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Modeled steric and mass-driven sea level change caused by Greenland Ice Sheet melting

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ABSTRACT

Meltwater from the Greenland Ice Sheet (GIS) has been a major contributor to sea level change in the recent past. Global and regional sea level variations caused by melting of the GIS are investigated with the finite element sea-ice ocean model (FESOM). We consider changes of local density (steric effects), mass inflow into the ocean, redistribution of mass, and gravitational effects. Five melting scenarios are simulated, where mass losses of 100, 200, 500, and 1000 Gt/yr are converted to a continuous volume flux that is homogeneously distributed along the coast of Greenland south of 75°N. In addition, a scenario of regional melt rates is calculated from daily ice melt characteristics. The global mean sea level modeled with FESOM increases by about 0.3 mm/yr if 100 Gt/yr of ice melts, which includes eustatic and steric sea level change. In the global mean the steric contribution is one order of magnitude smaller than the eustatic contribution. Regionally, especially in the North Atlantic, the steric contribution leads to strong deviations from the global mean sea level change. The modeled pattern mainly reflects the structure of temperature and salinity change in the upper ocean. Additionally, small steric variations occur due to local variability in the heat exchange between the atmosphere and the ocean. The mass loss has also affects on the gravitational attraction by the ice sheet, causing spatially varying sea level change mainly near the GIS, but also at greater distances. This effect is accounted for by using Green's functions.

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1. Introduction

During the last decades, global mean sea level has risen due to climate change (Church et al., 2001). The increase in mean temperature results in a thermal expansion of the ocean, which causes about 60% of the observed sea level rise (Bindoff et al., 2007). Another significant contribution to sea level change arises from the ice mass loss in ice covered regions, especially Greenland and Antarctica. Recently, numerous studies have investigated mass variations of ice sheets using observations from the satellite mission GRACE (Gravity Recovery and Climate Experiment, Tapley et al., 2004). These studies motivate the melt rates that are used in the simulations of this study. For example, ice mass loss of 101 ± 16 Gt/yr in Greenland between 2003 and 2005 was derived from GRACE data by Luthcke et al. (2006). The observations indicated a mass loss of 155 Gt/yr below 2000 m and a gain of ice mass at higher elevations, with a strong seasonal cycle below 2000 m. Wouters et al. (2008) estimated an ice mass loss of 179 ± 26 Gt/yr in Greenland between 2003 and 2007, including a negative mass balance above 2000 m in 2007. The loss of Greenland and Antarctic ice mass was estimated by Velicogna (2009) for the period between April 2002 and February 2009 again using GRACE measurements. For the GIS, a mass loss of 137 Gt/yr was found between 2002 and 2003, and 286 Gt/yr between 2007 and 2009, while an ice mass loss of 143 ± 73 Gt/yr was estimated for the Antarctic Ice Sheet. Gunter et al. (2009) compared mass variations in Antarctica derived from the GRACE and ICESat missions. Both datasets showed similar mass losses of about 100 Gt/yr, mainly located at the West Antarctic Ice Sheet. These findings agree with a study by Rignot et al. (2008), who estimated a similar mass loss in the Antarctic in year 2000 using interferometric synthetic-aperture radar data from various remote sensing satellite missions. During the entire period of investigation (1996–2006) they found an increasing rate of ice mass loss, from 78 Gt/yr in 1996 to 153 Gt/yr in 2006.

The fresh water inflow from the two major ice sheets causes sea level rise and as a consequence strongly influences the state of the ocean. Density variations change sea level locally due to the freshening of the ocean. Gerdes et al. (2006) investigated this reaction of the ocean to fresh water anomalies caused by the GIS melting under different boundary conditions. From their simulations they inferred reduced overturning and gyre circulation in the

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North Atlantic. Stammer (2008) investigated, along with salinity and temperature variations, the response of the sea surface height (SSH) of the ocean to melting in Greenland and Antarctica using a different ocean general circulation model. They found a depression of SSH located in the center of the sub-polar North Atlantic and the western subtropical North Atlantic associated with a cold water mass. A reduced meridional overturning circulation (MOC) in the North Atlantic was also found. In the Southern Ocean, the fresh water inflow, mainly from the West Antarctic Ice Sheet, strengthens the MOC in the southern hemisphere after 30 years. Marsh et al. (2009) forced an eddy-permitting ocean model with fresh water inflow at the Greenland coast from 1991 to 2000. They found only a small impact on large scale ocean circulation. The sea level, caused by density variations, changed mostly in the Baffin Bay because the additional fresh water accumulated west of Greenland.

When mass of a major ice sheet is lost the bedrock below the ice sheet responds to reduced loading with a slow uplift, heavily affecting the sea level. The ongoing glacial isostatic adjustment (GIA) after the last glacial maximum, results in global mean sea level change of about −0.3 mm/yr (Peltier, 2004), which is of the same magnitude as the effect of the estimated mass loss of the West Antarctic Ice Sheet (100 Gt/yr). In addition, the reduced ice mass has smaller gravitational attraction, causing the sea level to fall near the source of changing ice masses and to slightly rise farther away. The resulting fingerprints are discussed by (Mitrovica et al., 2001, 2009) for ice mass loss in Greenland, West Antarctica, and of some small mountain glaciers. For the last century they estimated an ice mass loss in Greenland equivalent to about 0.6 mm/yr. Riva et al. (2010) computed fingerprints of relative sea-level change due to ice mass change of the major glacial regions using GRACE measurements, which are corrected for GIA (Peltier, 2004), and the sea level equation of Farrell and Clark (1976). Globally, Riva et al. (2010) found a eustatic sea-level rise of 1.0 ± 0.4 mm/yr including regional variations caused by decreased gravitational attraction of the reduced ice masses. Sea level change caused by gravitational effects have also been investigated in different studies (e.g., Clark and Lingle, 1977; Mitrovica et al., 2001, 2009; Milne et al., 2009; Riva et al., 2010).

Here, the finite element sea-ice ocean model (FESOM, Timmermann et al., 2009; Böning et al., 2008) is used to investigate the influence of the melting of the GIS on regional and global sea level. Theoretical melting scenarios are introduced into the model. Four different rates of idealized fresh water inflow have been applied (100, 200, 500, and 1000 Gt/yr), as well as a realistic melt sequence to investigate the influence of time-varying melt rates on the sea level. The gravitational effects are analyzed here, which account for the reduced ice mass due to melting (Farrell, 1972; Francis and Mazzega, 1990). These effects are taken into account by applying Green's functions and maps of melt rates, created from melt extent data (Abdalati and Steffen, 2001; Abdalati, 2009). The present study does not account for effects caused by GIA. Also the changes in Earth rotation caused by the mass redistribution, as described by Mitrovica et al. (2001), are not considered here.

2. Method and data

2.1. Finite element sea-ice ocean model

Ocean circulation and sea level are simulated using the finite element sea-ice ocean model (FESOM, Timmermann et al., 2009; Böning et al., 2008). The model solves the primitive equations including the Boussinesq approximation. In order to approximate mass conservation in the model, a correction after Greatbatch (1994) is applied to account for steric effects (Böning, 2009). The model is discretised on a global tetrahedral grid, with its surface nodes being 1.5° apart. The nodes are aligned in the vertical at 26 unequally spaced levels. The bottom nodes are allowed to deviate from the z-levels to realistically approximate the ocean bottom topography. Modeled sea level is computed relative to the equipotential surface (geoid) when the ocean is at rest. Its change is affected by steric effects due to thermal and haline expansion, flow divergence via the continuity equation, and water mass fluxes at the ocean surface. The model is driven by atmospheric wind, pressure and fresh water fluxes (precipitation – evaporation + river runoff).

2.2. Gravitational effects

In addition to the steric and mass-driven effects from melt water, a local loss in ice mass also results in a loss of gravitational attraction. This effect does not change the global mean sea level, but strongly affects regional sea level. The direct effect of sea level change due to the deformation of the ocean floor of the elastic Earth caused by loading is not resolved by the ocean model, because modeled sea level is computed with respect to the deformed geoid. Only the indirect effect, that is the gravity anomaly change in the gravity field associated to the Earth's deformation response to load changes leads to small changes in modeled regional sea level (as seen from altimetry measurements). These effects are estimated using Green's functions of Farrell (1972).

The sea level redistribution S due to the gravitational attraction in equivalent water height for a location (ϕ,λ) is given by the convolution (Francis and Mazzega, 1990)

$$S(\phi,\lambda)=\rho_w\sum_{i=0}^{N}G_k(\alpha_i)F_i(\phi',\lambda')dA_i. \qquad (1)$$

$F_i(\phi',\lambda')$ is the change of the water level at location (ϕ',λ'),where ϕ is latitude and λ is longitude. α is the spherical distance between ϕ,λ and ϕ',λ', dA_i is the surface area and N is the number of oceanic elements in the model. In choosing the convolution accuracy is preferred over computational cost (Schrama, 2008). The distribution of the GIS melt is derived from the melt extent estimated by Abdalati and Steffen (2001) and Abdalati (2009), with the mass loss, $F_i(\phi',\lambda')$, converted to equivalent water height before the convolution. The Green's function G_k is defined as

$$G_k(\alpha)=\frac{a}{M_e}\sum_{n=0}^{\infty}(1+k'_n)P_n(\cos(\alpha)) \qquad (2)$$

where the mean radius of the Earth is denoted as a, the total mass of the Earth is M_e, and P_n are the Legendre polynomials (Farrell, 1972). The load love number k'_n accounts for the indirect gravity effect due to the deformation of the elastic Earth.

2.3. Reference simulation

The reference model simulation is forced with atmospheric fields of the NCAR/NCEP reanalysis (Kalnay et al., 1996). The parameters used are 10 m wind, 2 m temperature, specific humidity, total cloud cover and sea level pressure. The fresh water budget includes precipitation and evaporation, which is computed from latent heat flux, also provided by the NCAR/NCEP reanalysis. River runoff is provided by the land surface discharge model (LSDM, Dill, 2008). The LSDM model uses a seasonally driven discharge model for glaciered regions, which ensures that snow accumulation and melting are considered but it does not include estimates of long term ice mass loss or transport of ice. The mass balance of the source terms is not in equilibrium. To avoid unrealistic trends, a 2 year high pass filter

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