Technical Report
TR-22-02
August 2022

Uncertainties in modelled climate changes at Forsmark over the next 1 million years

Charles J R Williams
Daniel J Lunt
Alan T Kennedy-Asser
Natalie S Lord

SVENSK KÄRNBRÄNSLEHANTERING AB

SWEDISH NUCLEAR FUEL
AND WASTE MANAGEMENT CO

Box 3091, SE-169 03 Solna
Phone +46 8 459 84 00
skb.se

SVENSK KÄRNBRÄNSLEHANTERING

ISSN 1404-0344
SKB TR-22-02
ID 1983154

August 2022

Uncertainties in modelled climate changes at Forsmark over the next 1 million years

Charles J R Williams, Daniel J Lunt, Alan T Kennedy-Asser
University of Bristol

Natalie S Lord, Fathom, Bristol

Keywords: Future climate change, Model projections, Uncertainty.

This report concerns a study which was conducted for Svensk Kärnbränslehantering AB (SKB). The conclusions and viewpoints presented in the report are those of the authors. SKB may draw modified conclusions, based on additional literature sources and/or expert opinions.

This report is published on www.skb.se

Preface

This report concerns modelling of the Forsmark climate over the next 1 million years. The general methodology, including the set of scenarios and numerical models, are adopted from a previous study conducted at SKB (TR-19-09). However, while only a single projection of the Forsmark climate over the next 1 million years was provided in TR-19-09, the present study documents 89 projections in addition to the one in TR-19-09. The objective is to characterise scenario uncertainty with respect to the future climate evolution. To this end, the results will be very useful when designing representative climate developments (climate cases) that are used in SKB's assessments of post-closure safety, in particular those that cover a long time-span of 1 million years.

The study was conducted by Charles J R Williams, Daniel J Lunt and Alan T Kennedy-Asser (University of Bristol) and Natalie Lord (Fathom, Bristol). The report manuscript was factually reviewed by Johan Liakka and Jens-Ove Näslund (SKB).

Stockholm, June 2022

Jens-Ove Näslund
Coordinator Climate Research Programme SKB

Abstract

The long-term (up to one million years) disposal of nuclear waste in geological repositories requires a detailed assessment of possible future climates. Uncertainty in climate model future projections can be explored using a number of model-simulated alternative projections (ensemble members), which considered together provide a range in which future climate will likely sit.

This report builds on previous work described in SKB Technical Report TR-19-09, using a near-identical methodology. The aim of that work was to provide physically-based projections of future climate on the one million year timescale, both globally and regionally at the Forsmark site (using bias-correction downscaling). The projections were also run over a period of 500 000 years in the past, and validated against available proxy data. The primary difference is that here, rather than considering one ensemble member, a total of 90 different ensemble members are considered for a number of key climate variables, providing a range of scenarios at the Forsmark site.

The results suggest that, in an increasingly warming world, the onset of the next glacial period is pushed increasingly later, with all ensemble members suggesting that this onset would be over 200 000 years after present in a high emissions scenario. This is more than double that of a case with only natural climate variability (without anthropogenic emissions). A similar delay in hydroclimate (such as precipitation changes) is shown. The level of agreement between the ensemble members is discussed, as well as related uncertainties.

Sammanfattning

Det långsiktiga (upp till en miljon år) förvaringen av radioaktivt avfall kräver detaljerad utvärdering av tänkbara framtida klimat. Osäkerheten i framtida klimat kan utforskas med klimatmodeller med hjälp av ett antal alternativa projektioner (ensemblemedlemmar). Projektionerna beskriver tillsammans ett intervall inom vilket den verkliga framtida klimatutvecklingen sannolikt kommer att hamna.

Denna rapport bygger på arbetet som beskrivs i SKB TR-19-09. Syftet med den studien var att tillhandahålla projektioner av framtida klimat över kommande en miljon åren, både globalt och regionalt vid Forsmark (med hjälp av nedskalning och bias-korrektion). Projektionerna validerades också mot tillgängliga proxydata över en historisk period på 500 000 år. I stället för att betrakta endast en till Forsmark nedskalad ensemblemedlem, vilket gjordes i TR-19-09, används i denna studie totalt 90 olika ensemblemedlemmar för ett antal viktiga klimatvariabler, vilket ger upphov till ett flertal klimatprojektioner för Forsmark.

Resultaten tyder på att uppkomsten av nästa glaciationsperiod förskjuts allt längre in i framtiden i en varmare värld. I ett scenario med höga antropogena utsläpp av växthusgaser inträffar nästa glaciation efter 200 000 år för alla ensemblemedlemmar. Det motsvarar en fördröjning på mer än 100 000 år jämfört med ett scenario som med enbart naturlig variabilitet (utan antropogena utsläpp). En liknande förskjutning i hydroklimatet (t ex nederbördsförändringar) noteras också. Graden av överensstämmelse mellan ensemblemedlemmarna diskuteras i rapporten, liksom relaterade osäkerheter.

Contents

1 Introduction

The long-term disposal of nuclear waste in geological repositories requires a detailed assessment of likely future climates, on timescales up to one million years (IAEA 2020). This is also the case for safety assessments performed for the planned repository for spent nuclear fuel in Sweden (SKB 2011). Simulations from climate models can be compared to reconstructions from the geological past to validate and test the accuracy of the models (e.g. Lord et al. 2017), which gives confidence when the same models are then used to simulate future climates; something which it is clearly not possible to validate. Instead, uncertainty in projections can be explored using a number of model-simulated alternative projections (ensemble members), which considered together provide a range or envelope in which the future climate will likely sit.

This report builds on the work described in Lord et al. (2019) (SKB TR-19-09; equivalent to Posiva 2020), in which new research was presented into future climate change occurring over the next one million years (1 Ma) at Forsmark and Olkiluoto. In the present report, rather than considering one ensemble member (detailed extensively in Lord et al. 2019; see Section 3.1.3 and Figure 3-4 in that report), a number of different ensemble members are considered for a number of key climate variables, providing a range of projections at the Forsmark site.

On timescales of up to 1 Ma, there are two primary forcings of long-term future climate change that are used as input to the simulations: anthropogenic CO_2 emissions and the Earth's orbital configuration. For the former, various standard scenarios of anthropogenic CO_2 emissions are adopted based on the Radiative Concentration Pathways (RCPs) used in the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). For the latter, changes in the Earth's astronomical parameters impact the seasonal and latitudinal distribution of incoming solar radiation (insolation) at the top of the atmosphere (e.g. Laskar et al. 2004). Even though changes in these orbital parameters have a negligible forcing at the global annual mean scale, internal feedbacks serve to mediate the seasonal and latitudinal signal of this forcing, for example feedbacks associated with the carbon cycle and ice sheets (detailed extensively in Lord et al. 2019; see Sections 2.1.2, 2.1.3 and 2.2 in that report). Furthermore, the climate system response to these CO_2 and orbital forcings is heavily influenced by multiple climate feedbacks, both positive and negative. The aim of the work described in Lord et al. (2019) was to develop a methodology to account for these forcings and feedbacks to provide physically-based projections of future climate on the 1 million year timescale, which were validated by similar methodologies applied to the past. Although many ensemble members were initially produced, only one was propagated further to simulate future climate with the emulator, and so uncertainty in the climate response was not fully explored.

2 Methods

The methodology used here is almost identical to that described in Lord et al. (2019), so it will only be very briefly discussed here. In short, insolation and CO_2 data were used to force a conceptual global sea level model (CGSLM; see Lord et al. 2019, Section 3.1 and Figure 3-2), producing firstly an index corresponding to three climate regimes (interglacial, mild glacial and full glacial) and secondly global ice volume data, both for the next 1 Ma. The global ice volume data were then converted (using a scaling factor) into global sea level data (see Lord et al. 2019, Section 3.1.3 and Figure 3-6). These global sea level data, along with the original insolation and CO_2, were then used to force a statistical emulator, producing a number of climate variables covering the next 1 Ma at both a global scale and downscaled to the Forsmark site. See the Methods section of Lord et al. (2019) for a full description of this multistep process. In particular, Section 3.1 in Lord et al. (2019) deals with the climate forcing data used, including atmospheric CO_2 (Section 3.1.1), orbital variations (Section 3.1.2), and global sea level and the CGSLM (Section 3.1.3). Section 3.2 in Lord et al. (2019) then deals with the configuration of the statistical emulator, beginning with the GCM simulations used to calibrate the emulator (Section 3.2.1), the optimisation and evaluation of the emulator (Section 3.2.2), the validation of the emulator using proxy climate reconstructions (Section 3.2.3) and the forcing data going into the emulator (Section 3.2.4). Finally, Section 3.3 deals with the downscaling of data coming out of the emulator, focusing firstly on bias-correction downscaling (Section 3.3.1) and secondly on physical-statistical downscaling (Section 3.3.2). Here, consistent with the results section of Lord et al. (2019) (Section 4.2.2 in that report), for downscaled temperature and precipitation only the bias-correction method is presented.

Of particular relevance here is the fact that the GCSLM contains eight tunable parameters (see Table 3.1 in Lord et al. 2019 for a list of these), the importance of which was examined via a number of sensitivity experiments, detailed in Lord et al. (2019), Section 3.1.3 and Figure 3-5. As a result of this sensitivity testing, the parameters that were found to have the most significant impact on the model results were varied randomly, using Latin hypercube (LHC) sampling to create 1 000 different sets of values for each of these parameters (see Lord et al. 2019 for details on this method, in particular Section 3.1.3 and page 24). The GCSLM was then run with each sample in turn, with the results being compared to paleo proxy reconstructions from the last 500 000 years (500 ka) in order to eliminate some of these samples. The process of elimination was based on three comparisons. Firstly, the general climate state of the Last Glacial Maximum (LGM) was considered, with any ensemble member that produced mild glacial or interglacial conditions (using the above index) at this time being eliminated. Secondly, given that reconstructions from the LGM suggest that maximum ice volume occurred at ~18 ka before present (BP), any members showing maximum ice volume more than 1 ka before or after this were also eliminated. Lastly, the model configuration was independently optimised, and any ensemble member showing a root mean square error (RMSE) greater than the one produced by this independent simulation was also eliminated. As a result of this elimination process, of the 1 000 original ensemble members, 90 were retained. In Lord et al. (2019), only one of these 90 simulations (ensemble member 67) was chosen, being the best member compared to the reconstructions (i.e. with the lowest RMSE), and used to force the statistical emulator, with the results then being downscaled. The global and downscaled emulated temperature and precipitation presented in Lord et al. (2019) (Sections 4.2.1 and 4.2.2, and Figures 4-1 to 4-18 in that report) are therefore only based on one GCSLM ensemble member being input to the emulator.

In contrast, in the present report, the emulator is run 90 times using each of the 90 retained ensemble members, producing climate data for each of these and therefore giving a range of possible projections. Nine variables in total are produced by the emulator: surface air temperature (SAT), precipitation, evapotranspiration, sea ice, soil moisture, soil temperature, snow depth, vegetation fraction and wind speed, and two of these (SAT and precipitation) are further downscaled. In this report, for brevity, only the first three of these variables (SAT, precipitation and evapotranspiration) are presented, with all three being shown at the Forsmark site. However, the data from all nine variables and for all 90 ensemble members from the emulator, as well as all 90 ensemble members of glacial/interglacial timings and durations from the CGSLM, have been provided to SKB. Consistent with Lord et al. (2019), all variables presented here are shown under four different scenarios of future warming (based on CO_2

emissions): ranging from a natural scenario (as if there were no anthropogenic emissions), a mitigation scenario (RCP 2.6, representing a significant decrease in emissions) up to a worst-case, high emissions scenario (RCP 8.5). The code for the CGSLM, emulator and downscaling are archived on GitHub at https://github.com/ATK-A/PosivaSKB.

3 Results

Here, the results are divided into three sections. Firstly, the focus is on how the three chosen climate variables (for each ensemble member produced by the emulator) evolve over the next 1 Ma (Section 3.1), secondly the level of agreement between the ensemble members is considered (Section 3.2), and thirdly the onset of the next full glacial period across the ensemble is presented (Section 3.3). Please note that, in an effort to keep the main report is succinct as possible, many figures presented in the following appendices are discussed in the text below (because they are relevant to the results). These have been divided into two categories: i) results from the CGSLM (Appendix A); and ii) non-downscaled results from the emulator (Appendix B).

3.1 Evolution of climate variables over the next 1 Ma

Figure 3-1 shows the downscaled local (over Forsmark) mean annual SAT output from the emulator for the next 1 Ma for each scenario. Here, all 90 ensemble members are shown, as well as the single member (member 67) used in Lord et al. (2019), and the ensemble mean. It should be noted that, because the distribution across the ensemble is not uni-modal (i.e. ensemble members tend to cluster around glacials or interlacials, similar to two attractors in a chaotic system), the ensemble mean is not a realistic projection; however, it is useful as a reference point to show the central tendency. For comparison, the non-downscaled global and local annual mean SAT anomaly from the emulator is shown in Appendix A (Figure B-1 and B-2, respectively), as is the global annual mean SAT anomaly from the CGSLM (including the past 500 ka as well as the next 1 Ma, Figure A-1). Before the Forsmark temperatures (either downscaled or not) are discussed, two observations are noteworthy from the global SAT in Figures A-1 and B-1. Firstly, the length of time after present (AP before global SAT significantly falls below zero, is dramatically increased under the warmer scenarios; in the natural scenario this occurs within the first 100 ka AP, whereas it does not occur until ~150 ka AP in RCP 4.5 and, even later, not until after 200 ka AP in RCP 8.5. Secondly, in all of the scenarios (especially RCP 2.6, 4.5 and 8.5), there is a clear divide between the ensemble members for the first 500 ka, with some of them showing a consistent and stable preference towards warmer conditions whereas others show unstable and varying conditions, changing between glacial and interglacial periods. For the lower emission scenarios (e.g. RCP 2.6), qualitatively the ensemble mean seems to be approximately halfway between these two groups, but for RCP 8.5 the results suggest that, after 200 ka AP, although there are some ensemble members showing glacial temperatures, the majority (and therefore the ensemble mean) are showing interglacial conditions similar to the pre-industrial era (PI). After 500 ka, this divide becomes less obvious in the lower emission scenarios, but is still clear in RCP 8.5.

Returning to local Forsmark temperatures, the downscaled results are shown in Figure 3-1 and the non-downscaled results are shown in Figure B-2. Despite more variability, which is expected compared to the global mean, the same two observations can again be made in both figures. The onset of the next glacial period becomes later as the scenarios show higher emissions, and within the first 500 ka AP some of the ensemble members, the most in RCP 8.5, suggest interglacial conditions throughout the period; in RCP 8.5; this is true even after 500 ka AP. In addition, under the highest emission scenario (RCP 8.5) all ensemble members suggest a clear increase in SAT to near PI levels between ~400–500 ka AP, which remains stable for ~100 ka.

Concerning other variables, such as those relating to hydroclimate, Figures 3-2 and 3-3 show the downscaled emulated monthly mean precipitation and non-downscaled emulated monthly mean evapotranspiration anomaly at the Forsmark site, again for the next 1 Ma for each scenario; see Appendix B for the non-downscaled local emulated precipitation (Figure B-3). Downscaled emulated evapotranspiration was not calculated, because of the lack of robust modern observations for non-temperature or non-precipitation variables. In all of these three figures, and in a similar way to the SAT results, almost all ensemble members agree that the timing of any major change becomes later under the higher emission scenarios, with precipitation being close to or above PI levels (i.e. between 40–50 mm month^{-1} in Figure 3-2) for the first ~50 ka in all scenarios, but it stays this way or even increases for over 100 ka in RCP 4.5 and over 200 ka in RCP 8.5 (Figures 3-2 and B-3).

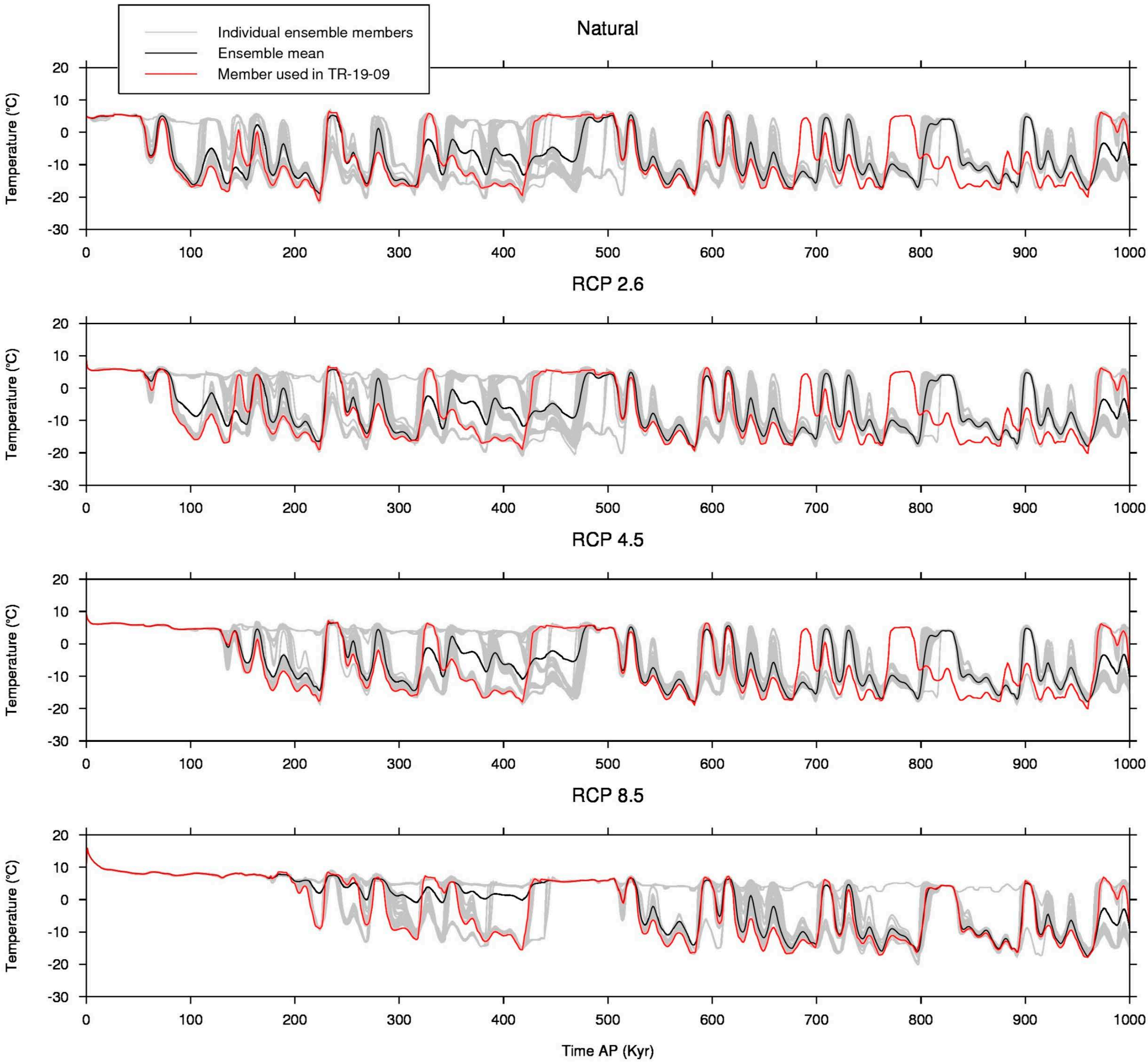

Figure 3-1. *Timeseries of downscaled emulated mean annual SAT (°C) for the next 1 Ma at the Forsmark site, for all 90 ensemble members, for each scenario. Grey lines show individual ensemble members, black line shows ensemble mean, red line shows the ensemble member used in the previous report (Lord et al. 2019).*

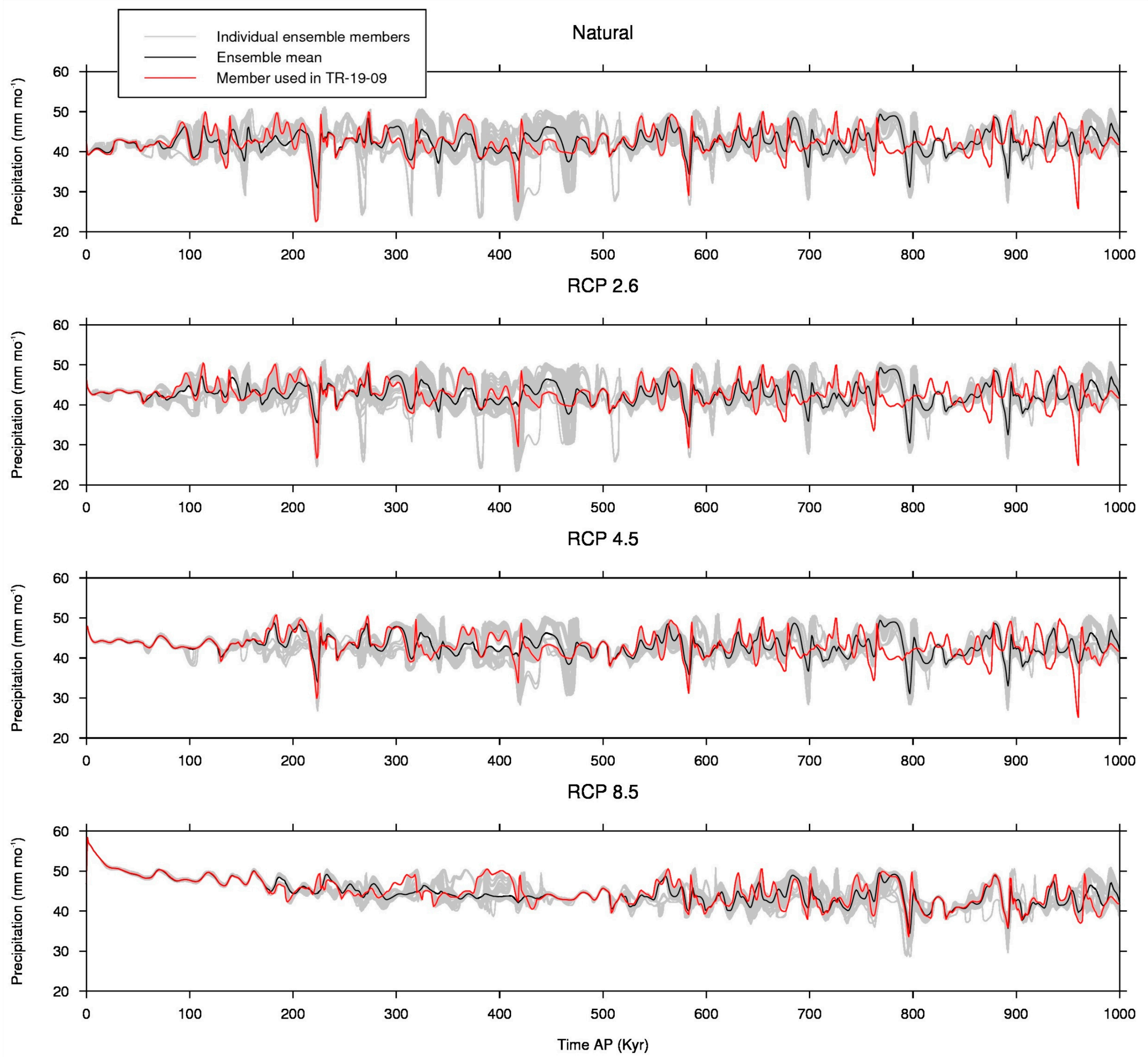

Figure 3-2. *Timeseries of downscaled emulated monthly mean precipitation (mm mo^{-1}) for the next 1 Ma at the Forsmark site, for all 90 ensemble members, for each scenario. Grey lines show individual ensemble members, black line shows ensemble mean, red line shows the ensemble member used in the previous report (Lord et al. 2019).*

The same is true for evapotranspiration (Figure 3-3), with all ensemble members suggesting that any major shift in this variable becomes progressively later under the higher emission scenarios. In addition, both of these variables show the aforementioned stable period during 400–500 ka AP under RCP 8.5.

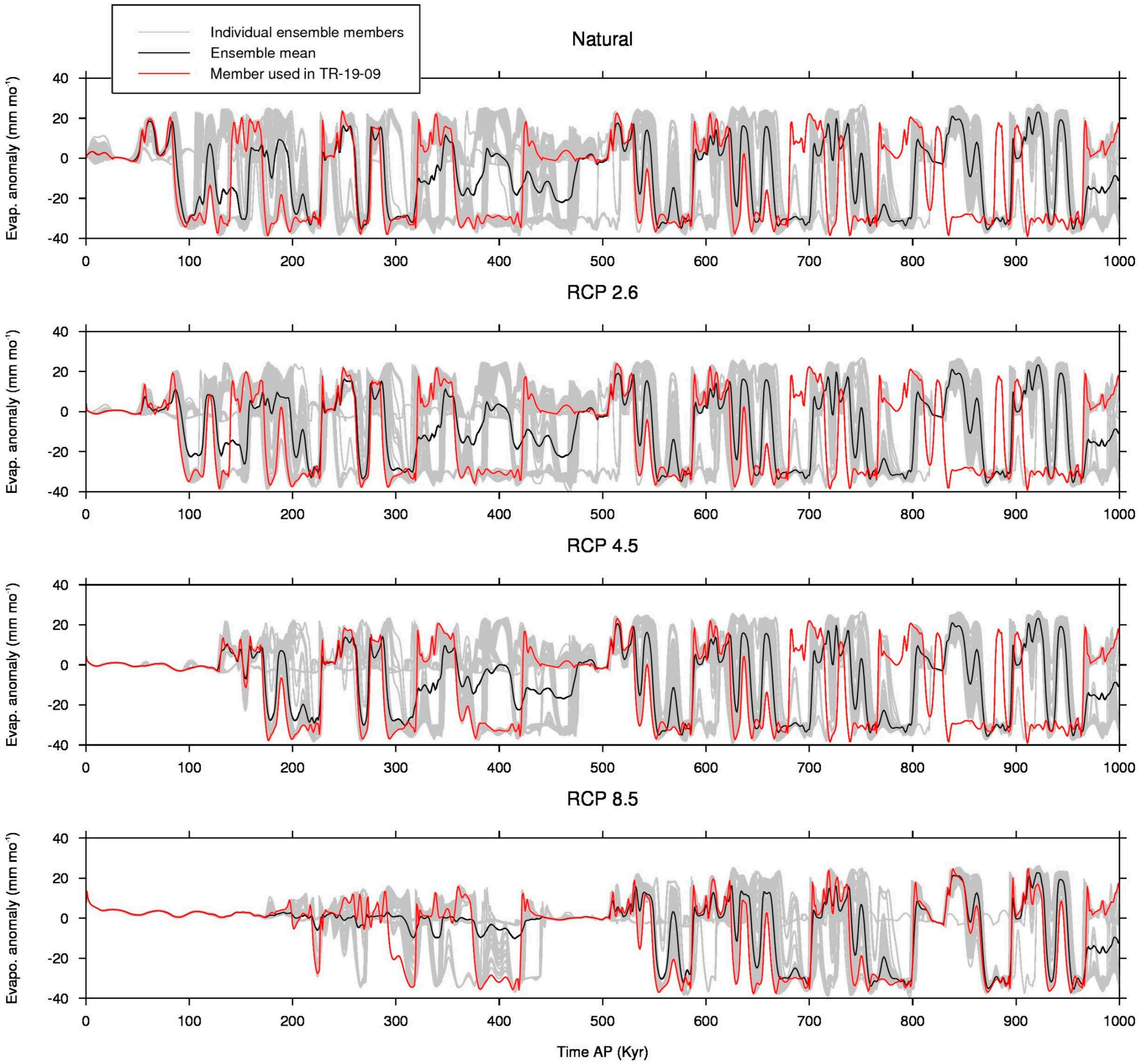

Figure 3-3. *Timeseries of non-downscaled emulated monthly mean evapotranspiration anomaly (mm mo^{-1}) for the next 1 Ma at the Forsmark site, for all 90 ensemble members, for each scenario. Grey lines show individual ensemble members, black line shows ensemble mean, red line shows the ensemble member used in the previous report (Lord et al. 2019).*

3.2 Agreement between ensemble members

To give a clearer indication about the level of agreement between the ensemble members and each projection, climate state output from the CGSLM is presented in Appendix A (Figure A-2), showing the percentage of the 90 ensemble members falling into each of the three climate states for any given year. Again, two points are noteworthy, similar to the above observations. Firstly, under all scenarios, 100 % of ensemble members agree on interglacial conditions for the first ~50 ka AP, and this period increases under the higher emission scenarios to over 100 ka AP in RCP 4.5 and almost 200 ka AP in RCP 8.5. At the end of this period, mild glacial conditions develop for the next ~100 ka AP in all scenarios, but the percentage of ensemble members in this category decreases as the scenarios show higher emissions; almost 100 % of members show mild glacial conditions under the natural scenario, decreasing to ~80 % in RCP 4.5 and only ~20 % in RCP 8.5, with the remaining members suggesting continued interglacial conditions in both. Secondly, the percentage of ensemble members suggesting a full glacial decreases as the scenarios show higher emissions, with almost 80 % of members showing full glacial conditions just after 200 ka AP in RCP 4.5 but only ~20 % of members showing this in RCP 8.5.

A similar result is shown by SAT output from the emulator. Figure 3-4 is similar to Figure A-2, in that it shows the percentage of ensemble members falling into each climate regime for any given year, but rather than directly using global climate state data from the CGSLM this uses downscaled emulated SAT for the next 1 Ma at Forsmark, using two temperature thresholds to define each climate regime: Regime 1 is where temperature is greater than −8 °C, Regime 2 is where temperature is between −8 °C and −15 °C, and Regime 3 is where temperature is less than −15 °C. These thresholds were not arbitrarily chosen, but rather match the global sea level thresholds discussed in Lord et al. 2019; in that study, global sea level thresholds of −93 m and −53 m were used to represent a low and high confidence of glaciation, respectively. Here, a comparison was made between downscaled SAT over Forsmark from the emulator and global sea level from the CGSLM, for one ensemble member (that presented in Lord et al. 2019), shown in Figure B-4. Quantitatively averaged across all scenarios, these two global sea level thresholds equate to SAT thresholds of −7.93 °C and −14.75 °C, respectively, hence rounded up to −8 °C and −15 °C. A comparison was made between a −14 °C and a −15 °C threshold, and the results concerning the percentage of ensemble members in agreement were very similar (not shown). Therefore, although the three regimes shown here are indirectly related to the interglacial, mild glacial and full glacial states of Figure A-2, they cannot be directly associated with these states because they are based on thresholds in a continuously varying parameter, rather than categorical climate state data. Nevertheless, the observations made above still hold true when emulated SAT is considered in Figure 3-4. Again, for the first ~50 ka AP, 100 % of members agree on Regime 1 conditions (the warmest regime), and this duration gets longer under the higher emission scenarios, with a transition to Regime 2 (the intermediate regime) only occurring after 100 ka AP and 200 ka AP in RCP 4.5 and 8.5, respectively. Even when this transition does occur in RCP 8.5, only up to ~20 % of ensemble members suggest this, with the remaining showing continued Regime 1 conditions. Likewise, a transition to Regime 3 (the coldest regime) occurs later under the higher emission scenarios, with a low (and decreasing) number of ensemble members suggesting this transition; under RCP 8.5, for example, this transition does not occur until ~400 ka AP, and even then only ~20 % of members suggest this. Finally, the highest emission scenario (RCP 8.5) is again showing the stable and prolonged (~100 ka) period of Regime 1 conditions at ~400–500 ka AP, after which time all scenarios (even RCP 8.5) suggest a transition to the colder Regime 2 or 3 conditions.

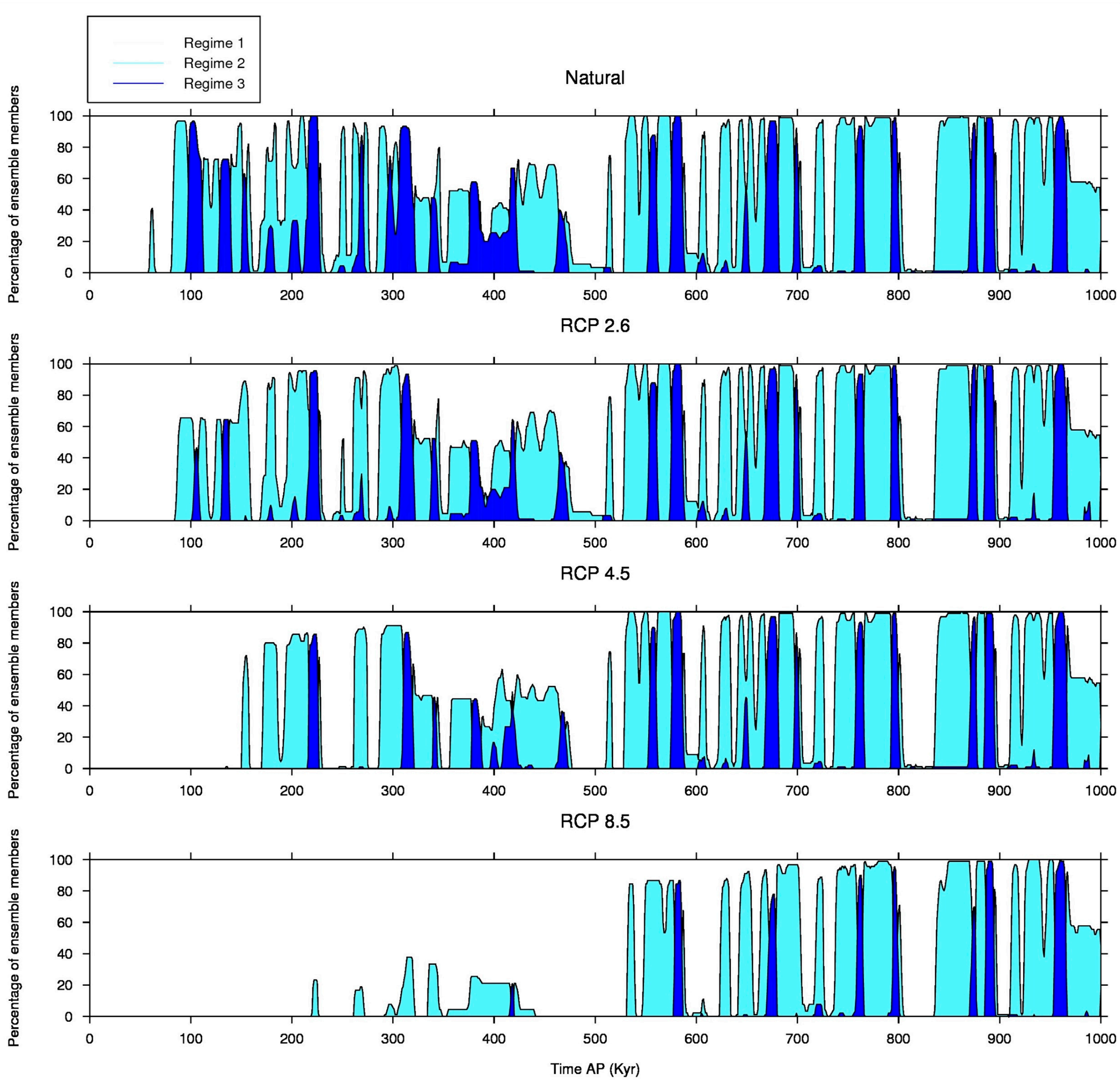

Figure 3-4. *Percentage of ensemble members going into a given climate regime, based on downscaled emulated temperature over Forsmark for the next 1 Ma, for all 90 ensemble members, for each scenario. Regime 1 is where temperature is greater than −8 °C, Regime 2 is where temperature is between −8 °C and −15 °C, and Regime 3 is where temperature is less than −15 °C.*

3.3 Onset of the next full glacial period

Figure 3-5 shows the percentage of ensemble members first going into an intermediate and cold regime, again based on downscaled emulated SAT over Forsmark and using the same two temperature thresholds as in Figure 3-4 to define this state, i.e. −8 °C (transition between warm and intermediate regime, Figure 3-5a) and −15 °C (transition between intermediate and cold regime, Figure 3-5b). Again, as this is based on thresholds from downscaled emulated SAT, the entry into the coldest regime shown in Figure 3-5 cannot be directly attributed to entry into a full glacial state from the CGSLM; the same figure, but based on the categorical climate state data from the CGSLM, is shown in Appendix A (Figure A-3). Nevertheless, similar observations can be noted from both figures. Based on downscaled emulated SAT for Forsmark and under the natural scenario, almost all ensemble members go into the intermediate or cold regime by ~50 ka AP or ~100 ka AP respectively (Figure 3-5). Under both thresholds, this transition becomes later under the higher emission scenarios, and the number of ensemble members showing this transition is more staggered as the scenario show higher emissions; in RCP 4.5 under the high threshold, for example, ~80 % of members transition into a cold regime by 200 ka AP, but then it takes another ~350 ka for the rest of the members to also do so (Figure 3-5b). Under the highest emission scenario (RCP 8.5) and using the high threshold, no members show the transition into a cold regime until just after 200 ka AP, and it takes another ~500 ka for the rest of the members to gradually show this. Similar results are shown from the CGSLM (Figure A-3), with the transition to a full glacial state occurring later under the higher emission scenarios, and the percentage of ensemble members to reach this state gradually increasing over a period of more than 500 ka AP, unlike under the natural scenario where almost all ensemble members have reached this stage by ~150 ka AP.

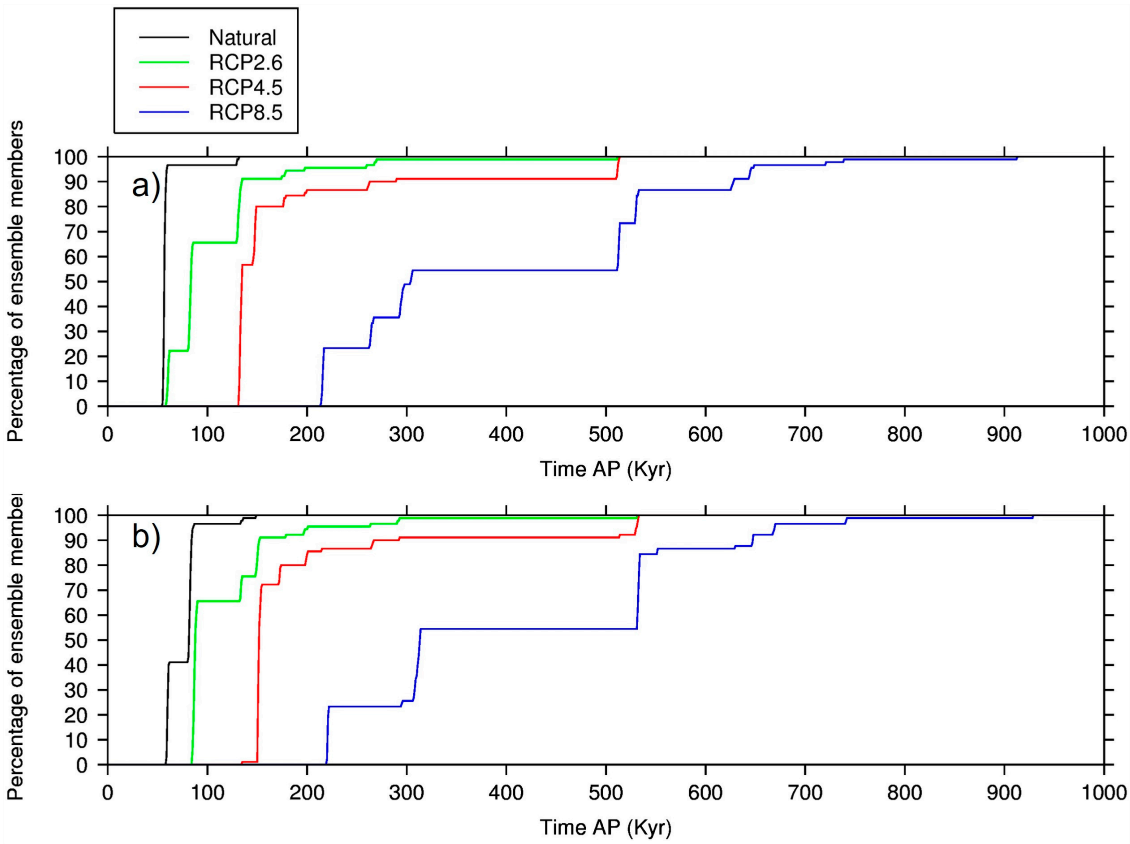

Figure 3-5. *Timeseries of cumulative ensemble members (percentage of total) going into a given climate regime (warm, intermediate and cold, where each of these is defined by two temperature thresholds), based on downscaled emulated temperature over Forsmark for the next 1 Ma, for all 90 ensemble members, for each scenario: a) temperature threshold = −8 °C; b) temperature threshold = −15 °C.*

4 Discussion of uncertainties

It is acknowledged that there are a number of uncertainties associated with these results. These relate to both the forcings going into the models (discussed extensively in Lord et al. 2019, Sections 2.1.1 and 2.1.2), particularly atmospheric CO_2 (as uncertainties concerning orbital parameters are negligible), and uncertainties concerning the methodology such as assumptions over the carbon cycle response, the methods used to update atmospheric CO_2 during glacial periods and the relatively simplistic nature of the CGSLM (discussed extensively in in Lord et al. 2019, Section 5.4). In addition, although we have fully explored in this study the uncertainties associated with uncertain parameters in the CGSLM, there are other uncertainties that have not been explored. In particular, we have only used one climate model, and therefore have not fully explored structural uncertainty in the predictions. Nevertheless, evaluation of the model against reconstructions from the geological past (e.g. Lord et al. 2017), allows the level of confidence in the results of the present study to be assessed. Moreover, in addition to the work presented here, a comprehensive quality assurance exercise was conducted, to identify and eliminate any errors (see Appendix C).

5 Summary

In this report, an extension to Lord et al. (2019) is presented, now including all 90 ensemble members of the GCSLM input to the statistical emulator and therefore providing an envelope of possible futures in which the climate at Forsmark is modelled to sit over the next one million years. The results firstly focused on the evolution of three key climate variables from the emulator, secondly on the level of agreement between the ensemble members, and lastly on the likely onset of the next full glacial period.

The SAT results from the emulator, either globally or locally over Forsmark (downscaled or not), suggest that, in an increasingly warming world, the onset of the next glacial period is pushed significantly later, with all ensemble members suggesting that this would be over 200 ka AP in the highest emission scenario. In contrast, assuming no anthropogenic emissions (i.e. the natural scenario), virtually all ensembles suggest that the onset of the next glacial period will occur before 100 ka AP. The same is true for variables relating to hydroclimate, with both Forsmark precipitation (downscaled or not) and evapotranspiration showing changes that become later and later under the higher emission scenarios. The increase in SAT between ~400–500 ka AP, which is noticeable in all emissions scenarios and all of the variables both globally and at Forsmark, suggests a return to stable warm conditions for approximately 100 ka, before again becoming more variable and switching between cold and intermediate conditions. There is a clear divide between the warmer and colder ensemble members for the first 500 ka AP, because some ensemble members do not predict a cold state until well after this. After 500 ka AP, most scenarios suggest intermittent returns to a cold period, however the higher CO_2 scenario has several ensemble members still suggesting PI (i.e. interglacial) conditions, even after 800–900 ka AP.

Concerning the level of agreement between the ensemble members, the results suggest, as with the above results, that under the warmer scenarios the duration of interglacial conditions gets longer, and even when intermediate glacial conditions do develop, they do not develop in all ensemble members and the percentage of members that agree on this decreases as the scenarios get more extreme. Likewise, the percentage of ensemble members showing full glacial conditions decreases as the scenarios show higher emissions, suggesting that even when a full glacial is predicted, it is only done so in a limited number of ensemble members. A similar observation is shown when various thresholds of emulated SAT is used to define the climate regime (Figure 3-4), with comparatively warmer conditions getting longer under the higher emission scenarios, and even when colder conditions are predicted, this is only the case in a limited number of ensemble members.

Concerning a possible onset of the next full cold state, the results suggest that, as the scenarios show higher emissions (i.e. warmer), the onset of the next full glacial (or extremely cold regime, as defined by temperature thresholds) period recedes further into the future, and the percentage of ensemble members showing this transition takes longer to increase (i.e. until they are all in agreement).

In conclusion, and despite the above uncertainties, a clear message can be drawn from these results: warm (and wet) interglacial-style conditions will persist for longer as the scenarios of future climate change (primarily CO_2-driven) show higher emissions, and the transition into colder, glacial-style conditions is pushed significantly later. Under the higher emission (i.e. warm) scenarios, even when this transition does occur, it is only occurring in a limited number of the emulator's ensemble members, with the rest suggesting continuing warm conditions.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.com/publications.

IAEA, 2020. Development of a common framework for addressing climate and environmental change in post-closure radiological assessment of solid radioactive waste disposal. IAEA-TECDOC-1904, IAEA, Vienna.

Laskar J, Robutel P, Joutel F, Gastineau M, Correia A C M, Levrard B, 2004. A long-term numerical solution for the insolation quantities of the Earth. Astronomy & Astrophysics 428, 261–285.

Lord N S, Crucifix M, Lunt D J, Thorne M C, Bounceur N, Dowsett H, O'Brien C L, Ridgwell A, 2017. Emulation of long-term changes in global climate: application to the late Pliocene and future. Climate of the Past 13, 1539–1571.

Lord S N, Lunt D J, Thorne M, 2019. Modelling changes in climate over the next 1 million years. SKB TR-19-09, Svensk Kärnbränslehantering AB.

Posiva, 2020. Modelling changes in climate over the next 1 million years. Posiva 2019-04, Posiva Oy, Finland.

SKB, 2011. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. SKB TR-11-01, Svensk Kärnbränslehantering AB.

Appendix A

Additional figures (CGSLM)

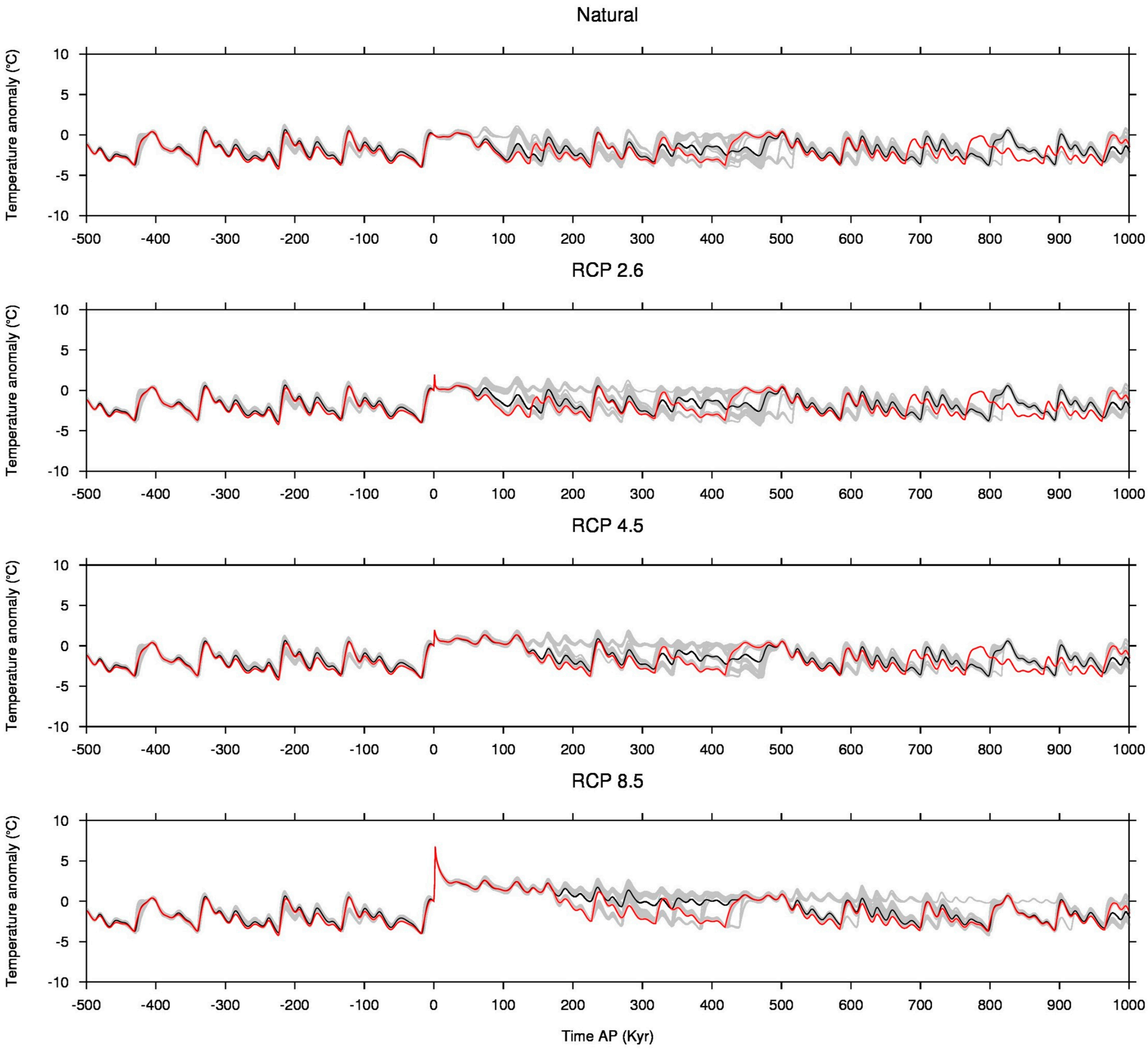

Figure A-1. *Timeseries of global mean annual SAT anomaly (°C) from the CGSLM for the last 500 ka and next 1 Ma, for all 90 ensemble members, for each scenario. Grey lines show individual ensemble members, black line shows ensemble mean, red line shows the ensemble member used in the previous report (Lord et al. 2019).*

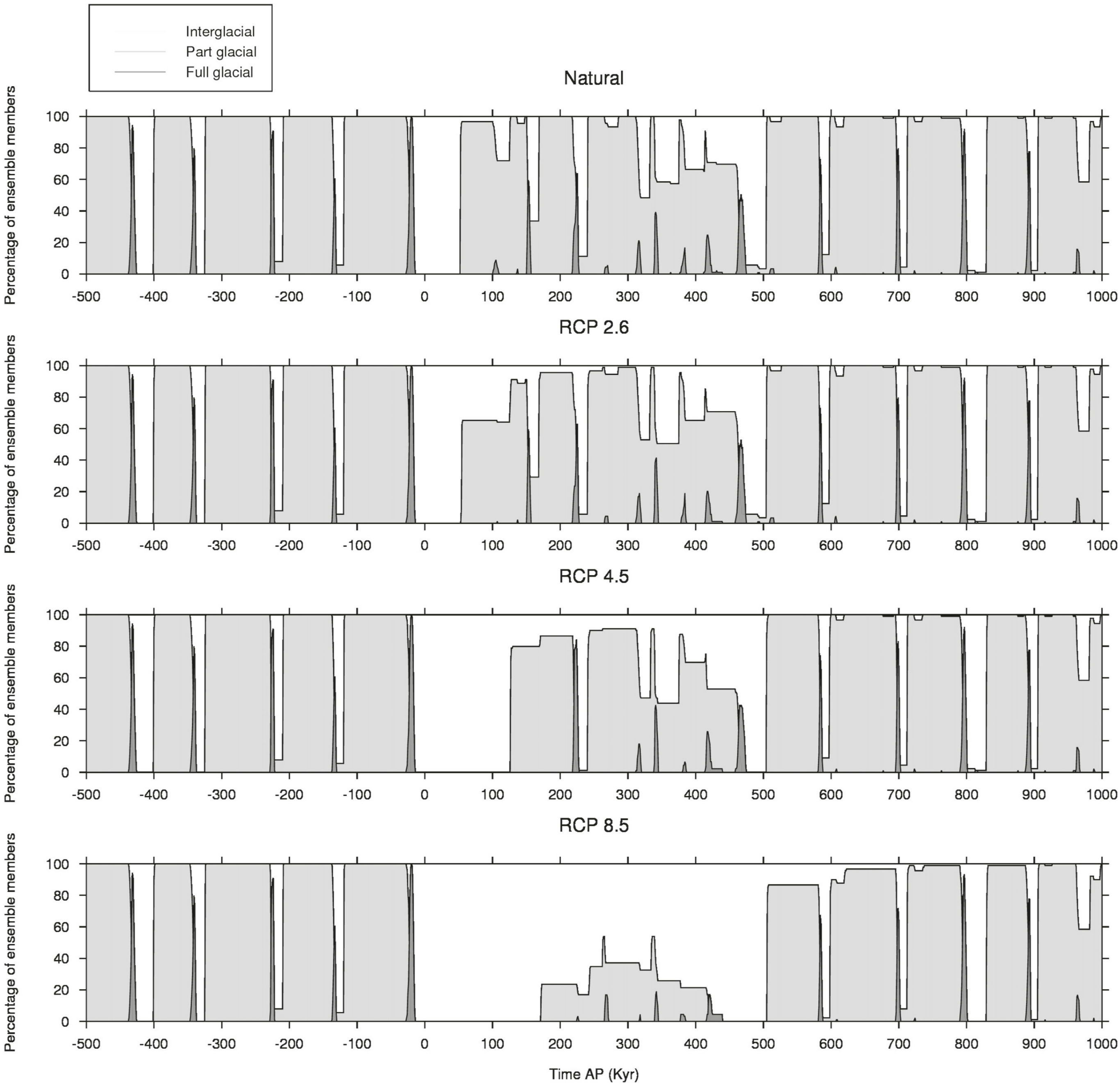

Figure A-2. *Percentage of ensemble members going into a glacial state (either interglacial, part glacial or full glacial), based on climate state output from the GCSLM for the last 500 ka and next 1 Ma, for all 90 ensemble members, for each scenario.*

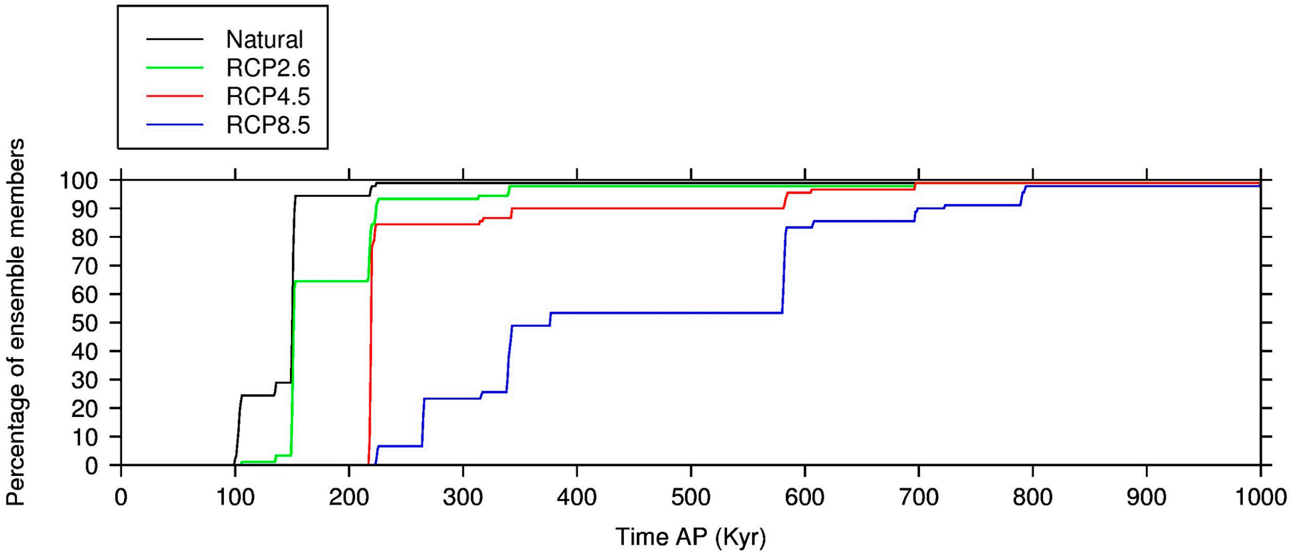

Figure A-3. *Timeseries of cumulative ensemble members (percentage of total) going into a glacial state, based on climate state output from the GCSLM for the next 1 Ma, for all 90 ensemble members, for each scenario.*

Appendix B

Additional figures (emulator)

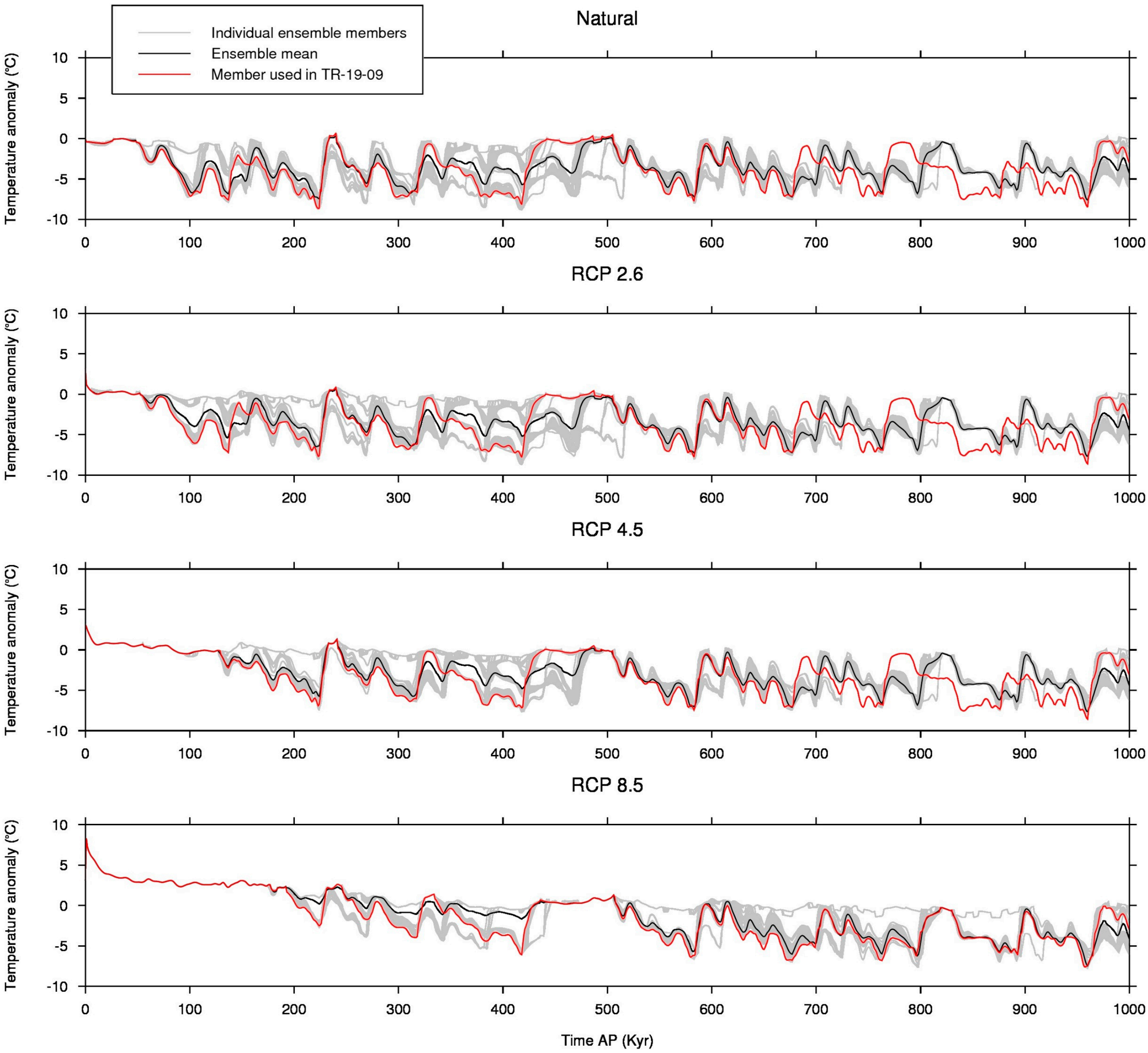

Figure B-1. *Timeseries of non-downscaled emulated global mean annual SAT anomaly (°C) for the next 1 Ma, for all 90 ensemble members, for each scenario. Grey lines show individual ensemble members, black line shows ensemble mean, red line shows the ensemble member used in the previous report (Lord et al. 2019, Figure 4-1).*

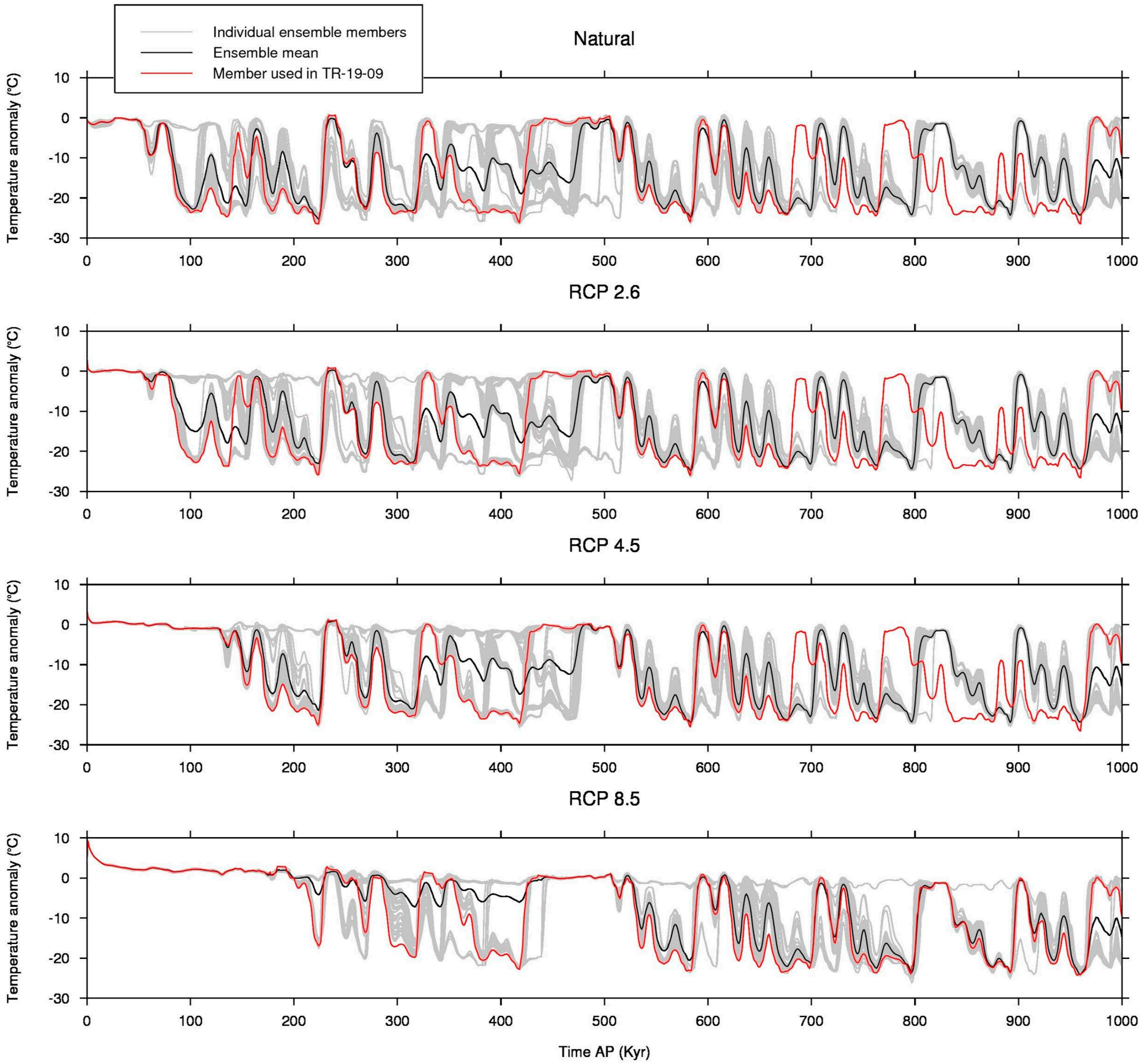

Figure B-2. *Timeseries of non-downscaled emulated mean annual SAT anomaly (°C) for the next 1 Ma at the Forsmark site, for all 90 ensemble members, for each scenario. Grey lines show individual ensemble members, black line shows ensemble mean, red line shows the ensemble member used in the previous report (Lord et al. 2019).*

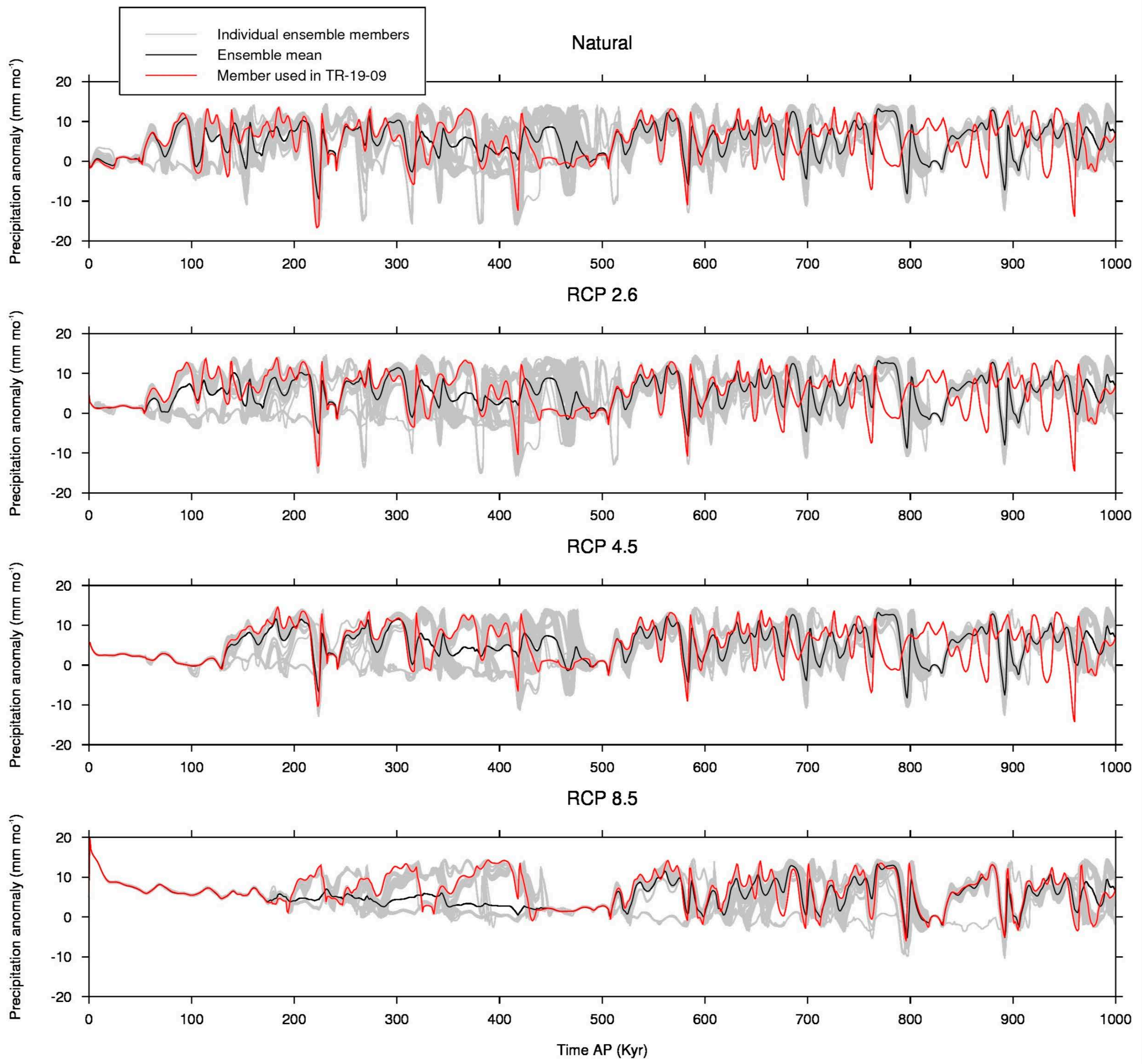

Figure B-3. *Timeseries of non-downscaled emulated monthly mean precipitation anomaly (mm mo^{-1}) for the next 1 Ma at the Forsmark site, for all 90 ensemble members, for each scenario. Grey lines show individual ensemble members, black line shows ensemble mean, red line shows the ensemble member used in the previous report (Lord et al. 2019).*

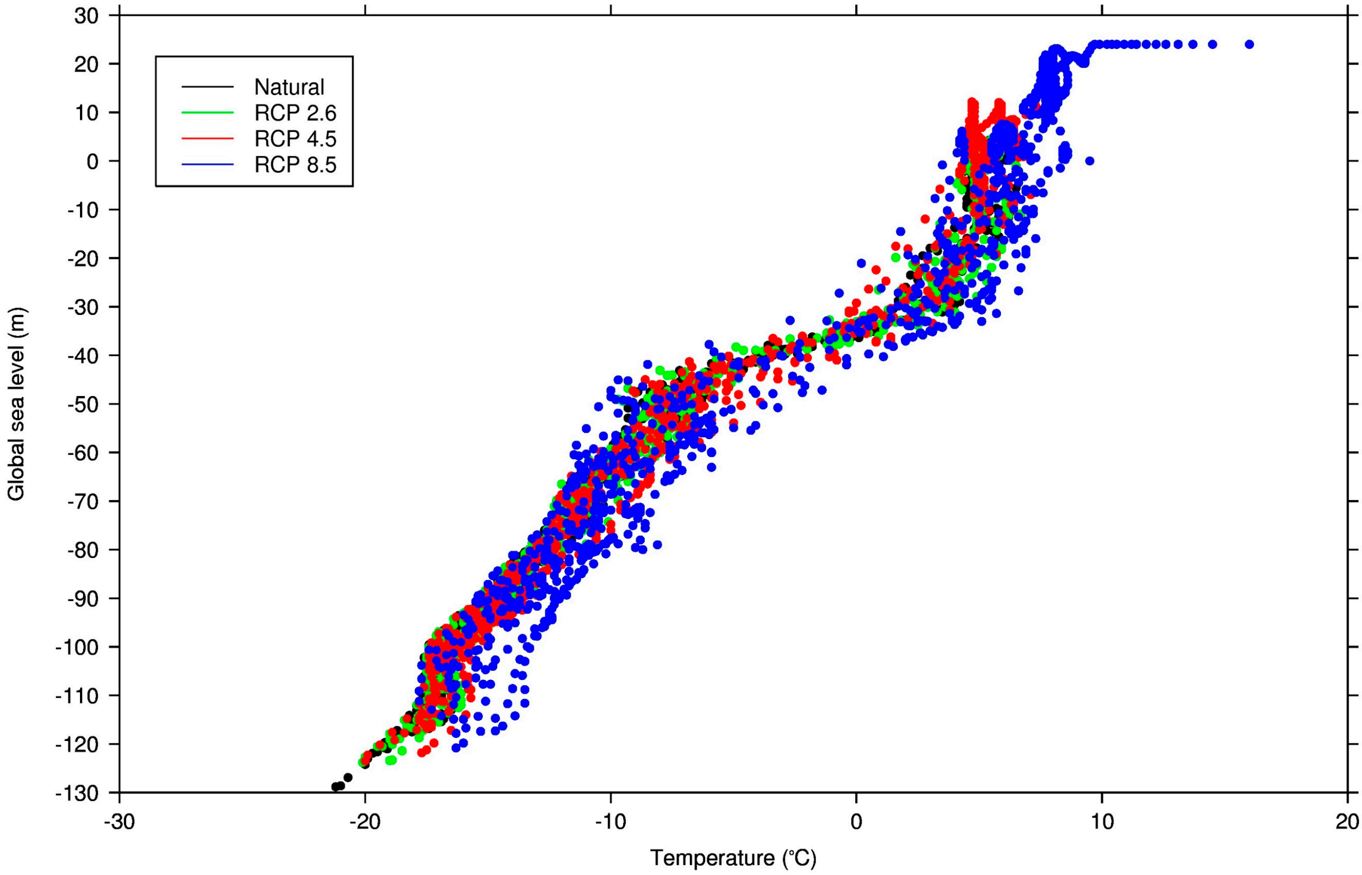

Figure B-4. *Scatterplot of downscaled emulated mean annual SAT (°C) at the Forsmark site versus global sea level (m) from the CGSLM, for the next 1 Ma, for each scenario and based on the ensemble member used in the previous report (Lord et al. 2019). Individual dots represent 1 ka.*

Appendix C

Quality assurance

The following quality assurance was undertaken, divided into three sections: i) Checking and improvement of code; ii) Qualitative checking of figures; and iii) Quantitative checking of data.

Checking and improvement of code

1. Removed all unnecessary comments from emulator code, and created more useful comments (searchable via "CW"). The code for the CGSLM, emulator and downscaling (in addition to the sensitivity experiments discussed below) are archived on GitHub at https://github.com/ATK-A/PosivaSKB.
2. Edited emulator code, replacing much of the repetition (e.g. writing out the data) with loops.
3. Automated process of running the emulator code i.e. it can now be started just once, and reads through all 9 variables for all 90 ensemble members, outputting results into individual and separate directories.
4. Modified emulator code to write out downscaled emulated precipitation data as text files.

Qualitative checking of figures

1. Ran original version of code (i.e. containing identified bug) and compared plots with original versions created by N. Lord (i.e. figures included in Lord et al. 2019). All figures are qualitatively the same.
2. Ran new version of code (i.e. without bug) and compared plots with new versions created by A. Kennedy-Asser (i.e. figures included in updated version of Lord et al. 2019). All figures are qualitatively the same.
3. Visualised climate state data coming out of CGSLM with that produced by A. Kennedy-Asser (i.e. using new version of code and included in updated version of Lord et al. 2019), but using different programming language to that used to create figures in updated version of Lord et al. (2019) (Matlab and R were used to create figures in the updated version of Lord et al. 2019, IDL was used here). Figures are qualitatively the same.
4. Visualised data coming out of emulator for three variables (temperature, precipitation and evapotranspiration) but using different programming language to that used to create updated version of Lord et al. (2019) (Matlab and R were used to create figures in the updated version of Lord et al. 2019, IDL was used here). Compared these figures with updated report (for temperature and precipitation), and they are qualitatively the same.
5. Visualised downscaled emulator data (both temperature and precipitation) and compared "corrected ensemble member" with new figures created by A. Kennedy-Asser (used in updated version of Lord et al. 2019). All figures are qualitatively the same.
6. Checked (qualitatively) report figures to make sure results look sensible. For example, in Figure 3-1, that the beginning of the SAT timeseries becomes gradually warmer under the higher emission scenarios (i.e. ~5 °C in the natural scenario, ~7.5 °C in RCP 2.6, ~9 °C in RCP 4.5 and ~15 °C in RCP 8.5). Likewise, in Figure 3-2, that the beginning of the precipitation timeseries becomes gradually wetter under the higher emission scenarios (i.e. ~40 mm month^{-1} in the natural scenario, ~45 mm month^{-1} in RCP 2.6, ~50 mm month^{-1} in RCP 4.5 and ~60 mm month^{-1} in RCP 8.5). Likewise, in Figures 3-4 and 3-5, that the percentage of ensemble members agreeing on (or remaining in) the warmest regime's conditions becomes gradually later under the higher emission scenarios (i.e. in Figure 3-4, Regime 1 persists for ~50 ka in the natural scenario, ~90 ka in RCP 2.6, ~150 ka in RCP 4.5 and > 200 ka in RCP 8.5).

Quantitative checking of data

1. Following removal repeated lines and replacement with loops (see above), checked raw data output against original (i.e. using repeated lines) and they are numerically identical.
2. Following automation process (see above), checked raw data output against original (i.e. without automation) and they are numerically identical.
3. Ran original version of code (i.e. containing identified bug) and compared data (both numerically and visually) with original versions created by N. Lord. All data (for all 9 variables, and all scenarios) are identical to 1 decimal place. Beyond 1 decimal place the results differ (by ~0.02), but this is just due to rounding errors, and can be corrected if the same level if rounding error in input is used (i.e. results are then numerically identical).
4. Ran new version of code (i.e. without bug) and compared data (both numerically and visually) with new versions created by A. Kennedy-Asser. Almost all (95 %) data (for 2 variables, and all scenarios) are identical to 1 decimal place. Beyond 1 decimal place the results differ (by ~0.02), but this is just due to rounding errors, and can be corrected if the same level of rounding error in input is used (i.e. results are then numerically identical).
5. Compared global annual mean temperature from the emulator with global mean temperature from the CGSLM, for all scenarios and all ensemble members. Temporal variation and patterns are qualitatively the same, and quantitatively the results are within 6 °C at all times.
6. Calculated global/local means from gridded temperature data (written out as netcdf), then compared these with global/local means written out as text files. Results are numerically identical.

Arkitektkopia AB, Bromma, 2022

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

skb.se