Uncertainty in future regional sea level rise due to internal climate variability

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[1] Sea level rise (SLR) is an inescapable consequence of increasing greenhouse gas concentrations, with potentially harmful effects on human populations in coastal and island regions. Observational evidence indicates that global sea level has risen in the 20th century, and climate models project an acceleration of this trend in the coming decades. Here we analyze rates of future SLR on regional scales in a 40-member ensemble of climate change projections with the Community Climate System Model Version 3. This unique ensemble allows us to assess uncertainty in the magnitude of 21st century SLR due to internal climate variability alone. We find that simulated regional SLR at mid-century can vary by a factor of 2 depending on location, with the North Atlantic and Pacific showing the greatest range. This uncertainty in regional SLR results primarily from internal variations in the wind-driven and buoyancy-driven ocean circulations. **Citation:** Hu, A., and C. Deser (2013), Uncertainty in future regional sea level rise due to internal climate variability, *Geophys. Res. Lett.*, *40*, 2768–2772, doi:10.1002/grl.50531.

1. Introduction

[2] Observational records show that global mean surface temperatures have warmed since the late 19th century [e.g., *Morice et al*., 2012] and that ocean heat content has increased over at least the past 50 years [*Levitus et al*., 2012]. Correspondingly, global mean sea level has been rising at an approximate rate of 1.8 cm/decade over the 20th century [*Church and White*, 2011], a pace that has accelerated to approximately 3.1 cm/decade in recent decades [*Church et al*., 2011]. Satellite-based observations suggest a significant and accelerating mass loss from the Greenland and Antarctic ice sheets, contributing approximately one third of the total global sea level rise (SLR) in recent years, with seawater thermal expansion and runoff from glaciers and mountain ice caps accounting for the rest [*Rignot et al*., 2011; *Church et al*., 2011; *Jacob et al*., 2012].

[3] Global mean sea level is controlled primarily by volume changes of the world's oceans [e.g., *Antonov et al*., 2002; *Munk*, 2002]. The total volume of seawater is affected by temperature and salinity changes (thermosteric and halosteric components, respectively) and by the buildup or melt-back of continental ice, including ice sheets, glaciers, and mountain ice caps (the eustatic component), and may also be affected by groundwater mining and dam building. A warmer and fresher ocean or a melt-back of continental ice will increase seawater volume, leading to a rise in sea level. Regionally, sea level is also affected by wind- and buoyancy-driven ocean currents associated with the redistribution of heat and salt in the ocean (the dynamical component). For example, the northward flowing Gulf Stream is balanced by higher sea level to its east and lower sea level along the east coast of the U.S. If the transport of the Gulf Stream diminishes due to changes in the buoyancy-driven and/or the wind-driven ocean circulation, then sea level along the eastern seaboard of the U.S. will increase [*Seidov et al*., 2001; *Yin et al*., 2009; *Hu et al*., 2011; *Tebaldi et al*., 2012; *Sallenger et al*., 2012; *Merrifield et al*., 2012].

[4] Due to warming of the world's oceans induced by increasing greenhouse gas (GHG) concentrations, global mean sea level is projected to rise by 30–42 cm by the end of the 21st century, depending on which Intergovernmental Panel on Climate Change Special Report on Emission Scenarios will be realized in the future [*Meehl et al*., 2007], and could be up to 100 cm based on a semiempirical estimation which relates the observed global mean temperature and sea level changes [*Vermeer and Rahmstorf*, 2009; *Meehl et al*., 2012]. Regionally, because of changes in wind- and buoyancy-driven ocean currents in response to global warming, local SLR could be a few times higher or lower than the global mean [e.g., *Nerem et al*., 2010]. In addition to the GHG-forced response, future regional sea level changes will be influenced by internal climate fluctuations on time scales ranging from years to multiple decades, for example ENSO, Pacific Decadal Variability [e.g., *Deser et al*., 2010], and Atlantic Multidecadal Variability [e.g., *Delworth and Mann*, 2000]. In this study, we evaluate the impact of internal climate variability on uncertainty in future regional SLR using an unprecedented 40-member ensemble of climate change projections with the Community Climate System Model version 3 (CCSM3) over the period 2000–2060. This ensemble has been used previously to investigate uncertainty in projected changes to atmospheric circulation patterns, precipitation, and air temperature [*Deser et al*., 2012a, 2012b].

[5] Due to the use of the Boussinesq approximation which requires conservation of the total ocean volume, CCSM3 and many other climate models are only able to simulate the dynamic component of sea level change associated with the redistribution of heat and salt (this term has a global mean of zero). The steric components of sea level change due to a net gain of heat or freshwater are diagnosed offline [*Greatbatch*, 1994]. Currently, the influence of eustatic sea

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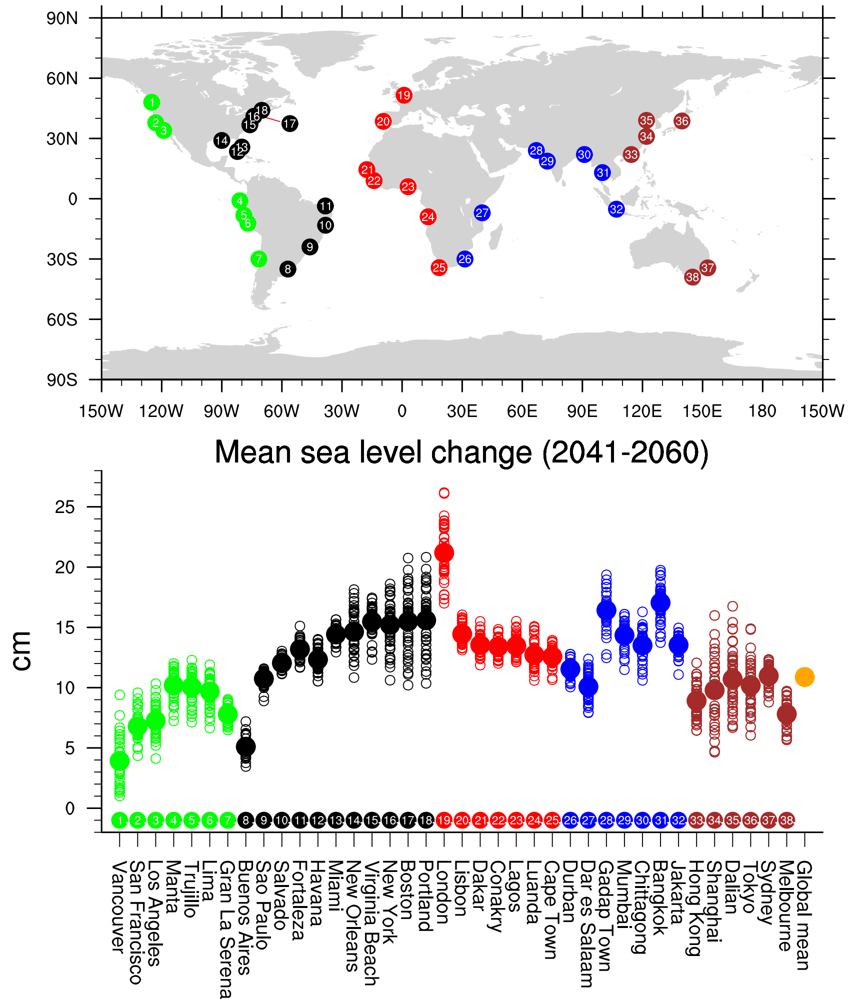

Figure 1. Simulated change in sea level (cm) between the periods 2041–2060 and 1980–1999 at selected coastal cities from the 40-member CCSM3 ensemble. The top panel shows the city locations, color-coded by region. The bottom panel shows the sea level changes using the same regional color-coding, with open circles for each of the 40 ensemble members and filled circles for the ensemble mean.

level change is not incorporated in climate models. Efforts have been made to count this effect [*Mitrovica et al*., 2009] although it has proven to be difficult [*Kopp et al*., 2010]. Therefore, here we focus on the contribution of the dynamic and diagnosed thermosteric components of sea level change only and refer to their sum as the total sea level change.

2. Model and Experiments

[6] The version of CCSM3 used here consists of Community Atmospheric Model version 3 at 2.8° horizontal resolution and 26 levels in the vertical, Parallel Ocean Program at 1° horizontal resolution with enhanced meridional resolution to 0.32° at the equator and 40 levels in the vertical, Community Sea Ice Model version 5 with elastic-viscous-plastic dynamics, and a land surface model Community Land Model, all described in *Collins et al*. [2006]. Each of the 40 ensemble members begins at the end of the same 20th century CCSM3 simulation and is subject to the identical GHG, stratospheric ozone, solar, and aerosol forcings during 2000–2060 [*Deser et al*., 2012a]. In these simulations, the initial ocean, sea ice, and land states are identical, but the initial atmospheric conditions are perturbed by selecting atmospheric states on different days between December 1999 and February 2000 from the 20th century simulation (further details on the experimental design are provided in *Deser et al*. [2012a]; perturbing the ocean initial state may increase the uncertainty sampled here.). Each of the 40 realizations represents a plausible outcome of climate change in the presence of internal variability over the next 50 years, and their spread represents the irreducible uncertainty of the predicted future climate [see *Deser et al*., 2012b].

3. Results

[7] Figure 1 (and Table S1 in the supporting online material) shows the ensemble spread of the mean SLR averaged over the last 20 years of the integration period (2041–2060) relative to the reference interval 1980–1999 at selected coastal cities. Although global mean SLR is almost identical among the different ensemble members (11 ± 0.2 cm), regional SLR can vary by a factor of 2 or more at many locations around the globe. For example, the projected range in SLR is: 4.3–9.6 cm at San Francisco, 4.1–10.3 cm at Los Angeles, 10.2–20.8 cm at Boston, 3.5–7.2 cm at Buenos Aires, 6.5–12.1 cm at Hong Kong, 4.6–16.0 cm at

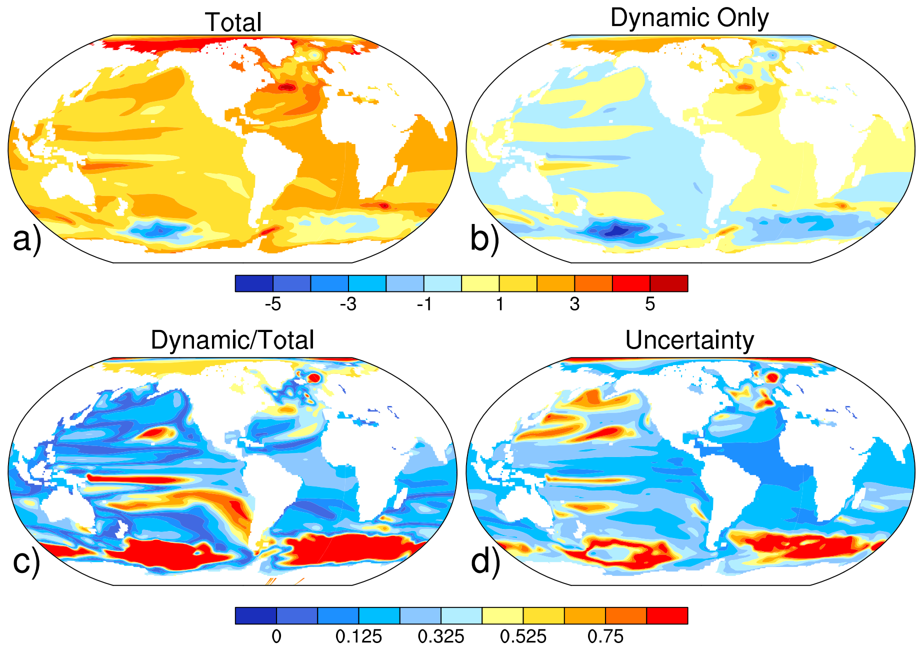

Figure 2. Projected ensemble-mean trends of (a) total and (b) dynamic sea level during 2000–2060 (cm/decade). Figure 2c shows the ratio of the dynamic sea level trend to the total sea level trend, and Figure 2d shows the uncertainty of the total sea level trend (see text for details).

Shanghai, and 6.1–14.9 cm at Tokyo. Other locations, including many at low latitudes, show a smaller spread, for example 12.9–15.6 cm at Miami, 11.9–15.5 cm at Dakar, 10.7–13.9 cm at Cape Town, and 11.1–15.0 cm at Jakarta. Some places (such as San Francisco and Mumbai) exhibit a peak in the SLR frequency distribution while others (such as Boston and London) do not (Figure S1). The ranges of future SLR depicted in Figure 1 could lead to significant challenges in mitigating their potential impacts on society, especially when compounded with storm surges [*Tebaldi et al*., 2012]. It is worth emphasizing that the diversity of SLR projections in this model ensemble is solely a result of unpredictable, internally generated climate variability. Structural differences between models and alternative GHG scenarios constitute additional sources of uncertainty for SLR projections. However, unlike those associated with internal climate variability, these additional sources of uncertainty may be reducible as models and predictions of GHG emissions improve [*Deser et al*., 2012b].

[8] Figure 2a shows the geographical distribution of the projected linear trend in total sea level (thermosteric plus dynamic) over the period 2000–2060, averaged over the 40 ensemble members: This constitutes the forced response to increasing GHGs in CCSM3. The total sea level trend is positive everywhere except portions of the Southern Ocean, with maximum values up to 5 cm/decade in the North Atlantic and Arctic basins. The Pacific shows generally weaker trends (1–2 cm/decade) than the Atlantic (2–3 cm/decade). The global mean SLR is primarily due to increased ocean heat storage. Although dynamical effects do not contribute to the increase in global mean sea level, they significantly impact the regional features of the forced component of total sea level change (Figure 2b). Without the thermosteric effect, sea level would rise in the Atlantic, Arctic, and North Indian Ocean basins, and fall in most areas of the Pacific and Southern Oceans over the next 60 years in response to increasing GHG. The contribution of dynamical effects to the change in total sea level is approximately 20–60% in the Atlantic and Arctic basins and portions of the Pacific, and >100% over parts of the Southern Ocean (Figure 2c).

[9] Uncertainty in the magnitude of future sea level trends due to internal climate variability is shown in Figure 2d. Here we define uncertainty as twice the standard deviation of the 40 sea level trends divided by the ensemble mean sea level trend at each grid box, in analogy with the 95% confidence level in the distribution of trends shown in Figure 1. The largest uncertainties occur mainly over middle and high latitudes, with values > 1 in the Southern and Arctic Oceans, and values approaching one in regions of the North Pacific, North Atlantic, and equatorial western Pacific. Such high values of projected sea level trend uncertainty indicate that the contribution from internal climate variability to local SLR can be comparable to that from GHG forcing in any single CCSM3 run, consistent with information shown in Figures 1 and S1. In contrast, much of the tropical eastern Pacific, tropical Atlantic and northern Indian Oceans exhibit low uncertainty, with values generally < 0.2 (Figure 2d).

[10] To further illustrate the relative contributions of internal and forced components of SLR in any single realization, Figure 3 shows the spatial distribution of projected trends in total sea level for ensemble members #29 and #35. These members were chosen based on their contrasting sea level pressure (SLP) trends as discussed below. While there are overall similarities between the two runs, regional details differ. For example, the area east of Japan shows a SLR of 4–5 cm/decade in run 29 (Figure 3a) compared with 0–1 cm/decade in run 35 (Figure 3b), while the region directly to the south shows a decrease in sea level (−1 to 0 cm/decade) in run 29 compared with a modest increase (2–3 cm/decade) in run 35. Differences in regional SLR are also found in the North Atlantic: Run 29 shows a band of relatively large SLR extending from Cape Hatteras eastward with maximum values

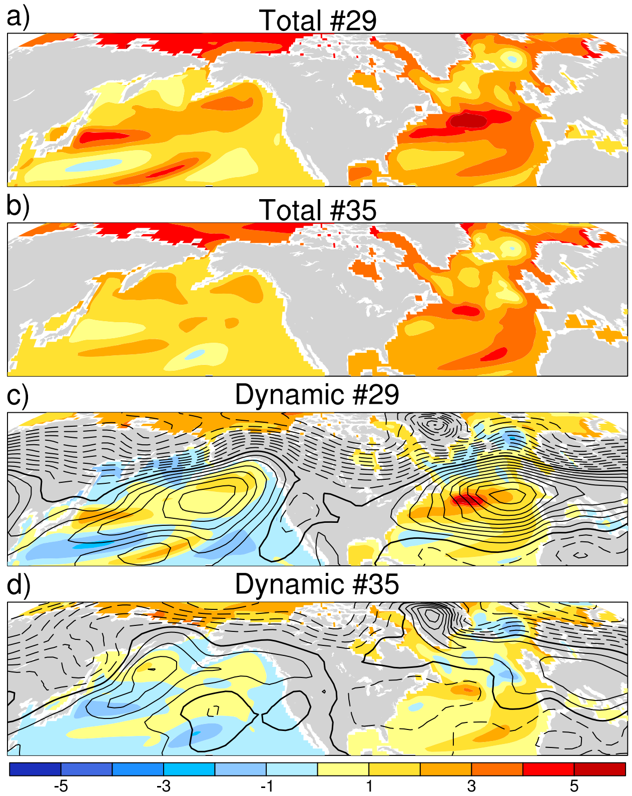

Figure 3. Projected trends of (a, b) total and (c, d) dynamic sea level (cm/decade) during 2000–2060 from two selected ensemble members (#29 and #35). The black contours in Figures 3c and 3d depict the corresponding trends in sea level pressure (contour interval of 0.1 hPa/decade), with solid (dashed) contours for positive (negative) trends.

of 4–6 cm/decade, while run 35 exhibits minimum values east of Cape Hatteras (1–2 cm/decade) and maximum values of only 2–3 cm/decade along the eastern Canadian seaboard.

[11] The dynamical component of SLR associated with changes in ocean circulation must account for the diversity in regional sea level trends in the two individual ensemble members, since the globally uniform thermosteric component is nearly identical for each run (recall Figure 1). Changes in ocean circulation are caused by variations in wind and buoyancy forcing. Figures 3c and 3d show the dynamical sea level trends for the same ensemble members as in Figures 3a and 3b. The accompanying trends in SLP, an indicator of wind forcing, are superimposed upon the dynamical sea level trends. The large-scale SLP trend patterns differ markedly between the two realizations. Run #29 exhibits large-amplitude positive SLP trends over the central North Atlantic and North Pacific and negative SLP trends at higher latitudes. This pattern resembles the positive phase of the Northern Annular Mode [*Thompson and Wallace*, 1998]. In contrast, run #35 exhibits much weaker SLP trends over both ocean basins.

[12] The contrasting atmospheric circulation trend patterns and amplitudes between the two ensemble members can be expected to have significantly different consequences for the wind-driven component of regional dynamic sea level. For example, the large positive SLP trends in member 29, corresponding to anticyclonic wind forcing, are associated with positive dynamic sea level trends locally and to the west, in qualitative agreement with simple theory [e.g., *Pedlosky*, 1998]. On the other hand, the muted SLP trends in member 35 are accompanied by generally weaker dynamic sea level trends in both basins. There is even a reversal in the sign of the dynamic sea level trends in the western portion of the North Pacific between runs 35 and 29, presumably associated with the different patterns of SLP trends. A quantitative analysis is beyond the scope of this study.

[13] The dynamic component of sea level trends depicted in Figures 3c and 3d are affected not only by the wind-driven gyre circulation but also by the buoyancy-forced Atlantic Meridional Overturning Circulation (AMOC). The AMOC is a global-scale ocean circulation that transports warm, saline surface waters northward into the subpolar North Atlantic where they lose heat to the overlying atmosphere and become dense and sink to depth, returning southward to eventually invade the rest of the global ocean [*Broecker*, 1997]. As the climate warms under GHG forcing, the AMOC is expected to slow down in all ensemble members due to weakened deep convection in the subpolar North Atlantic caused by changes in surface buoyancy forcing [*Gregory et al.*, 2005]. The expected signature of a slower AMOC in dynamic sea level is an increase of sea level in the Atlantic, especially along the North American coast and a decrease in the Pacific [e.g., *Yin et al.*, 2009; *Hu et al.*, 2011], consistent with the patterns shown in Figures 1b, 3c, and 3d. This effect is especially clear in the North Atlantic in both of the ensemble members shown in Figures 3c and 3d, despite their different wind forcings, suggesting the AMOC plays a major role in controlling SLR in the North Atlantic.

4. Summary

[14] A unique 40-member ensemble of climate change simulations with CCSM3 has been used to isolate uncertainty in future (2000–2060) sea level trends due to internal climate variations. This source of uncertainty is distinct from those associated with structural differences between models and with different GHG forcing scenarios. In our experiments, the uncertainties in projected 60 year regional sea level trends are due to unpredictable internal climate fluctuations. Our results show that global-mean SLR (not taking into account land-based ice melt) is primarily controlled by thermal expansion of seawater: The increase in globally averaged ocean heat storage varies only slightly among the different ensemble members. On the other hand, projected changes in regional sea level at mid-century are subject to considerable uncertainty, varying by a factor of 2 depending on location, with coastal areas bordering the North Pacific and Atlantic showing the greatest range. This range of projected SLR is due primarily to internally generated trends in large-scale wind patterns and changes in buoyancy forcing. When compounded with storm surges, this range of uncertainty could pose significant challenges for mitigating the potential threats of regional SLR to society. Changes in continental water storage, especially runoff from melting continental ice sheets can also contribute significantly to future SLR, an aspect not included in our model projections. As shown by previous studies, this runoff is not uniformly distributed within the ocean [*Mitrovica et al.*, 2009], adding another potential source of uncertainty to the projection of future local SLR.

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