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The sea level fingerprint of 21st century ice mass fluxes

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Abstract

The sea level contribution from glacial sources has been accelerating during the 21st century (Meier et al., 2007; Velicogna, 2009). This contribution is not distributed uniformly across the world's oceans due to both oceanographic and gravitational effects. We compute the sea level signature of 21st century ice mass fluxes due to changes in the gravity field, Earth's rotation and related effects. Mass loss from Greenland results in a relative sea level (RSL) reduction for much of North Western Europe and Eastern Canada. RSL rise from this source is concentrated around South America. Losses in West Antarctica marginally compensate for this and produce maxima along the coastlines of North America, Australia and Oceania. The combined far-field pattern of wastage from all ice melt sources, is dominated by losses from the ice sheets and results in maxima at latitudes between 20° N and 40° S across the Pacific and Indian Oceans, affecting particularly vulnerable land masses in Oceania. The spatial pattern of RSL variations due to the observed ice mass loss is temporally invariant. Thus, sea level rise, based on the land ice losses considered here, will be amplified for this sensitive region.

1 Introduction

It has been suggested that the ocean dynamic response to future climate change will result in enhanced sea level rise for the northeast coastline of the United States (Yin et al., 2009) and that steric anomalies, due to increased melt from the ice sheets, will result in long-lived local RSL variations (Stammer, 2008). The geodetic effects of regional ice melt and ongoing glacio isostatic adjustment (GIA) are, however, also not uniformly distributed across the World's oceans and have a markedly different and, importantly, time-invariant, spatial signature. The non-uniform effect on RSL of the melting of large ice masses, such as the Antarctic and Greenland ice sheets, due to changes in the Earth's gravity field was recognised over 30 years ago (Clark and Lingle, 1977). The original theory has been updated to include the effects of changes in Earth rotation, also known as true polar wander (TPW), and shoreline migration (Milne and Mitrovica, 1998). This updated theory has been used to examine the spatial pattern in relative sea level for a hypothetical wastage of large ice masses and to infer the mean rate of loss from Greenland over the 20th century (Mitrovica et al., 2001).

Up until recently, however, there has been limited quantitative information on the spatial pattern of mass loss from the ice sheets. Recent satellite observations, in particular from GRACE and synthetic radar aperture interferometry (InSAR), have, however, provided unprecedented insights into both the magnitude and pattern of ice loss from the three largest sources of mass to the oceans: the Greenland and Antarctic ice sheets and Alaskan glaciers (Berthier et al., 2010; Luthcke et al., 2008; Rignot et al., 2008b; van den Broeke et al., 2009). Furthermore, consistency between different approaches is now being achieved, providing greater confidence in the results (van den Broeke et al., 2009). Here, we use these detailed observations of the spatial pattern of mass loss to examine the signature of relative sea level resulting from changes to the gravity field, TPW and shoreline migration. Mountain glacier and ice cap (MG&IC) sources from elsewhere are, individually, considerably smaller than the three regions mentioned, and combined they contribute about 27% of the total for the period 2000–2009 (Meier et al., 2007; Hock et al., 2009; Chen et al., 2009; Wouters et al., 2008; Chen et al., 2007). We include, therefore, estimates of these smaller sources when considering the integrated pattern of SLR from ice melt (Fig. 1). We stress, however, that we consider, here, only the gravitationally consistent signature of ice melt. We do not include the response of ocean dynamics to the additional influx of freshwater nor other changes in ocean dynamics due to predicted climate change, which can have a significant impact on RSL over decadal timescales (Yin et al., 2009; Stammer, 2008). We also do not include spatially variable thermosteric effects on sea level (Lombard et al., 2005). It is worth noting, however, that, unlike the ice melt signal, both these effects have a transient, time-evolving spatial distribution and ocean circulation is not cumulative: it has no effect on eustatic[1] sea level.

2 Methods

In this study we consider mass trends for the 21st century (January 2000–January 2009), which requires extrapolation or interpolation of some of the time series available by 2–3 years at the beginning or the end of the epoch as explained below. What is also important for determining the gravitationally consistent pattern of RSL is knowledge of the spatial distribution of mass loss for the major sources considered (Fig. 1). For Antarctica we used a recent compilation of basin-scale mass budget calculations obtained from surface velocity, ice thickness and regional climate modelling data to derive the spatial distribution of losses (Rignot et al., 2008a). Results from GRACE suggest, however, a smaller average loss for the coincident period (Horwath and Dietrich, 2009; Velicogna, 2009) and, based on the analysis of elevation rates from radar altimetry (Zwally et al., 2005), we have assumed that the Abbots/Ferrigno ice shelf region along the Bellinghausen Sea sector (HH' in Rignot et al., 2008) of West Antarctica is in balance. The 2 sigma uncertainty in the mass budget estimate for this region is larger than the signal ($49\pm54\,\mathrm{Gt\,yr^{-1}}$). Taking this into account we obtain a mean rate for 2000–2009 of $135\,\mathrm{Gt\,yr^{-1}}$. For Greenland, we use a recent estimate of annually resolved, basin-scale, mass balance that combines mass budget and gravity-derived results (van den Broeke et al., 2009). Mass budget estimates are available for years 1996, 2000, 2004–2008, while the continuous GRACE time series begins in 2003. In this case extrapolation was not required and the mean loss for the epoch we consider here is $166\,\mathrm{Gt\,yr^{-1}}$ (van den Broeke et al., 2009). For Alaska we used our own GRACE-derived mass trends for 2003–2009 ($-61\,\mathrm{Gt\,yr^{-1}}$) and assumed the same

[1]Here we define eustatic changes as the global mean change in sea level due to mass changes

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values for 2000–2003. There is considerable inter-annual variability in mass balance and no clear trend for this region so we consider this to be a reasonable approximation (Luthcke et al., 2008). For smaller regional sources we used recent estimates for the magnitudes and temporal trends (Dyurgerov and Meier, 2005; Hock et al., 2009; Kaser et al., 2006; Meier et al., 2007; Chen et al., 2007; Wouters et al., 2008). Table 1 indicates the mass trends assumed for the eight regions considered here. The total mean flux over the period 2000–2009 is 497 Gt yr^{-1}, which is equivalent to 1.4 mm/yr eustatic SLR. The Himalayas were excluded for reasons explained elsewhere (supplementary information).

3 Results and discussion

The distribution of mass loss/gain is not uniform over the three major source areas (Fig. 1) and this has important consequences for the pattern of sea level variations due to these sources. Mass loss in Greenland is dominated by dynamic thinning in the south east and enhanced ablation around the margins (Fig. 1), especially along the southern half of the ice sheet (Ettema et al., 2009; van den Broeke et al., 2009). This pattern of mass loss results in a RSL lowering for the whole of the UK, Scandinavia Iceland, Quebec, the Hudson Bay and Nunavut (Fig. 2a). There is a negligible impact on the rest of northern Europe including the Netherlands, Atlantic coastline of Germany and along the Arctic coastline of Russia (Fig. 2a). The spatial pattern differs significantly from an earlier result that assumed uniform wastage across the ice sheet, which has the effect of pushing the zero RSL contour further north (Mitrovica et al., 2001). The far-field peak increase is less dependent on the precise pattern of mass loss and occurs in the South Atlantic and around the southern tip of Chile and Argentina, in broad agreement with an earlier study (Mitrovica et al., 2001). Mass loss from Antarctica is concentrated in key sectors of West Antarctica and the Peninsula (Fig. 1) (Rignot et al., 2008a). This has a marked effect on the zonal distribution of RSL , resulting in maxima around the coastline of North America and Australasia (Fig. 2b). In this region

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the increase is about 30% higher than the eustatic value (Bamber et al., 2009; Mitrovica et al., 2009).

Mass loss from the Gulf of Alaska results in RSL lowering over the northern Pacific Ocean and over most of the northern coastline of Canada (Fig. 2c). Sea level rise in the southern hemisphere is modest from this source (∼0.2 mm/yr) as the mass loss rate is less than half that of either ice sheet and does not appear to be accelerating (Luthcke et al., 2008). MG&IC losses are concentrated, primarily, in the high Arctic and Patagonia (Fig. 1) with the largest RSL effects close to these regions (Fig. 2d). Losses from MG&IC appear to be increasing (Meier et al., 2007) but at a more modest rate compared with the ice sheets, which are now the dominant source of mass to the oceans (van den Broeke et al., 2009; Velicogna, 2009). There is a large relative uncertainty in the individual MG&IC contributions (Dyurgerov and Meier, 2005) but in absolute terms, the errors are small (in the range 10–20 Gt/yr) compared with the contributions from the three major sources (61–166 Gt/yr). If the present-day distribution of ice loss is maintained, then the patterns of RSL in Fig. 2 will be the same but the scale will increase linearly with time.

It is important to consider the separate fingerprints of RSL from the major sources to understand their individual gravitationally-consistent "fingerprints", but for present-day and future trends in sea level, it is, perhaps, the combined signal that is important. This is shown in Fig. 3. In this case the maxima in RSL (∼1.23 times eustatic) are concentrated in a zonal band from about 20° N to 40° S in the Western Pacific and Indian Oceans, encompassing a number of islands that are particularly vulnerable to sea level rise (Nicholls and Tol, 2006), while Northern Europe experiences a RSL rise that is ∼45% less than eustatic. This is equivalent to rates of 1.6 and 0.8 mm yr^{-1}, respectively, for the ice losses considered here. Thus, the present-day, gravitationally consistent, sea level signature due to ice melt is a factor 2 larger for Australasia and Oceania than it is for Northern Europe. Figures 2 and 3 show estimates accounting for ice melt only. Another major long-term, secular trend in RSL is due to glacio-isostatic adjustment (GIA). This has three effects: vertical motion of the Earth's surface, changes to the gravity field, and TPW. GIA is largest for those land masses that have experienced the greatest changes in ice loading and, in particular, for North America and Fennoscandia (Fig. S1). The low-latitude impact, where the ice melt signature peaks in Fig. 3a, is negligible over the deep ocean. Close to the coast, continental uplift results in a small negative RSL signal (Fig. S1). Overall, GIA, and uncertainties in estimating it, have little impact on the regions of maximum RSL shown in Fig. 3.

In addition to GIA and mass exchanges, there are two processes within the oceans that affect relative sea level. Steric increases (density changes due to salt and heat content variations) were responsible for about a quarter of the total SLR rise over the last 50 years increasing to almost a half since 1993 but with large regional variations (Lombard et al., 2005; Nerem et al., 2006). Steric increases are, thus, both spatially and temporally highly variable. Some of this variability can be explained by major climate oscillations such as the El Nino Southern Oscillation and ocean currents (Nerem et al., 2006; Church et al., 2004). Not surprisingly, over multi-decadal time scales the spatial variations become less pronounced and almost an order of magnitude smaller in rate (Church et al., 2004). A further, transient signal is the effect that freshwater fluxes from ice melt have on ocean circulation (Stammer, 2008) and related dynamic effects due to predicted climate change (Yin et al., 2009). Locally, these can be significant (tens of centimetres deviation from the mean) but a critical difference between these effects and those due to self-gravitation and TPW is that they are transient and have a mean of zero. In this case, the ocean circulation response is not a rate (i.e. it is not cumulative) but an absolute sea surface height anomaly that is related to the magnitude of the freshwater flux entering the ocean (Stammer, 2008) and the reduction in the strength, for example, of the Atlantic meridional overturning circulation (Yin et al., 2009). The contribution from ice melt is, however, cumulative and the regional amplification is stationary in time for a given distribution of melt.

The RSL for the Western Pacific and Indian Ocean's is about 23% higher than the eustatic mean (Fig 3). Thus, the current pattern of ice melt, which is dominated by losses from Antarctica and Greenland, if continued into the future, will result in a substantially

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smaller RSL increase for Northern Europe and the Baltic coastline and, comparatively, about twice the RSL increase for an area that includes Micronesia, the Solomon and Marshal Islands, French Polynesia, the Maldives, South Asia and many small Atolls (Nicholls and Tol, 2006). This is a region where steric SLR has also been significantly above the global mean value for the last ~15 years and where the predicted sea surface height anomaly due to ocean dynamics is close to the global mean (Lombard et al., 2005;Nerem et al., 2006;Yin et al., 2009). It is a region that is particularly vulnerable but also particularly ill equipped to adapt to SLR.

Supplementary material related to this article is available online at: http://www.the-cryosphere-discuss.net/4/1593/2010/tcd-4-1593-2010-supplement.pdf.

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Table 1. Regional distribution of ice mass losses. Column three refers to the primary source for relative spatial distribution of losses. For mountain glaciers and ice cap regions the source references were not always explicit about the relative contributions. For NW USA we referred to Dyurgerov and Meier to determine the relative contributions but ensured that the total for non-ice sheet contributions agreed with Meier et al., 2007 and Dyurgerov and Meier, 2005. Our estimates for Greenland and Antarctica include MG&IC not connected to the ice sheets.

Region	Mean mass loss 2000–2008 Gt/yr	Primary source
Greenland	166	van den Broeke et al., 2009
Antarctica	135	Rignot et al., 2008[a]
Alaska	61	this study
Canadian Arctic	50	Hock et al., 2009
Svalbard	10	Wouters et al., 2008
Patagonia	30	Chen et al., 2008
NW USA	45	Meier et al., 2007; Dyurgerov and Meir, 2005

[a] Two estimates are provided: a net flux and net+. We use the latter, which is scaled to include unsurveyed areas and, therefore, includes a proportion of MG&IC in Meier et al., 2007. We also reduce losses in sector HH', as explained in the text, to provide greater consistency with GRACE and radar altimetry. The contribution of MG&IC around the periphery of Greenland is less significant and estimated to be around 25% of that for Antarctica for the period 1961–2004 (Hock et al., 2009).

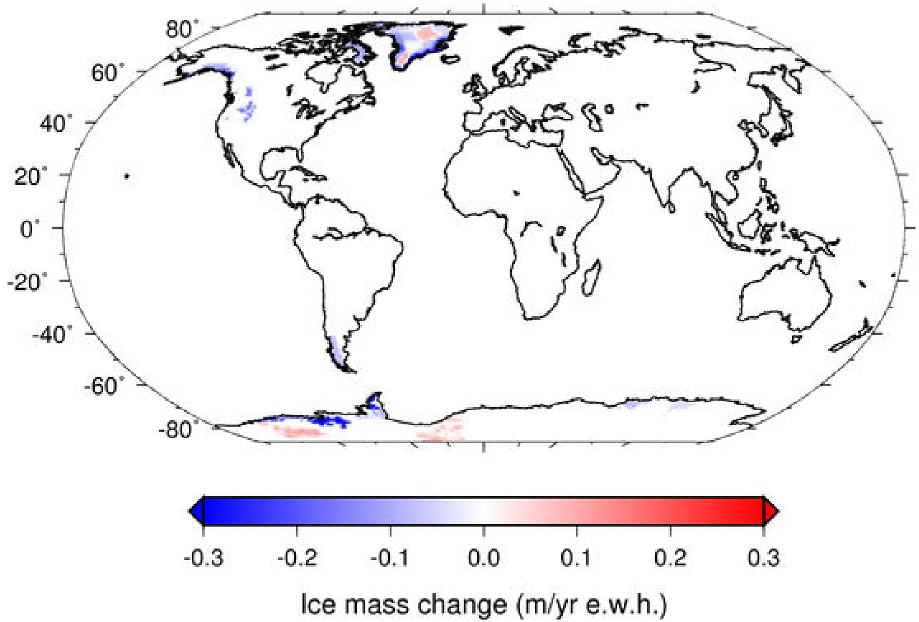

Fig. 1. Spatial distribution of ice mass trends for the regions listed in Table 1 for the period 2000–2008.

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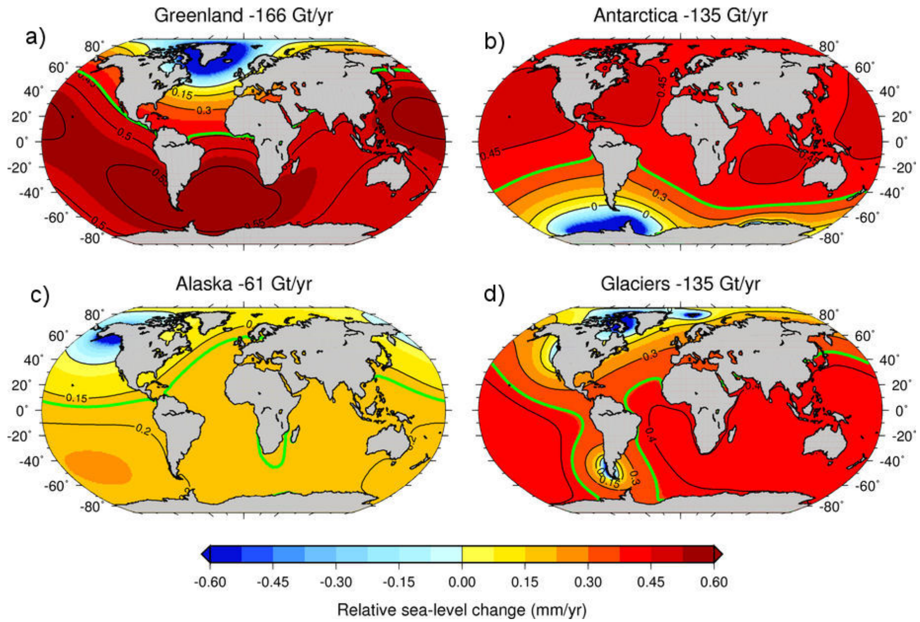

Fig. 2. Relative sea level variations due the gravitational and Earth rotational effects of recent (2000–2008) ice mass losses from different sources; **(a)** Greenland, **(b)** Antarctica, **(c)** Alaska, **(d)** mountain glaciers and ice caps in the Arctic, Patagonia and Rockies. The thick green contour indicates the global average eustatic RSL.

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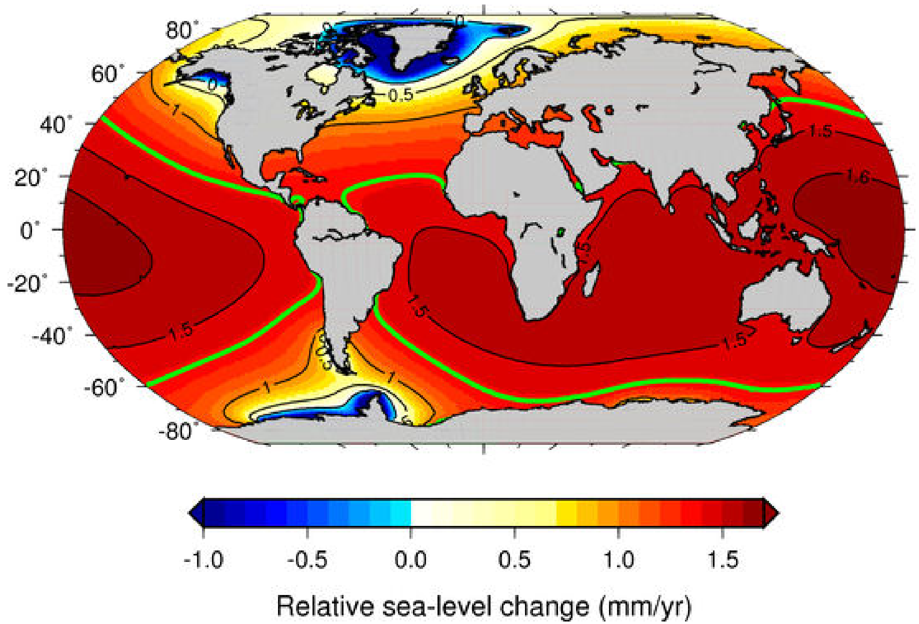

Fig. 3. The combined relative sea level variations for all ice masses. The thick green contour indicates the global average eustatic RSL.

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