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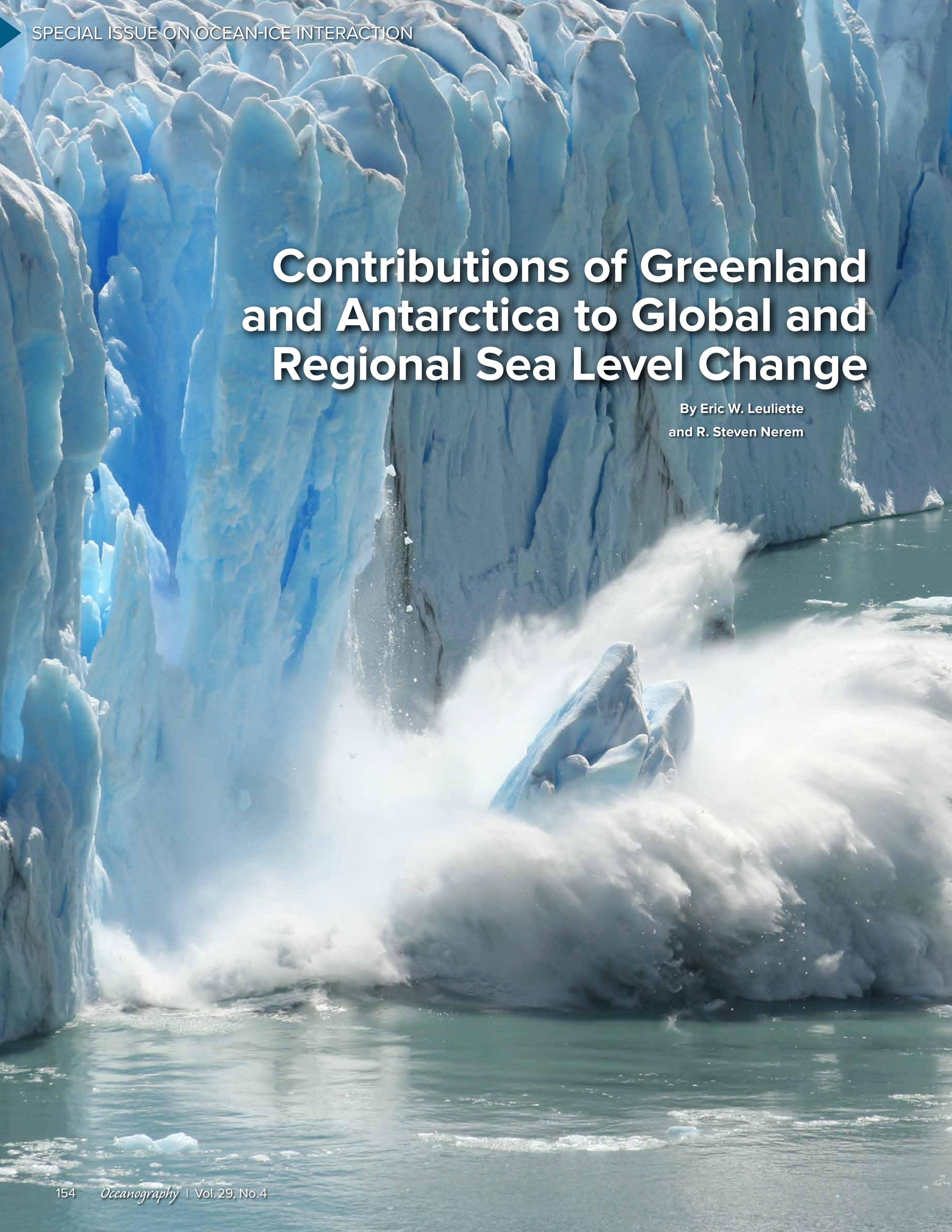

Contributions of Greenland and Antarctica to Global and Regional Sea Level Change

By Eric W. Leuliette
and R. Steven Nerem

ABSTRACT. While it is well known that the accelerating melting of the ice sheets of Greenland and Antarctica will increasingly raise global mean sea levels, it is less widely understood how the addition of meltwater from these ice sheets will affect regional patterns of sea level rise. The transfer of water mass from the ice sheets to the ocean will alter Earth's gravity field and rotation, resulting in local changes in sea levels. On time scales from months to decades, the addition of freshwater at high latitudes will alter the mean ocean circulation through a variety of mechanisms that will also alter regional rates of sea level change. The current ocean observing system, including radar and laser altimeters, satellite gravity missions, and the Argo network of profiling floats, has demonstrated the ability to close the sea level budget since 2005, confirming the contributions of ice sheets to contemporary sea level rise. The planned observing system will be capable of monitoring the regional variability of sea level change, which should help improve future projections.

INTRODUCTION

Sea level is rising around the world in response to climate change. Since 1993, global average sea level is rising at a rate of 3.3 ± 0.4 mm yr^{-1} (e.g., Leuliette and Scharroo, 2010; Nerem et al., 2010). Satellite and in situ measurements tell us that roughly one-third of this rise is due to thermal expansion, one-third to melting glaciers, and one-third to melting ice sheets in Greenland and Antarctica (Church et al., 2013). However, climate model projections suggest that Greenland and Antarctica will begin to dominate the sea level rise budget over the next century. As this happens, the ice sheets will also begin to drive regional patterns in sea level change (Church et al., 2013). In addition to societal impacts, changes in regional sea level can also impact ocean-ice interactions and accelerate the melting and retreat of ocean-terminating glaciers. Therefore, it is important to understand the role of the ice sheets in current and future sea level change. We can start by looking at the present role of the ice sheets in the observed changes in sea level.

GLOBAL MEAN SEA LEVEL VARIATIONS FROM SATELLITE ALTIMETRY

Since the launch of TOPEX/Poseidon (T/P) in October 1992, satellite altimetry has provided precise estimates of sea level change between 66°N and 66°S with 10-day temporal resolution and a point-to-point accuracy of a few centimeters. These measurements have been continued by Jason-1 (2001), Jason-2 (2008), and Jason-3 (2016). When averaged globally, these data provide estimates of global mean sea level every 10 days with an accuracy of ~4 mm (1-sigma). Figure 1 shows global mean sea level variations since the launch of T/P. While the trend over the entire 23 years is +3.3 mm yr^{-1}, there are substantial interannual and decadal variations. On interannual time scales, the variations are dominated by changes in land water storage, which themselves are largely driven by El Niño-Southern Oscillation (ENSO) variations in land-ocean precipitation and changes in ocean heat content. On average, global sea level tends to be higher during El Niño events (when ocean precipitation is greater) and lower during La Niña events (when land precipitation is greater). There is also substantial decadal variability in the time series—the rate of sea level rise is greater over the first decade (3.5 mm yr^{-1}) than over the second decade (2.7 mm yr^{-1}; Cazenave et al., 2014). It remains to be determined if this reflects errors in the data (e.g., Watson et al., 2015) or natural decadal variability. Satellite altimetry also provides estimates of the spatial variation of sea level rise over the same time period (Figure 2), although this map tends to be more influenced by decadal variability (Hamlington et al., 2016).

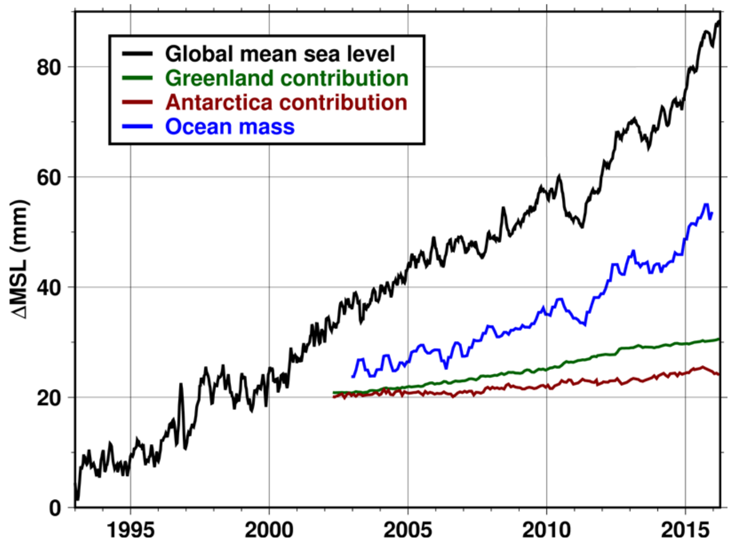

FIGURE 1. Global mean sea level variations from satellite altimetry, corrected for glacial isostatic adjustment, with seasonal variations removed, and smoothed using a 60-day boxcar filter (Leuliette and Scharroo, 2010). Also shown are global ocean mass variations computed from the Gravity Recovery and Climate Experiment (GRACE) mission (Johnson and Chambers, 2013) and the contributions of Greenland and Antarctica to global mean sea level change, also from GRACE measurements (Watkins et al., 2015).

GLOBAL OCEAN MASS VARIATIONS FROM GRACE COMPARED TO GLOBAL MEAN SEA LEVEL

Several approaches have been used to infer or directly measure changes in global ocean mass variations, sometimes referred to as the barystatic component of sea level change (Gregory et al., 2013). Changes in time-varying gravity observed from space missions, such as the Gravity Recovery and Climate Experiment (GRACE; Tapley et al., 2004), are used to directly observe variations in ocean mass after removing the variations in atmospheric mass and accounting for the effects of glacial isostatic adjustment. Launched in 2002, GRACE has also been successfully used to monitor changes in continental hydrology, particularly over the Greenland and Antarctic Ice Sheets (Figure 1).

For ocean mass, the seasonal maximum exchange of freshwater from land to ocean occurs in late Northern Hemisphere summer, and the barystatic component of sea level is dominated by a seasonal signal that is in phase with total sea level, but with a much larger amplitude, about 7 mm versus 4 mm (Chambers et al., 2004).

GRACE observations confirmed that the significant decrease in mean sea level from 2010 to the middle of 2011 was due to a large increase in water storage in northern South America and Australia, which was initially linked to the strong La Niña during that period (Boening et al., 2012). Further study indicated that the longevity of the anomaly, however, could be attributed to water storage in closed drainage basins in Australia caused by anomalous rainfall associated with a combination of La Niña, Indian Ocean Dipole, and Southern Annular Mode climates modes (Fasullo et al., 2013).

CLOSURE ANALYSIS USING ARGO DATA

For decadal and longer time scales, global mean sea level change results from two major processes that alter the total volume of the ocean: steric and mass changes. Changes in the total heat content and salinity produce density (steric) changes. The exchange of water between the ocean and other reservoirs (glaciers, ice caps, and ice sheets, and other terrestrial water reservoirs) results in mass variations. With sufficient observations of sea level, ocean temperatures and salinity, and either land reservoirs or ocean mass, the global mean sea level budget can in principle be closed. Expressed in terms of globally averaged height, contributions to the total budget of global mean sea level are

$$SL_{total} = SL_{steric} + SL_{mass},$$

where SL_{total} are variations in total sea level, SL_{steric} is the steric component of sea level, and SL_{mass} is the ocean mass/barystatic component.

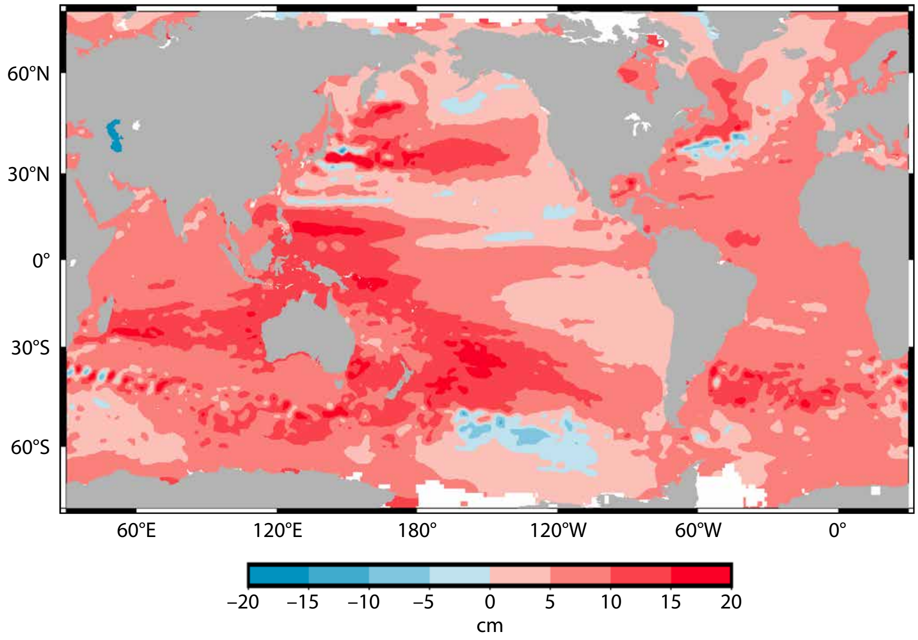

FIGURE 2. Sea level change during 1993–2015 observed by satellite altimetry.

Estimates of steric sea level variations in the upper ocean can be obtained from the global array of autonomous hydrographic profiling floats deployed by the Argo project beginning in 2000. In November 2007, the array surpassed 3,000 active floats, achieving a sampling of both temperature and salinity approximately every three degrees of latitude and longitude every 10 days. Now, with more than 3,900 active floats in June 2016, Argo creates a more uniform distribution than historical observations, providing dramatically improved coverage of the upper 700 m and increasingly the upper 2,000 m of the global ocean, particularly in the Southern Hemisphere. On a monthly basis, global mean steric sea level change in the upper ocean can be measured with errors around 3 mm (errors will decrease over time as more floats sample to 2,000 m with fewer biases). Some studies (e.g., Leuliette and Willis, 2011) suggest that Argo data are best suited for global analyses of upper-ocean steric changes only after 2005 due to a combination of interannual variability and significant biases when using earlier data that is based on sparser and shallower sampling.

On a monthly basis, the sum of the steric component estimated from Argo and the barystatic component from GRACE agree with total sea level from Jason-1 and Jason-2 within the estimated uncertainties (Figure 3), with the residual difference having an RMS of 1.6 mm for the period January 2005 to December 2015 (update of Leuliette, 2015) after two-month smoothing has been applied. Direct measurement of ocean warming above 2,000 m depth explains about one-third (1.1 mm yr^{-1})

of the observed rate of global mean sea level rise (3.3 mm yr^{-1}; Figure 3). The rate of GRACE-derived global barystatic sea level change (2.3 mm yr^{-1}) accounts for the remaining two-thirds of sea level rise. Direct observations accounting for systematic uncertainties find that the deep ocean (below 2,000 m) contributes only −0.13 ± 0.72 mm yr^{-1} to global sea level rise (Llovel et al., 2014).

CONTRIBUTIONS OF GREENLAND AND ANTARCTICA TO GLOBAL MEAN SEA LEVEL

Measurements from the GRACE mission provide one of the most unambiguous methods for determining how much Greenland and Antarctica are contributing to sea level change. These measurements show (Figure 1) that Greenland is currently contributing 0.78 ± 0.08 mm yr^{-1} to global mean sea level (GMSL) and Antarctica is adding another 0.33 ± 0.22 mm yr^{-1} (Rignot et al., 2011; Shepherd et al., 2012). The uncertainty is driven primarily by errors in the models for glacial isostatic adjustment (GIA) used to correct the GRACE data. Currently, these errors are greater for Antarctic ice mass loss than for Greenland. In addition, GRACE has detected a significant acceleration of ice mass loss in Greenland and West Antarctica. While other techniques (e.g., InSAR, laser altimetry, models) can be used to measure ice mass loss in Greenland and Antarctica, the results from these techniques are in broad agreement with the GRACE results (Shepherd et al., 2012).

While Greenland and Antarctica account for one-third of the current trend in GMSL, the ice sheets are a relatively small component of the interannual variability in GMSL, which is driven by changes in land water storage. The non-ice covered land areas are continually exchanging water with the ocean in response to changes in precipitation. The liquid water variations have much larger interannual mass variability than the frozen water.

REGIONAL SEA LEVEL PATTERNS DUE TO GREENLAND AND ANTARCTICA

It has been known for many years that large changes in ice mass stored on land will cause changes to Earth's gravity field and shape that will cause regional changes in relative and absolute sea level change (e.g., Mitrovica et al., 2001). When one of the ice sheets (say, Greenland) melts, sea level along the coast drops because there is less gravitational attraction provided by the ice (in other words, Earth's geoid changes, and the ocean's surface readjusts to the new geoid). In addition, the unloading of Earth's crust under Greenland causes a viscoelastic rebound, resulting in a drop in relative sea level along Greenland's coasts. Actually, this phenomenon affects not only Greenland but also regional sea levels on a global basis, and it includes changes in Earth's rotation in response to the mass redistribution caused by the ice melt. Figure 4 shows the regional sea level "fingerprints" (Adhikari et al., 2015) that have resulted from the melting of Greenland and Antarctica observed by GRACE since 2002. Even though the time frame is shorter, this regional sea level change is still much smaller than what is observed in satellite altimetry, because the altimetry is still dominated by ENSO, the Pacific Decadal Oscillation, and other phenomena (compare Figures 2 and 4, noting the scales are different). In the future, the ice sheets are expected to dominate sea level change, and the regional patterns shown in Figure 4 will describe the majority of the long-term variability in satellite-observed sea level change.

While the melting of Greenland and Antarctica doesn't cause much sea level change near the source of the ice loss, the melting of Antarctica can cause large sea level changes around Greenland, and vice versa. So in some respects, the two ice sheets on opposite sides of the world are tied together because sea level rise caused by one ice sheet can impact the interactions of the ocean with the other ice sheet. This will affect how much heat the ocean delivers to the outlet glaciers surrounding these ice sheets.

IMPACTS OF GREENLAND AND ANTARCTIC MELTWATER ON SEA LEVEL

The addition of freshwater into the ocean from the projected acceleration in ice sheet and glacier meltwater will result in both an increasing rate of global mean sea

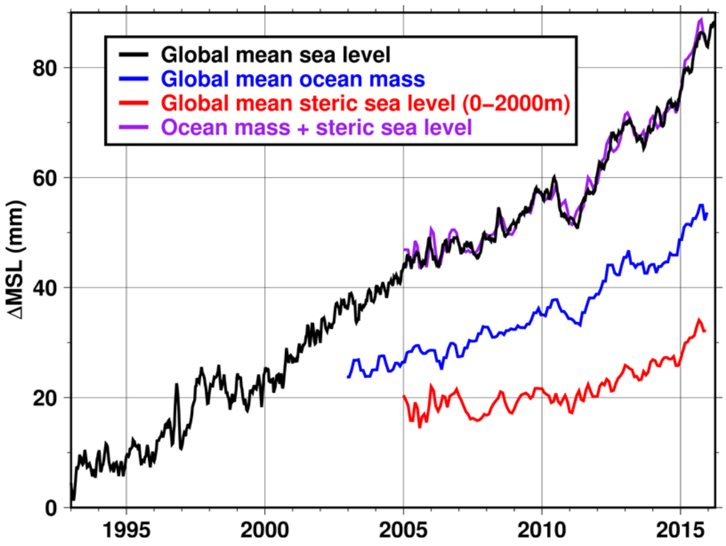

FIGURE 3. Comparisons of global mean sea level from the NOAA Laboratory for Satellite Altimetry (Leuliette and Scharroo, 2010), global mean ocean mass from GRACE (Johnson and Chambers, 2013), and steric (density) sea level from Argo (Roemmich and Gilson, 2009), with seasonal variations removed and two-month smoothing applied.

level rise and an alteration in the regional pattern of sea level rise. While this addition of freshwater to the ocean occurs mainly at high latitudes along the coasts of Greenland and Antarctica, the effect of this added mass is communicated around the entire ocean nearly immediately, within days through barotropic waves, resulting in a rise in global mean sea level (Gower, 2010; Kopp et al., 2010; Lorbacher et al., 2012). Each 360 gigatons of meltwater introduced into the ocean raises global mean sea level by 1 mm.

Dynamic changes in regional patterns of sea level rise from meltwater will occur at longer time scales through a variety of mechanisms. An increase in freshwater from melting ice in Greenland will result in a basin-wide steric response in the North Atlantic on time scales of a few years via boundary waves, equatorial Kelvin waves, and westward-propagating baroclinic Rossby waves (Stammer, 2008). Model simulations of the complete baroclinic adjustment of this injection of freshwater throughout the global ocean project that it may take as long as 500 years. Additionally, the adjustment of the ocean to the input of high-latitude meltwater will involve atmospheric and oceanic teleconnections, which can potentially trigger an ENSO-like response in the Pacific within just a few months (Agarwal et al., 2014). On time scales longer than a decade, freshwater input to the North Atlantic is expected to raise sea level in the Arctic Ocean and reverse the Bering Strait throughflow, transporting colder, fresher water from the Arctic Ocean into the North Pacific (Hu et al., 2010) and causing a relative cooling in the North Pacific (Okumura et al., 2009). Meltwater forcing in the North Atlantic also causes weakening of the Atlantic meridional overturning circulation, which in turn causes dynamic changes of sea level in the North Atlantic, particularly in its northwestern region (Srokosz et al., 2012). Model results suggest that the combination of this dynamic sea level rise and the global mean rise could lead to occurrence of the fastest and largest sea level rise along northeastern North America, compensated by a drop in sea level in the Southern Ocean (Yin et al., 2009; Pardaens et al., 2011).

DISCUSSION

During the last decade, advancements in the ocean observing system—satellite altimeters, hydrographic profiling floats, and space-based gravity missions—have allowed the sea level budget to be assessed with unprecedented accuracy from direct, rather than inferred, estimates. Balancing the sea level budget is critical to understanding recent and future climate change as well as balancing Earth's energy budget and water budget. In particular, the GRACE mission has allowed for the complete tracking of water mass movement throughout the Earth system, including measuring ice sheet mass balance and observing the mass flux in the ocean.

While continued warming of the ocean over the twenty-first century will continue to cause sea level rise from thermal expansion, loss of ice from Greenland and Antarctica, already the dominant contribution to total rise, is expected to continue to accelerate. Over the last decade, the spatial pattern of sea level change has been dominated by steric changes and wind-driven redistribution, but as the contribution from ocean mass becomes larger, very different patterns are expected (Figure 4).

The sea level climate data record from altimetry will continue as new reference missions (Jason-CS/Sentinel-6) with sufficient instrument stability to monitor sea level rise are planned for launch in 2020 and 2026. The instruments on the GRACE satellites have operated several years beyond their nominal mission design. In order to prevent or shorten a significant gap in observations, a follow-on mission is planned for launch in late 2017. The Argo array will need continual replacement of floats to maintain the network, as well as the development and deployment of Deep Argo floats capable of monitoring changes in the abyssal ocean.

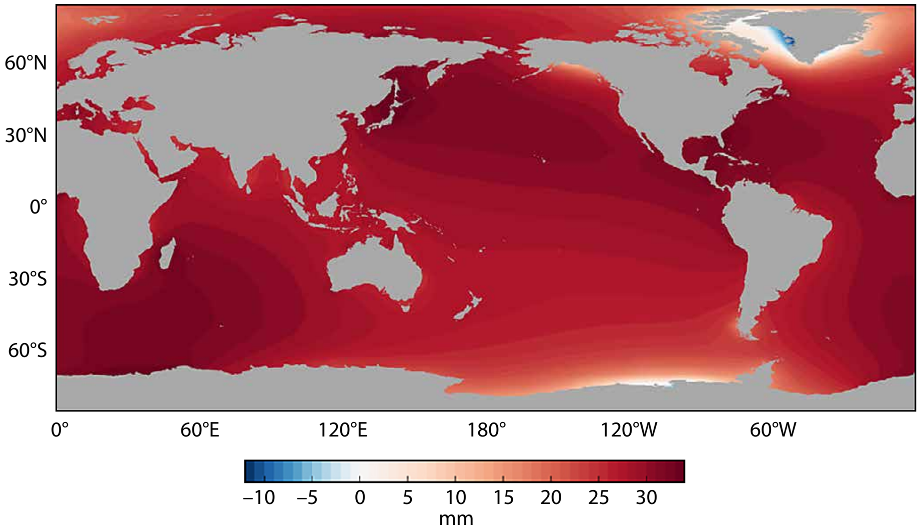

FIGURE 4. Mass contribution to absolute regional sea level change (land motion is not included) over 2002–2016 as observed by GRACE. GRACE-observed mass changes over the land areas were used to compute sea level "fingerprints" using the methods of Adhikari et al. (2015).

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