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LETTER

Additional contributions to CMIP5 regional sea level projections resulting from Greenland and Antarctic ice mass loss

N Agarwal[1,4], **J H Jungclaus**[1], **A Köhl**[2], **C R Mechoso**[3] **and D Stammer**[2]

[1] Max Planck Institut für Meteorologie, Hamburg, Germany
[2] Centrum für Erdsystemforschung und Nachhaltigkeit (CEN), Universität Hamburg, Germany
[3] Department of Atmospheric and Oceanic Sci., U. California Los Angeles (UCLA), Los Angeles, CA, USA
[4] Current affiliation: Atmospheric and Oceanic Sciences Group, Space Applications Centre, Ahmedabad, India

E-mail: neeraj@sac.isro.gov.in

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Abstract

The impact of Greenland and Antarctic ice sheet mass loss on regional sea level is evaluated here under RCP 4.5 and RCP 8.5 scenarios for the period 2081–2099. To this end, estimates of associated fresh water sources are added to the Max Planck Institute for Meteorology's Earth System Model ocean component and the dynamical impact is quantified in terms of the difference in sea level relative to previous phase 5 of the Coupled Model Intercomparison Project runs. Overall, the addition of these freshwater sources have only a small impact on regional sea level variations relative to the global mean (<2 cm in magnitude). However, in some regions, notably in the North Atlantic and Arctic Ocean, an additional increase in regional steric sea level by 4–8 cm can be obtained, which is ~20% more than the previous climate model response. Climate feedbacks can have additional sea level impacts regionally, e.g., through changes in the wind forcing or surface freshwater fluxes. Overall, the dynamical regional sea level response to the polar ice mass loss is of the same order as the simulated decadal sea level variability.

1. Introduction

Climate projections suggest that on regional scales the increase of sea level at the end of the 21st century can deviate substantially from a global mean value (see Perrette *et al* (2013) and for a recent estimate Slangen *et al* (2014)). This will hold especially in coastal regions of the western North Atlantic Ocean and Antarctic Circumpolar Current (ACC), where sea level rise by the end of the century could be higher by 30% than the global average (Carson *et al* 2015). In contrast, the sea level rise of the subpolar North Atlantic Ocean, Arctic Ocean and off the western Antarctic coast will likely reach only 50% of the global mean; in the vicinity of declining polar ice sheets sea level can even drop with respect to the present day levels. These estimates are based on projections resulting from the phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor *et al* (2012)). These simulations produce sea level changes associated with a changing ocean circulation and with an increased oceanic heat uptake combined with off-line (i.e., not part of the CMIP5 runs) estimates of regional sea level rise resulting from changes of land ice, groundwater depletion and glacial isostatic adjustment. However, substantial uncertainties remain in these estimates, partly due to both internal variability in the individual CMIP models and to shortcomings in our understanding of underlying processes.

Uncertainties in regional sea level projections can also result from hitherto neglected processes in the climate models such as the freshwater input originated by glacier and polar ice sheet mass loss. Stammer (2008) demonstrated that the ocean circulation will adjust regionally and dynamically to this addition of extra freshwater through steric processes, while Stammer *et al* (2011) suggested that an associated response of the coupled ocean–atmosphere system will lead to additional non-local sea level changes through faster atmospheric teleconnections, which was further

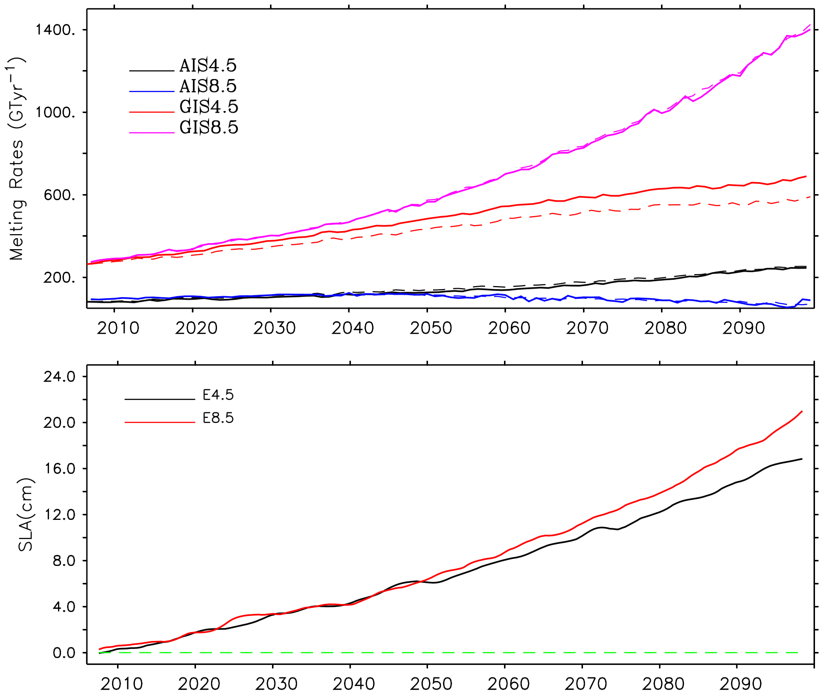

Figure 1. (top) Greenland and Antarctic Ice Sheet mass loss rates (Gtyr^{-1}) for RCP 4.5 and RCP 8.5 scenarios, respectively. Dashed lines indicate the corresponding mass loss rates from IPCC AR5 report. (bottom) Differences of low pass filtered global mean sea level (in cm) from (black line) E4.5 and (red line) E8.5. The dashed line in green represents the zero line.

investigated by Agarwal *et al* (2014). However, these previous studies were based on idealized freshwater input functions and do not provide quantitative estimates on the uncertainty in existing CMIP5 results originating from the neglect of any freshwater sources from glacier and ice sheet mass loss. Recently, van den Berk and Drijfhout (2014) assessed the impact of a high-end scenario of polar ice loss on a RCP8.5 scenario run of a CMIP5 model. Their assessment was based on prescribing a large mass loss from Antarctica of nearly 50 cm equivalent sea level rise and produced the largest impact on the Antarctic continental shelf. The extent to which this result is representative of CMIP type models under realistic conditions remains unclear.

The aim of this paper is to quantify the amplitude of an additional regional sea level change at the end of the 21st century that would result dynamically in a moderate (RCP 4.5) and a high-end (RCP 8.5) climate projection, respectively, if realistic local freshwater sources from retreating land ice masses were added to the model oceans. In this study we restrict our attention initially to water sources from Greenland and Antarctic only, while the contribution from continental glaciers is currently ignored due to the difficulties in prescribing glacier locations and associated hydrology for the melted water. We will argue below, however, that all cryospheric freshwater sources need to be added to future CMIP models to properly address the important question of regional sea level projections.

2. Methodology

All experiments analyzed in the present study use the low-resolution configuration of the Max Planck Institute for Meteorology Earth System Model (MPI-ESM), which was run under the CMIP5 protocol (Giorgetta *et al* 2013). The MPI-ESM model is a fully coupled Earth system model; however, it does not include land ice sheets and land glaciers. Hence the climate change feedbacks arising due to net mass loss of ice and glaciers are not included (Jungclaus *et al* 2006).

The MPI-ESM RCP 4.5 and RCP 8.5 simulations from the period 2006–2099 are our reference runs for each climate change scenario. Simulations were repeated under both scenarios starting in 2006, but now including additional time-dependent freshwater sources representing the mass loss of Greenland and Antarctic ice sheets (GIS and AIS, respectively) as projected during AR5. The differences between simulated results with and without the additional sources serve as the basis for our analysis. Present-day mass loss rates of GIS and AIS for 2006 are estimated to be 250 Gtyr^{-1} and 81 Gtyr^{-1}, respectively (Shepherd *et al* 2012). Starting from these values, time series of annual mean mass loss rate projections were constructed for the period 2006–2099 for both RCP 4.5 and RCP 8.5, which are consistent with recent AR5 global sea level change projections obtained by using surface mass balance models and ice dynamical contributions (J M Gregory, personal communication; see also (Church *et al* 2013)). The upper panel of figure 1 shows the resulting mass loss rates separately for GIS and AIS and for RCP 4.5 and RCP 8.5. On global average, these values add up to 16 cm and 20 cm respectively for RCP4.5 and RCP8.5 scenarios and are consistent with AR5 estimates (7–17 cm and 12–24 cm for RCP4.5 and RCP8.5, respectively). Helm *et al* (2014) critically discussed the differences in their mass loss estimates of 2011–2014 with those obtained by Shepherd *et al* (2012), which we have used in our study. We used the values of 250 Gtyr^{-1} and 81 Gtyr^{-1} for the starting year 2006 (start of CMIP5 runs). If we estimate the mass loss rates of 2014 from our figure 1 (upper panel) it comes out to be 320 Gtyr^{-1} and 100 Gtyr^{-1} making a combined loss of 420 Gtyr^{-1} which is quite close to the estimates given by Helm *et al* (2014).

According to figure 1, mass loss rates for GIS reach up to 700 Gtyr^{-1} and 1400 Gtyr^{-1} by the end of the 21st century for RCP 4.5 and RCP 8.5, respectively. For AIS, the mass loss rates under RCP 4.5 reach 250 Gtyr^{-1} by the end of the century while under RCP 8.5 these value initially increase, but decline after 2050 to around zero in 2097, after which they rise again. The decline in mass loss rates after 2050 is consistent with the AR5 report (upper panel figure 1). Church *et al* (2013) updated the records (shown in the upper panel of figure 1 as dashed lines), which led to changes mainly in the estimates for the RCP4.5 scenario. The AR5 authors point, however, to large uncertainties. We therefore consider the differences between the estimates by J M Gregory (personal communication) that we used in our study and the ones published in AR5 small and don't expect any significant change in our results due to this difference.

The associated freshwater input we prescribe into the model ranges from about 0.011 Sv to 0.022 Sv for RCP 4.5, and from 0.015 Sv to 0.05 Sv for RCP 8.5. Around Greenland the prescribed melt water flux was applied uniformly in space. For Antarctica the freshwater source was applied only around the West-Antarctic ice sheet. No source was prescribed around Eastern Antarctica, which has experienced mass gains in recent years (Shepherd *et al* 2012). In their study, van den Berk and Drijfhout (2014) used the outputs from iceberg model. However, since these outputs were not available to us, we use fixed patterns of runoff adjacent to the continents following Swingedouw *et al* (2013).

The experiments with additionally applied net mass loss rates due to polar ice sheet melting (PIM) are referred to hereafter as RCP4.5+PIM and RCP8.5+PIM, respectively. For each scenario, an ensemble of three member simulations was performed similarly to CMIP5. The results are discussed in the next section in terms of the difference between the ensemble means of the runs with PIM minus the simulations without PIM and will be referred to as E4.5 and E8.5, respectively.

We note for the later interpretation of results that under both climate scenarios the prescribed time-varying and slowly increasing freshwater forcing is substantially lower in amplitude than in Stammer *et al* (2011), who used a constant forcing of 0.0275 Sv for the entire 50 year period of their study. Only during the last 20 years of RCP8.5+PIM does our monotonically increasing forcing becomes comparable to the one used by Stammer *et al* (2011); for RCP4.5+PIM it is always less. The resulting differences in freshwater input are reflected in the differing global mean sea level rise, which in our case range between 16 and 20 cm over a 100-year period (figure 1(b)). By contrast, the global mean sea level rise in Stammer *et al* (2011) reached an amplitude around 11 cm within 50 years. In comparison to van den Berk and Drijfhout (2014), the total applied freshwater forcing in our scenario runs is about a factor 3–4 smaller; the input around Antarctica is in fact more than a factor of 10 smaller.

3. Results

The lower panel of figure 1 presents time series of global mean sea level differences (see definition in the previous section) corresponding to E4.5 and E8.5, respectively. This figure shows an increase in global mean sea level of about 17 cm and 21 cm in RCP4.5+PIM and RCP8.5+PIM, respectively. We note that in either case, the increase is about 1 cm higher than expected from the prescribed mass loss rates alone, a difference that emerges from additional surface freshwater flux related to climate feedbacks. The additional increase in sea level is similar to one that was discussed in Stammer *et al* (2011) where the GIS meltwater caused an additional increase in sea level anomaly.

All effective sources of freshwater (direct and indirect) are summarized in table 1 showing the direct freshwater discharge from AIS and GIS, together with the indirect, freshwater input resulting from aggregated differences in the net surface freshwater fluxes that take into account changes in evaporation minus precipitation over the ocean and river run-off. Relative to the discharge from AIS and GIS, however, the magnitude of the latter terms amounts to just a few percent.

To illustrate how the net freshwater volume added in high latitudes of the Atlantic and in the Southern Ocean is redistributed by the ocean circulation during the 100 year projection, table 1 shows the space-time-mean freshwater content differences integrated over individual ocean basins (Pacific, North and South Atlantic, Arctic, Southern and the Indian Ocean) averaged over the period 2081–2099. According to the table, less than 50% of the freshwater amount added around Greenland remains in the region in E4.5, while 20% moves into the Arctic. The amount accumulated in the Southern Ocean is more than double that of the freshwater added locally by AIS, indicating that a

Table 1. Total integrated freshwater discharge due to net mass loss rates from GIS and AIS and basin integrated freshwater content differences averaged for 2081–2099 (in 10^{13} m^3).

	Input freshwater volume				Integrated freshwater differences					
Scenario	GIS	AIS	E-P	NET	NA	SA	PAC	IO	AO	SO
RCP4.5	4.5	1.3	0.306	5.91	1.92	−0.69	2.43	−0.18	0.84	2.57
RCP8.5	6.3	0.91	0.901	7.57	4.86	0.25	−1.18	-0.56	0.61	1.89

NET refers to the sum of GIS, AIS and net E-P surface freshwater differences, including differences in run-off. Individual basins over which the freshwater content has been integrated are NA: North Atlantic, SA: South Atlantic, PAC: Pacific, IO: Indian Ocean, AO: Arctic Ocean, SO: Southern Ocean

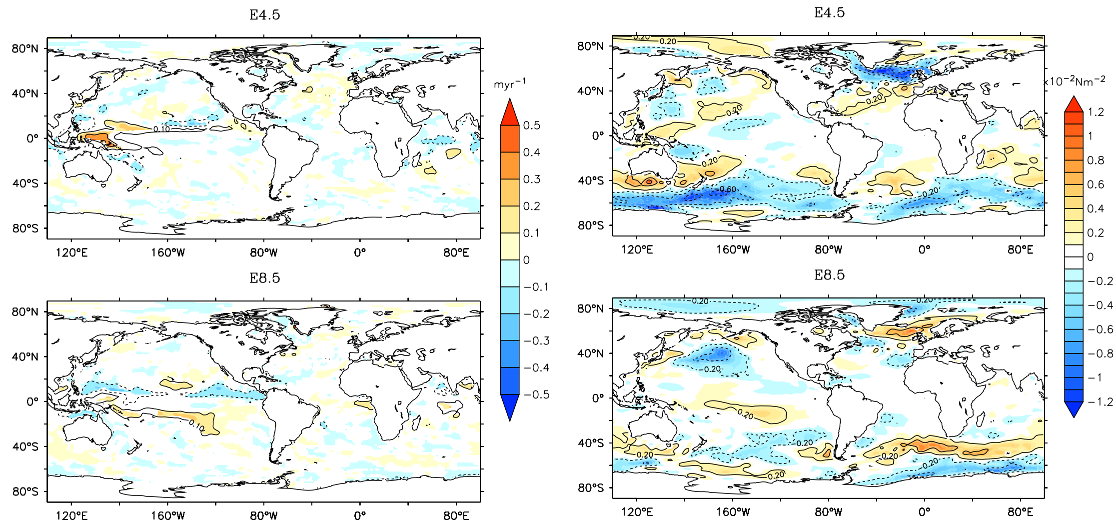

Figure 2. Differences of (left) freshwater fluxes (myr^{-1}) and, (right) zonal wind stress ($\times 10^{-2}$ Nm^{-2}), both averaged over the period 2081–2099 from (top) E4.5 and (bottom) E8.5.

significant amount of freshwater got redistributed to other parts of the world oceans.

We note that in contrast to E4.5, in which about 40% of the net freshwater input ends up in the Pacific Ocean, in E8.5 the Pacific Ocean is losing freshwater. However, in all regions (except in the North Atlantic) intra-ensemble deviations in circulation are substantial which does not allow for firm conclusions on scenario differences with our limited samples. The largest impact is expected from changes in the surface fluxes. The small size of the ensemble simulations does not allow us to carry out a quantitative uncertainty assessment in the results (see also discussion in section 4).

As can be expected from previous results of Stammer *et al* (2011), perturbing the coupled system by meltwater perturbation can lead to feedback mechanisms that will alter the surface fluxes of momentum (wind stress), heat, and even freshwater itself. The left column of figure 2 shows the respective ensemble mean of net surface freshwater flux changes in response to the additional freshwater forcing of the ocean. The largest changes occur over the tropical Pacific and Indian Ocean region. However, the comparison with the level of decadal variability of the pre-industrial control run shows only a few regions with values well beyond the system's internal variability (see also figure S1 in the supplementary material for similar differences from individual ensemble members).

The right column of figure 2 shows the ensemble mean differences in zonal wind stress from E4.5 and E8.5 over the period 2081–2099 (see also figure S2 in the supplementary material for similar differences from individual ensemble members). For E4.5, the westerly zonal wind stress is reduced in the subpolar region south of Greenland and increased in the subtropical North Atlantic. Similarly, in the Southern Ocean around 60°S, the westerly zonal wind stress is reduced. By contrast, E8.5 shows an increase in westerly zonal wind stress in the subpolar region south of Greenland and also in the Southern Ocean centered at 40°S between 50°W and 100°E. South of Greenland these results of E8.5 are similar to those of Agarwal *et al* (2014) who reported a strengthening of westerlies as a part of the early response to the net mass loss from the GIS. However, the weakening of westerly zonal wind stress in E4.5 is not in agreement with Agarwal *et al* (2014). One of the reasons for this could be the reduced strength of freshwater flux from GIS in case of E4.5. Furthermore, in E4.5 the negative anomaly south

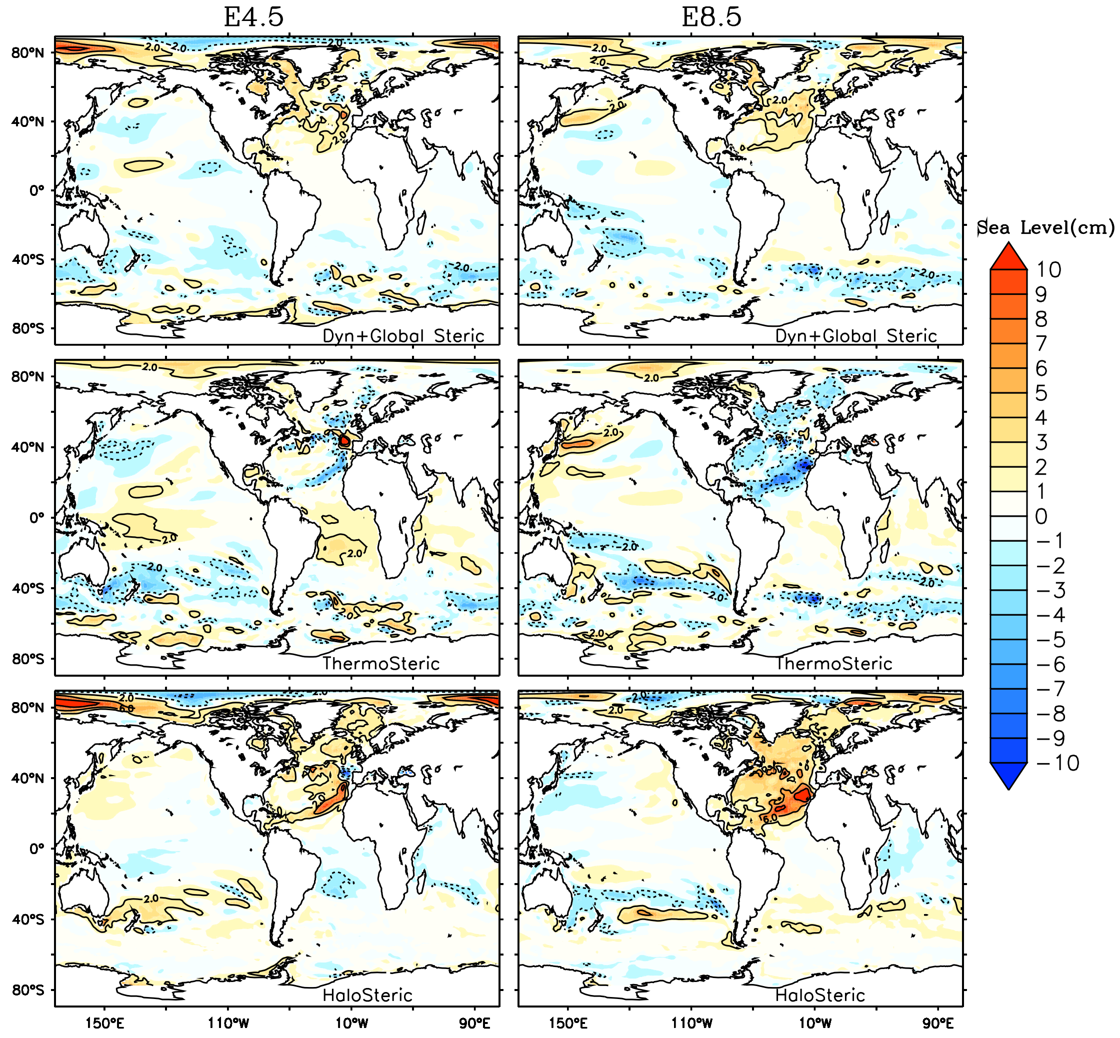

Figure 3. (top) Sea level (cm) change (dynamical + global mean steric), (middle) thermosteric and (bottom) halosteric sea level (cm) changes from (left) E4.5 and (right) E8.5 averaged over the period 2081–2099.

of Greenland was found to be a part of long-term (20 years) internal variability of the system. Particularly at higher latitudes, internal variability has been found to be large for sea level pressure and can easily obscure regional differences in projections (Deser *et al* 2012).

To provide an estimate of dynamical sea level changes missing in CMIP5 results due to the lack of freshwater source from polar ice mass loss, the left panels of figure 3 show the regional sea level in E4.5 (see also figure S3 in the supplementary material for similar differences from individual ensemble members). The values in the top panel of figure 3 correspond to the sea level changes (dynamical + global mean steric) between experiments with and without PIM. Sea level changes are mostly positive in the northern hemisphere, notably in the North Atlantic and the Arctic. In the North Atlantic and Nordic Seas the steric sea level increase in response to Greenland ice mass loss can be around 2–4 cm; however, the changes are substantially larger in the Arctic Ocean, thus enhancing the already large sea level rise there (compare figure 4). In contrast, positive sea level differences in the southern hemisphere are restricted to the immediate vicinity of the Antarctic continent; this holds also for the eastern Antarctic region where no perturbation was directly applied. Most of the remaining Southern Ocean, however, shows negative sea level changes relative to the global mean increase, which is consistent with the pole-ward shift in zonal wind stress described above and associated shift in the position of the ACC as described by Fyfe and Saenko (2006)

In E8.5, the sea level increase in the North Atlantic and in the Nordic Seas ranges between 0.5 and 2–4 cm, with higher values mainly in the Labrador Sea and in the subpolar and subtropical gyre regions. Despite the stronger freshwater input from Greenland, the sea level differences in the Arctic Ocean are weaker compared to E4.5 suggesting that the changes are likely due to climate variability rather than indicating a causal connection to the freshwater input.

The middle and bottom rows of figure 3 display the thermosteric and halosteric contributions to sea level changes, respectively. As can be expected,

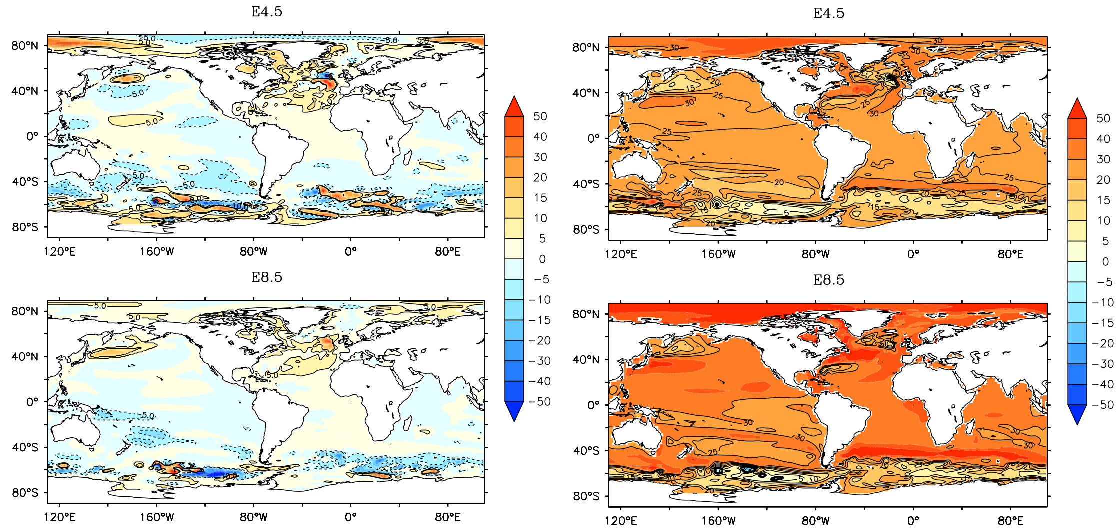

Figure 4. (left) Percentage change in the steric sealevel due to net mass loss rates from AIS and GIS for (top) E4.5 and (bottom) E8.5 averaged for the period 2081–2099 after normalization with the respective differences 2081–2099 minus 1986–2005. (right) 3-member ensemble averaged sea level (cm) change from (top) RCP4.5 and (bottom) RCP8.5 standard MPI-ESM CMIP5 reference runs averaged for 2081–2099. The change is computed with reference to sea level averaged over 1986–2005.

changes in the North Atlantic and Nordic Seas are mainly due to the halosteric component. The largest increase (around 10 cm) is in the southeast edge of the subtropical gyre; however this increase is compensated by a decrease in the thermosteric component and is probably related to the subduction of salinity differences. Note that the associated changes in spiciness also imply changes in subducted temperature anomalies. Due to the change in thermal expansion to haline contraction ratio along the subduction path, temperature differences will grow (Tailleux *et al* 2005), which explains the stronger thermosteric signal at the southern edge. In summary, in the North Atlantic, changes in the total and the components of the steric sea level response are similar in the two scenarios.

Along with the freshening of the North Atlantic, we diagnose a decrease in surface salinity in both E4.5 and E8.5 (SSS; not shown). Due to stronger mass loss rates in E8.5, the averaged SSS differences for the period 2081–2099 are larger in the North Atlantic. In contrast to van den Berk and Drijfhout (2014), in the regions where net mass loss from Antarctic is applied, both E4.5 and E8.5 show very little response in agreement with the weaker freshwater input. Sea Surface Temperatures (SST) are lower around Greenland in both scenarios, and in the subpolar gyre in E8.5 (not shown). A cooling in the subtropics can only be seen in E4.5; however, there are negative SST differences in Southern Ocean near the western Antarctic Peninsula. E8.5 also obtains negative differences in the South Atlantic.

In the North Atlantic we observe an increase in the halosteric component due to the increase in freshwater content and simultaneous decrease in the thermosteric component due to decrease in heat content. For E8.5, this results in a net change of around 2 cm in sea level by the end of the century. Since the amount of freshwater released in the North Atlantic is larger in E8.5 than in E4.5, one could have expected a larger difference between the experiments in terms of sea level change. However, although, the halosteric sea level change is in fact around 2 times larger in E8.5, the net effect on sea level is reduced due to a compensating effect created by a decrease in the thermosteric component. In most others locations, differences have very small magnitudes.

To quantify the relative contributions from halosteric and thermosteric changes to the net steric sea level changes, table 2 shows for each ocean basin separately the sea level differences and their halo-steric and thermo-steric contributions as basin averages. In both E4.5 and E8.5, the maximum change in sea level is in the North Atlantic and Arctic Oceans (~2 cm). We note, however, that for E8.5 in the North Atlantic an increase in the halosteric component (due to increased freshwater content) and a simultaneous decrease in the thermosteric component (due to decreased heat content) results in a net change of around 2 cm in sea level by the end of the century. In E4.5, the maximum change is mainly due to the halosteric component. Since the amount of freshwater released in the North Atlantic is larger in E8.5 than in E4.5, one could have expected a larger impact in terms of sea level change. However, although the halosteric sea level change is in fact around 2 times larger in E8.5 than in E4.5, the net effect on sea level is reduced due to a compensating effect created by a decrease in the thermosteric component. In most other regions the dynamical effects on regional sea level projections due to polar ice sheet mass loss appear insignificant.

During the first 60 years, the total steric change in the North Atlantic is around zero (not shown); during

Table 2. Basin-averaged steric, thermo-steric and halo-steric sea level differences averaged over the period 2081–2099 (in cm).

	RCP 4.5			RCP 8.5		
Basin	Steric	Thermo-steric	Halo-steric	Steric	Thermo-steric	Halo-steric
NA	1.848	0.12	1.78	1.78	−1.62	3.51
SA	0.57	1.348	−0.82	0.82	0.51	0.33
PO	0.35	0.07	0.29	0.187	0.402	−0.22
IO	0.41	0.56	−0.17	0.163	0.42	−0.271
AO	2.21	0.40	1.85	1.68	0.084	1.806
SO	0.53	0.09	0.45	0.296	−0.042	0.3472

Individual basins over which the freshwater content has been integrated are NA: North Atlantic, SA: South Atlantic, PAC: Pacific, IO: Indian Ocean, AO: Arctic Ocean, SO: Southern Ocean

the following years, however, sea level rises steadily with long term oscillations superimposed. In contrast, sea level in the Arctic Ocean rises from the beginning of the experiments with a steepened increase starting from 2070 to 2090 to be followed by a slight decrease towards the end of the century. There is a slight increasing trend in sea level in the South Atlantic beginning from year 2030, however the changes are quite small (1 cm). In other regions, changes in sea level are negligible and remain within the natural long term variability. To further quantify the relative impact of the impact of freshwater input, the left panels in figure 4 show the percentage change in steric sea level for both E4.5 and E8.5 scenarios during 2081–2099 after normalization with the changes 2081–2099 minus 1986–2005 of the MPI-ESM for RCP4.5 and RCP8.5, respectively. The ensemble mean sea level changes (in cm) from RCP4.5 and RCP8.5 are shown in the right panels as reference.

For RCP4.5 forcing, the maximum relative changes due to net mass loss rates from GIS and AIS appear in the North Atlantic and in the Arctic regions. In the regions around the coast of Greenland and north-east of North America, changes in sea level are up to 20% while in the Eurasian Basin of the Arctic the sea level increase is more than 20%. The changes in the subpolar and subtropical North Atlantic are between 2% and 4%. In the Southern Ocean, the changes in sea level are less than 10%. In E8.5, changes in sea level are between 10% and 20% around Greenland and in the Eurasian Basin of Arctic Ocean. Elsewhere, changes in sea level are less than 5%. The changes in subtropical North Atlantic are similar in the two experiments. There is a slight increase in sea level in the North Western Pacific; changes in the Southern Ocean remain small except in the sector 50°E–80°E.

4. Conclusions

The goal of this paper is to provide a quantitative assessment of the amplitude of regional sea level changes at the end of the 21st century that would result dynamically in RCP 4.5 and RCP 8.5 climate projections from previously missing local freshwater sources around retreating land ice masses. We recall that in this pilot study only the mass loss of polar ice sheets is considered. We therefore have to keep in mind that differences shown here are likely to be at the lower end of what will result from future CMIP runs with all melt water sources included.

The regional impact of the missing sources stays mostly below 2 cm with largest values not exceeding 10 cm. We note that this signal is a factor 2–3 times smaller in comparison to the recent study by van den Berk and Drijfhout (2014), who used a stronger forcing. We also find a weaker impact in the North Atlantic and Arctic Ocean as well as along the Antarctic shelf. The difference in the regions close to the Antarctic coast are negligible in magnitude, but are overall negative in the Southern Ocean.

The number of simulations in our ensembles are the same as in the CMIP5 runs of the model. Our estimate of statistical significance is based on a comparison with internal variability in the unforced control simulation. However, for an improved assessment of how robust our results are on regional scales, a substantially larger ensemble size would be needed. In an attempt to show systematic behaviors the supplementary material presents similar changes of surface freshwater and wind stress fluxes as well as those for net sea level for each member of the ensembles. Variability between ensemble members is inevitable as was highlighted recently by Deser *et al* (2012) and by Hu and Deser (2013) in terms of sea level.

Although our results suggest a small additional sea level signal which renders the current sea level changes mostly unaffected, regionally larger contributions of up to 20% exist implying that in future quantitative CMIP-type projections glacier mass loss has to be considered simultaneously with polar ice sheet mass loss and both effects should be build into climate models to include all components of regional sea level changes. Furthermore, substantially large ensemble size estimates are required for more accurate regional sea level change projections in any CMIP based analyses.

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