Potential for bias in 21st century semiempirical sea level projections

S. Jevrejeva,[1,2] J. C. Moore,[1,3,4] and A. Grinsted[1,5]

Received 1 March 2012; revised 20 August 2012; accepted 12 September 2012; published 26 October 2012.

[1] We examine the limitations of a semiempirical model characterized by a sea level projection of 73 cm with RCP4.5 scenario by 2100. Calibrating the model with data to 1990 and then simulating the period 1993–2009 produces sea level in close agreement with acceleration in sea level rise observed by satellite altimetry. Nonradiative forcing contributors, such as long-term adjustment of Greenland and Antarctica ice sheets since Last Glacial Maximum, abyssal ocean warming, and terrestrial water storage, may bias model calibration which, if corrected for, tend to reduce median sea level projections at 2100 by 2–10 cm, though this is within the confidence interval. We apply the semiempirical approach to simulate individual contributions from thermal expansion and small glacier melting. Steric sea level projections agree within 3 cm of output from process-based climate models. In contrast, semiempirical simulation of melting from glaciers is 26 cm, which is twice large as estimates from some process-based models; however, all process models lack simulation of calving, which likely accounts for 50% of small glacier mass loss worldwide. Furthermore, we suggest that changes in surface mass balance and dynamics of Greenland ice sheet made contributions to the sea level rise in the early 20th century and therefore are included within the semiempirical model calibration period and hence are included in semiempirical sea level projections by 2100. Antarctic response is probably absent from semiempirical models, which will lead to a underestimate in sea level rise if, as is probable, Antarctica loses mass by 2100.

Citation: Jevrejeva, S., J. C. Moore, and A. Grinsted (2012), Potential for bias in 21st century semiempirical sea level projections, *J. Geophys. Res.*, *117*, D20116, doi:10.1029/2012JD017704.

1. Introduction

[2] Making reliable predictions of sea level rise is an important practical problem that has serious economic, social, and political implications. To date, there have been two basic methods of estimating sea level rise as a function of climate forcing. The conventional approach is to use "process-based" models that estimate contributions from the sea level components such as thermal expansion and melting from glaciers and ice sheets simulated by process-based models [*Meehl et al.*, 2007a; *Pardaens et al.*, 2011; *Solomon et al.*, 2009]. Recently, semiempirical models of sea level rise were developed to extract statistical relationships between past sea level and forcing. All semiempirical models [*Rahmstorf*, 2007; *Rahmstorf et al.*, 2011; *Grinsted et al.*, 2010, *Jevrejeva et al.*, 2012] project higher sea level rise for the 21st century than those from the conventional approach.

[3] Process-based models include Atmosphere-Ocean Global Circulation Models (AOGCM) to simulate steric sea level due to changes in ocean heat content [e.g., *Gregory et al.*, 2006; *Pardaens et al.*, 2011], ice sheet surface mass balance models [e.g., *Mernild et al.*, 2010; *Graversen et al.*, 2011], ice sheet dynamics models [e.g., *Greve et al.*, 2011; *Price et al.*, 2011; *Seddik et al.*, 2012], and glacier mass balance models [*Radic and Hock*, 2011; *Slangen et al.*, 2011]. Semiempirical models are based on the physical relationships between sea level and changes in global mean temperature [*Rahmstorf*, 2007; *Grinsted et al.*, 2010] or total radiative forcing [*Jevrejeva et al.*, 2009, 2012]. Both process-based and semiempirical models suffer from their own limitations and have large uncertainties [e.g., *Meehl et al.*, 2007a; *Rahmstorf et al.*, 2011; *Jevrejeva et al.*, 2012]. Although the names for the differing approaches suggest that there is a strong division between statistical and basic principle models, in fact both rely heavily on physically plausible formulations and gross statistical extension in order to produce global sea level rise estimates.

[4] Of the various semiempirical models published to date, the *Jevrejeva et al.* [2012] (denoted here on as J11) is

[1]State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Global Change and Earth System Science, Beijing Normal University, Beijing, China.
[2]National Oceanography Centre, Liverpool, UK.
[3]Arctic Centre, University of Lapland, Rovaniemi, Finland.
[4]Department of Earth Sciences, Uppsala University, Uppsala, Sweden.
[5]Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark.

Corresponding author: S. Jevrejeva, National Oceanography Centre, Liverpool L3 5DA, UK. (sveta@noc.ac.uk)

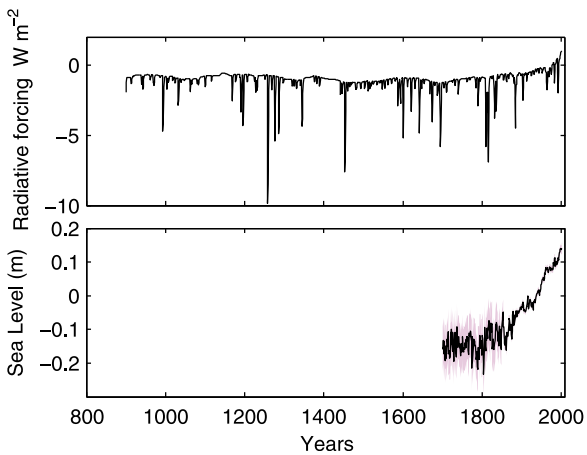

Figure 1. Initial data sets for calibration, showing (top) radiative forcing [*Crowley et al.*, 2003] and (bottom) sea level reconstruction (black line) with large error bars (purple shadow) for the first 150 years.

unique in being dependent on radiative forcing rather than temperature. This feature allows us to both separate different components of forcing (volcanic solar, greenhouse gases, etc.) and also to use forcing to drive the separate components of the sea level budget and it is this model that we evaluate in detail in this paper. In addition various semiempirical models have been criticized statistically on the grounds that the input data are relatively short and they are low-pass filtered [*Holgate et al.*, 2007; *Schmith et al.*, 2007]. However, the J11 approach uses the complete tide gauge record spanning 300 years and no data filtering is done. The J11 model projects the median of 73 cm (with 51–93 cm 2-sigma confidence interval) sea level rise by 2100 when driven by the new Representative Concentration Pathways (RCP4.5) scenario [*Moss et al.*, 2010]. Since earlier studies used forcing from the Special Report on Emission Scenario (SRES) [*Meehl et al.*, 2007a], we also refer to these results here. The RCP4.5 scenario [*Rogelj et al.*, 2012] which is closest to the SRES B2 scenario, leads to significantly lower warming at 2100 than the most commonly used SRES A1B scenario. Estimates of sea level rise from ocean thermal expansion by 2100 under the B2 scenario are about 20 cm [*Meehl et al.*, 2007a]. Glaciers and ice caps may contribute from 12 cm [*Radic and Hock*, 2011] to 17 cm [*Slangen et al.*, 2011] under the A1B scenario. Greenland ice sheet contributions may add up to 17 cm [*Graversen et al.*, 2011; *Seddik et al.*, 2012]. This contribution is made up of surface mass balance and parameterization of dynamic processes. If we use the upper limits of projections from thermal expansion and melting of glaciers and ice sheets then a total of 53 cm sea level rise by 2100 results, which can be compared with 73 cm from the J11 semiempirical model. This is a large difference, but just within 5–95% confidence interval in the J11 semiempirical model. Are we overestimating sea level rise using semiempirical approach?

[5] In this study we test J11 semiempirical simulations of sea level by 2100, by using different calibration periods, including a preindustrial "only-natural" forcing simulation of modern sea level rise. We examine the possible effects of varying sea level inputs from man-made terrestrial water storage and of long-term ice sheet response to deglaciation, both of which are not directly linked to ongoing changes in radiative forcing. We also use the semiempirical approach to simulate steric sea level rise separately from other components and compare that with AOGCM projections by 2100. Similarly we simulate the contribution to sea level rise from small glacier and ice caps and compare with estimates from process- based models. Finally we examine a possible contribution from Greenland ice sheet to projection of future sea level rise.

2. J11 Semiempirical Model Description

[6] *Von Storch et al.* [2008] used the ECHO-G millennial run results to demonstrate that sea level forced by radiative forcing (as used in this study) is significantly better on all timescales than forcing with temperatures. Another advantage of using the radiative forcing record is that greenhouse gases are well mixed; hence estimates from relatively few sources provide a much more representative measure of global forcing than is available from paleo temperature proxies. Finally using forcing rather than temperatures removes the uncertainty of Global Circulation Model (GCM) climate sensitivity. The J11 model uses a relationship between radiative forcing over the past 1000 years and a 300-year-long global sea level reconstruction based the global tide gauge database [*Jevrejeva et al.*, 2012]. The model links forcing to sea level in a physically plausible way and fits four parameters that define the sensitivity and response time of sea level to forcing and two constants [*Grinsted et al.*, 2010; *Jevrejeva et al.*, 2010, 2012]. Model runs explore response times ranging from ~10 to 5000 years [*Jevrejeva et al.*, 2012]. We use Monte Carlo methods to estimate the probability density functions of the four model parameters and then calculate median and 5–95% confidence interval for sea level projections. We force the J11 model with radiative forcing from the historical reconstruction by *Crowley et al.* [2003] (Figure 1). The global sea level reconstruction (Figure 1) is not "true" global sea level; there are uncertainties due to three causes. First, variation in tide gauge geographical coverage leads to representivity errors since regional differences in sea level trends can be quite large. This is particularly significant when individual ocean basins were not sampled by tide gauges [*Jevrejeva et al.*, 2006]. Second, the errors in sea level reconstruction are not independent but in fact are very highly autocorrelated because the inertia of the ocean and cryosphere system is very large. This effectively reduces the degrees of freedom available to any curve fitting. Third, our sea level reconstruction is calculated by integrating global sea level rates [*Jevrejeva et al.*, 2006, 2008; *Grinsted et al.*, 2007], and the errors in the global sea level rates are integrated as well; consequently uncertainties increase with time both before and after the reference period (which we arbitrarily takes as 1980–1999). *Grinsted et al.* [2010] estimates the uncertainty covariance matrix (C) quantifying the representativity and serial correlation errors (Figure 2). It is important to note that C matrix is a complete representation of the errors in the data; that is it, does not make any artificial assumption about the noise background probability distribution and in actually reveals that the uncertainty is neither white nor red noise. Hence when discussing the confidence intervals

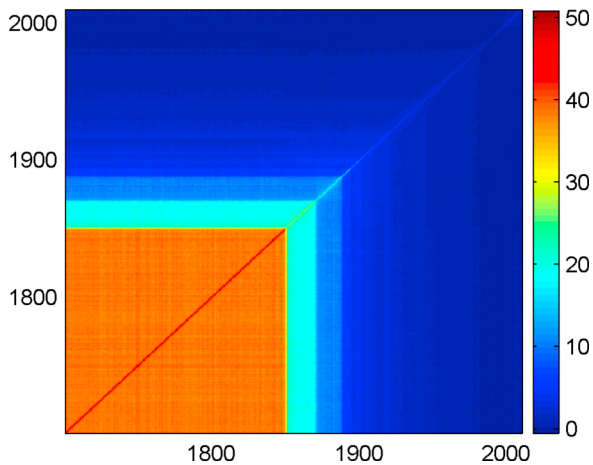

Figure 2. Uncertainty covariance matrix for the global sea level reconstruction since 1700, color bar in cm^2. The lowest uncertainties are during the period 1980–1999, the reference period. Uncertainty in early periods reflects tide gauge stations observations being only from Europe. The leading diagonal can be seen to have higher uncertainty than the perpendicular elements immediately adjacent to it, which reflects the decorrelation process whereby errors tend to cancel over time. The dominant characteristic is the persistent correlation in uncertainty reflected in the rectilinear error map and which is due to the lack of sampling of sufficient ocean basins. Alternatively the map can be thought of as integrating uncertainty as we go back in time from the present (known sea level); if an error exists at some point in time, it will also be present all preceding times, hence uncertainty must always increase with time from the baseline period.

of projections based on parameters estimated from C matrix, Monte-Carlo methods are essential since the low probability tails of the noise distribution affect the confidence intervals. This produces much more conservative (that is larger) uncertainty estimates than would be produced from simply assuming a Gaussian Normal distribution and estimating a standard deviation.

3. Results

3.1. Experiments With Model Parameter Sets Using Restricted Calibration Time Periods

[7] In this section we shall assume that global sea level changes are climate related and driven by changes in ocean heat content and mass loss from glaciers and ice sheets due to variability in total radiative forcing. In each experiment the data sets for calibration were curtailed and, model parameters estimated using a restricted calibration period. We can then validate the simulations against observed sea level.

[8] In our first experiment we investigate model skills in short-term prediction. We cut the calibration period at 1990, before the period of exceptionally high rate of sea level rise observed since 1993 [*Bindoff et al.*, 2007]. Figure 3 demonstrates that simulated sea level for the period 1993–2010 is in good agreement with observed sea level from satellite altimetry, available from http://sealevel.colorado.edu. The model does not include subdecadal scale processes like ENSO, so it is not expected to follow observations on decadal periods. We conclude that the J11 model can reasonably well reproduce short-term (20-year) sea level rise, even if that 20-year period is characterized with higher rates of sea level rise than during the calibration.

[9] If we use only data prior to 1950 for calibration, model simulations (not shown) are in error by about 20% compared with observed sea level rates for the period 1993–2010, and sea level projections by 2100 for RCP4.5 scenario is 60 cm with 5–95% confidence interval of 37–85 cm. The rate simulated by the model is 3.8 mm yr^{-1}, compared with 3.2 mm yr^{-1} observed by satellite altimetry. *Cazenave and Llovel* [2010] suggest an uncertainty of 0.4 mm yr^{-1} for altimetry observations based on comparisons with high-quality tide gauge data [e.g., *Leuliette et al.*, 2004; *Ablain et al.*, 2009]. Although the model predicts too high a rate compared with observations, the integrated simulated sea level change during the 1950–2009 period is almost 3 cm less (25%) than observed sea level. The reason for the difference may be due to the particular values of response time and sensitivity in the model or changes in relative contributions to the sea level budget, which the single box model J11 cannot reproduce.

[10] We next make an experiment in which we expect the model to perform badly. Figure 4 shows sea level simulations with calibration period of 1700–1870, the preindustrial period, when volcanic and solar forcing dominated and greenhouse gases and anthropogenic aerosols were negligible. Sea level over this period was close to equilibrium with climate [*Bindoff et al.*, 2007] (though sparse measurements lead to large variance in the sea level curve); hence determining sensitivity of sea level to forcing is challenging. This provides an indication of how a change in forcing regime (the Industrial Revolution) may seriously challenge a semi-empirical model. Observed global sea level since 1870 is

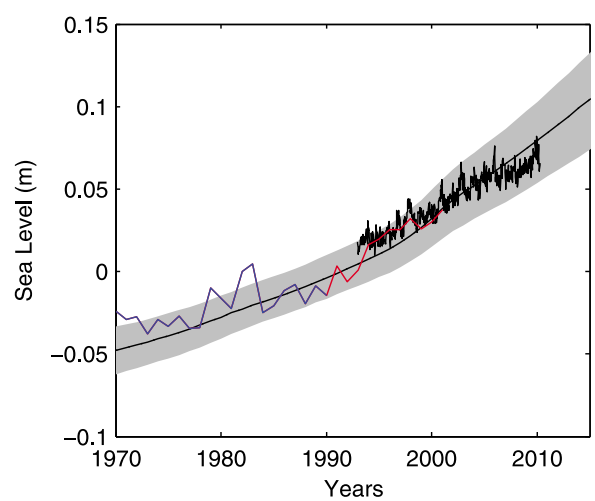

Figure 3. Sea level simulation (thick black line) with model parameters calculated using data prior to 1990. Blue line is tide gauge based sea level reconstruction before 1990 used for calibration; red line is tide gauge global sea level reconstruction, which was not included in calibration. Black think line is satellite altimetry derived sea level. Gray color shadow is 5–95% confidence interval for simulated sea level.

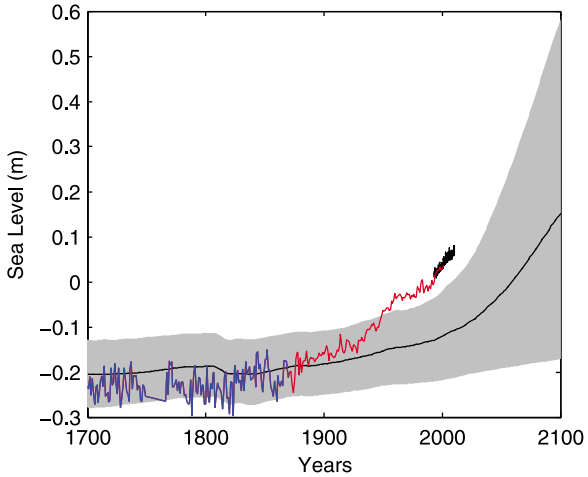

Figure 4. Simulated sea level (black solid line) with 5–95% confidence interval (gray shadow) using calibration period 1700–1870. Blue line is tide gauge sea level reconstruction used for calibration (1700–1870), red line is sea level reconstruction since 1870, and black line is satellite altimetry measurements of sea level.

inside the simulation confidence interval until 1950. That is 80 years after the calibration period. The J11 model underestimates sea level rise during the 20th century by 10 cm (median) or 5 cm (95% confidence limit). The median of the projected sea level rise with RCP4.5 scenario in the 21st century is 29 cm, with huge 5–95% confidence interval ranging from −6 to 72 cm. It is to be expected that the J11 model does not reproduce the 20th century sea level rise, which is mainly determined by the strong increase in anthropogenic radiative forcing [*Hegerl et al.*, 2007; *Jevrejeva et al.*, 2009], but which was not included in calibration period for this test.

[11] The three calibration period experiments illustrate that successful sea level prediction with the J11 model require calibrations periods with significant sea level variations away from equilibrium on multidecadal scales. Both the 1950 termination and 1870 termination calibration periods led to predictions within uncertainties for more than 60 years, longer-term predictions in cases of regime change of forcing is unreliable. However, an important point in interpreting these experiments is that the 19th century observations used have much greater uncertainties than the much better quality of observations available in the present era, which should provide better quality predictor models.

3.2. Experiments With Nonclimate Forced Sea Level Rise During the Calibration

[12] Here we assume that tide gauge measurements could be biased due to natural or human-induced effects, such as water storage in land reservoirs, groundwater pumping, or continued ice sheet adjustment from the last glaciation. Each of these effects individually and the total contribution to sea level rise are not directly related to the present-day climate change nor associated with changes in radiative forcing. These biases are expressed as a rate which we assume to be constant over both calibration and projection. We estimate the bias involved in projections by explicitly removing their contribution to global sea level prior to calibration.

[13] The latest estimate of contribution to sea level rise from dams and artificial reservoirs is about −0.55 mm yr^{-1} since the 1950s [*Chao et al.*, 2008]. A more modest estimate of −0.35 mm yr^{-1} since the 1950s is suggested by *Lettenmaier and Milly* [2009]. However, groundwater extraction may more than compensate for water storage in artificial reservoirs, and *Wada et al.* [2010] estimated a sea level contribution of 0.8 mm yr^{-1} since the 1960s. *Church et al.* [2011] suggested a net effect of −0.1 mm yr^{-1} since 1970, confirming a negligible net effect of −0.1 mm yr^{-1} by *Lettenmaier and Milly* [2009].

[14] In our experiments we explore the envelope of rates mentioned above using land storage corrections to the global sea level curve since 1950 and investigate the impact on semiempirical projections by 2100. To do this, we change the global sea level target for the J11 model by −1.0 mm yr^{-1} to +1.0 mm yr^{-1} in 0.1 mm yr^{-1} increments since 1950, resulting in up to ±5 cm (30%) increase/reduction of observed sea level rise during the 20th century. In each particular experiment we calculated a set of model parameters with global sea level curve changed by the land water storage correction (Figure 5). Corrections of 0.1 (−0.1) mm yr^{-1} have negligible effect on the projected sea level rise, with only 2–3 cm (3%) change from sea level projection of 73 cm using the RCP4.5 scenario. If we use −0.55 mm yr^{-1}, as suggested by *Chao et al.* [2008], which is the correction only due to the water storage in dams and could be canceled with corrections due to groundwater pumping, sea level projections would be 13 cm higher by 2100 (19%). Land water storage corrections larger than ±0.7 mm yr^{-1} will lead to sea level projections outside the J11 5–95% confidence interval.

[15] There has been a suggestion [*Church et al.*, 2001] that the Greenland and Antarctica ice sheets may have a contribution of 0.25 mm yr^{-1} to sea level rise due to long-term adjustments since the Last Glacial Maximum, which is not related to the present-day climate change. This is not an isostatic correction but a long-term dynamical adjustment

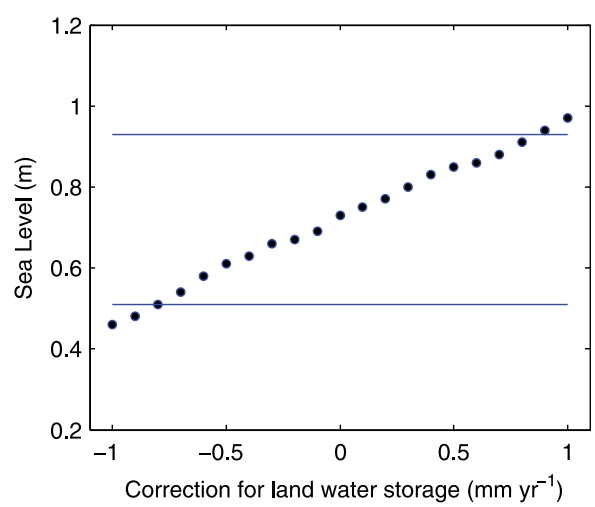

Figure 5. Projections (medians) of sea level rise with RCP4.5 scenario by 2100 using the land storage corrections to the sea level rise since 1950 ranging from −1.0 mm yr^{-1} to +1.0 mm yr^{-1}, blue horizontal lines correspond to the 5–95% confidence level in 73 cm sea level projection using J11 model.

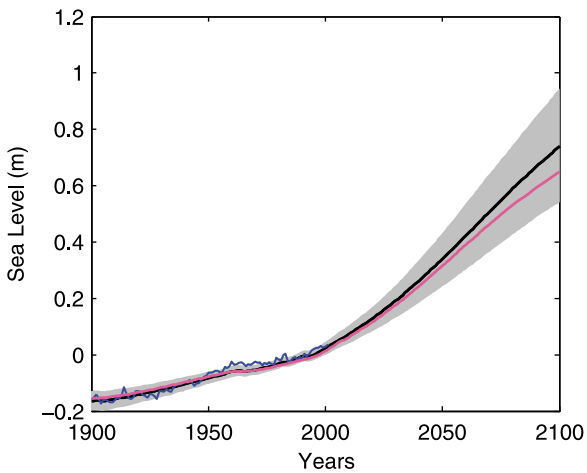

Figure 6. Simulation of future sea level rise by 2100. Black line is sea level projection using J11 model without the correction to the long-term adjustment by ice sheets with gray shadow representing 5–95% confidence interval for sea level projection; blue line is global sea level reconstruction and magenta is sea level projection with correction the ice sheet contribution due to long-term adjustments since the Last Glacial Maximum of 0.25 mm yr^{-1}.

[*Huybrechts et al.*, 1998]. This contribution is within uncertainties in closing the sea level budget since 1955 [*Moore et al.*, 2011; *Church et al.*, 2011] and paleo sea level reconstructions [*Bindoff et al.*, 2007]. Figure 6 shows that if we exclude such ice sheet long-term contribution from the sea level time series during the calibration period (1800–2001) than the median of sea level projection is 65 cm by 2100, which is, nevertheless, inside confidence interval of 51–99 cm of J11 projection.

3.3. Projections of Individual Sea Level Components Using a Semiempirical Approach

[16] The J11 semiempirical model does not separate the global sea level into contributions from individual processes. Here we break down the global sea level into individual components to investigate the potential biases that may arise due to this simplification. We apply the semiempirical approach to well-established components (from thermal expansion and glacier retreat) and compare the resulting projections.

[17] During the past few decades, significant progress has been made to attribute sea level rise to climate related and anthropogenic components. Most recent studies [e.g., *Cazenave and Llovel*, 2010; *Church et al.*, 2011; *Moore et al.*, 2011] show that the sea level budget since 1955 can be closed within uncertainties. Suggested contributions from components vary with different authors [*Church et al.*, 2011; *Cazenave and Llovel*, 2010; *Moore et al.*, 2011]; however, all results support the conclusion that more than 90% is climate-related components and only 1–5% could be attributed to human-induced land water storage.

[18] Prior to 1955, physical processes which could account for sea level rise are not well documented [*Moore et al.*, 2011; *Church et al.*, 2001]. Reconstructions of cumulative glacier mass balance extend to 1800 [*Leclercq et al.*, 2011]. Steric sea level from AOGCM [*Gregory et al.*, 2006] since 1800 is plotted with global sea level in Figure 7. We limit calibration at AD2000 eliminating the recent period of high ice sheets melt rate [*Rignot et al.*, 2011]. Records from tide gauges suggest global sea level rise of 28 cm since 1800 (Figure 7). However, the contribution from thermal expansion of the upper 700 m of ocean is estimated at only 5 cm [*Gregory et al.*, 2006]. This should be corrected to 6 cm for the deeper ocean to 3000 m depth [*Antonov et al.*, 2005]. Mountain glaciers and ice cap volume changes account for 8.4 cm since 1800 [*Leclercq et al.*, 2011] or 9.1 cm since 1850. Hence there is a large unexplained sea level rise (about 0.6 mm yr^{-1} or 40% of global sea level rise over the past 200 years), which is likely caused by combination of underestimating the contribution from melting ice masses (glaciers and ice sheets) and thermal expansion of the oceans. Decadal variability in unexplained sea level contributor is possibly associated with the hydrological cycle and climate-driven changes in continental water storage contribution. We assume the water storage reservoirs and groundwater pumping prior to 1950 to be insignificant [*Wada et al.*, 2010; *Chao et al.*, 2008].

3.3.1. Experiment With Steric Sea Level

[19] We utilize steric sea level simulated by AOGCM from 1800 to 2000 [*Gregory et al.*, 2006] to calculate model parameters and estimate steric sea level rise by 2100. There is an excellent agreement between projections by AOGCMs from Coupled Model Intercomparison Project (CMIP3) [*Meehl et al.*, 2007b] and the J11 model run forced by A1B, with a difference of 3 cm by 2100 (Figure 8). This test shows the J11 model does not overestimate contribution from thermal expansion in global sea level projections by 2100 and suggests that any regime shifts in heat uptake by the ocean during the next 100 years are missed equally in the process-based models and the J11 semiempirical model.

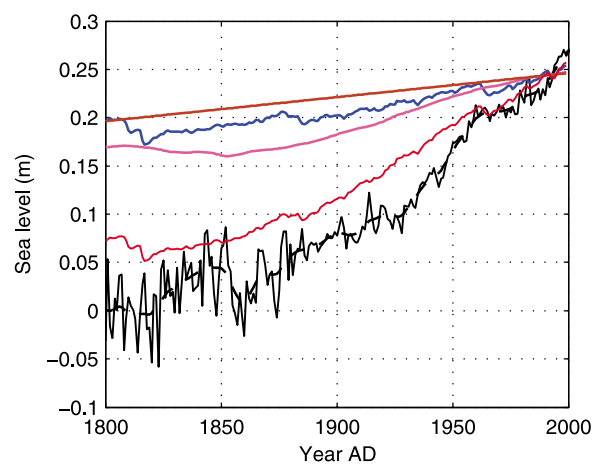

Figure 7. Sea level rise since 1800, raw (thick black) and 21-year smoothed (black dashed) sea level reconstructed from tide gauges, steric sea level simulated by AOGCM (blue), contribution from melting from glaciers and ice caps (magenta), constant 0.25 mm yr^{-1} assumed from long-term glacial adjustment (brown), reconstructed sea level (steric + contribution from melting from glaciers + 0.25 mm yr^{-1}) is red line. The curves are all referenced to the mean 1980–1999 sea level used as the reference period in the J11 model and zero is set to smoothed 1800 observed sea level.

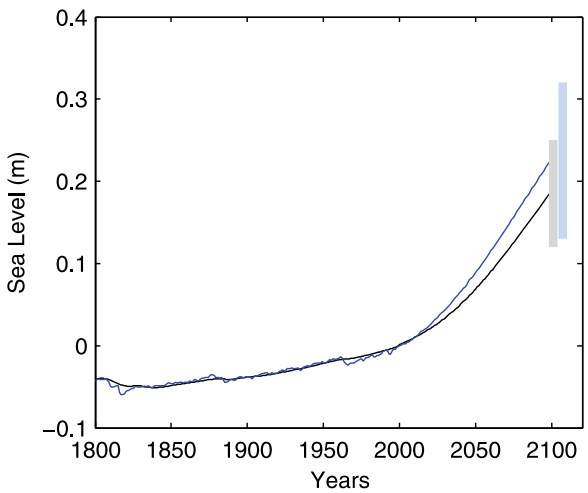

Figure 8. Steric sea level simulated with semiempirical model (black line) using the *Gregory et al.* [2006] data over period 1800–2000 for calibration (blue) and steric sea level after 2000 from CMIP3 AOGCM experiments (blue). Color bars are the 5–95% confidence limit for simulation by semiempirical model (gray) and AOGCMs (blue).

3.3.2. Experiment With Projection of Contribution From Melting of Glaciers

[20] To calculate the model parameters for the semiempirical approach to project the contribution from melting of glaciers, we have used the 200 yearlong reconstruction of *Leclercq et al.* [2011]. The J11 model projects a 26 cm sea level rise by 2100 with RCP4.5 scenario due to the contribution from melting of glaciers. Our estimate using the A1B scenario is 32 cm, which is two to three times as large as the 12 cm by *Radic and Hock* [2011] and 17 cm by *Slangen et al.* [2011] based on surface mass balance changes driven by climate models. However, the J11 simulation is consistent with estimates based on statistical extrapolation of glacier volume with assumed continuous warming of 18–37 cm by *Bahr et al.* [2009].

3.3.3. Possible Contribution From Greenland Ice Sheet Over the Past 200 Years

[21] Unlike the time series available for steric sea level and mountain glaciers, the large ice sheets have no continuous extensive records of mass balance. However, we can make inferences on their contribution by comparison with other data. Differentiating the mountain glacier contribution from *Leclercq et al.* [2011] shows the highest rate of reconstructed glacier contribution to sea level at the beginning of 20th century (Figure 9). The large rate of glacier loss over 1920–1940 is synchronous with substantial mass loss from Greenland ice sheet during the same time period [*Wake et al.*, 2009], shown also in Figure 9. *Wake et al.* [2009] show that prolonged negative surface mass balance anomalies at the beginning of the 20th century are related to increase in temperature, with the rate of warming in Greenland during 1920–1930 being about 50% higher than in 1995–2005 [*Chylek et al.*, 2006]. *Bjørk et al.* [2012] using historical aerial images with available satellite imagery over the past 80 years concluded that many land-terminated glaciers underwent a more rapid retreat in the 1930s than in 2000s with additional contribution from marine terminating glaciers and ice sheet. *Mitrovica et al.* [2001] estimated a contribution from Greenland of 0.6 mm yr^{-1} during the 20th century on the basis of the regional pattern of global sea level rise from tide gauge stations in comparison with models of regional patterns expected from mass loss from Antarctica and mountain glaciers.

[22] Unfortunately, we cannot quantify this contribution due to the lack of time series with surface mass balance and dynamical changes over the past 200 years. However, surface mass balance and dynamics contributions from Greenland ice sheet are included in semiempirical model calibration since the whole 20th century is well within the time period covered by tide gauge observations and therefore is implicitly included in the model parameters for sea level projections in 2100.

4. Discussion

[23] We demonstrate that heat uptake by the ocean in the J11 model is very similar to the heat uptake in climate models, suggesting that difference in projections from process-based and semiempirical models are due to the ice mass loss component. However, the ocean below 3000 m is largely unknown, but *Purkey and Johnson* [2010] estimate a contribution from the abyssal ocean of 0.09 mm yr^{-1} since the 1980s. There are no long-term observations to confirm if this is recent or persistent phenomena. If we assume a continuous abyssal ocean steric sea level term of 0.09 mm yr^{-1} since 1800 then it had caused 2 cm of sea level rise by 2000, with almost negligible effect on the projection by 2100.

[24] With the semiempirical approach using the RCP4.5 scenario we project 26 cm as a contribution from glaciers, which is 9–14 cm higher than the results found using process based models by *Slangen et al.* [2011] and *Radic and Hock* [2011]; however, calving is not included in these process-based models. Calving constitutes up to 40–50% of mass loss on marine terminating ice fronts [*Burgess et al.*, 2005, *Dowdeswell et al.*, 2008; *Walter et al.*, 2010; *Thomas et al.*,

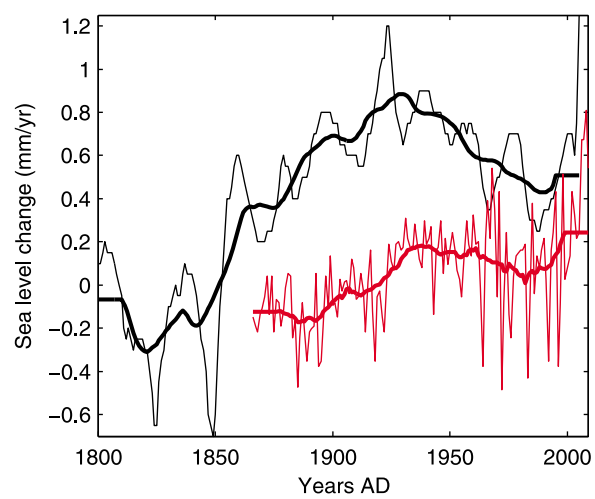

Figure 9. The rate of small ice cap and glacier contribution (from differentiating cumulative glacier mass balance in *Leclercq et al.* [2011]) (black) and Greenland ice sheet surface mass balance anomalies (red) [*Wake et al.*, 2009] to sea level rise. Data are annual with 21 year smooth (r = 0.3).

2004]. These results come from regions with relatively small contributions to sea level rise; however, *Jacob et al.* [2012] show that the overwhelming source of glacier mass lass comes from Greenland and Antarctica where marine terminating glaciers account for almost all mass loss through calving in the case of Antarctica and about 50% for Greenland.

[25] Glaciers from regions with dominantly marine ice fronts contribute 99% of total small glacier total mass loss [*Jacob et al.*, 2012], but the fraction of marine glaciers in those regions varies, e.g., about 13% of Alaskan glacier area drains through marine outlets as does 25% of Eastern Canadian Arctic (Randolph Glacier Inventory [*Arendt et al.*, 2012]). Though we do not know what fraction of mass loss is represented by these glaciers. *Cogley* [2009] shows that there is a systematic difference over the whole observational period in global glacier mass balance between direct glaciological estimates (requiring on ice measurement) and those based on geodetic methods (from imagery). This difference, *Cogley* [2009] suggested, may be due to lack of representation of large tidewater glaciers in traditional mass balance estimates. Since surface mass balance may be expected to be similar on both land-based and marine-terminating glaciers, the difference in total contribution between the regions with marine glaciers and those that do not is strong evidence that calving is an important process in mass loss and likely has been for the last few decades at least. Furthermore, statistical extrapolation is essential for all estimates of small glacier mass loss since there are 200,000 glaciers and ice caps worldwide [*Bahr and Dyurgerov*, 1999], but less than 120 have had their mass balance directly measured and for only 37 of these are there records extending beyond 30 years [*Bamber*, 2012]. *Hock et al.* [2009] argue that the contribution from small glaciers and ice caps in the polar regions (which have been historically difficult to study) have been underestimated. These glaciers typically have response times of order 200 years and are located in regions where polar amplification of global warming subjects them to greater summer melting than glaciers in more temperate climate zones. *Hock et al.* [2009] suggest that the peripheral Antarctic glaciers and ice caps added of 0.22 mm yr^{-1} since 1961–2004, which is 28% of the total small glacier contribution to sea level rise. Hence J11 estimates of larger loss from small glaciers than process models may point to the missing physics of calving and uncertainty in the statistical extrapolation of mass balance inherent in present-day process models.

[26] Could the J11 model overestimate contribution from melting of glaciers due to their limited size, and hence diminishing capacity to supply meltwater over time? Total small glacier volume amounts to about 60 cm [*Radic and Hock*, 2010], so the J11 model would remove about half the small glacier volume. However, the retreat of nonmarine terminating glaciers to higher altitudes could slow their melt considerably. Marine terminating glaciers that overwhelmingly dominate present-day glacier contribution to sea level rise [*Jacob et al.*, 2012] have less capacity to retreat to higher and cooler climates than do the high mountain glaciers. The mass turnover on maritime glaciers is also, and will remain, considerably greater than continental glaciers. Hence while retreat may lead to overestimation of mass loss in the model, the outlets from large ice sheets will maintain marine terminations even after small glaciers disappear completely.

[27] In the J11 model of global sea level mass loss from glaciers and ice sheets are modeled with a single response time. Could that lead to overestimation of sea level rise? Ice sheet behavior is determined by the difference between surface mass balance and dynamical loss through the large and fast-flowing outlet glaciers; these have exhibited changes on relatively short periods [*Wingham et al.*, 2009; *Rignot and Kanagaratnam*, 2006; *Wake et al.*, 2009; *Bjørk et al.*, 2012] indicating centennial timescales may be appropriate for the Greenland ice sheet contribution to sea level. Small glaciers were the largest contributor to sea level rise over the last 50 years, and the polar peripheral and marine terminating glaciers played a leading role due to polar amplification of climate warming [*Hock et al.*, 2009; *Moore et al.*, 2011].

[28] In future the outlets from Greenland may start to dominate the sea level budget, given polar amplification of global warming and rapid acceleration seen in Greenland mass loss over the last 10 years [*Rignot et al.*, 2011; *Moon et al.*, 2012]. The significant changes in surface mass balance of the Greenland ice sheet during the early 20th century have been proposed to have generated dynamical changes in peripheral areas of ice sheet [*Wake et al.*, 2009]; for example, *Csatho et al.* [2008] detected thinning of Jakobshavn Isbræ during 1902–1913, linking this behavior to the interaction of ice dynamics with changes upstream of Jakobshavn Isbræ. We consider it likely that Greenland ice sheet also played a substantial role to sea level rise during the relatively warm episodes in the calibration period for our model (for example, 1920–1950).

[29] Process models of ice sheet response to climate attempt to quantify the surface mass balance change and the ice dynamical response separately. The surface mass balance component depends to a large degree on the atmospheric forcing and parameterization of the ice melting process. Surface mass balance changes in Greenland under RCP4.5 forcing contribute to the sea level rise by 2100 between 2 cm [*Seddik et al.*, 2012] to 4.6 cm [*Price et al.*, 2011]. However, there is a much greater range of predictions of contribution to sea level rise from the dynamical response of Greenland to warming. At present no process-based models incorporate basal sliding, calving, or grounding line retreat as a function of atmospheric and oceanic forcing. Indeed no formulation for calving has yet been agreed as suitable for models, though several have been proposed [*Benn et al.*, 2007; *Nick et al.*, 2010; *Bassis*, 2011]. Grounding line migration appears to require knowledge of basal topography at sub-kilometer resolution [*Durand et al.*, 2011; *Schoof*, 2007a, 2007b], which is not yet available for Antarctica. Hence dynamical estimates come from ice sheet models with prescribed changes in boundary conditions to illustrate the envelope of possible ice loss by various mechanisms. For example, *Seddik et al.* [2012] using a full Stokes finite element flow model examine the difference in ice loss if the basal drag coefficient in three Greenland outlet glaciers is reduced by a factor of 2 relative to that at present and find an additional 13 cm of sea level rise by 2100. In contrast, *Price et al.* [2011] using a first-order approximate (but probably quite realistic) flow model examine the impact of perturbations to the marine terminations (to simulate calving) of the same three large Greenland outlets and estimate a dynamical

contribution of 6 mm by 2100. Similar process studies are being attempted in Antarctica [*Winkelmann et al.*, 2012], and while still at an early stage appear to show that ice sheet history and not just instantaneous configuration is an important factor in present-day response to forcing.

[30] Calibrating the model with data to 1990 and then simulating the period 1993–2009 produces sea level rise of 3.8 mm yr^{-1} in fair agreement with 3.2 mm yr^{-1} sea level rise observed by satellite altimetry. Sea level simulations 1990–2010 with process based approach produce 2 mm yr^{-1} (only 62% of observed sea level rise) [*Pardaens et al.*, 2011], similar to the estimates for sea level rise by AR4 IPCC [*Meehl et al.*, 2007a] and discussed in *Rahmstorf et al.* [2007] as being systematically low.

5. Conclusion

[31] We performed several experiments to explore the skills and limitations of the J11 semiempirical model. We provide evidence that model performance is robust with different calibration periods and show that possible corrections of global sea level rise due to human-induced contribution from water reservoir on the land and groundwater pumping are small. The test with a nonradiative forcing component reflecting long-term adjustment of Greenland and Antarctica ice sheets since the Last Glacial Maximum amounting to 0.25 mm yr^{-1}, leads to lowering of future sea level projections by 6 cm at the end of the 21st century. However, it is not clear if such long-term trend contribution is really present or not (but is not likely to be larger than 0.5 mm yr^{-1}) and requires better constraints from global isostasy models.

[32] Semiempirical estimates of future contribution from steric sea level by 2100 is in excellent agreement with AOGCMs based studies and the J11 semiempirical model mimics the ocean heat uptake in process-based AOGCMs. The semiempirical model projects 26 cm sea level rise due to melting from glaciers by 2100, which is twice as large as process-based estimates of 12–17 cm. There are at least two explanations for this difference: the present lack of calving physics in process-based models or failure of the semiempirical model. The semiempirical approach naturally includes calving and also dynamical ice sheet effects that occur during the calibration period. This leads to higher projections of sea level rise than using present-day process based models. Surface mass balance and dynamic changes of the Greenland ice sheet has been detected in several studies during the past 150 years (e.g., 1920s). Hence it is reasonable to assume that a dynamic contribution from Greenland ice sheet is included in the J11 sea level projection by 2100.

[33] There are several sources of bias in the J11 semiempirical model in addition to those we explore here.

[34] 1. Perhaps the largest uncertainty from semiempirical models is change in relative contributions from large ice sheets and glaciers. For example, if Antarctica past behavior is different in its relation to climate forcing then the future, e.g., through lowering sea level by increased precipitation or raising it by large ice shelf disintegration [*Hellmer et al.*, 2012]. If Antarctica is now making a positive contribution to sea level rise, as some recent observations suggest [*Rignot et al.*, 2008; *Ramillien et al.*, 2006; *Cazenave et al.*, 2009; *Velicogna and Wahr*, 2006; *Velicogna*, 2009], it is hard to see how a warming will reverse the trend. This is because the increased precipitation expected in warmer conditions will likely be overwhelmed by a dynamic ice loss through calving and loss of ice shelf buttressing effects. This dynamical contribution will be additional to the J11 model projection, if it has not been present during the period of calibration of the model (the last 300 years). This will of course mean a higher sea level rise estimate than the J11 (and other semiempirical) model shows, which would certainly not mean that these models are over predicting sea level rise.

[35] 2. The single response time in the model does not represent the reality that different glaciers will have different response times. Changes in model response time over the calibration time must be compensated by changes sensitivity of sea level rise to forcing in order to fit the data. As a consequence 21st century sea level projected by the semiempirical model is shown to be insensitive to the choice of response time [*Grinsted et al.*, 2010]. This is probably a less significant problem than the first issue.

[36] 3. Changing climate forcing may induce a change of glacier response time, most easily seen in relation to surface mass balance which depends on ablation and accumulation rates that are directly related to forcing. However, since the glaciers will all have individual response times and rates of change, this effect seems likely to be negligible.

[37] 4. There is considerable uncertainty in the estimates of historical radiative forcing primarily because of the uncertain forcing associated with aerosols [*Kiehl*, 2007]. We investigate how this uncertainty cascades through the semiempirical model by considering four separate estimates of forcing historical [*Jevrejeva et al.*, 2009]. We find that forcing uncertainty does impact fitted semiempirical model parameters [*Jevrejeva et al.*, 2009]; however, that data uncertainty in the global sea level reconstruction dominates the uncertainty budget for projections [*Jevrejeva et al.*, 2010].

[38] **Acknowledgments.** Work was supported by China's National Key Science Program for Global Change Research (2010CB950504, 2010CB951401, and 2012CB957704), NSFC 41076125, NERC consortium "Using Inter-glacials to assess future sea level scenarios" (NE/1008365/1), and is publication 13 of the Nordic Centre of Excellence SVALI, Stability and Variations of Arctic Land Ice funded by the Nordic Top-level Research Initiative. We are grateful to three anonymous reviewers for helpful comments.

References

Ablain, M., A. Cazenave, G. Valladeau, and S. Guinehut (2009), A new assessment of the error budget of global mean sea level rate estimated by satellite altimetry over 1993–2008, *Ocean Sci.*, *5*, 193–201, doi:10.5194/os-5-193-2009.

Antonov, J. I., S. Levitus, and T. P. Boyer (2005), Thermosteric sea level rise, 1955–2003, *Geophys. Res. Lett.*, *32*, L12602, doi:10.1029/2005GL023112.

Arendt, A., et al. (2012), Randolph Glacier Inventory [v1.0]: A dataset of global glacier outlines, 28 pp., Global Land Ice Meas. From Space, Boulder, Colo.

Bahr, D. B., and M. B. Dyurgerov (1999), Characteristic mass balance scaling with valley glacier size, *J. Glaciol.*, *45*(149), 17–21.

Bahr, D. B., M. Dyurgerov, and M. F. Meier (2009), Sea-level rise from glaciers and ice caps: A lower bound, *Geophys. Res. Lett.*, *36*, L03501, doi:10.1029/2008GL036309.

Bamber, J. L. (2012), Climate change: Shrinking glaciers under scrutiny, *Nature*, *482*, 482–483, doi:10.1038/nature10948.

Bassis, J. N. (2011), The statistical physics of iceberg calving and the emergence of universal calving laws, *J. Glaciol.*, *57*(201), 3–16, doi:10.3189/002214311795306745.

Benn, D. I., C. W. Warren, and R. H. Mottram (2007), Calving processes and the dynamics of calving glaciers, *Earth Sci. Rev.*, *82*, 143–179, doi:10.1016/j.earscirev.2007.02.002.

Bindoff, N. L., et al. (2007), Observations: Oceanic climate change and sea level, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 386–432, Cambridge Univ. Press, Cambridge, U. K.

Bjørk, A. A., et al. (2012), An aerial view of 80 years of climate-related glacier fluctuations in southeast Greenland, *Nat. Geosci.*, *5*, 427–432, doi:10.1038/ngeo1481.

Burgess, D., M. Sharp, D. Mair, J. Dowdeswell, and T. Benham (2005), Flow dynamics and iceberg calving rates of Devon Ice Cap, Nunavut, Canada, *J. Glaciol.*, *51*, 219–230, doi:10.3189/172756505781829430.

Cazenave, A., and W. Llovel (2010), Contemporary sea level rise, *Annu. Rev. Mar. Sci.*, *2*, 145–173, doi:10.1146/annurev-marine-120308-081105.

Cazenave, A., et al. (2009), Sea level budget over 2003–2008: A reevaluation from GRACE space gravimetry, satellite altimetry and Argo, *Global Planet. Change*, *65*, 83–88, doi:10.1016/j/gloplacha.2008.10.004.

Chao, B. F., Y. Wu, and Y. Li (2008), Impact of artificial reservoir water impoundment on global sea level, *Science*, *320*(5873), 212–214, doi:10.1126/science.1154580.

Church, J. A., et al. (2001), Changes in sea level, in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., pp. 639–694, Cambridge Univ. Press, Cambridge, U. K.

Church, J. A., N. J. White, L. F. Konikow, C. M. Domingues, J. G. Cogley, E. Rignot, J. M. Gregory, M. A. van den Broeke, A. J. Monaghan, and I. Velicogna (2011), Revisiting the Earth's sea-level and energy budgets from 1961 to 2008, *Geophys. Res. Lett.*, *38*, L18601, doi:10.1029/2011GL048794.

Chylek, P., M. K. Dubey, and G. Lesins (2006), Greenland warming of 1920–1930 and 1995–2005, *Geophys. Res. Lett.*, *33*, L11707, doi:10.1029/2006GL026510.

Cogley, J. G. (2009), Geodetic and direct mass-balance measurements: Comparison and joint analysis, *Ann. Glaciol.*, *50*(50), 96–100, doi:10.3189/172756409787769744.

Crowley, T. J., S. K. Baum, K. Y. Kim, G. C. Hegerl, and W. T. Hyde (2003), Modeling ocean heat content changes during the last millennium, *Geophys. Res. Lett.*, *30*(18), 1932, doi:10.1029/2003GL017801.

Csatho, B., T. Schenk, C. J. van der Veen, and W. B. Krabill (2008), Intermittent thinning of Jakobshavn Isbræ, West Greenland, since the Little Ice Age, *J. Glaciol.*, *54*(184), 131–144, doi:10.3189/002214308784409035.

Dowdeswell, J. A., T. J. Benham, T. Strozzi, and O. Hagen (2008), Iceberg calving flux and mass balance of the Austfonna ice cap on Nordaustlandet, Svalbard, *J. Geophys. Res.*, *113*, F03022, doi:10.1029/2007JF000905.

Durand, G., O. Gagliardini, L. Favier, T. Zwinger, and E. le Meur (2011), Impact of bedrock description on modeling ice sheet dynamics, *Geophys. Res. Lett.*, *38*, L20501, doi:10.1029/2011GL048892.

Graversen, R. G., S. Drijfhout, W. Hazeleger, R. van de Wal, R. Bintanja, and M. Helsen (2011), Greenland's contribution to global sea level rise by the end of the 21st century, *Clim. Dyn.*, *37*, 1427–1442, doi:10.1007/s00382-010-0918-8.

Gregory, J. M., J. A. Lowe, and S. F. B. Tett (2006), Simulated global mean sea level change over the last half-millennium, *J. Clim.*, *19*(18), 4576–4591, doi:10.1175/JCLI3881.1.

Greve, R., F. Saito, and A. Abe-Ouchi (2011), Initial results of the SeaRISE numerical experiments with the models SICOPOLIS and IcIES for the Greenland ice sheet, *Ann. Glaciol.*, *52*, 23–30, doi:10.3189/172756411797252068.

Grinsted, A., J. C. Moore, and S. Jevrejeva (2007), Observational evidence for volcanic impact on sea level and the global water cycle, *Proc. Natl. Acad. Sci. U. S. A.*, *104*(50), 19,730–19,734, doi:10.1073/pnas.0705825104.

Grinsted, A., J. C. Moore, and S. Jevrejeva (2010), Reconstructing sea level from paleo and projected temperatures 200 to 2100AD, *Clim. Dyn.*, *34*, 461–472, doi:10.1007/s00382-008-0507-2.

Hegerl, G. C., F. W. Zwiers, P. Braconnot, N. P. Gillett, Y. Luo, J. A. Marengo Orsini, N. Nicholls, J. E. Penner, and P. A. Stott (2007), Understanding and attributing climate change, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 663–745, Cambridge Univ. Press, Cambridge, U. K.

Hellmer, H., H. F. Kauker, R. Timmermann, J. Determann, and J. Rae (2012), Twenty-first-century warming of a large Antarctic ice-shelf cavity by a redirected coastal current, *Nature*, *485*(7397), 225–228, doi:10.1038/nature11064.

Hock, R., M. deWoul, V. Radiac, and M. Dyurgerov (2009), Mountain glaciers and ice caps around Antarctica make a large sea-level rise contribution, *Geophys. Res. Lett.*, *36*, L07501, doi:10.1029/2008GL037020.

Holgate, S., S. Jevrejeva, P. Woodworth, and S. Brewer (2007), Comment on "A semi-empirical approach to projecting future sea-level rise," *Science*, *317*(5846), 1866, doi:10.1126/science.1140942.

Huybrechts, P., A. Abe-Ouchi, I. Marsiat, F. Pattyn, T. Payne, C. Ritz, and V. Rommelaere (1998), Report of the Third EISMINT Workshop on Model Intercomparison, 140 pp., Eur. Sci. Found., Strasbourg, France.

Jacob, T., J. Wahr, W. T. Pfeffer, and S. Swenson (2012), Recent contributions of glaciers and ice caps to sea level rise, *Nature*, *482*, 514–518, doi:10.1038/nature10847.

Jevrejeva, S., A. Grinsted, J. C. Moore, and S. Holgate (2006), Nonlinear trends and multi-year cycle in sea level records, *J. Geophys. Res.*, *111*, C09012, doi:10.1029/2005JC003229.

Jevrejeva, S., J. C. Moore, A. Grinsted, and P. L. Woodworth (2008), Recent global sea level acceleration started over 200 years ago?, *Geophys. Res. Lett.*, *35*, L08715, doi:10.1029/2008GL033611.

Jevrejeva, S., A. Grinsted, and J. C. Moore (2009), Anthropogenic forcing dominates sea level rise since 1850, *Geophys. Res. Lett.*, *36*, L20706, doi:10.1029/2009GL040216.

Jevrejeva, S., J. C. Moore, and A. Grinsted (2010), How will sea level respond to changes in natural and anthropogenic forcings by 2100?, *Geophys. Res. Lett.*, *37*, L07703, doi:10.1029/2010GL042947.

Jevrejeva, S., J. C. Moore, and A. Grinsted (2012), Sea level projections by AD2500 with a new generation of climate change scenarios, *Global Planet. Change*, *80*, 14–20, doi:10.1016/j.gloplacha.2011.09.006.

Kiehl, J. T. (2007), Twentieth century climate model response and climate sensitivity, *Geophys. Res. Lett.*, *34*, L22710, doi:10.1029/2007GL031383.

Leclercq, P. W., J. Oerlemans, and J. G. Cogley (2011), Estimating the glacier contribution to sea-level rise over the period 1800–2005, *Surv. Geophys.*, *32*, 519–535, doi:10.1007/s10712-011-9121-7.

Lettenmaier, D. P., and P. C. D. Milly (2009), Land waters and sea level, *Nat. Geosci.*, *2*(7), 452–454, doi:10.1038/ngeo567.

Leuliette, E. W., R. S. Nerem, and G. T. Mitchum (2004), Results of TOPEX/Poseidon and Jason-1 calibration to construct a continuous record of mean sea level, *Mar. Geod.*, *27*, 79–94, doi:10.1080/01490410490465193.

Meehl, G. A. et al. (2007a), Global climate projections, in *Climate Change 2007: Contribution of Working Group I to the Fourth Assessment Report of the IPCC*, edited by S. Solomon et al., pp. SM10.1–SM10.8, Cambridge Univ. Press, Cambridge, U. K.

Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor (2007b), The WCRP CMIP3 multi-model dataset: A new era in climate change research, *Bull. Am. Meteorol. Soc.*, *88*, 1383–1394, doi:10.1175/BAMS-88-9-1383.

Mernild, S. H., G. E. Liston, C. A. Hiemstra, and J. H. Christensen (2010), Greenland ice sheet surface mass-balance modeling in a 131-yr perspective, 1950–2080, *J. Hydrometeorol.*, *11*, 3–25, doi:10.1175/2009JHM1140.1.

Mitrovica, J. X., M. E. Tamisiea, J. L. Davis, and G. A. Milne (2001), Recent mass balance of polar ice sheets inferred from patterns of global sea-level change, *Nature*, *409*, 1026–1029, doi:10.1038/35059054.

Moon, T., I. Joughin, B. Smith, and I. Howat (2012), 21st-century evolution of Greenland outlet glacier velocities, *Science*, *336*(6081), 576–578, doi:10.1126/science.1219985.

Moore, J. C., S. Jevrejeva, and A. Grinsted (2011), The historical sea level budget, *Ann. Glaciol.*, *52*(59), 8–14.

Moss, R., et al. (2010), The next generation of scenarios for climate change research and assessment, *Nature*, *463*, 747–756, doi:10.1038/nature08823.

Nick, F. M., C. J. Van der Veen, A. Vieli, and D. I. Benn (2010), A physically based calving model applied to marine outlet glaciers and implications for the glacier dynamics, *J. Glaciol.*, *56*(199), 781–794, doi:10.3189/002214310794457344.

Pardaens, A. K., J. A. Lowe, S. Brown, R. J. Nicholls, and D. de Gusmão (2011), Sea-level rise and impacts projections under a future scenario with large greenhouse gas emission reductions, *Geophys. Res. Lett.*, *38*, L12604, doi:10.1029/2011GL047678.

Price, S. F., A. J. Payne, I. M. Howat, and B. E. Smith (2011), Committed sea-level rise for the next century from Greenland ice sheet dynamics during the past decade, *Proc. Natl. Acad. Sci. U. S. A.*, *108*, 8978–8983, doi:10.1073/pnas.1017313108.

Purkey, S. G., and G. C. Johnson (2010), Warming of global abyssal and deep Southern Ocean waters between the 1990s and 2000s: Contributions to global heat and sea level rise budgets, *J. Clim.*, *23*(23), 6336–6351, doi:10.1175/2010JCLI3682.1.

Radic, V., and R. Hock (2010), Regional and global volumes of glaciers derived from statistical upscaling of glacier inventory data, *J. Geophys. Res.*, *115*, F01010, doi:10.1029/2009JF001373.

Radic, V., and R. Hock (2011), Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise, *Nat. Geosci.*, *4*, 91–94, doi:10.1038/ngeo1052.

Rahmstorf, S. (2007), A semi-empirical approach to projecting future sea-level rise, *Science*, *315*, 368–370, doi:10.1126/science.1135456.

Rahmstorf, S., et al. (2007), Recent climate observations compared to projections, *Science*, *316*, 709, doi:10.1126/science.1136843.

Rahmstorf, S., M. Perrette, and M. Vermeer (2011), Testing the robustness of semi-empirical sea level projections, *Clim. Dyn.*, *39*, 861–875, doi:10.1007/s00382-011-1226-7.

Ramillien, G., A. Lombard, A. Cazenave, E. R. Ivins, M. Llubes, F. Remy, and R. Biancale (2006), Interannual variations of the mass balance of the Antarctica and Greenland ice sheets from GRACE, *Global Planet. Change*, *53*, 198–208.

Rignot, E., and P. Kanagaratnam (2006), Changes in the velocity structure of the Greenland Ice Sheet, *Science*, *311*(5763), 986–990, doi:10.1126/science.1121381.

Rignot, E., J. L. Bamber, M. R. van den Broeke, C. Davis, Y. Li, W. J. van de Berg, and E. van Meijgaard (2008), Recent Antarctic ice mass loss from radar interferometry and regional climate modeling, *Nat. Geosci.*, *1*, 106–110, doi:10.1038/ngeo102.

Rignot, E., I. Velicogna, M. R. van den Broeke, A. Monaghan, and J. Lenaerts (2011), Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, *Geophys. Res. Lett.*, *38*, L05503, doi:10.1029/2011GL046583.

Rogelj, J., M. Meinshausen and R. Knutti (2012), Global warming under old and new scenarios using IPCC climate sensitivity range estimates, *Nat. Clim. Change*, *2*, 248–253, doi:10.1038/nclimate1385.

Schmith, T., S. Johansen, and P. Thejll (2007), Comment on "A semi-empirical approach to projecting future sea-level rise," *Science*, *317*(5846), 1866, doi:10.1126/science.1143286.

Schoof, C. (2007a), Ice sheet grounding line dynamics: Steady states, stability, and hysteresis, *J. Geophys. Res.*, *112*, F03S28, doi:10.1029/2006JF000664.

Schoof, C. (2007b), Marine ice-sheet dynamics, Part 1. The case of rapid sliding, *J. Fluid Mech.*, *573*, 27–55, doi:10.1017/S0022112006003570.

Seddik, H., R. Greve, T. Zwinger, F. Gillet-Chaulet, and O. Gagliardini (2012), Simulations of the Greenland ice sheet 100 years into the future with the full Stokes model Elmer/Ice, *J. Glaciol.*, *58*(209), 427–440, doi:10.3189/2012JoG11J177.

Slangen, A. B. A., C. A. Katsman, R. S. W. van de Wal, L. L. A. Vermeersen, and R. E. M. Riva (2011), Towards regional projections of twenty-first century sea-level change based on IPCC SRES scenarios, *Clim. Dyn.*, *38*, 1191–1209, doi:10.1007/s00382-011-1057-6.

Solomon, S., G. Plattner, R. Knutti, and P. Friedlingstein (2009), Irreversible climate change due to carbon dioxide emissions, *Proc. Natl. Acad. Sci. U. S. A.*, *106*, 1704–1709, doi:10.1073/pnas.0812721106.

Thomas, R. H., E. J. Rignot, K. Kanagaratnam, W. B. Krabill, and G. Casassa (2004), Force-perturbation analysis of Pine Island Glacier, Antarctica, suggests cause for recent acceleration, *Ann. Glaciol.*, *39*, 133–138, doi:10.3189/172756404781814429.

Velicogna, I. (2009), Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, *Geophys. Res. Lett.*, *36*, L19503, doi:10.1029/2009GL040222.

Velicogna, I., and J. Wahr (2006), Measurements of time-variable gravity show mass loss in Antarctica, *Sciencexpress*, *311*, 1754–1756, doi:10.1126/science.1123785.

Von Storch, H., E. Zorita, and J. F. Gonzalez-Rouco (2008), Relationship between global mean sea-level and global mean temperature in a climate simulation of the past millennium, *Ocean Dyn.*, *58*(3–4), 227–236, doi:10.1007/s10236-008-0142-9.

Wada, Y., L. P. H. van Beek, C. M. van Kempen, J. W. T. M. Reckman, S. Vasak, and W. F. P. Bierkens (2010), Global depletion of groundwater resources, *Geophys. Res. Lett.*, *37*, L20402, doi:10.1029/2010GL044571.

Wake, L. M., P. Huybrechts, J. E. Box, E. Hanna, I. Janssens, and G. A. Milne (2009), Surface mass-balance changes of the Greenland ice sheet since 1866, *Ann. Glaciol.*, *50*, 178–184, doi:10.3189/172756409787769636.

Walter, F., S. O'Neel, D. McNamara, W. T. Pfeffer, J. N. Bassis, and H. A. Fricker (2010), Iceberg calving during transition from grounded to floating ice: Columbia Glacier, Alaska, *Geophys. Res. Lett.*, *37*, L15501, doi:10.1029/2010GL043201.

Wingham, D. J., D. W. Wallis, and A. Shepherd (2009), Spatial and temporal evolution of Pine Island Glacier thinning, 1995–2006, *Geophys. Res. Lett.*, *36*, L17501, doi:10.1029/2009GL039126.

Winkelmann, R., A. Levermann, K. Frieler, and M. A. Martin (2012), Uncertainty in future solid ice discharge from Antarctica, *Cryosphere Discuss.*, *6*, 673–714, doi:10.5194/tcd-6-673-2012.