THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

BY MARK E. TAMISIEA AND JERRY X. MITROVICA

The Moving Boundaries of Sea Level Change

Understanding the Origins of Geographic Variability

ABSTRACT. As ice sheets gain or lose mass, and as water moves between the continents and the ocean, the solid Earth deforms and the gravitational field of the planet is perturbed. Both of these effects lead to regional patterns in sea level change that depart dramatically from the global average. Understanding these patterns will lead to better constraints on the various contributors to the observed sea level change and, ultimately, to more robust projections of future changes. In both of these applications, a key step is to apply a correction to sea level observations, based on data from tide gauges, satellite altimetry, or gravity, to remove the contaminating signal that is due to the ongoing Earth response to the last ice age. Failure to accurately account for this so-called glacial isostatic adjustment has the potential to significantly bias our understanding of the magnitude and sources of present-day global sea level rise. This paper summarizes the physics of several important sources of regional sea level change. Moreover, we discuss several promising strategies that take advantage of this regional variation to more fully use sea level data sets to monitor the impact of climate change on the Earth system.

INTRODUCTION

Sea level displays complex variability in both space and time that reflects the broad suite of geophysical forcings that act upon Earth. When considering this variability, people often think of dynamic processes, such as changing tides, winds, currents, temperature, and salinity. However, few consider how the ground moving beneath them or changes in gravity can impact sea level. Modern mass loss from glaciers and ice sheets, for example, as well as changes in the water stored on continents, cause crustal motions that perturb Earth's gravity. In addition, Earth is still adjusting to the collapse of the large ice sheets from the last ice age. Both of these processes—associated with recent and ancient changes in the Earth system—introduce large-scale regional variations into sea level change.

In tabulating the various contributions to sea level rise, the focus has frequently been on changes to the total ocean mass associated with freshwater flux from grounded ice sheets, and on volume changes linked, for example, to temperature and salinity variations (e.g., Willis et al., 2008). This focus makes sense when the goal is to understand global averages. However, there are at least three reasons for moving beyond estimates of global means. First, and most importantly, local rather than global variations in sea level have the greatest and most immediate impact on society. Woodworth et al. (2011, in this issue) show the dramatic geographic variability

in recent sea level rates observed in the ocean. Understanding this variability, now and into the future, is the principal concern for coastal communities. Second, until recently, our sampling of the ocean has been incomplete. Thus, if the underlying processes giving rise to regional sea level trends were not well understood, this incomplete sampling could lead to significant biases in attempts to infer global averages. Finally, without understanding these processes, which ultimately requires a full accounting of regional variation, efforts to project future sea level rise will be profoundly hampered.

This paper explores two causes of regional sea level change in detail. The first is the ongoing response of Earth and the ocean to the collapse of the Pleistocene ice sheets since the Last Glacial Maximum of the most recent ice age, about 20,000 years ago. This process is called glacial isostatic adjustment (GIA), or post-glacial rebound. We will use both terms, although the former is preferred because it is more general, encompassing regions of crustal subsidence as well as rebound. While there is a rich literature on the time history of sea level change caused by GIA (Wu and Peltier, 1983; Nakada and Lambeck, 1989; Mitrovica, 1996; Peltier, 1998; Milne et al., 1999; Kendall et al., 2005), this paper focuses only on the contribution to present-day sea level observations, such as tide-gauge and altimetry records as well as mass changes derived from the Gravity Recovery and Climate Experiment (GRACE) satellite mission. As we will demonstrate, if these observations were interpreted as being due only to present-day changes in polar ice mass flux or the thermosteric contribution, any resulting inference would be biased. In fact, in the case of GRACE gravity observations, any inferred ocean mass changes are of the same magnitude as the contribution from GIA. We emphasize that, for the purpose of this paper, the term GIA will be specifically associated with the response to ice sheet changes associated with the last glacial cycle.

The second cause of regional sea level

variability we explore is ongoing water exchange between the continents and the ocean. This water can come from melting ice sheets and glaciers, or from the hydrological cycle over the continents, and in either case the time scale of sea level variability will match the fluctuations in the source. Frequently, these ongoing fluxes are expressed in terms of an equivalent, globally averaged change in sea level, such as, for example, 0.3 mm yr^{-1} from Greenland. However, this method of reporting often contributes to the mistaken impression that the processes lead to a geographically uniform sea level change. In contrast, we will show that the patterns of sea level change show dramatic geographic variability and that each source, whether it is a melting ice sheet or a varying groundwater reservoir, will be characterized by a distinct variability. The so-called "fingerprints" of sea level change allow us to gain more information from historical records and provide a more societally relevant prediction of regional sea level change.

BACKGROUND

Oceanographers generally consider the ocean's two bounding surfaces, the solid crust and the geoid, to be time-invariant. The geoid is typically defined as the time-averaged equipotential surface that corresponds to the sea surface if no dynamic processes (e.g., ocean circulation) occurred. In this paper, we ignore dynamic processes and simply refer to the top of the ocean as the sea surface. This terminology is adopted because the value of the equipotential that defines the sea surface will actually change with time as Earth deforms and/or water enters and leaves the ocean.

The assumption that the two boundaries are time-invariant intrinsically assumes that the solid Earth is rigid and that the water (mass) moving around in the ocean and on the continents does not generate any gravitational forces. However, Earth is far from rigid, and its behavior depends upon the time scale of the forcing that is applied to it. For example, the motions of Earth's tectonic plates are ultimately driven by thermal convective fluid flow in Earth's mantle. Similarly, the ellipticity of Earth's figure is due to rotation and it can be accurately predicted by treating the planet as a rotating fluid (Nakiboglu, 1982). Note that mantle convection results in a small but important deviation from this form. We will return to this issue later. In contrast to this fluid behavior, on very short time scales, hours to decades, Earth responds nearly elastically to applied forcing. Commonly cited examples of this behavior are propagation of seismic waves from the source of an earthquake and deformation of the solid Earth due to tidal forcing, both discussed a century ago by Love (1911). However, another loading example comes to mind: when a river basin fills with water, the crust is depressed, and when the excess water migrates out of the basin, the crust returns to its initial position. In between these two end-member behaviors of Earth, for loading time scales that range from hundreds to many thousands of years, Earth exhibits more complex, viscoelastic behavior. In this case, an initial elastic response to loading (or unloading) is followed by viscous flow. In geophysics, the canonical example of such behavior is post-glacial rebound—the adjustment of the crust in areas like Canada and Sweden associated with the deglaciation of these regions at the end of the last ice age.

When measuring present-day sea level change, we often rely on three different observation systems: tide gauges, satellite altimetry, and gravity changes inferred from GRACE. Although temperature and salinity changes derived from the Argo float system provide an important fourth observation set, we will not include it because this paper does not consider thermosteric contributions to sea level. Tide gauges, for example, measure the change of the sea surface relative to a nearby benchmark connected to the solid Earth, leading to the term relative sea level. Thus, a sea level rise can result from either crustal subsidence or a rise in the sea surface. The model predictions described below include global-scale estimates of both vertical crustal motion and changes to the height of the sea surface. The difference between these two changes, sea surface minus crustal height, is the change in thickness of the ocean at any given point, which is directly comparable to tide-gauge data. We note that the integral of this difference taken over the entire ocean geometry is precisely the change in the volume of the ocean.

In contrast to tide-gauge measurements, satellite altimetry measures the height of the sea surface. This height must be measured with respect to some reference point, such as the center of mass of the whole Earth system.

Mark E. Tamisiea *(mtam@pol.ac.uk) is Scientist, National Oceanography Centre, Liverpool, UK.* **Jerry X. Mitrovica** *is Professor of Geophysics, Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA.*

However, establishing such a point is difficult in practice, and the current, best effort to do so is represented by the International Terrestrial Reference Frame (ITRF; e.g., Altamimi et al., 2011). The difficulty in establishing the motion of the reference frame is that it cannot be measured directly, but must inferred from tracking of Earth-orbiting satellites, particularly from satellite laser ranging. Imperfect observation models combined with a temporally varying (due to fluctuations in observation station funding) and spatially inhomogeneous (e.g., lack of stations in the Southern Hemisphere) observing network can result in biases in this center of mass rate. The results of Beckley et al. (2007) highlight the importance of establishing a stable reference frame, and they show that regional estimates of sea surface height from altimetry exhibit differences of up to 1.5 mm yr^{-1} when the solutions are changed from the ITRF2000 to the ITRF2005 reference frame.

Finally, most of the gravity changes inferred from GRACE satellite records are caused by the motion of water about Earth's surface (i.e., hydrological processes). Thus, when reported, these observed gravity changes are converted to a change in the thickness of water (i.e., water equivalent) that would lead to the same gravity change on an elastic Earth (e.g., Wahr et al., 1998). This mapping is reasonable for any study considering present-day changes of water in the ocean, over the ice sheets, or on the continents. However, in the case of ongoing GIA, the majority of the associated gravity change is caused by motion of the solid Earth. Because the crust and mantle have a much higher density than water, the standard conversion of the GRACE data into water equivalent will yield numbers much greater than the actual change in the relative sea level. We return to this issue in detail below.

GLACIAL ISOSTATIC ADJUSTMENT

The impact on regional sea level observations most commonly associated with GIA is the uplift, or post-glacial rebound, of the crust near the centers of the former ice sheets. A classic example is the observed evolution of shorelines around the Gulf of Bothnia, which drove much of the early development of the theory behind GIA modeling (Ekman, 2009). Figure 1 shows a selection of some of the high-quality, long-term tide-gauge records along the east coast of Sweden. While the loading centers

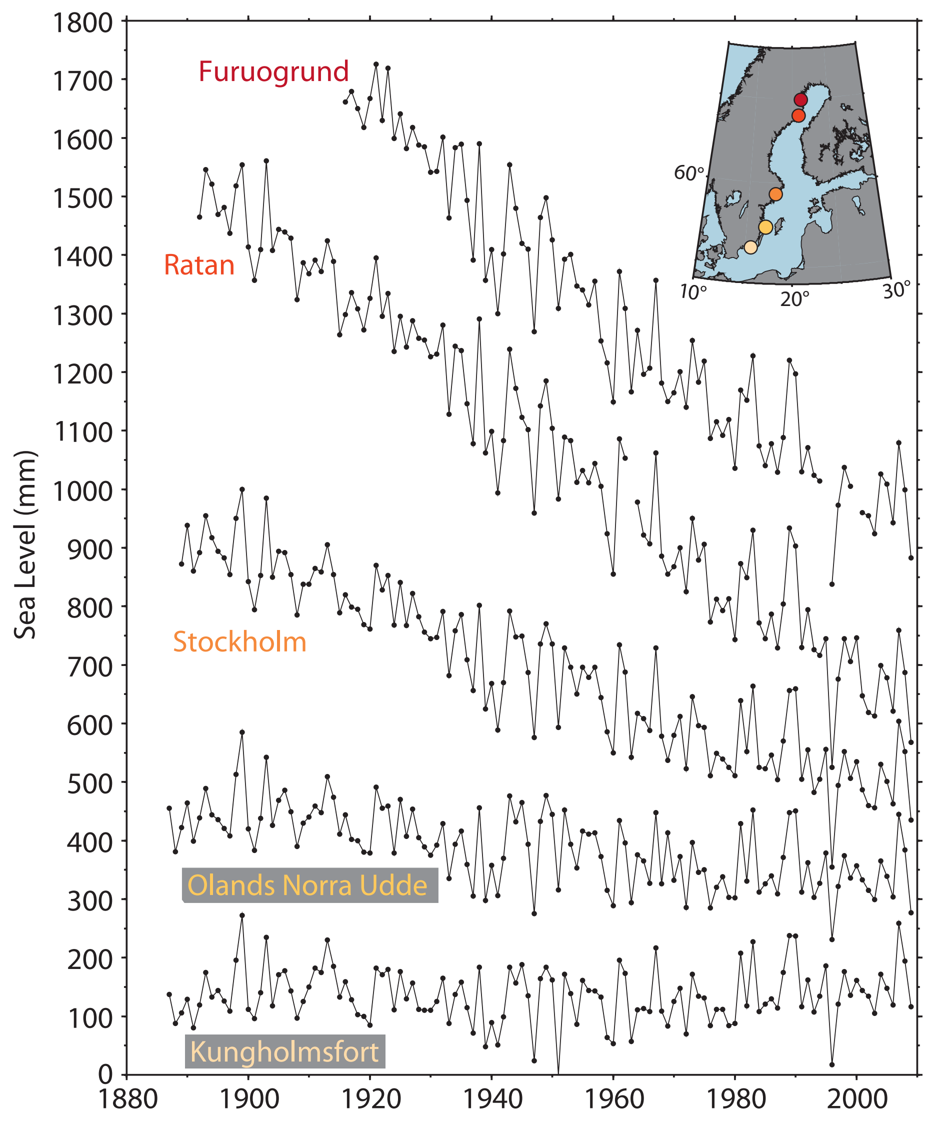

Figure 1. Tide-gauge data from Swedish stations in the Baltic. Moving closer to the center of the former Fennoscandian ice sheet, between Stockholm and Ratan, the trends become increasingly more negative as the rate of post-glacial rebound increases. The time series are obtained from the Permanent Service for Mean Sea Level (Woodworth and Player, 2003), and they have been offset by arbitrary amounts for clarity.

were subject to ice cover, mantle material flowed from the region beneath them to the surrounding regions to create a forebulge. Now that the ice sheets are gone, or have decreased in size in the case of Greenland and Antarctica, the process is reversed; mantle material is flowing back from the bulges to previously glaciated areas, causing the former to subside and the latter to uplift (see Figure 2a). The uplift results in local tide gauges measuring a sea level fall. Returning to Figure 1, note that the rate of relative sea level fall generally increases the further north the tide-gauge site is located along the coast. This characteristic of the observations occurs because the Fennoscandian ice sheet that covered the region was thicker along this profile, reaching a maximum between Stockholm and Ratan in a recent reconstruction (Lambeck et al., 2010). The greater thickness caused a larger crustal depression, leading to a larger present-day uplift. In the neighboring regions, where the forebulge is collapsing, tide gauges would measure a sea level rise. As an example, the forebulge associated with the Laurentian ice sheet that covered most of Canada and the northeastern United States at Last Glacial Maximum is located, in part, along the US East Coast. Consequently, tide gauges along much of this coast are characterized by larger-than-average relative sea level rates (see Engelhart et al., 2011, in this issue).

The tide-gauge observations discussed above are not only caused by land motion. The motion of mantle material also contributes to gravity field changes in the region. The progressive increase in mass as the former loading centers uplift increases its gravitational attraction. In turn, this increase in gravitational attraction causes sea surface height to increase, with the opposite effect in the forebulge areas. Within the near field of the ice sheets, model predictions of the GIA process estimate the ratio of the uplift to the sea surface change over Hudson Bay in Canada to be approximately 10:1, with a slightly higher ratio of 20:1 in the Gulf of Bothnia. This additional contribution to the measurements is important to

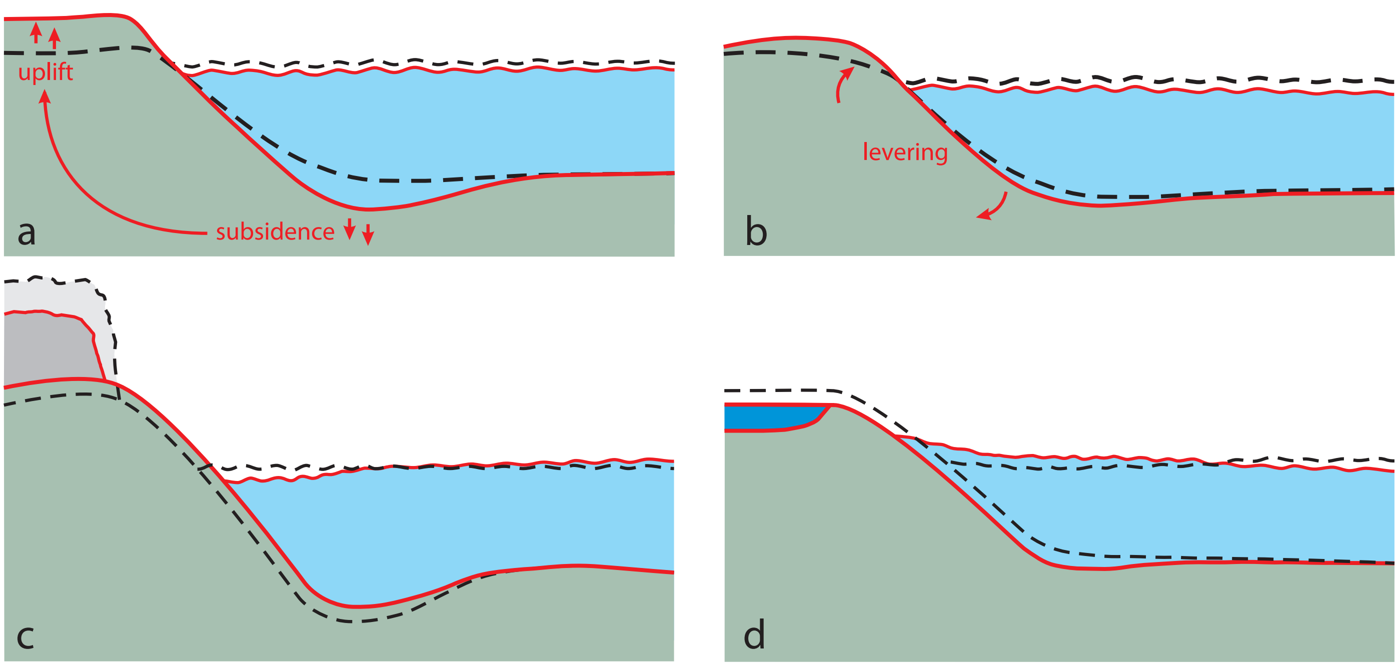

Figure 2. Schematics demonstrating different mechanisms by which crustal motion and changes in gravity contribute to regional sea level variations. In each case, the black lines represent the locations of the crust and the sea surface at some point in the past. The red lines represent the present position of these surfaces; (a) and (b) show mechanisms associated with glacial isostatic adjustment, while (c) and (d) illustrate the impact of present-day mass changes. (a) A profile from the center of a former loading region into the surrounding ocean. The center is uplifting while the nearby crustal forebulge in the ocean collapses as mantle flows back toward the previously glaciated area. (b) A profile from a continental region into the adjacent ocean in an area at great distance from the centers of glaciation (i.e., the far field). As the ocean basins are now loaded with meltwater, offshore regions are levered downward and the adjacent continent upward as mantle material flows from under the former to under the latter. (c) A profile from the middle of a rapidly melting ice sheet into the surrounding ocean. The reduced mass of the ice sheet allows the crust to rebound and reduces the gravitational force that attracted ocean water toward the ice sheet. (d) A profile of a river basin exhibiting an increase in water storage. Opposite to (c), the additional mass on the continent attracts water toward the shore and depresses the crust.

keep in mind when considering recent efforts to remove GPS-derived vertical land motion (VLM) from tide-gauge results. VLM at tide-gauge stations can be caused by many mechanisms, such as sedimentation and groundwater extraction, as well as GIA. Removing the VLM accounts for the primary impact of these local mechanisms, as well as allowing for easier comparison to altimetry results, which are relative to the center of mass of the Earth system (Wöppelmann et al., 2009). Correcting for crustal deformation does not remove the gravity contribution of GIA to the tide-gauge measurement (nor, for that matter, any of the gravity contributions of the VLM processes listed above), and thus these results cannot be considered fully "GIA corrected."

Formally, tide gauges only measure local sea surface change relative to a nearby benchmark. However, from GIA modeling, we are able to compute global maps of the change in the position of the sea surface relative to the crust. Thus, we can create global maps of what a tide gauge would measure at every point in the ocean, which is equivalent to the change in thickness of the ocean everywhere (Figure 3a). The nonlinear color scale for Figure 3 highlights far-field sea level changes, and thus is highly saturated near the loading centers where GIA predictions of relative sea level fall can exceed 1 cm yr^{-1}. As noted earlier, we are assuming that GIA is not contributing any water to the ocean at present. Thus, because relative sea level refers to a change in thickness of the ocean, Figure 3a sums to zero by definition. Therefore, if one could perfectly sample this field, ongoing GIA should have no effect on the global averaged relative sea level change.

The large GIA-induced changes local to the ancient ice sheets have motivated some to simply avoid observations from these regions as a method for excluding the contaminating impacts of GIA in their analysis of present-day sea level change. This course is, for at least two reasons, difficult to take, particularly in regards to the analysis of tide gauges. First, a number of the longest and highest-quality records are in the Northern Hemisphere, in the near field of the Pleistocene ice sheets. Second, GIA has a far-field signal (of amplitude ~ 0.5 mm yr^{-1}) that remains a significant contributor to rates inferred from tide-gauge data in such areas (Mitrovica and Davis, 1995). Indeed, the far-field GIA signal can strongly impact global sea level trends derived from tide-gauge records, space-based altimetry, or gravity measurements.

To understand the far-field effects of GIA on sea level measurements, let us return to Figure 2a. This figure illustrates the case where the forebulge is located off the coast of a continent, such as the east coast of North America. As the forebulge collapses, water flows from the far field to fill this newly vacated volume. A second far-field effect contributes an additional, ongoing redistribution of water. Consider the profile (Figure 2b) along a path extending from the continent into the ocean in regions far from the former ice sheets. Meltwater released from the former ice sheets during the last ice age deglaciation, which reached a globally averaged thickness of about 130 m, loaded the ocean basins. This load introduces a so-called "levering" effect, causing the continents to be pushed upward while the surrounding coastal regions subside (Nakada and Lambeck, 1989). Similar to the forebulge collapse, this mechanism also causes water to flow into the coastal areas from the far field. As an example of relative amplitudes, the first effect contributes ~ 60% to the relative sea level fall at Malden Island in the middle of the Pacific, while levering contributes the other ~ 40% (Mitrovica and Milne, 2002).

Both of the mechanisms described above lead to an increase in the volume of the ocean basins. However, as assumed previously, no further water is entering the ocean due to GIA. Thus, in order to compensate (i.e., to conserve ocean mass), the global sea surface average must decrease. The predicted present-day sea surface height change shown in Figure 3b illustrates this sea surface subsidence, which has come to be known as ocean siphoning (Mitrovica and Peltier, 1991; Mitrovica and Milne,

"SEA LEVEL DISPLAYS COMPLEX VARIABILITY IN BOTH SPACE AND TIME THAT REFLECTS THE BROAD SUITE OF GEOPHYSICAL FORCINGS THAT ACT UPON EARTH."

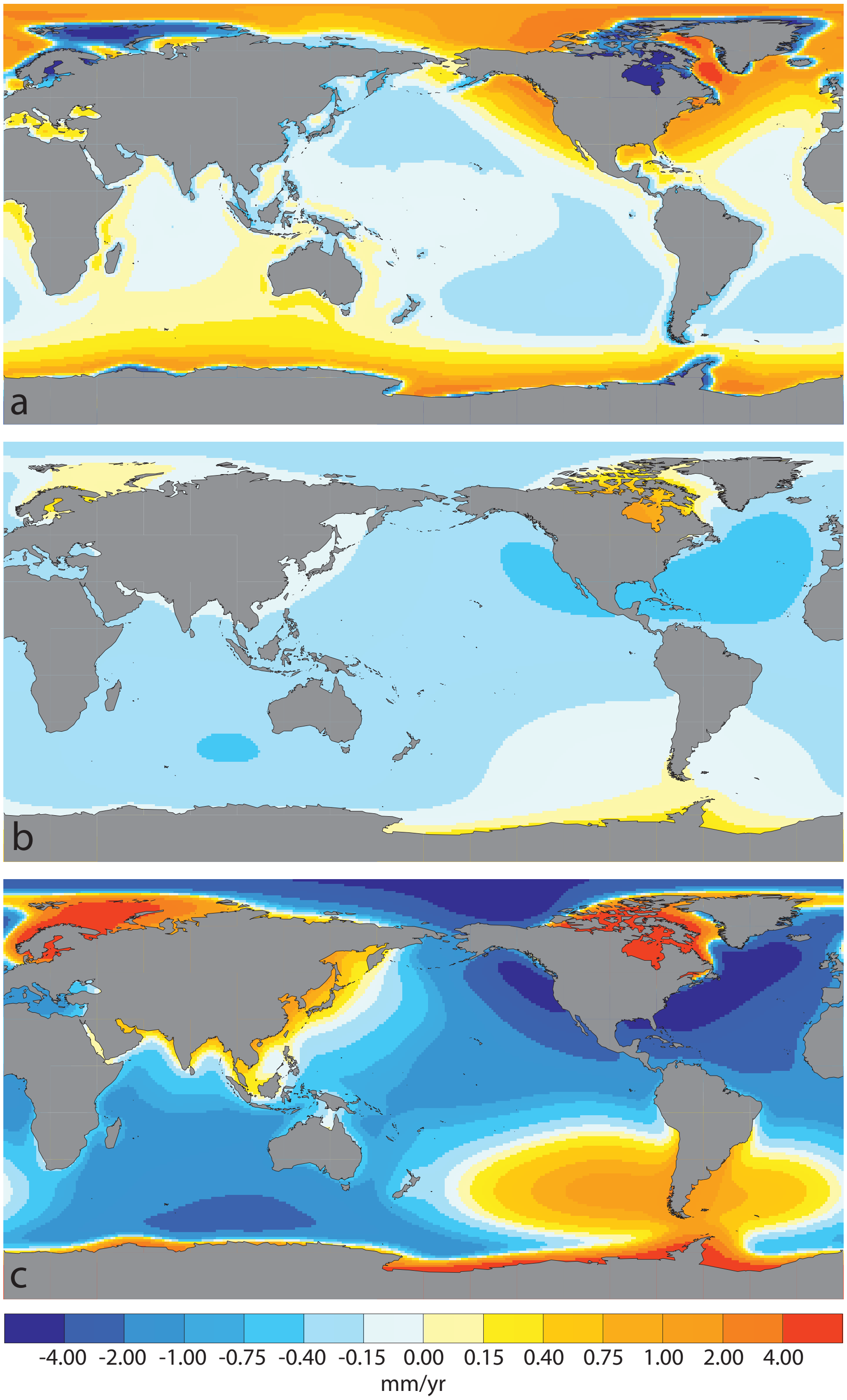

Figure 3. Numerical prediction of the present-day impact of glacial isostatic adjustment on (a) relative sea level measured by tide gauges, (b) change in sea surface height as measured by altimetry, and (c) estimated change in water thickness inferred from a gravity satellite mission. The nonlinear color bar has been chosen to highlight the far-field changes.

2002). Note that this field is much smoother than the relative sea level rates shown in Figure 3a, where the crustal uplift introduces greater local variations into the result. The far-field amplitude of the sea surface subsidence rate in Figure 3b is greater than the associated subsidence rate of the crust, and thus the net effect is that GIA contributes a submillimeter relative sea level fall in such regions (Figure 3a).

In the specific prediction shown in Figure 3b, the average sea surface height change over the ocean is –0.25 mm yr^{-1}, which is in good agreement with the value of –0.3 mm yr^{-1} derived by Peltier (2001) for the GIA correction to global sea surface height change inferred from satellite altimetry. Because of the smoothness of the sea surface height prediction in Figure 3b, the global average would not be greatly affected by choosing a different area of the ocean over which to average (Peltier, 2009).

The final issue we consider is the impact of GIA on inferences of mass balance derived from GRACE satellite gravity measurements. The goal of ocean mass-balance studies is to estimate the relative contributions to the observed sea level change associated with water flux from the continents and thermosteric changes. An important preliminary to this separation is an estimation of the GIA contribution to the mass estimate. At present, GIA causes mantle material, on average, to move from under the ocean to under the continents. If the gravity changes due to GIA are interpreted as a change in water thickness, as is usually done with GRACE data, then the associated GIA correction (in units of equivalent water thickness) is shown in Figure 3c. Note that these inferred changes in equivalent water thickness are much larger than the actual change in water thickness (Figure 3a). This happens because changes in the height of the solid Earth are being represented in terms of an equivalent height of water, which has a smaller density. The correction to the GRACE inference for the contaminating effect of GIA can be derived by taking the average value of the prediction in Figure 3c over the ocean, which yields –0.96 mm yr^{-1}. Thus, for GRACE to observe no mass change over the ocean, nearly 1 mm yr^{-1} of water would have to be lost from the continents (including ice sheets) to balance this GIA signal. While the magnitude of the GIA contribution has been estimated to be between 1 to 2 mm yr^{-1} (Willis et al., 2008; Cazenave et al., 2009; Leuliette and Miller, 2009; Peltier, 2009), the lower end of this range is correct for the particular ice sheet and Earth model used in these studies (Chambers et al., 2010).

It is important to note that a number of common processing techniques used in GRACE analysis can impact this computed correction. For example, a 500-km Gaussian smoothing is often applied to GRACE data in order to reduce the impact of short-length-scale errors in the observations. If this smoothing is applied to Figure 3c, it has the effect of adding more positive signal from over the continents into the average, and the above correction reduces to –0.77 mm yr^{-1}. To address this leakage, another standard processing technique applied to GRACE data over the ocean is to exclude any region within a prescribed distance from the continents before taking the average. If we average over the ocean, but exclude regions within 300 km of the coast and latitudes above ± 66°, and also use 300-km Gaussian smoothing (similar to Leuliette and Miller, 2009), the GIA correction becomes –1.09 mm yr^{-1}. It is clear that, due to the large spatial variability in Figure 3c, changing the averaging region of the GRACE data will impact the GIA contribution to GRACE estimates of ocean mass balance. In addition, uncertainties in the ice sheet and Earth models can also contribute to a range in this correction.

An alternate method of constraining mass flux into the ocean would be to estimate regional ice mass loss, in particular over Greenland or Antarctica using GRACE measurements. However, GIA would still play a large role in the interpretation of such estimates, because ice age changes in the volume of the polar ice sheets contribute to the ongoing trends in the gravity signal over these areas. Thus, GIA predictions and their uncertainties have become a central issue in assessing the robustness of inferences based on GRACE measurements. This issue can be mitigated if sufficient terrestrial GPS data are available (Ivins et al., 2011). However, there are currently problems related to spatial coverage of the stations and short time span of many of the existing observations.

The results in Figure 3 are derived by solving the so-called sea level equation, which governs the gravitationally self-consistent redistribution of ocean mass on a deformable planet when dynamic effects are excluded. Farrell and Clark (1976) first derived this sea level equation. In recent years, the theory underlying the equation has been extended to include shoreline migration, the advance and retreat of marine-based ice, and the feedback into sea level of contemporaneous ice age perturbation in the orientation of the rotation pole with respect to surface geography (henceforth true polar wander, or TPW; Milne and Mitrovica, 1998; Mitrovica and Milne, 2003; Kendall et al., 2005). The solution of the sea level equation requires two basic inputs. The first is the space-time evolution of ice age ice cover. The second is a model for the viscoelastic structure of the solid Earth. In almost all previous applications, the Earth model is assumed to vary with depth alone, and in this case, the elastic and density structures are taken from the seismic model PREM (preliminary reference Earth model; Dziewonski and Anderson, 1981). The thickness of the lithosphere, generally taken to be purely elastic (i.e., of infinitely high viscosity) and the radial profile of mantle viscosity are quite often treated as free parameters in GIA modeling, with the latter commonly divided into two isoviscous layers coinciding with the upper and lower mantle. In this regard, the predictions in Figure 3 adopt the ice history ICE-5G and the viscosity profile VM2 (Peltier, 2004). Improving both the ice history and associated Earth models is a continuing goal of the GIA community.

Two important advances in GIA modeling that have taken place over the last few years deserve mentioning. First, a growing number of groups have developed spectral and finite element numerical methods for treating three-dimensional variations in Earth structure, and in particular, lateral variations in viscosity (e.g., Martinec, 2000; Zhong et al., 2003; Wu, 2004; Latychev et al., 2005). These lateral variations can have an impact on the correction applied to tide-gauge observations (Kendall et al., 2006). Second, an improvement in the treatment of Earth's background ellipticity has been incorporated in predictions of ice age Earth rotation (Mitrovica et al., 2005). The effect of rotation, and in particular TPW feedback, on sea level predictions is evident in Figure 3b. The spherical harmonic degree two-order one signal, which is the most affected by TPW and is the component that divides Earth's surface into four quadrants, is visible in the plot. For example, note the negative peaks over North America and the southern Indian Ocean, and positive peaks over southern South America and Asia, where the continents obscure the quadrants.

PRESENT-DAY MASS CHANGES

As demonstrated in the last section, ancient changes in ice sheets can have a significant, ongoing impact on sea level as measured today. However, most of the current focus in regard to the mass component of sea level changes concentrates on present-day contributors of water from the continents, specifically, mass loss from ice sheets and glaciers, changes in the hydrological cycle, impoundment of water behind dams, and others. Often, the impacts of these sources are reported in terms of global average sea level change calculated as the volume of water divided by the ocean's area. As discussed above, this calculation reinforces the impression that sea level changes associated with the above processes are geographically uniform.

Even in the context of these present-day changes, the solid Earth deforms, the motion of water about the planet changes the gravitational field, and the orientation of the rotation pole is perturbed. In assessing how these processes affect sea level, the solid Earth is modeled as being purely elastic; if a load is applied, then the crust is depressed instantly, and if the load is subsequently removed, the crust recovers to its undeformed position immediately. The underlying assumption is that changes in the surface mass load and pole position are rapid enough that the mantle does not viscously flow to relax the strains generated by these applied stresses. This assumption is reasonable for decadal to centennial time scales for many regions, though crustal material may flow on shorter time scales in some areas, such as Alaska (Larsen et al., 2005) or Patagonia (Dietrich et al., 2010).

Treating Earth deformation as elastic has several significant advantages over the viscoelastic ice age calculations discussed above. First, the computed response will only depend on the elastic properties of the Earth model, which are known through seismic studies (Dziewonski and Anderson, 1981). This knowledge contrasts with uncertainties associated with the radial profile of mantle viscosity, for example, which are about an order of magnitude at all depths (Mitrovica, 1996). Second, the elastic response is only a function of the contemporaneous load, and therefore knowledge of the complete time history of the loading is unnecessary. We note also that this response is a linear function of the load size—if the load is doubled, for example, while keeping the geometry the same, then the response doubles. Thus, any spatial patterns in sea level change predicted using an elastic model can be normalized by the mass loss, a feature that will be exploited in a number of ways in the analyses below.

So, if the sea level change associated with relatively rapid ice melting is not uniform, what does it look like? In a somewhat counterintuitive result, sea level in the vicinity of a melting ice sheet will fall (Clark and Lingle, 1977; Clark and Primus, 1987). As the ice sheet loses mass, the crust underneath the region of ice loss, as well as in the surrounding area, uplifts (see Figure 2c). In addition, because of the ice loss, the gravitational attraction of the ice sheet on the water also decreases, causing a corresponding decrease in the nearby sea surface. Both effects combine to cause a relatively large relative sea level fall when compared to the globally averaged rise. Of course, given that sea level in areas near the melting ice sheets is dropping, sea level in other areas must increase at a rate greater than the global average in order to conserve mass.

> "...IF THE SEA LEVEL CHANGE ASSOCIATED WITH RELATIVELY RAPID ICE MELTING IS NOT UNIFORM, WHAT DOES IT LOOK LIKE?"

To illustrate these concepts, we consider a prediction of sea level change arising from uniform melting of either the Greenland (Figure 4a) or the West Antarctic (Figure 4b) Ice Sheet with a magnitude equal to a globally averaged sea level rise of 1 mm yr^{-1}. Because the sea level trend is a strong function of the location of the melting ice complex, the two scenarios in Figure 4a,b show distinct spatial geometries. Indeed, these geometries will be unique to a given ice source, and so they have come to be known as sea level fingerprints. Notice that the zone of sea level fall around a

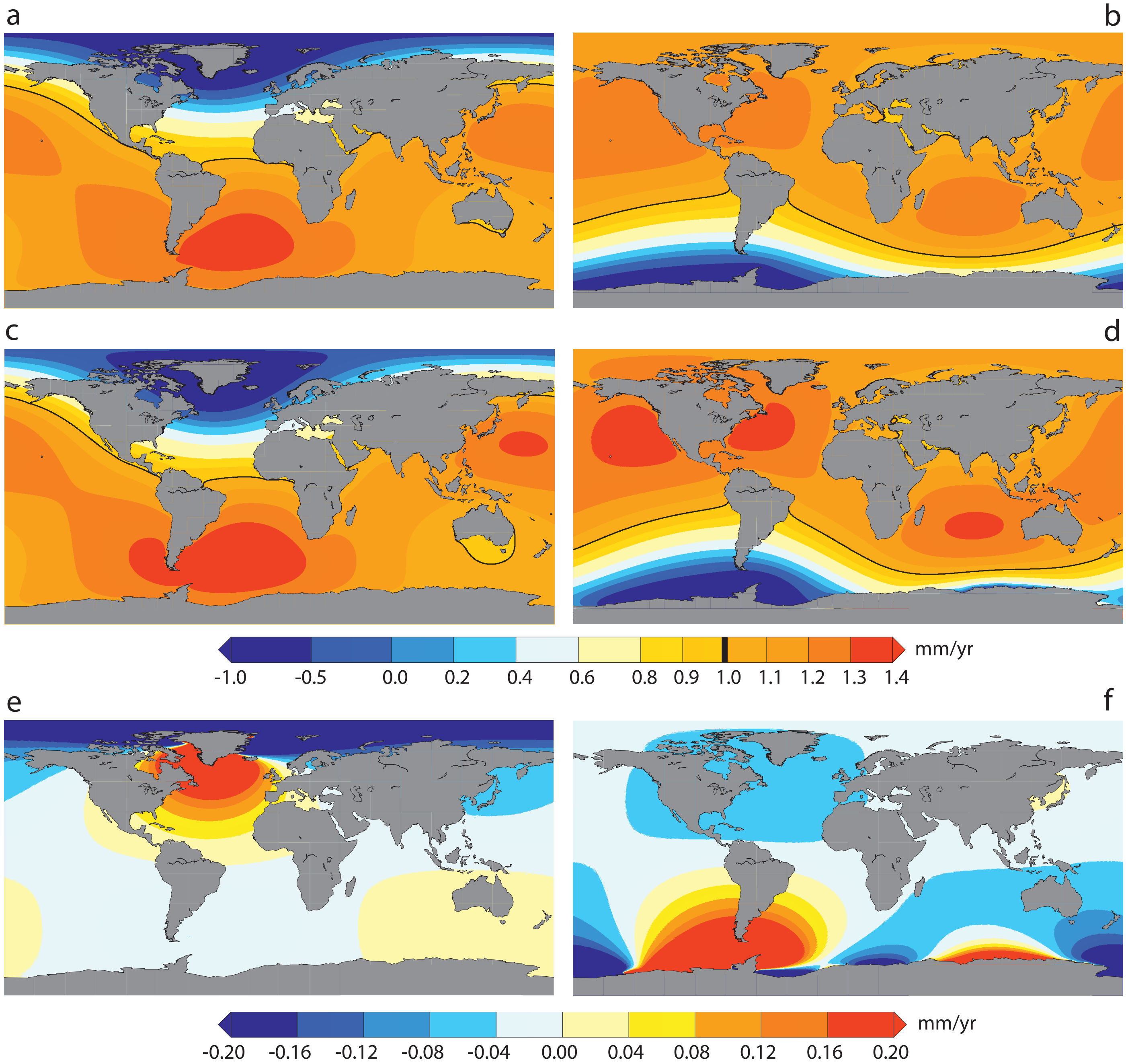

Figure 4. Relative sea level change, as would be measured by tide gauges or bottom pressure recorders, caused by a mass loss equivalent to a 1 mm yr^{-1} globally averaged sea level rise. The patterns are derived assuming that the melting occurs uniformly over (a) Greenland or (b) West Antarctica. (c) and (d) are based on the same net melting, but the pattern is obtained from realistic mass loss estimates for specific years over Greenland and Antarctica. (e) The difference of (a) and (c). (f) The difference of (b) and (d).

melting ice sheet extends ~ 2,000 km from the margin of the ice sheet. Thus, melting of Greenland ice, for example, leads to a drop in sea level as far south as Newfoundland in Canada and northern Britain, while melting from the West Antarctic Ice Sheet leads to no sea level change at the southernmost tip of South America. Adjacent to the melting ice sheets, the sea level fall peaks at a value more than an order of magnitude greater than the globally averaged rise, while in the far field of the melting ice sheet the sea level rise reaches a value ~ 30% higher than this average.

We note that Figure 4a,b shows the spherical harmonic degree two-order one imprint on sea level of rotational feedback. In these elastic calculations, the polar motion is such that the local pole moves toward the region losing ice. In the case of Greenland melting, this feedback leads to accentuated sea level rise in the South Atlantic and the northwestern Pacific, while melting from the West Antarctic increases the predicted sea level rise along the coasts of both the United States and the Indian Ocean. The predictions for the US East Coast illustrate the rather different outcomes of sea level associated with melting from the two polar ice sheets. In the case of melting from Greenland, the rate of sea level rise increases southward to a value of over 0.8 mm yr^{-1} at the southern tip of Florida. In contrast, melting from West Antarctica causes sea level to rise nearly uniformly at a rate of ~ 1.2 mm yr^{-1} along this coast.

If actual ice-sheet melting were uniform, the patterns of sea level change in Figure 4a,b could be scaled to the appropriate observed value of melting in Greenland and Antarctica. However, this scenario is clearly highly idealized because melting will not be uniformly distributed. The results from the GRACE satellite mission (see, for example, Woodworth et al., 2011, in this issue) show that the mass loss is localized to smaller areas of the ice sheet. However, even these inferences likely overestimate the spatial distribution of ice loss, given the smoothing that is applied when analyzing GRACE data (as discussed above).

To illustrate how sea level patterns are affected by the geometry of mass loss within an ice sheet, we used a map of the spatial distribution of the mass loss for the year 2000 in Greenland and 2006 in Antarctica (Rignot et al., 2008a,b) derived using mass budget methods (i.e., the combined effect of ice discharge and surface mass balance changes). We scaled these derived patterns of mass loss so that they would also contribute 1 mm yr^{-1} to sea level change. Figure 4c,d shows the results.

In the case of Greenland, the differences in the near field are very large, greater than 1 cm yr^{-1}. However, the amplitude of these differences falls off relatively quickly. Along most of the US East Coast, the difference in the fingerprints is generally smaller than 15% of the global average (Figure 4e). For this particular example, the line where sea level changes from negative (falling) to positive (rising) shifts to the south, because melting during 2000 in Greenland was primarily along the southeast and west-central coasts. We note that this concentration of mass loss further to the south means that the displacement of the pole and the rotational feedback is increased. Bamber and Riva (2010) showed similar differences using the observed mass loss trend over the period 2000–2008.

In the case of Antarctica, the largest sea level differences between the scenarios of uniform melt and the 2006 melt geometry occur in the Southern Ocean (Figure 4f). In particular, in 2006, relatively more mass was lost from the Antarctic Peninsula compared to a scenario where mass loss was uniformly distributed over West Antarctica. This mass loss shifts the predictions to more negative values along the South American coasts. The 2006 melt geometry also drove a larger TPW and associated sea level feedback, which contributed to the accentuated sea level change along the South American coast. Differences in the sea level predictions for the rest of the world are generally less than 10% of the global average.

We thus arrive at several conclusions. While the near-field predictions of sea level change following rapid melting of ice sheets will be highly sensitive to melting geometry, the far-field patterns are less sensitive to this geometry. For present-day observations, we can derive estimates of the spatial change of mass loss from GRACE (e.g., Riva et al., 2010). However, even over the observational period of GRACE (2002 to present), the relative distribution of mass loss has changed in Greenland, for example, increasing along the west-central coast (Rignot et al., 2008b). Thus, associated sea level fingerprints also evolved with time. Therefore, when considering longer sea level time series where the exact spatial distribution is unknown, it may be best to perform a fingerprinting analysis on far-field data using the geometries predicted from a uniform melt scenario (e.g., Mitrovica et al., 2001).

Changes in sea level associated with solid Earth deformation and gravity perturbations can arise from processes other than mass flux from ice sheets. The hydrological cycle causes large changes in water storage in certain areas on annual and interannual time scales. In the case of the annual cycle, there is an interesting balance between the phase of the local water storage cycle and global ocean volume (see Figure 5). For example, in the Northern Hemisphere, more water is stored on the continents during the winter, leading to less water in the ocean. As Figure 2d shows, the local effect of this additional water storage is to both depress the crust and increase the gravitational field. However, at the same time, there is less water in the ocean, leading to a decrease in global average sea level. The combination of these two effects effectively cancels, reducing the predicted annual amplitude of sea level due to water exchange to less than 50% of the global average near the coasts of Canada. However, in other regions, such as Bangladesh, the maximum water storage occurs at the same time as the maximum of water volume in the ocean. Thus, the amplitude of annual sea level variation in these regions can be nearly twice the global average (Tamisiea et al., 2010).

Knowledge of these regional variations in sea level can be used in a number of ways. One possibility is to examine the spatial variation in rates obtained from long tide-gauge records to estimate century-scale melting from each of the polar ice masses. Using a small set of tide gauges that had previously been adopted to determine the long-term global mean sea level rate (Douglas, 1991), Mitrovica et al. (2001) found that

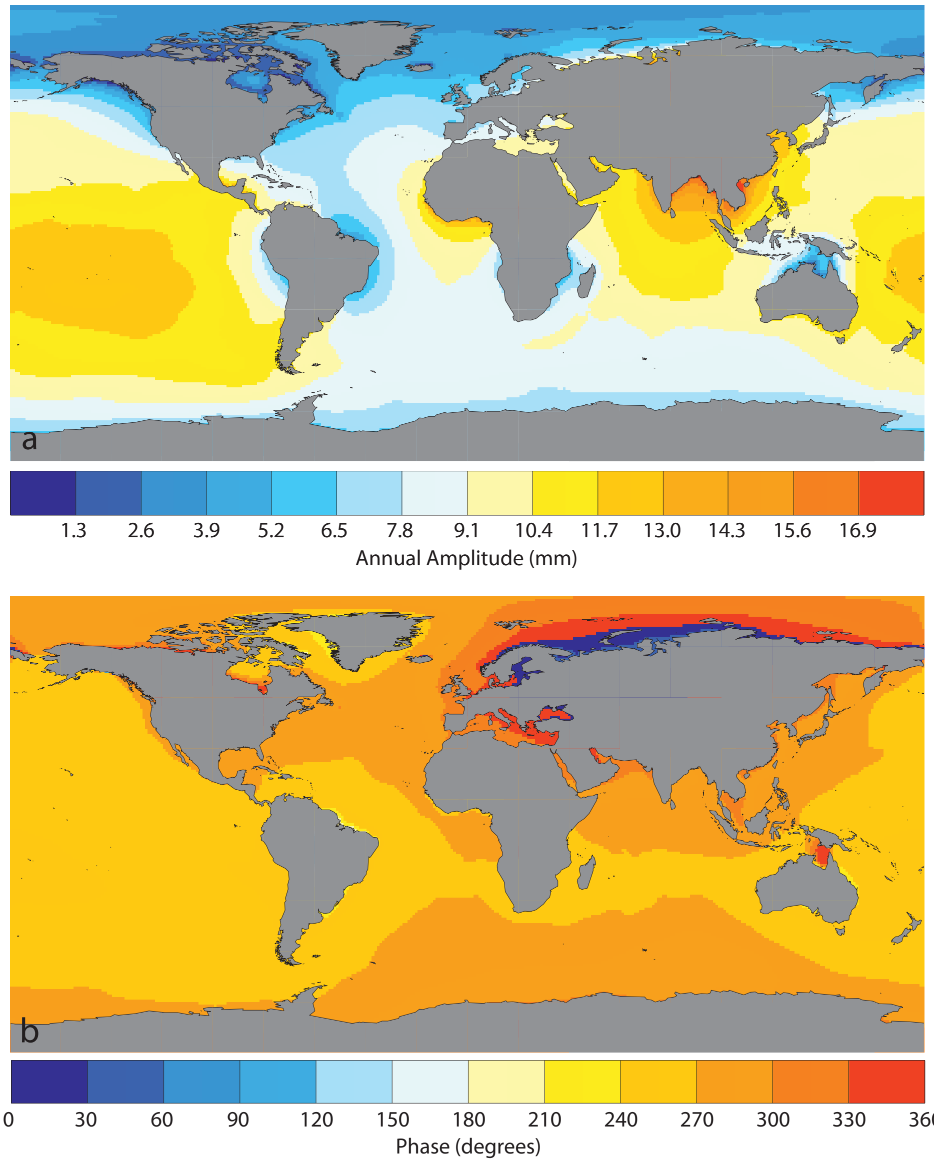

Figure 5. Model prediction of (a) the annual amplitude and (b) the phase of relative sea level caused by the exchange of water between the continents (hydrology), the atmosphere, and the ocean for the period 1980–1997. This calculation also accounts for the loading signal due to dynamic changes in bottom pressure derived from an ocean model over the same period. The average amplitude of mass change is 9.1 mm. The phase in degrees is measured from 1 January so that each division roughly corresponds to a month. Based on the results of Tamisiea et al. (2010, Figure 6).

the geographic variability introduced by melting from Greenland could reconcile the long-noted, subaverage rates of sea level rise in northern Europe. Mitrovica et al. (2001) emphasized that this conclusion was preliminary because they assumed, for example, that the fingerprint of thermosteric trends was geographically uniform. Indeed, in more recent studies that have included an increasingly complete catalog of processes contributing to geographic variability (e.g., thermosteric trends [Wake et al., 2006] and dynamic variability driven by winds and pressure changes [Marcos and Tsimplis, 2007]), a consistent solution for century-scale mass loss from the large ice sheets has not emerged. Part of the difficulty in this effort is the presence of significant decadal variability in tide-gauge records (e.g., Douglas, 2008).

Bottom pressure may serve as a better observation of this mass component than sea level. Ocean model results, which represent only dynamic processes, suggest that bottom pressure in the deep ocean exhibits much smaller variability than sea level (Vinogradova et al., 2007). Thus, in principle, it should be easier to detect a 1-cm annual change in ocean level in a measurement of bottom pressure than in a sea level measurement. As an initial study, Vinogradova et al. (2010) found that the variance explained in the annual cycle doubled when comparing bottom pressure records to a combination of static signals and an ocean model result (32%), relative to an analysis based on the ocean model alone (17%).

> "...IDENTIFYING THE SOURCE(S) OF THE OBSERVED VARIATION IN SEA LEVEL WILL BE CRUCIAL TO GAINING A DEEPER UNDERSTANDING OF THE PROCESSES CONTRIBUTING TO THE RISE AND MORE ACCURATELY PROJECTING SEA LEVEL CHANGES INTO THE FUTURE."

While it may be difficult to use the regional variability in sea level discussed here to independently extract the mass contribution to sea level change from historical data, the patterns are a well-understood and easily modeled component of regional sea level change. Thus, this contribution to regional sea level variability may be understood without extracting it independently from the data. GRACE provides an independent estimate of mass change over the continents. Assuming that water in the system is conserved, the GRACE estimate of mass change can be used as modeling input to derive the associated static sea level change. Riva et al. (2010) recently used GRACE data to estimate mass contribution to the ocean at a rate of 1.0 ± 0.4 mm yr^{-1} from glaciated areas (Greenland, Antarctica, Alaska, Patagonia, Svalbard, and parts of Arctic Canada), and they calculated the corresponding spatial pattern. They argued that net changes in mass over all other continental areas contributed a statistically insignificant change (–0.1 ± 0.3 mm yr^{-1}) in mean sea level over the period 2003–2009. However, there were localized regions of mass loss and gain, leading to geographic patterns with magnitudes generally below 0.5 mm yr^{-1} near the coast, but occasionally reaching as large as 0.9 mm yr^{-1}. Wouters et al. (2011) took a similar approach to explore annual sea level variations using mass changes derived from GRACE.

Another possible use of the fingerprint physics mechanism is to examine sea level variations that resulted from historical records of water storage on land, such as the impoundment of water behind dams. Using various estimates of total water storage, Fiedler and Conrad (2010) found that increased water storage on continents over the twentieth century would lead to smaller sea level fall along the coasts compared to the ocean (again, explained by Figure 2d). Tide gauges, given their location near the continents, would only record ~ 60% of the 30-cm mean sea level drop due to twentieth-century water storage estimated by Chao et al. (2008). This result illustrates another example where analyzing regional variations without understanding the underlying physical processes responsible for these variations may lead to a systematic bias in the inferred global average.

The fingerprinting methodology will also be important in efforts to predict future sea level changes arising from various climate-change scenarios. As an example, variations in ice mass predicted by future climate scenarios may be used to make projections of future sea level changes (e.g., Slangen et al., 2011). When combined with other contributors to future sea level change, these studies provide a framework for an integrated assessment of future risk. If mass loss from ice sheets approaches the decimeter level, then regional variability in static sea level will dominate dynamic variability over most of the ocean (Kopp et al., 2010).

Finally, the fingerprinting theory can also be used to address more "extreme" scenarios, such as the impact on sea level of the collapse of marine-based sectors of the West Antarctic Ice Sheet (see Figure 6). The pattern of sea level change differs from the simple mass loss from West Antarctica shown in Figure 4a due to the loss of marine-based ice. For the marine-based ice, the ice volume grounded below sea level causes a slight sea level fall because of differences in density between ice and water. However, removing the load causes crustal uplift, pushing water from marine settings into the far field. Overall, collapse of the West Antarctic Ice Sheet would lead to a 30% greater than average sea level change along the US coasts (Mitrovica et al., 2009). Bamber et al. (2009) argue that the global average sea level rise associated with potentially unstable sectors of the West Antarctic Ice Sheet is 3.3 m.

CONCLUSIONS

While globally averaged sea level rise provides an important integrated measure of changes in the Earth system, regional sea level changes have a more direct impact on society and provide greater information for scientists interested in the response of the planet to climate change. Indeed, identifying the source(s) of the observed variation in sea level will be crucial to gaining a deeper understanding of the processes contributing to the rise and more accurately projecting sea level changes into the future. Mass loss from ice sheets and glaciers, as well as evolving water storage on continents, introduces unique patterns of sea level change characterized by regional variations that can differ significantly from the global average. Perhaps the most notable example of this departure is the sea level fall predicted at the margin of a rapidly melting ice sheet. In any case, the unique fingerprint that characterizes the various contributors to sea level change may, at least in theory, provide a route to robustly estimating the sources of recent sea level rise. However, even without this complete understanding of sea level geometry, the fingerprints of at least some contributors (e.g., hydrological fluxes, polar ice sheet melting) are reasonably well understood and easily modeled, providing a means of identifying other processes in available records.

In any effort to analyze present-day observations of sea level change, it is important to understand and estimate the contaminating influence of the ongoing responses of Earth's land and ocean to the last ice age, or GIA. Failure to account for the GIA contribution may introduce a significant bias into interpretations of present-day observations. In the case of tide gauges, many of the longest records are in the Northern Hemisphere, where the GIA signal will be the largest. In the case of altimetry and gravity observations, even global sampling will not eliminate the GIA contribution to inferred sea level changes. For example, GIA contributes about -0.3 mm yr^{-1} to the mean sea surface height change observed using satellite altimetry. Moreover, inferred mass changes over the ocean based on GRACE gravity data are comparable in magnitude to the signal associated with GIA. The importance of the GIA signal suggests that long-standing efforts to improve models for the history of the Late Pleistocene ice sheets and the viscosity structure of Earth's mantle should remain an area of focused activity.

ACKNOWLEDGMENTS

Work for this manuscript was carried out at the National Oceanography Centre under the Natural Environment Research Council's Oceans 2025 program, and JXM was supported by Harvard University and the Canadian Institute for Advanced Research. We

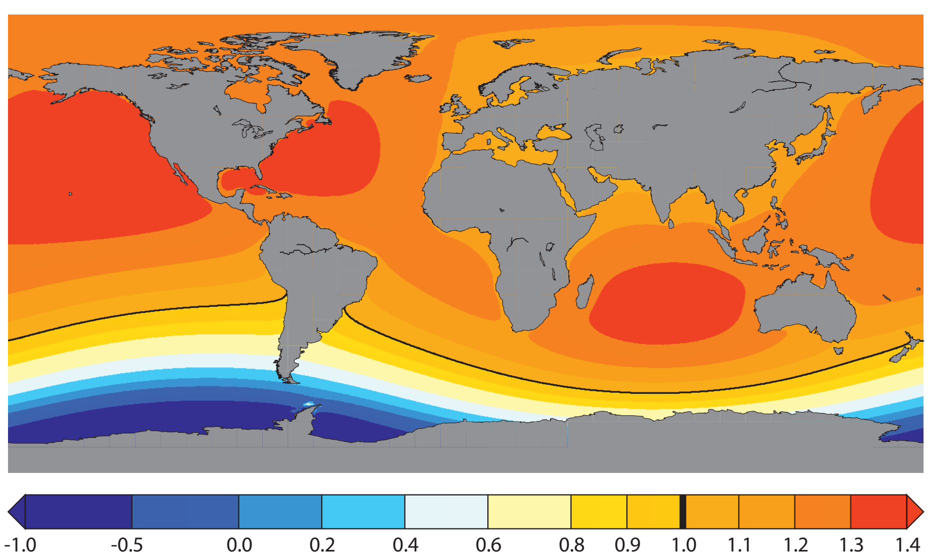

Figure 6. Pattern of relative sea level rise that would result from collapse of the West Antarctic Ice Sheet. The plot has been normalized so that a value of 1.0 corresponds to the average increase in sea level.

would like to thank Isabella Velicogna for providing us with the gridded maps of mass loss used to produce Figure 4c,d; Matt King, Riccardo Riva, and Philip Woodworth for suggestions; and Erik Ivins and an anonymous reviewer for helpful comments that improved the manuscript.

REFERENCES

Altamimi, Z., X. Collilieux, and L. Métivier. 2011. ITRF2008: An improved solution of the international terrestrial reference frame. *Journal of Geodesy*, doi:10.1007/s00190-00011-00444-00194.

Bamber, J., and R. Riva. 2010. The sea level fingerprint of recent ice mass fluxes. *The Cryosphere* 4(4):621–627, doi:10.5194/tc-4-621-2010.

Bamber, J.L., R.E.M. Riva, B.L.A. Vermeersen, and A.M. LeBrocq. 2009. Reassessment of the potential sea-level rise from a collapse of the West Antarctic Ice Sheet. *Science* 324:901–903, doi:10.1126/science.1169335.

Beckley, B.D., F.G. Lemoine, S.B. Luthcke, R.D. Ray, and N.P. Zelensky. 2007. A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits. *Geophysical Research Letters* 34, L14608, doi:10.1029/2007GL030002.

Cazenave, A., K. Dominh, S. Guinehut, E. Berthier, W. Llovel, G. Ramillien, M. Ablain, and G. Larnicol. 2009. Sea level budget over 2003–2008: A reevaluation from GRACE space gravimetry, satellite altimetry and Argo. *Global and Planetary Change* 65:83–88.

Chambers, D.P., J. Wahr, M.E. Tamisiea, and R.S. Nerem. 2010. Ocean mass from GRACE and glacial isostatic adjustment. *Journal of Geophysical Research* 115, B11415, doi:10.1029/2010JB007530.

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

Clark, J.A., and C.S. Lingle. 1977. Future sea level changes due to West Antarctic ice-sheet fluctuations. *Nature* 269:206–209.

Clark, J.A., and J.A. Primus. 1987. Sea-level changes resulting from future retreat of ice sheets: An effect of CO_2 warming of the climate. Pp. 256–370 in *Sea-Level Change*. M.J. Tooley and I. Shennan, eds, Institute of British Geographers, London, United Kingdom.

Dietrich, R., E. Ivins, G. Casassa, H. Lange, J. Wendt, and M. Fritsche. 2010. Rapid crustal uplift in Patagonia due to enhanced ice loss. *Earth and Planetary Science Letters* 289:22–29, doi:10.1016/j.epsl.2009.10.021.

Douglas, B.C. 1991. Global sea level rise. *Journal of Geophysical Research* 96:6,981–6,992, doi:10.1029/91JC00064.

Douglas, B.C. 2008. Concerning evidence for fingerprints of glacial melting. *Journal of Coastal Research* 24:218–227, doi:10.2112/06-0748.1.

Dziewonski, A.M., and D.L. Anderson. 1981. Preliminary reference earth model. *Physics of the Earth and Planetary Interiors* 25:297–356.

Ekman, M. 2009. *The Changing Level of the Baltic Sea During 300 Years: A Clue to Understanding the Earth*. Summer Institute for Historical Geophysics, Åland Islands, 155 pp.

Engelhart, S.E., B.P. Horton, and A.C. Kemp. 2011. Holocene sea level changes along the United States' Atlantic Coast. *Oceanography* 24(2):70–79, doi:10.5670/oceanog.2011.28.

Farrell, W.E., and J.A. Clark. 1976. On postglacial sea level. *Geophysical Journal of the Royal Astronomical Society* 46:647–667.

Fiedler, J.W., and C.P. Conrad. 2010. Spatial variability of sea level rise due to water impoundment behind dams. *Geophysical Research Letters* 37, L12603, doi:10.1029/2010GL043462.

Ivins, E.R., M.M. Watkins, D.N. Yuan, R. Dietrich, G. Casassa, and A. Rülke. 2011. On-land ice loss and glacial isostatic adjustment at the Drake Passage: 2003–2009. *Journal of Geophysical Research* 116, B02403, doi:10.1029/2010JB007607.

Kendall, R.A., J.X. Mitrovica, and G.A. Milne. 2005. On post-glacial sea level. Part II. Numerical formulation and comparative results on spherically symmetric models. *Geophysical Journal International* 161:679–706, doi:10.1111/j.1365-246X.2005.02553.x.

Kendall, R.A., K. Latychev, J.X. Mitrovica, J.E. Davis, and M.E. Tamisiea. 2006. Decontaminating tide gauge records for the influence of glacial isostatic adjustment: The potential impact of 3-D Earth structure. *Geophysical Research Letters* 33, L24318, doi:10.1029/2006GL028448.

Kopp, R.E., J.X. Mitrovica, S.M. Griffies, J. Yin, C.C. Hay, and R.J. Stouffer. 2010. The impact of Greenland melt on local sea levels: A partially coupled analysis of dynamic and static equilibrium effects in idealized water-hosing experiments. *Climatic Change* 103:619–625, doi:10.1007/s10584-010-9935-1.

Lambeck, K., A. Purcell, J. Zhao, and N.O. Svensson. 2010. The Scandinavian ice sheet: From MIS 4 to the end of the last glacial maximum. *Boreas* 39:410–435, doi:10.1111/j.15023885.2010.00140.x.

Larsen, C.F., R.J. Motyka, J.T. Freymueller, K.A. Echelmeyer, and E.R. Ivins. 2005. Rapid viscoelastic uplift in southeast Alaska caused by post-Little Ice Age glacial retreat. *Earth and Planetary Science Letters* 237:548–560, doi:10.1016/j.epsl.2005.06.032.

Latychev, K., J.X. Mitrovica, J. Tromp, M.E. Tamisiea, D. Komatistsch, and C.C. Christara. 2005. Glacial isostatic adjustment on 3-D Earth models: A finite-volume formulation. *Geophysical Journal International* 159:421–444.

Leuliette, E.W., and L. Miller. 2009. Closing the sea level rise budget with altimetry, Argo, and GRACE. *Geophysical Research Letters* 36, L04608, doi:10.1029/2008GL036010.

Love, A.E.H. 1911. *Some Problems of Geodynamics: Being an Essay to Which the Adams Prize in the University of Cambridge was Adjudged in 1911.* University Press, Cambridge, UK, 180 pp.

Marcos, M., and M.N. Tsimplis. 2007. Forcing of coastal sea level rise patterns in the North Atlantic and the Mediterranean Sea. *Geophysical Research Letters* 34, L18604, doi:10.1029/2007GL030641.

Martinec, Z. 2000. Spectral-finite element approach to three-dimensional viscoelastic relaxation in a spherical Earth. *Geophysical Journal International* 142:117–141.

Milne, G.A., and J.X. Mitrovica. 1998. Plostglacial sea-level change on a rotating Earth. *Geophysical Journal International* 133:1–19.

Milne, G.A., J.X. Mitrovica, and J.L. Davis. 1999. Near-field hydro-isostasy: The implementation of a revised sea-level equation. *Geophysical Journal International* 139:464–482.

Mitrovica, J.X. 1996. Haskell [1935] revisited. *Journal of Geophysical Research* 101:555–569.

Mitrovica, J.X., and J.L. Davis. 1995. Present-day post-glacial sea level change far from the late Pleistocene ice sheets: Implications for recent analyses of tide gauge records. *Geophysical Research Letters* 22:2,529–2,532, doi:10.1029/95GL02240.

Mitrovica, J.X., and G.A. Milne. 2002. On the origin of late Holocene sea-level highstands within equatorial ocean basins. *Quaternary Science Reviews* 21:2,179–2,190.

Mitrovica, J.X., and G.A. Milne. 2003. On post-glacial sea level: I. General theory. *Geophysical Journal International* 154:253–267.

Mitrovica, J.X., and W.R. Peltier. 1991. On postglacial geoid subsidence over the equatorial oceans. *Journal of Geophysical Research* 96:20,053–20,071, doi:10.1029/91JB01284.

Mitrovica, J.X., N. Gomez, and P.U. Clark. 2009. The sea-level fingerprint of West Antarctic collapse. *Science* 323:753, doi:10.1126/science.1166510.

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* 409:1,026–1,029.

Nakada, M., and K. Lambeck. 1989. Late Pleistocene and Holocene sea-level change in the Australian region and mantle rheology. *Geophysical Journal of the Royal Astronomical Society* 96:497–517.

Nakiboglu, S.M. 1982. Hydrostatic theory of the Earth and its mechanical implications. *Physics of the Earth and Planetary Interiors* 28:302–311, doi:10.1016/0031-9201(82)90087-5.

Peltier, W.R. 1998. Postglacial variations in the level of the sea: Implications for climate dynamics and solid-earth geophysics. *Reviews of Geophysics* 36:603–689.

Peltier, W.R. 2001. Global glacial isostatic adjustment and modern instrumental records of relative sea level history. Pp. 65–95 in *Sea Level Rise: History and Consequences*. B.C. Douglas, M.S. Kearney, and S.P. Leatherman, eds, International Geophysics Series, vol. 75. Academic Press.

Peltier, W.R. 2004. Global glacial isostasy and the surface of the Ice age Earth: The ICE-5G(VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences* 32:111–149.

Peltier, W.R. 2009. Closure of the budget of global sea level rise over the GRACE era: The importance and magnitudes of the required corrections for global glacial isostatic adjustment. *Quaternary Science Reviews* 28:1,658–1,674, doi:10.1016/j.quascirev.2009.04.004.

Rignot, E., J.L. Bamber, M.R. Van Den Broeke, C. Davis, Y. Li, W.J. Van De Berg, and E. Van Meijgaard. 2008a. Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nature Geosciences* 1:106–110, doi:10.1038/ngeo102.

Rignot, E., J.E. Box, E. Burgess, and E. Hanna. 2008b. Mass balance of the Greenland ice sheet from 1958 to 2007. *Geophysical Research Letters* 35, L20502, doi:10.1029/2008GL035417.

Riva, R.E.M., J.L. Bamber, D.A. Lavallée, and B. Wouters. 2010. Sea-level fingerprint of continental water and ice mass change from GRACE. *Geophysical Research Letters* 37, L19605, doi:10.1029/2010GL044770.

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. *Climate Dynamics*, doi:10.1007/s00382-011-1057-6.

Tamisiea, M.E., E.M. Hill, R.M. Ponte, J.L. Davis, I. Velicogna, and N.T. Vinogradova. 2010. Impact of self-attraction and loading on the annual cycle in sea level. *Journal of Geophysical Research* 115, C07004, doi:10.1029/2009JC005687.

Vinogradova, N.T., R.M. Ponte, and D. Stammer. 2007. Relation between sea level and bottom pressure and the vertical dependence of oceanic variability. *Geophysical Research Letters* 34, L03608, doi:10.1029/2006GL028588.

Vinogradova, N.T., R.M. Ponte, M.E. Tamisiea, J.L. Davis, and E.M. Hill. 2010. Effects of self-attraction and loading on annual variations of ocean bottom pressure. *Journal of Geophysical Research* 115, C06025, doi:10.1029/2009JC005783.

Wahr, J., M. Molenaar, and F. Bryan. 1998. Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE. *Journal of Geophysical Research* 103:30,205–30,229.

Wake, L., G. Milne, and E. Leuliette. 2006. 20th century sea-level change along the eastern US: Unravelling the contributions from steric changes, Greenland ice sheet mass balance and Late Pleistocene glacial loading. *Earth and Planetary Science Letters* 250:572–580, doi:10.1016/j.epsl.2006.08.006.

Willis, J., D.P. Chambers, and R.S. Nerem. 2008. Assessing the globally averaged sea level budget on seasonal to interannual timescales. *Journal of Geophysical Research* 113, C06015, doi:10.1029/2007JC004517.

Woodworth, P.L., and R. Player. 2003. The permanent service for mean sea level: An update to the 21st century. *Journal of Coastal Research* 19:287–295.

Woodworth, P.L., W.R. Gehrels, and R.S. Nerem. 2011. Nineteenth and twentieth century changes in sea level. *Oceanography* 24(2):80–93, doi:10.5670/oceanog.2011.29.

Wöppelmann, G., C. Letetrel, A. Santamaria, M.N. Bouin, X. Collilieux, Z. Altamimi, S.D.P. Williams, and B.M. Miguez. 2009. Rates of sea-level change over the past century in a geocentric reference frame. *Geophysical Research Letters* 36, L12607, doi:10.1029/2009GL038720.

Wouters, B., R.E.M. Riva, D.A. Lavallée, and J.L. Bamber. 2011. Seasonal variations in sea level induced by continental water mass: First results from GRACE. *Geophysical Research Letters* 38, L03303, doi:10.1029/2010GL046128.

Wu, P. 2004. Using commercial finite element packages for the study of earth deformations, sea levels and the state of stress. *Geophysical Journal International* 158:401–408.

Wu, P., and W.R. Peltier. 1983. Glacial isostatic adjustment and the free air gravity anomaly as a constraint on deep mantle viscosity. *Geophysical Journal of the Royal Astronomical Society* 74:377–449.

Zhong, S.J., A. Paulson, and J. Wahr. 2003. Three-dimensional finite element modeling of Earth's iscoelastic deformation: Effects of lateral variations in lithospheric thickness. *Geophysical Journal International* 155:679–695.