

Reviewer #1 (Lauren Gregoire)

The manuscript suggests we know what the cause of the 8.2 kyr event was. I would be more careful in stating this. Although the 8.2 ka climatic event has been linked to the Agassiz lake discharge, the climate forcing is probably more complex than the freshwater flux used in this study. The lake release could have happened in two stages (Teller et al., 2002), potentially centuries apart and there may have been a pulse of meltwater from the Laurentide ice sheet (Gregoire et al., 2012). Törnqvist and Hijma [2012] provide a review of the 8.2 ka from a sea level point of view.

We added a sentence to the Introduction, pointing out these uncertainties. Then, we added a more complete summary of these uncertainties, including all the references suggested by the reviewer, to the Discussion.

p 3951 line 21 “the 8.2 ka event [...] duration [...] and forcing are well constrained”. I think “well constrained” is overstated.

Agreed, especially since one of our conclusions is that the duration and forcing are not well constrained. Replaced “well constrained” with “constrained by the proxy record” with no commentary on how well constrained.

Model description page 3952 line 6 : there needs to be a bit more detail on what are the “simplifications applied to the atmosphere component” of LOVECLIM. It could be important for understanding the results. A sentence would be enough.

We added sentences regarding the prescription of clouds, simplified vertical profiles of temperature and specific humidity, and the freshwater flux correction between atmosphere and ocean subcomponents.

page 3953 line 28 Why did you choose to use a ModelE-R experiment that was started from a period of weak AMOC ? Referring to the LeGrande and Schmidt, 2008 paper cited there, I can see that the weak AMOC state produces a better match to proxy records. I would like to see a bit more explanation on these AMOC states in this manuscript. If there were/are different AMOC states, is there a reason to think that the AMOC would have been in a weak AMOC state (no Labrador sea convection) at the 8.2 ka event ?

We added a sentence to explain that the weak case was chosen because it exhibits the response with longest duration and because Labrador Sea convection might have been weaker/absent in the early Holocene.

page 3954 line 1 : “we reduced the influence of this unforced variability through examining “decadal” results for this model (i.e., the 10-yr mean of the MWP experiment less the 30-yr mean of the relevant control years).” I don’t understand what this means, can this be clarified?

We have attempted to explain this better. In a nutshell, we are trying to more clearly show the transient response to the MWP, which can be obscured in this model due to large decadal variability.

page 3958, line 16, add a reference to Morrill et al. 2012

Done.

p 3959 line 6 : “Another factor in the model-data mismatch could be the size of the MWP”. Add here more discussion on the cause of the event and the fact that the freshwater forcing could be more complex.

We added a more complete summary of these uncertainties, including all the references suggested by the reviewer, to the Discussion.

Discussion section, page 3959, line 28: “A last explanation for the model-data discrepancies is that the models are not sensitive enough to freshwater perturbations.” Would it be possible to add a comment on how sensitive these GCMs are compared to other CMIP or PMIP GCMs ?

This is an interesting idea, but difficult given the few intercomparisons that have been completed for freshwater perturbation experiments. We added two sentences to the final paragraph that summarize what is known.

References: review the references carefully, I could not find any reference for Morrill et al. 2012 or Hu et al. 2009.

We added these, as well as Hoffman et al. 2012, Winsor et al., 2012, and Wagner et al., 2013 (all papers that were previously cited as in review).

figure 5 : I find it difficult to interpret anomalies in sea ice area. Can you add contours of sea ice extent on these plots ?

Done.

figure 8 : replace “the sign of the temperature anomaly” by “the sign of the precipitation anomaly”

Done. Thanks!

figure 8 : express the precipitation anomalies in % for consistency with the lower panel.

Done. Also, Figure 8b was updated with one additional proxy estimate of precipitation, as suggested by a reviewer of the companion Climate of the Past paper that summarizes the proxy record.

Reviewer #2 (Anonymous)

Major concerns:

Only decadal averages are shown for ModelE-R instead of annual averages for all the other models. This is motivated by large decadal variability (p3953, l29) and the availability of model data (caption of fig. 2). Regarding the first point, I strongly feel that the same data frequency should be shown for all models. A temporal filter can be applied to deal with low-frequency variability as has been for the other models. The reader should be given the opportunity to judge for himself. If indeed annual output was not kept in the original simulation, the authors should be able to re-run it with reasonable effort. They have the expertise as one of the co-authors has published with ModelE-R in the past and given the very low resolution of the model the simulation of 200 years can not take more than a couple of hours on a modern desktop computer.

While we agree with the reviewer in principle, annual data are not available and it is not feasible at this time to re-run the simulations. We argue for two reasons that the decadal averages are sufficient for this study. First, the main conclusions of this paper would not change were the annual data presented. Event duration is best discussed on a decadal basis, and the multi-model ensemble mean anomaly maps are averaged over 50 years. Second, annual output would not improve model-data comparisons because most proxy records do not have annual resolution and no proxy records have age models with +/- one year uncertainty.

The discussion of circulation changes is limited to the AMOC. Several recent studies demonstrated that changes in the deep ocean circulation can not be fully understood without addressing the routing of the freshwater anomaly by surface currents. Condrón and Winsor (2011) showed that more freshwater is entrained in the Atlantic subtropical gyre with higher spatial model resolution, a theory that could easily be tested in the present study. Proxy data (Lewis et al., 2012) and a coarse resolution model (Born et al., 2010) suggest that a sizable portion of the freshwater volume did reach the Nordic Seas. In addition to the modification of the freshwater pulse by the surface (gyre) circulation, this latter study also concludes that the subpolar gyre circulation reacted to the forcing, speculating that this might have contributed to the onset of Labrador Sea deep convection. I suggest to include figures for mixed layer depth and barotropic stream function for all models.

We added these figures for mixed layer depth and barotropic stream function (new figures 2 and 6). Regarding routing of freshwater by surface currents, we expanded that discussion in section 3.2 and added the references suggested by the reviewer. None of the models in this study is eddy-resolving, so our ability to test the results of Condrón and Winsor (2011) is limited. New text sections in 3.1 and 3.3 were added to present the mixed layer depth and barotropic stream function results.

Partly related to this previous point, the discussion of the role of Labrador Sea deep convection is confusing and probably too brief. I think this is important to discuss since Labrador Sea deep convection started at about the time of the 8.2 ka event (Hillaire-Marcel et al., 2001) and has been associated with the freshwater pulse (Born et al., 2010).

- a) What exactly causes the different response in LOVECLIM compared to ECBilt-Clío if the two models are virtually identical?
- b) Did the background freshwater flux in CCSMall shut down Labrador Sea deep convection?
- c) The motivation for CCSMog was that it was more like ModelE-R in terms of boundary conditions but would it not be worthwhile to analyze a second version of ModelE-R with Labrador Sea convection in order to compare it to CCSM3?

New text sections in 3.1 and 3.3 describe the mixed layer depth and barotropic stream function results. We do not observe a strengthening of the subpolar gyre, as in Born et al. (2010), and this is discussed further in section 3.3. To make the ECBilt-CLIO and LOVECLIM experiments more directly comparable, we re-ran the LOVECLIM simulation with complete 8.5 ka boundary conditions (all tables and figures have been updated with the new LOVECLIM simulation). The boundary conditions did not explain the different outcomes to freshwater forcing in the simulations, so we also added text to the discussion to offer some other possible explanations. We explain in section 3.1 and new

figure 2 that the background freshwater flux in CCSMall does not shut down Labrador Sea convection. We chose not to include a second version of the ModelE-R in this paper because, unlike the CCSM experiments, it has been documented thoroughly in the published literature (LeGrande et al., 2006; LeGrande and Schmidt, 2008) and our goal was to present the experiments with longest response to the freshwater perturbation.

Minor comments:

p3951, l8: "...Earth system models of..." - "system" missing
Done.

p3952, l24: "pre-industrial" - with lowercase "i"
Done.

p3953, l9: "Global mean ocean..." - please include a reference.
Done.

p3955, l12: "...it appears that then a significant amount enters the Greenland-Iceland-Norwegian Seas..." - This can not be seen in the figure. Has it been quantified?
This sentence was changed as part of the revisions related to gyre transport (see above).

p3955, l21: "Areas of positive SSS ... are caused by the cessation of the 0.05 Sv background meltwater flux..." - Can this be quantified? This statement seems highly unlikely given the weakness of the freshwater flux and the large positive salinity anomaly. Since the subpolar front and the North Atlantic Current are also located in this region, a shift of the current provides another plausible explanation. The analysis of changes in the barotropic stream function can clarify this question as well as some of the issues mentioned above.

We considered these other explanations, but cessation of the 0.05 Sv background meltwater flux seems to be the most likely cause. We observed a large negative salinity anomaly in the same location and of the same absolute magnitude when we began to add the 0.05 Sv background flux to the control simulation. Also, the changes in the barotropic stream function associated with the MWP (now shown in Figure 6) are not in the correct direction to explain a large positive salinity anomaly. These two facts lead us to believe that the large positive salinity anomaly is associated with the cessation of the background flux rather than the MWP. We also note that while the 0.05 Sv flux is small, it is five times the normal output of the St. Lawrence River in the model.

p3956, l19: subscript "all" and "og" misplaced
These must have been errors in the typesetting, as they are correct in the Microsoft Word document we submitted.

The reference for the following citations is missing (not a comprehensive list): Hoffmann et al., 2012; Winsor et al., 2012; Morrill et al., 2012.

We added full references for these citations and checked for others that were missing.

Model sensitivity to North Atlantic freshwater forcing at 8.2 ka

C. Morrill^{1,2}, A. N. LeGrande³, H. Renssen⁴, P. Bakker⁴ and B.L. Otto-Bliesner⁵

[1]{Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO USA}

[2]{National Oceanic and Atmospheric Administration's National Climatic Data Center, Boulder, CO USA}

[3]{NASA Goddard Institute for Space Studies and Center for Climate Systems Research, New York, NY USA}

[4]{Department of Earth Sciences, VU University Amsterdam, The Netherlands}

[5]{Climate and Global Dynamics, National Center for Atmospheric Research, Boulder, CO USA}

Correspondence to: C. Morrill (carrie.morrill@colorado.edu)

Abstract

We compared four simulations of the 8.2 ka event to assess climate model sensitivity and skill in responding to North Atlantic freshwater perturbations. All of the simulations used the same freshwater forcing, 2.5 Sv for one year, applied to either the Hudson Bay or Labrador Sea. This freshwater pulse induced a decadal-mean slowdown of 10-25% in the Atlantic Meridional Overturning Circulation (AMOC) of the models and caused a large-scale pattern of climate anomalies that matched proxy evidence for cooling in the Northern Hemisphere and a southward shift of the Intertropical Convergence Zone. The multi-model ensemble generated temperature anomalies that were just half as large as those from quantitative proxy reconstructions, however. Also, the duration of AMOC and climate anomalies in three of the simulations was only several decades, significantly shorter than the duration of ~150 years in the paleoclimate record. Possible reasons for these discrepancies include incorrect

representation of the early Holocene climate and ocean state in the North Atlantic and uncertainties in the freshwater forcing estimates.

1 Introduction

The Atlantic Meridional Overturning Circulation (AMOC) plays a key role in the climate system, particularly through its control on heat transport and storage of carbon in the deep ocean. Changes in the AMOC can have far-reaching effects on the El Niño-Southern Oscillation (Timmermann et al., 2005), Atlantic hurricane development (Zhang and Delworth, 2006), tropical rainfall (Vellinga and Wood, 2002), and marine ecosystems (Schmittner, 2005). Model simulations of the 21st century with prescribed greenhouse gas concentrations increasing according to the Intergovernmental Panel on Climate Change (IPCC) scenario SRESA1B uniformly show a reduction in the strength of the AMOC (Schmittner et al., 2005). This multi-model ensemble yields a mean decrease of 25% by 2100, but there is a large range in the individual model results that indicates substantial uncertainties in the AMOC response to climate change.

Several previous model intercomparison projects were undertaken to improve understanding of the large spread in modeled AMOC. Schmittner et al. (2005) considered the skill of nine coupled climate models in matching observations of modern hydrography. They found that the models were more successful at reproducing temperature patterns than either salinity patterns or pycnocline depth. Stouffer et al. (2006) examined the response of both Earth system models of intermediate complexity (EMICs) and coupled atmosphere-ocean general circulation models (AOGCMs) to North Atlantic freshwater forcings of 0.1 and 1.0 Sv (Sverdrup = 10⁶ m³/s) for 100 years. While there were some robust patterns among the models, important disagreements existed in model sensitivity and in reversibility following AMOC shutdown. Since these were idealized experiments, no comparison to observations was possible. Otto-Bliesner et al. (2007) compared AMOC in four Last Glacial Maximum simulations from the second phase of the Paleoclimate Modelling Intercomparison Project (PMIP2). These models gave very different glacial circulations and a comparison to paleoclimate proxy evidence indicated serious mismatches for several of the simulations.

For the third phase of PMIP, the 8.2 ka event has been targeted for a new model intercomparison. Of past abrupt changes in the AMOC, the 8.2 ka event provides a particularly useful case study because its duration (~150 years; Thomas et al., 2007) and

forcing are ~~well~~-constrained by the proxy record, making an achievable target for climate model simulations (Schmidt and LeGrande, 2005). There are still some uncertainties regarding the hypothesized forcing of the event, including the volume of ~~The hypothesized cause of the 8.2 ka event, haline forcing from the~~ drainage ~~of from~~ proglacial Lake Agassiz-Ojibway (hereafter Lake Agassiz; Barber et al., 1999) into the Hudson Bay ~~and the possibility of multiple meltwater pulses from both the lake and the collapsing Laurentide Ice Sheet (Teller et al., 2002;Gregoire et al., 2012).~~ ~8200 years ago, is not a perfect analog to the thermal forcing of the AMOC predicted for the future (Gregory et al., 2005). Model sensitivity to some of these uncertainties has been explored elsewhere (Renssen et al., 2001;Wiersma et al., 2006;LeGrande and Schmidt, 2008;Clarke et al., 2009;Wiersma and Jongma, 2010;Wagner et al., 2013). The target of this intercomparison is to use a median value for the forcing of the 8.2 ka event and compare model sensitivity to North Atlantic surface buoyancy anomalies that have precise dating and a duration short enough to make simulations with state-of-the-art coupled climate models feasible ~~Nonetheless, the 8.2 ka event offers a test of model sensitivity to North Atlantic surface buoyancy anomalies that has precise dating, quantified forcing, and a duration short enough to make simulations with state-of-the-art coupled climate models feasible~~ (Schmidt and LeGrande, 2005;Thomas et al., 2007;Kobashi et al., 2007).

2 Models and experiments

We compare 8.2 ka experiments completed with three models: the Community Climate System Model version 3 (CCSM), the Goddard Institute for Space Studies (GISS) ModelE-R and LOVECLIM version 1.2. CCSM and ModelE-R are atmosphere-ocean general circulation models (AOGCMs) coupled without flux adjustments. LOVECLIM is an Earth system model of intermediate complexity with its most significant simplifications applied to the atmosphere component (Table 1). These simplifications include clouds that are prescribed and vertical profiles of temperature and specific humidity that are limited by three atmospheric levels. LOVECLIM also employs a freshwater flux correction between the atmosphere and ocean subcomponents that removes excess precipitation from the Arctic and Atlantic and adds it to the North Pacific (Goosse et al., 2010).

Of relevance to this study, the ocean models of ModelE-R and LOVECLIM are mass-conserving, in which the addition of freshwater causes a rise in the free surface of the ocean

1 and reduces salinity purely through dilution. The ocean model component of CCSM uses the
2 rigid-lid approximation, which does not permit vertical motion at the top of the ocean and
3 parameterizes the addition of freshwater as a salt extraction while keeping the volume of the
4 ocean constant. Yin et al. (2009) discuss the differences between these two approaches and
5 compare results from two versions of the GFDL CM2.1 model using each formulation. For a
6 large freshwater forcing that is similar in magnitude to that used in 8.2 ka experiments, the
7 rigid-lid version exaggerates the forcing and there are significant regional biases in sea
8 surface salinity (SSS). Despite this, the AMOC behaves similarly in the two versions and
9 many fundamental aspects of the two simulations are qualitatively similar.

10 Boundary conditions specified for the control simulations are listed in Table 2. Early
11 Holocene orbital forcing increased the seasonality of insolation in the Northern Hemisphere
12 and decreased seasonality in the Southern Hemisphere relative to the present (Berger, 1978).
13 Greenhouse gas concentrations for the Early Holocene were nearly identical to those for the
14 recent pre-Industrial period (Flückiger et al., 2002; Monnin et al., 2004). Two of the control
15 simulations, CCSM_{all} and LOVECLIM, incorporated the surface albedo and elevation effects
16 of the remnant of the Laurentide Ice Sheet that was present near Hudson Bay at 8.5 ka, as
17 reconstructed by Peltier (2004). These same control simulations also included a small (~0.05
18 Sv) background flux of Laurentide meltwater (Licciardi et al., 1999). In CCSM_{all}, this
19 freshwater flux was added to the modeled St. Lawrence River at its outflow, and was spread
20 as a virtual salinity flux along the coast near the river's mouth. In LOVECLIM, the freshwater
21 was added as a volume to the upper layer of the ocean at the Hudson Strait. Since the ocean
22 model in LOVECLIM has a free surface, this effectively means that the surface height was
23 raised. The temperature of the added freshwater in LOVECLIM was assigned the same
24 temperature as the water in the ocean cell to which it was added. Both of these control
25 simulations with background meltwater flux were integrated until reaching a quasi-
26 equilibrium, in which SSS of the North Atlantic had stabilized. Global mean ocean salinity
27 decreases slowly throughout these control simulations due to the background meltwater flux,
28 a trend that parallels observed freshening ~~during the late glacial and early Holocene~~ since the
29 Last Glacial Maximum (Adkins et al., 2002). A second CCSM control simulation (CCSM_{og},
30 OG=orbital and greenhouse gas only) without a Laurentide Ice Sheet and background
31 meltwater flux is included in this study for a more direct comparison to ModelE-R results.

For the 8.2 ka event experiments, a meltwater pulse (MWP) of 2.5 Sv for 1 year was added to each of the control simulations to represent the drainage of Lake Agassiz. This freshwater volume was the best estimate for the drainage event based on flood hydrograph simulations (Clarke et al., 2004). Following the one-year perturbation, the MWP ceased and the climate was allowed to recover. In the models with a free-surface ocean, the MWP was added as a volume to a limited number of grid cells. In ModelE-R, freshwater was added to the approximately 20 grid boxes in the Hudson Bay and was assigned a temperature of 0°C. In LOVECLIM, freshwater was added to the upper layers of the ocean at the Hudson Strait and was assigned the same temperature as the water in the ocean cell to which it was added. The virtual salinity flux in CCSM required a larger area for the MWP (50°-65°N, 35°-70°W).

The control simulation for ModelE-R displayed a number of transient, quasi-stable states with either strong or weak AMOC (LeGrande et al., 2006; LeGrande and Schmidt, 2008). For this study, we use an experiment begun from a period of weak AMOC. The weak case was chosen because it exhibited the longest response to the 2.5 Sv x 1 year forcing, and because it may more closely emulate the early Holocene than periods with strong AMOC since it lacks deep convection in the Labrador Sea (see LeGrande and Schmidt, 2008 for further detail). Since the weak case exhibits some high amplitude decadal variability, we ~~reduced the influence of this unforced variability through examining~~ examined “decadal” results for this model (i.e., the 10-year mean of the MWP experiment less the 30-year mean of the ~~relevant closest~~ control years) in order to more clearly show the transient response to the MWP.

3 Response to freshwater forcing

3.1 AMOC

AMOC intensity is defined here as the maximum of the Atlantic overturning streamfunction excluding the surface (<500 m) wind-driven overturning circulation. Mean values for the control simulations range from 16 to 20 Sv (Figure 1), and interannual variability is small in the three simulations with available annual output (standard deviations: LOVECLIM = 0.7, CCSM_{og} = 1.1, CCSM_{all} = 0.9 Sv). AMOC intensity is lower by several Sv in the simulations with a background meltwater flux. AMOC has a similar structure in all the control simulations. The northward flow of warm, salty water occurs in the upper 1000 m, while the southward return flow of North Atlantic Deep Water occurs between 1000-3000 m. The

anticlockwise cell in the deep ocean, associated with Antarctic Bottom Water formation, has a strength of about 4 Sv in all control simulations.

The values of AMOC intensity in the control simulations are generally similar to the strength of the modern-day AMOC (Meehl and Coauthors, 2007). Proxy evidence suggests that the strength of the AMOC during the early Holocene was probably not that different from today (Bianchi and McCave, 1999; Hall et al., 2004; Oppo et al., 2003; McManus et al., 2004; Praetorius et al., 2008). There is some proxy evidence for lack of convection and deep water formation in the Labrador Sea during the early Holocene, however (e.g., Hillaire-Marcel et al., 2001; Solignac et al., 2004; Fagel et al., 2004). To reconcile a vigorous AMOC with lack of Labrador Sea convection, some other convection area, perhaps in the Irminger Basin, might have been stronger in the early Holocene to offset the weaker Labrador Sea convection (Hall et al., 2010).

The location and strength of convection areas in the North Atlantic varies significantly among the control simulations (Figure 2). Convection occurs primarily in the Nordic Seas in one of the models (LOVECLIM), primarily in the Irminger Sea in another (ModelE-R), and in both the Nordic Seas and just east of the Labrador Sea in the third model (CCSM). Notably, the background meltwater flux of 0.05 Sv does not shut down convection just east of the Labrador Sea in the CCSM_{all} control simulation (Figure 2), as that flux is routed to the south of the Labrador Sea by ocean surface currents.

Following the 2.5 Sv MWP for one year, AMOC intensity decreases in all simulations (Figure 23). The maximum decadal-mean decline in LOVECLIM and CCSM is about 10%, while for ModelE-R it is about 25%. The decline in AMOC intensity in LOVECLIM and CCSM is relatively short-lived, on the order of several decades, and generally within the range of natural variability of AMOC in their control simulations. Similarly, mixed-layer depths shoal significantly following the MWP, but this weakening of convection also lasts several decades or less (not shown). The response in ModelE-R is more pronounced and longer-lived, extending on the order of 100-120 years. Proxy records do not provide a quantitative estimate of AMOC weakening at 8.2 ka, but do suggest a duration of 100-200 years (Ellison et al., 2006; Kleiven et al., 2008).

3.2 Ocean salinity and temperature

Significant freshening of the North Atlantic occurs following the MWP in all simulations (Figure 34). The largest anomalies are generally along the coast of Labrador and are up to 1 psu when averaged over the first fifty years following the MWP. Areas of positive SSS anomalies at the mouth of the St. Lawrence River in CCSM_{all} are caused by cessation of the 0.05 Sv background meltwater flux once Lake Agassiz has drained. Globally, negative anomalies greater than 0.2 psu are confined to the North Atlantic and Arctic oceans (not shown).

Patterns of SSS anomalies suggest that ~~From the Labrador Sea,~~ freshwater travels eastward from the Labrador Sea into the North Atlantic in all simulations. For most of the simulations, ~~it appears that then a significant amount enters~~ SSS decreases in both the Greenland-Iceland-Norwegian Seas and ~~a somewhat smaller amount is entrained~~ in the subtropical gyre. This pathway is different from that inferred by Keigwin et al. (2005), who used $\delta^{18}\text{O}$ of planktic foraminifera to suggest salinity was decreased near Cape Hatteras around 8.2 ka. Also, it has been argued that freshwater released from Hudson Strait would not reach the Nordic Seas, instead being ~~would be~~ trapped along the North American coast ~~and would not easily escape to the open North Atlantic~~ (e.g., Wunsch, 2010) or circulating in the subtropical gyre (Condrón and Winsor, 2011). However, ~~there is evidence from~~ several proxy records from the Irminger and Labrador Seas ~~that~~ combine $\delta^{18}\text{O}$ and Mg/Ca of planktic foraminifera to infer decreases in $\delta^{18}\text{O}$ of seawater at 8.2 ka of up to 1‰ (Came et al., 2007; Thornalley et al., 2009; Ellison et al., 2006; Winsor et al., 2012; Hoffman et al., 2012), which would be equivalent to a freshening of ~0.7 psu assuming the Laurentide Ice Sheet meltwater was about -25‰ (Hillaire-Marcel et al., 2007) . Also, the location of detrital carbonate layers deposited around 8.2 ka indicate greater freshwater transport in the outer branch of the Labrador Current, which typically mixes with the North Atlantic Current and travels to the Nordic Seas (Lewis et al., 2012). The model simulations presented here, as well as others published by Born and Levermann (2010) and Spence et al. (2008), tend to support some amount of freshwater transport into the Nordic Seas. Areas of positive SSS anomalies at the mouth of the St. Lawrence River in CCSM_{all} are caused by cessation of the 0.05 Sv background meltwater flux once Lake Agassiz has drained. Globally, negative anomalies greater than 0.2 psu are confined to the North Atlantic and Arctic oceans (not shown).

Likewise, sea surface cooling is concentrated in the North Atlantic in all simulations (Figure 45). Mean anomalies across the North Atlantic for the first fifty years following the MWP are on the order of 1°C, though they exceed 2°C locally in the CCSM and ModelE-R experiments. Maximum anomalies in the LOVECLIM simulation are on the order of ~0.5°C and are located in the far North Atlantic. ModelE-R shows cooling on the order of several tenths of a degree Celsius across most of the Southern Hemisphere. The other simulations show little significant change south of 30°N with the exception of CCSM_{all}, which has some significant warming in the south Atlantic.

3.3 Barotropic streamfunction

A common model diagnostic for the ocean circulation, including the strengths of the subtropical and subpolar gyres in the North Atlantic, is the vertically-integrated mass transport (barotropic) streamfunction. Values for this quantity are available for three of the simulations (Figure 6). In all of these simulations, transports in both the subtropical gyre and the subpolar gyre weaken for a few decades following freshwater forcing. This result is consistent with the concept that reduction of deep convection in the core of the subpolar gyre, as occurs briefly in these simulations in the Labrador and/or Irminger Seas, weakens this circulation (e.g., Häkkinen and Rhines, 2004).

On the other hand, Born and Levermann (2010) found a prolonged strengthening of the subpolar gyre circulation in a simulation of the 8.2 ka event with the CLIMBER-3 α model. In this model, a reduction of deepwater formation in the Nordic Seas intensified the subpolar gyre and triggered internal feedbacks to increase and maintain deep convection in the Labrador Sea. If true, this could explain the onset of deepwater formation in the Labrador Sea around the time of the 8.2 ka event (e.g., Hillaire-Marcel et al., 2001). The different response in CLIMBER-3 α might be explained by the fact that the freshwater perturbation had less of a direct impact on the Labrador Sea convection region and instead had greater advection to the Nordic Seas (Born and Levermann, 2010).

3.3.4 Sea ice

All of the simulations have areas of significantly expanded sea ice following freshwater forcing, particularly in the Labrador Sea and in the Norwegian and/or Barents Sea (Figure 57). Generally, these changes for the first fifty years following the MWP are on the order of

5-10%, although they can be as large as 20-25% in some areas. Sea ice changes in the Southern Ocean have a heterogeneous spatial pattern and generally are not statistically significant.

3.43.5 Surface air temperature

The North Atlantic region and the Arctic become significantly colder in most simulations during the first fifty years following the MWP, with mean annual temperatures in the multi-model ensemble decreasing less than $\sim 0.5^{\circ}\text{C}$ over Europe and $\sim 1.0^{\circ}\text{C}$ over Greenland (Figure 68). These results hold for individual ensemble members, as well, for both Europe (40°N - 60°N , 10°W - 30°E ; anomalies are LOVECLIM = 0.0°C , CCSM_{og} = -0.3°C , CCSM_{all} = -0.5°C , ModelE-R = -0.6°C) and Greenland (60°N - 80°N , 60°W - 20°W ; anomalies are LOVECLIM = 0.0°C , CCSM_{og} = -0.6°C , CCSM_{all} = -0.4°C , ModelE-R = -0.8°C). Temperature changes are minimal in the tropics and the Southern Hemisphere. This spatial pattern agrees well with proxy records, which clearly indicate colder conditions across the Northern Hemisphere during the 8.2 ka event but suggest that any Southern Hemisphere temperature changes were likely regional (Figure 68).

The magnitude of circum-North Atlantic temperature changes inferred from proxies is somewhat larger than those in the models. Temperature reconstructions from pollen and $\delta^{18}\text{O}$ in Europe consistently show anomalies of about -1.1 to -1.2°C in mean annual temperature during the 8.2 ka event, although standard errors of these reconstructions are nearly as large as the anomalies themselves (Veski et al., 2004; von Grafenstein et al., 1998; Sarmaja-Korjonen and Seppä, 2007; Feurdean et al., 2008). Nitrogen isotopes from Greenland indicate temperatures decreased about 2.2°C averaged over the duration of the event, with an even larger decrease of 3.3°C during the most extreme 60-year period (Kobashi et al., 2007).

Anomalies over the North Atlantic in the LOVECLIM and CCSM experiments are short-lived; generally, temperature values are outside the range of natural variability (defined as the mean ± 2 standard deviations of the control) for less than two decades (Figure 79). Anomalies are longer-lived in the ModelE-R simulation, lasting on the order of 100 years. These longer-lived anomalies are a better match to high-resolution proxy records from Europe and Greenland, which consistently show an event duration of 100 to 150 years (Morrill et al., 2012).

3.53.6 Precipitation

Despite the noise inherent in precipitation, a number of features are common among the model simulations for the fifty years following the MWP. In all cases, the most important changes are a reduction in precipitation over the North Atlantic and Northern Hemisphere tropics, and an increase in precipitation over the Southern Hemisphere tropics (Figure 108). The tropical pattern, consistent with a southward shift of the mean position of the Intertropical Convergence Zone, is clearest over the Atlantic Ocean (Figure 119). Tropical proxy records from both speleothem $\delta^{18}\text{O}$ measurements and indicators of lake water balance support this spatial pattern (Figure 108).

Several quantitative estimates of drying exist from proxies in high northern latitudes; these include an ~8% reduction in accumulation in central Greenland ice cores and an ~17% reduction in rainfall inferred from pollen north of the Mediterranean, although again the standard errors of these reconstructions are nearly as large as the anomalies themselves (Feurdean et al., 2008; Pross et al., 2009; Hammer et al., 1997; Rasmussen et al., 2007). The model simulations generally match the magnitude of drying in central Greenland, but typically do not match either the direction or magnitude of change in southeastern Europe. Additionally, evidence for wetter conditions at 8.2 ka from pollen and lake geochemical records in northern Europe is not matched by the freshwater experiments (Figure 108).

4 Discussion and Conclusions

To summarize, the models generally do a good job in reproducing large-scale patterns of temperature and precipitation changes at 8.2 ka inferred from proxy records. These patterns include cooling across most of the Northern Hemisphere and a southward shift of the Intertropical Convergence Zone. The models have less success in matching the magnitude and duration of climate anomalies. Temperature changes in the multi-model ensemble are about half the size of those of quantitative proxy records from Europe and Greenland. For all but one of the simulations, the duration of the 8.2 ka climate anomalies is on the order of several decades rather than the ~150 years observed in proxy records. Also, there are discrepancies between model and data for some regional-scale anomaly patterns, including precipitation changes in Europe. These patterns are less well-constrained by proxy evidence, however.

1 The background climate state of the early Holocene, and the location of convection areas in
2 the North Atlantic more specifically, might explain some of the differences we see between
3 models and proxy data. The ModelE-R simulation has the best match to proxies for event
4 duration, and it has been previously demonstrated for this model that the lack of Labrador Sea
5 convection is essential for this response (LeGrande and Schmidt, 2008; LeGrande et al., 2006).
6 Previous work with the ECBilt-CLIO model also supports this interpretation; when Labrador
7 Sea convection is weakened by the background meltwater flux, ~~in that model,~~ the ocean's
8 ability to transport freshwater anomalies away from the North Atlantic is diminished and the
9 response to freshwater forcing is prolonged (Wiersma et al., 2006). On the other hand, lack of
10 convection in the Labrador Sea does not lead to a long-lived climate response in ~~the~~
11 ~~LOVECLIM experiment~~ this model's successor, LOVECLIM. While the exact reasons for this
12 have yet to be determined, the background meltwater flux used in the LOVECLIM
13 experiment is less than that in the ECBilt-CLIO experiments (0.05 vs. 0.17 Sv; Wiersma et
14 al., 2006; Li et al., 2009) and it seems that LOVECLIM is also less sensitive to freshwater
15 perturbations than its predecessor. Plus Also adding uncertainty to the importance of
16 convection strength in the Labrador Sea, proxies indicate that AMOC strength was not too
17 different from today during the early Holocene. In this case, some other convection area,
18 perhaps in the Irminger Basin, might have been stronger in the early Holocene to offset the
19 weaker Labrador Sea convection (Hall et al., 2010). If this was true, the strengthened
20 convection areas elsewhere might be able to compensate for decreased freshwater divergence
21 in the Labrador Sea.

22 Another factor in the model-data mismatch could be the size or the complexity of the MWP.
23 The model simulations were forced with 2.5 Sv for one year, which was the best estimate of
24 the flood hydrograph simulations of Clarke et al. (2004). As these authors point out, though,
25 the total volume of Lake Agassiz ~~w~~ould have generated twice this forcing and more complex
26 multipulse patterns are possible (Teller et al., 2002). Their flood model generates a stable
27 drainage channel that prohibits complete drainage, but this result might be unlikely for an
28 outburst flood from Lake Agassiz. In addition, uncertainties in the reconstructed position of
29 the ice-margin on the northern side of Lake Agassiz translate into a range of possible lake
30 volumes spanning 45-200% of the best estimate (Tornqvist and Hijma, 2012).
31 Reconstructions of sea level rise at 8.2 ka support the idea of a larger freshwater drainage.
32 Using peat deposits from the Mississippi River delta, Li et al. (2012) reconstructed a total
33 eustatic sea level rise of 0.8 to 2.2 m at 8.2 ka. Another reconstruction from the Rhine-Meuse

delta implies a sea level rise of 3.0 ± 1.2 m (Hijma and Cohen, 2010). ~~This~~ ~~These~~ ~~is~~ ~~are~~ significantly larger than the forcing of 2.5 Sv for one year (~0.2 m sea level equivalent) or even than the best estimate of the entire volume of Lake Agassiz (~0.4 m sea level equivalent). Recent model simulations suggest that the collapse of the Laurentide ice-sheet saddle around 8.2 ka provided this larger volume of freshwater (Gregoire et al., 2012), and that this forcing results in a cooling event that matches many proxy records (Wiersma and Jongma, 2010; Wagner et al., 2013).

The difference in boundary conditions between the control simulations does not obviously account for divergent model responses. As shown in the comparison of the two CCSM simulations, CCSM_{og} and CCSM_{all}, the addition of a remnant Laurentide Ice Sheet and a background meltwater flux does not alter the model response to freshwater forcing, either in magnitude or duration. It is worth noting, however, that these boundary conditions were important in previous experiments with ECBilt-~~CLio~~ CLIO for prolonging the AMOC response to Lake Agassiz drainage (Wiersma et al., 2006). Thus, the effects of these boundary conditions might be very model-dependent. Differences between early Holocene and preindustrial orbital forcing and greenhouse gas concentrations are relatively minor, and are not expected to have an important influence. This should be verified, though, with additional model experiments.

A last explanation for the model-data discrepancies is that the models are not sensitive enough to freshwater perturbations. If true, this finding would have important implications for future climate projections, particularly as models suggest that continued melting of the Greenland Ice Sheet at its current rate will have a significant impact on the AMOC (Hu et al., 2009).

There are few model intercomparisons to determine whether the sensitivity of these three models to freshwater perturbations is representative of coupled climate models as a whole. For hosing experiments of 0.1 Sv for 100 years under modern boundary conditions, earlier versions of the CCSM3 (CCSM2) and LOVECLIM (ECBilt-CLIO) have AMOC and surface air temperature responses close to the multi-model ensemble mean (Stouffer et al., 2006). For hosing experiments in a Last Glacial Maximum climate, however, AMOC decreases somewhat less in the CCSM3 and LOVECLIM compared to the multi-model ensemble mean (Kageyama et al., 2012). Improved constraints on the size of freshwater forcing and its location with respect to early Holocene convection areas are necessary to rule out the possibility of inadequate model sensitivity.

Acknowledgements

We thank Lauren Gregoire and an anonymous reviewer for their helpful comments. Funding for the CCSM simulations was provided by ~~a~~ grants from the U.S. National Science Foundation, Office of Polar Programs, to CM ([ARC-0713951](#)) and BLO-B ([ARC-0713971](#)) and supercomputer time was provided by a grant from the National Center for Atmospheric Research (NCAR) Computational Information Systems Laboratory (CISL). ~~We~~ CM and BLO-B thank Nan Rosenbloom for running the CCSM_{all} simulations, Ellen Ward for assistance with figures, and Amy Wagner for helpful discussions. ANL thanks NASA GISS for institutional support. This is Past4Future contribution no 37. The research leading to these results has received funding from the European Union's Seventh Framework programme (FP7/2007-2013) under grant agreement no 243908, "Past4Future. Climate change - Learning from the past climate."

1 **References**

- 2 Adkins, J. F., McIntyre, K., and Schrag, D. P.: The salinity, temperature, and $\delta^{18}\text{O}$ of the
3 glacial deep ocean, *Science*, 298, 1769-1773, 2002.
- 4 Barber, D. C., Dyke, A., Hillaire-Marcel, C., Jennings, A. E., Andrews, J. T., Kerwin, M. W.,
5 Bilodeau, G., McNeely, R., Southon, J., Morehead, M. D., and Gagnon, J.-M.: Forcing of the
6 cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes, *Nature*, 400, 344-
7 348, 1999.
- 8 Berger, A. L.: Long-term variations of caloric insolation resulting from the Earth's orbital
9 elements, *Quaternary Research*, 9, 139-167, 1978.
- 10 Bianchi, G. G., and McCave, I. N.: Holocene periodicity in North Atlantic climate and deep-
11 ocean flow south of Iceland, *Nature*, 397, 515-517, 1999.
- 12 Born, A., and Levermann, A.: The 8.2 ka event: Abrupt transition of the subpolar gyre
13 toward a modern North Atlantic circulation, *Geochemistry, Geophysics, Geosystems*, 11,
14 Q06011, 10.1029/2009GC003024, 2010.
- 15 Came, R. E., Oppo, D. W., and McManus, J. F.: Amplitude and timing of temperature and
16 salinity variability in the subpolar North Atlantic over the past 10 k.y., *Geology*, 35, 315-318,
17 2007.
- 18 Clarke, G. K. C., Leverington, D. W., Teller, J. T., and Dyke, A. S.: Paleohydraulics of the
19 last outburst flood from glacial Lake Agassiz and the 8200 BP cold event, *Quaternary Science*
20 Reviews, 23, 389-407, 2004.
- 21 Clarke, G. K. C., Bush, A. B. G., and Bush, J. W. M.: Freshwater discharge, sediment
22 transport, and modeled climate impacts of the final drainage of Glacial Lake Agassiz, *Journal*
23 *of Climate*, 22, 2161-2180, 2009.
- 24 Collins, W. D., Bitz, C. M., Blackmon, M. L., Bonan, G. B., Bretherton, C. S., Carton, J. A.,
25 Chang, P., Doney, S. C., Hack, J. J., Henderson, T. B., Kiehl, J. T., Large, W. G., McKenna,
26 D. S., Santer, B. D., and Smith, R. D.: The Community Climate System Model Version 3
27 (CCSM3), *Journal of Climate*, 19, 2122-2143, 2006.
- 28 Condrón, A., and Winsor, P.: A subtropical fate awaited freshwater discharged from glacial
29 Lake Agassiz, *Geophysical Research Letters*, 38, L03705, 10.1029/2010GL046011, 2011.

1 Ellison, C. R. W., Chapman, M. R., and Hall, I. R.: Surface and deep ocean interactions
2 during the cold climate event 8200 years ago, *Science*, 312, 1929-1932, 2006.

3 Fagel, N., Hillaire-Marcel, C., Humblet, M., Brasseur, R., Weis, D., and Stevenson, R.: Nd
4 and Pb isotope signatures of the clay-size fraction of Labrador Sea sediments during the
5 Holocene: Implications for the inception of the modern deep circulation pattern,
6 *Paleoceanography*, 19, PA3002, 2004.

7 Feurdean, A., Klotz, S., Mosbrugger, V., and Wolhfarth, B.: Pollen-based quantitative
8 reconstructions of Holocene climate variability in NW Romania, *Palaeogeography*,
9 *Palaeoclimatology*, *Palaeoecology*, 260, 494-504, 2008.

10 Flückiger, J., Monnin, E., Stauffer, B., Schwander, J., Stocker, T. F., Chappellaz, J., Raynaud,
11 D., and Barnola, J.-M.: High-resolution Holocene N₂O ice core record and its relationship
12 with CH₄ and CO₂, *Global Biogeochemical Cycles*, 16, 1010, 10.29/2001GB001417, 2002.

13 Goosse, H., Brovkin, V., Fichefet, T., Haarsma, R., Huybrechts, P., Jongma, J., Mouchet, A.,
14 Selten, F., Barriat, P.-Y., Campin, J.-M., Deleersnijder, E., Driesschaert, E., Goelzer, H.,
15 Janssens, I., Loutre, M. F., Morales Maqueda, M. A., Opsteegh, T., Mathieu, P.-P.,
16 Munhoven, G., Pettersson, E. J., Renssen, H., Roche, D. M., Schaeffer, M., Tartinville, B.,
17 Timmermann, A., and Weber, S. L.: Description of the Earth system model of intermediate
18 complexity LOVECLIM version 1.2, *Geoscientific Model Development*, 3, 603-633,
19 doi:10.5194/gmd-3-603-2010, 2010.

20 Gregoire, L. J., Payne, A. J., and Valdes, P. J.: Deglacial rapid sea level rises caused by ice-
21 sheet saddle collapses, *Nature*, 487, 219-223, 2012.

22 Häkkinen, S., and Rhines, P. B.: Decline of subpolar North Atlantic circulation during the
23 1990s, *Science*, 304, 555-559, 2004.

24 Hall, I. R., Bianchi, G. G., and Evans, J. R.: Centennial to millennial scale Holocene climate-
25 deep water linkage in the North Atlantic, *Quaternary Science Reviews*, 23, 1529-1536, 2004.

26 Hall, I. R., Becker, J., Thornalley, D., and Hemming, S. R.: Holocene variability of North
27 Atlantic deep water: palaeocurrent reconstruction of component water masses close to their
28 source, 10th International Conference on Paleoceanography, La Jolla, CA, 2010.

29 Hammer, C. U., Andersen, K. K., Clausen, H. B., Dahl-Jensen, D., Hvidberg, C. S., and
30 Iversen, P.: The stratigraphic dating of the GRIP ice core, Special Report of the Geophysical

1 Department, Niels Bohr Institute for Astronomy, Physics and Geophysics, University of
2 Copenhagen, 1997.

3 Hijma, M. P., and Cohen, K. M.: Timing and magnitude of the sea-level jump preluding the
4 8200 yr event, *Geology*, 38, 275-278, 2010.

5 Hillaire-Marcel, C., de Vernal, A., Bilodeau, G., and Weaver, A. J.: Absence of deep-water
6 formation in the Labrador Sea during the last interglacial period, *Nature*, 410, 1073-1077,
7 2001.

8 Hillaire-Marcel, C., de Vernal, A., and Piper, D. J. W.: Lake Agassiz final drainage event in
9 the northwest North Atlantic, *Geophysical Research Letters*, 34, L15601,
10 10.1029/2007GL030396, 2007.

11 Hoffman, J. S., Carlson, A. E., Winsor, K., Klinkhammer, G. P., LeGrande, A. N., Andrews,
12 J. T., and Strasser, J. C.: Linking the 8.2 ka event and its freshwater forcing in the Labrador
13 Sea, *Geophysical Research Letters*, 39, L18703, 2012.

14 Hu, A., Meehl, G. A., Han, W., and Yin, J.: Transient response of the MOC and climate to
15 potential melting of the Greenland Ice Sheet in the 21st century, *Geophysical Research*
16 *Letters*, 36, L10707, 2009.

17 Kageyama, M., Merkel, U., Otto-Bliesner, B., Prange, M., Abe-Ouchi, A., Lohmann, G.,
18 Roche, D. M., Singarayer, J., Swingedouw, D., and Zhang, X.: Climatic impacts of fresh
19 water hosing under Last Glacial Maximum conditions: a multi-model study, *Climate of the*
20 *Past Discussions*, 8, 3831-3869, 2012.

21 Keigwin, L. D., Sachs, J. P., Rosenthal, Y., and Boyle, E. A.: The 8200 yr BP event in the
22 slope water system, western subpolar North Atlantic, *Paleoceanography*, 20, PA2003,
23 10.1029/2004PA001074, 2005.

24 Kleiven, H. F., Kissel, C., Laj, C., Ninnemann, U. S., Richter, T. O., and Cortijo, E.: Reduced
25 North Atlantic Deep Water coeval with the Glacial lake Agassiz freshwater outburst, *Science*,
26 319, 60-64, 2008.

27 Kobashi, T., Severinghaus, J. P., Brook, E. J., Barnola, J.-M., and Grachev, A. M.: Precise
28 timing and characterization of abrupt climate change 8200 years ago from air trapped in polar
29 ice, *Quaternary Science Reviews*, 26, 1212-1222, 2007.

1 LeGrande, A. N., Schmidt, G. A., Shindell, D. T., Field, C. V., Miller, R. L., Koch, D. M.,
2 Faluvegi, G., and Hoffmann, G.: Consistent simulations of multiple proxy responses to an
3 abrupt climate change event, *Proceedings of the National Academy of Sciences*, 103, 837-
4 842, 2006.

5 LeGrande, A. N., and Schmidt, G. A.: Ensemble, water isotope-enabled, coupled general
6 circulation modeling insights into the 8.2 ka event, *Paleoceanography*, 23, PA3207,
7 10.1029/2008PA001610, 2008.

8 Lewis, C. F. M., Miller, A. A. L., Levac, E., Piper, D. J. W., and Sonnichsen, G. V.: Lake
9 Agassiz outburst age and routing by Labrador Current and the 8.2 cal ka cold event,
10 *Quaternary International*, 260, 83-97, 2012.

11 Li, Y.-X., Renssen, H., Wiersma, A. P., and Tornqvist, T. E.: Investigating the impact of Lake
12 Agassiz drainage routes on the 8.2 ka cold event with a climate model, *Climates of the Past*,
13 5, 471-480, 2009.

14 Li, Y.-X., Tornqvist, T. E., Nevitt, J. M., and Kohl, B.: Synchronizing a sea-level jump, final
15 Lake Agassiz drainage, and abrupt cooling 8200 years ago, *Earth and Planetary Science*
16 *Letters*, 315-316, 41-50, 2012.

17 Licciardi, J. M., Teller, J. T., and Clark, P. U.: Freshwater routing by the Laurentide ice sheet
18 during the last deglaciation, in: *Mechanisms of Global Climate Change at Millennial Time*
19 *Scales*, edited by: Clark, P. U., Webb, R.S. and Keigwin, L.D., American Geophysical Union,
20 Washington, D.C., 177-201, 1999.

21 McManus, J. F., Francois, R., Gherardi, J.-M., Keigwin, L. D., and Brown-Leger, S.: Collapse
22 and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes,
23 *Nature*, 428, 834-837, 2004.

24 Meehl, G., and Coauthors: Global Climate Projections, in: *Climate Change 2007: The*
25 *Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of*
26 *the Intergovernmental Panel on Climate Change*, edited by: Solomon, S., Qin, D., Manning,
27 M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge
28 University Press, New York, N.Y., 747–846, 2007.

29 Monnin, E., Steig, E. J., Siegenthaler, U., Kawamura, K., Schwander, J., Stauffer, B., Stocker,
30 T. F., Morse, D. L., Barnola, J.-M., Bellier, B., Raynaud, D., and Fischer, H.: Evidence for
31 substantial accumulation rate variability in Antarctica during the Holocene, through

1 synchronization of CO₂ in the Taylor Dome, Dome C and DML ice cores, *Earth and Planetary*
2 *Science Letters*, 224, 45-54, 2004.

3 Morrill, C., Anderson, D. M., Bauer, B. A., Buckner, R., Gille, E. P., Gross, W. S., Hartman,
4 M., and Shah, A.: Proxy benchmarks for intercomparison of 8.2 ka simulations, *Climate of*
5 *the Past Discussions*, 8, 3765-3789, 2012.

6 Oppo, D. W., McManus, J. F., and Cullen, J. L.: Deepwater variability in the Holocene epoch,
7 *Nature*, 422, 277-278, 2003.

8 Otto-Bliesner, B. L., Brady, E. C., Clauzet, G., Tomas, R., Levis, S., and Kothavala, Z.: Last
9 Glacial Maximum and Holocene climate in CCSM3, *Journal of Climate*, 19, 2526-2544,
10 2006.

11 Otto-Bliesner, B. L., Hewitt, C. D., Marchitto, T. M., Brady, E., Abe-Ouchi, A., Crucifix, M.,
12 Murakami, S., and Weber, S. L.: Last Glacial Maximum ocean thermohaline circulation:
13 PMIP2 model intercomparisons and data constraints, *Geophysical Research Letters*, 34,
14 L12706, 2007.

15 Peltier, W. R.: Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2)
16 model and GRACE, *Annual Review of Earth and Planetary Science*, 32, 111-149, 2004.

17 Praetorius, S., McManus, J. F., Oppo, D. W., and Curry, W. B.: Episodic reductions in
18 bottom-water currents since the last ice age, *Nature Geoscience*, 1, 449-452, 2008.

19 Pross, J., Kutthoff, U., Muller, U. C., Peyron, O., Dormoy, I., Schmiedl, G., Kalaitzidis, S.,
20 and Smith, A. M.: Massive perturbation in terrestrial ecosystems of the Eastern Mediterranean
21 region associated with the 8.2 kyr B.P. climatic event, *Geology*, 37, 887-890, 2009.

22 Rasmussen, S. O., Vinther, B. M., Clausen, H. B., and Andersen, K. K.: Early Holocene
23 climate oscillations recorded in three Greenland ice cores, *Quaternary Science Reviews*, 26,
24 1907-1914, 2007.

25 Renssen, H., Goosse, H., Fichefet, T., and Campin, J.-M.: The 8.2 kyr BP event simulated by
26 a global atmosphere-sea ice-ocean model, *Geophysical Research Letters*, 28, 1567-1570,
27 2001.

28 Russell, G. L., Miller, J. R., and Rind, D.: A coupled atmosphere-ocean model for transient
29 climate change studies, *Atmosphere-Ocean*, 33, 683-730, 1995.

1 Russell, G. L., Miller, J. R., Rind, D., Ruedy, R. A., Schmidt, G. A., and Sheth, S.:
2 Comparison of model and observed regional temperature changes during the past 40 years,
3 *Journal of Geophysical Research*, 105, 14891-14898, doi:10.1029/2000JD900156, 2000.

4 Sarmaja-Korjonen, K., and Seppä, H.: Abrupt and consistent responses of aquatic and
5 terrestrial ecosystems to the 8200 cal. yr cold event: a lacustrine record from Lake Arapisto,
6 Finland, *The Holocene*, 17, 457-467, 2007.

7 Schmidt, G. A., and LeGrande, A. N.: The Goldilocks abrupt climate change event,
8 *Quaternary Science Reviews*, 24, 1109-1110, 2005.

9 Schmidt, G. A., Ruedy, R., Hansen, J. E., Aleinov, I., Bell, N., Bauer, M., Bauer, S., Cairns,
10 B., Canuto, V., Cheng, Y., Del Genio, A., Faluvegi, G., Friend, A. D., Hall, T. M., Hu, Y.,
11 Kelley, M., Kiang, N. Y., Koch, D., Lacis, A. A., Lerner, J., Lo, K. K., Miller, R. L.,
12 Nazarenko, L., Oinas, V., Perlwitz, J. P., Perlwitz, J., Rind, D., Romanou, A., Russell, G. L.,
13 Sato, M., Shindell, D. T., Stone, P. H., Sun, S., Tausnev, N., Thresher, D., and Yao, M.-S.:
14 Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and
15 reanalysis data, *Journal of Climate*, 19, 153-192, doi:10.1175/JCLI3612.1, 2006.

16 Schmittner, A.: Decline of the marine ecosystem caused by a reduction in the Atlantic
17 overturning circulation, *Nature*, 434, 628-633, 2005.

18 Schmittner, A., Latif, M., and Schneider, B.: Model projections of the North Atlantic
19 thermohaline circulation for the 21st century assessed by observations, *Geophysical Research*
20 *Letters*, 32, L23710, 10.1029/2005GL024368, 2005.

21 Solignac, S., deVernal, A., and Hillaire-Marcel, C.: Holocene sea-surface conditions in the
22 North Atlantic - contrasted trends and regimes in the western and eastern sectors (Labrador
23 Sea vs. Iceland Basin), *Quaternary Science Reviews*, 23, 319-334, 2004.

24 Spence, J. P., Eby, M., and Weaver, A. J.: The sensitivity of the Atlantic meridional
25 overturning circulation to freshwater forcing at eddy permitting resolutions, *Journal of*
26 *Climate*, 21, 2697-2710, 2008.

27 Stouffer, R. J., Yin, J., Gregory, J. M., Dixon, K. W., Spelman, M. J., Hurlin, W., Weaver, A.
28 J., Eby, M., Flato, G. M., Hasumi, H., Hu, A., Jungclaus, J. H., Kamenkovich, I. V.,
29 Levermann, A., Montoya, M., Murakami, S., Nawrath, S., Oka, A., Peltier, W. R., Robitaille,
30 D. Y., Sokolov, A., Vettoretti, G., and Weber, S. L.: Investigating the causes of the response

1 of the thermohaline circulation to past and future climate changes, *Journal of Climate*, 19,
2 1365-1387, 2006.

3 Teller, J. T., Leverington, D. W., and Mann, J. D.: Freshwater outbursts to the oceans from
4 glacial Lake Agassiz and their role in climate change during the last deglaciation, *Quaternary*
5 *Science Reviews*, 21, 879-887, 2002.

6 Thomas, E. R., Wolff, E. W., Mulvaney, R., Steffensen, J. P., Johnsen, S. J., Arrowsmith, C.,
7 White, J. W. C., Vaughn, B., and Popp, T.: The 8.2 ka event from Greenland ice cores,
8 *Quaternary Science Reviews*, 26, 70-81, 2007.

9 Thornalley, D. J. R., Elderfield, H., and McCave, I. N.: Holocene oscillations in temperature
10 and salinity of the surface subpolar North Atlantic, *Nature*, 457, 711-714, 2009.

11 Timmermann, A., An, S.-I., Krebs, U., and Goosse, H.: ENSO suppression due to weakening
12 of the North Atlantic thermohaline circulation, *Journal of Climate*, 18, 3122-3139, 2005.

13 Tornqvist, T. E., and Hijma, M. P.: Links between early Holocene ice-sheet decay, sea-level
14 rise and abrupt climate change, *Nature Geoscience*, 5, 601-606, 2012.

15 Vellinga, M., and Wood, R. A.: Global climatic impacts of a collapse of the Atlantic
16 thermohaline circulation, *Climatic Change*, 54, 251-267, 2002.

17 Veski, S., Seppä, H., and Ojala, A. E. K.: Cold event at 8200 yr BP recorded in annually
18 laminated lake sediments in eastern Europe, *Geology*, 32, 681-684, 2004.

19 von Grafenstein, U., Erlenkeuser, H., Muller, J., Jouzel, J., and Johnsen, S.: The cold event
20 8200 years ago documented in oxygen isotope records of precipitation in Europe and
21 Greenland, *Climate Dynamics*, 14, 73-81, 1998.

22 Wagner, A. J., Morrill, C., Otto-Bliesner, B. L., Rosenbloom, N., and Watkins, K. R.: Model
23 support for forcing of the 8.2 ka event by meltwater from the Hudson Bay ice dome, *Climate*
24 *Dynamics*, submitted, 2013.

25 Wiersma, A. P., Renssen, H., Goosse, H., and Fichefet, T.: Evaluation of different freshwater
26 forcing scenarios for the 8.2 ka BP event in a coupled climate model, *Climate Dynamics*, 27,
27 831-849, 2006.

28 Wiersma, A. P., and Jongma, J. I.: A role for icebergs in the 8.2 ka climate event, *Climate*
29 *Dynamics*, 35, 535-549, 2010.

1 Winsor, K., Carlson, A. E., Klinkhammer, G. P., Stoner, J. S., and Hatfield, R. G.: Evolution
2 of the northeast Labrador Sea during the last interglaciation, *Geochemistry, Geophysics,*
3 *Geosystems*, 13, Q11006, 10.1029/2012GC004263, 2012.

4 Wunsch, C.: Towards understanding the Paleoocean, *Quaternary Science Reviews*, 29, 1960-
5 1967, 2010.

6 Yin, J., Stouffer, R. J., Spelman, M. J., and Griffies, S. M.: Evaluating the uncertainty induced
7 by the virtual salt flux assumption in climate simulations and future projections, *Journal of*
8 *Climate*, 23, 80-96, 2009.

9 Zhang, R., and Delworth, T. L.: Impact of Atlantic multidecadal oscillations on India/Sahel
10 rainfall and Atlantic hurricanes, *Geophysical Research Letters*, 33, L17712,
11 10.1029/2006GL026267, 2006.

12

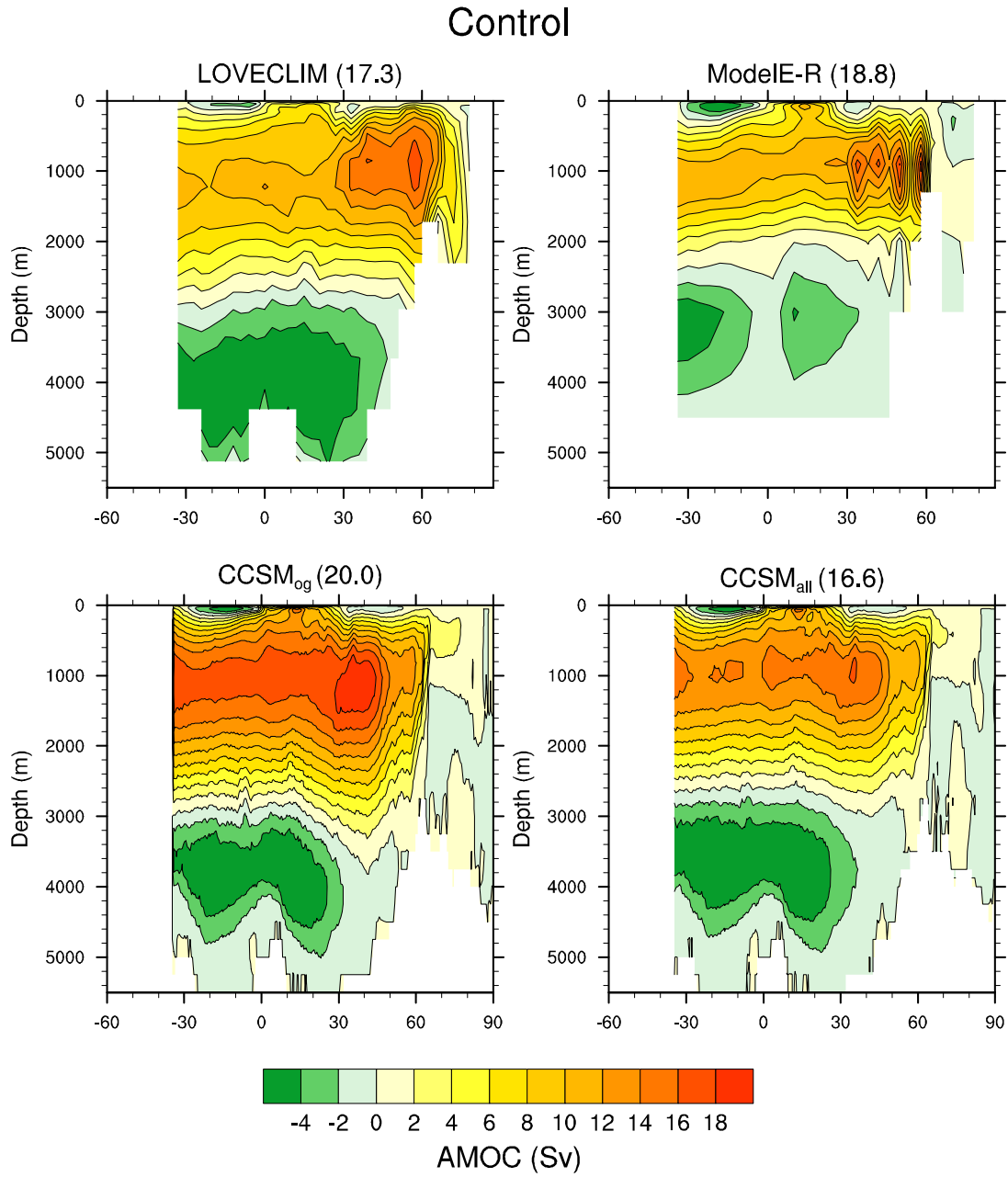
13

Table 1. Participating models

Model	Atmospheric model	Oceanic model	Citations
CCSM3	CAM3: T42 (~2.8°x2.8°), 26 levels	POP: ~1°x~1°; ~0.3°x~0.3° in North Atlantic, 40 levels, volume-conserving	Collins et al. (2006) Otto-Bliesner et al. (2006) Wagner et al. (2013)
GISS ModelE-R	ModelE: M20 (4°x5°), 20 levels	Russell: 4°x5°, 13 levels, mass-conserving	Schmidt et al. (2006) Russell et al. (2000;1995) LeGrande et al. (2006) LeGrande and Schmidt (2008)
LOVECLIM1.2	ECBilt2: T21 (5.625°x5.625°), 3 levels	CLIO3: 3°x3°, 20 levels, mass-conserving	Goosse et al. (2010)

Table 2. Boundary conditions for control simulations

Simulation	Orbital parameters	Greenhouse gas concentrations	Ice sheet	Background meltwater flux
CCSM _{og}	8.5 ka	CO ₂ =260 ppm CH ₄ = 660 ppb N ₂ O = 260 ppb	none	none
CCSM _{all}	8.5 ka	CO ₂ = 260 ppm CH ₄ = 660 ppb N ₂ O = 260 ppb	ICE-5G	0.05 Sv added to St. Lawrence River
ModelE-R	1880 A.D.	CO ₂ = 285 ppm CH ₄ = 791 ppb N ₂ O = 275 ppb	none	none
LOVECLIM	1880 A.D.-8.5 ka	CO ₂ = 280 -260 ppm CH ₄ = 760 -660 ppb N ₂ O = 270 -260 ppb	ICE-5G	0.05 Sv added to Hudson Strait

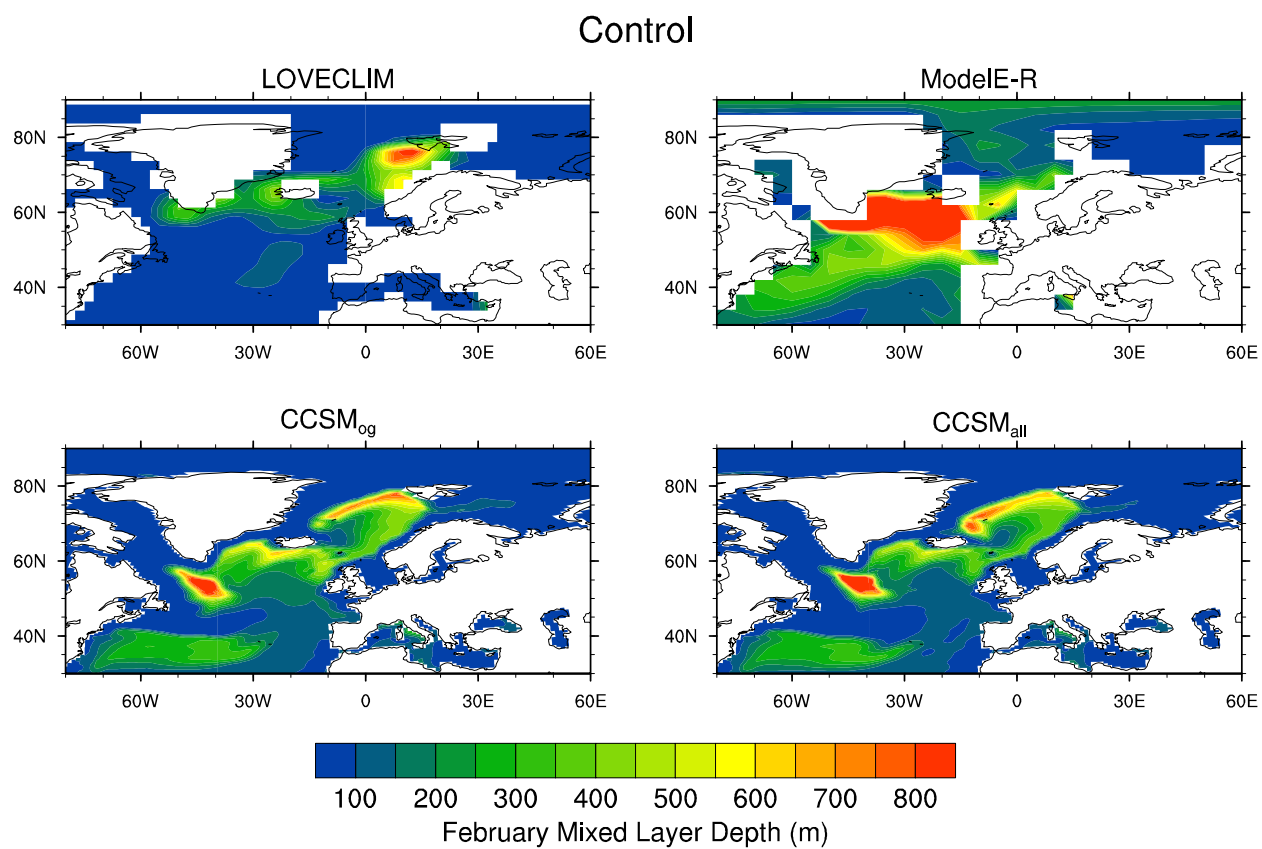


2

3 Figure 1. The Atlantic meridional overturning streamfunctions of the control simulations (see
 4 Table 2), in Sv ($1 \text{ Sv} = 10^6 \text{ m}^3/\text{s}$). Plotted values are 200-year means except for CCSM_{og},
 5 which is a 150-year mean. Values in parentheses following the model names are long-term
 6 means for the maximum of the streamfunction below 500m water depth.

7

1



2

3 Figure 2. Control values of February mixed layer depth, in meters. Plotted values are 100-year
 4 means.

5

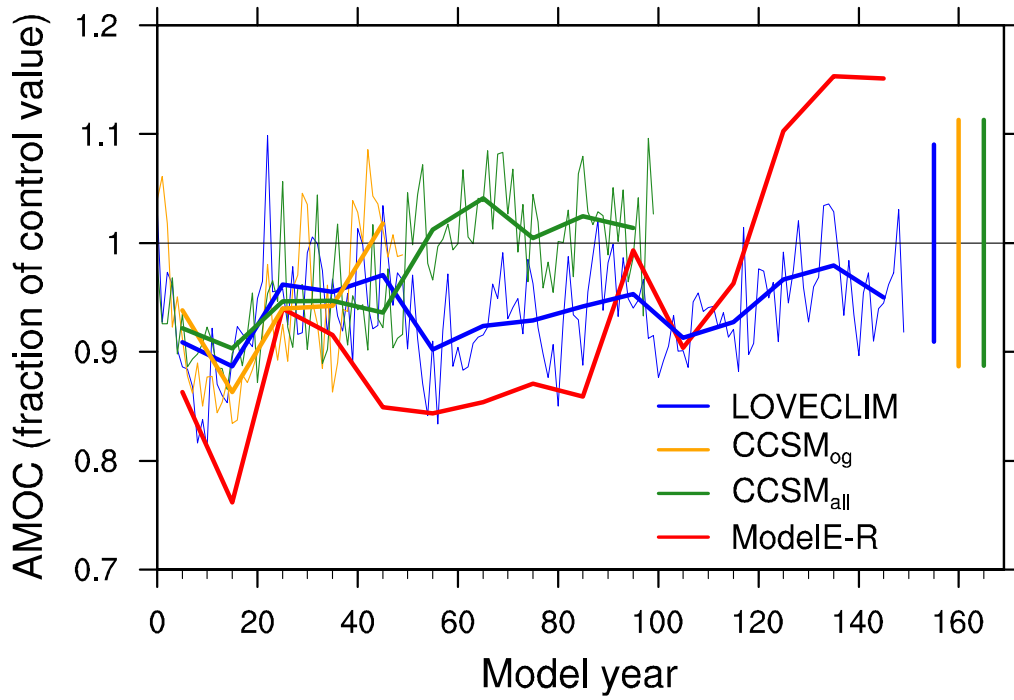


Figure 23. Time series of AMOC intensity anomalies following the MWP, expressed as a fraction of the long-term control mean. The MWP of 2.5 Sv for one year was added at Model year 1. AMOC intensity is defined as the maximum value of the overturning streamfunction below 500m water depth (excludes shallow wind-driven overturning). Heavy lines are decadal averages. Vertical lines on the right show the 2-sigma range of interannual variability in the control simulations, and are not shown for ModelE-R since only 30-year control averages are available.

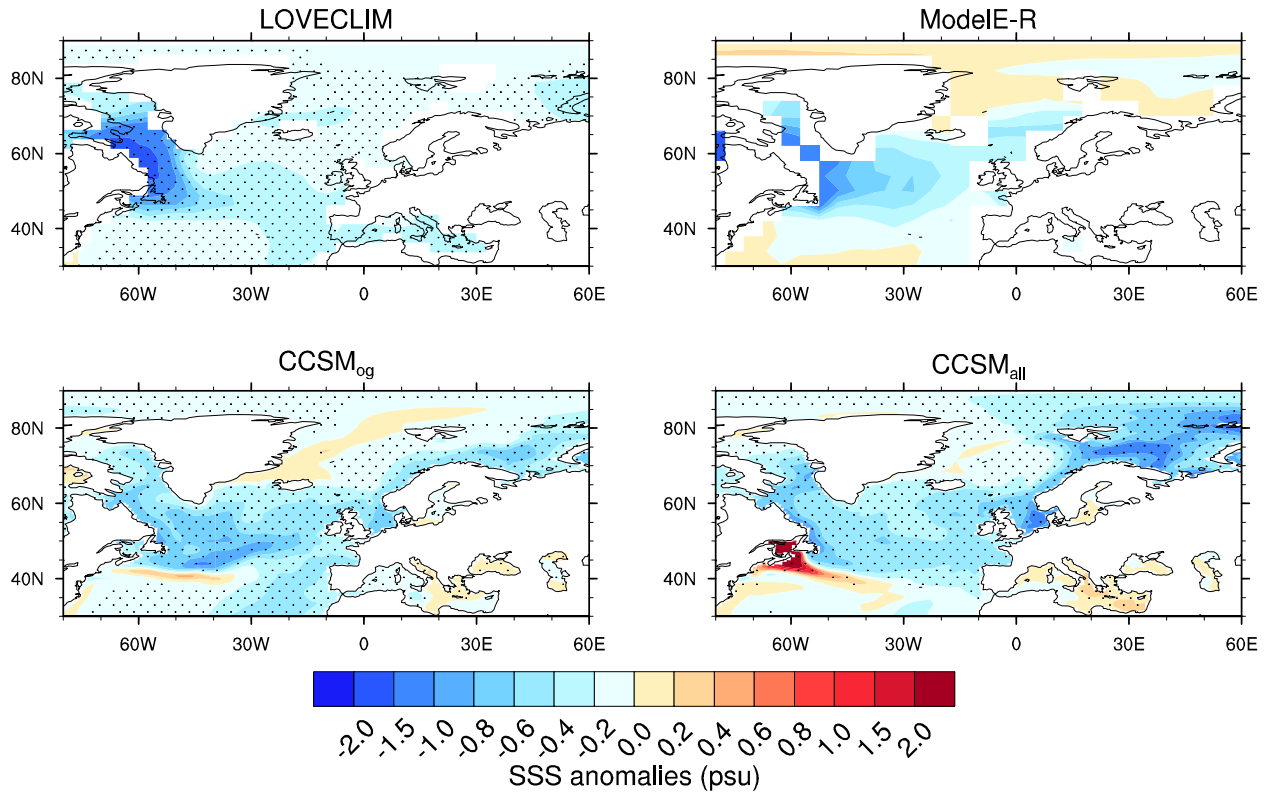


Figure 34. Anomalies of annual-mean sea surface salinity in the first fifty years following the MWP relative to the control simulation, in practical salinity units. Stippling shows statistical significance at the 95% level according to a Student's t-test. Statistical tests were not performed for ModelE-R since only decadal averages were available.

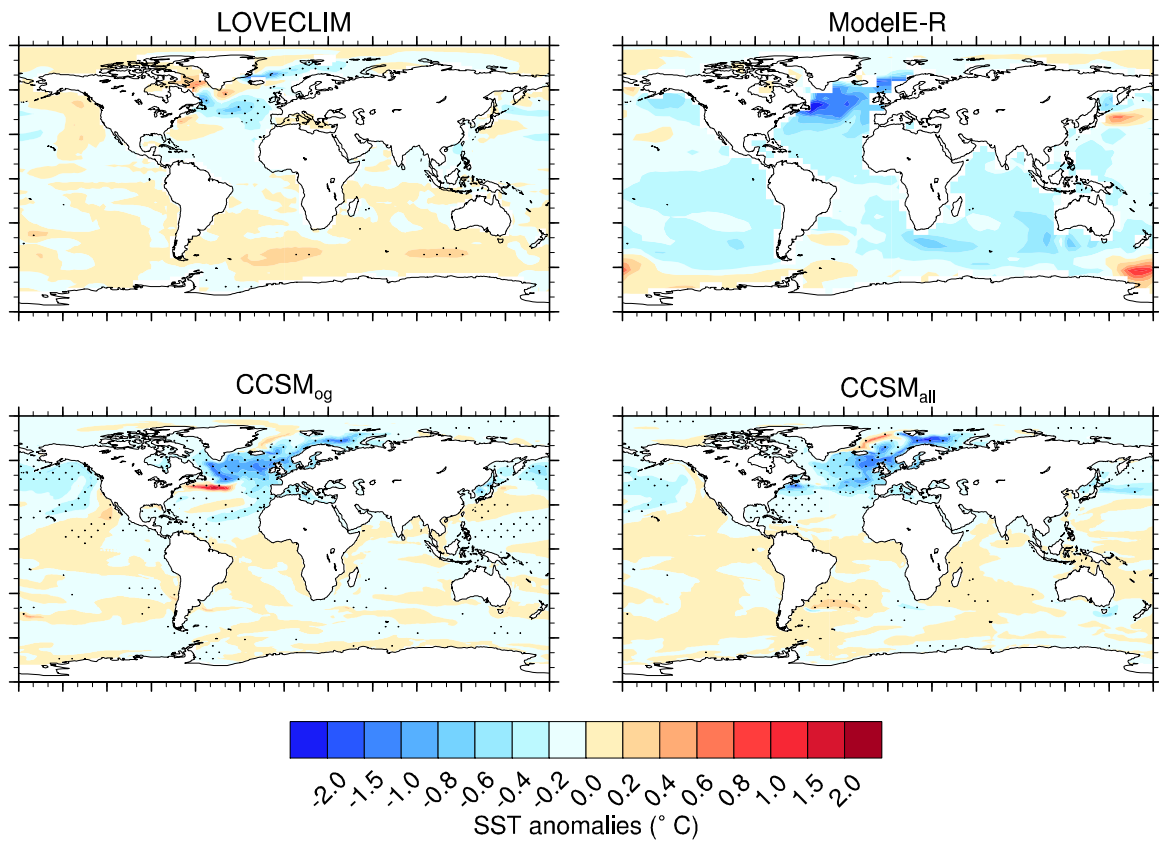


Figure 45. Anomalies of annual-mean sea surface temperature in the first fifty years following the MWP relative to the control simulation, in degrees Celsius. Stippling shows statistical significance at the 95% level according to a Student's t-test. Statistical tests were not performed for ModelE-R since only decadal averages were available.

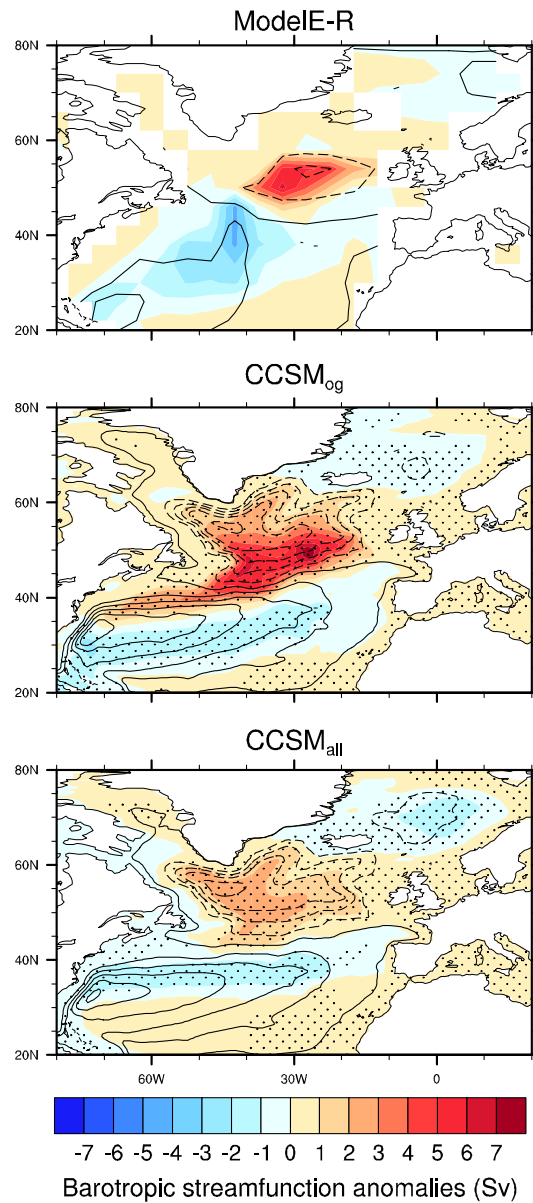


Figure 6. Control values for barotropic streamfunction (contour lines) and streamfunction anomalies in the first fifty years following the MWP relative to the control simulation, in Sv (colored contours). The contour interval for the control values is 10 Sv. Dashed lines show negative streamfunction values, or a cyclonic circulation. Positive (negative) anomalies for a cyclonic (anticyclonic) circulation indicate weakening of the transport. Stippling shows statistical significance for anomalies at the 95% level according to a Student's t-test. Statistical tests were not performed for ModelE-R since only decadal averages were available.

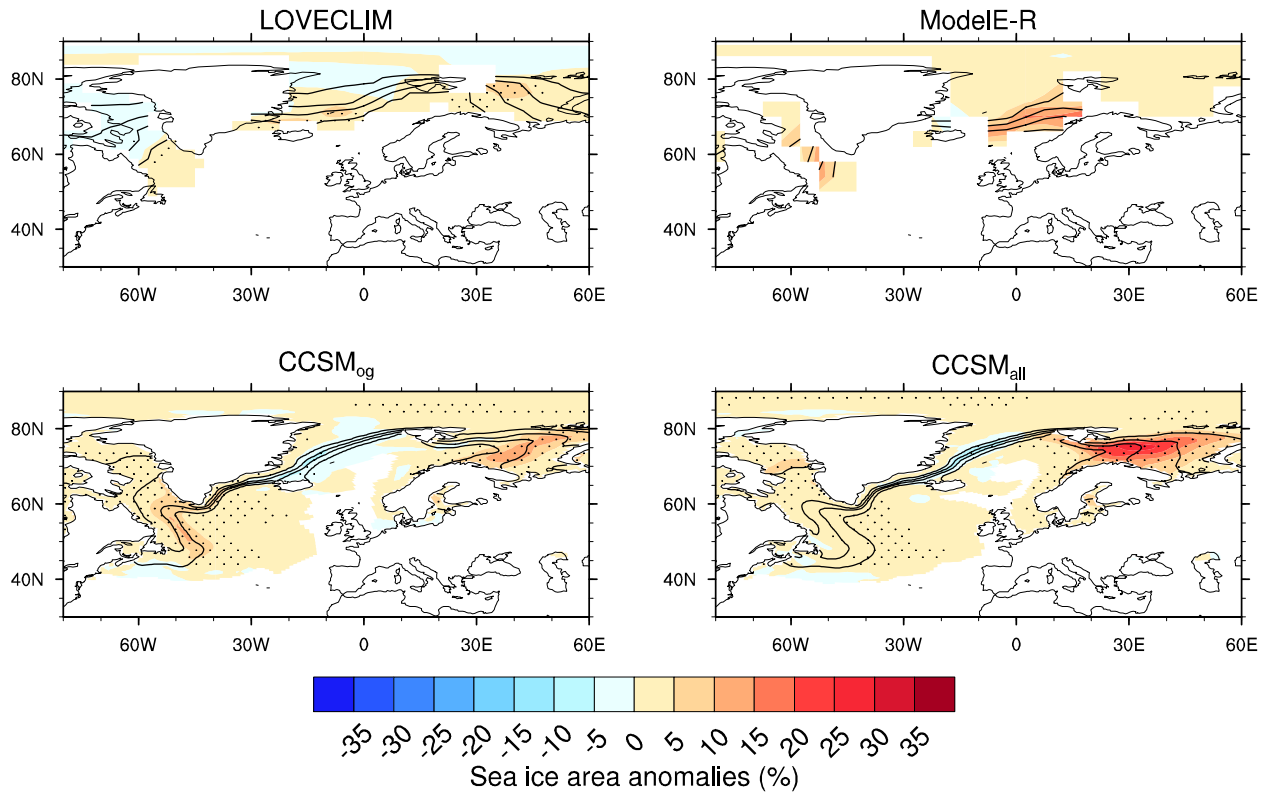


Figure 57. Control values (contour lines) and a anomalies of annual-mean sea ice area in the first fifty years following the MWP relative to the control simulation (colored contours), in percent. The contour lines show values of 5%, 25%, 50% and 75%. Stippling shows statistical significance at the 95% level according to a Student's t-test. Statistical tests were not performed for ModelE-R since only decadal averages were available.

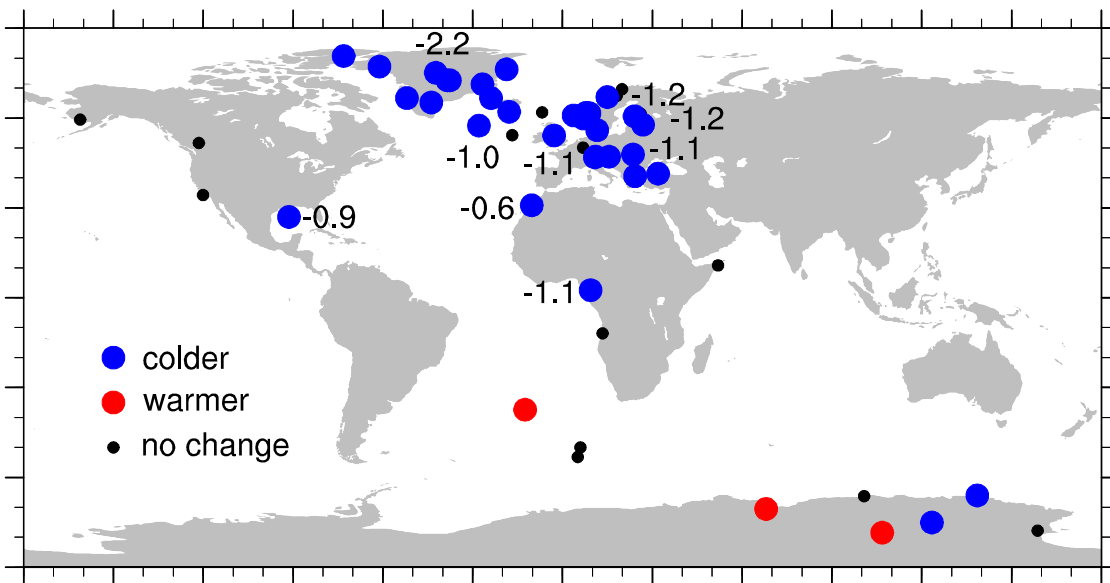
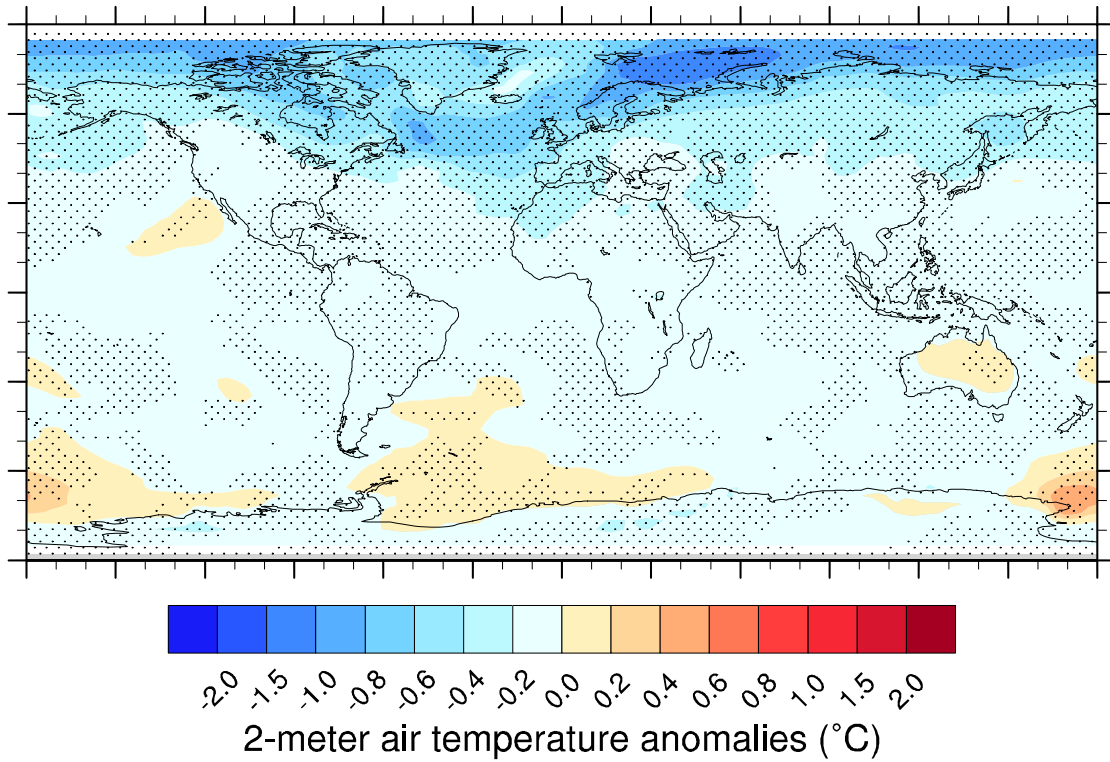


Figure 68. (Top) Multi-model ensemble mean anomalies of annual-mean 2-meter air temperature in the first fifty years following the MWP relative to the control simulations, in degrees Celsius. Stippling shows grid cells where at least three of the simulations agree on the sign of the temperature anomaly. (Bottom) Qualitative and quantitative mean-annual temperature anomalies relative to the early Holocene background climate, in degrees Celsius, inferred from proxy records for the 8.2 ka event, as summarized by Morrill et al. (2012).

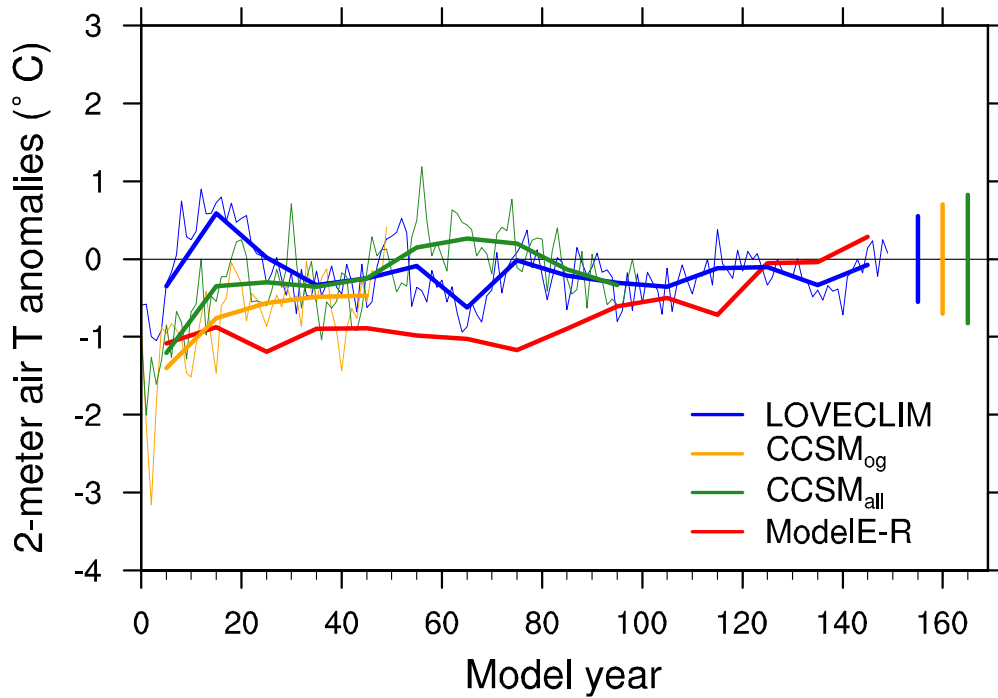


Figure 79. Time series of annual-mean surface air temperature averaged over the region 50°-70°N, 60°W-10°E in the North Atlantic, expressed as anomalies in degrees Celsius from the long-term control average. The MWP of 2.5 Sv for one year was added at Model year 1. Vertical lines on the right show the 2-sigma range of interannual variability in the control simulations, and are not shown for ModelE-R since only 30-year control averages are available.

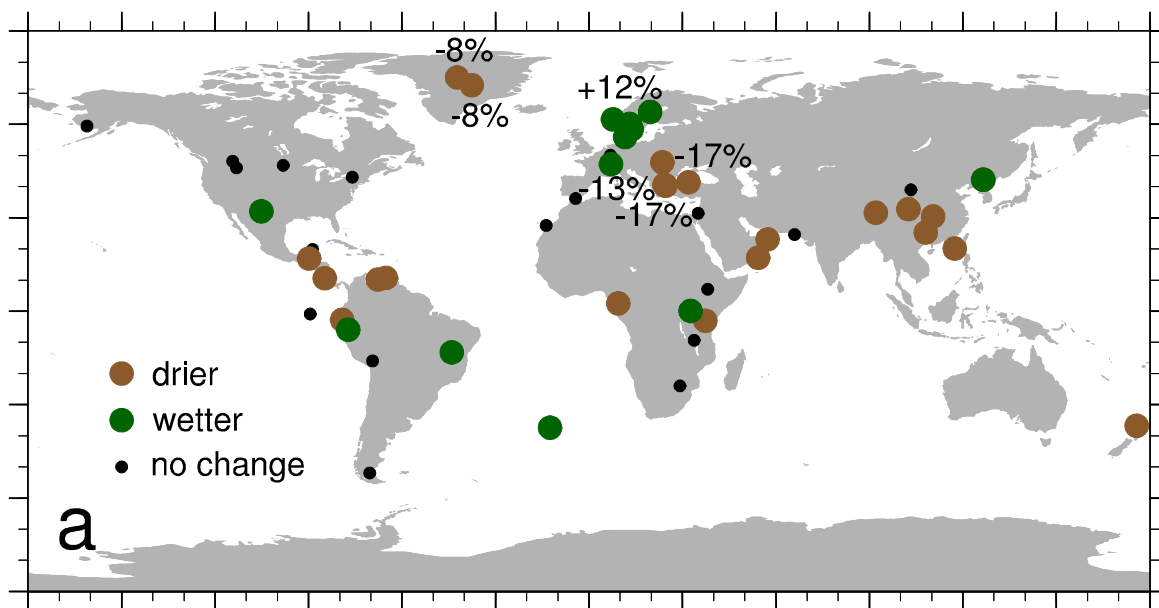
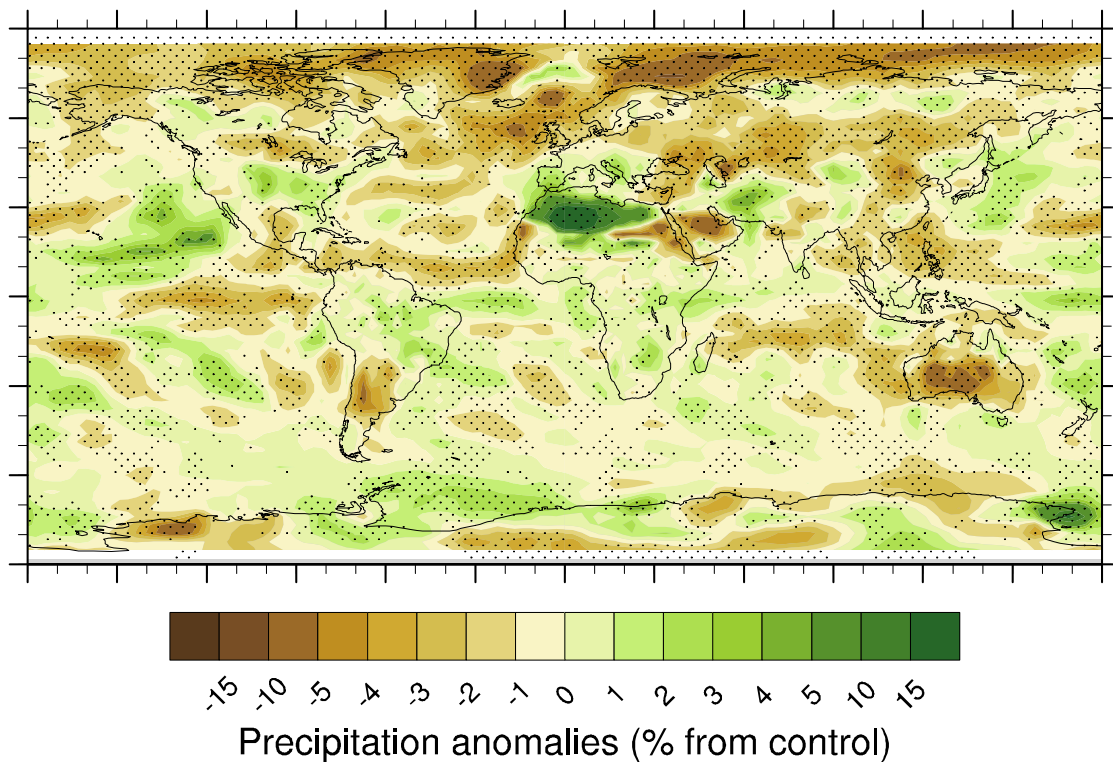


Figure 810. (Top) Multi-model ensemble mean anomalies of annual-mean precipitation in the first fifty years following the MWP relative to the control simulations, in em/year% change from control. Stippling shows grid cells where at least three of the simulations agree on the sign of the temperature-precipitation anomaly. (Bottom) Qualitative and quantitative annual-mean precipitation anomalies, in % change from early Holocene background climate, inferred from proxy records for the 8.2 ka event, as summarized by Morrill et al. (2012).

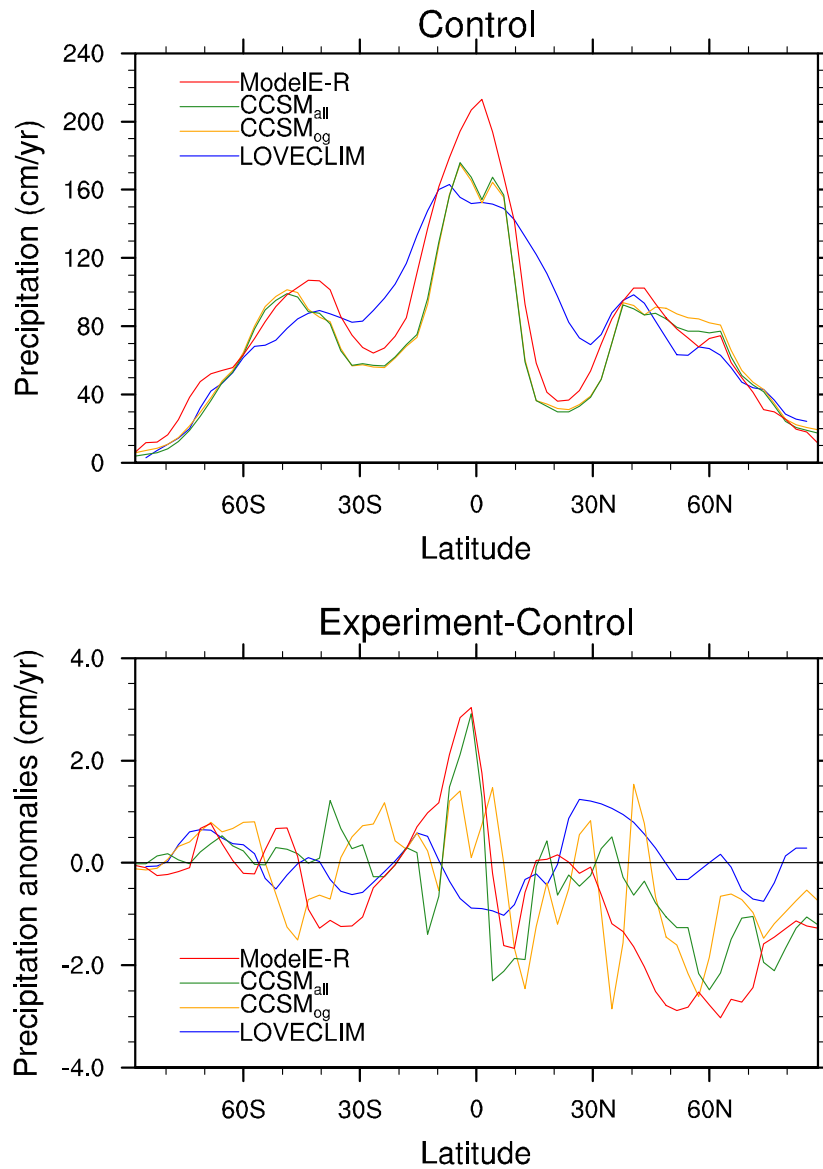


Figure 911. (Top) Annual-mean precipitation zonally-averaged across the Atlantic (90°W - 40°E) in the control simulation, in cm/year. (Bottom) Anomalies of Atlantic annual-mean precipitation for the first fifty years following the MWP relative to the control simulation, in cm/year.