in increased mass release, whereas such increased releases are not observed at lower permeability values.

A noticeable trend exists between mass release from the host rock and its **porosity**. Lower porosity values lead to higher mass releases. As porosity increases, the release generally decreases, with few exceptions. A reduction of effective porosity decreases the volume available for radionuclide transport within the porous medium. The average interstitial velocity is defined as the quotient of the Darcy velocity divided by the effective porosity. Thus, lower porosities increase the linear velocity, which may explain the observed trend. Another contributing factor is the relationship between porosity and the calculation of the molecular diffusion. As described in Chapter 6.3, the applied correlation indicates that lower porosities lead to higher molecular diffusion coefficients. This trend is only evident in cases with high mass release from the host rock.

The log-normally distributed **hydraulic gradient** across the model domain does not exhibit a clear trend. A minor trend suggests that higher hydraulic gradients may lead to increased mass release from the host rock, while lower gradients result in slightly reduced release. Again, this trend is only visible in cases with high mass release.

The range of samples for the **sorption coefficient** was defined using a logarithmic uniform distribution. The scatterplots show a clear negative correlation between the sorption coefficient and mass release from the host rock. As the sorption coefficient increases, indicating stronger retention of radionuclides on the rock surface, the mass discharge from the host rock decreases. Beyond a value of approximately $2.5 \cdot 10^{-4} \text{ m}^3 \text{ kg}^{-1}$, no mass is discharged from the host rock during the evaluation period. An exception is a single simulation case where mass release is observed despite a very high sorption coefficient. This simulation case has the fourth highest permeability value of all simulation cases and lies in the highest 5 % values for the hydraulic gradient and the top 7.5 % values for the

molecular diffusion. In this simulation, strong sorption alone is not sufficient to prevent discharge from the host rock, as the values of the other three parameters are high.

The **molecular diffusion coefficient** in the host rock is derived from porosity and the effective diffusion coefficient. The scatterplot reveals a significant influence of the molecular diffusion coefficient on mass release. Lower coefficients result in reduced release, indicating a positive correlation between input parameters and model output. Compared to other plots, this scatterplot shows the most distinct clustering along a theoretical curve. Above this curve, only a few simulation cases are present; below it, the results are distributed similarly to other parameters. Below a molecular diffusion coefficient of $3 \cdot 10^{-11} \text{ m}^2 \text{ s}^{-1}$, fewer data points are observed, as almost no mass is released in these cases. Simulation cases with negligible release are not visible on the logarithmic y-axis due to the low ratio of initial to final mass.

Overall, the scatterplots provide a clear indication of which parameters primarily influence mass release from the host rock. These are mainly sorption and the molecular diffusion coefficient, with porosity also showing a visible trend.

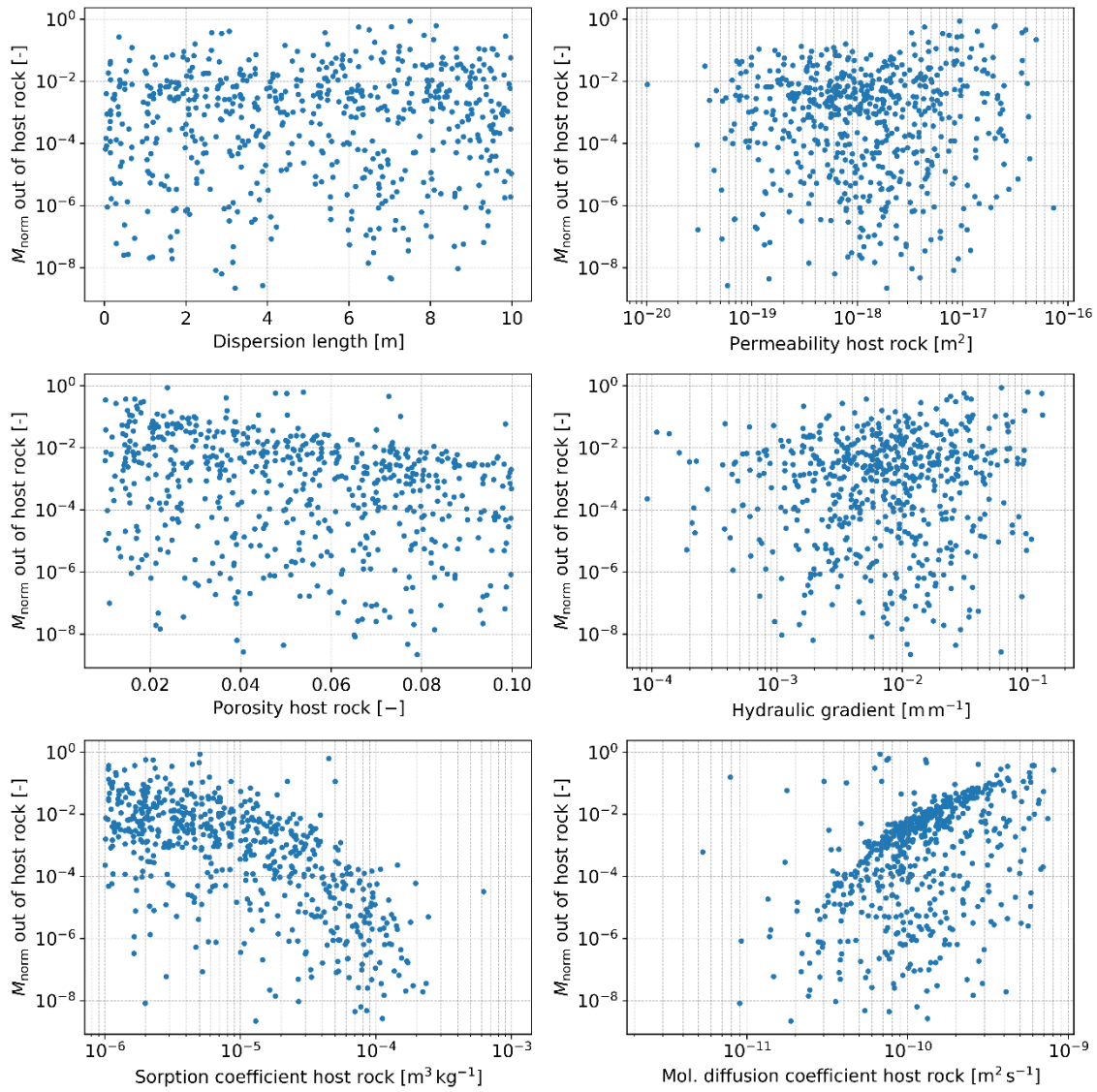


Figure 46: Scatterplots for the ratio between mass in the host rock at simulation start and simulation end for the six parameters dispersion length, permeability, porosity, hydraulic gradient, sorption coefficient and molecular diffusion coefficient.

6.4.2 Evaluation of the CSM and CUSUNORO plots

The Contribution to the sample mean (CSM) plot provides a comparative view of how different input parameters influence the model output across their respective value distributions. The shape and curvature of each CSM curve reveal whether a parameter has a consistent, threshold-based, or range-specific impact. Below is an interpretation of each parameter.

The **sorption coefficient** CSM curve (grey, Figure 47) has a negative sensitivity and rises steeply up to approximately 45 %, has an additional increase before 60 % of the proportion of runs, then flattens significantly (Figure 47). This indicates that low sorption values have a strong influence on the release of radionuclides out of the host rock and the model domain. A high sorption coefficient ensures that the radionuclides remain in the host rock and play a minor role for the mass fractions outside of the host rock.

This behaviour indicates greater sensitivity of smaller sorption coefficients, as the discharge from the host rock varies more strongly at smaller sorption coefficients. At high sorption coefficients, less mass is transported from the host rock overall, leading to a flattening of the CSM curve at higher values. This aligns with findings from scatterplot analyses, which show sorption as a key factor in controlling the release of substances from the host rock.

The **porosity of host rock** CSM curve (blue, Figure 47) shows a negative sensitivity and a moderate rise up to approximately 50 % of the proportion of runs with flat progression. This suggests that lower porosity values contribute more strongly to the output, while higher values have a reduced effect. This is due to the dependence between the effective diffusion coefficient and porosity to calculate the molecular diffusion coefficient for the model simulations (see Chapter 6.3). Low porosity values lead to higher molecular diffusion coefficients and thereby to a higher discharge from the host rock.

The **molecular diffusion coefficient of host rock** CSM curve (brown, Figure 47) showing a positive sensitivity with a low influence for lower molecular diffusion coefficients and a higher sensitivity for higher values. The overall shape of the curve shows that higher diffusion values have more impact on the radionuclide mass out of the host rock.

The **dispersion length** CSM curve (orange, Figure 47) is relatively flat in the lower half of the input distribution and begins to rise more steeply after 50 % of the proportion of runs. At 80 % of the proportion of runs the curve switches to a low negative sensitivity. This finding is interesting in relation to the complex issue of scale dependence of dispersion for numerical groundwater models. Overall, the curve shows a low sensitivity compared to all other parameters.

The CSM curves for the **hydraulic gradient** (light blue, Figure 47) and the **permeability of host rock** (dark grey, Figure 47) occur similar in its behaviour. Both curves remain flat until approximately 70 % of the proportion of runs after which they increase more rapidly. This implies that low to medium hydraulic gradients have limited influence, while higher gradients significantly affect the output. For permeability, low to medium values have minimal influence, while high permeability values affect the model output stronger compared to low values (see also the scatterplots in Figure 46). This reflects a threshold-like sensitivity, where permeability becomes relevant only in the upper range. This supports the interpretation that high hydraulic gradients, in combination with high permeability, enhance mass flow from the host rock, especially when the discharge from the host rock is already higher due to low sorption or high diffusion. With a high lateral transport from the repository to the overlaying unit the higher hydraulic gradient lead to a faster transport in horizontal direction, creating a steeper concentration gradient between host rock and Aptian.

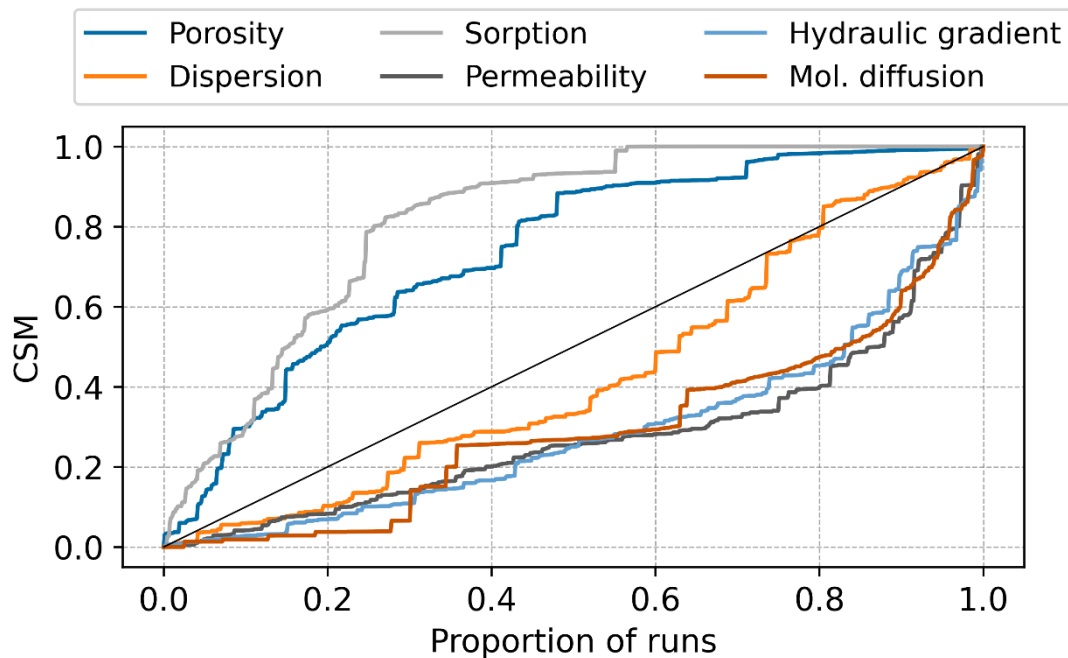


Figure 47: CSM plot for the six parameters considered in the sensitivity analysis.

The Cumulated sums of normalised reordered output (CUSUNORO) plot provide, like the CSM plot, a comparative view on the influence of input parameters on the model output across the range of value distributions.

A left-skewed curve shows that high parameter values affect the result, while right-skewed curves mean that low parameter values influence the result. If a triangular shape with a distinct peak and straight flanks emerges, a kind of threshold in the model behaviour can be inferred based on the parameter. The flat flanks indicate that this parameter has little influence in this value range.

Sorption and porosity show negative correlations, with sorption being more strongly left-skewed. Low sorption values therefore have a greater influence on the result than higher values. At high sorption coefficients ($>2.5 \cdot 10^{-4} \text{ m}^3 \text{ kg}^{-1}$), no radionuclides are released from the host rock. For this reason, the curve remains almost straight for about 50 % of the parameter values. Conversely, this trend can be seen in molecular diffusion. Low molecular diffusion coefficients result in little or no transport from the host rock.

Overall, apart from the different representation of the axes and their mathematical description, the CUSUNORO curve does not show any significant deviations from the CSM curves described above. Overall, the curves are not very smooth, so further simulations should be performed to further strengthen the reliability of the analysis.

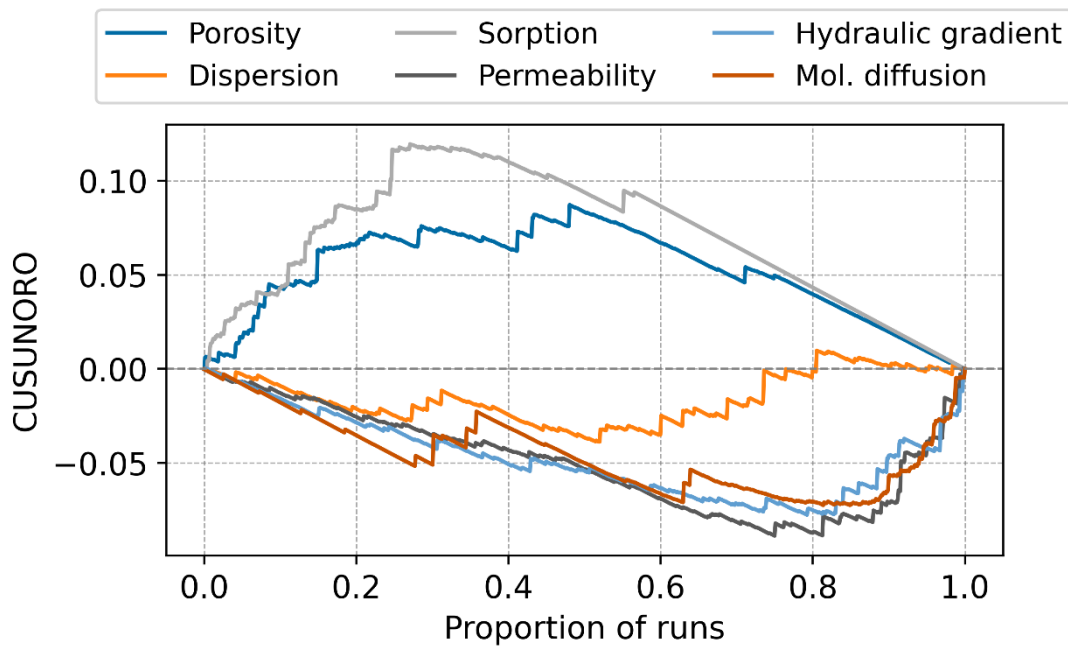


Figure 48: *CUSUNORO plot for the six parameters considered in the sensitivity analysis.*

6.4.3 Evaluation of SRC and SRRC

Since correlation- and regression-based methods have long been the most widely used approaches in sensitivity analysis, extensive investigations using these techniques were conducted with the AnSichT model. The aim was to establish a reference point for comparison. This chapter presents and explains the results obtained from these analyses.

SRC and SRRC provide important results for quantifying the sensitivity of the parameters. The SRRC is intended to provide clearer results through rank transformation. The transformation can lead to differences in the not ranked and ranked coefficients. Differences indicate that the different parameters have varying levels of influence on the upper or lower ranges of the output value. In addition, the different parameter sizes,

bandwidths, and distribution functions influence the differences between the SRC and SRRC coefficients. From model input parameters in the value range of $1 \cdot 10^{-6}$ – $1 \cdot 10^{-3}$ over 4 orders of magnitude for the sorption coefficients, ranks from 1 to 1,000 are then defined in the rank transformation, as are the model results with mass ratios from $1 \cdot 10^{-8}$ to $1 \cdot 10^{-0}$. The evaluation for SRC and SRRC may therefore differ for the parameters. A small SRC and a large SRRC have a greater effect on lower output values. A high SRC and a small SRRC, on the other hand, have a greater effect on high output values.

The absolute SRRCs range between 0.03 and 0.76 (Figure 49). The sorption coefficients and porosity have negative correlations with the result value. The parameters of molecular diffusion, the hydraulic gradient, the permeabilities, and the dispersion have positive correlations. The most sensitive process represented in the model is sorption. Lower sorption coefficients lead to higher discharges from the host rock. At higher sorption coefficients, a smaller amount or no amount of radionuclides is discharged from the host rock. The second most sensitive parameter is molecular diffusion with an SRRC of 0.41. Here, low molecular diffusion coefficients lead to lower model outputs. Porosity (SRRC = 0.24), hydraulic gradient (SRRC = 0.15), permeability (SRRC = 0.08), and dispersion (SRRC = 0.03) show lower sensitivities.

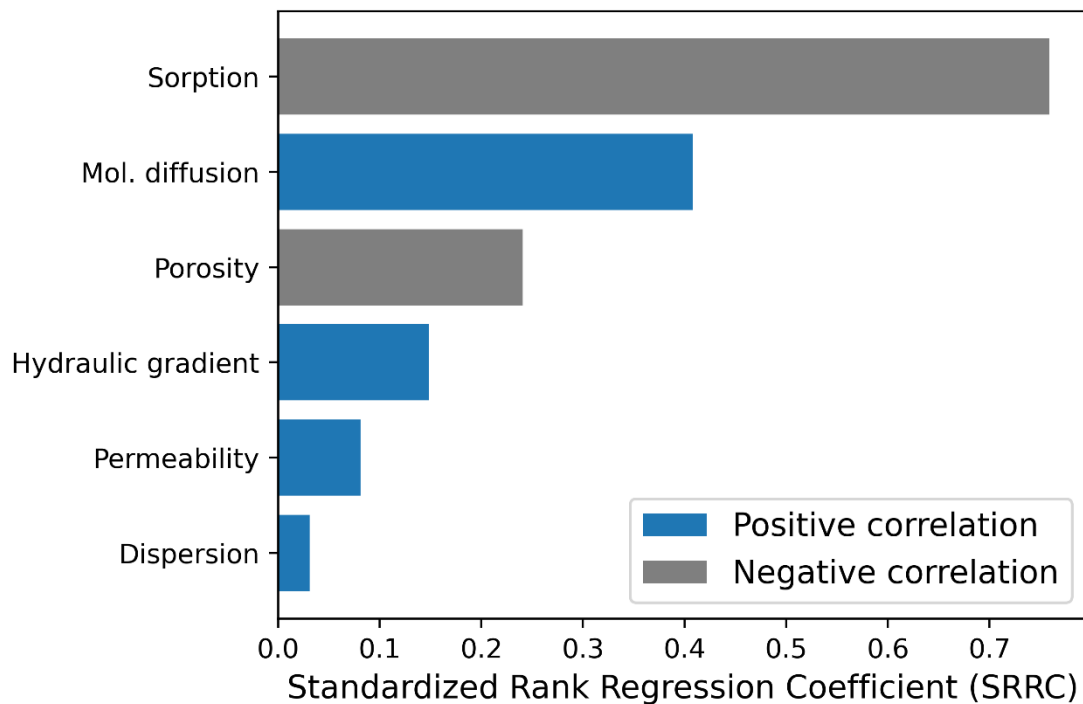


Figure 49: SRRC tornado plot for the six varied parameters.

The SRC analysis shows a different ratio of SRC coefficients compared to the SRRC (Figure 50). With the SRRC, a clear distinction between the most sensitive parameters was evident. In the SRC, the hydraulic gradient (SRC = 0.24), permeability (SRC = 0.225), and molecular diffusion (SRC = 0.221) show high values. SRC values of 0.2 to 0.3 are relatively high and represent a strong influence on the upper range of the

result values. The values suggest that the hydraulic gradient and permeability have a strong influence on the high release rates, as the SRRC value is low and the SRC value is high. If the sorption coefficients have high values and the diffusion coefficients have low values, little is discharged from the host rock and the permeability and hydraulic gradient are not very sensitive. These influences are often not noticeable in the scatter-plots, as there are only a few points that can influence the SRC. The molecular diffusion coefficients show high values for both, SRC and SRRC, so the parameter have influence on the results on upper and lower parameter range.

Porosity (SRC = 0.18), sorption (SRC = 0.13), and dispersion (SRC = 0.05) show lower SRC values. Sorption therefore has little influence on the result at high values, since at high sorption values, considering the amount that flows out of the host rock, it has no influence below a certain value. In contrast to the other parameters, dispersion shows low sensitivity in all analyses and, with these model properties, has no relevant influence on the result.

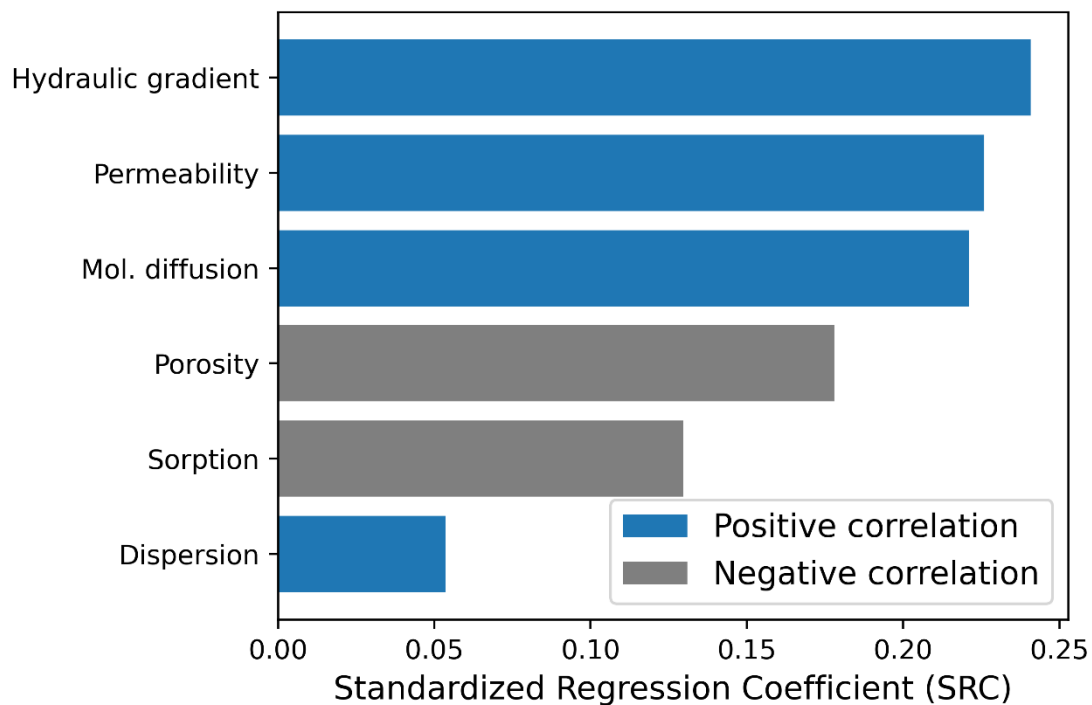


Figure 50: SRC tornado plot for the six varied parameters.

7 Conclusion

The objective of the REDUKLIM project was to identify and quantify uncertainties associated with long-term climate evolution and its implications for geological processes. These uncertainties, particularly those arising from the influence of complex processes and parameters, were addressed and partially quantified through global climate models and regional generic groundwater models. The presented work in this report gives answers to key research questions, which include the timing and drivers of the next glacial period and its dependence on cumulative anthropogenic CO₂ emissions; the potential deviation of future glacial cycles from the cycles observed over the past million years; the translation of climate modelling results into stylised climatic states, and the implications of these findings for uncertainties concerning the long-term safety of radionuclide confinement in a repository for high-level radioactive waste.

7.1 Conclusion of global climate modelling

Based on the experiments conducted by Kaufhold et al. (2025b) and the projections outlined by Archer & Ganopolski 2005 and Lord, Lunt & Thorne 2019, Germany is expected to remain largely ice-free for the next 150,000 years. This is because, under the natural climate evolution and low-emission scenarios, NH ice sheets will generally remain small due to the weak insolation minima. For cumulative carbon emissions larger than 1,000 PgC, glacial inception is unlikely to occur within the next 100,000 years. Given that the insolation minimum at ~175,000 years in the future is particularly low (3rd lowest minimum, Figure 11), it is likely that Germany will see glacial conditions for emission scenarios 1000 PgC and lower at that time. This assumption that all scenarios (regardless of cumulative emission) will begin a “proper” glacial inception (i.e., one not weakened by low orbital forcing) after 170,000 years is backed by Lord, Lunt & Thorne 2019 and Archer & Ganopolski 2005.

Given current uncertainties in volcanic outgassing, the natural timing of the next glacial inception is expected to occur within the next ~50,000–125,000 years. Since CO₂ concentrations have remained nearly constant over the past 800,000 years when averaged over glacial cycles, the shorter end of this range (~50,000 years), where geological sources and sinks during the PI are not in balance, is considered more realistic. However, it cannot be ruled out that glacial inception may instead occur around 125,000 years from now. Historical cumulative CO₂ emissions (~500 PgC) are unlikely to delay a glacial inception naturally expected at ~50,000 years. Glacial inception is likely within the next 200,000 years under nearly all considered emission scenarios because the deep insolation minimum at ~170,000 years could trigger ice sheet growth even at relatively high CO₂ levels.

Uncertainties in these estimates are primarily linked to the long-term carbon cycle and Earth’s equilibrium climate sensitivity (ECS). Kaufhold et al. (2025a) show that the land

carbon pool significantly affects the removal of atmospheric CO₂, whereas studies omitting it (e.g., Lord et al. 2016) likely overestimate future atmospheric CO₂ concentrations and, subsequently, peak global temperatures, enhancing weathering. CLIMBER-X also suggests a shorter silicate weathering timescale than previously estimated, due to its detailed spatially explicit weathering scheme and relatively high PI fluxes. A shorter timescale implies atmospheric CO₂ could return to PI levels faster than prior simulations. However, it was shown that ECS represents the largest uncertainty in long-term CO₂ uptake. In Kaufhold et al. 2025a it was determined that higher equilibrium climate sensitivity accelerates silicate weathering, thereby reducing CO₂ faster. Depending on the Earth's ECS, the silicate weathering timescale can range from 54,000 to 153,000 years, and potentially shorter if ECS exceeds 4 °C (Knutti, Rugenstein & Hegerl 2017).

Although it is unlikely based on the amount of modelling work done towards the lifetime of CO₂ emissions in the atmosphere, uncertainty in ECS means that glacial inception could potentially occur during the 17,000- or 35,000-year insolation minima. However, an earlier inception would not necessarily result in a longer or more extensive glacial state, given the ~100-kyr periodicity and similar extent of previous glacial cycles. We therefore assume that shifts in inception timing would have limited effects on the overall duration and maximum extent of glaciation.

Based on Kaufhold et al. (2025b) and the rule proposed in Ganopolski (2024), a plausible set of future climate developments was constructed. With this, glacial inception is projected to occur at least eight times over the next 1 million years, a timeline broadly consistent with previous studies (Lord, Lunt & Thorne 2019). It is also assumed that there will be another prolonged interglacial period in 400,000 years, linked to another eccentricity minimum (a pattern also observed in Lord, Lunt & Thorne 2019, and Talento & Ganopolski 2021). These projections are based on the strong assumption that future glacial cycles will operate as they have in the past, following the same orbital and carbon cycle dynamics that have governed Earth's climate. Despite differences in models and approaches, the timing of glacial inception and termination in our scenarios generally aligns with previous studies.

Germany is expected to remain in a “temperate climate” for the next several millennia before the resumption of glacial cycles, which are assumed to follow past patterns. Ice sheets are expected to remain small over the next ~150,000 years due to weak orbital forcing, making significant expansion into Germany (and permafrost development, see Figure 17 and Figure 19) unlikely. Once a future glacial inception begins, we assume that ice sheets will gradually expand to a size at least as large of the LGM, however, it cannot be ruled out that it will reach a size comparable to that of the Saalian or Elsterian glacial maximum (see Figure 6). During the early transition from interglacial to glacial, small ice sheets will form, cooling the NH and placing Germany in a cool climate domain. Evidence from past cycles suggests ice sheets will spend most of their time at intermediate size, keeping Germany predominantly in a cold climate domain with some

permafrost. Once ice sheets reach maximum extent, Germany will become largely ice-covered with widespread permafrost. In Figure 17 and Figure 19, we show the potential extent of permafrost area, which is at least 1m thick.

7.2 Conclusion of the dose estimations

According to § 7 EndlSiAnfV (2020), the radiation dose for a representative person needs to be estimated. The calculation basis and exposure pathways are defined by BASE (BASE 2022). Since the assessment period for a final repository span over 1 Mio. years, varying climatic conditions influence exposure pathways and, consequently, dose estimation. Water availability for agriculture is particularly relevant: during periods of insufficient precipitation, irrigation using contaminated groundwater may become necessary, representing a key pathway for radionuclides into the biosphere.

Climate data from CLIMBER-X simulations were used for the analysis. The reference state is a PI cool-temperate climate. Additional scenarios include cool, cold, and ice-covered states, as well as six Anthropocene emission scenarios (up to 5,000 PgC). Dose conversion factors (DCF) were calculated for 27 radionuclides, representing the dose per unit groundwater contamination (1 Bq L^{-1}).

The analysis reveals several notable trends across different climate and emission scenarios. The vegetation period exhibits significant variability. It shortens significantly in colder climates, with complete absence under persistent ice coverage, while under high-emission conditions, it may extend to as long as eight months. Precipitation patterns follow a similar divergence, decreasing in cold states and increasing substantially under elevated emissions.

Irrigation deficits are absent in cold scenarios but rise proportionally with anthropogenic emissions during the Anthropocene, reaching up to a factor of five compared to the reference scenario. Dose conversion factors (DCF) span a range from $1 \cdot 10^{-7}$ to $1 \cdot 10^{-2} \text{ Sv L Bq}^{-1}$, with ingestion of contaminated food identified as the dominant exposure pathway. In colder climates, DCF values decrease by up to an order of magnitude, whereas warmer scenarios exhibit increases of up to a factor of four. Notably, the radionuclide Se-79 demonstrates non-linear behaviour across these conditions.

In conclusion, climatic conditions exert a decisive influence on irrigation requirements and, consequently, on estimated radiation doses from contaminated groundwater. Warmer climate states are associated with increased irrigation deficits, leading to higher potential radiation exposure, whereas cooler climates, without irrigation needs due to shortened or absent vegetation periods, result in significantly lower DCF. Overall, warmer climatic conditions are more likely to increase radiation exposure compared to cooler states. The effects discussed are exclusively related to processes within the

biosphere; potential reinforcing or counteracting influences from radionuclide transport in the geosphere have not been considered.

7.3 Conclusion of the numerical modelling of climate states

The results shown here provide a better insight into the possible effects of different climate states on radionuclide transport on the overburden of a repository in clay stone, taking into account the rate of distribution of tracer within and out of the host rock. The model used reflects a possible geological rock sequence in Germany and thus provides an indication of the transport behaviour of radionuclides. The different rock properties lead to different flow velocities in the model, which are also influenced by the different climate conditions. Glaciation leads to a higher pressure gradient from North to South of the model and results in higher horizontal flow velocities, which causes the concentration at the model surface and in the outflow above the host rock to be lower than in other climate states. With favourable diffusion coefficients after StandAG, the requirement after the EndISiAnfV is not exceeded as long as the entire host rock is considered as CRZ. Depending on the actual parameter of the layers at a real site, the CRZ to be defined could even be significantly smaller.

Although the climate states result in differences in the concentration curves at different observation points in the model, these are to be classified as minor in relation to the influence of the parameter variations like diffusion and sorption on the concentration curves. The diffusion and sorption coefficients are more relevant than the climate states for the simulations presented in this work. Here, the climate states were considered stationary over the entire assessment period, so the influence on the concentration distribution can be considered to be less for shorter periods. Aspects that should be considered in the future are cross correlations of parameters and climate states, and temperature-dependent simulations in connection with hydraulic groundwater flow simulations.

The possible climate scenarios for various climate emission scenarios described in chapter 4 and Kaufhold et al. 2025b are also subject to uncertainties. Here, too, the choice of parameters influences the results and thus the time periods over which a certain climate state would be possible in Germany. This results in a combination of uncertainties that influence and increase the possible range of radionuclide discharge from the host rock and developments in the model. A clear quantification of the uncertainties across all parameters and modelling steps is therefore not expedient and would not be meaningful. However, the models can be used to identify sensitivities and individual model, parameter and scenario uncertainties.

7.4 Conclusion of the sensitivity analysis

The evaluation of the long-term safety of existing or planned geological repository systems relies fundamentally on the use of numerical models. These models are designed to represent either the entire repository system or specific subsystems and serve as the basis for deriving safety-relevant conclusions. Since such models depend on a range of input parameters – many of which are subject to considerable uncertainty – any resulting safety statement inherently carries a degree of uncertainty. To ensure that these uncertainties are properly accounted for in the safety assessment, a systematic quantification is required. This is achieved through uncertainty and sensitivity analysis.

Uncertainty analysis focuses on the variability of model outputs resulting from uncertain input parameters, without attributing the uncertainty to specific sources. In contrast, sensitivity analysis provides a mathematical framework for identifying, isolating, and quantifying the influence of individual parameters and their interactions on the overall uncertainty of the model output. A global sensitivity analysis considers all parameter uncertainties simultaneously, each across its full range of possible values. This is typically implemented through probabilistic methods, involving a large number of model simulations with systematically varied parameter combinations.

The objective of the project described in this report was to investigate the influence of various parameters and climate states on the long-term containment of radioactive waste in a deep geological repository. A key outcome of this and previous studies is the recognition that sensitivity analysis is a powerful tool for gaining deeper insight into the behaviour of complex simulation models. It enhances understanding of the model's internal mechanisms and supports transparent communication of its functioning. Moreover, it can increase confidence in the model's reliability or reveal potential weaknesses and modelling errors. Conservative parameter ranges were selected for the model simulations performed here, in which the mass proportions transported from the host rock were to be considered overestimated. The value ranges were selected in order to identify the most important parameters for transport from the host rock and also to reflect the conditionally favourable and not just the favourable value ranges of the StandAG.

The sensitivities of the parameters could already be clearly identified using scatterplots. The sorption and diffusion coefficients had the strongest impact on the maximum mass discharge from the host rock. A trend can also be seen in porosity in relation to maximum discharge, but no clear trend can be identified in the scatterplots for dispersion, permeability and the hydraulic gradient.

The CSM and CUSUNORO evaluations show the similar trends, in different coordinate systems according to their mathematical description. For porosity and sorption, there is a negative correlation between input parameters and model output. For both parameters, lower values have a greater influence on the mass discharged. If higher sorption

coefficients are applied, discharge from the host rock only occurs in some simulation cases at values $>2.5 \cdot 10^{-4} \text{ m}^3 \text{ kg}^{-1}$. For this reason, the curve is a straight line in the range from 50 % bis 100 % of the simulation cases. Due to the positive correlation of the other four parameters, these straight lines are more frequently found in the lower value range from 0 bis 65 %. The dispersion length shows less sensitivity in the curve and even changes to a negative correlation in the higher value range. The resolution of the curves show that more simulations are needed to make the analyses more reliable in their evaluation.

The SRRC supports the results of the scatterplots. According to the SRRC analysis, sorption (negative correlation) has the strongest influence on the model results, followed by molecular diffusion (positive correlation), which also provided the clearest visual trends in the scatterplots. This is followed by porosity with a negative correlation but already a significantly lower influence on the results. The hydraulic gradient, permeability, and dispersion have minor impact to the model results. Due to its mathematical description, the SRRC evaluation reflects the influence primarily on the low output values, i.e., on the results with high sorption or low molecular diffusion.

The SRC show results that can be interpreted less by the scatterplots and better by the CSM and CUSUNORO plots. Due to the non-rank-based method, individual outliers can have a major influence on the SRC. This may explain the high SRC for the hydraulic gradient and permeability. High diffusion coefficients and low sorption coefficients lead to higher transport from the host rock, which is then amplified by higher hydraulic gradients and permeabilities, causing the uniformly high SRCs. Porosity and sorption have lower SRCs compared to the hydraulic gradient, permeability, and molecular diffusion. Dispersion has the lowest SRC and shows the lowest sensitivity in all parameter sensitivity analyses.

Furthermore, the various analyses have shown the dominant influence of the sorption and the diffusion coefficient on the model output. Climate developments are also partially represented by varying the parameter values. Variations in the hydraulic gradient or changes in porosity can represent developments such as glaciation. Thus, the sensitivity analysis also represents climate developments to a limited extent. Developments such as permafrost or the formation of erosion channels were not covered by the sensitivity analysis, but they had less influence on the discharge from the host rock than climate developments such as glaciation. In addition to these substantive findings, the study also demonstrates the feasibility of conducting sensitivity analyses using complex two-dimensional numerical models for flow and transport processes, implemented with the simulation code d³f++.

7.5 Key findings for the site selection

The results of the REDUKLIM project provide significant added value to the site selection process for a deep geological repository for high-level radioactive waste in Germany.

The REDUKLIM project focused on future climate development and the consideration and reduction of uncertainties. The climate modelling carried out in this project provided further insights into future climate scenarios. Various scenarios with different anthropogenic emissions show possible climate developments for the next million years. The results can be used to derive initial and boundary conditions for other models and the safety assessments of potential repository sites. The work also determined the timing of the next glacial period. The timing of the next glacial cycle can support future studies investigating the effect of mechanical stress or hydraulic conditions by providing a timeframe for the different climate states. The findings help illustrate the range of possible climate extremes that Germany may face over the next million years and provide critical information on temperature, precipitation, and other parameters relevant for safety analyses. It also forms the basis for mandatory dose estimation scenarios as required by BASE (2022) and guides the selection of exploration objectives and methods. Furthermore, the results highlight climate states that require particular attention in biosphere dose assessments, ensuring that long-term safety considerations are robust and comprehensive.

In the second part of the project possible climate developments were stylised into climate states. Afterwards the impact of the climate states on the radionuclide transport from the host rock was investigated. The climate states were represented due to changes in initial and boundary conditions. A sensitivity analysis with six parameters was carried out, considering that parameter changes also represent climate developments. With this study parameter sensitivities in relation to the radionuclide transport from the host rock were identified.

7.6 Answers to Research Questions

Chapter 1, *Purpose of the Report*, introduced four research questions that guided the analysis and content of this report. This section provides clear and explicit answers to each of these questions, drawing on the findings and evidence presented throughout the report:

1. When will the next glacial period begin, and how does the timing of the next glacial advance depend on cumulative anthropogenic CO₂ emissions? Which regions of Germany will be affected, and to what extent? How great are the uncertainties?

Under the modelling configuration where we have a slight imbalance at present-day between volcanic outgassing and silicate weathering, we estimate that next

glacial will occur within the next ~50,000–170,000 years (Kaufhold et al. 2025b). Present-day emissions will still permit inception at 50,000 years, while a doubling of present-day emissions will push closer to 100,000. Generally, higher emission scenarios tend to the higher end of this range.

The modelling with CLIMBER-X did not allow us to simulate the dynamic evolution of the ice sheets far beyond inception. Therefore, we assume that future ice sheets could reach at least the extent of the LGM. However, the current modelling work cannot rule out larger ice sheet extents, such as those reached during the Saalian or Elsterian glaciations, or account for the potential contribution of Alpine glaciers. Assuming that future ice sheets reach at least the extent of the LGM, future glacial maxima would mainly affect northern Germany, while areas farther south would remain largely ice-free but could still experience colder conditions and other periglacial effects (e.g., permafrost cover, Figure 19). In previous glacial cycles, the major continental ice sheets generally remained north of the Central German Uplands, although their exact southern extent varied between glaciations. If future ice sheets reached Saalian or Elsterian extents, the area directly affected by glaciation could therefore extend much farther south into central Germany, beyond the regions affected during the LGM.

There are still large uncertainties in these estimates, mainly related to the long-term carbon cycle and ECS. Kaufhold et al. (2025a) found that ECS is likely the largest source of uncertainty for long-term CO₂ uptake, and therefore, the timing of the next glacial cycle (as the timing can be reasonably by the level of CO₂ in the atmosphere). Should ECS be high, it will lead to stronger peak warming and faster silicate weathering, meaning that atmospheric CO₂ could return towards pre-industrial levels sooner and the climate could return to more Holocene-like conditions earlier. Over the coming decades, the expanding observational record should help to better constrain ECS and reduce this uncertainty.

2. Will the glacial cycles within the next million years differ significantly from those of the last million years? Is it possible that instead of regular 100,000-year cycles, much longer glacial cycles with more extensive ice advances will occur?

Presently, it is not possible to determine whether the periodicity of glacial cycles over the next 1 million years will differ significantly. Ultimately, this depends on what the mechanism behind the change from 40,000 year cycles to 100,000 year cycles was. Should the change be dependent on physical mechanisms, e.g., sediment cover in the NH high-latitudes (i.e., the regolith hypothesis), it is possible that the period of cycles might increase given future changes in sediment cover and potentially lead to larger ice sheets. Should it instead be dependent on phase locking of orbital parameters and the nonlinear response of ice sheets, then the ~100,000 year periodicity could persist even if the underlying physical conditions remain relatively similar. However, it cannot be ruled out that there could be longer glacial cycles with more extensive ice sheet coverage.

3. How can the results from climate modelling be converted into stylised climatic conditions that need to be considered when assessing the dose estimate?

While CLIMBER-X simulations provide a comprehensive representation of climatic variables and their temporal evolution, radiological safety assessments require a simplified description of future environmental conditions that can be implemented within the biosphere models prescribed by BASE 2022. Consequently, the complex climate projections must be translated into a limited number of characteristic climate states defined by parameters relevant to radionuclide transfer and exposure pathways.

Climatic conditions influence both the duration of the growing season and agricultural water demand. Mean monthly air temperatures determine the length of the vegetation period, whereas plant water requirements are additionally affected by precipitation and relative humidity, following the approach described by BASE 2022. Within this framework, a climatic state can be characterized by a set of mean monthly values for air temperature, precipitation, and relative humidity, from which the irrigation deficit is calculated. The irrigation deficit represents the amount of supplementary water required to sustain agricultural production. Because this water is assumed to be supplied using contaminated groundwater extracted from a well, the irrigation deficit constitutes a key parameter governing the transfer of radionuclides from groundwater to agricultural soils, plants, livestock products, and ultimately humans.

The CLIMBER-X simulations indicate that the various climatic states can be grouped according to their irrigation requirements. Cool, cold, and ice-covered climates are characterized by shortened or absent growing seasons and low agricultural water demand. Under such conditions, precipitation is either sufficient to satisfy plant water requirements, and no irrigation deficit occurs, or agriculture can even be excluded due to permafrost or extensive glaciation. Consequently, contaminated groundwater is not used for irrigation, and several important exposure pathways, particularly those involving contaminated plants and agricultural soils, become inactive. From the perspective of biosphere dose assessment, these climates therefore exhibit similar behavior and can be represented by a single stylized class of cold climatic conditions without irrigation demand.

The cool-temperate pre-industrial climate represents an intermediate state characterized by a moderate seasonal irrigation deficit. In this case, both irrigation-dependent and irrigation-independent exposure pathways contribute to the estimated dose. This climate therefore provides a natural reference against which the radiological implications of alternative climatic conditions can be evaluated.

A third class comprises the transient warming scenarios associated with the active Anthropocene. Rising temperatures extend the growing season and increase evapotranspiration, thereby enhancing agricultural water demand. Although precipitation generally increases as well, this increase is insufficient to offset the

additional water loss. As a result, irrigation deficits become larger and persist for longer periods. As irrigation water is assumed to originate from contaminated groundwater, radionuclide transfer to soils, plants, livestock products, and other environmental compartments increases accordingly. Dose conversion factors therefore rise with increasing cumulative carbon emissions and may reach values several times higher than those obtained under present-day climatic conditions.

These results demonstrate that the irrigation deficit is an effective integrative metric for translating climate model output into stylized climatic conditions relevant to radiological dose assessment. Rather than classifying future climates solely on the basis of temperature, precipitation, and relative humidity, it is more meaningful to distinguish them according to their influence on agricultural water demand and the associated radionuclide exposure pathways. This approach reduces complex climate projections to a small set of biosphere-relevant climate states while retaining all relevant processes for estimating doses dose to a representative person. The calculations further show that warmer climates associated with increased irrigation demand generally produce higher dose estimates, whereas colder climates without irrigation requirements lead to substantially lower doses. Consequently, long-term safety assessments can define stylized climatic conditions primarily through their effect on irrigation demand and the resulting transfer of radionuclides within the biosphere.

4. What implications do the results of the climatic model calculations have for the uncertainties regarding the safe confinement of radionuclides in a repository for high-level radioactive waste?

Numerical groundwater models are used to simulate 'what-if' scenarios or conditions that are as realistic as possible with regard to the flow and transport behaviour of water and pollutants, to provide a better understanding of groundwater conditions, and to estimate potential migration pathways, distances or masses for the future. However, the models are always a simplification of reality; in these studies in particular, a simplified lithostratigraphic model based on German geology was used, which does not represent any actual site. Boundary conditions and parameters in the model were modified to take the climate states into account in the groundwater models. The simulations were carried out using the same climate state throughout the entire assessment period in order to examine the greatest possible effects on discharge from the repository and transport through the geosphere. Climate states have an influence on the discharge of radionuclides from the host rock. This influence is minimal in this hydrogeological model for a repository in claystone, as the host rock remains intact and the flow and transport behaviour is only slightly affected by the near-surface effects of climate changes.

In addition to climatic states, other transport-relevant parameters were varied. These parameters include diffusion and dispersion, which are taken into account

in groundwater models using the diffusion coefficient and dispersivity. A change in the diffusion coefficient resulted in a significant change in the discharge from the host rock, as did the inclusion of radionuclide-specific properties, such as sorption, which is modelled using the sorption coefficient. These two parameter values have a greater influence on contaminant distribution within the host rock than the different regarded climatic states. It should be noted that this model did not consider any climatic transitions, which may also influence the discharge. Based on these results and the insights derived from them, the parameter variation was extended to a sensitivity analysis (SA) of six different model parameters. This SA identifies the sorption and diffusion coefficients as the most sensitive parameters when evaluating the Standardised Rank Regression Coefficient (SRRC). The obtained results show that the host rock properties have a greater influence on the barrier effect for the safe containment of radionuclides than future climate changes in the regarded simulations.

7.7 Overall conclusions

An essential part of the work carried out dealt with climate scenarios. In the past, institutions have developed climate scenarios in several projects. These differed in terms of the projected time periods, regions covered, model assumptions and codes used. The climate scenarios indicate different points in time for the next glacial phase. In REDUKLIM, new simulations were carried out using CLIMBER-X. Various CO₂ emission scenarios were considered. The CO₂ emissions considered a range from zero global emissions up to the emission of all global fossil fuel reserves. In addition, several processes were considered in contrast to earlier models. These include, but are not limited to, differing ECS, the inclusion of the land carbon pool, spatially explicit weathering, the methane cycle, and an assumed geological carbon cycle imbalance. More details can be found in (Kaufhold et al. 2025a; Kaufhold et al. 2025b). Based on the simulations for different climate states (i.e., cool, cold, ice-covered, and temperate), monthly averages for temperature, precipitation and relative humidity were output from CLIMBER-X. This data has been archived, and can be found at Kaufhold & Ganopolski (2025). Using this data, dose estimations were carried out based on the calculation basis for dose estimation for the final storage of high-level radioactive waste as required by § 7 of the Repository Safety Requirements Ordinance.

Numerical groundwater models were set up to quantify the radionuclide transport from a final repository in accordance with § 4 of the Repository Safety Requirements Ordinance. First, the climate states were converted into stylised conditions with different assumptions, parameters and boundary conditions, and the radionuclide transport was modelled over a one million years. In addition, sorption, diffusion and dispersion values were varied in order to evaluate the influence of these parameters on the discharge of radionuclides from the host rock. Glaciation with ice margins in Germany can cause higher radionuclide discharge from the host rock due to a higher hydraulic gradient. Under the model

assumptions made, erosion effects and permafrost conditions have only a minor impact on radionuclide discharge. In contrast, variations in the diffusion and sorption coefficients have a major influence. A sensitivity analysis was carried out to quantify this influence with a more statistic method.

8 Outlook

A core assumption of our work is that future glacial cycles will unfold as they have in the past. As ice core data reveals that glacial cycles have shifted in frequency in the past, from roughly 41,000-year cycles to the current ~100,000-year cycles, it is possible that glacial cycles could change frequencies in the future. One reason could be, for example, the regolith hypothesis (i.e., if more bedrock is exposed from future ice sheets, permitting an even larger and more persistent growth of ice sheets). Future studies could aim to develop a conceptual model based on, for example, Talento & Ganopolski (2021) which is capable of directly assessing this possibility, especially given the long-term decline in CO₂ since the onset of the Pliocene. Such a model could provide further robustness to our constructed climate scenarios and could be used to explore speculative scenarios. Such speculations may include: can glacial cycles change frequencies in the future? Or, is it indeed possible to avoid a global glaciation by maintaining CO₂ concentration at 350-400 ppm (as discussed in Chapter 2.4.3)?

Additionally, projections of future coastlines and regional inundation offer essential input for evaluating processes such as subsidence and groundwater flow, as hydraulic gradients may change under these conditions. Previous studies assessing potential sea level rise often rely on the “bathtub” approach, which assumes a uniform rise in global sea level of ~7 metres for the complete melting of the Greenland ice sheet or ~58 metres for the Antarctic ice sheet. However, sea level change is highly spatially heterogeneous because it is influenced by the gravitational pull of ice sheets and regional variations in solid Earth and mantle dynamics. Therefore, the bathtub method is unlikely to provide an accurate representation of long-term future inundated areas. Furthermore, the potential contribution of sea level rise from ocean thermal expansion is not accounted for by these methods. Ongoing work with CLIMBER-X aims to identify which regions of the world would be inundated under a partial or complete melt of the Greenland ice sheet, the West Antarctic ice sheet, and all ice sheets, and to quantify the resulting effects on regional climate and ocean thermal expansion. This will be especially useful for identifying which areas of Germany need to take sea level rise into account as a potential factor affecting the repository system.

Further work could be carried out in the future in direct relation to the site selection process for a repository for high-level radioactive waste. A study of climate developments and their relevance for all host rocks could provide the basis for a comprehensive comparison of host rocks. The influence of climatic factors may affect host rocks to varying degrees and may vary in intensity depending on regional conditions. In addition, climate conditions have influence on dose calculations. The application of the results of regional climate models is thus of high importance in phases II and III of the site selection process.

In this project, generic assumptions were made for the groundwater model, which should be replaced in future by site specific data from sub-areas in order to set up models for

which validation options could exist in future. The stylisation of climate conditions in groundwater models can be refined, for example by taking a closer look at pressure conditions beneath a glacier in connection with the probabilities of an ice sheet and its thickness in potential sub-areas. Parameterisation can also be further narrowed down with a regional reference, so that the parameter ranges and thus also the parameter uncertainties can be reduced. According to this study, the most important parameters would include the sorption of radionuclides or the diffusion behaviour of radionuclides in clay rock. The simulation of additional cases, possibly with different parameter ranges, for the existing model could make the sensitivity analysis more robust.

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