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QUANTIFYING REGIONAL SEA LEVEL RISE CONTRIBUTIONS FROM THE GREENLAND ICE SHEET

ABSTRACT. This study projects the sea level contribution from the Greenland ice sheet (GrIS) through to 2100, using a recently developed ice dynamics model forced by atmospheric parameters derived from three different climate models (CGCMs). The geographical pattern of the near-surface ice warming imposes a divergent flow field favoring mass loss through enhanced ice flow. The calculated average mass loss rate during the latter half of the 21st century is ~0.64 ± 0.06 mm/year eustatic sea level rise, which is significantly larger than the IPCC AR4 estimate from surface mass balance. The difference is due largely to the positive feedbacks from reduced ice viscosity and the basal sliding mechanism present in the ice dynamics model. This inter-model, inter-scenario spread adds approximately a 20% uncertainty to the IPCC ice model estimates. The sea level rise is geographically non-uniform and reaches 1.69 ± 0.24 mm/year by 2100 for the northeast coastal region of the United States, amplified by the expected weakening of the Atlantic meridional overturning circulation (AMOC). In contrast to previous estimates, which neglected the GrIS fresh water input, both sides of the North Atlantic Gyre are projected to experience sea level rises. The impacts on a selection of major cities on both sides of the Atlantic and in the Pacific and southern oceans also are assessed. The other ocean basins are found to be less affected than the Atlantic Ocean.

KEY WORDS: Greenland ice sheet; sea level rise; climate change; Earth system modling.

INTRODUCTION

Quantifying sea-level rise (SLR) predictions is major challenge (IPCC AR4, 2007). At present, the melting of land ice almost equals the ocean thermal expansion [Meehl et al., 2007] and may increase in a warming climate [Rahmstorf, 2007]. The IPCC AR4 has identified the melting of the Greenland Ice Sheet (GrIS) as a critical, but as yet poorly understood, process in determining global climate change in the 21st century (Fig. 1). The IPCC estimates the contribution from GrIS to be 24 mm by 2100, when compared with 1990 levels. This is likely an underestimate, as recent observations indicate peripheral outlet glaciers are highly sensitive to atmospheric warming [Rignot and Kanagaratnam, 2006; Mernild et al., 2009; Van den Broeke, 2009]. At present the astronomical background is stable and there also is a lack of other obvious concurrent global forcing processes outside the climate system that contribute to an accelerated melting of ice sheet. Thus, the likely cause resides in the climate system. During the past decade, the large mass loss (reaching ~0.7 mm/yr sea level contribution in 2010)

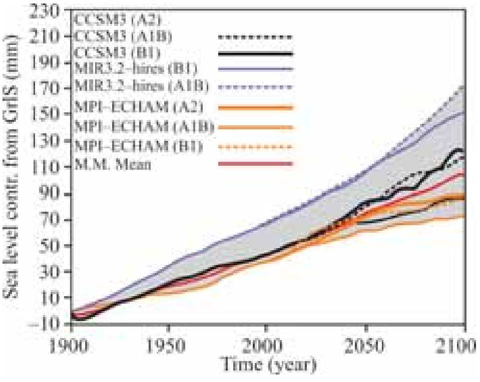

Fig. 1. The eustatic sea level rise (mm) contribution from the Greenland ice sheet for the 20th and 21st centuries. Atmospheric forcing parameters are provided by CCSM3, MPI-ECHAM and MIROC3.2-hires under the IPCC SRES A2, A1B and B1 scenarios, respectively.

The red curve is the multi-model multi-scenario mean. A 21-term binomial low-pass filter is applied on the annual time series to suppress short term (annual to decadal) variability. The color shades are the range of model spread

likely is the result of the impact of climate warming. The warming has lasted long enough for the already accumulated effects to be irreversible by just several opposing events, such as one or two years of cooler than annual mean temperatures. In fact, the recent eruption of the Iceland volcano did not slow the rate of melting. This modeling study attempts to reduce uncertainty in quantifying global SLR contributions from the GrIS, and its regional manifestations. A recently developed ice model, SEGMENT-ice, has a detailed, enhanced treatment of basal and lateral boundary conditions and "higher order" terms [Ren et al., 2010]. There are three positive feedbacks from the GrIS to a warming climate (see Supplementary Material, SM). SEGMENT-ice has been compared with other participants in the Sea-level Response to Ice Sheet Evolution (SeaRISE) project and shows skill in reproducing and explaining recent, dramatic ice sheet behavior [Ren et al. 2011a,b]. The present study is a modeling attempt to reduce the uncertainty range in quantifying the global SLR contribution from the Greenland Ice Sheet (GrIS), and its regional manifestations.

THE ICE MODEL

SEGMENT-ice is a component of an integrated scalable and extensible geo-fluid model (SEGMENT). Parameterization of viscosity is critical for ice creeping. SEGMENT-ice has two improvements over Glen's ice rheological law [Hooke, 1981; van der Veen, 1999], respectively for factoring in the flow induced anisotropy and granular basal condition. The flow enhancement by re-fabricating [Wang and Warner, 1999] is implemented so older ice, farther from the Summit, is easier to deform. SEGMENT-ice also allows a lubricating layer of basal sediments between the ice and bedrock which enhances ice flow and forms a positive feedback for mass loss in a warming climate (MacAyeal [1992], Alley et al. [2005], and [Ren et al. [2010], Fig. 2]). Because the ocean temperature is higher than that around Antarctica, there are no ice shelves around Greenland. There however are several water-terminating fast glaciers around the peripheral of GrIS, such as Jakobshavn (J), Kangerdlugssuaq (K), Helheim (H), and Petermann (P) glaciers. In SEGMENT-ice, ocean-ice interactions are parameterized so that the depressing of freezing point by solubles, salinity dependence of ocean water thermal properties, and ocean currents-dependent sensible heat fluxes are taken into consideration (SM).

As the climate warms, increased air temperature through turbulent sensible heat flux exchange increases surface melting and runoff. Similarly, changes in precipitation affects the upper boundary input to the ice sheet system. For the 200-year period of interest here, major ice temperature fluctuations are near the upper surface of the GrIS. The strain rate, however, can be large near the bottom and/or the surface, so SEGMENT-ice has a 31 vertical level stretched grid to better differentiate the bottom and near surface. The uppermost layer is 0.45 m thick near the GrIS Summit, fine enough to simulate the upper surface energy state on a

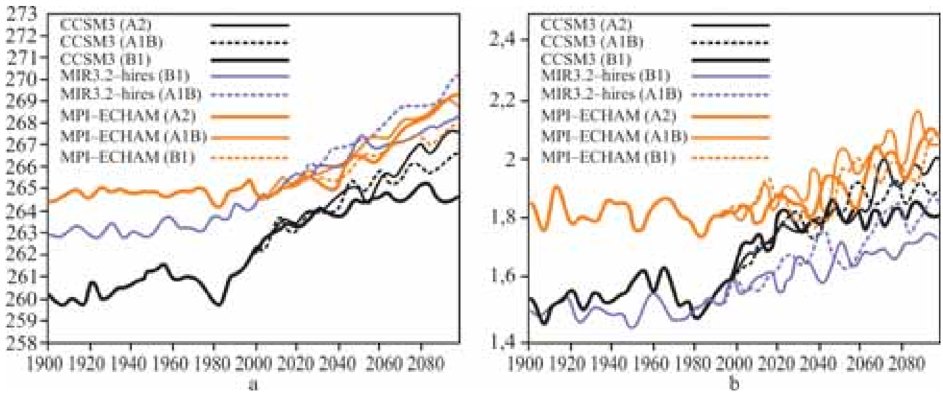

Fig. 2. Time series of low-pass filtered mean temperature (K) (*a*) and precipitation (mm/day) (*b*) over Greenland, from three climate model simulations with variations in anthropogenic forcing scenarios. Note that the SRES A2 simulation is not available for MIR3.2-hires

monthly time scale. Because of its location, the GrIS is an important contributor to eustatic SLR, ocean salinity and the North Atlantic thermohaline circulation [Yin et al., 2009; Alley, 2000]. In SEGMENT-ice, the total mass loss comprises surface mass balance and the dynamic mass balance due to ice flow divergence. Total mass balance is converted to water volume and is used here as a proxy for the eustatic SLR contribution.

In ice flow, inertial and viscous terms counteract pressure gradient forces. The full Navier-Stokes equations are used in the momentum equations of SEGMENT-ice. Because of comparably large aspect ratios, ice streams and surrounding transition zones are the areas where a full Stokes model is most needed [Zwinger et al., 2007]. Finally, there are two important improvements in the SEGMENT-ice numerics. Recently, the RAW (Amezcua et al. 2011; Williams 2009) filter has been adopted, in place of the more commonly used Asselin time filter. This treatment has improved both spin-up and the conservation energetics of the physical processes. A second improvement is in the optimization procedure of the data assimilation code. A quasi-Newton minimization scheme is now used instead of the conjugate-gradient scheme, which is less robust and less efficient for real, noisy data.

INPUT AND VERIFICATION DATA

SEGMENT-ice requires initial conditions and static inputs, such as ice thickness, free surface elevation, and the three-dimensional ice temperature field at the initial time of integration, obtained from the SeaRISE project (http://websrv.cs.umt.edu/isis/index.php), at 5 km horizontal resolution. The bottom geothermal distribution is assumed constant over the 200 year simulation. The SLR contribution from the GrIS is from the total mass balance: that is, input (e.g., snow precipitation, flow convergence) minus output (e.g., surface melt water runoff, flow divergence to open waters or calving). Atmospheric temperature, precipitation and near surface radiative energy fluxes are critical factors for the future total mass balance of the GrIS. The CGCMs provide the meteorological forcing. The large natural variability [Alley, 1993] justifies using extended atmospheric time series to extract the first-order feedback signal of the GrIS in a warming climate. The three independent CGCMs (MPI-ECHAM, NCAR CCSM3 and MIROC3.2-hires, see http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php) are chosen for having relatively fine resolution and providing all atmospheric parameters required by SEGMENT-ice. Their projections of precipitation and temperature, two key factors affecting ice sheet mass balance, produce a large spread in the multi-model assessments (Chapter 10, IPCC AR4) by 2100.

In addition to atmospheric parameters, investigating the ice ocean interactions at the water terminating glaciers (e.g., J, K, H, and P), the ocean flow speed ($\vec{V}$), potential temperature (*T*), salinity (*S*), and density (ρ) also are needed. Density is not an independent property because it is a function of temperature, salinity and pressure. For the outlet glaciers north of 70°N, the CGCM's ocean model output at depth 0, 10, 20, 30, 50, 75 and 100 m depths are interpolated to SEGMENT-ice grids. For the Helheim glacier, which resides in the Sermilik fjord, the 1-km resolution ice thickness data obtained from SeaRISE indicates that the terminus depth is about 700 m, close to the estimation of Thomas et al. (2000). Oceanic parameters up to 1000 m are used for this glacier. The University of Hawaii data (http://uhslc.soest.hawaii.edu/jasl.html) is used to evaluate the projections of regional SLRs.

RESULTS

SEGMENT-ice is integrated with climate model meteorological forcing over the GrIS, to provide the trend of total mass loss over the 21st century. The monthly atmospheric forcing and the advanced numerics of SEGMENT-ice can in principle produce physically realistic monthly fluctuations in ice sheet properties. However, interannual and decadal climate variations in CGCMs largely are random noise, as are ice model projected quantities on the same temporal scales. Thus there is no attempt to make a comparison with *in situ* observations of the model projections of inter-annual to decadal scales. Monthly (ice model output) quantities therefore are averaged to obtain annual mean values. A 21-point binomial smoother is applied to the annual means to remove any short-term variability. The smoothed lines in Fig. 1 show the eustatic SLR contribution from the GrIS for the 20th and 21st centuries. For each model, the atmospheric forcing is under the three non-mitigated IPCC Special Report on Emission Scenarios (SRESs): B1 (low); A1B (medium); and A2 (high rate of emission). Total ice volume is a highly aggregated metric and the trend is the resultant of several factors. Because inland GrIS remains cold, the feedback from increased precipitation (Fig. 2) is significant. Therefore, estimates of the GrIS contribution to SLR are less sensitive to scenario assumptions before 2030, even though the atmospheric forcing diverges from the year 2000. After 2030, as the atmospheric forcing diverges further, the differences become clear. The terms in the total mass balance indicate that the higher precipitation amounts from the strong scenario (Fig. 2) eventually is dominated by increases in ice flow divergence and surface melt water runoff. After 2060, there is an accelerated mass loss rate, as basal sliding becomes significant, especially beneath the southern tip and the north east ice stream, signifying a faster mass shed [Alley et al. 2005]. For the GrIS, the positive feedback from strain heating and reduced ice viscosity may have longer time scales (SM). The consensus is that weak scenario B1 causes far less total mass loss than the A2 and A1B scenarios, by the late 21st century.

As the climate warms, increases of temperature and precipitation scale nonlinearly with the emission strength (Fig. 2). Because increased temperature and precipitation are opposites as contributors to ice mass balance, a numerical model is needed to ascertain the sign of the total mass change and to quantify inter-scenario differences. SEGMENT-ice shows that the temperature signal is dominant. Both surface runoff and ice divergence increase as air temperatures increases. The relative contributions from surface melt and from ice flow divergence and calving indicate that the fraction from ice flow divergence increases during the transient climate change period. Thus, the total glaciated area varies little but the mass loss accelerates as the climate warms. At present, surface melt and ice flow divergence are almost equal [Rignot and Kanagaratnam, 2006]. This partitioning is symptomatic of near-surface warming. By the late 21st century, for the moderate A1B scenario, the ice divergence will contribute about 60%, outweighing the contributions from all other surface processes. After inter-model and inter-scenario averaging, the eustatic sea level contribution from GrIS is ~0.64 mm/yr for 2050-2100, significantly beyond the IPCC AR4 estimates. Inter-model and inter-scenario differences contribute ~20% uncertainty to sea level projections. Model simulations and observational studies [Mernild et al., 2009; Van den Broeke, 2009] of GrIS the last decade already indicate that 0.64 mm/yr is reachable (e.g., 0.7 mm/yr in Mernild et al. [2009]; 0.75 mm/yr in Van den Broeke [2009]). The lower bounds of the IPCC AR4 estimates should be raised by ~30 mm by 2100, assuming other SLR contributions are as estimated (by IPCCAR4). The eustatic SLR is an average of many factors on different time frames, including glacial isostatic adjustment [Peltier, 2001], expansion of water due to heat uptake (thermosteric), input from land ice, and changes in water storage on land and in the atmosphere. Because it is affected by wind stress, water temperature and salinity patterns, the absolute sea surface height (relative to the geoid) is high over tropical Pacific and Indian oceans and low over the Southern Ocean (south of ~ 55 °S surrounding Antarctica) and the Arctic Ocean. CGCM model projections of the dynamic sea level are similar in geographic distribution across both models and scenarios.

Sea surface topography is maintained by atmospheric parameters, so it is sensitive to climate changes and it produces corresponding regional sea level adjustments. In addition to factors affecting global SLR, the geographical distribution of SLR adds complexity, being further affected by changes in flow divergence/convergence from ocean currents [Landerer et al., 2007; Yin et al., 2009]. For example, owing to the Coriolis force associated with the Gulf Stream, the regional sea surface along the east coast of the United States has a slope tilting sea-ward. Fresh water discharge from the GrIS weakens the Atlantic meridional overturning circulation, suggesting a dynamic adjustment of sea surface elevation. For northeast coastal United States, this results in an additional SLR superimposed on the eustatic SLR. All CGCMs show the largest sea level rebound near the southern part of the Labrador Sea. However, the southern oceans are quite different. With the future strengthening of the Antarctic circumpolar circulation (ACC), the ocean surface slope maintained by the Coriolis force increases, with a significant SLR over an ocean belt at ~46 degree south. The mean change for 2091–2100, relative to 1981–2000, projected by three AR4 climate models under the A1B scenario, reaches 0.4 m over a 10^5 km^2 area of the southern Indian Ocean. A similar, smaller pattern occurs along the east coast of South America.

Contributions to SLR from GrIS melting are shown for 8 coastal cities, calculated from sea level changes with and without GrIS water routing. Southern hemispheric cities, Cape Town and Sao Paulo, are selected for their proximity to western boundary retroflection currents. Unlike the eustatic sea level change, which can be approximated empirically [Rahmstorf, 2007], quantifying the geographic manifestation of the 0.64 mm/yr global mean SLR requires including ocean currents. A CCSM3 sensitivity experiment was used to identify regional GrIS contributions to SLR. As the three major contributors: steric, melt water input and ocean dynamics are inter-connected, a coupled climate model is needed to investigate the effects of fresh water input. For a given scenario, a monthly injection is made from 1900 into the Atlantic Ocean. The GrIS net mass loss rate matches the time series in Fig. 2 but uses the geographical routing pattern from the ice model. Fig. 3 shows the geographic significance of the SLR, the sea level time series for three coastal cities: London, New York and San Francisco. The ensemble means of projected sea level change series from CCSM3 after 1900 and expected ensemble mean CGCM projections, neglecting GrIS contributions are compared. The CCSM3 rates are lower than observations (Fig. S4 has 5 other cities). For a 99.5% confidence interval, linear trends for observed and modeled SLRs are: 1.77 ± 0.35 and -0.13 ± 0.7 mm/yr for London; 1.84 ± 0.51 and 0.05 ± 0.1mm/

yr for San Francisco; and 2.64 ± 3.05 and 0.31 ± 0.67 mm/yr for New York. GrIS melting reduces the underestimation, especially for Atlantic Ocean cities (1.16 ± 0.7 for New York and 0.47 ± 1.0 mm/yr for London). The greatest rise, which is for New York City, is from 0.31 to 1.16 mm/yr and is 1/3 closer to reality. For the latter half of this century, the global 0.64 mm/yr SLR increases to ~1.69 mm/year near New York. Fresh water from the GrIS contributes most to SLR northwest of the north Atlantic gyre, with greater vulnerability for cities like New York City. For ocean dynamic adjustment, alone, the London SLR slows and ceases after 2050 [Yin et al., 2009] as the water mass is redistributed to the west coast of the Atlantic Ocean, adapting to a reduced Coriolis force. However, fresh water from the GrIS increases sea levels near London. In contrast, melt water from GrIS is not a major SLR contributor in the Pacific Ocean (e.g., San Francisco) and in the southern oceans (e.g., Sao Paulo) where dynamic sea level adjustments are significant but the GrIS contribution is small.

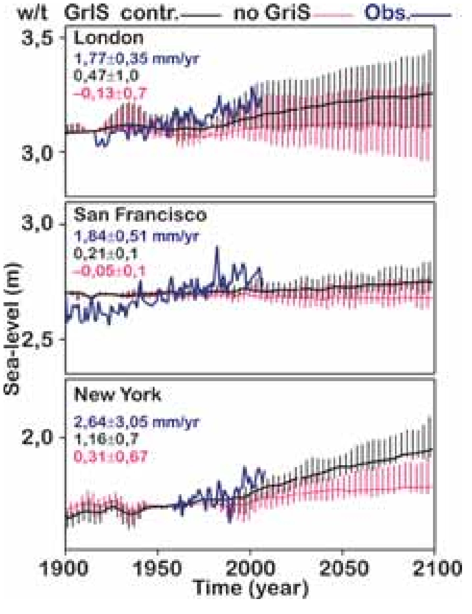

Fig. 3. CCSM3 simulated sea level evolution during 1900–2100. Model simulations are performed under the corresponding scenario run but with fresh water routing from the GrIS. The thick, 20-year smoothed black (red) curves are ensemble mean of the multiple model runs with (without) fresh water routing from the GrIS. Vertical bars are the upper and lower envelopes. Blue lines are from tide gauge observations (UHSLC research quality sea level station data). Climate model predictions are shifted so observed and modelled values match at the first observational data grid. The trends and uncertainty range (p = 0.05) over the observational period are also given. In generating the fresh water routing scenario, SEGMENT-ice is forced by CGCMs under different scenarios. For melting fraction of water, the routing scheme of the existing river transport model is used (over the GrIS, close to the basin division in Zwally and Giovinetto [2001]). The calving ice is transformed into a fraction of sea ice with zero salinity

DISCUSSION

Current CGCMs are not coupled with sophisticated land-ice models, so the uncertainty of the GrIS melting contribution to SLR is large. This study projects the eustatic SLR contribution from GrIS using a new ice dynamics model, SEGMENT-ice [Ren et al., 2011a]. Forced by CCSM3 atmospheric parameters, the SEGMENT-ice model is integrated for 200 years (1900-2100). The near-surface ice temperature increases for most of the GrIS (Fig. 5, [Ren et al. 2011b]). The greatest warming of over 3 °C by 2100, under SRES B1, corresponds to high precipitation areas in a band along the 2000 m GrIS elevation contour. The ice warming decreases inland and is minimal (~0.5 °C for SRES B1) at the Summit. As ice viscosity decreases with increasing temperature, the warming pattern adds extra divergence to the original flow field. This ice discharge process probably scales in proportion to surface temperature changes.

The average mass loss rate projected by SEGMENT-ice over the latter half of the 21st century is equivalent to ~0.64mm/year global mean SLR, significantly greater than the IPCC AR4 estimates. The lower limits of the IPCC AR4 estimation (0.01 m, under A1B) therefore should be increased to ~30 mm by 2100, with 95% confidence, assuming other sea level change contributors remain unchanged. To investigate the spatial distribution of the melt water, ice model simulated GrIS mass loss time series are used as input to climate models. The SLR is geographically non-uniform, reaching 1.69 mm/year for the northeast coastal United States, being amplified by a weaker meridional overturning circulation in the Atlantic Ocean. In other oceans, such as the Pacific and southern oceans, the projected changes are much smaller.

Both steric effects and contributions from melting mountain glaciers flatten with warming [Raper and Braithwaite, 2006] but the GrIS melting contribution accelerates before declining surface area becomes a limiting factor; this is highly unlikely during the 21st century.

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