

We want to thank the reviewers for their constructive suggestions and comments. We have responded to their points below. The reviewers comments are in black and our responses in indented blue italic text. A marked-up version of the manuscript showing the changes we have done follows after that.

5 **Anonymous Referee #1**

This is a completely rewritten paper that compares the climate response to 1.5C and 2.0C global mean warming in uncoupled, slab-ocean and fully coupled simulations with the NorESM model. Compared to the previous version, the manuscript has greatly improved featuring 1) a more focussed approach, 2) the inclusion of fully coupled simulations and 3) a clearer motivation for using the slab-ocean version of the model. I appreciate the efforts that went into this. I do have, however, major and minor concerns that the authors should address before I can recommend publication of this manuscript.

General:

1) The paper focusses on 'the role of ocean and sea-ice feedbacks', implying that the difference in response between the model versions is only due to the fact that feedbacks are allowed in the slab ocean and fully coupled version and not allowed in the AMIP version. An important aspect that is not elaborated on however is the fact that the prescribed SST and SI fields in the AMIP runs are taken from the CMIP5 multi-model mean (more specifically: the HAPPI-mip protocol), and not from the coupled NorESM model. If the AMIP boundary conditions were taken from the coupled NorESM model instead, the difference between the coupled and uncoupled response and hence the 'role of ocean and sea-ice feedbacks' would presumably be substantially smaller (this could be tested). My guess is that the larger polar amplification in the coupled model is not because ocean and sea-ice feedback amplify the polar amplification, but simply because of the fact that the coupled NorESM has a larger polar amplification than the multi-model mean of the CMIP5 models (the boundary conditions of the AMIP model). This puts into question the authors' interpretation of results, in particular the importance of ocean and sea ice feedbacks in explaining the response difference between the different model versions. I don't think this is a show-stopper. Documenting the difference in response between AMIP, SO and fully coupled model versions is a usefull excersize, but I do have concerns regarding the attribution of this differences to coupled ocean and sea ice feedbacks.

This is a valid point — many thanks for pointing it out! To assess whether the Arctic amplification in NorESM1-Happi is indeed larger than the CMIP5 multi-model mean (used for calculating SSTs for HAPPI), we have computed the polar amplification factor (PAF) for several RCPs, including RCP2.6, using the CMIP5 models that were used to create the SST increments for the AMIP runs, and the corresponding simulations from NorESM1-Happi. The results show that the PAF for NorESM1-Happi is indeed in the upper range of the CMIP5 responses. We have added a figure showing this (Figure 8 in the revised manuscript), along with discussion both in the results section and in the summary and discussion section.

It is now clearly stated that though they may be a contributing factor, the feedbacks are not the sole contributors to the differences between the AMIP and the SO and fully coupled simulations. We have toned down the focus on sea-ice and ocean feedbacks in the abstract, introduction, and summary and discussion. We have also changed the title from “The NorESM1-Happi used for evaluation the role of ocean and sea-ice feedbacks under global warming of 1.5°C and 2.0°C” to “Arctic amplification under global warming of 1.5°C and 2.0°C in NorESM1-Happi”.

2) While I appreciate the addition of the fully coupled simulations, the authors have not included a description of how the scenarios for these simulations were constructed (section 2.2). How was it determined that the combination of RCP2.6 forcings and the adjusted CO2 evolution would result in global mean temperature stabilization? What was the physical reasoning behind these choices? Sanderson et al. (2017) constructed the scenario using an emulator, Sigmond et al. (2018) established stabilization by switching off all anthropogenic emissions, but how did you determine the scenario?

The details of the fully coupled scenarios were determined through an iterative trial-and-error process. We have added more description of how the scenarios were constructed in the revised manuscript.

3) I find the structure of sections 2-4 non-intuitive. I would make this one section with section 2.1 describing the model and section 2.2 describing the model versions.

We have restructured sections 2–4. Now the description of the model comes first (including the slab-ocean version), followed by the section about the CMIP5 experiments and then the 1.5 K and 2.0 K warming experiments.

5 **Other:**

4) There are still quite a number of typos, e.g. P. 1, p. 25: increase --> increases, P. 1, p. 29: it-->is, p. 2:l. 10: is to presented --> is to be presented

Sorry about this. We have corrected the mentioned typos and proofread the manuscript.

10

5) l. 22: The combination of 'Compared to the AMIP runs' and 'relative to the present day climate' is confusing. Perhaps remove 'relative to the present day climate' ?

This sentence has been rewritten.

15

6) p. 2, l. 29, p. 6, l. 9 and p. 19 l. 14: An other relevant paper that should be cited here is doi: 10.1038/s41558-018-0124-y who performed 1.5C and 2.0C stabilized warming simulations with a coupled model, by switching off all anthropogenic emissions in a 'free-CO2' mode

20

We are aware of this reference and already cited it a few times (p 17 l 14 and p 19 l 7 in the previous version of the manuscript). The reviewer is however correct in that it is relevant in other places as well and it has been added where suggested.

25

7) p. 4, line 24: 'specific to our set-up': a bit confusing, this suggests that the points listed below this statement are specific to the NorESM model and hence differ from the standard HAPPI specifications, but I don't think that is meant by the authors

We agree that this is confusing. The description of the set-up includes the treatment of the sea-ice thickness which is not a part of the HAPPI protocol, and is as such is specific to the set-up of the HAPPI experiments in the NorESM. To make this clearer, we have removed the “specific to our statement” statement and taken the part about sea-ice thickness out of the bullet list, so that the list only includes the standard HAPPI specifications. The part about sea-ice thickness now directly follows the list in a separate paragraph.

8) p. 6, l. 3: please also include the warming relative to the preindustrial run.

CPL-15 is 1.51 K warmer than pre-industrial conditions and CPL-20 is 1.97 K warmer. This is now stated in the revised manuscript.

9) p. 6, l. 28: Here is should be noted why the authors did not use the AMIP-15 and AMIP-20 boundary conditions to calibrate the SO model. If they had chosen that, the difference between the AMIP and SO responses (and hence the assessment of the importance of atmosphere-ocean feedbacks) would be much smaller (see my comment #1). Also, on p. 10, l. 29-30 the authors state that 'The experiments with NorESM1-HappiSO are designed to be comparable to the NorESM1-HappiAMIP experiments'. Based on this statement it would more sense to me to use the AMIP-PD, AMIP-15 and AMIP-20 fields as an input to the calibration.

The increments could alternatively be taken from the AMIP experiments and we have attempted to do this, but this resulted in strong changes in the Hadley circulation and in the jets during winter and spring for reasons we do not fully understand. This behavior is not seen in the AMIP runs and might not be realistic. Therefore, we use SST increments from the fully coupled runs rather than from the AMIP runs to make sure that the increments are consistent with the climate response of the coupled system in the model. This is now stated in the revised manuscript.

10) p. 9, l. 28: 'SST is (in this connection) the mixed-layer temperature: I suggest changing the notation to something like T_{mix}. Also, SST_{ext} should be defined here, and not later in the paper.

For consistency, we have changed the notation of the mixed-layer temperature to T_{mix} , and the corresponding external field to T_{mixExt} . However, we also note in the text that in this version of NorESM, the mixed-layer temperature and sea surface temperature are equal. Therefore, we can still use observed SST as an external field during the calibration phase. We have also moved the definition of so T_{mixExt} . It is now defined in the first paragraph following equation 1.

11). section 4.1: I think find this a bit confusing, it would make more sense if in p. 10 l. 16 alpha is not set to 0 (is this a typo?).

You are correct, this is a typo and has been corrected. We have added the missing constants in equation (1) such that $\alpha = 1$ is the natural choice during calibration.

12) p. 11, l. 9: It may be useful for the reader to include here an explanation for why the AMIP forcing agents are used in the SO runs, and not those used in the coupled runs (with the adjusted CO2 concentrations).

The purpose of the SO runs is to have experiments where the sea ice is free to respond to the imposed changes, but that otherwise are as similar as possible to the AMIP experiments. Furthermore, while the SO-model runs are estimating differences between states in equilibrium, the coupled runs are evolving with time. Therefore, the forcings are as far as possible the same as for the AMIP experiments, with the exception that the SST increments are from the fully coupled run (see reply to comment 9).

13) p. 12, l. 5: I'm not sure how the smaller 1.5K-PD and 2.0K-PD differences can be explained by a cold bias in PD? Shouldn't the cold bias in the PD cancel out in the response? The 1.5K, 2.0K and PD are all expected to suffer from a cold bias, correct? (the same applies to p. 14, l. 1-3)

It is well established that the model has a tendency to produce a too cold climate compared to observations and re-analyses. This is also shown in the supplement, and we also relate this to underestimated cloudiness and the strong Atlantic Meridional Overturning Circulation, which efficiently transfers heat into the deep ocean, leaving less for atmospheric temperature increase. (See Tables S3 and S4 and Figures S5, S7 and S14 in the supplement, and Figures 3 and 4 in the main paper.) We have slightly expanded on this discussion in the paper.

Note that biases can vary between different climate states in the same model version, so one cannot simply assume that they will cancel out when computing the differences between the warmer climates and the present-day climate. A in-depth discussion of the potential state-dependence of the biases in the model is, however, beyond the scope of the study.

14) Fig. 18: The observational estimates (presumably shown by 'solid black contours'), are unclear. They are hardly visible and it is not clear what the contour levels are. It's probably better to show the observations in separate panels. Also, there seems to be something wrong with the colors in panels e, f, i, j, with positive ($>+2.5\%$) responses all the way down to the UK.

We agree that the observations were hard to see, and have adjusted the color scale for the model fields to better show the observations. Contour intervals for the observations are the same as for the model. We have not opted to show the observations in a separate panel, as we feel this would make it more difficult to compare the observations with the fields from the models. Also, by an incurie, the same observational month was shown in both March and September; this has been corrected.

The contour intervals in panels e–l was not consistent with the colorbar in panels e, f, i, and j, which resulted the figures indicating increased sea ice concentration in large areas. Now, this has been corrected and panels e–l all have the same contour intervals.

15) Section 8: The last 2 column of table 4 should be discussed here (not in section 5). What are the observed mean values of Sea ice extent/area, and how do they compare to the CLP-PD and SO-PD values? Fig. 19 suggest to me that the interannual variability in the coupled model is biased low.

5 *We prefer to keep some of the discussion of table 4 in section 5 (now section 4), but we now also discuss it in section 8 (now section 7). We have also added observed mean values of sea-ice extent and a discussion of these in section 8. The interannual variability in the coupled model is lower than in the SO model, but this is likely due to the sea-ice cover being too thick in the former case. We now discuss this in section 8. We identified an error in Figure 19 (now*
10 *Figure 20), this is now corrected and does not affect the interpretation of the results.*

16) p. 17, l. 3 and l. 11: In line 3 it is noted that the SO has too little sea ice. This suggest that the ice-free frequencies under warming would be overestimated, correct? If yes this should be noted/discussed in lines 12-14.

15 *The reviewer is correct, we now discuss this in connection with Figure 19.*

Anonymous Referee #2

The paper is much improved from before, and now reads in a coherent way, and is far less confusing, so I'd recommend minor corrections. The only thing I think needs clearing up is the key messages they are trying to get across. At the moment, I think the novelty of the paper is in comparing
5 atmospheric dynamics across three different model setups, (which are an atmosphere-only, a slab-ocean, and a fully coupled model version), in the context of future projections. However, reading the paper, I believe the authors are putting more emphasise on the scientific understanding of these dynamical events, from single model experiments, rather than the differences between experimental setups. This is dangerous, and many of the features they report on (blocking etc), have significant
10 biases, and there is a body of research suggesting that multi-model studies are needed to look at these.

In summary, I would suggest that the authors rework the abstract, discussions, and a little bit of the intro, to highlight more clearly that they are looking at how these different experimental setups can change the atmospheric dynamic responses in the model. I also suggest they play down a little bit the
15 reported numbers, on, say the latitudinal gradients etc

*We agree with the reviewer and have toned down the focus on the ocean and sea-ice feedbacks in the abstract, introduction, and summary and discussion and in the title. We have added a paragraph to the summary and discussion emphasizing that differences between the AMIP
20 experiments and the experiments with an active ocean model are affected by the experimental set-ups. We have also removed the numbers for the relative changes in the polar amplification factor from the abstract. (See also response to reviewer 1's general remark 1.)*

*The reviewer is correct that there are large biases in the blocking frequency, and we clearly
25 state in several places that the results are generally inconclusive. While multi-model studies are absolutely needed, we still feel that it is worthwhile to report results from individual models.*

~~The “NorESM1-Happi” used for evaluating the role of ocean and sea-ice feedbacks~~Arctic amplification under global warming of 1.5 °C and 2 °C in NorESM1-Happi

Lise S. Graff¹, Trond Iversen^{1,2}, Ingo Bethke³, Jens B. Debernard¹, Øyvind Seland¹, Mats Bentsen^{4,3}, Alf Kirkevåg¹, Camille Li^{3,4}, Dirk J. L. Olivié¹

¹Norwegian Meteorological Institute, P.O. Box 43, Blindern, 0313 Oslo, Norway

²Dep. of Geosciences, University of Oslo, P.O. Box 1047 Blindern, 0315 Oslo, Norway

~~³Uni Research Climate, Bjerknes Centre for Climate Research, P.O. Box 7810, 5020 Bergen, Norway~~

~~^{3,4}Geophysical Institute, University of Bergen, Bjerknes Centre for Climate Research, P.O. Box 7803, 5020 Bergen, Norway~~

~~⁴NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, P.O. Box 22 Nygårdstangen, 5838 Bergen, Norway~~

Correspondence to: Lise S. Graff (lise.s.graff@met.no)

Abstract. Differences between a 1.5 K and a 2.0 K warmer climate than 1850 pre-industrial conditions are investigated using a suite of uncoupled (AMIP), fully coupled, and slab-ocean experiments performed with ~~the~~ NorESM1-Happi, an upgraded version of NorESM1-M. The data from the AMIP-type runs with prescribed sea-surface temperatures (SSTs) and sea ice ~~from the NorESM1-Happi~~ were provided to a model intercomparison multi-model project (HAPPI, <http://www.happimip.org/>). This paper compares the AMIP results to those from the fully coupled version and the slab-ocean version of the model (NorESM1-HappiSO) in which SST and sea ice are allowed to respond to the warming, focusing on ~~the role of ocean and sea ice feedbacks and~~ Arctic amplification of the global change signal.

The fully coupled and the slab-ocean runs generally show stronger responses than the AMIP runs in the warmer worlds. ~~Arctic amplification of the change in near surface temperature is larger in the runs with active ocean models. Compared to the AMIP runs, t~~The Arctic polar amplification factor is ~~54 % and 27 %~~ stronger in the fully coupled and slab oceanSO 1.5 K runs than in the AMIP runs, both in the 1.5 K warming ~~run runs relative to the present day climate, and 46 % and 19 % stronger~~ with the additional 0.5 K warming. The low-level equator-to-pole temperature gradient consistently weakens more between the present-day and the 1.5 K warmer climate in the experiments s with an active ocean components~~ss~~. The magnitude of the upper-level equator-to-pole temperature gradient increasess in a warmer climate, but is not systematically larger in the experiments with an active ocean components~~s~~. Implications for storm-tracks and blocking are investigated. We find~~There are~~ considerable reductions in the Arctic sea-ice cover in the slab-oceanSO model runs; while

ice-free summers are rare under 1.5 K warming, they ~~are estimated to~~ occur 18 % of the time ~~under in the~~ 2.0 K warming simulation. The fully coupled model does not however reach ice-free conditions as it too cold and has too much ice in the present-day climate.

1 Introduction

In *The Paris Agreement*, the parties to the United Nations Framework Convention on Climate Change (UNFCCC) established a long-term temperature goal for climate protection of “holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change” (UNFCCC, 2015). This has triggered considerable attention from climate modelling groups and researchers alike (e.g. Hulme, 2016; Peters, 2016; Rogelj and Knutti, 2016; Mitchell et al., 2016; Anderson and Nevins, 2016; Boucher et al., 2016; Schleussner et al., 2016; and the special issue of the electronic journal *Earth System Dynamics*: https://www.earth-syst-dynam.net/special_issue909.html). The Special Report from the Intergovernmental Panel on Climate Change (IPCC) ~~was published~~is to be presented in October -2018 (<http://www.ipcc.ch/report/sr15/>).

In addressing differences in the climate impacts of the 1.5 K and 2 K global warming targets~~st~~ (we use the word “targets”, although “upper bounds” would be more correct), there are two basic weaknesses of the available climate projections from the Coupled Model Intercomparison Project (CMIP) as reported in the assessment reports from the Intergovernmental Panel on Climate Change (IPCC). There is a small body of research assessing impacts of 1.5 K warming compared to that for higher emission scenarios (James et al., 2017). The CMIP simulations are moreover generally designed on the basis of development scenarios that give rise to ~~a~~ certain top-of-the-model-atmosphere (TOA) radiative forcings, rather than selected temperature targets. Because different models simulate different responses of global, near-surface temperature to a given TOA radiative forcing, new types of model simulations are necessary to provide a scientifically-based evaluation of climate statistics for specific temperature targets.

Under the acronym *HAPPI* (Half a degree additional warming, prognosis and projected impacts, <http://www.happimip.org/>), Mitchell et al. (2017) provided an experimental framework for model simulations of the present-day climate and climates that are 1.5 K and 2.0 K warmer than the pre-industrial. The experiments are similar to those under the Atmospheric Model Inter-comparison Project (AMIP) protocol, employing active atmosphere and land components from state-of-the-art coupled Earth System Models (ESMs) and prescribed sea-surface temperatures (SST) and sea ice. A multi-model ensemble with several hundred members was produced, enabling robust statistics for flow changes and rare events (e.g. Baker et al., 2018; Barcikowska et al., 2018; Li et al., 2018; Liu et al., 2018; Senerivatne et al., 2018; Wehner et al., 2018).

Using a different approach, Sanderson et al. (2017) Warming of 1.5 K and 2.0 K has also been investigated in fully coupled models. Sanderson et al. (2017) developed and applied an emulator to arrive at forcing scenarios that would produce global warming of 1.5 K and a 2 K above the pre-industrial levels in a model-simulated stable climate the Community Earth System Model version 1 (CESM1; Hurrell et al., 2013). Sigmond et al. (2018) created scenarios by first running the representative concentration pathway scenario corresponding to an increased radiative forcing of 8.5 W m^{-2} by the end of the 21st century (RCP8.5; van Vuuren et al., 2011) and then branching off the 1.5 K and 2.0 K warming experiment when the near-surface temperature warming was 1.5 K and 2.0 K relative to pre-industrial conditions, setting the emissions of anthropogenic CO₂ and aerosols to zero. Both Sanderson et al. and Sigmond et al. They carried out century-scale ensemble simulations with the fully coupled Community Earth System Model version 1 (CESM1; Hurrell et al., 2013). One striking result from these studies is the strong increase in the probability of having an ice-free Arctic Ocean in the summer with the additional 0.5 K warming (the difference between the 1.5 K and 2 K warming scenarios). This aspect of the response to the 1.5 K and 2.0 K warming ~~is was~~ not evident in the HAPPI experiments because the sea ice is prescribed, but will be further addressed in the present paper.

We use various configurations of the Norwegian Earth System Model, *NorESM1-Happi*, which is an upgraded version of the NorESM1-M used in CMIP5 (Bentsen et al., 2013; Iversen et al., 2013; Kirkevåg et al., 2013). The upgrades include double horizontal resolution and improved treatment of sea ice. The model was previously run in AMIP mode (*NorESM1-HappiAMIP*) to contribute a large ensemble of simulations to HAPPI. In order to study the role of ~~feedbacks associated with~~ the ocean and sea ice, we here provide fully coupled simulations targeting quasi-sustained global warming levels of 1.5 K and a 2 K above pre-industrial levels. The forcings are constructed on the basis of those from the ~~representative concentration pathway scenarios (RCPs; van Vuuren et al., 2011)~~ corresponding to an increased radiative forcing of 2.6 W m^{-2} and 4.5 W m^{-2} by the end of the 21st century (RCP2.6 and RCP4.5), but with important changes to the time evolution of the CO₂ concentrations. We also use a configuration where the full ocean model is replaced by a thermodynamic slab-ocean (SO) model (*NorESM1-HappiSO*). This configuration is ~~applied as~~ an intermediate option between the fully coupled (~~CPL~~) and the AMIP configurations, applied in order to partly correct for temperature biases in the fully coupled ~~CPL~~ simulations, but still allowing for SST and sea ice feedbacks.

The role of Arctic amplification for specific warming levels (Arrhenius, 1896; Manabe and Stouffer, 1980, Holland and Bitz, 2003, Feldl et al., 2017) is relevant for the consequences of the Paris agreement. This is primarily due to the associated in-situ changes in the sea-ice and snow-cover, but also due to the potential triggering of irreversible feedbacks, ~~such as~~ Other important feedbacks include changes in mid-latitude weather patterns and variability (Francis and Vavrus, 2012; Screen and Simmonds, 2013; Cohen et al., 2014; Screen, 2014; Barnes and Polvani, 2015; Screen and Francis, 2016; Screen, 2017a,b; Vihma, 2017; Screen et al., 2018; Cournou, et al., 2018).

Arctic amplification is predominantly driven by a positive regional lapse-rate feedback (negative at lower latitudes) in winter and a positive albedo feedback in summer (Winton, 2006; Pithan and Mauritsen, 2014). While the amplitude and pattern of Arctic amplification varies between models, it is nevertheless a robust response to global warming. Even the remotely localized forcing caused by reduced European sulphate aerosols since the 1980s produces maximum warming in the Arctic (Acosta Navarro et al., 2016). Under the CMIP6 protocol, a Polar Amplification Model Intercomparison Project (PAMIP) is endorsed (Smith et al., 2018).

In this paper, we focus on the Northern Hemisphere (NH) climate response to global warming of 1.5 K and 2 K above pre-industrial levels in the NorESM, and on how the response differs depending on whether the model is run with fixed SSTs and sea ice (as in HAPPI) or with active ocean and sea-ice models~~role of SST and sea-ice feedbacks. This includes~~We study changes in Arctic amplification, Arctic sea ice, ~~midlatitude~~ meridional temperature contrasts for different heights, and the storm tracks. We also consider blocking, although its representation in rather coarse resolution climate models is known to be of mixed quality (Dawson et al., 2012; Davini and D'Andrea, 2016; Woolings et al., 2018).

~~Section 2 describes the experiments in this paper.~~ Section 2.3 provides an overview of the NorESM1-Happi and its SO version NorESM1-HappiSO, along with a summary of ~~emphasizing the changes-differences between NorESM1-Happi and its predecessor since~~ NorESM1-M. ~~Section 4 provides a description of the slab ocean version NorESM1-HappiSO. The 1.5 K and 2.0 K warming scenarios are described in Sect. 3.~~ Results are presented in Sect. 4.5–7.8. A summary and discussion ~~is~~are given at the end in Sect. 7.9. A Supplement to the paper contains an extensive validation of NorESM1-Happi in line with the CMIP5 protocol.

~~2.1 The 1.5 K and 2.0 K warming scenarios~~

~~2.1.1 The AMIP experiments~~

~~The “AMIP experiments” are those performed with NorESM1-Happi for the multi-model HAPPI project. The target of the experiments is to investigate the regional impacts of global warming under stabilisation scenarios that are 1.5 K and 2.0 K warmer than the 1850 climate. The three large ensemble experiments are: the present decade (PD; 2006–2015), a climate that is 1.5 K warmer than the pre-industrial (1850) climate, and a climate that is 2.0 K warmer. We refer to these as the AMIP-PD, the AMIP-15, and the AMIP-20 experiments.~~

~~Designing a coupled model experimental protocol for 1.5 K and 2.0 K warming targets requires determining forcing conditions that will produce the target global mean temperature change, and other characteristics of the warmer climate state. The same forcing conditions may however produce different temperature responses in different models. The CMIP5 models for instance display considerable spread in the near surface temperature (2-m temperature) response to RCP2.6. While the multi-model mean response is very close to 2.0 K, the spread across the 95–5% range is approximately 1.5 K (see Fig. 2 in Mitchell et al., 2017). Fully~~

~~coupled models are moreover computationally expensive because they require centuries or longer to approach new equilibria after sustained shifts in the TOA radiation balance.~~

~~The experiments in the HAPPI project were therefore run with prescribed SSTs and sea ice. This constrains the climate state and makes it computationally feasible to run large ensembles. The experimental set-up resembles the AMIP protocol, thus we refer to the version of the NorESM1-Happi that follows the HAPPI protocol as NorESM1-HappiAMIP.~~

~~The construction of the input data for the HAPPI experiments is described in detail by Mitchell et al. (2017). The main points specific to our set-up are listed below:~~

- ~~• In the AMIP-PD experiment, the SST and sea-ice fields are based on observations (Taylor et al., 2012). Sea-ice thickness is fixed at 2 m in the NH and 1 m in the Southern Hemisphere (SH). Anthropogenic greenhouse gas (GHG) concentrations (including CO₂, CH₄, N₂O, and CFCs), emissions of aerosols and their precursors, ozone concentrations, and land use changes are taken from RCP8.5 for years 2006–2015, as it is common procedure to use RCP8.5 to extend the historical period beyond 2005 (van Vuuren et al., 2011).~~

- ~~• In the AMIP-15 experiment, anthropogenic GHG and ozone concentrations, land use and aerosols data are taken from RCP2.6 for year 2095. The SST increase relative to PD is the CMP5 multi-model mean difference between years 2091–2100 from RCP 2.6 and 2006–2015 from RCP8.5. Natural forcings are as for PD. Sea-ice concentrations are estimates from a linear regression between observed anomalies of SST and sea ice (see Mitchell et al., 2017 p. 575 for details).~~

- ~~• In the AMIP-20 experiment, the SST and sea-ice concentration differences are derived in a similar way, but using a weighted mean between RCP2.6 and RCP4.5 (0.41 for RCP2.6 and 0.59 for RCP4.5). The same weights are used for CO₂ (assuming a logarithmic relation). All other forcings are as for AMIP-15.~~

~~The NorESM1-HappiAMIP data set includes 125 ensemble members for each experiment, each of length 10 years (after a 1-year spin-up), giving 3750 years of data. To enable dynamical downscaling, output from 25 members of each experiment were stored with high temporal resolution. The data is available for download at <http://portal.nerse.gov/e20c/data.html>.~~

2.21.1 The fully coupled (CPL) experiments

~~One shortcoming of the AMIP-type simulations is that they neglect the effect of ocean and sea-ice related feedback mechanisms apart from the patterns included in the prescribed SST and sea-ice fields. These feedbacks are particularly important in the Arctic, where albedo and lapse rate feedbacks amplify the low-level temperature response relative to the global mean (Pithan and Mauritsen 2014; see also Fig. S14 in the Supplement).~~

To investigate the effect of such feedbacks, we have conducted 1.5 K and 2.0 K warming experiments (CPL-15 and CPL-20) with the fully coupled NorESM1-Happi. The forcings in the experiments are based on RCP2.6 and RCP4.5, but with important differences in the CO₂ concentration (Fig. 1). In CPL-15, the CO₂ concentration follows RCP2.6 from year 2000 to year 2095, after which it stays constant until year 2170, and then decreases following the pattern assumed in the original RCP2.6 from year 2095 onwards (i.e. the decrease is delayed 75 years compared to RCP2.6). In CPL-20, the CO₂ concentration follows RCP4.5 from year 2000 to year 2050, then stays constant until year 2170, after which it decays in the same fashion as CPL-15, but from the higher concentration level. The other GHGs and forcing-producing elements are as in RCP2.6.

The fully coupled present-day (CPL-PD) climate is represented by the 30-year time period 1991–2020 using output from the CMIP5 experiments carried out with NorESM1-Happi. We use the period 1991–2005 from three individual simulations of the historical climate (Hist1, Hist2, and Hist3; see Sect. 3.1 or Table S1 in the Supplement) and extend them with years 2006–2020 from three individual simulations of RCP8.5 (Sect. 3.1). Thus, CPL-PD, CPL-15, and CPL-20 are all sampled by 90 years of simulations with the fully coupled NorESM1-Happi.

The scenario runs CPL-15 and CPL-20 both start from simulation year 2005 of the Hist1 experiment. Figure 2 shows the change in near-surface temperature for Hist1 (1850–2005) and for CPL-15 and CPL-20 experiments (2006–2230) relative to the pre-industrial climate calculated under constant driving conditions valid for year 1850 (the piControl experiment, see Sect. 3.1 or Table S1). The global-mean temperature warms rapidly between years 1960 and 2050, then the response flattens out over the next 150 years. In what follows, we study results from the 90-year periods 2111–2200 for which the mean temperature increase in CPL-15 and CPL-20 is 0.69 K and 1.15 K relative to CPL-PD (see discussion of Table 3 in Sect. 5.1).

The experiments are, however, not entirely stabilized. By the end of the 22nd century, both CPL-15 and CPL-20 still have a positive radiative imbalance at the top of the model atmosphere (around 0.7 W m⁻², not shown) and a positive heat flux into the ocean at depths below 200 m (Fig. 3). The net heat uptake in the upper ocean is, however, small at that point. The Atlantic meridional overturning circulation (AMOC) decreases with time over the first 100 years and is relatively stable over the last 150 years (Fig. 4).

Our fully coupled experiments differ from those in Sanderson et al. (2017), who first used a climate emulator to construct concentration scenarios, and then used these scenarios to produce stabilized 1.5 K and 2.0 K with the CESM1. The simulations presented in this study are far from reaching equilibrated climate states, but are quasi-stable over 90-year periods after spinning up for 100 years from present day. Full equilibration over several centuries is likely to produce different climate states (Gillett et al., 2011).

2.31.1 The slab-ocean (SO) experiments

While results from the coupled simulations above will help us understand how 1.5 K and 2.0 K warming might manifest in the fully coupled earth system, CPL-15 and CPL-20 are not stabilized scenarios like the AMIP

experiments. Moreover, Fig. 5 shows that the fully coupled PD experiments (panels a, d, g, and j) exhibits larger biases than the AMIP experiments (panels e, f, i, and l) relative to ERA Interim (Dee et al., 2011) in all seasons. Prescribing the SSTs and sea ice to observationally based fields constrains the climate in the AMIP-PD experiments, yielding smaller biases in the simulated climate. To be able to examine 1.5 K and 2.0 K warming experiments in a model which has smaller biases, but where the sea ice and SSTs are also free to respond, we have designed a slab ocean configuration of NorESM1-Happi, NorESM1-HappiSO (see Sect. 4 for details).

We have conducted free-running SO experiments for the PD climate (SO-PD), and climates that are 1.5 K and 2.0 K warmer than the pre-industrial (SO-15 and SO-20). The SO model has been calibrated to mimic the three HAPPI experiments, using the same forcings for GHGs, aerosols, ozone, and land use. In SO-PD, the SSTs are constrained to stay close to the observed values from AMIP-PD. The SST difference for SO-15 and SO-20 are based on the SST response in CPL-15 and CPL-20 relative to CPL-PD for consistency with the model climate in the NorESM1-Happi. The SO model and the set up of the experiments are described in more detail in Sect. 4 and Table 2.

We carried out 150-year simulations for SO-PD, SO-15, and SO-20. After a spin up of 60 years, a new quasi-equilibrium is reached, leaving three equilibrated periods of 90 years each (270 years in total).

The biases in the near surface temperature for the present day climate are shown in Fig. 5b, e, h, and k (for the four seasons). While the biases are larger than those from AMIP-PD, they are still clearly reduced compared to CPL-PD. For instance, the global mean bias in NH winter (December, January, and February; DJF) is reduced by 35 % in the SO and 64 % in AMIP model compared to the fully coupled model.

3.2 The model

In this section, we give a brief overview of the fully coupled NorESM1-Happi, which is [an upgraded version of](#) NorESM1-M used for CMIP5 ~~with some upgrades~~. A more exhaustive overview of the NorESM1-M is given in Bentsen et al. (2013), Iversen et al. (2013), and Kirkevåg et al. (2013).

NorESM1-M is based on the fourth version of the Community Climate System Model (CCSM4) developed in the Community Earth System Model project at the US National Center for Atmospheric Research (NCAR) in collaboration with many partners (Gent et al., 2011).

The atmosphere component of the NorESM1-M and [NorESM1-Happi](#) is the “Oslo” version of the CCSM4’s Community Atmosphere Model version 4 (CAM4-Oslo). It is based on the CAM4 (Neale et al., 2010; Neale et al., 2014), but has a different aerosol module for aerosol lifecycle calculations and aerosol-cloud-radiation interactions (Kirkevåg et al., 2013).

The ocean component is an elaborated version of the Miami Isopycnic Community Ocean Model (MICOM). This is an entirely different ocean component than the one used in the CCSM4. The MICOM version used in

the NorESM1-M and -Happi has been adapted for multi-century simulations in coupled mode (Assmann et al., 2010; Otterå et al., 2010) and includes several extensions compared to the original MICOM (Bentsen et al., 2013).

The land and sea-ice component and the coupler are the same as in the CCSM4. The land component is the fourth version of the Community Land Model (CLM4; Oleson et al., 2010; Lawrence et al., 2011), including the SNow, ICe, and Aerosol Radiative model (SNICAR; Flanner and Zender, 2006). The sea-ice component is the fourth version of the Los Alamos Sea Ice Model (CICE4~~;~~) (Gent et al., 2011; Holland et al., 2012). The coupler is the version 7 coupler (CPL7~~;~~) (Craig et al., 2012).

The ocean and sea-ice components of NorESM1-M and NorESM1-Happi were run with the standard CCSM4 land mask and ocean grid (the gx1v6) with 1.125 ° resolution along the equator and with the NH grid singularity located over Greenland. The atmosphere component, CAM4-Oslo~~;~~ was run with a horizontal resolution of 0.95 ° latitude by 1.25 ° longitude (in short: 1° resolution) in NorESM1-Happi and the double of the mesh-width (2 ° resolution) in NorESM1-M. In both versions, CAM4-Oslo has 26 vertical hybrid sigma-pressure levels and a model top at 2.194 hPa. The land component CLM4 employs the same horizontal grid as CAM4-Oslo, except for the river transport model which is configured on its own grid with a horizontal resolution of 0.5 ° in both model versions.

Differences between NorESM1-Happi and NorESM1-M include finer horizontal resolution in the atmosphere and land, as described above, but also a few upgrades in the ocean, sea ice, and atmosphere components. In NorESM1-Happi, inertial-gravity waves are damped in shallow ocean regions in order to remove spurious oceanic variability in high-latitude shelf regions (Seland and Debernard, 2014). Wet snow albedo on sea ice is reduced by increasing the wet snow grain size and by allowing a more rapid metamorphosis from dry to wet snow. This affects the Arctic sea ice more than the Antarctic sea ice, since the latter is less frequently influenced by mild and humid air (Seland and Debernard, 2014).

In the atmosphere, an error in the aerosol life-cycle scheme (Kirkevåg et al., 2013) was found and rectified, resulting in faster condensation of secondary gas-phase matter on pre-existing particles. The changes in atmospheric residence time of aerosols compared to NorESM1-M are minor, except for the reductions for black carbon (BC) and organic matter due to more efficient wet deposition. Samset et al. (2013) and Allen and Landuyt (2014) indicated that NorESM1-M has~~d~~ too high upper-air concentrations of BC aerosols. This could cause overestimated absorption of solar radiation, suppressed upper-level cloudiness, and exaggerated static stability.

The increased efficiency of aerosol condensation in NorESM1-Happi enhances the scavenging efficiency of BC compared to NorESM1-M. This is mainly affecting the upper-air BC concentrations (Fig. S1 in the Supplement) with minor impacts on surface temperatures, surface energy fluxes, and multi-decadal variability associated with the deep oceans (Sand et al., 2015; Stjern et al., 2017). To the extent that the observations from

the HIPPO-campaign (Schwarz et al., 2013) is representative for the vertical distribution of BC in general, the model still mixes the BC too high up [in the troposphere](#). A comprehensive discussion of the aerosols in a recently updated NorESM version (NorESM1.2) is given in Kirkevåg et al. (2018).

~~3.11.1 Qualifying NorESM1-Happi: CMIP5 experiments~~

~~We performed a full range of CMIP5 experiments with NorESM1-Happi to document the performance of the model, and to obtain valid historical and RCP8.5 runs for the CPL-PD experiment (Sect. 2.2). The experiments are summarized in Table S1 in the Supplement. The set up of the simulations follows that of the original CMIP5 simulations with NorESM1-M (Bentsen et al., 2013; Iversen et al., 2013; Kirkevåg et al., 2013).~~

~~The NorESM1-Happi with 1° resolution was spun up for 1850 conditions over 300 years, starting from model year 600 of the NorESM1-M spin up with 2° resolution atmosphere and land. The ocean and sea ice were in both cases run with 1° resolution. The pre-industrial control experiment (piControl) was started from the end of the spin-up in model year 900. The three historical experiments start from the piControl in model years 930 (Hist1), 960 (Hist2) and 990 (Hist3). The code upgrades were introduced during the spin-up period, while the bug fix in the aerosol scheme was introduced at the beginning of the piControl experiment, causing some adjustments over the first few years.~~

~~Here we briefly summarize the extensive model validation of NorESM1-Happi against NorESM1-M, observations and reanalysis given by tables and figures, which are commented, in the Supplement. The pre-industrial control simulation is considerably more stable for NorESM1-Happi than for NorESM1-M, mainly because the control run started from a state closer to equilibrium in NorESM1-Happi. The NorESM1-Happi piControl experiment also deviates less from the World Ocean Atlas of 2009 (Locarnini et al., 2010; Antonov et al., 2010) than NorESM1-M. The increased horizontal resolution lead to reduced cloudiness in NorESM1-Happi, and along with this a cold bias, a faster atmospheric cycling of fresh water, and overestimated precipitation globally (Table S4 and Figure S5). The atmospheric residence time and ocean to continent transport of water vapour appears satisfactory (Table S6). Also, the thermohaline forcing of the AMOC was strengthened, and is probably too strong (Figure S14).~~

~~NorESM1-Happi has a better representation of sea ice (Table S5 and Figure S4), improved NH extratropical cyclone (Figure S11) and blocking activity (Figure S12), and a fair representation of the Madden-Julian oscillation (Figure S10). The amplitude of the El Niño-Southern Oscillation (ENSO) signals is reduced and is too small, although the frequency is improved (Figure S13). NorESM1-Happi is less sensitive (3.34 K at CO₂ doubling) than NorESM1-M (3.50 K) and slightly more sensitive than CCSM4 (3.20 K; Table S7). The lapse rate, albedo, and to a smaller extent the short-wave water vapour feedbacks contribute to Arctic amplification in both model versions (Fig. S15).~~

42.1 Emulating the oceanic response with a slab-ocean model

NorESM1-HappiSO, the ~~slab-ocean~~ (SO) (slab-ocean) model version of the NorESM1-Happi, has the same atmosphere, land, and sea-ice components, and coupler as the fully coupled model. The ocean component is however replaced by a SO model, which is a simplified 2-dimensional ocean model that represents a well-mixed surface mixed layer. ~~Note that it allows for using the same sea ice model as in the fully coupled model.~~

A SO model does not calculate the ocean circulation and associated fluxes, but treats the upper-ocean mixed layer as a single layer which buffers heat-fluxes through the ocean surface, ~~that is, i.e.~~ a thermodynamic “slab” governed by the equation

$$\rho_0 c_0 h_{mix} \frac{\partial T_{mix}^{SST}}{\partial t} = F_{net} - Q_f - \alpha \rho_0 c_0 h_{mix} (T_{mix}^{SST} - SST_{mixExt})/\tau \quad (1)$$

where h_{mix} is the thickness of the slab which varies in space but not in time, ρ_0 and c_0 are the density and specific heat capacity of the sea-water, T_{mix}^{SST} is ~~(in this connection)~~ the mixed-layer temperature, F_{net} is the net input of heat through the ocean surface from the atmosphere and sea ice, and Q_f is the net divergence of heat not accounted for by the explicit processes which are needed to maintain a stable climate with a predefined geographical distribution of SST. The last ~~restoring~~ term on the right-hand side is a restoring term that can, depending on the value of α , be used to relax the T_{mix} field toward an externally imposed temperature field T_{mixExt} . ~~could be used to when~~ estimating Q_f ~~depending on the value of α . τ is the prescribed time-scale for the adjustment.~~ For free SO runs $\alpha = 0$.

The realism of the SO model climate depends on how Q_f is prescribed. In Bitz et al. (2012), Q_f is calculated using h_{mix} , T_{mix}^{SST} , and F_{net} from a fully coupled stable control simulation, setting $\alpha = 0$. Both h_{mix} and T_{mix}^{SST} should represent an assumed well-mixed layer in the vertical. With an annual mean (but still spatially variable) mixed-layer thickness, it is quite straightforward to obtain balance with the annual cycle of heat (Bitz et al., 2012). This method gives a mean SST distribution from the SO model which is very similar to, and consistent with, the climate of the fully coupled model when the external forcing is unchanged. Here, this method has been used when estimating the equilibrium climate sensitivity (ECS) for runs with abrupt CO₂ doubling ($\Delta T_{eq} = 3.31$ ~~KK~~) and CO₂ quadrupling ($\Delta T_{eq4} = 6.74$ ~~KK~~), giving an global-mean average change in the equilibrium near-surface temperature ($\Delta T_{eq} = -3.34$ ~~K~~) of 3.34 K for doubling of the atmospheric CO₂ concentrations (Table S7 ~~in the Supplement~~). The Q_f used in these experiments was diagnosed from the 1850 fully coupled piControl experiment with NorESM1-Happi (Sect. 2.2-3.4), and kept constant in the different SO runs.

4.1 Calibration of NorESM1-HappiSO experiments

Here, the primary purpose of running NorESM1-HappiSO is to carry out simulations that are similar to the AMIP simulations performed for the HAPPI project, but where the sea ice is free to respond to the imposed warming. One drawback with the method of Bitz et al. (2012) for quantifying Q_f is that biases in SST and the

mean climate from the fully-coupled model are reflected in the SO model. ~~This~~ which makes comparison with the AMIP experiments, where the present-day (PD) SSTs and sea-ice cover are determined from observations, difficult. Therefore, as an alternative, we ~~also~~ use a restoring method similar to Williams et al. (2001) and Knutson (2003), where a separate calibration run of the SO model is done by setting $\alpha = 10$ in Eq. equation
 5 ~~(1). The SST_{ext} is an externally imposed temperature SST field. T_{mixExt} SST_{ext} is an is~~ valid for some specific period and can be based on (observations or model outputbased) with τ as a prescribed time scale for adjustment. After this run, the new Q_f is defined by adding the monthly climatology of the restoring flux to the Q_f used in the calibration run. Then, when used in a free SO run (setting $\alpha = 0$), the new Q_f ensures a modelled T_{mix} ~~SST~~ climate which is close to the T_{mixExt} ~~SST_{ext}~~ fields imposed during the calibration. Note
 10 that in the versions of NorESM considered here, the mixed layer temperature T_{mix} is equivalent to the SST field. Therefore, we can use observed SST as the imposed external field during the calibration phase.

We have kept the sea-ice model free without any restoring or constraints to observed fields during the calibration. This increases the realism of the ice-ocean heat fluxes going into F_{net} , and ensures consistent changes in sea-ice mass and energy. As in Bitz et al. (2012), the sea ice in the SO set-up employs the full
 15 CICE4 dynamic and thermodynamic model, which is the same as that used in the fully coupled NorESM1-M and NorESM1-Happi. However, some tuning of snow albedo over sea ice has been done to increase the realism of sea-ice extent under PD conditions when using the restoring method for specifying Q_f . See section 3.3 for more details on the experimental set-up.

2.2 Qualifying NorESM1-Happi: CMIP5 experiments

20 We performed a full range of CMIP5 experiments with the fully coupled NorESM1-Happi to document the performance of the model, and to obtain valid historical and RCP8.5 runs for the fully coupled CPL-PD experiment (Sect. 3.2.2.2). The CMIP5 experiments are summarized in Table S1 in the Supplement. The set-up of the simulations follows that of the original CMIP5 simulations with NorESM1-M (Bentsen et al., 2013; Iversen et al., 2013; Kirkevåg et al., 2013).

25 The NorESM1-Happi with 1 ° resolution was spun up for 1850 conditions over 300 years, starting from model year 600 of the NorESM1-M spin-up with 2 ° resolution atmosphere and land. The ocean and sea ice were in both cases run with 1 ° resolution. The pre-industrial control experiment (piControl) was started from the end of the spin-up, in model year 900. The three historical experiments were started from the piControl in model years 930 (Hist1), 960 (Hist2) and 990 (Hist3). The three RCP8.5 experiments were started from the three
 30 historical experiments in year 2006. The code upgrades were introduced during the spin-up period, while the bug-fix in the aerosol scheme was introduced at the beginning of the piControl experiment, causing some adjustments over the first few years.

Here we briefly summarize the extensive model validation of NorESM1-Happi against NorESM1-M, observations, and reanalysis given by [Tables S1–S7](#) and [Figures S1–S15](#), which are commented, in the Supplement. The pre-industrial eControl simulation for NorESM1-Happi is considerably more stable for NorESM1-Happi than [that](#) for NorESM1-M, mainly because the control run started from a state closer to equilibrium in NorESM1-Happi. The NorESM1-Happi piControl experiment also deviates less from the World Ocean Atlas of 2009 (Locarnini et al., 2010; Antonov et al., 2010) than NorESM1-M. The increased horizontal resolution [results in](#) lead to reduced cloudiness in NorESM1-Happi ([compared to NorESM1-M](#)), and along with this a cold bias, a faster atmospheric cycling of fresh water, and overestimated precipitation globally (Table S4 and [Fig. ure S5](#)). The atmospheric residence time and ocean-to-continent transport of water-vapour appears satisfactory (Table S6). Also, the thermohaline forcing of the [Atlantic Meridional Overturning Circulation \(AMOC\)](#) [wh](#)as strengthened, and is probably too strong ([Fig. ure S14](#)).

NorESM1-Happi has a better representation of sea ice (Table S5 and [Fig. ure S4](#)), improved NH extratropical cyclone [activity](#) ([Fig. ure S11](#)) and blocking activity ([Fig. ure S12](#)), and a fair representation of the Madden-Julian oscillation ([Fig. ure S10](#)). The amplitude of the El Niño-Southern Oscillation (ENSO) signals is reduced and is too small, although the frequency is improved ([Fig. ure S13](#)). NorESM1-Happi [has lower climate sensitivity](#) is less sensitive (3.34 K at CO₂ doubling) than NorESM1-M (3.50 K) and slightly [higher](#) [more climate](#) sensitivity than CCSM4 (3.20 K; Table S7). The lapse-rate, albedo, and to a smaller extent the short-wave water vapour feedbacks contribute to Arctic amplification in both model versions ([Fig. S15](#)).

3 The 1.5 K and 2.0 K warming scenarios

3.1 The AMIP experiments

The “AMIP experiments” are those performed with NorESM1-Happi for the [multi-model intercomparison project HAPPI](#) [project](#). The target of the experiments is to investigate the regional impacts of global warming under stabilisation scenarios that are 1.5 K and 2.0 K warmer than the 1850 climate. The three large ensemble experiments are: the [PD climate](#) [present decade](#) ([for years PD](#); 2006–2015), a climate that is 1.5 K warmer than the pre-industrial (1850) climate, and a climate that is 2.0 K warmer. We refer to these as the AMIP-PD, the AMIP-15, and the AMIP-20 experiments, [respectively](#).

Designing a coupled model experimental protocol for 1.5 K and 2.0 K warming targets requires determining forcing conditions that will produce the target global-mean temperature change, and other characteristics of the warmer climate state. The same forcing conditions may, however, produce different temperature responses in different models. The CMIP5 models, for instance, display considerable spread in the near-surface temperature ([2-m temperature](#)) response [for](#) [to](#) RCP2.6. While the multi-model mean response is very close to 2.0 K, the spread across the 95–5% range is approximately 1.5 K (see Fig. 2 in Mitchell et al., 2017). Fully

coupled models are moreover computationally expensive because they require centuries or longer to approach new equilibria after sustained shifts in the TOA radiation balance.

The experiments in the HAPPI project were therefore run with prescribed SSTs and sea ice. This constrains the climate state and makes it computationally feasible to run large ensembles. The experimental set-up resembles the AMIP protocol, thus we refer to the version of the NorESM1-Happi that follows the HAPPI protocol as NorESM1-HappiAMIP.

The construction of the input data for the HAPPI experiments is described in detail by Mitchell et al. (2017). The main points specific to our set-up are listed below:

- In the AMIP-PD experiment, the SST and sea-ice fields are based on observations (Taylor et al., 2012). Sea-ice thickness is fixed at 2 m in the NH and 1 m in the Southern Hemisphere (SH). Anthropogenic greenhouse gas (GHG) concentrations (including CO₂, CH₄, N₂O, and CFCs), emissions of aerosols and their precursors, ozone concentrations, and land-use changes are taken from RCP8.5 for years 2006–2015, as it is common procedure to use RCP8.5 to extend the historical period beyond 2005 (van Vuuren et al., 2011).
- In the AMIP-15 experiment, anthropogenic GHG and ozone concentrations, land-use and aerosols data are taken from RCP2.6 for year 2095. The SST increase relative to PD is the CMIP5 multi-model mean difference between years 2091–2100 from RCP-2.6 and 2006–2015 from RCP8.5. Natural forcings are as for AMIP-PD. Sea-ice concentrations are estimated from a linear regression between observed anomalies of SST and sea ice (see Mitchell et al., 2017 p. 575 for details).
- In the AMIP-20 experiment, the SST and sea-ice concentration differences are derived in a similar way, but using a weighted mean between RCP2.6 and RCP4.5 (0.41 for RCP2.6 and 0.59 for RCP4.5). The same weights are used for CO₂ (assuming a logarithmic relation). All other forcings are as for AMIP-15.

The HAPPI experimental protocol does not cover sea-ice thickness. As is standard in NorESM, the sea-ice thickness is held fixed at 2 m in the NH and 1 m in the Southern Hemisphere (SH).

The NorESM1-HappiAMIP data set includes 125 ensemble members for each experiment, each of length 10 -years (after a 1-year spin-up which is discarded from the analysis), giving 3750 years of data. To allow for enable dynamical downscaling, high temporal resolution output from 25 -members of each experiment were stored with high temporal resolution. The data is available for download at <http://portal.nersc.gov/c20c/data.html>.

3.2 The fully coupled (CPL) experiments

One shortcoming of the AMIP-type simulations is that while they calculate neglect the effects of prescribed changes in the ocean and sea-ice on the atmosphere, they cannot calculate how these atmospheric changes may feed back on the ocean and sea-ice-related feedback mechanisms apart from the patterns included in the prescribed SST and sea-ice fields. These feedbacks are particularly important in the Arctic, where albedo and lapse-rate feedbacks amplify the low-level temperature response relative to the global mean (Pithan and Mauritsen 2014; see also Fig. S14 in the Supplement).

To investigate the effects of having ocean and sea-ice components that are free to respond to changes and variability in other parts of the climate system of such feedbacks, we have conducted fully coupled experiments with NorESM1-Happi that target 1.5 K and 2.0 K warming experiments compared to pre-industrial temperature levels (CPL-15 and CPL-20) with the fully coupled NorESM1-Happi. The forcings data in these experiments are based on RCP2.6 and RCP4.5, but with important differences. The emissions of anthropogenic aerosols and aerosol precursors, land-use changes, and concentrations of GHGs apart from CO₂ follow those in RCP2.6. Thus, we have chosen to mimic the evolution towards the two temperature targets by manipulating the prescribed time-evolution of in the CO₂ concentration (Fig. 1).

It should be made clear that other temperature evolutions are possible by alternative combinations of forcing data, but an adequate discussion of this is far beyond the scope of the present paper. Furthermore, it is impossible in practice to constrain atmospheric concentrations directly. Atmospheric concentration levels result from the combination of emissions and removal processes, some of which are controllable in practice. We emphasize that because the CO₂ in NorESM1-Happi is concentration-driven, and not emission-driven as in Sigmond et al. (2018), switching off the anthropogenic CO₂ emissions to create stabilized scenarios with this model, is impossible.

The constructed scenarios were inspired by those in HAPPI, with the CPL-15 being based on RCP2.6 and CPL-20 being based on a combination of RCP2.6 and RCP4.5. The details of the scenarios were determined through an iterative trial-and-error process. Although also inspired by the much more sophisticated method by Sanderson et al. (2017), we simply ran the model for 1–2 centuries based on a few constructed time profiles of CO₂ concentrations. The results in this paper are taken from the version that was most successful in hitting the two temperature targets.

In CPL-15, the CO₂ concentration follows RCP2.6 from year 2000 to year 2095, after which it stays constant until year 2170, and then decreases following the pattern assumed in the original RCP2.6 from year 2095 onwards. Thus (i.e. the decrease is delayed 75 years compared to RCP2.6). In CPL-20, the CO₂ concentration follows RCP4.5 from year 2000 to year 2050, then stays constant until year 2170, after which it decays in the same fashion as CPL-15, but starts from the higher concentration level. The other GHGs and forcing producing elements are as in RCP2.6.

The fully coupled ~~PD~~present-day (CPL-PD) climate is represented by the 30-year time period 1991–2020 using output from the CMIP5 experiments carried out with NorESM1-Happi. We use the period 1991–2005 from three individual simulations of the historical climate (Hist1, Hist2, and Hist3; see Sect. 2.23.4 or Table S1 in the Supplement) and extend them with years 2006–2020 from three individual simulations of RCP8.5 (Sect. 2.23.4). Thus, CPL-PD, CPL-15, and CPL-20 are all sampled by 90 years of simulations with the fully coupled NorESM1-Happi.

The scenario runs CPL-15 and CPL-20 both start from simulation year 2005 of the Hist1 experiment. Figure -22 shows the change in near-surface temperature for Hist1 (1850–2005) and for the CPL-15 and CPL-20 experiments (2006–2230) relative to the pre-industrial climate calculated under constant driving conditions valid for year 1850 (the piControl experiment, see Sect. 2.23.4 or Table S1). The global-mean temperature warms rapidly between years 1960 and 2050, then the response flattens out over the next 150 years. In what follows, we study results from the 90-year periods 2111–2200 for which the mean temperature increase in CPL-15 and CPL-20 is 1.51 K and 1.97 K relative to pre-industrial conditions and 0.69 K and 1.15 K relative to CPL-PD (see discussion of Table 3 in Sect. 4.15.4).

The experiments are, however, not entirely stabilized. By the end of the 22nd century, both CPL-15 and CPL-20 still have a positive radiative imbalance at the top of the model atmosphere (around 0.7 W m⁻², not shown) and a positive heat flux into the ocean at depths below 200 m (Fig. 3). The net heat uptake in the upper ocean is, however, small at that point. The Atlantic meridional overturning circulation (AMOC) decreases with time over the first 100 years and is relatively stable over the last 150 years (Fig. 4).

Our fully coupled experiments differ from those in Sanderson et al. (2017) and in Sigmond et al. (2018). Sanderson et al. who first used a climate emulator to construct concentration scenarios, and then used these scenarios to produce stabilized 1.5 K and 2.0 K warming experiments with the CESM1. Sigmond et al. (2018) branched the warming experiments off from RCP8.5, setting the emissions of anthropogenic CO₂ and aerosols to zero. The simulations presented in this study are far from reaching equilibrated climate states, but are quasi-stable over 90-year periods after a spin-up of 100 years from present day. Full equilibration over several centuries is likely to produce different climate states (Gillet et al., 2011).

3.3 The slab ocean (SO) experiments

While results from the coupled simulations above will help us understand how 1.5 K and 2.0 K warming might manifest in the fully coupled earth system, CPL-15 and CPL-20 are not stabilized scenarios like the AMIP experiments. Moreover, Fig. 55 shows that the fully coupled PD experiments (panels a, d, g, and j) exhibits larger biases than the AMIP experiments (panels c, f, i, and l) relative to ERA-Interim (Dee et al., 2011) in all seasons. Prescribing the SSTs and sea ice to observationally-based fields constrains the climate in the AMIP-PD experiments, yielding smaller biases in the simulated climate. To be able to examine 1.5 K and 2.0 K warming experiments in a model which has smaller biases, but where the sea ice and SSTs are also free to

respond, we ~~have designed a SO configuration~~ have designed a slab-ocean configuration of NorESM1-Happi, NorESM1-HappiSO (see Sect. 2.1.4 for details).

We have conducted free-running SO experiments for the PD climate (SO-PD), and ~~for~~ climates that are 1.5 K and 2.0 K warmer than the pre-industrial (SO-15 and SO-20). The SO model has been calibrated to mimic the three HAPPI experiments AMIP-PD, AMIP-15, and AMIP-20, using the same forcings for GHGs, aerosols, ozone, and land-use. In SO-PD, the SSTs are constrained to stay close to the observed values from AMIP-PD. The SST differences ~~for~~ for SO-15 and SO-20 are based on the SST response in CPL-15 and CPL-20 relative to CPL-PD for consistency with the model climate in the NorESM1-Happi. The SO model and the set-up of the experiments are described in more detail in Sect. 4 and This is in line with the recommendations of Bitz et al. (2012) when the sea-ice model is the same as in the fully coupled model version. An overview of the experiments is provided in Table 2 ~~Table 2~~.

In the present case, the purpose of the SO model is to emulate regional patterns of the climate response given a targeted global near-surface temperature change relative to the pre-industrial climate, considering the observed and analysed climate at PD (2006–2015). The experiments with NorESM1-HappiSO are designed to be comparable to the NorESM1-HappiAMIP experiments, in which the SST and sea ice are prescribed (see Sect. 3.1–2.4). Three different calibrations of Q_f (Eq. 1) are therefore performed using the restoring method (Sect. 2.1). For SO-PD we use 12-year averaged SSTs determined by the observationally based *Operational Sea Surface Temperature and Sea Ice Analysis* (OSTIA) for the years 2005–2016 (Donlon et al., 2012). In practice, this calibration also reduces biases. For SO-15 and SO-20, we determine new Q_f fields ~~that~~ which adjust the model to ~~an~~ SST fields which ~~are~~ is consistent with 1.5 K and 2.0 K warming. To obtain these fluxes, we compute SST increments based on the difference between CPL-15 and CPL-PD and between CPL-20 and CPL-PD and add these ~~were obtained by adding SST increments based on the difference of the CPL-15 and CPL-20 runs relative to CPL-PD~~ to the OSTIA PD SST field.

One may argue that it would produce be a more consistent comparison with the NorESM1-HappiAMIP to calibrate the SO-model from the SST increments designed for HAPPI, and used in the AMIP-15 and AMIP-20 experiments. This was also our first attempt, which resulted in strong changes in the Hadley circulation and in the extratropical jets during winter and spring for reasons we do not fully understand. This behavior is neither seen in the AMIP nor the fully coupled runs, and we are not confident that the response is realistic, but a result of enforcing SST patterns that are too different from the model's own climate. When we instead employ the SST increments from the fully coupled NorESM1-Happi runs, we do not see this kind of behavior. The results are much more consistent with the climate response of the coupled system (CPL-15 and CPL-20).

~~The different Q_f -fields thus~~ emulate the effects of oceanic circulation changes on the heat flux divergence in the upper mixed layer of the ocean.

The Q_f -fields are determined for each month of the year, and the values used in the SO model at a given grid-point and a given time are determined by linear interpolation between the former and the next monthly value. The same Q_f fields are used every year of the simulation. Fig. 6 shows annual averages for SO-PD together with the increments for the 1.5 K and the 2.0 K warmer worlds (SO-15 and SO-20). ~~In addition, we use the same CO_2 levels, aerosols and precursor emissions, and other active forcing agents as in the AMIP experiments.~~ The Q_f for SO-PD (Fig. 6a), which includes bias corrections, is dominated by large negative values (hence SST increase) along the major currents in the North Pacific, North Atlantic, Southern Indian Ocean, and the Atlantic sector of the Arctic. Positive values are mainly seen along the equator and in some coastal upwelling zones. The increment patterns (Fig. 6b and c) appear largely independent of the level of the warming, with positive values (decreasing SST) over the Labrador Current, negative values (increasing SST) south of Iceland, and values of both signs over the Southern Ocean.

Having determined the Q_f -fields, we carried out 150-year simulations for SO-PD, SO-15, and SO-20. After a spin-up of 60 years, a new quasi-equilibrium is reached, leaving three equilibrated periods of 90 years each (270 years in total).

The biases in the near-surface temperature for the present day climate are shown in Fig. 55b, e, h, and k (for the four seasons). While the biases are larger than those from AMIP-PD, they are still clearly reduced compared to CPL-PD. For instance, the global-mean bias in NH winter (December, January, and February; DJF) is reduced by 35 % in the SO and 64 % in AMIP model compared to the fully coupled model.

54 Temperature response

In what follows we study ~~results from the PD climate and the~~ warming response ~~to the warming~~ in the 1.5 K experiment (with respect to PD) and the extra 0.5-K difference (between the 2.0 K and 1.5 K experiments) from three versions of the NorESM1-Happi: (1) NorESM1-HappiAMIP forced with prescribed SST and sea ice (Sect. 3.12.4); (2) NorESM-Happi which is fully coupled (Sect. 3.2-2.2); (3) NorESM1-HappiSO which ~~employs~~ has a slab ocean model (Sect. 3.3 2.3 and 2.14). The disadvantage with the AMIP model is that it does not capture any ocean and sea-ice feedbacks. The coupled model ~~on the other hand~~ however has larger biases, for instance in ~~the~~ near-surface temperatures (Fig. 55). The SO model offers an intermediate solution with smaller biases than the fully coupled model (Fig. 55), while still including feedbacks that are missing in the AMIP model set-up. The AMIP experiments however comprise a much larger ensemble of experiments, which may enable statistical significance of smaller trends (e.g. Li et al., 2018).

5.14.1 Temperature targets and the polar amplification factor

The changes in the global-mean near-surface temperature for the 1.5 K and 2.0 K warmer worlds are given in [Table 3](#)~~Table 3~~. Note that these runs are designed to have temperature increases of 1.5 K and 2.0 K relative to *pre-industrial* conditions, whereas we are comparing them to the PD climate, which is assumed to be 0.8 K warmer based on observations (Mitchell et al., 2017). Therefore, the ideal temperature increase between the PD experiments and the 1.5 K and 2.0 K warming experiments is 0.7 K and 1.2 K.

NorESM1-HappiAMIP hits the temperature targets of 0.7 K and 1.2 K ~~abovewith respect to the~~ PD temperatures quite accurately. The corresponding numbers are 0.56 K and 1.02 K for NorESM1-HappiSO and 0.69 K and 1.15 K for NorESM1-Happi. The warming ~~compared with respect to~~ the PD climate is thus somewhat too low in the SO model whereas it is closer to the targets in the fully coupled one. The difference between the 2.0 K and 1.5 K warming experiments is quite similar across the models: 0.49 K for NorESM-HappiAMIP, 0.43 K for NorESM-HappiSO, and 0.46 K for NorESM1-Happi.

~~It is not entirely clear what is causing the smaller temperature response in the SO experiments; we believe it is mainly caused by the model's is caused by a cold bias over land (Table 4~~~~Table 4~~, see discussion below).
The cold bias over the continents is not ~~which cannot be~~ adequately controlled by the adjusted ocean Q_f -fluxes. As shown in the supplement (Tables S3 and S4 as well as Fig. S5 and S7), the fully coupled model has a pronounced negative temperature bias which is stronger over continents than oceans. This can be related to generally underestimated cloudiness and to the strong vertical overturning circulation in the Atlantic Ocean (Figs. S14 in the supplement, and Fig. 4) which efficiently transfers heat into the deep ocean (Fig. 3) leaving less for ground surface heating. These properties are carried over to the SO model by the cloud properties of the atmospheric model and by the fluxes used to calibrate the future scenario states.

The time-evolution of the global-mean near-surface temperature response to 1.5 K and 2.0 K warming in NorESM1-Happi is shown alongside the response for the Arctic region (area poleward of 65 ~~deg~~^oN) in Fig. 7. The temperature response is clearly amplified ~~inover~~ the Arctic compared to the global mean. The ratio of the polar to the global near-surface temperature response defines the polar amplification factor (PAF; [Table 3](#)~~Table 3~~). The PAF is considerably larger in the Arctic than in the Antarctic, consistent with polar amplification being more pronounced in the NH. The Arctic amplification (NH-PAF) is furthermore stronger in the 1.5 K than in the 2.0 K warming scenarios.

The Arctic amplification is enhanced in the experiments with ~~an~~ active ocean components. Compared to NorESM1-HappiAMIP, the Arctic amplification is 27 % stronger in the 1.5 K warmer world in NorESM1-HappiSO and 54 % stronger in NorESM1-Happi. With the additional 0.5 K warming the Arctic amplification is moreover 19 % and 46 % stronger in the SO and the fully coupled model than in the AMIP model.

To assess how the strength of the Arctic amplification in NorESM1-Happi compares to the CMIP5 models, used for constructing the SST fields used in HAPPI (and thus in NorESM1-HappiAMIP), we have computed

the PAF for RCP2.6 and RCP8.5 for each of the CMIP5 models. Results are shown in Fig. 8, along with the PAF for RCP2.6 and RCP4.5 for NorESM1-Happi, and for the different 1.5 K and 2.0 K warming experiments. The figure shows that the PAF generally is larger in the NH than in the SH (consistent with Table 3), and that there is considerably more variability between the CMIP5 models when the forcing is weaker. Also, the CMIP5 multi-model median PAF is smaller for stronger forcing experiments (2.1 for RCP8.5 versus 2.4 for RCP2.6), in line with the results from the 1.5 K and 2.0 K warming runs. The Arctic amplification in NorESM1-Happi is in the upper range compared to the CMIP5 models. For RCP2.6, the PAF for NorESM1-Happi is 3.4, which puts it above the median for the CMIP5 models (2.4) and somewhat below the 90th percentile (3.6).

Table 4 shows similar statistics as Table 3, but for the NH extratropical (poleward of 20 °N) winter and summer land temperatures, land precipitation rates, and sea-ice area. The winter climate is colder over land in the fully coupled and SO models than in the AMIP model by -0.54 K for the fully coupled model and -0.57 K, respectively, for the SO model with respect to the AMIP model. During summer, land temperatures are almost as high in the SO model as in the AMIP model, whereas the fully coupled model is 1.58 K colder. This is in line with the larger bias in the fully coupled model during this season (Fig. 5g–i).

The fully coupled model has the largest reduction in sea-ice area in the warmer climates during summer and winter. The SO model has larger changes than those prescribed in the AMIP model during summer and smaller changes during winter.

During summer, the SO model and the fully coupled models have the largest changes in land temperatures and precipitation in the 1.5 K warming experiment, whereas the AMIP model has the largest changes with the additional 0.5 K warming. During winter, the AMIP model has the largest changes in precipitation and temperature in with the 1.5 K warming and the smallest changes in precipitation with the additional 0.5 K warming.

So far we have considered changes in surface fields, but changes are also occurring aloft. Figure 9 shows the zonal-mean temperature response to the 1.5 K warming relative to the PD climate for NH winter (DJF) and NH summer (June, July, and August; JJA). There is low-level warming in the Arctic and high upper-level warming in the tropics in all three models. The Arctic warming is strongest in the fully coupled model, consistent with the PAF results in Table 3. The upper-level warming is somewhat more pronounced in the AMIP model over the tropics and appears to be more consistent between the seasons and than the Arctic Amplification is somewhat more pronounced in the AMIP model.

5.24.2 Equator-to-pole temperature gradients

The warming pattern in Fig. 98 is consistent with a sharpening of the upper-level equator-to-pole temperature gradient and a weakening of the lower tropospheric gradient. Li et al. (2018) considered the multi-model mean changes in these gradients in five of the models contributing to the HAPPI project, including NorESM1-

HappiAMIP. They found that the low-level gradient changes more with the initial 0.7 K warming (1.5 K–PD) than with the additional 0.5 K warming (2.0 K–1.5 K) in all the models. The upper-level gradient on the other hand strengthens more with the additional 0.5 K warming than with the initial 0.7 K, except in NorESM1-HappiAMIP where the changes are ~~more~~ similar.

5 ~~Figures 10~~~~Figure 9~~ and ~~11~~~~10~~ show the temperature gradients between the equator and the North Pole at 200 hPa and 850 hPa (e.g. Harvey et al., 2014) for the PD experiment and the 1.5 K and 2.0 K warming experiments ~~within~~ NorESM1-Happi, NorESM1-HappiSO and NorESM1-HappiAMIP, separated by and for ~~each of the~~ seasons.

10 The magnitude of the PD gradients is generally smaller~~weaker~~ in the fully coupled than in the SO and AMIP models, except during summer ~~when the low level gradient is stronger in the fully coupled model~~. While the fully coupled model might seem like an outlier, the upper-level gradient is actually closer to the one in ERA-Interim (Dee et al., 2011), indicating that the SO and AMIP models overestimate the upper-level pole-to-equator temperature contrast (Fig. ~~109~~). At low levels the fully coupled model underestimates the gradient during winter and spring (March, April, and May; MAM), while the gradients in the SO and AMIP models are stronger and closer to the reanalysis (Fig. ~~11~~~~10~~). During summer (JJA) and fall (September, August, and November; SON) the fully coupled model has the smallest bias and the strongest contrasts at lower levels.

15 In line with the zonal-mean response in Fig. ~~98~~, the upper~~high~~-level gradient generally increases with ~~the~~ warming (Fig. ~~109~~) while the low-level gradient decreases (Fig. ~~11~~~~10~~). The low-level gradient decreases more with the initial ~~the~~ 0.7 K warming than with the additional 0.5 K, consistent with Li et al. (2018). The decrease with the initial 0.7 K is moreover larger in the fully coupled and SO models than in the AMIP model, consistent the stronger Arctic amplification in these models (~~Table 3~~~~Table 3~~).

20 Changes in the upper-level gradient are less consistent across the experiments and seasons. There is however little change with the initial 0.7 K warming in the fully coupled and SO models. During winter and spring, the gradient strengthens with the additional 0.5 K warming in all three models. ~~There is however little change with the initial 0.7 K warming in the fully coupled and SO models~~. During summer and fall, the upper-level gradient strengthens more with the initial 0.7 K warming than with the additional 0.5 K warming, like at low levels, only with no obvious differences between the model versions.

25 It is not clear why there is less warming aloft in the fully coupled model and SO model than in the AMIP model. It is possible that the ~~upper level warming in the fully coupled and to SO experiments are affected by~~ cold biases in the tropics are contributing. ~~As discussed above, B~~both the fully coupled and the SO models are colder over land than the AMIP model during winter (~~Table 4~~~~Table 4~~), and the fully coupled model additionally has cold biases over the tropical oceans (Fig. ~~55~~).

65 Extratropical storm-track activity

Changes in the temperature gradients are known to be associated with changes in the extratropical storm tracks, with stronger gradients being associated with poleward shifts and weaker gradients with equatorward shifts (Brayshaw et al., 2008; Graff and LaCasce, 2012; Harvey et al., 2014; Shaw et al. 2016).

5 Extratropical storm tracks can be defined as regions of growing and decaying baroclinic waves embedded in the zones of pronounced meridional temperature gradient and mean westerly winds~~currents~~. Here we represent the storm-track activity in terms of atmospheric fields, such as geopotential height, that have been bandpass filtered in time to isolate disturbances with timescales between 2.5 and 6 days (following Blackmon, 1976 and Blackmon et al., 1977). The variability of the resulting fields is dominated by growing and decaying baroclinic waves, and the storm tracks are taken to be maxima in the bandpass-filtered variance fields (e.g. Blackmon et al., 1977; Chang et al. 2002; Chang et al., 2012).

~~Figure 12~~~~Figure 11~~ shows the bias in the PD storm-track activity in terms of bandpass-filtered geopotential height at 500 hPa for NorESM1-Happi, NorESM1-HappiSO and NorESM1-HappiAMIP. The fully coupled model underestimates the variability in all seasons. The bias is largest over the North Atlantic during winter ~~when the storm-track activity is underestimated~~ on the equatorward side of the storm track and over the Nordic Seas, consistent with the North Atlantic storm track being overly zonal in the NorESM (Iversen et al., 2013). The SO and AMIP models have both positive and negative biases over the storm-track regions, and a North-Atlantic storm track which extends too far downstream over central Europe.

The storm-track biases are largest in the fully coupled model whereas they are substantially smaller in the SO and AMIP models. The area-averaged winter bias for the region shown in ~~Figure 12~~~~Figure 11~~ is for instance -4.24 m (13 % relative to ERA-Interim climatology) in the fully coupled model, 0.89 m (2.73 %) in the SO model, and 0.51 m (1.56 %) in the AMIP model.

~~Figures 13~~~~Figure 12 and 14~~ shows the changes in upper-level storm-track activity ~~within~~ the initial 0.7-1.5 K warming and with the additional 0.5 K warming-experiments for the three models and all four seasons. Li et al. (2018) found that while there is a poleward shift in upper-level storm-tracks activity with both the initial 0.7 K and the additional 0.5 K warming in the HAPPI multi-model ensemble. Here, the NorESM1-HappiAMIP model consistently has the most consistent changes with displays more storm-track activity at high latitudes and less at lower latitudes with both warmings, consistent with a poleward shift, for all seasons. The exception is, as in Li et al., over the North Pacific where there is an equatorward shift of during summer with the initial 0.7 K warming, and equatorward shift near the North-American west coast region during winter with both the 0.7 K and the additional 0.5 K warming.

~~and a more general equatorward shift of the whole storm track during summer. The results for the AMIP model are in line with the multi-model mean results in Li et al. (2018).~~

Changes in the fully coupled and the SO model are relatively consistent with those in the AMIP for the additional 0.5 K warming (Fig. 14)~~less consistent~~. This is most clearly seen over the North Atlantic, where there tends to be more storm activity on the poleward side and less on the equatorward side. ~~The poleward shifts are~~The poleward shift is in line with changes in the upper-level temperature gradient, which strengthens with the 0.5 K warming for all cases.

~~During summer and fall~~Changes are however less consistent with the initial 0.7 K warming (Fig. 13). The response in the fully coupled and SO experiments resemble that~~he changes resemble those~~ in the AMIP ~~model~~experiments during summer and fall, with more activity ~~at~~over the high latitudes and less ~~at~~over the low latitudes. The reductions ~~on the equatorward side~~ are however stronger for the fully coupled and the SO model.

Changes during winter and spring are more complicated, and do not particularly resemble those in the AMIP model.

~~The upper-level storm track response to the additional 0.5 K warming is shown in Fig. 13. Here the changes are more similar across the models and seasons, particularly over the North Atlantic where there tends to be more storm track activity on the poleward side and less on the equatorward side. The poleward shifts are in line with changes in the upper-level temperature gradient, which strengthens with the 0.5 K warming for all cases.~~

~~The white dots in Fig. 12 and 13 indicate that only the very strongest changes are significant in NorESM1-Happi and NorESM1-HappiSO whereas the changes in NorESM1-HappiAMIP are more generally significant. This could be caused by the smaller number of model years available for the fully coupled and SO model, but it could also reflect a larger spread between the decades/members. The similarity, or lack thereof, between the storm track response in the two coupled models and the AMIP model does nonetheless increase, or reduce, our confidence in the AMIP results.~~

~~Li et al. (2018) found that while there is a poleward shift in upper-level storm tracks activity with both the initial 0.7 K and the additional 0.5 K warming in the HAPPI multi-model ensemble, Li et al. (2018) found the changes in the at lower-levels storm tracks to be are less consistent and, a similar conclusion can be drawn from the present results. Figure 14 shows the changes in the low level storm track activity in the 1.5 K warming experiment for NorESM1-Happi, NorESM1-HappiSO, and NorESM1-HappiAMIP during winter and summer. We consider Tthe low-level summer and winter storm tracks are given in terms of the bandpass-filtered meridional eddy heat flux. As in Li et al., the response to the initial 0.7 K warming (Fig. 15) is generally a reduction in storm-track activity, here indicating that the storm-track eddies are transporting less heat poleward. The decrease over the North-Atlantic region is stronger in the fully coupled and the SO model than in the AMIP model. Changes during summer are weak.~~

~~The change in the low level storm track activity in response response to the additional 0.5 K warming (is shown in Fig. 1615 for summer and winter) is~~ Again ~~changes are also~~ weak during summer. During winter, the AMIP and SO models have an increase southwest of the British Isles~~over the Nordic Season~~, but this is

less pronounced (and not significant) in the fully coupled model. A similar increase is ~~however~~ present in the multi-model mean in Li et al. ~~(2018)~~.

The white dots in Fig. 13–16 indicate that only the very strongest changes are significant in NorESM1-Happi and NorESM1-HappiSO whereas the changes in NorESM1-HappiAMIP are more generally significant. This could be caused by the smaller number of model years available for the fully coupled and SO model, but it could also reflect a larger spread between the decades/members. While not all differences are significant, the similarity (or lack thereof) between the differences in the experiments with active ocean components and in the AMIP experiments does nonetheless increase (or reduce), our confidence in the AMIP results.

7.6 Blocking frequency

Extratropical blocking is closely connected to persistent anticyclones, which can suppress precipitation at mid-latitudes for periods of up to several weeks. The ability of climate models to simulate the occurrence of droughts at mid-latitudes in the present and in future climates is conditioned by the models ability to simulate blocking (e.g. Woolings et al., 2018).

~~Figure 17~~Figure 16 shows the PD blocking frequency for NorESM1-Happi, NorESM1-HappiSO, and NorESM1-HappiAMIP for the winter and summer seasons. The blocking frequency is underestimated over the North Atlantic and western Europe during winter and over large parts of Eurasia during summer. ~~The~~ performance of the three models is generally similar, although some differences can be seen. The overestimation in NorESM1-Happi at 120 °W is for instance not as pronounced in the other two models. The SO and AMIP models perform slightly better over the Pacific, but the blocking occurrence is still underestimated in the Atlantic sector.

It is well established that many global climate models have problems simulating the occurrence and duration of blocking in the Euro-Atlantic sector and that the systematic errors are particularly large during NH winter. Several studies tie these problems to poor horizontal resolution, but there are likely other factors (Dawson et al., 2012; Davini and D’Andrea, 2016; Woolings et al., 2018).

The changes in the occurrence of winter and summer blocking in the 1.5 K warming experiment (relative to PD) and with the additional 0.5 K warming are shown in Fig. ~~18~~17 for ~~the~~ NorESM1-Happi, NorESM1-HappiSO, and NorESM1-HappiAMIP. The magnitude of the response varies dramatically between the models, and there is generally little consistency between the models regarding the sign and significance (indicated by the asterisk) of the response for the difference longitudes. ~~and a~~Although not shown, the same lack of consistency is also found for spring and fall.

~~The magnitude of the changes is largest in the fully coupled model, but are almost as large in the SO model.~~There are indications of more consistent changes between the model versions with the additional 0.5 K

~~incremental warming during NH summer, with increased blocking occurrence over parts of western Europe, the eastern Pacific, and the western Pacific. Changes are in these cases larger in the coupled models, but most significant in the AMIP model.~~ Note that the AMIP response can be statistically significant relative to the internal variability in the ~~AMIP~~-model, even though the amplitude of the response is small.

5 ~~There is, however, little consistency between the sign and significance (indicated by the asterisk) of the response for the different longitudes. There are indications of more consistent changes between the model versions with the 0.5 K incremental warming during NH summer, with increased blocking occurrence over parts of western Europe, the eastern Pacific, and the western Pacific. Changes are in these cases larger in the coupled models, but most significant in the AMIP model.~~ Nevertheless, the results concerning NH blocking
10 generally remain inconclusive.

87 Arctic sea-ice reduction

The extent, thickness and concentration of sea ice are important properties of the climate system. ~~Figure 19~~~~Figure 18~~ shows the concentration of Arctic sea ice in March and September for NorESM1-Happi and NorESM1-HappiSO. For PD (Fig. ~~19~~~~18~~a–d) the modelled concentrations are compared to remotely retrieved
15 data from OSI-SAF (2017).

The quality of the model data is better in March than in September, when the SO model seems to underestimate the concentration—~~while the CPL-PD overestimates the ice cover. This is also seen when comparing the mean sea-ice extent to observations. For CPL-PD, the sea-ice extent in March/September is 14.26 (0.34) / 7.38 (0.62) 10⁶ km², and the observed for the relevant years (1996–2015) is 14.87 (0.36) / 5.71 (0.94) 10⁶ km². For the~~
20 ~~SO-PD, the March/September extent is 14.54 (0.36) / 4.22 (1.04) 10⁶ km² and the observed for the relevant time period (2005–2015) is 14.69 (0.33) / 5.04 (0.58) 10⁶ km². The numbers in parenthesis are inter-annual standard deviation. The March sea-ice cover seems to be rather well constrained by the gradients in SST while summer extent is more influenced by local processes such as the ice — open water albedo feedback.~~

~~From Table 4 (Sect. 4.1), we know that the NH winter sea-ice areas are overestimated in CPL-PD and SO-PD compared with AMIP-PD which is based on observations. The reason for this is not fully understood. The PD climate in the fully coupled model is too cold with too thick sea ice (not shown). This gives little summer melt, and rather large sea-ice extent during early winter. For the SO-PD, the model is also cold during winter, but this might be related partly to the large ice cover. The use of annual-mean mixed layer depths in the SO model underestimates the mixed layer depth during autumn and winter. This might give too low effective heat~~
25 ~~capacity in the ocean slab, which then causes too rapid refreezing during autumn and early winter.~~
30

The sea-ice concentration is reduced in the warmer climates. In March, the largest changes occur along the edges of the ice (Fig. ~~19~~~~18~~e–f, i–j). There is a larger reduction in the fully coupled than the SO model with the

initial 0.7 K warming, whereas the changes are more similar with the additional 0.5 K. The changes occur over a larger fraction of the sea-ice covered area in September (Fig. 1948g–h, k–l) than in March. ~~While the e~~Changes are again ~~are~~ larger with the 0.7 K than with the additional 0.5 K warmings in the fully coupled model, ~~whereas they~~ sea-ice response to the 0.7 K and the 0.5 K warmings are more similar comparable in the SO model.

While the sea-ice concentration is reduced more with the warming in the fully coupled model, ice-free summers are more likely in ~~the~~ SO model. ~~Figure 20~~Figure 19 shows histograms of the relative occurrence of NH September sea-ice extent for NorESM1-Happi (Fig. 2049a) and NorESM1-HappiSO (Fig. 2049b). The sea-ice extent is shown for the observed and the modelled PD climate and the 1.5 K and 2.0 K warming experiments. For PD climate, the SO model produces too few cases with the largest sea-ice extent whereas the fully coupled model has too many. The overrepresentation in the latter case is likely caused by the cold bias in the model and the thick multi-year sea ice.

The probability of having an ice-free Arctic in September, ~~that is, i.e. having~~ a sea-ice extent between 0 and 1×10^6 km², is practically zero for PD conditions in both models. The fully coupled model does not reach ice-free conditions with 1.5 K nor with 2.0 K warming (Fig. 2049a). This is perhaps not surprising as the model is too cold and has too much sea ice in the PD climate. So even though there are larger reduction in the sea-ice concentration in the fully coupled model, it does not ~~produce~~have an ice-free Arctic in September. Also, the inter-annual variability is smaller in the fully coupled model than in observations. We attribute this to the generally large sea-ice extent, and thick multi-year ice. The model has a delayed Arctic sea-ice decline during the historic period compared with observations. The inter-annual variability in the model is comparable to that given from observation in the period 1979–2004, before the recent rapid sea-ice decline.

Results are different for the SO model, which ~~exhibits~~has smaller biases in temperature and sea-ice extent. ~~While i~~Ice-free September conditions are rather unlikely under 1.5 K, ~~but~~ but the probability increases substantially to about 18 % with the additional 0.5 K warming (Fig. 2049b). The difference between the two temperature targets is therefore potentially very large for the Arctic sea ice in summer and fall, ~~a result that was also found by Jahn (2018) and Sigmond et al. (2018).~~ The NorESM1-HappiSO tends to underestimate the relative occurrence of the highest sea-ice extent and overestimate the occurrence of the smaller extents in the PD climate (comparing the blue and black bars in Fig. 20a), which could indicate that there is an overestimation of ice-free conditions in the model. A substantial reduction in sea-ice extent between 1.5 K and 2.0 K warming is however also seen in CESM1 (Sanderson et al., 2017; Jahn, 2018) and in CanESM2 (Sigmond et al., 2018).

98 Summary and discussion

In This paper, ~~we focus on the response to~~ ~~presents an evaluation of the importance of ocean and sea ice~~ ~~feedbacks under~~ global warming of 1.5 K and 2.0 K relative to pre-industrial conditions ~~in different versions~~ ~~of NorESM~~. We compare results from a fully coupled and a SO (slab-ocean) ~~simulations~~ ~~version of the~~ ~~NorESM1-Happi~~ to results from the AMIP-style simulations that were carried out for the multi-model HAPPI project (Mitchell et al., 2017; <http://www.happimip.org/>).

Because the AMIP runs are forced with prescribed SSTs and sea ice they have small biases, but they also predefine aspects of the Arctic amplification. The fully coupled and the SO models allow for changes in SST and sea ice that can influence the surface albedo and atmospheric lapse rate, which are major elements in producing Arctic amplification (Pithan and Mauritsen, 2014). The motivation for using a SO model in addition to the fully coupled one is that the SO model has smaller biases, while still allowing the ocean and sea ice to respond to the forcing in the warming runs.

We consider the PD (present day) climate, the response to the 0.7 K warming between the PD and the 1.5 K warming experiments (assuming 0.8 K warming between 1850 and PD), and the response to the 0.5 K warming between the 1.5 K ~~experiment~~ and the 2.0 K experiments.

Results show that Arctic amplification, as measured by the PAF (polar amplification factor) for the NH, is larger in the models with ~~an~~ active ocean components. In the fully coupled model, the PAF is 54 % stronger than in the AMIP model with the initial 0.7 K warming, and 46 % stronger with the additional 0.5 K warming. The difference is not as large for the SO model which has 27 % and 19 % stronger PAF ~~values~~ for the same warmings.

Arctic amplification weakens the lower tropospheric equator-to-pole temperature gradient, and this decrease is larger with the initial 0.7 K warming than with the additional 0.5 K for all seasons. A similar result is also found in ~~the AMIP runs from the~~ five HAPPI models (including NorESM1-HappiAMIP) studied by Li et al. (2018). ~~The~~ ~~is~~ ~~present~~ study however shows that the changes with the initial 0.7 K warming is larger in the fully coupled and SO models than in the AMIP model, particularly during summer (JJA) and fall (SON).

The changes in the upper-level equator-to-pole gradients are less consistent. The gradients generally increase with the warming because the tropics are warming aloft (e.g. Collins et al., 2013). During summer and fall, the ~~upper-level~~ gradient changes more with the initial 0.7 K warming, similar to ~~with~~ the low-level gradient. The magnitude of the response is however not systematically larger in the experiments with ~~an~~ active ocean components. During winter and spring, the upper-level gradient changes very little with the initial 0.7 K warming in the coupled models and more with the additional 0.5 K, whereas the AMIP model has more similar changes with the 0.7 K and the 0.5 K warming. The changes in the upper-level gradient are also less consistent than those in the low-level gradient in Li et al. (2018); while the upper-level gradient changes more with the additional 0.5 K in the multi-model mean, there is considerable spread among the models.

Changes in temperature gradients are known to be associated with changes in the storm tracks, with the tracks shifting poleward with stronger gradients and equatorward with weaker ones (Brayshaw et al., 2018; Graff and LaCasce, 2012; Harvey et al., 2014; Shaw et al., 2016). Li et al. (2018) identified poleward shifts in the multi-model mean upper-level storm tracks with the initial 0.7 K warming and with the additional 0.5 K warming.

5 We find that while the AMIP model displays consistent poleward shifts in the upper-level storm-track activity with the initial 0.7 K warming for all seasons, the results from the coupled models are less consistent during winter and spring. The models agree more on the response to the additional 0.5 K. However, only the strongest changes in the fully coupled model and in the SO model are significant.

10 The low-level storm-track activity decreases with the initial 0.7 K warming. Changes with the additional 0.5 K warming are weak in the AMIP model, whereas the fully coupled and SO models have stronger reductions. All model versions have indications of more activity westeast of the British Isles, a response also seen in the multi-model mean in Li et al. (2018). These changes are however mostly not significant in the coupled models. To the extent that reduced low-level storm-track activity can be interpreted as slower propagation of cyclone waves in the westerlies, this can be associated with the reduced low-level temperature gradient associated with the high-latitude warming inover the Arctic (e.g. Francis and Vavrus, 2012; Screen and Simmonds, 2013). ~~The results for blocking activity for the most remain inconclusive due lack of consistency between the model versions and the low statistical significance of the changes. Many aspects of blocking are also poorly simulated, likely because of relatively coarse model resolution (Woollings et al., 2018).~~

20 Our findings indicate that the storm-track response is not always very consistent between the model versions. There are moreover sizable biases in the storm tracks with respect to reanalysis, especially in the fully coupled model. Barcikowska et al. (2018) provided a study of the Euro-Atlantic winter storminess which showed that modelling the regional atmospheric circulation, extreme precipitation and winds with acceptable quality requires an atmospheric model with higher horizontal resolution (0.25° in their study) than that used in the present study and in CMIP5 models.

25 The results for blocking activity for the most remain inconclusive due to lack of consistency between the model versions and to the low statistical significance of the changes. Many aspects of blocking are also poorly simulated, likely because of the relatively coarse model resolution (Woollings et al., 2018).

30 The SO model simulates considerable differences in the reduction of sea ice in the Arctic between a 1.5 K and a 2.0 K warmer world. Ice-free summer conditions in the Arctic are estimated to be rare under 1.5 K warming, while occurring 18 % of the time under 2.0 K warming. This number may however be too high as the SO model does tends to overestimate the relative occurrence of the lower sea-ice extent and underestimate the highest extent in the PD climate. A strong increase in the probability of having ice-free conditions when going from 1.5 K to 2.0 K is ~~These results are~~ nonetheless consistent with other studies (Jahn, 2018; Sigmond et al., 2018; Notz and Strove, 2018). The fully coupled model is ~~however~~ too cold. It produces too much sea ice

under PD conditions and is consequently not able to reach ice-free conditions in neither the 1.5 K nor the 2.0 K warming experiment.

This paper does not discuss practical or scientific challenges that must be addressed in order to avoid exceeding certain temperature targets. Mathews et al. (2009) and Gillett et al. (2011) indicate that a constant equilibrium response in surface air temperature to anthropogenic CO₂ is determined by the accumulated carbon emissions. Hence, an ESM which calculates the atmospheric concentrations of CO₂ on-line from emissions, should produce quite rapid stabilization of the global mean surface temperature (e.g. Sigmond et al., 2018). This is possible ~~enabled~~ if the ocean thermal inertia is balanced by decreasing atmospheric concentrations of CO₂ due to ocean uptake. NorESM1-Happi is not equipped with the possibility to run emission-driven GHG scenarios with on-line carbon-cycling. Instead, the atmospheric concentrations of CO₂ are prescribed.

Results in this study show that there are important differences in the modelled response to 1.5 K and 2.0 K warming in NorESM1-Happi depending on whether the model is run with prescribed SSTs and sea ice as in the AMIP runs, with the full ocean and sea-ice model, or with the sea-ice model coupled to a simplified ocean model. These differences could be due to the active sea-ice and ocean models allowing for feedbacks that are neglected in the AMIP runs, but they may also be affected by the experimental set up. Compared to the CMIP5 models, the Arctic amplification in NorESM1-Happi is in the high end of the range of responses. This indicates that the difference between the AMIP experiments and the ones with an active ocean model could have been smaller if the prescribed SST were based on results from NorESM1-Happi rather than from the CMIP5 multi-model mean. More experiments are needed to understand this, such as those planned under PAMIP (Smith et al., 2018) to investigate the role of the background state.

10 Code and Data Availability

The source code for NorESM1-Happi is not open for everyone to download, because parts of the code is imported from several other code development centres. The code can be made available within the framework of an agreement. Data from the model experiments in this study can be made available as well, see e.g. NCC / NorESM1-HAPPI at <http://portal.nersc.gov/c20c/data.html>. Contacts: oyvindse@met.no and Ingo.Bethke@uib.no ingo.bethke@uni.no.

Acknowledgements

This work received financial support from the Norwegian Research Council, project no. 261821 (HappiEVA), from the EU Framework Programme for Research and Innovation, project no. 641816 (EU-H2020-CRESCENDO), and in-kind support from Geophysical Institute, Univ. of Bergen, UniResearch, Bergen, and from MET Norway. Jan Fuglestad, Cicero, Norway, Dann Mitchell, Univ. Bristol, UK, and Myles Allen,

Univ. Oxford, UK, were instrumental in inspiring the initiating this work, and have strongly contributed in discussions. HPC-resources for the NorESM runs were provided in-kind from Bjerknes Centre for Climate Research, MET Norway, and Sigma2/Vilje (nn2345k). Storage for NorESM data was provided through Norstore/NIRD (ns9082k). The development of NorESM has been possible because of the granted early access to the later public versions of the CCSM4 and CESM1 by the US National Center for Atmospheric Research (NCAR). Changes in NorESM1-Happi compared to NorESM1-M were developed in the project ACCESS (Arctic Climate Change, Economy and Society) financed under the 7th Framework Programme of the European Union (<http://www.access-eu.org/>) and in the Norwegian Research Council, project Earth system modelling of climate Variations in the Anthropocene1 (EVA, 229771/E10).

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Tables

Table 1: overview of the NorESM1-X versions referred to in this paper.

X =	Definition	Purpose	References
M	Fully coupled GCM for CMIP5 with concentration-driven GHGs: 2 ° atmosphere and land, 1 ° ocean and sea ice. 26 atmospheric levels, model top at 2.194 hPa.	Reference for model evaluation of NorESM1-Happi	Bentsen et al. ⁵ (2013); Iversen et al. (2013); Kirkevåg et al. (2013)
Happi	Fully coupled GCM. Differences from NorESM1-M: 1 ° atmosphere and land; adjusted aging of snow on sea ice, with reduced albedo; bug-fix in the aerosol scheme, with faster removal of BC particles.	Basic GCM evaluation (Table S1); Coupled model scenarios targeting 1.5 K and 2.0 K above piControl	Seland and Debernard (2014)
HappiSO	Atmosphere, land and sea-ice models from NorESM1-Happi with slab-ocean replacing full ocean model.	Estimate equilibrium climate sensitivity (ECS); extend HAPPI AMIP-type runs which enables sea-ice response (Table 2 Table 2)	This study
HappiAMIP	Atmosphere and land models from NorESM1-Happi with 1 ° resolution, set up with prescribed SST and sea ice.	Contribute to HAPPI: ensembles of AMIP-type runs with prescribed SST and sea ice, targeting <u>the</u> present-day (2006–2015) <u>climate and</u> ; 1.5 K; and 2.0 K <u>warming</u> above pre-industrial.	Mitchell et al. (2017); http://www.happimip.org/

Table 2: overview of the NorESM1-HappiSO experiments and their calibration. Q_f is the net divergence of heat not accounted for by the explicit processes, which is needed to maintain a stable climate with a predefined geographical distribution of SST. In SO-PD, SO-15, and SO-20, a restoring term $-(\text{SST}_{mix} - \text{SST}_{mixExt})/\tau$ is included in Q_f , where $\tau = 30$ days is the applied time-scale of adjustment.

5 Notice that sea ice is not restored except for via the indirect effect of the SST restoring term.

Name	Definition	Calibration	Length (years)
SO-piControl	Pre-industrial 1850 control run with constant external forcing.	Q_f calculated using h_{mix} , T_{mix} , SST , and F_{net} (see Eq. 1) from a stable control simulation, piControl, for 1850 with NorESM1-Happi.	150
SO-4xCO ₂	Scenario-run with constant 4xCO ₂ mixing ratio.	As for SO-piControl	150
SO-PD	Present-day (2005–2016) equilibrium control.	Q_f calculated with T_{mix} , SST restored to 12-year averaged SST _{mixExt} determined by the <i>Operational Sea Surface Temperature and Sea Ice Analysis</i> (OSTIA) for 2005–2016 (Donlon et al., 2012), thus reducing SST biases. No restoring of sea ice.	150
SO-15	Equilibrium climate change for a global <u>near</u> -surface air temperature response of 0.7 K above PD.	Forcing agents as in AMIP-15. Q_f calculated as for SO-PD by adding the CPL-15–CPL-PD increments to the OSTIA (2005–2016) climatology.	150
SO-20	Equilibrium climate change for a global <u>near</u> -surface air temperature response of 1.2 K above PD.	Forcing agents as in AMIP-20. Q_f calculated as for SO-15 using the CPL-20–CPL-PD increments.	150

Table 3: the NH and SH polar amplification factor (NH-PAF and SH-PAF) and global-mean near-surface temperature (T_{as}) in the PD experiments and differences associated with 1.5 K warming, 2.0 K warming, and the 0.5 K difference for NorESM1-Happi, NorESM1-HappiSO and NorESM1-HappiAMIP. PAF is defined as $\Delta T_{Polar}/\Delta T_{Global}$, where T is the near-surface temperature, and the Global and Polar (poleward of 60 °) subscripts indicate the averaging region.

	Period or Difference	NH-PAF	SH-PAF	T_{as} K
NorESM1-HappiAMIP 125×10 years	AMIP-PD			287.30
	AMIP-15–AMIP-PD	2.34	1.62	0.71
	AMIP-20–AMIP-PD	2.17	1.35	1.20
	AMIP-20–AMIP-15	1.93	0.95	0.49
NorESM1-HappiSO 90 years	SO-PD			287.13
	SO-15–SO-PD	2.98	-0.04	0.56
	SO-20–SO-PD	2.68	0.30	1.02
	SO-20–SO-15	2.29	0.77	0.43
NorESM1-Happi 90 years	CPL-PD			286.72
	CPL-15–CPL-PD	3.60	0.23	0.69
	CPL-20–CPL-PD	2.99	0.56	1.15
	CPL-20–CPL-15	2.81	1.06	0.46

Table 4: Similar as [Table 3](#), but for near-surface temperature over land, precipitation on land, and sea-ice area in the NH (20 °N–90 °N) during winter (DJF) and summer (JJA).

	Period or Difference	$T_{\text{Land}}^{\text{DJF}}$ K	$T_{\text{Land}}^{\text{JJA}}$ K	$P_{\text{Land}}^{\text{DJF}}$ mm d ⁻¹	$P_{\text{Land}}^{\text{JJA}}$ mm d ⁻¹	$\text{AREA}_{\text{SeaIce}}^{\text{DJF}}$ 10 ⁶ km ²	$\text{AREA}_{\text{SeaIce}}^{\text{JJA}}$ 10 ⁶ km ²
NorESM1-HappiAMIP 125×10 years	AMIP-PD	265.87	292.62	1.214	2.532	11.26	5.81
	AMIP-15–AMIP-PD	+1.52	+0.84	+0.070	+0.104	-0.97	-0.54
	AMIP-20–AMIP-PD	+2.36	+1.65	+0.091	+0.139	-1.36	-0.86
	AMIP-20–AMIP-15	+0.83	+0.81	+0.021	+0.035	-0.39	-0.32
NorESM1-HappiSO 90 years	SO-PD	265.30	292.44	1.212	2.559	12.52	5.48
	SO-15–SO-PD	+1.46	+1.12	+0.041	+0.120	-0.65	-0.86
	SO-20–SO-PD	+2.19	+1.87	+0.078	+0.126	-1.02	-1.41
	SO-20–SO-15	+0.73	+0.75	+0.036	+0.006	-0.36	-0.55
NorESM1-Happi 90 years	CPL-PD	265.33	291.04	1.248	2.337	12.51	7.59
	CPL-15–CPL-PD	+1.44	+1.14	+0.048	+0.136	-1.41	-1.73
	CPL-20–CPL-PD	+2.41	+1.86	+0.073	+0.161	-1.93	-2.29
	CPL-20–CPL-15	+0.97	+0.71	+0.025	+0.025	-0.51	-0.56

Figures

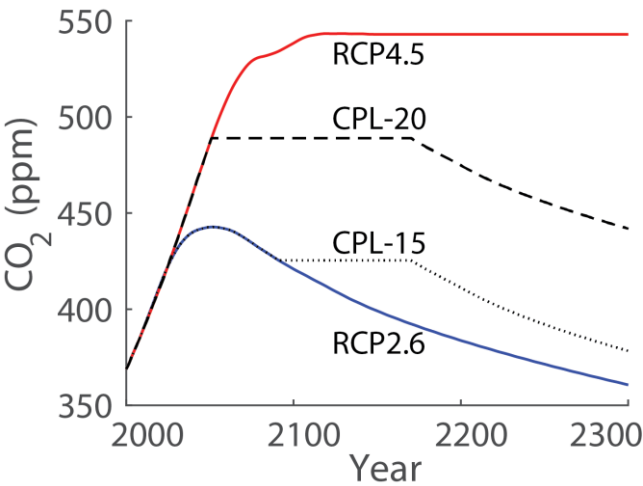


Figure 1: time-evolution of prescribed Aatmospheric CO₂ concentration for the 1.5 K and 2.0 K warming experiments with NorESM1-Happi. The 1.5 K experiment (black dotted line) initially follows RCP2.6 (blue solid line). At year 2095 the concentration deviates from RCP2.6, staying constant until year 2170, and decreases thereafter. The 2.0 K experiment (black dashed line) similarly follows RCP4.5 (red solid line) at first, but branches off at year 2050. The concentration is then constant until year 2170 before decreasing in the same fashion as in the 1.5 K experiment. Units are ppm.

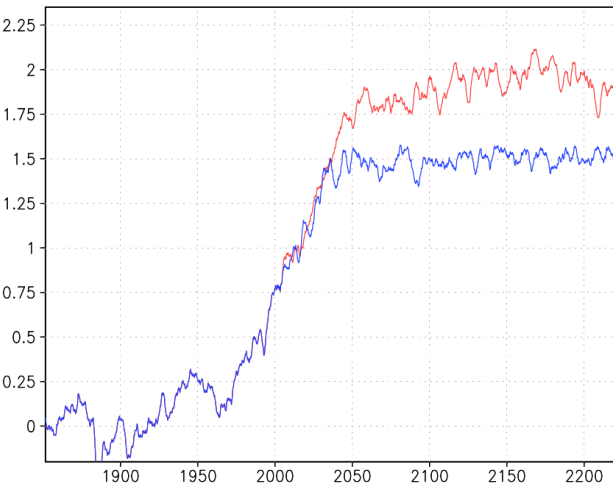


Figure 2: Time-evolution of the global-mean near-surface temperature response in the Hist1 experiment (1850–2005; blue) and the CPL-15 (2006–2230; blue) and the CPL-20 experiment (2006–2230; red) relative to pre-industrial conditions (years 1850–1852). A three-year running average is used for both curves. Units are K.

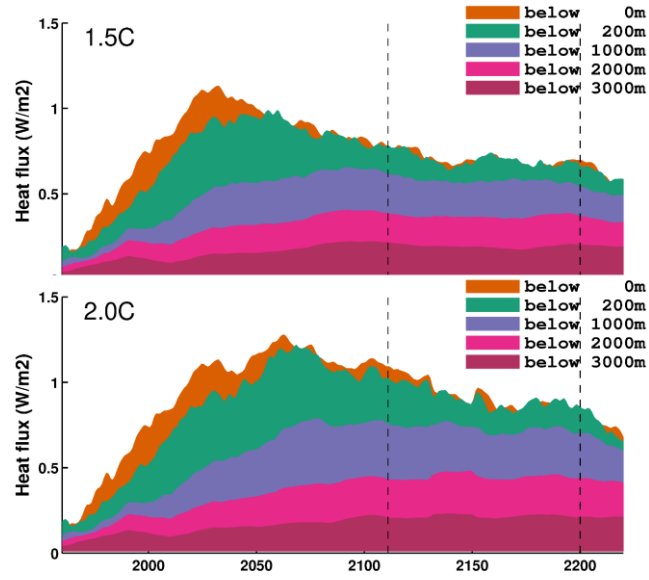


Figure 3: Ocean heat uptake as a function of time in the CPL-15 (a) and CPL-20 (b) experiments. Shown is the heat uptake for depths 0–200 m (orange shading), 200–1000 m (green shading), 1000–2000 m (blue shading), 2000–3000 (pink shading), and below 3000 m (dark pink shading). Dashed vertical lines emphasize the time period analyzed in this study. Units are W m^{-2} .

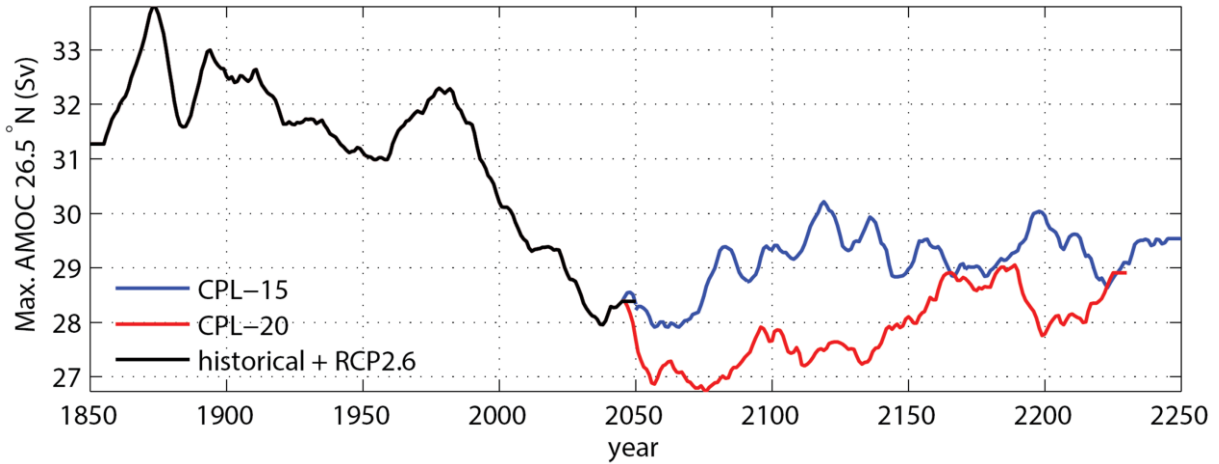


Figure 4: Time-evolution of the maximum in the AMOC (Atlantic meridional overturning circulation) at 26.5 °N in Hist1 and RCP2.6 (black) and in the 1.5 K (red) and 2.0 K (blue) warming experiments with NorESM1-Happi. A 10-year running average is used for all curves. Units are Sv.

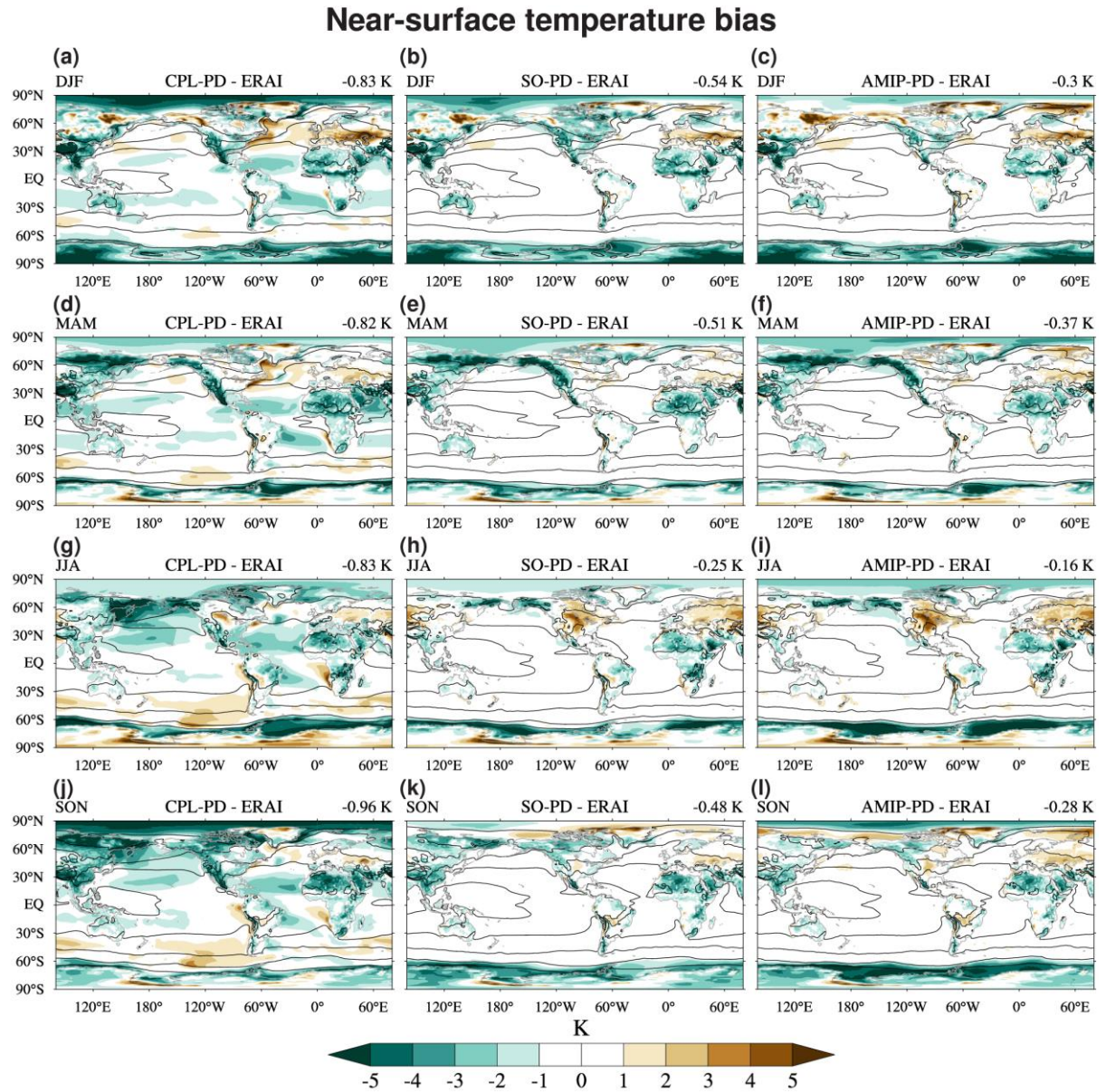


Figure 5: nNear-surface temperature bias relative to ERA-Interim (colors) and near-surface temperature climatology (black contours; 260 to 350 K in increments of 10 K) for PD experiments from NorESM1-Happi (left), NorESM1-HappiSO (middle), and NorESM1-HappiAMIP (right). We use years 1986–2015 from ERA-Interim. The time periods for the NorESM experiments are the default periods given in Sect. 3. The global-mean ensemble-mean bias is given in the upper-right corner of each panel. Units are K (a–l).

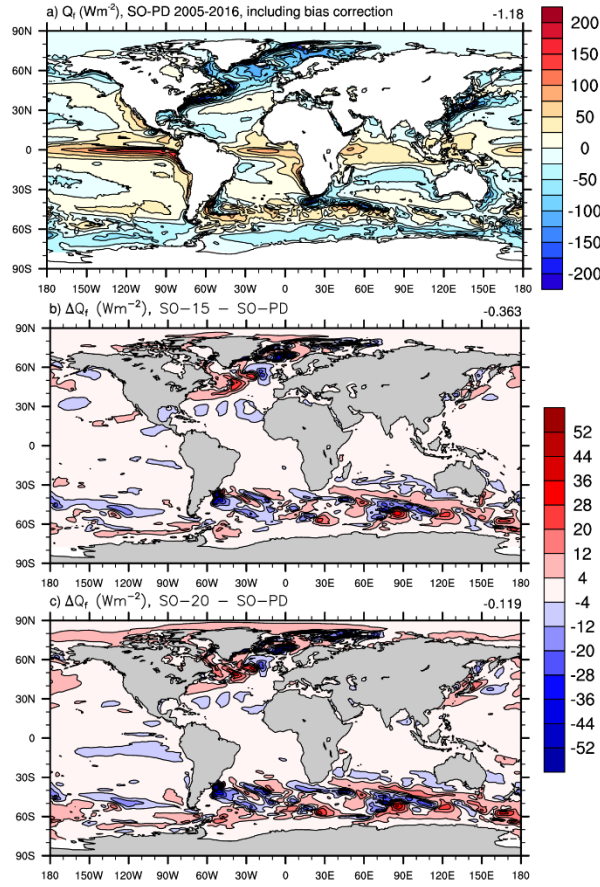


Figure 6: The annual-mean ocean heat flux Q_f needed in NorESM1-HappiSO to maintain a stable PD climate that is close to the observed SST used during calibration (a), and the change in Q_f for SO-15 (b) and SO-20 (c) compared to SO-PD. Negative values contribute to increasing SST (Eq. 1). Units are W m^{-2} (a–c).

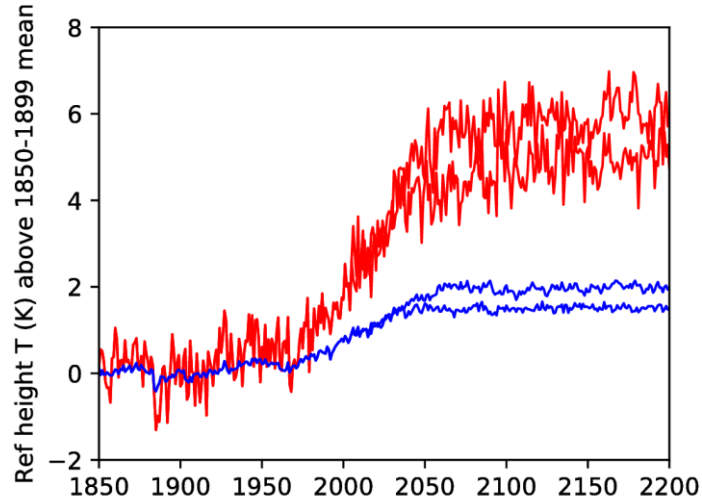


Figure 7: Time-evolution of global-mean near-surface temperature for Hist1 (1850–2005) and CPL-15 and CPL-20 (2005–2200) from NorESM1-Happi relative to the 1850–1899 average. Fields are shown for the global average (blue) and for an average taken over the area north of 65°N (red), i.e. ca. 4.7 % of the global area. Units are K.

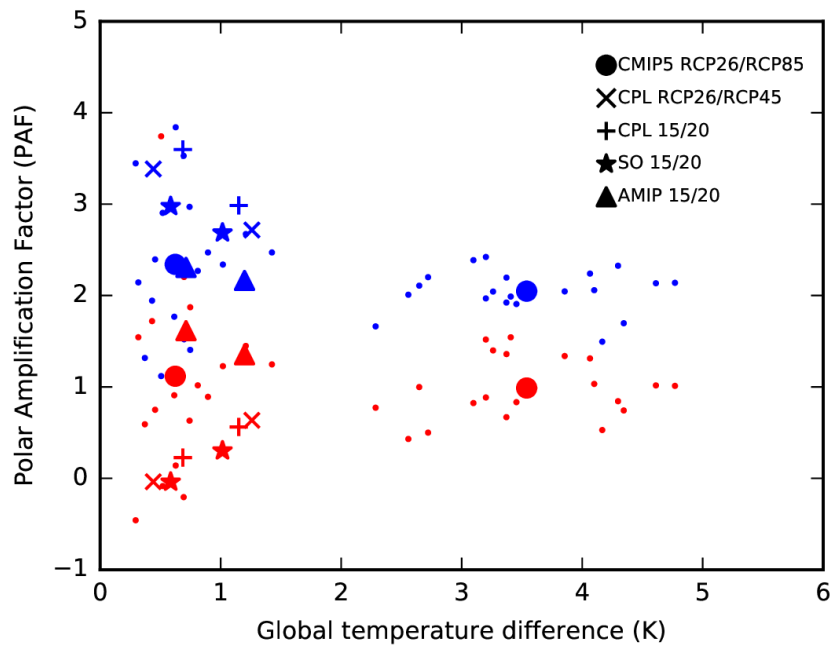


Figure 8: the PAF versus the change in the global-mean near-surface temperature. Blue markers show values for NH and red markers for the SH. The small dots show the values for the CMIP5 models used in HAPPI, including NorESM1-M, for RCP2.6 (values with warming below 2 K) and RCP8.5 (values with warming above 2 K). The large dots show the CMIP5 multi-model means. Also shown are the values for NorESM1-Happi for RCP2.6 (left cross) and RCP4.5 (right cross), for CPL-15 (left plus sign) and CPL-20 (right plus sign), for SO-15 (left asterisk) and SO-20 (right asterisk), and for AMIP-15 (left triangle) and AMIP-20 (right triangle). For RCP2.6, RCP4.5, and RCP8.5, the PAF is computed by differencing the 10-year periods 2091-2100 from the respective RCP's to 2006-2015 from RCP8.5 (as it is commonly used to extend the historical period beyond 2005). The values from the 1.5 K and 2.0 K warming runs correspond to those in Table 3.

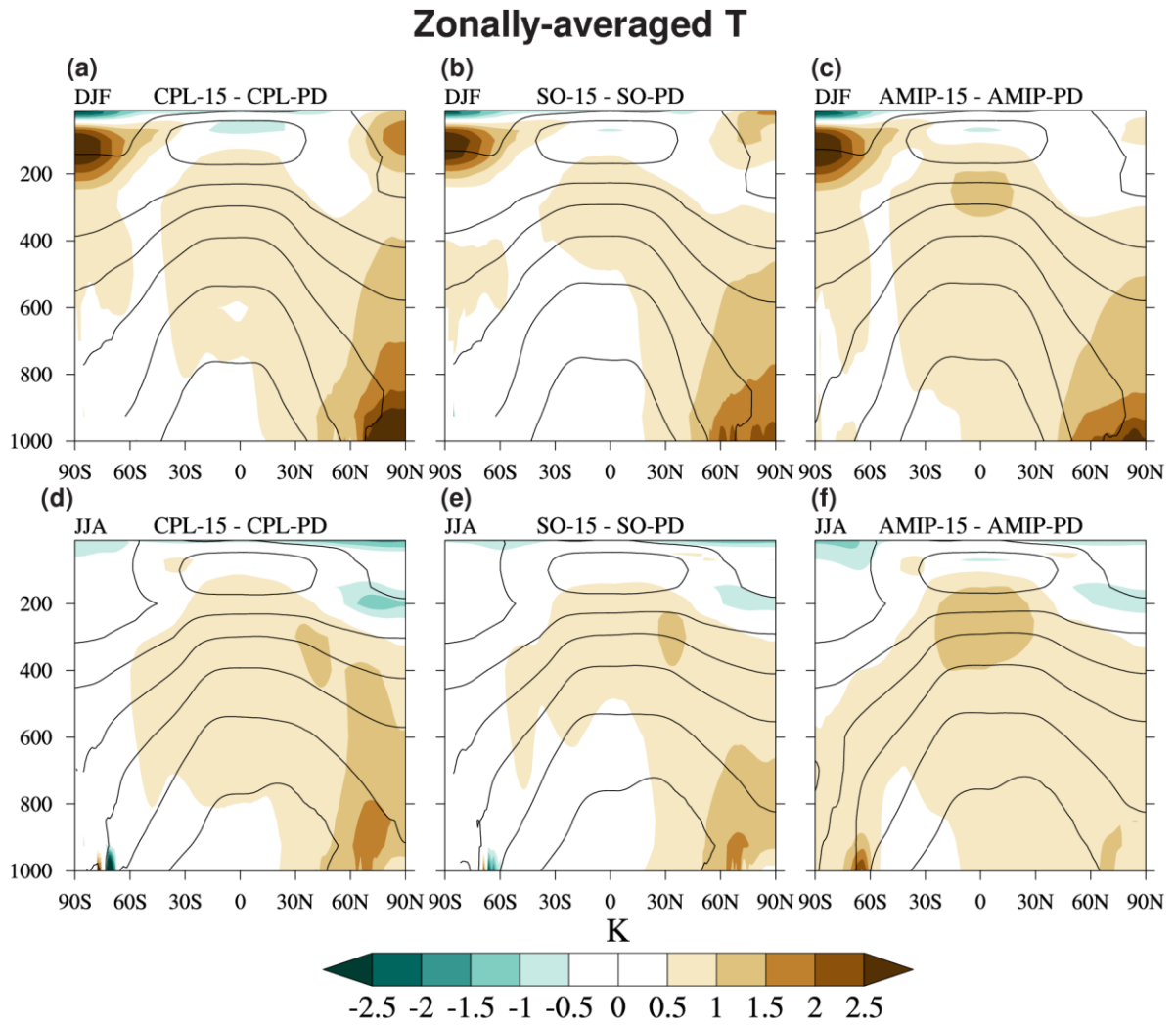


Figure 98: Zonal-mean temperature response (K) relative to PD (colors) and climatology (solid black contours; 210 K to 285 K in increments of 15 K) for the 1.5 K experiment from NorESM1-Happi (left; a, d), NorESM1-HappiSO (middle; b, e), and NorESM1-HappiAMIP (right; c, f). Fields are shown for DJF (top row; a–c) and JJA (bottom row; d–f). The fields are shown for the default periods given in Sect. 3. Units are K (a–f).

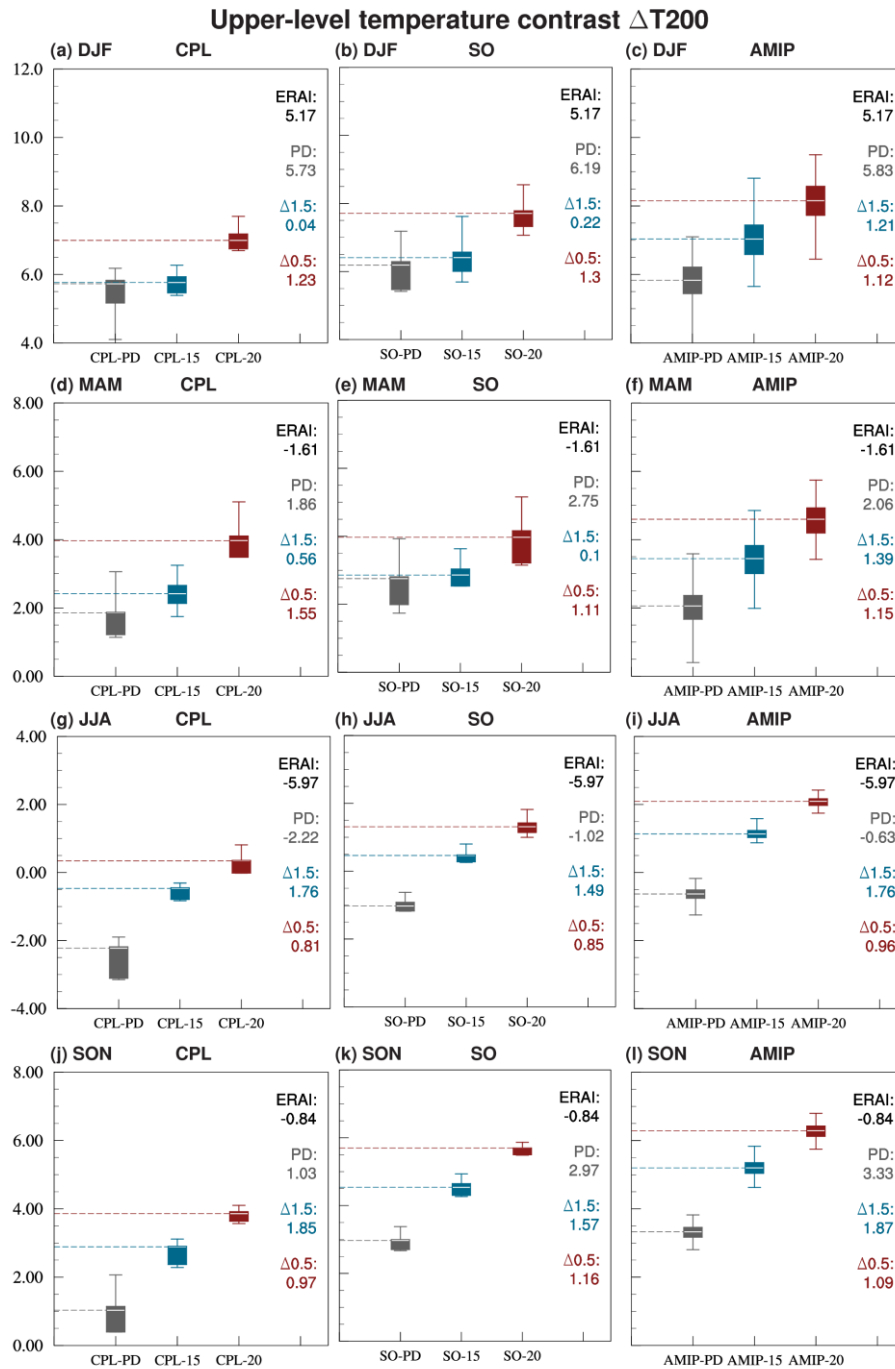
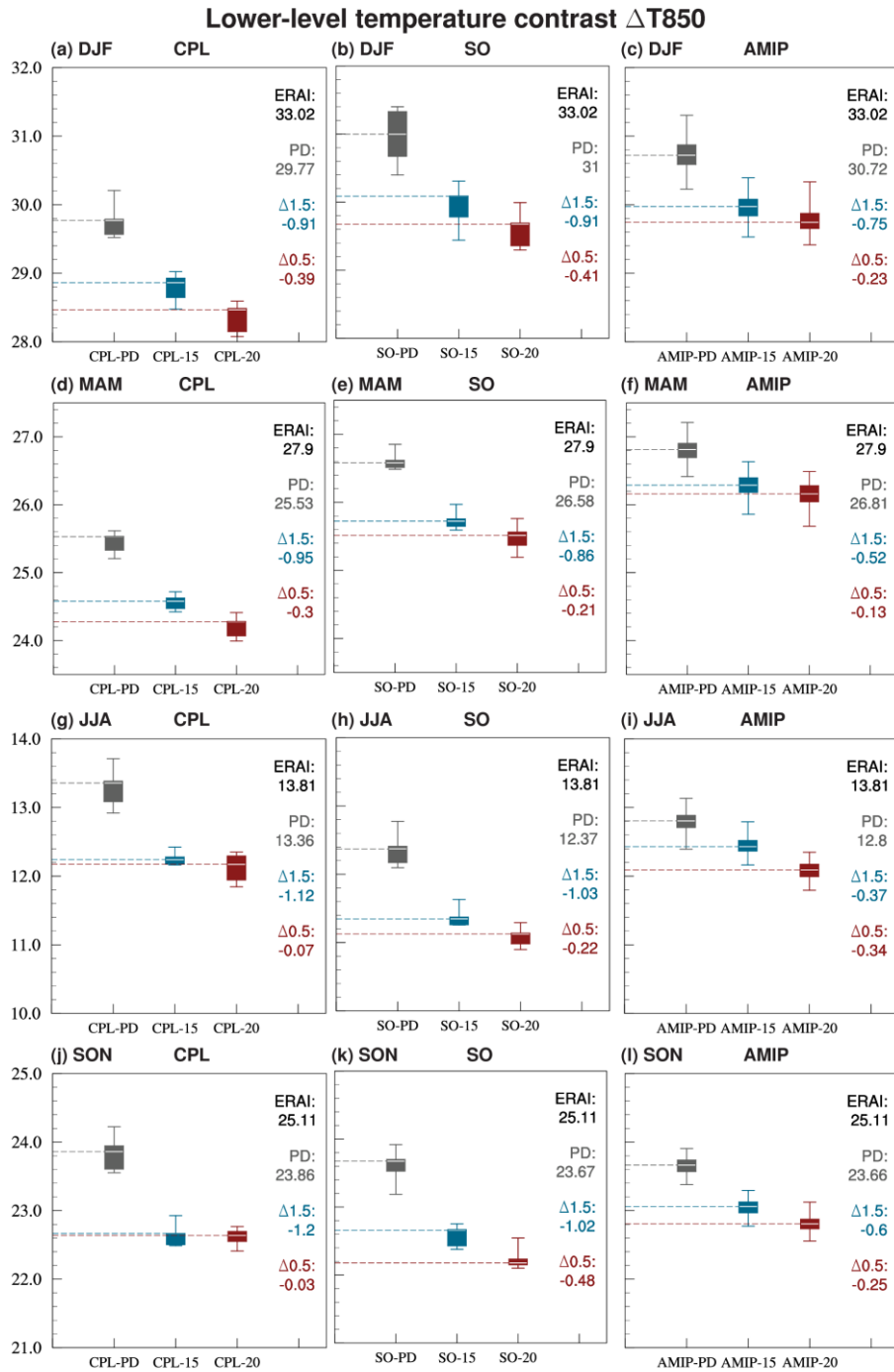


Figure 109: Upper tropospheric temperature contrast in the PD (grey), 1.5 K (blue), and 2.0 K (red) experiments from NorESM1-Happi (left column; a,d,g,j), NorESM1-HappiSO (middle column; b,e,h,k), and NorESM1-HappiAMIP (right column; c,f,i,l) for DJF (top row; a–c), MAM (middle row; d–f), JJA (third row; g–i), and SON (bottom row; j–l). The upper-level temperature contrast ΔT_{200} is defined as the 200 hPa temperature difference between an area over the tropics (30 °S–30 °N) and an area over the Arctic (poleward of 60 °N). The white lines within the boxes indicate the median values, the boxes indicate the inter-quartile range, and the whiskers the full spread of the different decades in each experiment (9 in NorESM1-Happi, 9 in NorESM1-HappiSO, and 125 in NorESM1-HappiAMIP). The dashed horizontal lines emphasize the median values. Numbers are shown on the right side of each panel for ERA-Interim (top black), PD

(second from top, grey), the change with 1.5 K warming relative to PD (third from top, blue), and the change with the additional 0.5 K warming (bottom, red). The ERA-Interim values are computed using years 1986–2015. The NorESM data is for the default periods given in Sect. 3. Units are K (a–l).



5 Figure 1140: ΔT_{850} as in Figure 10, but for the lower tropospheric temperature contrast at 850 hPa (ΔT_{850}).

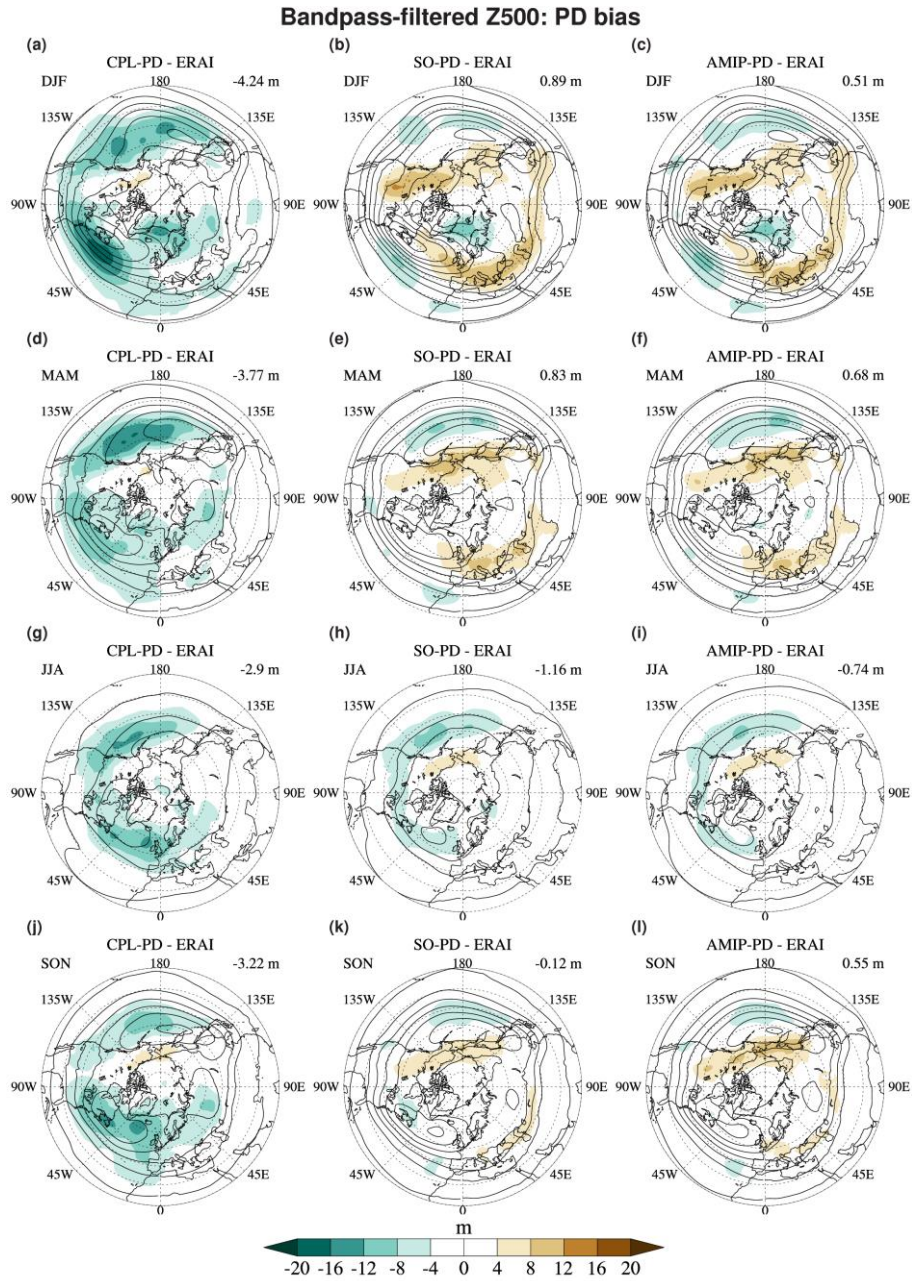


Figure 1244: Upper-level storm-track bias relative to ERA-Interim (colors) and climatology (black contours; 8 m to 70 m in increments of 8 m) for the PD experiment from NorESM1-Happi (left; a, d, g, j), NorESM1-HappiSO (middle; b, e, g, k), and NorESM1-HappiAMIP (right; c, f, I, l) for DJF (top row; a–c), MAM (second row; d–f), JJA (third row; g–i), and SON (bottom row; j–l). The bias is computed relative to ERA-Interim for years 1986–2015. The NorESM data is for the default periods given in Sect. 3. The numbers in the upper-right corners of each plot give the mean bias for the area shown on the plot (latitudes poleward of 20 °N). Units are m (a–l).

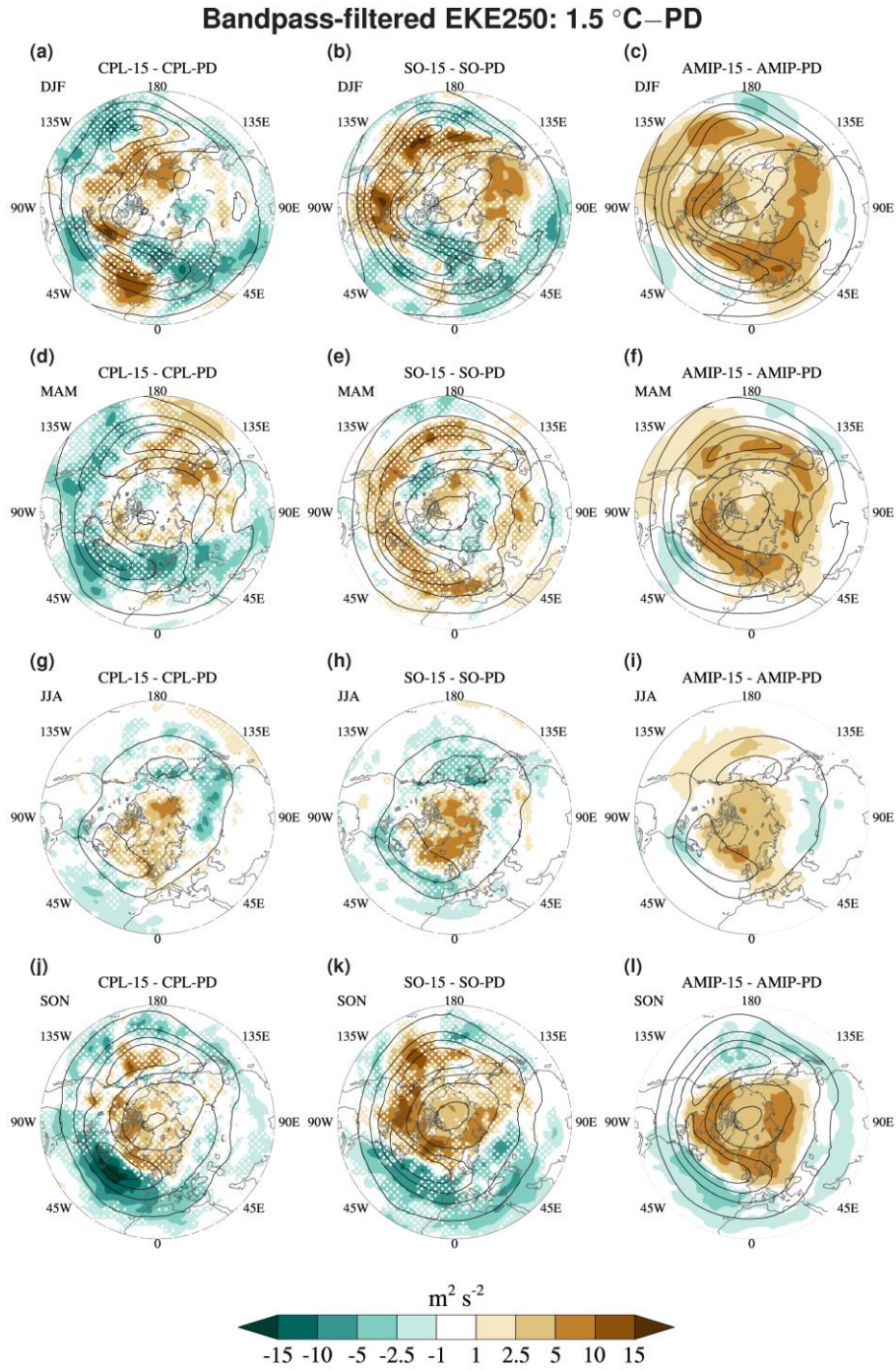


Figure 1342: **c**Changes in upper-level storm-track activity relative to PD (colors) and climatology (black contours; 40 to 240 $\text{m}^2 \text{s}^{-2}$ in increments of 40 $\text{m}^2 \text{s}^{-2}$) for the 1.5 K experiment from NorESM1-Happi (left; a, d, g, j), NorESM1-HappiSO (middle column; b, e, h, k), and NorESM1-HappiAMIP (right; e, f, i, l) for DJF (top row; a–c), MAM (middle row; d–f), JJA (third row; g–i), and SON (bottom; j–l). The storm tracks are represented in terms of bandpass-filtered EKE (eddy kinetic energy) at 250 hPa. The white dots indicate that the differences are not significant at the 5 % level according to the Welch t-test. The fields are shown for the default periods given in Sect. 3. Units are $\text{m}^2 \text{s}^{-2}$ (a–l).

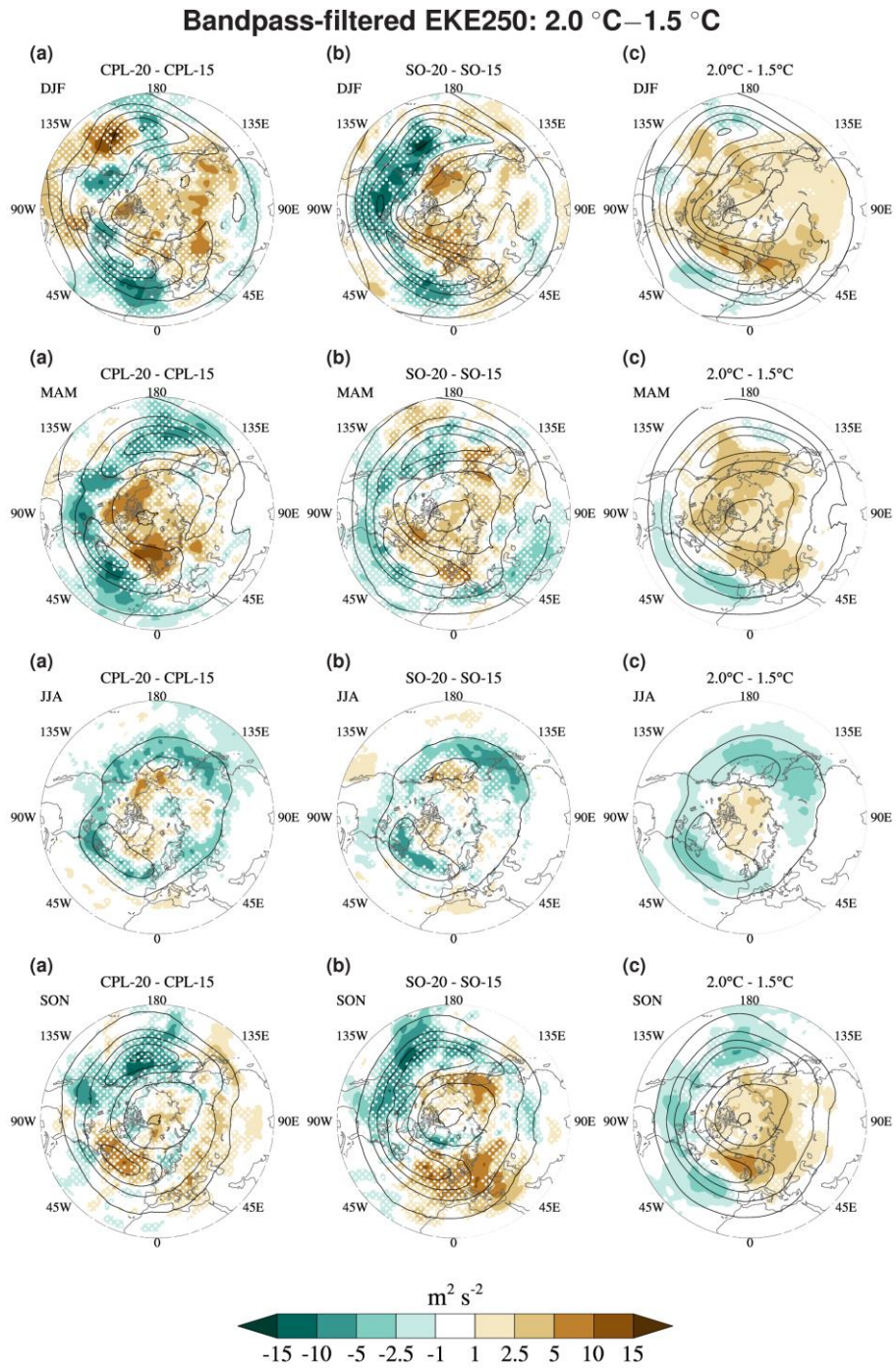


Figure 1443: aAs in Figure 13Figure 12, but for the upper-level storm-track response to the additional 0.5 K warming (i.e. the difference between the respective 2.0 K and 1.5 K experiments).

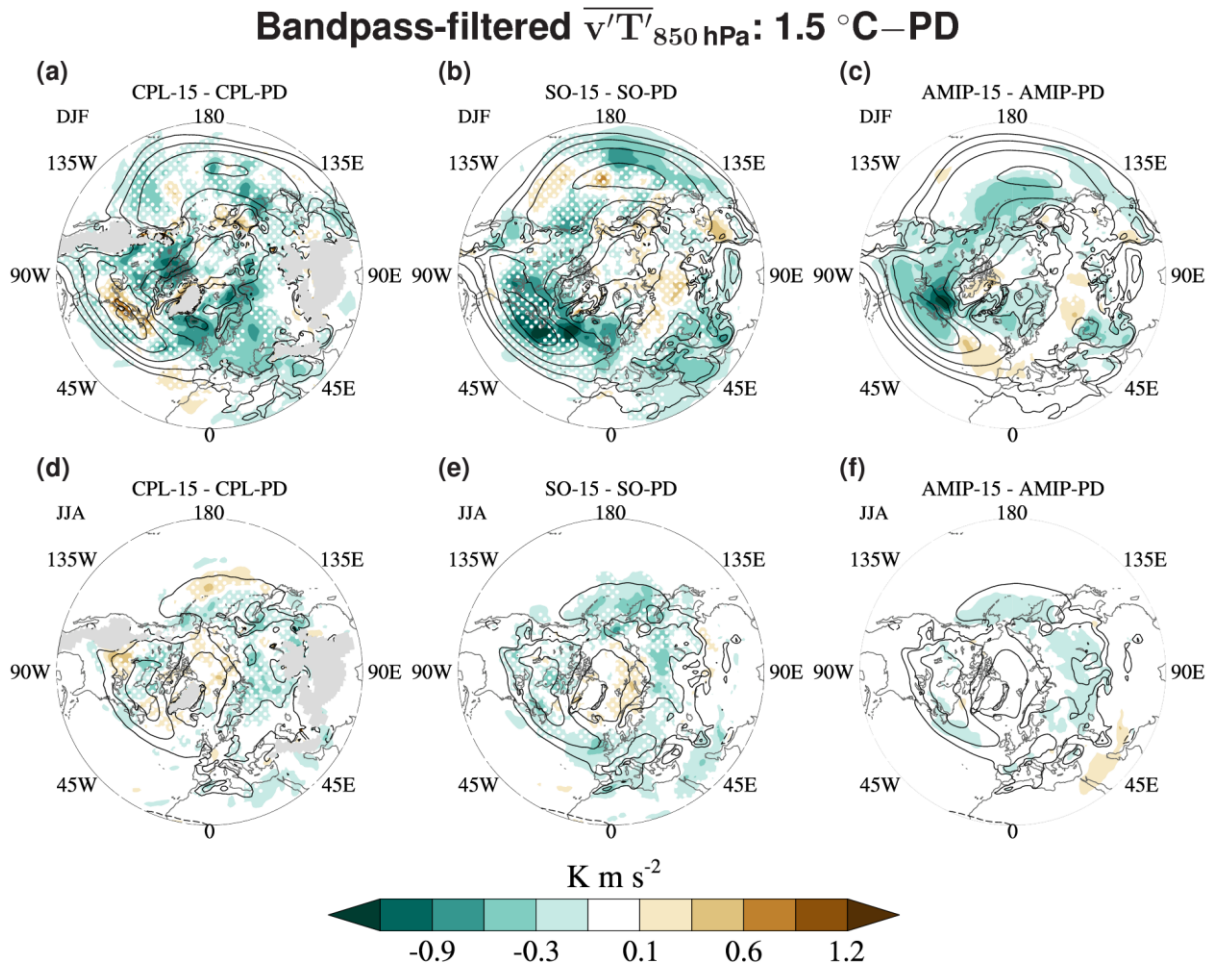


Figure 15-14: $\overline{v'T'}$ Changes in the low-level storm-track activity relative to PD (colors) and PD climatology (black contours; -12 to 12 K m s^{-2} in increments of 4 K m s^{-2}) for the 1.5 K experiment from NorESM1-Happi (left; panels a and d), NorESM1-HappiSO (middle; panels b and e) and NorESM1-HappiAMIP (right; panels c and f) for DJF (top; panels a–c) and JJA (bottom; panels d–f). The storm tracks are represented in terms of the bandpass-filtered eddy heat flux $\overline{v'T'}$ at 850 hPa. The white dots indicate that the differences are not significant at the 5 % level according to the Welch t-test. The fields are shown for the default periods given in Sect. 3. Units are K m s^{-2} (a–f).

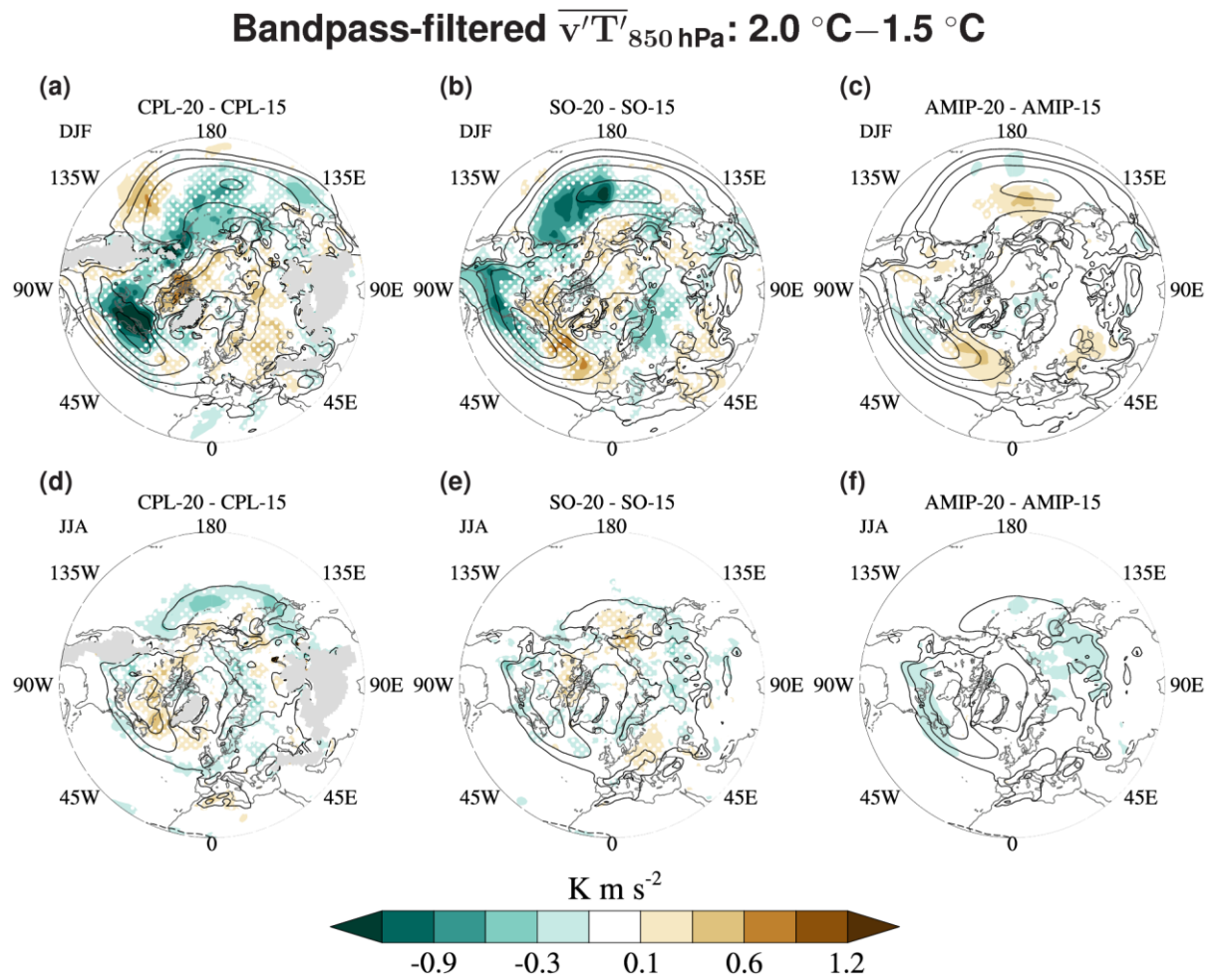


Figure 1645: As in Figure 15Figure 14, but for the low-level storm-track response to the additional 0.5 K warming (i.e. the difference between the 2.0 K and 1.5 K experiments).

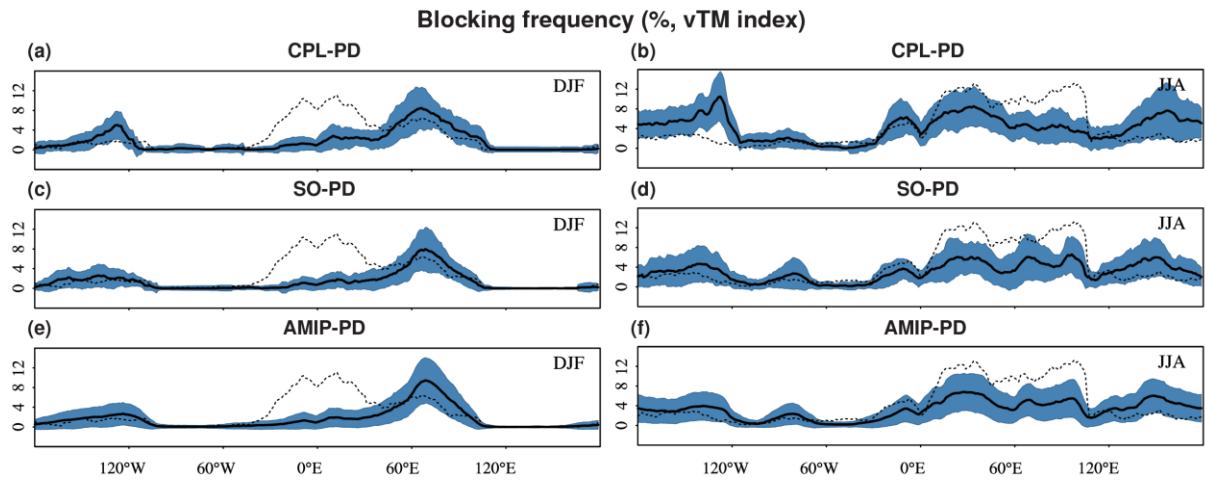


Figure 1746: PD climatology of blocking frequency from NorESM1-Happi (a–b), NorESM1-HappiSO (c–d), and NorESM1-HappiAMIP (e–f) for DJF (left; a, c, e) and JJA (right; b, d, f). Shown are the mean (solid black curve) and the spread (\pm one standard deviation) computed over the number of available decades (9 for NorESM1-Happi and NorESM1-HappiSO, and 125 for NorESM1-HappiAMIP) for the default time periods given in Sect. 3. Blocking frequency from ERA-Interim is shown for the period 1986–2015 (dotted black). The blocking events are identified using the the vTM index (Tibaldi and Molteni, 1990; Pelly and Hoskins, 2003), as in Iversen et al. (2013). It is based on the TM-index (Tibaldi and Molteni, 1990), which uses a persistent reversal of the meridional gradient of the 500-hPa geopotential height around the predefined central blocking latitude at 50 °N as an indicator for blocking. The reversal must be present at 7.5 ° consecutive longitudes and persist for at least 5 days. In the vTM index the requirement of a predefined central blocking latitude is relaxed in order to reduce spurious detection (Pelly and Hoskins (2003). The central latitude is allowed to vary with longitude following the latitude of the maximum in the climatological storm track (using bandpass-filtered geopotential height at 500 hPa). To account for the seasonal cycle of the cyclone activity, the central latitude for a given month is calculated as the climatological 3-month moving average centred on that month. Units are % (a–f).

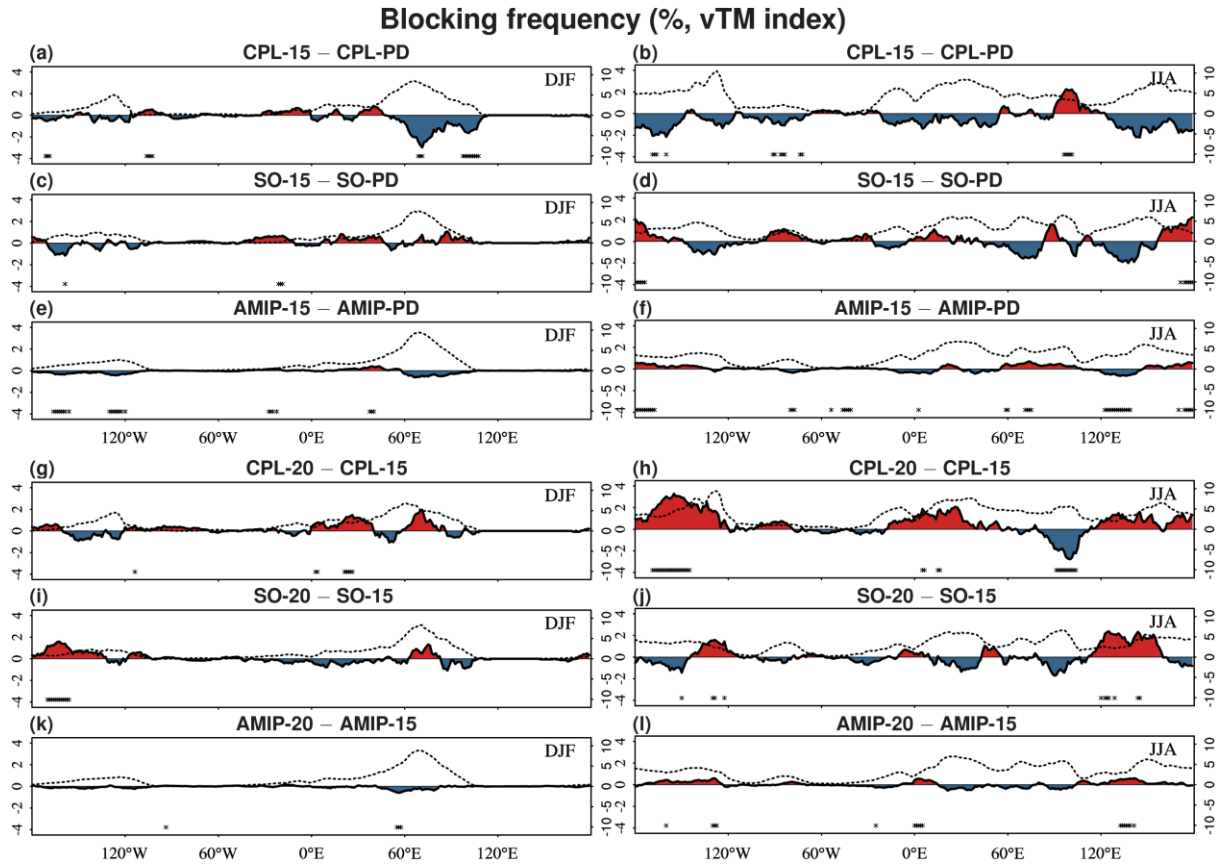


Figure 1817: Change in blocking frequency (solid black line with red and blue shading) in the 1.5 K experiment relative to PD (top three rows; a–f) and for the additional 0.5 K of warming (2.0 K–1.5 K; bottom three rows; g–l), shown along with the blocking climatology for the PD experiment (dotted black line). The fields are shown for the NorESM1-Happi (a, b, g, h), NorESM1-HappiSO (c, d, i, j), and NorESM1-HappiAMIP (e, f, k, l) during DJF (left; a, c, e, g, i, k) and JJA (right; b, d, f, h, j, l) for the default periods given in Sect. 3. The asterisks along the x-axis indicate where the changes at that longitude are statistically significant at the 5 % level according to the Welch t-test. Note that the left y-axis is for the difference field and the right y-axis is for the climatology. Units are % (a–l).

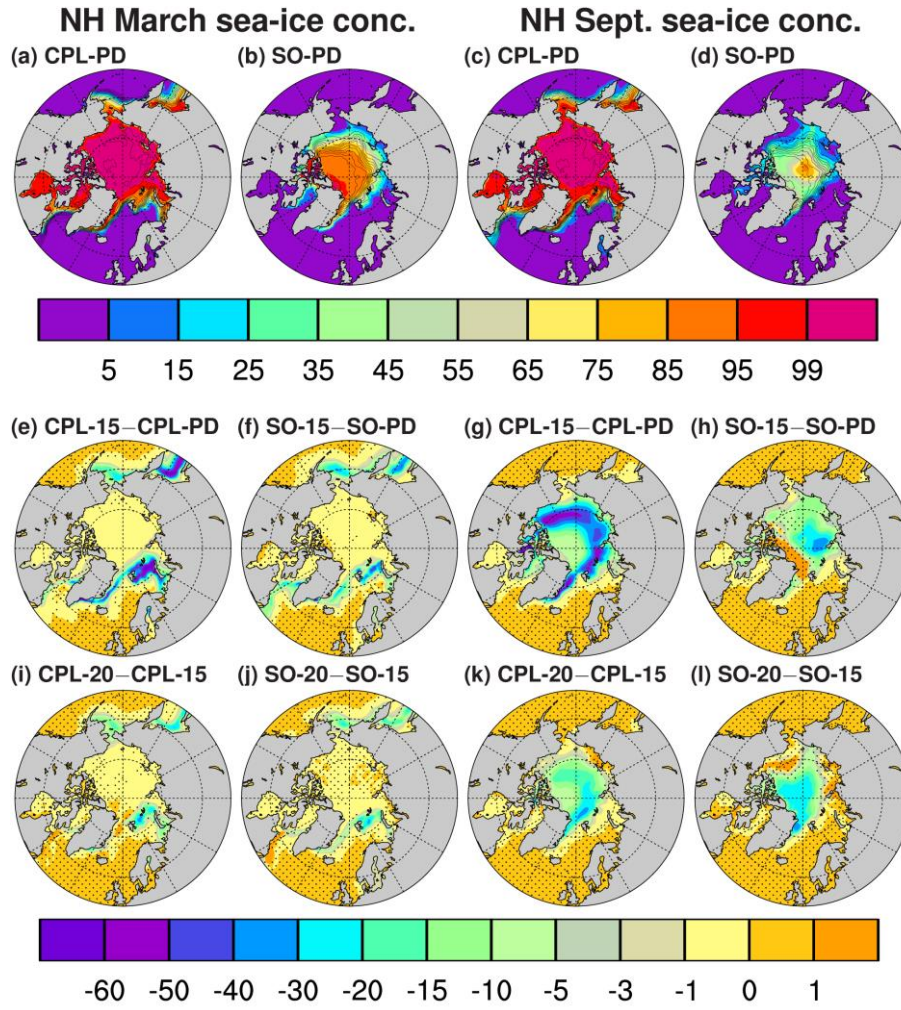


Figure 1948: NH monthly-mean sea-ice concentrations for PD (top; a–d), the 1.5 K warming relative to PD (second row; e–h), and the 0.5 K warming (bottom row; i–l) from NorESM1-Happi (first and third column; a, c, e, h, i, k) and NorESM1-HappiSO (second and fourth column; b, d, f, h, j, l). Fields are shown for March (first and second column; a, b, e, f, i, j) and September (third and fourth column; c, d, g, h, k, l). The concentrations from the SO model are averaged over 90 years after 60 years of spin-up. The PD results (colors; top color bar) are shown together with observational estimates (OSI-SAF, 2017; solid black contours). Differences that are not statistically significant at the 5 % level according to the Mann-Whitney U test are marked with black dots. Units are % of ocean surface area (a–l).

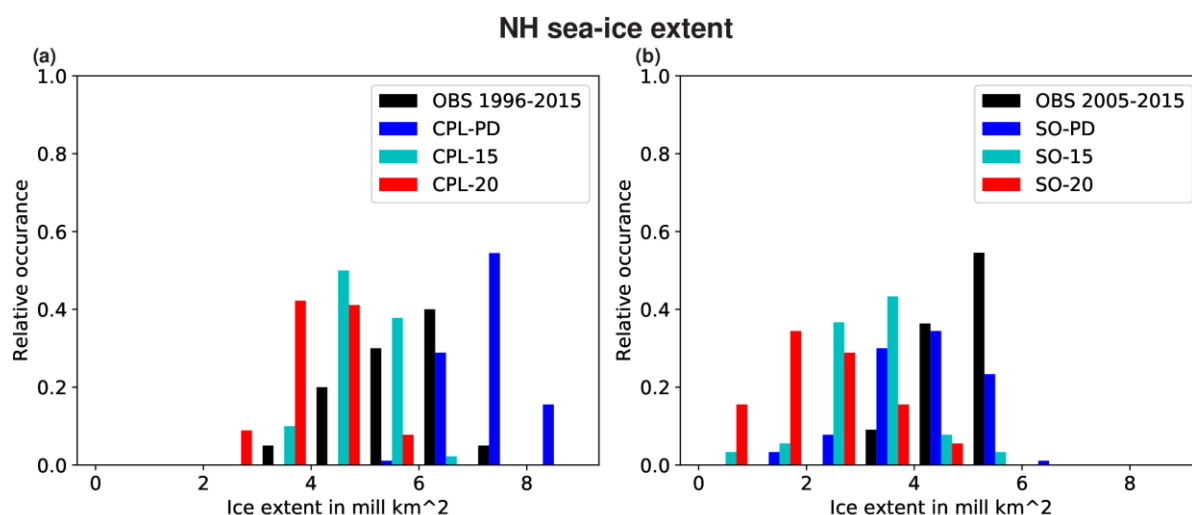


Figure 2019: The relative occurrence of NH monthly-mean sea-ice extent in September for observations (black bars; OSI-SAF, 2017), the PD experiments (blue bars), and the 1.5 K (green bars) and 2.0 K warming experiments (red bars) from NorESM1-Happi (a) and NorESM1-HappiSO. The sea-ice extent is binned in 1.0×10⁶ km² increments. The observations are from 1996–2015 (20 values) in (a) and from 2005–2015 (11 values) in (b). The PD values from NorESM1-Happi and NorESM1-HappiSO are from the default 90-year periods (Sect. 3.22).