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^{o}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

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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.
Keywords: Sea level change, Greenland, ice sheet melting, gravitational attraction

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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 $\pm$ 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 to 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 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 $\pm$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), Milne et al. (2009) , Mitrovica 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^o 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))

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

$F_i(\phi', \lambda')$ 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

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

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 two year high pass filter eliminates mass trends in the ocean over longer time scales, following the method of Böning et al. (2008). The simulation is initialized with temperature and salinity values from the World Ocean Atlas (WOA01) and runs from 1958 to 2009 with a time step of 2 hours.

2.4. Melting scenarios

Sea level change is calculated by computing the differences between the following model experiments that include the additional runoff due to ice sheet melting and the reference model simulation. All experiments convert the mass flux to an additional fresh water flux at the Greenland coast resulting in an unbalanced long term trend.

2.4.1. Constant melt rates

Four simulations have been performed using different mass loss rates along the Greenland coast of 100, 200, 500, and 1000 Gt/yr. The mass losses of 100 Gt/yr and 200 Gt/yr span the range of observational studies (e.g. Rignot et al. (2008), Wouters et al. (2008), Velicogna (2009)). The two extreme cases are intended to represent scenarios where the mass loss from the GIS has drastically increased. The continuous fresh water flux which is added to the model is evenly distributed along the Greenland coast south of 75^oN (Figure 1a). The simulations run for 48 years, starting in 1960.

2.4.2. Varying melt rates

In an additional experiment, the influence of time-varying melt rates on the sea level is investigated. Here, a time series of regional melt rates has been created to investigate the influence of variations in the water inflow. The distribution of the ice mass loss is approximated by using maps of daily melt extent data, defined on a 25 km × 25 km grid (Abdalati and Steffen, 2001; Abdalati, 2009). The melt extent data provides information about the region and the days, when melting occurs. The total ice melt over five years (805 Gt, Wu et al. (2010)) is then distributed over the melt extent of this period. This results in melt rates of for example 133 Gt/yr in 2003 and 207 Gt/yr in 2007. Figure 1b shows the total melt of the year 2007 in equivalent water height, with the corresponding water inflow in Figure 1c. Here, the daily mass losses at the different locations are transformed into a fresh water flux and are applied to the nearest coastal nodes. Weekly sea level variations are analyzed from 2003 to 2007 after the daily fresh water inflow fields are included into the model. These results are compared with those found from a melt scenario, where, similar to the first set of experiments, a continuous fresh water inflow of 161 Gt/yr is evenly distributed along the Greenland coast south of 75^{o}N latitude.

3. Results

3.1. Global mean sea level change

The global mean sea level rises when the GIS melts (Figure 2a). Its amount is given by the amount of ice mass change and the geometry of the model ocean as well as by steric effects. The global mean sea level rises by about 0.3 mm/yr when 100 Gt/yr of land ice mass flow as additional fresh water into the ocean, in general agreement with e.g. Hanna et al. (2005), Luthcke et al. (2006), Broeke et al. (2009). In addition, steric effects due to the additional fresh water change the global mean sea level by about one order of magnitude less than the mass-driven contribution (Figure 2b).

Compared to a continuous melt rate, a clear seasonal variability in global mean sea level is predicted in the case of daily varying fresh water inflow (Figure 2c). Here, a strong increase in global mean sea level occurs during the summer months, whereas in winter sea level stays nearly constant, when there is no melting. In fact, during winter and spring, a slight steric decrease in sea level can be observed, for example in the beginning of 2006, due to dynamic effects, which change the heat flux exchange between atmosphere and ocean and hence the sea surface temperature (Figure 2d).

3.2. Regional sea level change

3.2.1. Constant melt rates

The sea level change is not uniform. Figure 3 depicts the deviation of global mean sea level change after 5, 15, 35, and 48 years of model integration for the case of 200 Gt/yr of melt water being released into the ocean along the Greenland coast. During the first years the sea level rise near the coast of Greenland, mainly in the Baffin Bay and the Labrador Sea, is much higher than the global mean sea level change. After about five years, this sea level anomaly enters the North Atlantic near the east coast of Canada via the Labrador Current. Then it slowly follows the North Atlantic Drift, and reaches Europe after about one decade. From there, the anomaly follows the subtropical gyre to the equatorial region of the Atlantic Ocean while another branch enters the Arctic Ocean along the eastern coast. After 48 years, the sea level change anomaly has reached the whole North Atlantic, but the centre of the subtropical gyre is not affected, as also suggested by Gerdes et al. (2006). Different melting scenarios around Greenland lead to a similar spatial and temporal evolution of regional sea level anomalies (Figure 3d-f). Adding fresh water to the model changes the ocean circulation slightly resulting in small variations in atmosphere-ocean fluxes. The changes are small as compared to the direct meltwater response. Here, the pattern of regional sea level change appears to be smoother for higher meltwater source strength because the changes are higher above the noise level than the patterns originating from lower melt rates.

The pattern of the spatial variability in sea level change mostly results from salinity changes due to the fresh water input (Figure 4). The structure of the variations in salinity and temperature in the North Atlantic Ocean at 100 m depth is very similar to the modeled sea level change, as shown in Figure 3. The negative surface salinity anomaly is a direct consequence of the additional fresh water, which remains in the upper 200 m above the saltier ocean water, and follows the ocean currents. The sea surface temperature change does not show a specific structure, as it is dominated by the unchanged atmospheric forcing.

In the Baffin Bay, the sea surface salinity is reduced by about 0.2 psu due to the additional fresh water. The correspondingly reduced surface density stabilizes the near-surface water column. This reduces vertical mixing in the upper water layers and the heat exchange between the colder water at the top and the warmer sub-surface water leads to a reduced erosion of the temperature maximum at around 450 m depth. A slight warming between 100 and 1000 m thus occurs. Also, salinity exchange is decreased in the top 500 m, leading to an increased salinity at around 200 m depth.

No melt water is transported to the South Atlantic west of Namibia by surface circulation. Hence, there is no significant change of surface water properties. However, the reduced upwelling of cold, fresh water leads to a warming and increased salinity of subsurface water at around the 200 m level. In the North Atlantic, more fresh water is found at the surface, reducing sea surface salinity by about 0.1 psu. The reduced surface density here again increases the stabilization of the near-surface water column, reducing the vertical mixing in the top water layers with less heat exchanged between the warmer surface waters and the colder sub-surface water. The ocean thus warms by 0.1 ^{o}C at 100 m depth, and cools by 0.01-0.05 ^{o}C at depths between 200 and 1200 m.

After 48 years, the global mean sea level rise is 28.6 mm with a local maximum of 49.8 mm along the coast of Nova Scotia (Canada) due to steric effects. The steric effects also lead to more sea level rise along at the European and North American coasts (Figure 5). However, sea level around Greenland falls by 0.14 m due to the reduced gravitational attraction, leading to a large net decrease in sea level. Note, that the gravitational effect will also cause an additional increase in sea level at distances greater than 70 degree. Hence, sea level in the Southern Ocean will rise slightly faster than the eustatic value.

3.2.2. *Time varying melt rates*

Ice sheet melting, however, is generally not continuous over time but varies with the seasons. For Greenland, melting occurs mainly in the summer months between July and September. Introducing melt rates with a seasonal cycle into the model allows the variability of melt water inflow to be considered (Abdalati and Steffen, 2001; Abdalati, 2009). The structure of sea level change after five years (Figure 6b) is similar to that of using continuous melt rates of 161 Gt/yr (Figure 6a). The global mean sea level rises by 0.46 mm/yr. The regional sea level increases mainly west of Greenland, but in this case, sea level rise is stronger in the Baffin Bay. In the Labrador Sea it is similar to the case of continuous melting. Due to the gravitational effect, ocean water is attracted less and sea level is falling near the Greenland coast by about 6 mm and in large regions of the Arctic Ocean by about 0.8 mm after five years. The sea level slightly rises up to 0.5 mm farther away with a maximum in the Southern Ocean. Note that the regional pattern (Figure 6c) does not account for the change in Earth rotation as discussed by Mitrovica et al. (2001). Total sea level change including the gravitational effect is depicted in Figure 6d. There is only a slight sea level rise along the east coast of Greenland and in the Labrador Sea. An increased sea level in the Baffin Bay remains. In addition, sea level stays almost constant in the Norwegian and Barents Seas. This is seen as a result of the reduced gravitational attraction of the ice sheet balancing the added water volume.

4. Conclusions

Global mean sea level rises by about 0.3 mm/yr when the GIS melt at a rate of 100 Gt/yr. Steric effects lead to small additional variations in global mean sea level. These are about one order of magnitude smaller than the direct effect due to the addition of water. Regionally, steric effects lead to high deviations from the global mean sea level change.

The impact of fresh water inflow along the Greenland coast on the oceans is not restricted regionally but distributed over the global ocean. The regional initial sea level change anomalies follow the surface currents and mainly result from changes in temperature and salinity in the upper 200 m. After 48 years the change in steric sea level is distributed through the North Atlantic reaching equatorial regions. In addition, some fresh water enters the Arctic Ocean. Note, that due to the coarse resolution, some weaknesses in the estimated currents in the Norwegian Sea lead to slightly lower fresh water flux into the Arctic Ocean than expected. This will be solved in the future by modeling variations in sea level using a grid with higher spatial resolution.

The decrease in ice mass in Greenland also reduces its gravitational attraction, which leads to lower sea level near the Greenland coast, as well as more sea level rise farther away. Variations in ice sheet melting in Greenland, when compared to continuous melting, influence the sea level change in the North Atlantic, mainly near the source of melting. After five years, the sea level change is more restricted to Baffin Bay with a smaller influence in the Labrador Sea compared to the case of continuous melting.

In future studies, the sea level equation (Farrell and Clark, 1976) will be solved including effects due to GIA, modified Earth rotation and loading.

In addition, a new model setup having a higher spatial resolution will be used to investigate small scale changes in ocean circulation. Then, new data of Greenland mass loss will be included into the model and results will be compared with different measurements, e.g., derived from tide gauges.

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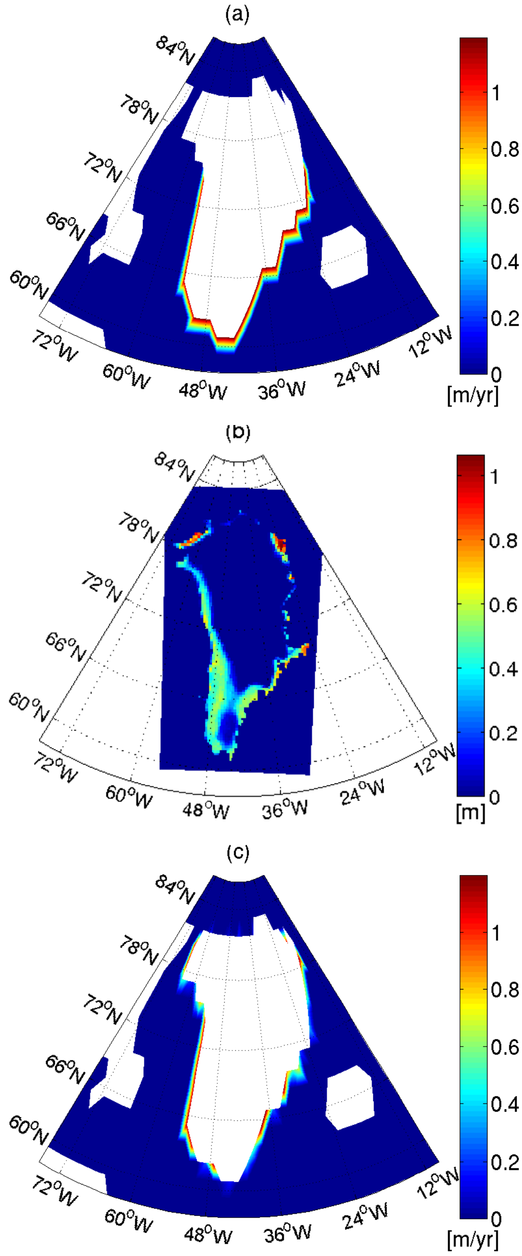

Figure 1: (a) Continuous fresh water inflow (m/yr), due to the melting of the Greenland Ice Sheet (200 Gt/yr), (b) the total loss (in water equivalent) from the Greenland Ice Sheet in 2007 and (c) the corresponding water inflow in equivalent water height (in total 207 Gt) (Abdalati, 2009)

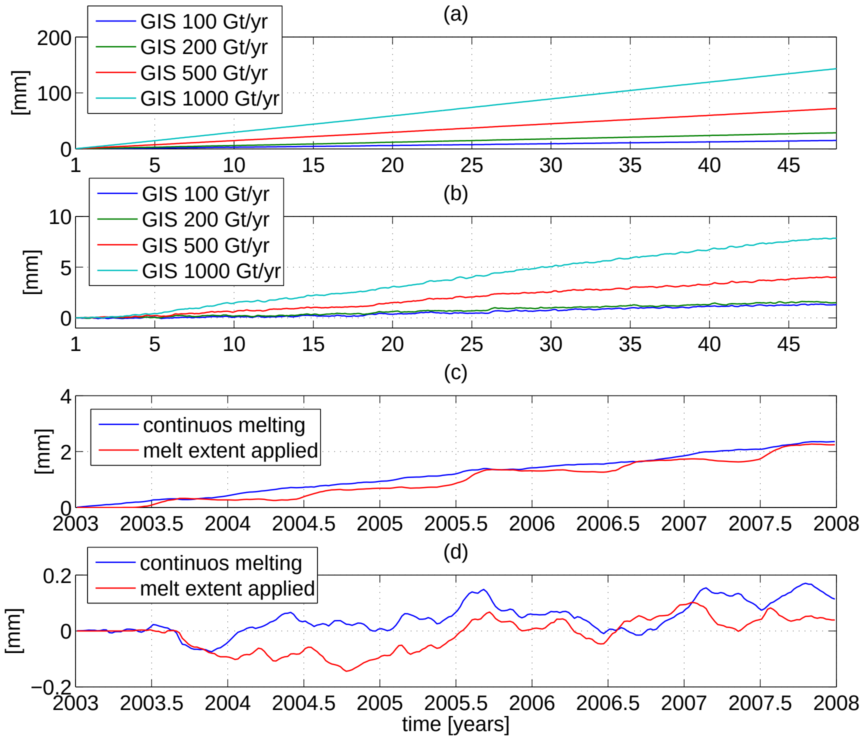

Figure 2: Response of global mean sea level to the melting of the Greenland Ice Sheet (mm), (a) for various continuous melt scenarios over 48 years including the steric contribution, which is shown in (b), as well as (c) the melting of 161 Gt/yr from 2003 to 2007 for continuous melt (blue line) and melt distributed over melting extent (red line) (d) including the steric contribution shown in (d).

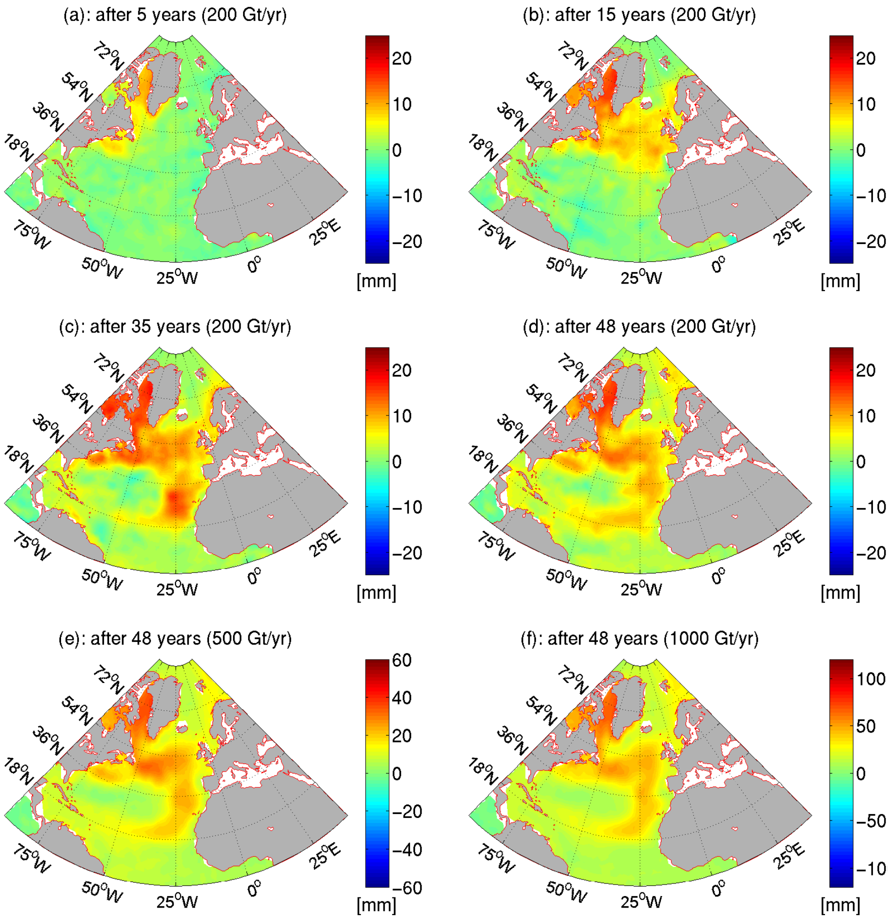

Figure 3: (a-d) Regional sea level change as deviation from its global mean (mm) with respect to the reference model simulation if 200 Gt/yr of the Greenland Ice Sheet melts, after (a) 5 years, (b) 15 years, (c) 35 years, and (d) 48 years. Sea level change for higher melt rates of 500 and 1000 Gt/yr are shown in panels (e) and (f), respectively. Note the change in color scale which is scaled according to the source strength.

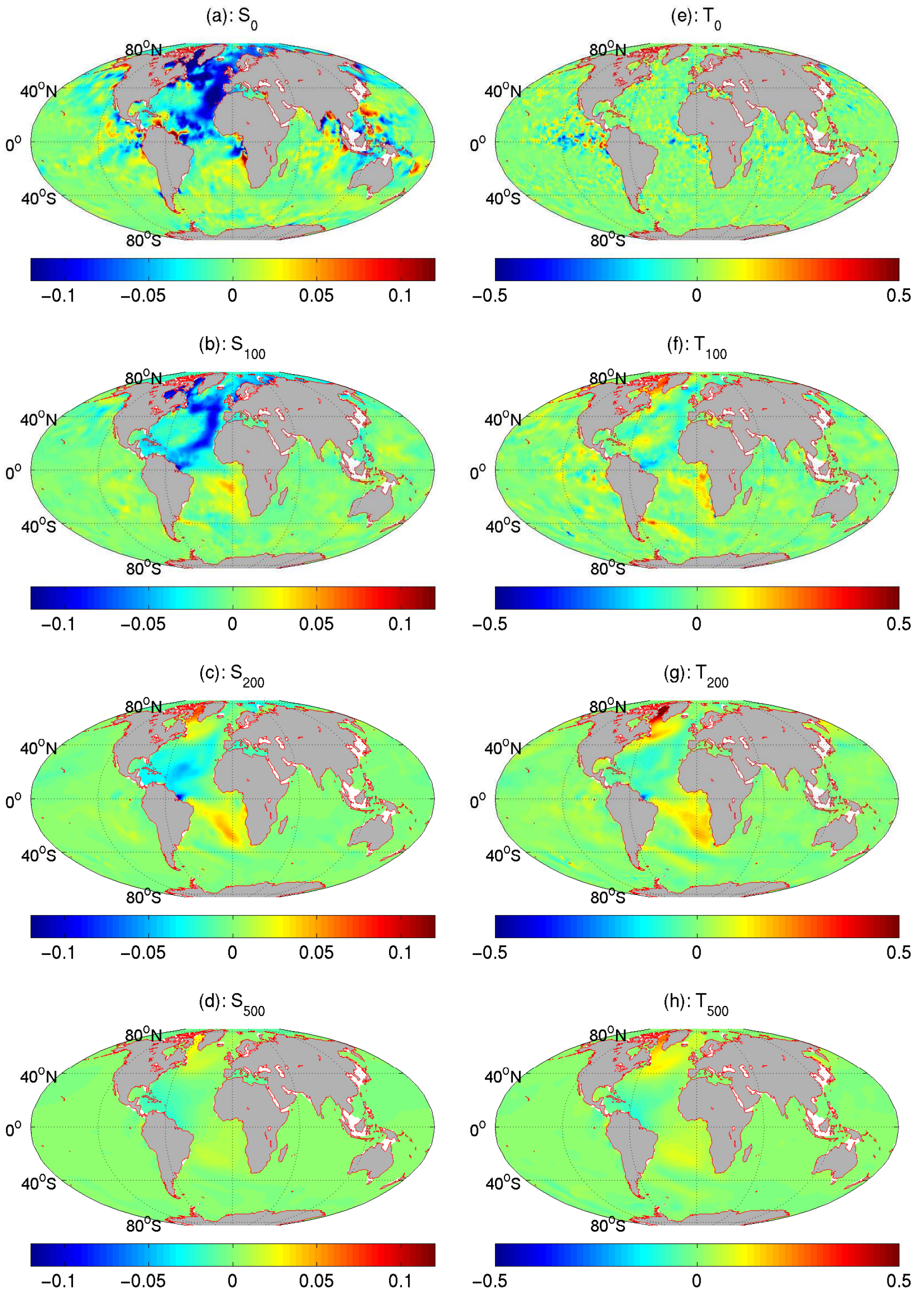

Figure 4: Difference in salinity (psu) and temperature (^{o}C) after 48 years for the scenario of 200 Gt/yr of Greenland ice being released into the ocean with respect to the reference simulation without additional melt water input; (a) difference in sea surface salinity, and salinity difference at (b) 100 m (c) 200 m and (d) 500 m depth, as well as (e) difference in sea surface temperature, and temperature difference at (f) 100 m, (g) 200 m and (h) 500 m depth

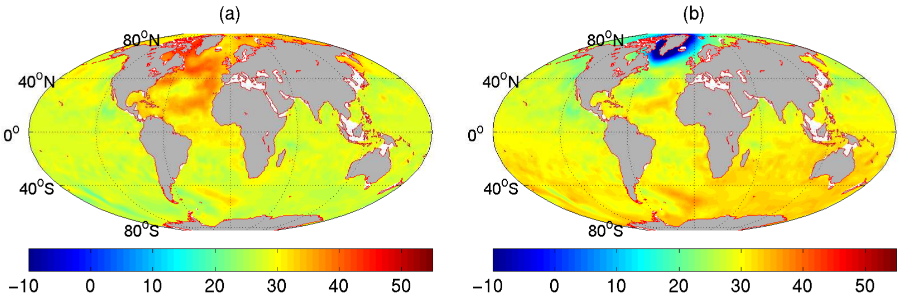

Figure 5: Sea level change (mm) with respect to the reference model simulation resulting from the Greenland Ice Sheet melting at a rate of 200 Gt/yr after 48 years; (a) sea level change with respect to an undisturbed geoid including regional and global mean sea level change and (b) sea level change with respect to the adjusted geoid as seen from altimetry after adding the gravitational effect due to Greenland ice mass loss

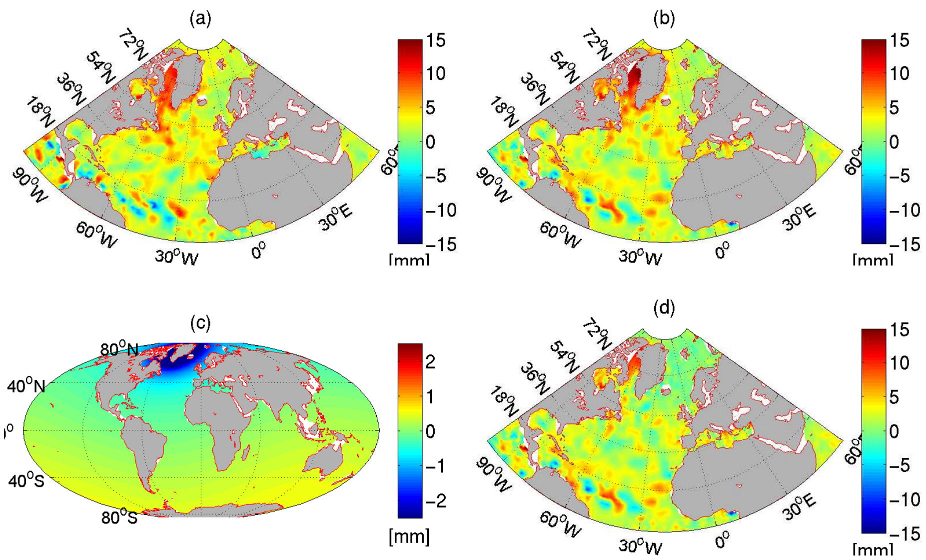

Figure 6: Sea level change (mm) with respect to the reference model simulation resulting from Greenland Ice Sheet melting of 161 Gt/yr after 5 years (2003-2008), (a) with continuous melting equally distributed at coastal nodes south of 75^oN, (b) distributed to the melt extent (Abdalati and Steffen, 2001; Abdalati, 2009), (c) sea level change due to the gravitational effect of Greenland ice sheet melting of 805 Gt, corresponding to 2.35 mm mean sea level equivalent, and (d) the total sea level change including regional and global mean sea level change and the gravitational effect related to Greenland Ice Sheet melting