BY ERIC W. LEULIETTE AND JOSH K. WILLIS

Balancing the Sea Level Budget

ABSTRACT. Sea level rise is both a powerful impact of and indicator for global warming and climate change. Observing sea level change, as well as its causes, is therefore a top priority for scientists and society at large. By measuring the ocean's temperature, salinity, mass, and surface height, the relative sources of recent sea level rise can be discerned. With these observations, sea level change is determined in terms of total sea level and its two major components, ocean mass and steric (density-related) sea level. The sea level budget is closed when the sum of the independent components agrees with measurements of total sea level, indicating that the observations can be used to interpret the causes of sea level change. While nearly global monitoring of sea level from space-based radar altimeters has been available since the early 1990s, satellite gravity missions capable of weighing changes in ocean mass have been available for less than 10 years. Even more recently, the Argo array of profiling floats achieved a level of coverage that now allows assessment of global sea level change due to temperature and salinity in the upper 2,000 m of the ocean. Only during the overlapping period of all three observing systems can the sea level budget be directly addressed by observations.

INTRODUCTION

As we anticipate the next 100 years of humanity's impact on the climate, global sea level rise stands out as both an impact and an indicator. The ocean is the primary reservoir for the storage of extra heat in the climate system as well as the water mass lost from melting ice sheets and glaciers. In this sense, sea level rise is a powerful indicator of human influence on the climate. With hundreds of millions of people living in coastal zones worldwide, the rising seas will exact their own toll as societies attempt to adapt (see Nicholls, 2011, in this issue). Given the possibility of further acceleration over the next century (see Church et al., 2011, in this issue), it seems obvious that we need a robust system for measuring sea level rise, as well as its causes.

Fortunately, the past decade has seen a revolution in observations of sea level rise and its causes. We now have observing systems that are capable of measuring global sea level change with an accuracy of a few millimeters, as well as systems that can directly measure the causes of this change. Elsewhere in this issue, Woodworth et al. (2011) describe observations of sea level rise over the past 100 plus years, including evidence for an acceleration during the twentieth century. In addition, Tamisiea and Mitrovica (2011, in this issue) explain the geophysical contributions to sea level change, such as the ongoing deepening of the ocean basins, and how corrections are applied for them in various types of observations. Here, we consider the causes of sea level rise during the modern era and examine our ability to observe them.

The most socially relevant quantity in the study of sea level is the local, relative rate change at the coast (Nicholls, 2011, in this issue). The primary quantity of interest for climate scientists, however, is the change in volume of the global ocean. An accounting of the major processes that alter this volume is often referred to as an assessment of the sea level budget. In practice, the ocean's total volume is not directly measured. Instead, changes in volume are inferred by observing variations in globally averaged sea level, and modeling the changes in ocean-basin shape that are driven by geophysical processes. In a sea level budget, the individual causes of volume change can be expressed as two separate physical processes, density (steric) changes and water exchange between the ocean and continents. Changes in ocean temperature and salinity produce density changes. Water exchange between the ocean and other reservoirs (such as glaciers, ice caps, ice sheets, and groundwater) results in variations in the ocean's total mass. To meaningfully interpret the causes of sea level change during a particular period, the budget must be closed. In other words, changes in observed sea level should be equal to the sum of the changes attributable to density changes and water mass exchange. This closure implies that the observations are complete and accurate.

Quantifying the causes of sea level rise individually is important for predicting how much sea level will rise in the future, as well as understanding the magnitude of the changes that have already occurred. The steric changes, for example, are dominated by ocean warming and reflect changes in the net amount of heat stored there. Because over 90% of the excess heat trapped by greenhouse gases winds up warming the ocean (Bindoff et al., 2007), this heat storage reflects the net radiative forcing applied to Earth's climate. Furthermore, if the rate of global sea level rise continues to accelerate over the next century, it is likely that the primary cause will be increased melting and mass loss from the ice sheets in Greenland and Antarctica (see Church et al., 2011, in this issue; Pfeffer, 2011, in this issue).

The global sea level rise budget for the last half of the twentieth century is reasonably well understood. For example, a recent analysis (Domingues et al., 2008) found the budget from 1961–2003 to be closed within estimated uncertainties. For that period, the steric (0.7 ± 0.5 mm yr^{-1}) and mass (0.8 ± 0.5 mm yr^{-1}) contributions are approximately equal. The sum of the two components (1.5 ± 0.7 mm yr^{-1}) agrees with the estimate for the rate of total sea level (1.6 ± 0.2 mm yr^{-1}).

Historical budget analyses such as these are limited by significant uncertainties, largely due to instrument limitations and sparse sampling or, in some cases, biases in the data. Multidecadal records of total sea level are only available at tide gauges, meaning that measurements will only be on coasts and islands. Prior to the satellite gravity era, long-term estimates of ocean mass had to be inferred by totaling the changes in all aspects of land-based water storage, using limited records of ice sheets, glaciers, reservoirs, and groundwater. Steric sea level is available only where hydrographic (temperature and salinity) profiles were cast. In the last century, most hydrographic profiles were made for specific applications, and the instrumentation and sampling were not designed for climatic studies. Biases have been identified in one of the most widely used instruments in the historical data set, expendable bathythermographs (XBTs). Attempts to correct these biases are ongoing, but early efforts (Domingues et al., 2008; Ishii and Kimoto, 2009; Levitus et al., 2009; Gouretski and Reseghetti, 2010) have reduced the decadal variability in estimates of thermosteric sea level rise and ocean heat content and brought them into better agreement with coupled climate simulations (Domingues et al., 2008).

THE OCEAN OBSERVING SYSTEM

International collaborations in recent years have implemented a global ocean observing system that monitors the variability of not only total sea level but also the major contributions to sea level change. The combination of contemporaneous measurements from this observing system—satellite altimeters, hydrographic profiling floats, and space-based gravity missions—allows the observational sea level budget to be assessed from direct, rather than inferred, estimates.

Total sea level has been continuously monitored since 1992 by satellite radar altimeters (TOPEX/Poseidon, Jason-1, Jason-2, and Envisat) with sufficient accuracy and stability to monitor global trends in total sea level (Figure 1). Estimates of global mean sea level rise from 1992 to 2010 are higher, 3.3 mm yr^{-1} (Leuliette and Scharroo, 2010; Nerem et al., 2010; Cazenave and Llovel, 2010; Beckley et al., 2010), than the late twentieth century rate, 1.8 mm yr^{-1} (Church and White, 2006). Sea level rise estimates from altimetry can be independently verified using a network of tide gauges (Mitchum, 2000). Tide-gauge calibrations for the combined 18-year record show that any drifts in TOPEX/Poseidon, Jason-1, and Jason-2 (-0.1 ± 0.4 mm yr^{-1}) are consistent with no trend. Based on the tide-gauge calibration, the errors in each

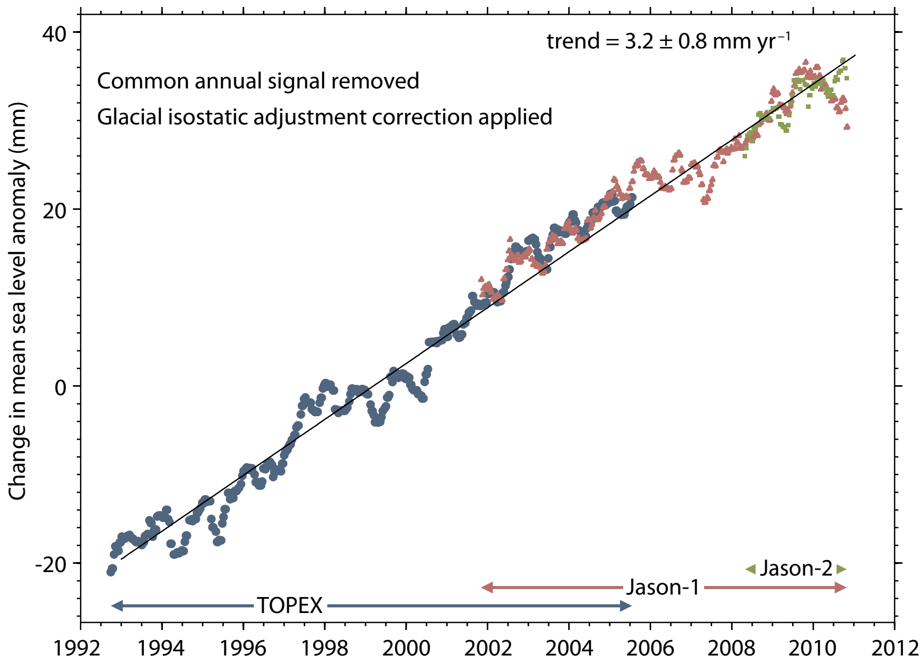

Figure 1. Global mean sea level change from TOPEX/Poseidon, Jason-1, and Jason-2 has had a relatively consistent trend of 3.2 ± 0.8 mm yr^{-1} over 18 years. A common annual signal from a least squares fit has been removed, an adjustment for glacial isostatic adjustment has been applied, and the time series has been smoothed with a 60-day boxcar. The error bounds represent the 95% confidence interval obtained from the least squares fit and the uncertainty in drift estimate from tide gauges.

10-day sample of global mean sea level for Jason-1 and Jason-2 are estimated to be 4 mm.

Steric sea level changes are largely a response to changes in temperature with local contributions from salinity. Sustained estimates of steric sea level variations in the upper ocean can now be obtained from the global array of Argo project autonomous hydrographic profiling floats that measure temperature and salinity. Argo deployments began in 2000, and in November 2007, the planned array of 3,000 floats was achieved. The Argo array creates a more uniform distribution than historical observations with sampling at approximately every three degrees of latitude and longitude, providing dramatically improved coverage of the upper 2,000 m of the global ocean, particularly in the Southern Hemisphere (Lyman and Johnson, 2008). On a monthly basis, the global mean steric sea level change in the upper ocean can be found with errors around 3 mm. The global mean contribution of steric sea level rise in the abyssal ocean (below 4,000-m depth) and in the deep (1,000–4,000 m) Southern Ocean is around 0.1 mm yr^{-1}, although this contribution may be as much as 1 mm yr^{-1} locally in the Southern Ocean (Purkey and Johnson, 2010).

Tracking water mass movements at unprecedented spatial scales has been possible since the launch in 2002 of GRACE (Gravity Recovery and Climate Experiment), a pair of satellites that monitor changes in Earth's gravity field. Once corrected for the motion of the mass in the atmosphere and the solid Earth, the remaining changes in the gravity field are the result of the redistribution of water mass on Earth's surface. At roughly monthly intervals, GRACE can provide observations of terrestrial water storage, the exchange of water between the ocean and the continents, and the redistribution of mass within the ocean. The largest signals in the gravity field come from the seasonal variations of water stored on the continents as snow, ice, and water in rivers, reservoirs, and underground. Using GRACE measurements alone, for regions near coasts, it is impossible to distinguish whether gravity variations are influenced by water changes on land or in the ocean. Therefore, when analyzing the gravity field for mass variations in the ocean, techniques must be used to prevent the large land hydrology signal from being misinterpreted as changes in ocean mass. Several methods can be employed to reduce this ambiguity, usually called leakage error, including masking out the ocean near coasts, using special averaging functions, mass concentration (mascon) methods, and removing a hydrology model from the fields. Based on these leakage errors and GRACE instrument errors, the error bounds for monthly changes in the global mean of ocean mass anomalies are roughly 2 mm.

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BUDGET CLOSURE

Studies using altimetry, Argo, and GRACE data show the annual signal of the recent sea level budget to be closed (Willis et al., 2008, Leuliette and Miller, 2009; Cazenave et al., 2009). The observed seasonal variation in global mean sea level, which has an amplitude of about 4 mm, reaches a maximum in late Northern Hemisphere summer (see Figure 2).

For ocean mass, the seasonal maximum exchange of freshwater from land to ocean occurs in late Northern Hemisphere summer, and therefore the seasonal ocean mass signal is in phase with total sea level, but with a much larger amplitude, about 7 mm (Chambers et al., 2004). When water is added to the ocean in Northern Hemisphere summer, global sea level adjusts, rapidly resulting in a relatively uniform spatial pattern for the seasonal ocean mass signal, as compared to the seasonal steric signal, which has very large regional amplitudes (Chambers, 2006).

The seasonal signal of the global mean of the steric component has an amplitude roughly half that of the ocean mass component (~ 4 mm). In contrast to annual variations in ocean mass, the steric sea level variations largely cancel between the Northern and Southern Hemispheres because the seasonal heating cycle in each hemisphere has an opposite phase. Because most of the ocean is in the Southern Hemisphere, the seasonal maximum in the steric component occurs in late Southern Hemisphere summer, when heat storage in the majority of the ocean peaks (Figure 2). Note that although cancellation in the global average causes the steric annual cycle to be small, the seasonal cycles in the hemispheric average of steric height are actually much larger than any of the globally averaged seasonal signals.

Initial studies of the sea level budget over a four-year period starting in mid 2003 found that the budget did not close to better than 3 mm yr^{-1} in terms of its secular trend, which was more than the expected uncertainties. This lack of closure suggested a systematic drift in one or more of the observing systems (Willis et al., 2008; Chang et al., 2010). For a slightly different period (2004–2008) that included significantly better Argo coverage of the Southern Hemisphere, Leuliette and Miller (2009) and Cazenave et al. (2009) found that the observational sea level rise budget could be closed within applicable uncertainties. However, these studies differed significantly in their estimates of the partition of steric and mass contributions, principally because of different choices of glacial isostatic adjustment (GIA) models used to account for geophysical changes in the shape of the ocean basins.

GIA is the response of the solid Earth and ocean to past changes in the ice sheets, largely due to the slow viscous response of Earth's mantle as it rebounds after the disappearance of the giant ice sheets from the last ice age. This process involves a variety of changes in Earth's crust, rotational axis, and gravity field, as explained in detail in Tamisiea and Mitrovica (2011, in this issue).

In the global average, GIA causes a small net sinking of the ocean floor relative to Earth's center, which, if the sea surface did not change, would imply a small secular increase in volume. Thus, to account for GIA effects, +0.3 mm yr^{-1} must be added to the rate of sea level rise observed by altimeters so that the estimate reflects the change in ocean volume (Douglas and Peltier, 2002). Similarly, a GIA signal must be removed from GRACE observations to isolate ocean mass variations. While the GIA signal for altimetry reflects changes in ocean volume, the GIA correction for ocean mass variations from GRACE accounts for mass redistribution from crustal motion, which produces significantly larger apparent changes in terms of equivalent water height (see Tamisiea and Mitrovica, 2011, in this issue for further discussion). While Willis et al. (2008) and

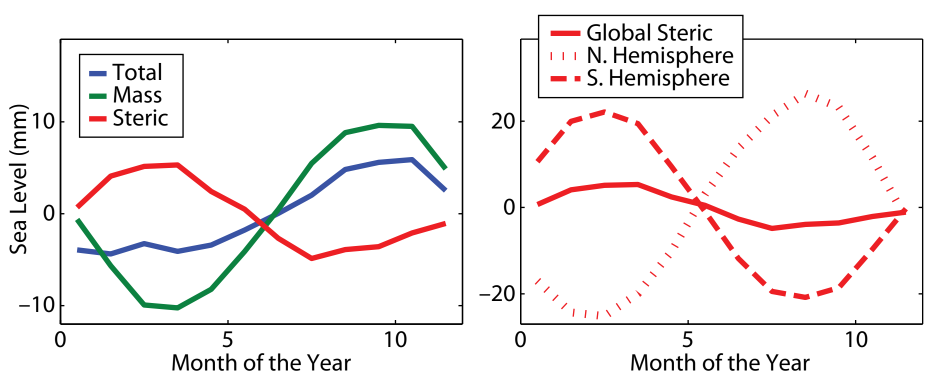

Figure 2. The seasonal cycle of globally averaged sea level and its components (left panel). Strong cancellation occurs in the global average of the steric signal due to out-of-phase seasonal heating between the hemispheres. The right panel shows the steric signal in each hemisphere. Note the difference in the vertical scale.

Leuliette and Miller (2009) applied a near +1 mm yr^{-1} correction based on GIA model predictions developed by Paulson et al. (2007), Cazenave et al. (2009) adopted a correction of +2 mm yr^{-1} based on Peltier (2009). This switch in corrections sparked considerable debate over the appropriate GIA correction for GRACE (Milne et al. 2009). Recently, Chambers et al. (2010) suggested that the Paulson et al. (2007) model is more appropriate for correcting global ocean mass calculations from GRACE.

With several improvements, recent analyses of the sea level rise budget found closure at the 0.2 mm yr^{-1} level using time series starting in 2005 when nearly uniform coverage of Argo data was first available (Chambers and Willis, 2010; Leuliette and Miller, 2010). Since the initial budget studies, additional pressure corrections for certain types of Argo floats have been made available and a newer version of Jason-1 data was released. These corrections have substantially improved closure of the sea level budget. For example, an update of Leuliette and Miller (2009) using the latest versions of the data shows that the rate of total sea level rise is 1.5 ± 0.9 mm yr^{-1} for the period January 2005 to September 2010. The combination of the steric (0.5 ± 0.5 mm yr^{-1}) and ocean mass components (1.1 ± 0.6 mm yr^{-1}) for this period is 1.6 ± 0.6 mm yr^{-1} (Figure 3). The error bounds represent the 95% confidence interval obtained from the least squares fit.

The above numbers represent globally averaged changes in sea level with magnitudes on the order of millimeters per year. Regional patterns of sea level change, however, are many times larger and can be extremely complex. Steric sea level change is the dominant contributor to the spatial trend patterns observed for total sea level (Figure 4). While the global ocean has been gaining mass from the continents during this period, the Indian Ocean continues to show a net loss of mass to the other basins (Chambers and Willis, 2009).

It is important to note that results of recent studies of the observational sea level budget are not truly global, but are limited to the region where all three observing systems are valid. The analyses to date have been limited to the Jason ground track coverage between 66°S and 66°N, regions where Argo has profiled 900 m or deeper, and areas away from coasts in order to limit potential leakage of land hydrology into the GRACE gravity signals. For the 18-year sea level record from altimetry, the rate of sea level rise is close to the same value as for the entire ocean (Prandi et al., 2009). However, for the shorter recent period over which data availability makes the budget analysis feasible, the trend can be slightly different. For example, for January 2005 to September 2010, total sea level rise measured by the Jason-1 and Jason-2 altimeters is 2.2 ± 0.8 mm yr^{-1}, somewhat higher than the rise in the area used for the budget. In particular, the regional seas surrounding Indonesia exhibit a large rise during 2005–2010 that significantly changes the trend when this area is excluded from the budget analyses (Han et al., 2010).

THE FUTURE OF THE OBSERVATIONAL SEA LEVEL BUDGET

Because of both uncertainties in the observational systems and interannual variations, it has been estimated that

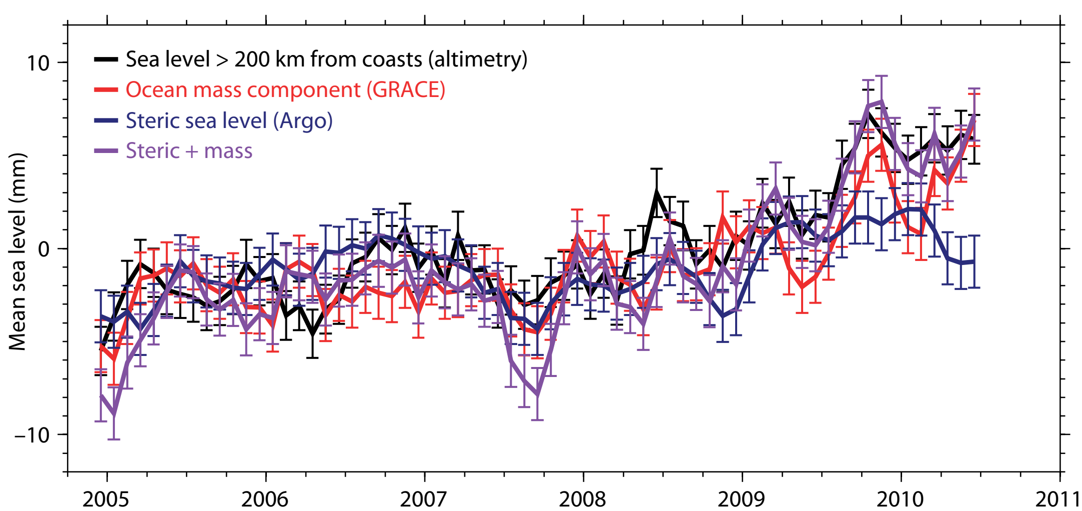

Figure 3. Monthly estimates from Jason-1 and Jason-2 of global mean sea level for areas greater than 200 km from the coast (black), which are in general agreement with the sum (purple) of the ocean mass component from the Gravity Recovery and Climate Experiment, GRACE (red), and the steric component of the upper 900 m from Argo (blue). Seasonal signals have been removed and smoothed with a three-month running mean. The error bars are one standard error.

a minimum of 10 years is necessary to meaningfully interpret global trends in sea level rise and its components (Nerem et al., 1999). Surprisingly, sea level rise since the early 1990s has progressed at a relatively consistent rate (see Figure 1) despite evidence of acceleration in the melting of mountain glaciers and ice sheets in Greenland and Antarctica. The resulting acceleration in the rate of ocean mass increase may have been compensated by a decrease in the rate of steric rise due to thermal expansion. However, the heat required to raise global sea level by 1 cm is 40 to 70 times greater than the heat required to melt an equivalent amount of land ice. Therefore, a simple compensation between thermal expansion and ice melt in the presence of a constant planetary heating rate can be ruled out by energy considerations.

Continued observation of global sea level and its causes will remain an important observational priority. Warming over the next century will continue to cause thermal-expansion-related sea level rise, but the dominant contribution will likely be loss of ice from the continents of Greenland and Antarctica. As Figure 4 shows, the patterns of sea level change over interannual time scales are dominated by steric changes, but as the contribution from ocean mass becomes larger, very different patterns are expected (see Tamisiea and Mitrovica, 2011, in this issue). Global warming is also expected to drive changes in ocean circulation, such as the Atlantic meridional overturning, that would result in substantial regional changes in steric sea level (Hu et al., 2009). Projecting regional rates of future sea level rise will require careful and comprehensive assessments of factors such as these.

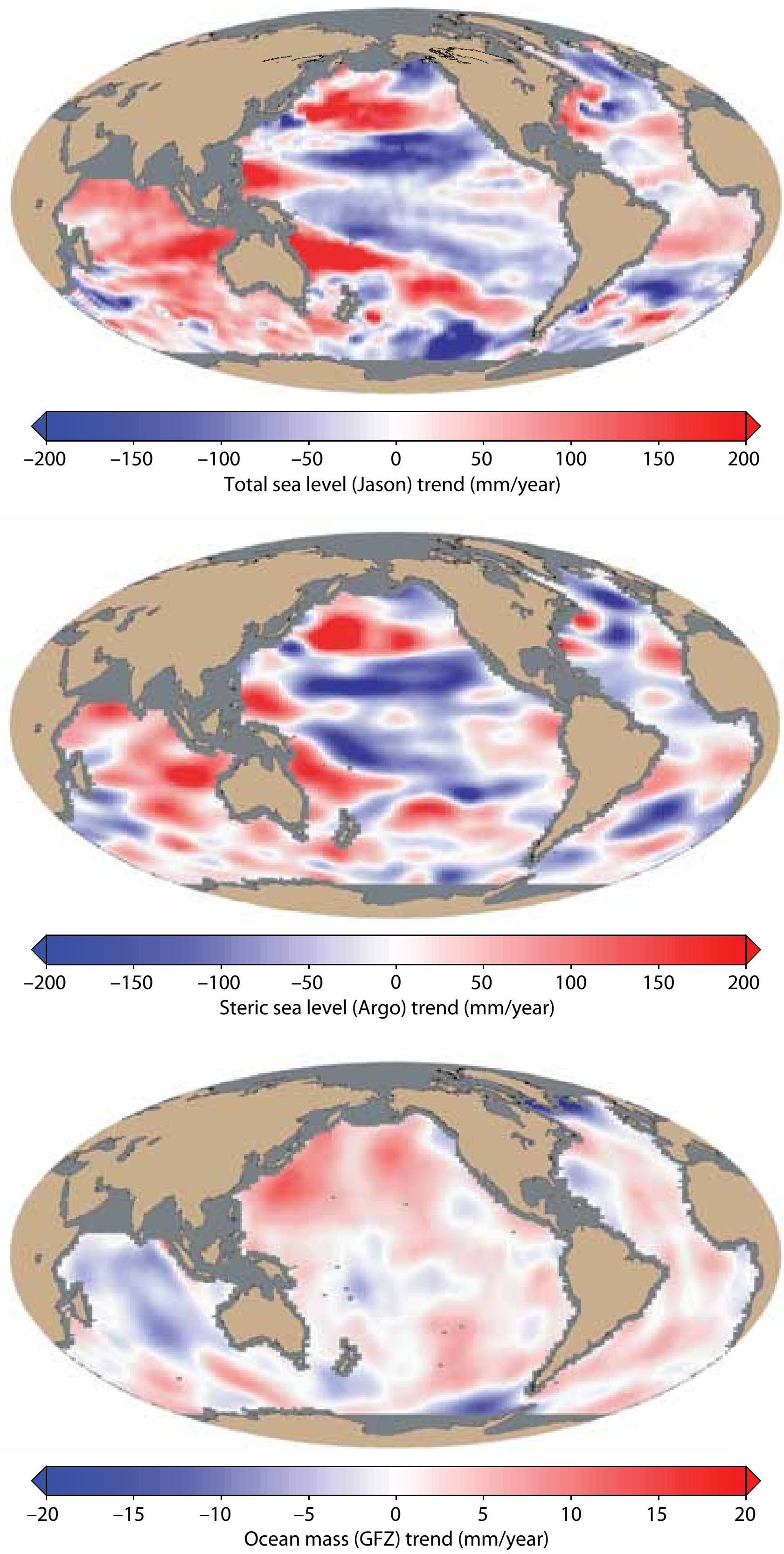

Figure 4. Spatial distribution of the trends from January 2005 through September 2010 in (top) total sea level from Jason-1 and Jason-2, (middle) steric sea level from Argo, and (bottom) ocean mass from GFZ GRACE fields in terms of equivalent sea level.

Such efforts will undoubtedly occupy researchers for many years to come, and global, accurate observations of steric sea level, ocean mass, and total sea level will be central to achieving any fidelity in such projections.

The systematic errors discovered in the early sea level budget analyses underscore the need for the continual examination of satellite and in situ data as well as the need for independent observing systems such as multiple satellite altimeters, the tide-gauge network, Argo, and GRACE. Further improvements in GIA modeling and reference frames (Collilieux and Wöppelmann, 2011) are also needed to reduce the errors in the budget and increase the certainty of the long-term rates of rise. Investigations of the observational budget on basin scales (e.g., Llovel et al., 2010; Chang et al., 2010) suggest that even longer observational periods will be necessary to confidently understand spatial variability in the secular trend budgets.

It is clear that maintaining global systems for observing sea level rise and determining its causes is necessary as the planet continues to adjust to the warming climate. The sea level climate data record from altimetry will continue with new reference missions such as Jason-3, planned for launch in 2013, that will allow for a one-year calibration with Jason-2. The instruments on the GRACE satellites have operated several years beyond nominal mission design, and efforts to extend the lives of their batteries now restrict the months when observations can be made. In order to prevent or limit a significant gap in observations, a follow-on mission will need to be on orbit soon.

> "MAINTAINING GLOBAL SYSTEMS FOR OBSERVING SEA LEVEL RISE AND ITS CAUSES IS NECESSARY AS THE PLANET CONTINUES TO ADJUST TO THE WARMING CLIMATE."

New floats continue to be added to the Argo array to maintain the target of 3,000 operating instruments.

Despite efforts to maintain them, there are still limitations to the current observing systems. Coverage of the ice-covered and marginal seas is not possible with the current generation of Argo floats, and there is no systematic network for measuring steric changes in the deep ocean. Challenges also remain for altimeter measurements poleward of the 66° turning latitude of the reference missions and in regions covered by sea ice. Finally, leakage of hydrologic and ice melt signals complicate interpretations of gravity signals observed by GRACE in coastal areas. While these regions are expected be relatively small contributions to the global sea level budget, efforts to address these limitations will continue, as the observing systems are extended and expanded.

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