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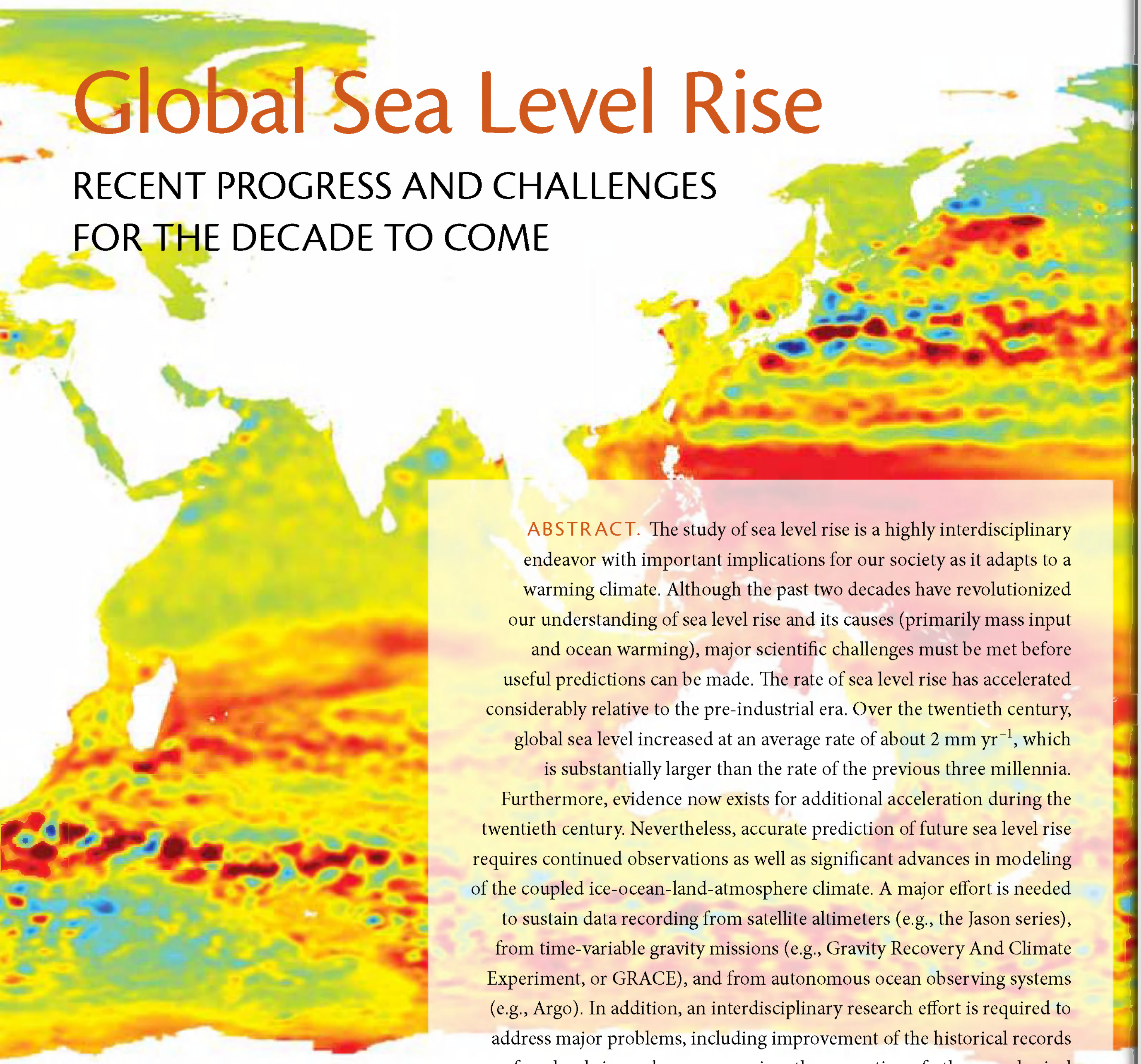

Global Sea Level Rise

RECENT PROGRESS AND CHALLENGES FOR THE DECADE TO COME

ABSTRACT. The study of sea level rise is a highly interdisciplinary endeavor with important implications for our society as it adapts to a warming climate. Although the past two decades have revolutionized our understanding of sea level rise and its causes (primarily mass input and ocean warming), major scientific challenges must be met before useful predictions can be made. The rate of sea level rise has accelerated considerably relative to the pre-industrial era. Over the twentieth century, global sea level increased at an average rate of about 2 mm yr^{-1}, which is substantially larger than the rate of the previous three millennia. Furthermore, evidence now exists for additional acceleration during the twentieth century. Nevertheless, accurate prediction of future sea level rise requires continued observations as well as significant advances in modeling of the coupled ice-ocean-land-atmosphere climate. A major effort is needed to sustain data recording from satellite altimeters (e.g., the Jason series), from time-variable gravity missions (e.g., Gravity Recovery And Climate Experiment, or GRACE), and from autonomous ocean observing systems (e.g., Argo). In addition, an interdisciplinary research effort is required to address major problems, including improvement of the historical records of sea level rise and ocean warming, the separation of other geophysical processes from sea level rise signals, and a more complete understanding of interactions between the ocean and ice sheets.

INTRODUCTION

Historically, sea level rise has not been a topic of keen interest among physical oceanographers. Rather, it was geologists and geophysicists who pioneered the discovery of modern-day sea level rise and placed it in context with the ebbs and flows of the ice ages, when sea levels rose and fell by more than 100 m. Interest in this topic has spread since it has become clear that modern-day sea level rise is due in part to human-induced global warming and that thermal expansion accounts for a significant part of it (Hegerl et al., 2007, section 9.5.2). Today, understanding and predicting sea level rise, both locally and globally, has become a major focus not just for oceanographers but also for climatologists, geophysicists, and glaciologists alike (see Douglas et al., 2001, for an excellent introductory text on sea level rise).

This renewed enthusiasm for the study of sea level rise is driven by more than just academic interest. It was recently estimated that 145 million people live within 1 m of present-day sea level worldwide (Anthoff et al., 2006), and in the United States, 30% of the population lives near coastal regions (Crowell et al., 2007). These population data provide enormous incentive to develop accurate predictions of sea level rise for the coming decades and centuries. Such predictions (Gregory et al., 2006) remain elusive, however, primarily because of the absence of coupled ice-sheet modeling in climate-model projections, and the controversy surrounding them (e.g., Rahmstorf, 2007; Holgate et al., 2007; Schmith et al., 2007) provides a stark reminder of the challenges faced by the sea level science community.

Our understanding of modern-day sea level rise was revolutionized by a series of satellite altimeters, beginning with the launch of TOPEX/Poseidon in 1992, and continuing with Jason-1 in 2001 and Jason-2 in 2008. Together with data from the European Remote Sensing (ERS)-1/-2/Envisat satellites (1991–present), and the Geosat Follow-On missions (1998–2008), they have provided a continuous and near-global record of modern-day sea level change since 1992. Figure 1 shows that sea level change revealed by the altimeters over 17 years is highly nonuniform. Its spatial variability is complex, reflecting a multitude of different physical processes with different time scales. In fact, this pattern is dominated by interannual to decadal variability that is simply aliased into the 17-year trend. Understanding these processes and distinguishing them from one another in the sea level record remains one of the primary challenges to the sea level community for decades to come. Untangling these signals requires not only continued satellite and in situ measurements but also improvements in global coupled climate models.

By defining globally averaged sea level relative to a fixed point at the center of Earth, the physical causes of sea level change can be expressed very simply as either a change in ocean volume or a change in ocean-basin shape. Changes in the basins are driven by geophysical processes such as glacial isostatic adjustment (GIA), which refers to the ongoing rebound of Earth's mantle in response to the disappearance of the giant ice sheets over North America and northern Europe about 20,000 years ago at the end of the last ice age. Over the ocean floor, GIA causes a net sinking, but such changes are thought to be small and secular components of modern-day sea level rise (Douglas and Peltier, 2002). Nevertheless, this effect is removed from most estimates of globally averaged sea level rise in the literature that are intended to serve as estimates of changes in the ocean's volume.

Changes in ocean volume can be caused either by thermal expansion from a net gain or loss of heat by the ocean or by a net exchange of freshwater between the ocean and the continents (including the ice sheets in Greenland and Antarctica, as well as mountain glaciers and groundwater storage). Because the overall salt content of the ocean is approximately conserved, and the water storage capacity of the atmosphere is small, these processes contribute negligibly to modern-day global mean sea level change. In principle, the redistribution of salt and heat due to mixing or other processes could change ocean volume because of the nonlinearity of the equation of state of seawater. However, such changes have also been estimated to be very small (Gille, 2004). This leaves the net input of heat and freshwater as the dominant mechanisms for the ocean volume change responsible for global sea level rise.

Locally, the sea level picture is more complicated. Changes in ocean circulation result in local sea level variability and can manifest as changes in density (associated with local changes in ocean temperature and/or salinity), redistribution of ocean mass that appears as a change in bottom pressure, or some combination of these processes. Sea level fluctuations of this nature are typically on the order of tens of centimeters, but can be as large as one meter. They can occur on spatial scales as small as a few

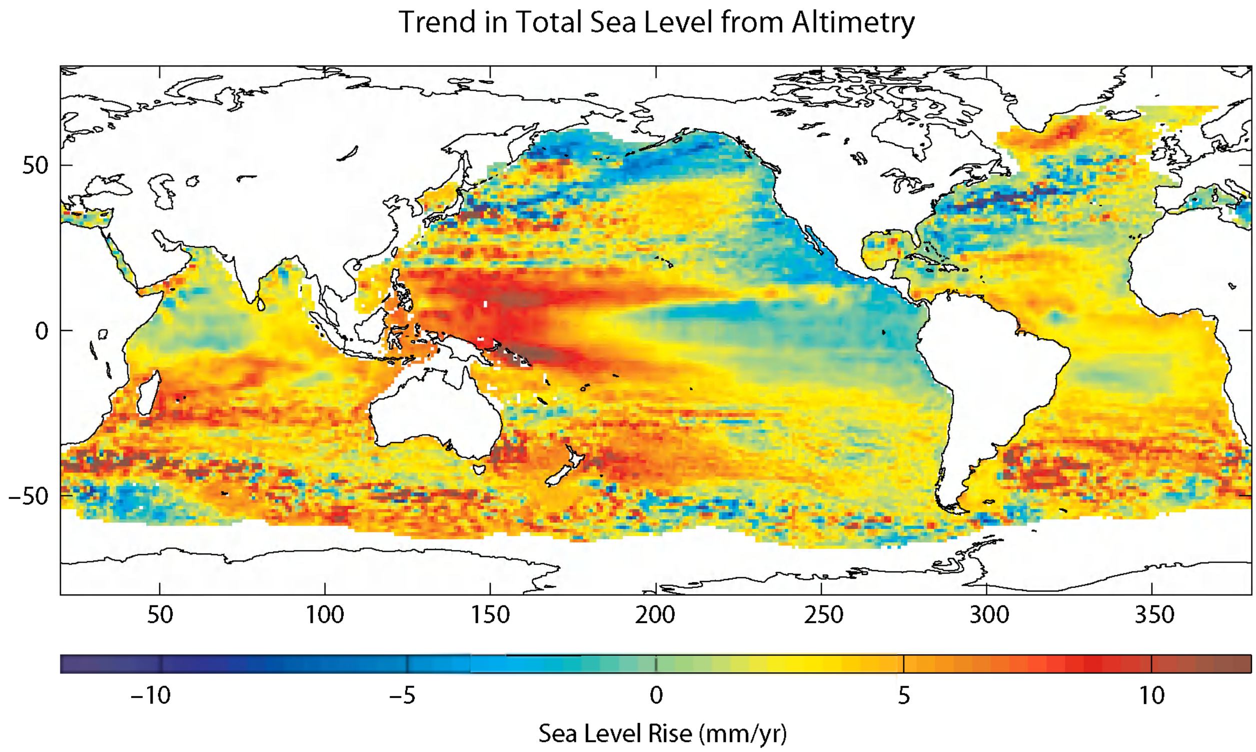

Figure 1. The regional change in sea level based on the 17-year trend from 1993 through 2009 from radar altimeter data from several satellites. Despite a fairly steady increase in globally averaged sea level rise (see Figure 2, inset), regional- scale changes over this duration are complicated and generally reflect changes in ocean circulation. Patterns reflecting other geophysical impacts, such as the net input of freshwater and changes in the gravity field due to loss of land ice, are expected to become clearer as the record length increases.

tens of kilometers or as large as an entire ocean basin, with time scales from a few weeks to semi-permanent. Indeed, many of the features visible in the 17-year trend shown in Figure 1 are likely to be related to ocean circulation changes (including interannual to decadal changes such as El Niño and the Pacific Decadal Oscillation). Distinguishing these changes from those driven by the net uptake of heat or freshwater in the ocean, or changes in the gravity field, remains an important part of ongoing research.

Local sea level changes may also be driven by changes in the local geoid, or gravity field. Recent work suggests that continued loss of continental ice will result in geoid changes that have a significant impact on regional sea level (e.g., Bamber et al., 2009). Although these effects have so far been too small to detect in the sea level data, credible projections will need to include these effects, as they will become more important as ice loss continues or increases. In coastal regions with shrinking glaciers, relative sea level is also affected by uplift of the land as the local crust responds to the loss of mass, as recently observed in Greenland (Jiang et al., 2010)

Measurement of the gravity field has also become an important technique for understanding sea level rise. Loss of ice mass from Greenland, Antarctica, and glaciers elsewhere will cause a reduction in gravity over the ice sheet, but a gain in gravity over the ocean. Although the gravity changes are small, they are measurable. In 2002, a pair of satellites called the Gravity Recovery and Climate Experiment (GRACE) was launched to measure these subtle gravity fluctuations. Since then, these satellites have made monthly observations of changes in Earth's gravity field, providing a powerful tool for understanding sea level

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rise. These observations have been used to estimate mass loss from ice sheets in Greenland, Antarctica, and glaciers in Alaska and Patagonia, all of which contribute to sea level rise. In addition, these data provide estimates of the total increase in ocean mass from freshwater exchange with the continents, changes in ocean bottom pressure associated with ocean circulation, and GIA in certain continental regions with large signals caused by postglacial rebound.

It is important to remember that while GRACE and altimeters observe these changes in a fixed global reference frame, it is the relative sea level rise that is important for any given coastline. All of the processes mentioned above must be considered independently from the local rate of land uplift or subsidence. Local changes in land elevation may be driven by tectonic activity, mining of ground water or hydrocarbons, GIA, or even elastic rebound of Earth's crust caused by present-day ice loss as noted above. Although these processes will for the most part be beyond the scope of this article, they serve to underscore the interdisciplinary nature of predicting sea level rise and its impacts.

Other important data for understanding the mechanisms of sea level rise are direct measurements of temperature and salinity in the water column. Although such measurements (especially salinity) were relatively sparse even in the upper ocean before 2000, over the last decade there has been a rapid increase in the abundance of such measurements due to the buildup of the Argo array of profiling floats. In 2007, this project achieved its goal of seeding the ocean with 3000 autonomous floats that measure temperature and salinity to a depth of 2000 m across the global, ice-free ocean.

This article presents an overview of recent progress in understanding the problem of present-day sea level rise, with an aim toward highlighting the major research questions of the next decade and beyond. Although such an exercise may be inherently speculative, what is absolutely clear is that satellite observations will continue to play a critical role in the study of sea level rise. Although the impacts of sea level rise are local, many of the physical processes are inherently global, and many important research questions will hinge on the continuation and ongoing improvement of satellite observations.

TIDE GAUGES AND THE HISTORICAL RECORD OF SEA LEVEL RISE

Although satellites have yielded a remarkable level of detailed knowledge about sea level rise, tide gauge records offer a link to the past as well as a critical calibration tool for satellite observations. It was tide gauge data that provided the first evidence of an accelerated rate of sea level rise for the twentieth century relative to pre-industrial periods (Lambeck et al., 2002; Gehrels et al., 2006; Kemp et al., 2009; also see Figure 2).

Calculating global mean sea level rise from the limited tide gauge network has proven to be difficult. Because tide gauges are inherently local measurements, changes in ocean circulation can have a considerable impact. As Figure 1 illustrates, such changes can be as large as tens of centimeters and persist for decades. These changes are clearly significant relative to the historical rate of global mean sea level rise, about 2 mm yr^{-1}, or about 20 cm over the twentieth century (Bindoff et al., 2007).

Numerous techniques have been employed to reduce the effects of ocean circulation when averaging tide gauge records. The most widely used method involves averaging records from different locations to reduce this effect. Early estimates of ocean volume increase simply averaged together as many long records from tectonically stable regions as possible (Douglas, 2001). More recent efforts have attempted to group records into geographically similar locations before averaging (Merrifield et al., 2009). Other researchers have made use of satellite altimeter data to account for ocean circulation. For instance, Church and White (2006) estimated the dominant spatial patterns of sea level change based on altimeter data, and then fit these patterns to the tide gauge records.

Although considerable progress has been made, further improvements to the historical record are still needed. A more accurate sea level record will illuminate decadal variations in sea level rise as well as the relationship between global sea level and surface temperature in a warming world. Improving our ability to account for ocean circulation changes in the tide gauge records will be a critical part of this effort. Ocean models, especially those that use data assimilation methods, may prove to be important tools in this effort.

Finally, tide gauge records also provide a critical set of independent data for comparison with satellite observations. Ongoing comparisons between tide gauge records and satellite altimeter data have become an integral part of maintaining the satellites' accuracy. Numerous biases and errors have been

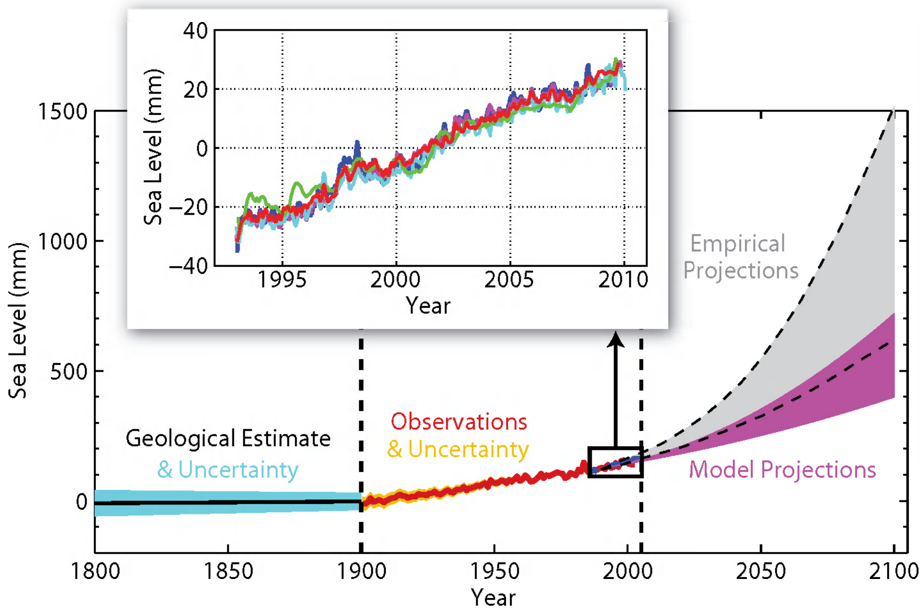

Figure 2. Current knowledge of estimated, observed, and projected global sea level rise from 1800 to 2100, updated from Shum et al. (2008). The pre-1900 estimate is based on geological evidence, which suggests a rise of 0.1–0.2 mm yr^{-1} during this period (Lambeck et al., 2002). The tide gauge record is shown from 1900 to 2005 (red, uncertainty bounds shaded yellow, from Church and White, 2006), and the satellite altimetry record is shown from 1985 to 2005 (blue, from Kuo, 2006). The projected twenty-first century sea level rise of 26–59 cm is based on coupled climate models using the A1F1 scenario, which assumes high global economic growth and continued heavy reliance on fossil fuels for the remainder of the century (pink envelope, from IPCC, 2007). Using semi-empirical methods, Rahmstorf (2007) projected much higher sea level rise (50–140 cm) than the IPCC AR4. The inset shows estimates of globally averaged sea level rise from five different investigators (author Chambers, present work; Kuo, 2006; Nerem et al., 2010; Leuliette and Scharroo, 2010; Albain et al., 2009), with the averaged trend being 3.2 ± 0.5 mm yr^{-1}. Here, the seasonal signals have been removed and all the corrections are applied, including the small impact of net sinking across the ocean floors (also known as glacial isostatic adjustment, or GIA).

detected and removed through such comparisons (e.g., Mitchum, 1998; Chambers et al., 2003). For this reason, maintaining a robust network of tide gauges will also continue to be a priority for the sea level science community.

SATELLITE ALTIMETRY

The launch of TOPEX/Poseidon (T/P) in 1992 led to a revolution in sea level change science. Because of T/P instrument precision, improvements in determining the satellite's orbit, and improved global ocean tide models (computed from the T/P measurements), scientists are now able to compute sea level variations along the ground track at a level approaching the accuracy of a single tide gauge. Unlike a tide gauge, however, the measurements are distributed nearly globally. Repeat measurements are made only every 10 days, not every hour as they are at most tide gauges. Nevertheless, the 10-day sampling is sufficient to measure the climatic signals in global mean sea level (Figure 2, inset).

Numerous authors have estimated global mean sea level using altimetry data. After correcting the measurement for several known biases and drifts, the most recent estimates all agree that sea level has been rising at around 3 mm yr^{-1} over the last decade and a half (e.g., Kuo, 2006; Ablain et al., 2009; Leuliette and Scharroo, 2010; Nerem et al., 2010; Shum and Kuo, 2010). Differences are all smaller than the 0.5 mm yr^{-1} uncertainty of the altimeter observations. There are also significant seasonal and interannual fluctuations around the trend (Figure 2 inset). The main difficulty with determining accurate sea level rise from altimetry arises from drifts and bias changes in the measurement. It is not a trivial matter to determine such changes, especially because the original requirement for the T/P mission was a bias that was stable at only 1 cm yr^{-1}. As discussed in the previous section, significant work has been done to devise methods to accurately calibrate altimeter measurements against a global network of tide gauges. Because of such calibration efforts, a number of drifts and bias changes have been discovered and corrected in the T/P data. These range from an early software error that caused the estimate to be nearly 7 mm yr^{-1} too high (Mitchum, 1998), to drifts in the water vapor correction from the microwave radiometer (Keihm et al., 2000), to changes in the sea state bias model (Chambers et al., 2003). It is vital that such calibration efforts continue in order to obtain an accurate climate record from satellite altimetry.

Figure 2 summarizes the current knowledge of estimated, observed, and projected sea level rise from 1800 to 2100. This figure reveals significant acceleration in sea level rise since about 1900, coinciding with increased temperatures and human-caused climate forcing. Although the observational record is becoming clearer, projections remain controversial (e.g., Rahmstorf, 2007; Holgate et al., 2007; Schmith et al., 2007; Grinsted et al., 2010), with semi-empirical techniques generally providing much higher projections than coupled ocean-atmosphere climate model results, and no coupled ice-sheet model efforts so far. The semi-empirical techniques, however, have been widely criticized for their lack of physical complexity (Taboada and Anadón, 2010; Vermeer and Rahmstorf, 2010).

HYDROGRAPHIC MEASUREMENTS

Observations of ocean temperature and salinity over depth play a critical role in understanding global sea level rise. A great deal of the regional variability in sea level observed by altimeters is also reflected in subsurface temperature and salinity. These temperature and salinity variations affect seawater density and cause changes in sea surface height, or sea level. Such density-driven changes in sea surface height are known as *steric changes*. For much of the ocean, temperature changes dominate the steric variations, and thermosteric sea level often accounts for a large part of observed sea level variations. Figure 3 illustrates this, and shows the trend in upper-ocean thermosteric sea level over the same period as that of Figure 1. The excellent correspondence is a reflection of the fact that regional variations in sea level on these time scales are primarily caused by ocean circulation changes, which appear in both upper ocean density and sea level. For some regions, however, salinity does play an important role. Note that the strong warming trend in thermosteric sea level in the eastern part of the far North Atlantic is not reflected in the altimeter data. Here, the thermosteric signal is compensated by a strong negative halosteric trend. Unfortunately, ocean salinity observations were much too sparse to compute such trends in most regions until observations from Argo floats became widespread during the first decade of the twenty-first century.

In addition to explaining many of the regional changes in sea level, steric changes have been invoked to explain a significant fraction of global sea level rise, or more specifically, ocean volume change. In addition to providing information about sea level rise, estimates of thermosteric expansion are of considerable importance to the climate science community because they are comparable to estimates of volume-averaged ocean warming, or ocean heat content. Because the ocean is the dominant reservoir for the storage of excess heat in the climate system, increases in ocean heat content reflect an imbalance in the planet's

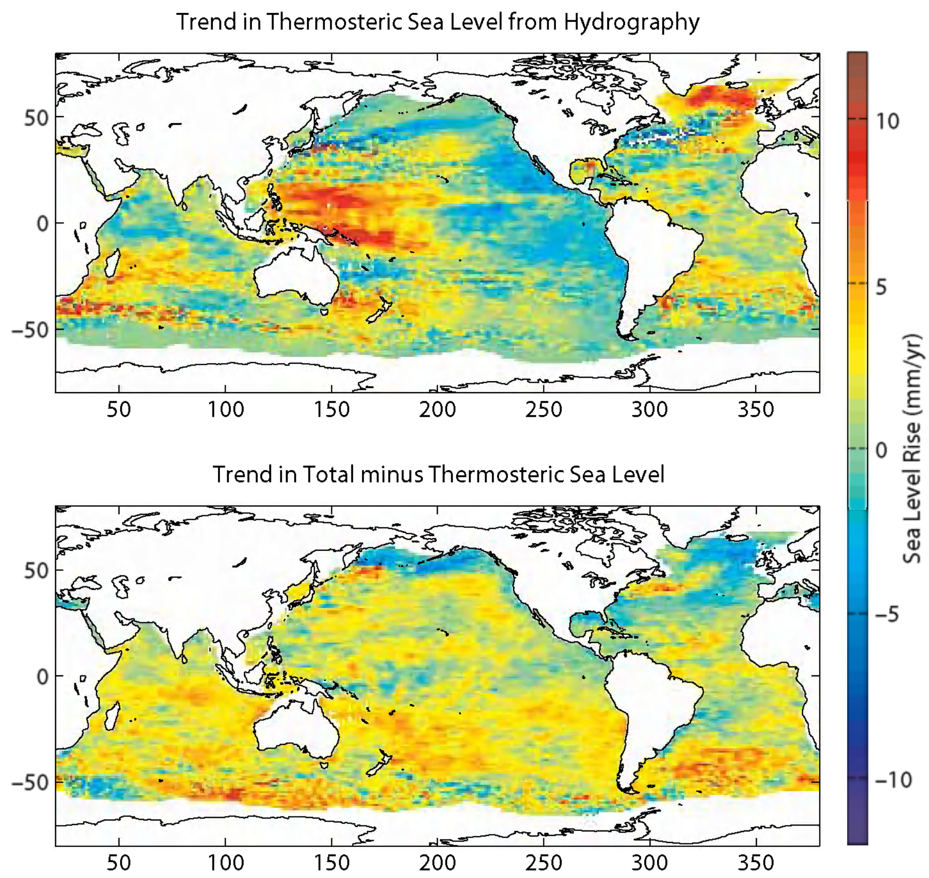

Figure 3. (top) 1993 to 2008 trend in thermosteric sea level for the upper 750 m of the ocean based on a combination of altimeter and temperature profile data, updated from Willis et al. (2004). These regional variations mostly reflect changes in ocean circulation that affect upper ocean density (primarily driven by temperature) and hence sea level. (bottom) Difference between total and thermosteric sea level trend. Note that many of the regional signals in total sea level rise are removed by subtracting the upper-ocean thermosteric component. The remaining signal is due in part to ocean mass increase (which has a comparatively uniform spatial pattern), deep steric changes (which are likely to be present in the boundary current regions and at high latitudes), and steric changes due to salinity (such as those found in the subpolar North Atlantic).

radiation budget, or net climate forcing. Ocean temperature, therefore, provides a cumulative record of the radiative forcing applied to Earth's climate.

Estimates of thermosteric sea level rise have been significantly revised recently due to the discovery of biases in one of the most widely used instruments in the historical data set, expendable bathythermographs (XBTs). Attempts to correct these biases (Domingues et al., 2008; Ishii and Kimoto, 2009; Levitus et al., 2009) reduced the decadal variability in estimates of thermosteric sea level rise and ocean heat content, and brought them into better agreement with estimates of decadal variability in coupled climate models (Domingues et al., 2008). Despite efforts to remove them, significant biases in the XBT data remain (Lyman et al., 2010). The most recent estimates of upper-ocean thermosteric sea level rise range from 0.4 mm yr^{-1} to 0.8 mm yr^{-1}, accounting for 20–60% of total sea level rise since the late 1960s (Domingues et al., 2008; Ishii and Kimoto, 2009; Levitus et al., 2009). Trends during the altimeter period, however, are significantly larger, ranging from 1.4–2.0 mm yr^{-1} for the period from 1993 to 2008 (Lyman et al., 2010). It is still unknown, however, whether the recent trends are caused by interannual to decadal fluctuations or a long-term acceleration in the rate of ocean warming. It is also clear from Lyman et al. (2010) that further work will be needed to reduce the systematic errors in the XBT data before interannual variability in the pre-Argo years can be accurately characterized. Understanding and accounting for the impacts of data scarcity and biases in the historical record of ocean temperature data will continue to be an important research focus for the coming decade.

Another important focus will be to understand the ability of the deep ocean to absorb heat and how quickly it does so. How much steric sea level rise is caused by warming below 1000 m, or even 3000 m? Lack of data from the deep ocean precludes making global estimates like those for the upper ocean. However, when integrated over the entire ocean, small temperature changes in the deep ocean are not negligible, and efforts to observe warming in the deep ocean will be another important observational priority in the years to come.

COMBINING HYDROGRAPHY, ALTIMETRY, AND GRACE

For the first time in the history of measuring sea level change, we now have not only near-global measurements of total sea level change from satellite altimetry, but also near-global measurements of the steric component from Argo and the mass component from GRACE. Almost as soon as the GRACE data became available, studies began comparing the three data sets to understand the contributions to globally averaged sea level. Chambers et al. (2004) considered only the seasonal component, and they verified previous estimates based on model results (Chen et al., 1998) that found ocean mass has a large seasonal amplitude (equivalent to ~ 1 cm global sea level change). The seasonal mass signal is out of phase with the steric component, which has a smaller amplitude (~ 5 mm) due to strong cancellation between the Northern and Southern hemispheres. When computed on the same near-global average, the combined effect of the steric and mass components leads to the observed seasonal variation in total sea level, which has an amplitude of ~ 5 mm.

Subsequent studies extended the comparison to longer time scales, interannual fluctuations, and trends (Willis et al., 2008; Leuliette and Miller, 2009; Cazenave et al., 2009). Willis et al. (2008) found closure of the sea level budget on one- to two-year periods. (The mean sea level budget is expressed as: total sea level from satellite altimetry equals the sum of the steric component [as observed from Argo] and the changes in ocean mass [observed by GRACE].) They also confirmed the existence of relatively large interannual changes in ocean mass that are directly reflected in sea level. For example, between 2004 and 2006, Willis et al. (2008) found that most of the nonseasonal increase in ocean volume could be attributed to ocean mass change and not ocean warming. By extending their analysis from mid 2003 through mid 2007, they found that the budget did not close to better than 3 mm yr^{-1}, which was more than the expected uncertainties. This finding indicated a systematic drift in one or more of the observing systems. Leuliette and Miller (2009) and Cazenave et al. (2009) also considered the sea level budget from January 2004 through early 2008. All three studies reached different conclusions about closure of the sea level budget over these multiyear periods. Efforts to characterize and remove systematic errors from these observing systems are ongoing.

Much of the discrepancy in sea level budget has since been resolved by additional data processing. In addition to problems arising from sparse sampling in early 2004, small pressure corrections continue to be applied to certain types of Argo floats. Several biases in the altimeter time series have also affected these studies. The most updated version of the Jason-1 altimeter data at the time of this writing (GDR-C) includes improvements to the sea state bias model, which applies a correction for the presence of gravity waves, the microwave radiometer measurement that is used to correct the data for the delay caused by water vapor in the atmosphere, and several other updates. After correction for all of these biases, globally averaged sea level in the Jason-1 GDR-C data has a significantly lower trend over the time intervals considered in the three studies, by 0.7 mm yr^{-1} (Nerem et al., 2010). These biases underscore the need for continual scrutiny of the satellite and in situ data and a need for independent observing systems such as multiple satellite altimeters with differing instrument designs, the tide gauge network, Argo, and GRACE.

After eliminating biased floats and using the latest Jason-1 data (GDR-C), there is no significant difference in the sea level budget after 2005. Subtracting Argo steric height from altimetric total sea level gives an inferred estimate of ocean mass, which can be compared with GRACE (Figure 4). The residual trend between ocean mass from GRACE and that computed from steric-corrected altimetry is less than 0.1 mm yr^{-1}, which is much smaller than the expected uncertainty of any component. All three data sets agree that the mass component of sea level rise between 2005 and 2010 is 1.3 ± 0.6 mm yr^{-1}. It should be noted, however, that there is still significant uncertainty in this trend, including potential long-term systematic errors due to, for example, inaccuracies in the GIA correction, drifts in the altimeter data, and pressure biases in the Argo data. Furthermore, care should be used in assuming this value is representative of the longer-term trend. As Willis et al. (2008) noted, there are large interannual fluctuations in mass related to water exchange with the continents. It will take a time series that is much longer than a decade to average out these transient fluctuations in order to quantify the true long-term rate of mass gain in the ocean.

FUTURE CHALLENGES

Although the science of sea level rise has grown rapidly over the past two decades, major challenges remain. Moving toward meaningful predictions of sea level rise requires observing systems to be improved and sustained, as well as an interdisciplinary approach by researchers. The aim of this research should be to account for all of the factors that affect sea level, including oceanographic, cryospheric, and geophysical. While this article has focused primarily on the oceanographic aspects of sea level rise, major work in predicting future sea level hinges on the ability of glaciologists to predict the shrinking of the ice sheets in Greenland and Antarctica. Recent work suggests that changes in ocean circulation may play a crucial role in that process as well (Rignot et al., 2010; Straneo et al., 2010). Understanding the interactions between the ocean and ice sheets is just one multidisciplinary aspect of future sea level rise research.

It is also important to continue to

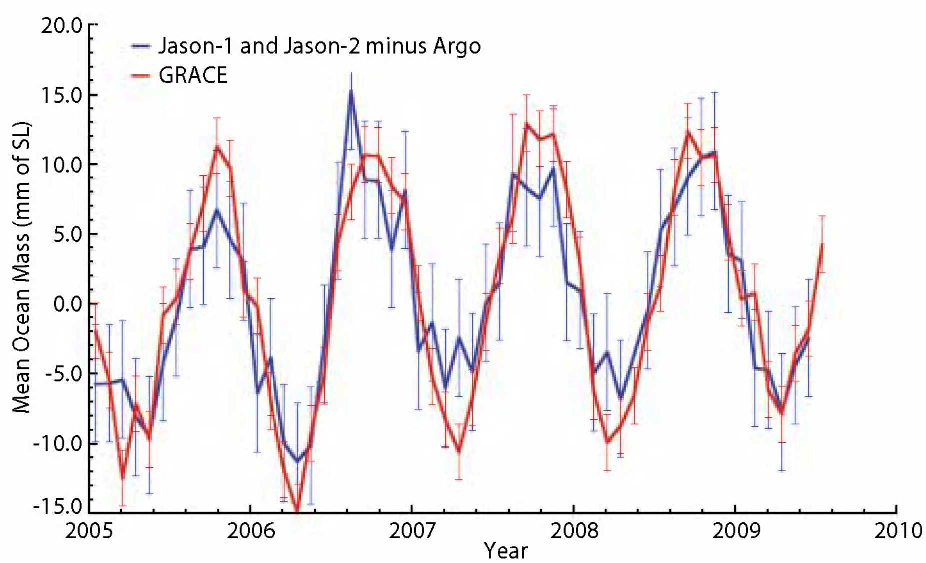

Figure 4. Ocean mass measured from the time-variable gravity satellite mission GRACE (Gravity Recovery And Climate Experiment, red) and inferred from steric-corrected Jason-1 and Jason-2 altimetry (blue). The steric correction is calculated from Argo data with all potentially biased float data removed. To allow for adequate global coverage by Argo, the inferred estimate of ocean mass is computed only for the years from 2005 on. The most recently released Jason-1 and Jason-2 data (GDR-C) were used here, and the GRACE data were corrected for GIA using the model recommended in Chambers et al. (in press). The excellent agreement suggests that the three observing systems, Jason, GRACE, and Argo, are accurate enough to capture total sea level variation and its causes on these time scales. The seasonal cycle is dominated by the yearly exchange of water between ocean and land related to the hydrologic cycle. The trend between 2005 and 2010 is 1.3 ± 0.6 mm yr^{-1}.

quantify the effects of local decadal variations in ocean currents on the trends estimated from tide gauges. We need to understand not only the effect of averaging such variations on estimates of mean sea level, but we also need to quantify the patterns, amplitudes, and frequency of past variations. Although there are numerous plans (including those of the United States, European Union, India, and China) to launch ongoing satellite altimeter missions, it is vital to maintain dedicated and knowledgeable science teams to calibrate and validate the measurements in order to maintain a stable climate record. To accomplish this task, the tide gauge network that exists today must be maintained, along with the measurements that enable us to compute a stable terrestrial reference frame. The measurements include data from satellite laser ranging and very-long baseline interferometry in addition to GPS.

To make predictions of future sea level rise, we must first understand the mechanisms of past and current sea level change. To address these issues, we must improve estimates of historical temperature change from instruments such as XBTs, continue the Argo program, and begin observing the temperature changes in the deep ocean on a global basis. Finally, we must continue to measure global time-variable mass changes in the ocean and ice sheets from a mission like GRACE. Ice sheets are the largest sources of potential sea level rise, yet they are also the most uncertain variable in terms of predicting future rise. Measurements from GRACE give a unique perspective on how the ice sheets are changing in our current climate. GRACE measurements, however, are the most likely to disappear sometime in the next few years. The original three-year mission has been extended well into eight years, but the satellites are not likely to last beyond 2013 because they will encounter increasing atmospheric density as their orbits decay. A plan to replace GRACE has recently been put into place, but it remains unclear whether the current satellites will last long enough to provide overlap with their replacement.

The prediction of sea level rise has profound implications for society. Of all the challenges described above, predicting future sea level rise remains the most difficult and the most important. In the decade to come, space-based observing systems will continue to provide a global view of sea level rise and its causes. These observations will lay the groundwork, but a comprehensive multidisciplinary effort is required to move toward complete understanding of sea level change.

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REFERENCES

Anthoff, D., R.J. Nicholls, R.S.J. Tol, and A.T. Vafeidis. 2006. Global and regional exposure to large rises in sea-level: A sensitivity analysis. *Working Paper 96*. Tyndall Centre for Climate Change Research, Norwich. Available online at: http://www.tyndall.ac.uk/biblio/working-papers?biblio_year=2006 (accessed September 19, 2010).

Ablain, M., A. Cazenave, S. Guinehut, and G. Valladeau. 2009. A new assessment of global mean sea level from altimeters highlights a reduction of global slope from 2005 to 2008 in agreement with in-situ measurements. *Ocean Sciences* 5:193–201.

Bamber, J.L., R.E.M. Riva, B.L.A. Vermeersen, and A.M. LeBroq. 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.

Bindoff, N.L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, and others. 2007. Observations: Oceanic climate change and sea level. Pp. 385–432 in *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds, Cambridge University Press, Cambridge, UK, and New York, NY.

Cazenave, A., K. Dominh, S. Guienhut, E. Berthier, W. Llovel, G. Ramillien, M. Ablain, and G. Larnicol. 2009. Sea level budget over 2003–2008: A re-evaluation from GRACE space gravimetry, satellite altimetry and Argo. *Global and Planetary Change* 65(1–2):83–88.

Chambers, D.P., S.A. Hayes, J.C. Ries, and T.J. Urban. 2003. New TOPEX sea state bias models and their effect on global mean sea level. *Journal of Geophysical Research* 108(C10), 3305, doi:10.1029/2003JC001839.

Chambers, D.P., J. Wahr, and R.S. Nerem. 2004. Preliminary observations of global ocean mass variations with GRACE. *Geophysical Research Letters* 31, L13310, doi:10.1029/2004GL020461.
Chambers, D.P., J. Wahr, M.E. Tamisiea, and R.S. Nerem. In press. Ocean mass from GRACE and Glacial Isostatic Adjustment. *Journal of Geophysical Research*.
Chen, J.L., C.R. Wilson, D.P. Chambers, R.S. Nerem, and B.D. Tapley. 1998. Seasonal global water mass balance and mean sea level variations. *Geophysical Research Letters* 25:3,555–3,558.
Church, J.A., and N.J. White. 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* 33, L01602, doi:10.1029/2005GL024826.
Crowell, M., S. Edelman, K. Coulton, and S. McAfee. 2007. How many people live in coastal areas? *Journal of Coastal Research* 23:5.
Domingues, C.M., J.A. Church, N.J. White, P.J. Gleckler, S.E. Wijffels, P.M. Barker, and J.R. Dunn. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature* 453:1,090–1,095.
Douglas, B.C. 2001. Sea level change in the era of the recording tide gauge. Pp. 37–64 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.
Douglas, B.C., and W.R. Peltier. 2002. The puzzle of global sea-level rise. *Physics Today* 55(3):35–40.
Douglas, B.C., M.S. Kearney, and S.P. Leatherman, eds. 2001. *Sea Level Rise: History and Consequences*. International Geophysical Series, vol. 75, Academic Press, 232 pp.
Gehrels, W., W. Marshall, M. Gehrels, G. Larsen, J. Kirby, J. Eiríksson, J. Heinemeier, and T. Shimmield. 2006. Rapid sea-level rise in the North Atlantic Ocean since the first half of the nineteenth century. *The Holocene* 16:949–965.
Gille, S.T. 2004. How nonlinearities in the equation of state of seawater can confound estimates of steric sea level change. *Journal of Geophysical Research* 109, C03005, doi:10.1029/2003JC002012.
Gregory, J., J. Lowe, and S. Tett. 2006. Simulated global-mean sea-level changes over the last half-millennium. *Journal of Climate* 19:4,576–4,591.
Grinsted, A., J.C. Moore, and S. Jevrejeva. 2010. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Climate Dynamics*. 34:461–472.
Hegerl, G.C., F.W. Zwiers, P. Braconnot, N.P. Gillett, Y. Luo, J.A. Marengo Orsini, N. Nicholls, J.E. Penner, and P.A. Stott, 2007. Understanding and attributing climate change. Pp. 663–745 in *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds, Cambridge University Press, Cambridge, UK, and New York, NY.
Holgate, S.J., S. Jevrejeva, P.L. Woodworth, and S. Brewer. 2007. Comment on "A semi-empirical approach to projecting future sea-level rise." *Science* 317:1,866, doi:10.1126/science.1140942.
IPCC. 2007. Summary for policymakers. Pp. 1–18 in *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds, Cambridge University Press, Cambridge, UK, and New York, NY.
Ishii, M., and M. Kimoto. 2009. Reevaluation of historical ocean heat content variations with time-varying XBT and MBT depth bias corrections. *Journal of Oceanography* 65:287–299.
Jiang, Y., T.H. Dixon, and S. Wdowinski, 2010. Accelerating uplift in the North Atlantic region as an indicator of ice loss. *Nature Geoscience* 3:404–407.
Keihm, S.J., V. Zlotnicki, and C.S. Ruf. 2000. TOPEX microwave radiometer performance evaluation. *IEEE Transactions on Geoscience and Remote Sensing* 38:1,379–1,386.
Kemp, A.C., B.P. Horton, S.J. Culver, D.R. Corbett, O. van de Plassche, W.R. Gehrels, B.C. Douglas, and A.C. Parnell. 2009. Timing and magnitude of recent accelerated sea-level rise (North Carolina, United States). *Geology* 37(11):1,035–1,038, doi:10.1130/G30352A.1.
Kuo, C.Y. 2006. *Determination and Characterization of 20th Century Global Sea Level Rise*. Ohio State University Report No. 478.
Lambeck, K., T. Esat, and E. Potter. 2002. Links between climate and sea levels for the past three million years. *Nature* 419:199–206.
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.
Leuliette, E., and R. Scharroo. 2010. Integrating Jason-2 into a multiple-altimeter climate data record. *Marine Geodesy*. 33:504–517, doi:10.1080/01490419.2010.487795.
Levitus, S., J.I. Antonov, T.P. Boyer, R.A. Locarnini, H.E. Garcia, and A.V. Mishonov. 2009. Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. *Geophysical Research Letters* 36, L07608, doi:10.1029/2008GL037155.
Lyman, J.M., S.A. Good, V.V. Gouretski, M. Ishii, G.C. Johnson, M.D. Palmer, D.M. Smith, and J.K. Willis. 2010. Robust warming of the global upper ocean. *Nature*, 465:334–337, doi:10.1038/nature09043.
Merrifield, M.A., S.T. Merrifield, and G.T. Mitchum. 2009. An anomalous recent acceleration of global sea level rise. *Journal of Climate* 22:5,772–5,781.
Mitchum, G.T. 1998. Monitoring the stability of satellite altimeters with tide gauges. *Journal of Atmospheric and Oceanic Technology* 15:721–730.
Nerem, R.S., D.P. Chambers, C. Choe, and G.T. Mitchum. 2010. Estimating mean sea level change from the TOPEX and Jason altimeter missions. *Marine Geodesy,* 33:435–446, doi:10.1080/01490419.2010.491031.
Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science* 315:368–370.
Rignot, E., M. Koppes, and I. Velicogna. 2010. Rapid submarine melting of the calving faces of West Greenland glaciers. *Nature Geosciences* 3:187–191.
Shum, C., and C. Kuo. 2010. Observation and geophysical causes of present-day sea level rise. Chapter 7 in *Climate Change and Food Security in South Asia*. R. Lal, M. Sivakumar, S.M.A. Faiz, A.H.M. Mustafizur Rahman, and K.R. Islam, eds, Springer Verlag, Holland.
Shum, C., C. Kuo, and J. Guo. 2008. Role of Antarctic ice mass balances in present-day sea level change. *Polar Science* 2:149–161.
Schmith, T., S. Johansen, and P. Thejll. 2007. Comment on "A semi-empirical approach to projecting future sea-level rise." *Science* 317:1866c.
Straneo, F., G.S. Hamilton, D.A. Sutherland, L.A. Stearns, F. Davidson, M.O. Hammill, G.B. Stenson, and A. Rosing-Asvid. 2010. Rapid circulation of warm subtropical waters in a major glacial fjord in East Greenland. *Nature Geosciences* 3:182–186.
Taboada, F.G., and R. Anadón. 2010. Critique of the methods used to project global sea-level rise from global temperature. *Proceedings of the National Academy of Sciences of the United States of America* 107:E116–E117.
Vermeer, M., and S. Rahmstorf. 2010. Reply to Taboada and Anadón: Critique of sea-level rise study invalid. *Proceedings of the National Academy of Sciences of the United States of America* 107:E118.
Willis, J.K., D.P. Chambers, and R.S. Nerem. 2008. Assessing the globally averaged sea level budget on seasonal to interannual time scales. *Journal of Geophysical Research* 113, C06015, doi:10.1029/2007JC004517
Willis, J.K., D. Roemmich, and B. Cornuelle. 2004. Interannual variability in upper ocean heat content, temperature, and thermosteric expansion on global scales. *Journal of Geophysical Research* 109, C12036, doi:10.1029/2003JC002260.