Understanding the Uncertainty in the 21st Century Dynamic Sea Level Projections: The Role of the AMOC

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Abstract Climate models show that the largest uncertainties in the 21st century dynamic sea level (DSL) projections are in the high latitudes of the North Atlantic and Southern Oceans. We conduct an intermodel singular value decomposition analysis and find that the DSL uncertainties in these two oceans are both intrinsically connected to the uncertainty in the change of the Atlantic meridional overturning circulation (AMOC). We further conduct a freshwater hosing experiment to show that the AMOC decline not only accounts for the dipole pattern in the DSL change in the North Atlantic but also remotely induces a poleward shift in the Southern Hemisphere westerlies that helps build a belted pattern of DSL change in the Southern Ocean. Our results suggest that reducing the intermodel spread in the change of the AMOC can greatly improve the consistency of DSL projection among models not only in individual basins but over the global ocean.

Plain Language Summary State-of-art climate models project distinct patterns of regional sea level change. Most of these patterns arise from a dynamic change in the ocean, which has been named the dynamic sea level (DSL) change. However, climate models project different regional DSL changes in the 21st century, especially those in the North Atlantic and Southern Oceans. Any connection between intermodel uncertainties in the DSL projections in different basins has largely been ignored. We argue here that the change in the Atlantic meridional overturning circulation (AMOC) is a key factor that controls the intermodel uncertainty of regional DSL projections on a global scale. A weakening AMOC alters the DSL pattern in the North Atlantic and concurrently remotely affects the DSL over the Southern Ocean. In particular, we find that a decline in the AMOC could cause a poleward shift of the Southern Hemisphere westerly winds and thereby lead to a zonal belt-like change of the DSL in the Southern Ocean. These results imply that improving the intermodel consistency of the projected changes in the AMOC will greatly improve the reliability of future sea level projections on a global scale.

1. Introduction

Sea level has been observed to have undergone a rapid rise during the past century (Church & White, 2011; Dangendorf et al., 2017; Ray & Douglas, 2011) and is predicted to rise even more rapidly throughout the current century (Church et al., 2013). However, this rise is not globally uniform (Bouttes & Gregory, 2014; Church et al., 2013; Pardaens et al., 2011; Slangen et al., 2014; Yin, 2012). Regional sea level change is mainly driven by alterations in ocean dynamics (ocean density and circulation) and land-ice discharge (Bamber & Riva, 2010; Bouttes & Gregory, 2014; Kopp et al., 2010; Perrette et al., 2013). Particularly, the former contribution, also named the dynamic sea level (DSL) change, is considered to be dominant even though land-ice change is predicted to become increasingly important later in the century (Bamber & Riva, 2010; Church et al., 2013; Horton et al., 2018; Kopp et al., 2010; Perrette et al., 2013).

State-of-art climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) project distinct patterns of regional DSL change (Perrette et al., 2013; Yin, 2012). However, these models disagree on some of the details in the DSL change patterns, especially for those in the North Atlantic and Southern Oceans (Bouttes et al., 2012; Little et al., 2015; Yin, 2012). The intermodel spread in the DSL projections can be substantial when compared to the global mean sea level rise (Church et al., 2013) and hence become a serious impediment to sea level projection. To reduce the uncertainty in DSL and improve the reliability of sea level projection, it is important to understand the physical mechanisms governing the intermodel spread in regional DSL.
In previous studies, several mechanisms were proposed to explain the intermodel uncertainty in the regional DSL projections for individual basins. For example, over the Atlantic, the magnitude of regional DSL rise was found to be significantly correlated with the degree of weakening of the Atlantic meridional overturning circulation (AMOC) projected by each model (Pardaens et al., 2011). In the Southern Ocean, it was suggested that the poleward-intensification of the westerly wind stress accounts for most of the intermodel disagreement in the projected change of regional DSL (Bouttes et al., 2012). However, the mechanisms driving the intermodel uncertainty in regional DSL projections were examined basin-by-basin and interpreted separately ignoring any intrinsic connections in the DSL responses between basins. The intermodel uncertainty of regionally varying DSL change had rarely been examined on a global scale.

In this study, we explore the key factor controlling the uncertainty in the projection of regional DSL on a global scale. We perform a singular value decomposition (SVD) analysis of CMIP5 model projections and find that intermodel uncertainties in the regional DSL projections are commonly linked to the uncertainty in the AMOC response. The mechanism by which the AMOC affects the regional DSL pattern is further elaborated in a freshwater hosing experiment. Here it is worth noting that the aim of the freshwater hosing experiment is different from previous studies. In previous hosing experiments, a weakening of the AMOC was suggested to be responsible for the pattern of the DSL change in the North Atlantic (Bouttes & Gregory, 2014; Hu et al., 2011; Levermann et al., 2005; Yin et al., 2009, 2010) and partially responsible for the DSL change in the Southern Ocean (Yin et al., 2010). However, the dynamical processes through which the AMOC affects DSL changes—especially those over the Southern Ocean—were not explored in detail. Consequently, understanding the physical processes that couple the interbasin response serve as the focus in our analysis of freshwater hosing experiment.

2. Data, Methods, and Model

2.1. CMIP5 Models and Simulations

We use historical and representative concentration pathways 4.5 (RCP4.5) simulations (Taylor et al., 2012) from 30 available CMIP5 models (Table S1 in the supporting information). Only one member run (r1i1p1) is selected from each model to ensure equal model weighting in the intermodel analysis. DSL is the sea level deviation from the global mean (its global average is zero). Some models show DSL drifts in their preindustrial control runs in which greenhouse gas concentrations are held constant (Sen Gupta et al., 2013). Therefore, a linear drift correction is applied to all climate models at each grid point for the simulations. For each model, variables are interpolated onto a common 1° × 1° latitude-longitude grid prior to analysis. For each variable, the projected change is calculated by subtracting the 25-year mean of 1976–2000 of the historical simulation from the 2076–2100 mean of the RCP4.5 runs. For reference, we also make a parallel analysis under the RCP8.5 scenario (Figure S1 in the supporting information) to show that our results are not scenario-dependent.

2.2. Methods

We calculate the AMOC streamfunction (ψ) from the meridional velocity (v) of the model outputs as

$$\psi(y, z) = \int_x^{x_e} \int_{x_w}^{x_e} v(x, y, z) dx dz$$

where x, y, and z are the zonal, meridional, and vertical coordinates and x_e and x_w are the eastern and western boundaries of the Atlantic Ocean. Also, we perform an intermodel SVD analysis, which is similar to a traditional SVD analysis (Wallace et al., 1992) but with the space-model field instead of the traditional space-time field. Intermodel SVD is usually applied to two data fields together to identify pairs of coupled spatial patterns, which explain as much as possible the covariance between the two variables (Long et al., 2016; Long & Xie, 2015; Shiogama et al., 2011; Wang et al., 2014). The detailed description of the intermodel SVD method can be found in Abe et al. (2011) and Shiogama et al. (2011). In this study, we apply the intermodel SVD to the changes in the DSL and AMOC to extract the statistically correlated modes. Note that the multimodel ensemble means of the DSL and AMOC are removed before the SVD analysis is performed.
2.3. CESM and the Freshwater Hosing Experiment

We use the Community Earth System Model version 1.2.2 (CESM; Hurrell et al., 2013), which is maintained by the National Center for Atmospheric Research (NCAR). The f19gx1v6 configuration used here has a finite-volume dynamical core with a nominal 2° horizontal atmosphere and land grid (1.9° latitude × 2.5° longitude) with 26 vertical layers in the atmosphere and a nominal 1° horizontal ocean and ice grid with 60 vertical layers in the ocean. The freshwater hosing experiment is conducted based upon the preindustrial CESM control run by adding freshwater to the North Atlantic between 50 to 70°N at a rate of 0.5 Sv and maintaining that input throughout the 150-year integration. Because the added freshwater inhibits deep convection and deep water formation in the North Atlantic, the AMOC rapidly weakens (within 50 years) from 18 to 1–2 Sv and remains in this weakened state throughout the simulation (Figure S2). The climatic response to the AMOC weakening is then calculated as the difference between the average of the last 50 years of the freshwater hosing experiment and the average of the 50 years of the control run.

3. Results

3.1. Effect of the Change in the AMOC on the Intermodel DSL Uncertainty

We first examine the ensemble mean and intermodel spread in the DSL change among CMIP5 models at the end of the 21st century. The ensemble-mean DSL changes exhibit distinct spatial patterns in high latitudes: a meridional dipole pattern in the North Atlantic Ocean and a belted pattern in the Southern Ocean (Figure 1a, also see Perrette et al., 2013; Saenko et al., 2005; Yin, 2012). The dipole pattern is characterized by larger sea level rise north of the Gulf Stream and smaller sea level rise to the south, while the belted pattern is characterized by smaller sea level rise south of 50°S and larger sea level rise to the north. In addition, the intermodel spread of the DSL change is large (Figure 1b) and comparable in magnitude to the ensemble mean (Figure 1a), indicative of large intermodel uncertainty in DSL projections. This DSL uncertainty is largest in the high latitudes of the North Atlantic and Southern Oceans where the ensemble-mean DSL changes are also large.

![Figure 1. Multimodel (a) ensemble mean and (b) spread (one standard deviation) of the Coupled Model Intercomparison Project Phase 5 (CMIP5) dynamic sea level change under the representative concentration pathway (RCP) 4.5 scenario. The dynamic sea level change is shown relative to the global mean sea level rise.](10.1029/2018GL080676)
We have been seeking a key factor that controls the intermodel uncertainty of regional DSL projections on a global scale, and it appears that the AMOC plays this role. To verify this, we perform an intermodel SVD analysis of the changes in the DSL and AMOC streamfunction under the RCP4.5 scenario (Figure 2). The results show that the DSL pattern of the first SVD mode possesses a dipole pattern in the North Atlantic Ocean and a belted pattern in the Southern Ocean (Figure 2a), which resembles the pattern of the ensemble-mean DSL alterations (Figure 1a). This DSL mode corresponds to a weakening AMOC mode, as indicated by the negative values of the AMOC streamfunction in the upper 2,000 m (Figure 2b). As such, this first SVD mode suggests that the DSL uncertainties over the North Atlantic and Southern Oceans are both connected through the variations in the AMOC. Statistically, this first coupled mode of the intermodel variance accounts for 68.7% of total covariance, meaning that the majority of the coupled variability between DSL and the AMOC is captured by this mode. The correlation coefficient (0.84) between the expansion coefficients of DSL and the AMOC is statistically significant at the 99% confidence level. Therefore, the SVD results suggest a strong and significant relationship between the changes of DSL and the AMOC. In addition, we perform a linear regression of the DSL alterations upon changes in the AMOC strength for CMIP5 models (Figure S3). We find that the regression map also shows a robust dipole pattern in the North Atlantic and a belted pattern in the Southern Ocean, which indicates that a larger (smaller) reduction in the AMOC will correspond to a more (less) pronounced change in the DSL pattern.

The results from the SVD and regression analyses show that the impact of the change in the AMOC on DSL change is not limited to the North Atlantic but extends to the Southern Ocean. To demonstrate the existence of this remote AMOC effect, we compose the changes in the zonal mean DSL, surface winds, and sea level pressures based on the degree of weakening of the AMOC in CMIP5 models (Figure S4). Compared to models with smaller AMOC weakening, models with larger AMOC weakening project a stronger intensification and larger poleward shifts of the westerly winds (Figure S4b) and sea level pressures (Figure S4c) over the Southern Ocean, which match the change in DSL (Figure S4a). This result suggests that change in the strength of the AMOC plays an important role in altering Southern

Figure 2. Spatial patterns of changes in the (a) dynamic sea level (DSL) and (b) Atlantic meridional overturning circulation (AMOC) for the first inter-model singular value decomposition mode (accounting for 68.7% of total covariance) under the representative concentration pathway 4.5 scenario. (c) Scatter plot and least squares regression line of the first mode expansion coefficients of DSL versus AMOC for the 30 Coupled Model Intercomparison Project Phase 5 (CMIP5) models (see Table S1 for model list). Both expansion coefficients have been normalized by their own standard deviations.
Ocean winds and therefore impacts the Southern Ocean DSL. However, the role of the AMOC cannot be demonstrated solely from the statistical analysis of CMIP5 model outputs alone. To examine the physical processes by which the variations in the strength of the AMOC affect regional DSL on a global scale, we carry out a freshwater hosing experiment in which anthropogenic forcing is excluded to isolate the AMOC change as the only factor driving changes of the climate system.

3.2. DSL Response in the Freshwater Hosing Experiment

Figure 3a shows the DSL response to the weakening of the AMOC in the freshwater hosing experiment. The change in the AMOC has a global impact on the change in DSL, with regional changes most pronounced in the North Atlantic and Southern Oceans. In the North Atlantic, the decline of the AMOC induces an anomalous heat flux and ocean circulation, which creates a strong north-south sea level gradient around 40°N (Bouttes & Gregory, 2014; Pardaens et al., 2011; Yin et al., 2009, 2010). This dipole pattern well reproduces the uncertainty pattern in the CMIP5 DSL in the North Atlantic from the previous SVD analysis (Figure 2a).

In the Southern Ocean, we find that the weakening of the AMOC causes an anomalously low (high) sea level around 65°S (50°S; Figures 3a and 3b). This belted pattern in the Southern Ocean DSL also captures the main structure of the first DSL mode in the SVD analysis (Figure 2a) and is also consistent with the results from Yin et al. (2010). Dynamically, the weakening of the AMOC reduces northward ocean heat transport, which leads to strong tropospheric cooling in the Northern Hemisphere and a mild tropospheric warming at middle and high latitudes of the Southern Hemisphere. The strongest warming in the Southern Hemisphere is located around 50°S (Figure 4a), which increases the poleward temperature gradient south of 50°S but decreases it to the north. Corresponding to these changes in the temperature gradient, the winds on the equatorward flank of the upper level subtropical westerlies weaken while those on its poleward flank intensify (Figure 4b), thus indicative of poleward shifts of the Southern Hemisphere westerly jet (Chavaillaz et al., 2013; Lu et al., 2008; Wilcox et al., 2012) and the Ferrell cell (Figure 4c). Similar poleward shifts are also evident in the surface winds (Figures S5 and S6) and sea level pressures (Figure S5).

Consistent with this poleward shift of the westerly winds, the zonal mean wind stress curl anomaly over the Southern Ocean possesses a dipole structure, with positive values north of 60°S and negative values to the

Figure 3. Dynamic sea level (DSL) and wind stress responses in the freshwater hosing experiment. Spatial patterns of (a) DSL and (c) surface wind stress. The zonal mean (b) DSL and (d) surface wind stress (red) and wind stress curl (black).
south (Figure 3d). This change in the surface wind forcing displaces the Deacon cell and in turn the residual
MOC in the Southern Ocean (Figure S7), leading to anomalous positive (negative) heat storage north (south)
(Bouttes et al., 2012; Fyfe et al., 2007; Liu et al., 2018; Morrison et al., 2016; Yin et al., 2010). As a
result of the vertically integrated effect of this anomalous heat storage, the sea level change forms a belted
pattern over the Southern Ocean (Figures 3a and 3b).

4. Summary

We investigate the intermodel uncertainty in the regional DSL projection on a global scale based on 30
CMIP5 models and focus on the role of the AMOC. We find that the largest uncertainties occur in the high
latitudes of the North Atlantic and Southern Oceans, which lower the confidence of future DSL projection.
An intermodel SVD analysis shows that the DSL uncertainties in the North Atlantic and the Southern

Figure 4. Meridional structure (color shading) of the zonal mean (a) temperature and (b) zonal winds, and (c) meridional
streamfunction in the freshwater hosing experiment. The overlapping black contour lines in each panel denote the cli-
matology of the control run.
Oceans are intrinsically connected, both being governed by the magnitude of the change in the AMOC. Further, a CESM freshwater hosing experiment shows that a weakening of the AMOC can cause an anomalous DSL dipole in the North Atlantic and remotely induce a belted DSL change over the Southern Ocean. Specifically, the weakening of the AMOC drives an increase (decrease) in the poleward tropospheric temperature gradient south (north) of 50°S. These changes in tropospheric temperature gradient cause a poleward shift of the westerly winds in the Southern Hemisphere, which in turn, generate a belted change pattern in DSL in the Southern Ocean. Our results suggest that the AMOC is likely the key to understanding the uncertainty of regional DSL projection on a global scale. Consequently, reducing the uncertainty in the projection of the strength of the AMOC will greatly improve the fidelity of DSL projections.

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References


