Causes for Contemporary Regional Sea Level Changes

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Abstract

Regional sea level changes can deviate substantially from those of the global mean, can vary on a broad range of timescales, and in some regions can even lead to a reversal of long-term global mean sea level trends. The underlying causes are associated with dynamic variations in the ocean circulation as part of climate modes of variability and with an isostatic adjustment of Earth's crust to past and ongoing changes in polar ice masses and continental water storage. Relative to the coastline, sea level is also affected by processes such as earthquakes and anthropogenically induced subsidence. Present-day regional sea level changes appear to be caused primarily by natural climate variability. However, the imprint of anthropogenic effects on regional sea level—whether due to changes in the atmospheric forcing or to mass variations in the system—will grow with time as climate change progresses, and toward the end of the twenty-first century, regional sea level patterns will be a superposition of climate variability modes and natural and anthropogenically induced static sea level patterns. Attribution and predictions of ongoing and future sea level changes require an expanded and sustained climate observing system.

1. INTRODUCTION

Global mean sea level (GMSL) has become a much-debated aspect of anthropogenic climate change, one with far-reaching consequences for the security and well-being of the global population. Changes in GMSL arise from many contributing factors that themselves result from changes in the ocean, the terrestrial hydrosphere, the cryosphere, and the solid Earth, making this a unique and integral diagnostic of climate change (Milne et al. 2009, Church et al. 2010). The scientific community is now in a position to understand and, to first order, close the net GMSL budget during the second half of the twentieth century, by quantifying contributions from individual components (Cazenave et al. 2009, Cazenave & Llovel 2010, Church et al. 2011). In particular, the increase in ocean heat content during the past few decades, changes in the ocean's freshwater content (e.g., Durack & Wijffels 2010), and their joint effect on GMSL can now be quantified (e.g., Bindoff et al. 2007, Domingues et al. 2008). Contributions from glaciers and ice sheets to GMSL rise can also be estimated, notably through new satellite observations (e.g., Steffen et al. 2010, Rignot et al. 2011, Jacob et al. 2012). Based on observational evidence available from satellite and in situ data, a consensus has emerged that GMSL during the past two decades has increased at a rate that is faster than the twentieth-century average (e.g., Merrifield et al. 2009). This higher rate is caused by an increased ocean thermal expansion and by the enhanced melting of glaciers and polar ice caps (e.g., Bindoff et al. 2007, Church et al. 2011).

Climate projections suggest that GMSL is likely to continue to rise at the current (or even at an accelerated) pace (e.g., Meehl et al. 2007). However, sea level change is not a smooth and globally uniform process. Instead, it shows strong regional patterns (in space and time) that can deviate substantially from global averages, to the point that local and global trends differ in sign at some locations. We note that sea level change is not a smooth process but rather one that shows strong modulations on all spatial and temporal scales. Even on the global scale, sea level is not rising monotonically but is instead showing substantial interannual to decadal fluctuations, superimposed on and often masking longer-term trends (Church & White 2011). More important, geographic patterns of sea level change are far from uniform, as revealed recently by altimeter satellites (e.g., Cazenave & Llovel 2010). When considering coastal security issues, it is especially the regional and local sea levels (relative to the coastline) that are relevant, not just the global mean (Milne et al. 2009). As no known process—whether associated with anthropogenic climate change or natural climate variations—will cause only a uniform sea level change, this behavior will continue to hold in the future under climate change conditions. Thus, attributions and predictions of ongoing and future sea level changes require that we understand all contributing processes at the regional and local levels.

The purpose of this review is to summarize regional aspects of sea level change and examine underlying mechanisms. Throughout the review, we use the term sea level change to refer to variability and trends. We discuss the existence, importance, and implications of regional sea level changes, including trends and natural variability, as well as all associated components and underlying processes. This discussion includes many dynamic aspects of sea level caused by changes in ocean circulation, which are superimposed on global changes. Other contributions originate from the solid Earth's response to past and present-day mass redistributions (e.g., due to land ice melt and land water storage changes) of either climatic or anthropogenic origin. We discuss observed and simulated (by numerical models) regional variability and trends. Our emphasis is on contemporary regional sea level changes (covering the past few decades) as well as their causes and attribution to natural or anthropogenic processes. We focus on interannual to multidecadal timescales. However, we do not discuss the seasonal cycle, nor do we address future centennial timescale changes. In addition, we do not address periodic variations such as those induced by low-frequency solid Earth tides and ocean tides.

Based on improved data sets from the ocean and the cryosphere and on better modeling capabilities, we can infer the underlying processes contributing to observed regional sea level change much better than was possible even 10 years ago. Improved process models enable us to focus on regional aspects of sea level change beyond global averaged changes, and ocean reanalyses and two-dimensional past sea level reconstructions are now available that can provide insight into past sea level changes and the underlying dynamic causes. Section 2 summarizes the mechanisms of regional relative sea level change, including dynamic effects in the ocean, large-scale land motions, and gravitational effects. Section 3 discusses insights into aspects of contemporary GMSL change. Section 4 focuses on observed and simulated contemporary regional sea level variability and changes, and Section 5 discusses aspects of regional sea level change not related to the ocean, such as contributions from the solid Earth's response to land ice/water-related mass redistribution (and the associated gravitational changes). Section 6 addresses coastal aspects and their implications for coastal security. Finally, Section 7 summarizes the review and addresses observations required to monitor future regional sea level changes and their underlying processes.

2. COMPONENTS OF REGIONAL SEA SURFACE HEIGHT CHANGES

Sea level changes at any point over the ocean are a composite of a GMSL change and regional processes. In the most general terms, sea level represents the mean height of the ocean sea surface as measured either with respect to Earth's center of mass (absolute sea level) or, alternatively, relative to the crust or seafloor (relative sea level). **Figure 1** illustrates this schematically.

Processes leading to changes in sea level are related on the global scale to changes in the total mass (freshwater content) and/or volume (heat content) of the oceans, but are also associated with geometric deformations of the seafloor. On regional scales, sea level can also be affected by changes in the atmospheric and oceanic circulations (hereafter referred to as dynamic changes) and by solid Earth processes, i.e., large-scale deformations of ocean basins and variations in Earth's gravity field plus local ground motion effects (hereafter referred to as static changes). In the following, we summarize relevant processes affecting regional sea level, separating them for convenience into dynamic and static components before discussing their contributions to present-day regional and coastal sea level variations in Sections 4–6.

2.1. Dynamic Regional Sea Level Changes

Dynamic regional sea level changes are primarily an expression of ocean dynamics, are highly variable in space and time, and have many causes, both natural and anthropogenic in nature. In particular, changing ocean currents are associated with the redistribution of mass, heat, and freshwater, which can result in substantial variability in sea level on interannual to decadal timescales superimposed on longer-term trends.

Changes in ocean temperature and salinity (called thermosteric and halosteric effects, respectively) affect sea level through the associated changes in density and volume. However, wind stress is a main driver of changes in mass and steric (thermosteric plus halosteric) height through numerous dynamic processes (e.g., Ekman pumping, planetary waves, coastal upwelling). These changes are directly related to coupled climate modes of variability, such as the El Niño/Southern Oscillation (ENSO), Pacific Decadal Oscillation, North Atlantic Oscillation, Indian Ocean Dipole, and Southern Annular Mode. Associated steric sea level changes relative to the global mean in different ocean basins are attributed to differential heating and freshening of various ocean layers

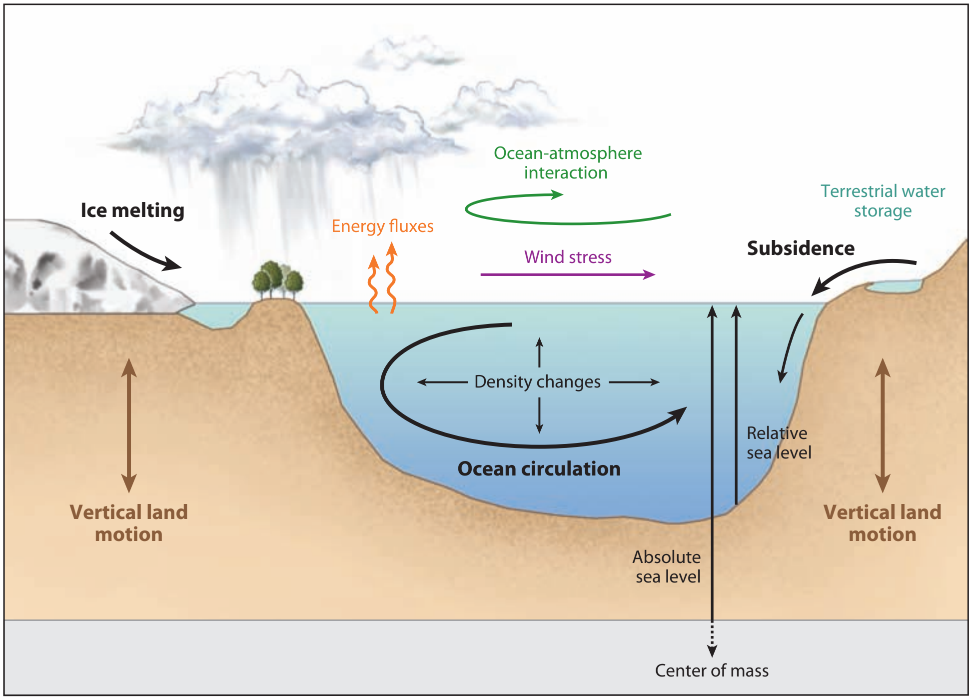


Figure 1

Processes that influence regional sea level.

and associated physical processes, such as surface feedbacks and lateral and vertical mixing or advective processes (Yin et al. 2010). Furthermore, steric changes tend to be larger in the interior (deep) ocean than over the shallow shelf regions (e.g., Bingham & Hughes 2012). As a result, mass exchange between the ocean interior and continental shelves can occur.

Historically, regional sea level changes were interpreted as being primarily thermosteric in nature, reflecting changes in the ocean's heat content (e.g., Levitus et al. 2000). However, recent observations indicate that salinity changes are also important for regional sea level evolution (Durack & Wijffels 2010) and that halosteric changes can enhance or compensate for thermosteric changes, depending on the regional temperature-salinity relationship (e.g., Köhl & Stammer 2008, Ponte 2012). Moreover, some regions are specifically affected by increased uptake of either heat or freshwater. Some of these regions coincide with places of deepwater mass formation, which provide windows for long-term heat and freshwater uptake (e.g., the subpolar North Atlantic and the subpolar convergence zone of the Southern Ocean). Halosteric effects can be especially important in regions of high-latitude water mass formation; e.g., model simulations suggest that halosteric changes will dominate sea level changes in the Arctic (e.g., Lowe & Gregory 2006, Pardaens et al. 2011). Recent observations suggest that this might be the case already (Giles et al. 2012, Morison et al. 2012).

The extent to which changes in surface air-sea fluxes of heat and freshwater play an important role in ongoing regional sea level changes is not yet fully quantified. However, it is anticipated that those fluxes will play an increasingly important role in a warming climate. Of particular concern are the processes involved in the sea level response to locally injected freshwater originating from melting glaciers or polar ice sheets. The response associated with the mass redistribution will occur quickly in terms of a barotropic global adjustment (e.g., Ponte 2006b, Lorbacher et al. 2012) in the form of planetary waves and basin modes. However, an influx of freshwater also changes the ocean's temperature and salinity, and hence polar ice sheet melting will also cause a dynamic sea level response in terms of long-term steric adjustments (Stammer 2008, Lorbacher et al. 2010, Stammer et al. 2011). In addition to a direct oceanic adjustment, the polar freshwater injection produces air-sea feedbacks that lead to a fast teleconnection in sea level changes between the Atlantic and North Pacific (Okumora et al. 2009, Stammer et al. 2011). An additional oceanic teleconnection through the Arctic contributes significantly to the North Pacific cooling through an anomalous Bering Strait throughflow, which transports colder, fresher water from the Arctic Ocean into the North Pacific (Hu et al. 2010).

2.2. Static Regional Sea Level Change

Not all components of regional sea level variability are dynamic in nature. In particular, the response to several types of ocean loading can lead to static variability, in which sea level changes mainly balance externally imposed loads in an isostatic manner, with negligible currents involved. One of the most important loads is associated with surface atmospheric pressure (Ponte 1993, Wunsch & Stammer 1997). On timescales longer than a few days, the ocean typically adjusts nearly isostatically to changes in atmospheric pressure (inverted barometer effect), such that for each 1-hPa increase in local sea level pressure (compared with the global ocean average) the ocean is depressed by approximately 10 mm, shifting the underlying mass to other regions. On annual and longer timescales, regional sea level variability associated with the inverted barometer effect can vary from <1 cm in the tropics to 2–3 cm at high latitudes (Ponte 2006a).

Loading effects on the ocean related to past and present-day changes in land ice and hydrology are also important. Associated surface mass redistribution causes viscoelastic/elastic adjustment of the solid Earth and gravitational changes. The collapse of the large ice sheets following the Last Glacial Maximum, and the subsequent loading of the ocean basins, resulted in deformation of the ocean floor and changes in the gravity field (Farrell & Clark 1976, Lambeck 1988, Peltier 2004). This process, known as glacial isostatic adjustment (GIA), continues to affect sea level observations. Present-day polar ice sheet melting also leads to a characteristic pattern of relative sea level fall close to those regions as well as a larger-than-average rise in the far field (Clark & Primus 1987, Mitrovica et al. 2001, Tamisiea & Mitrovica 2011). A similar response can be expected from changes in the hydrological cycle (e.g., terrestrial water storage) (Clarke et al. 2005, Riva et al. 2010, Tamisiea et al. 2010). All of these changes affect Earth's inertia tensor and therefore its rotation, which produces an additional sea level response (Milne & Mitrovica 1998). Other factors, such as tectonic processes and coastal processes resulting in erosion and sediment deposition and compaction, can cause highly localized sea level changes as well. These processes are discussed further in Sections 5 and 6.

3. SUMMARY OF GLOBAL MEAN SEA LEVEL OBSERVATIONS AND CAUSES

Before we discuss regional phenomena, a summary of GMSL changes is useful. Tide gauge measurements available since the late nineteenth century indicate that the GMSL has risen at a mean rate of 1.7–1.8 mm year^{-1} during the twentieth century (Jevrejeva et al. 2008, Church & White 2011); these values are typically uncertain to within 0.3 mm year^{-1}, but this uncertainty does not reflect uneven spatial sampling in time. Satellite altimetry data available since 1993 indicate a higher rate of ~3.2 ± 0.4 mm year^{-1} (e.g., Mitchum et al. 2010, Nerem et al. 2010). The

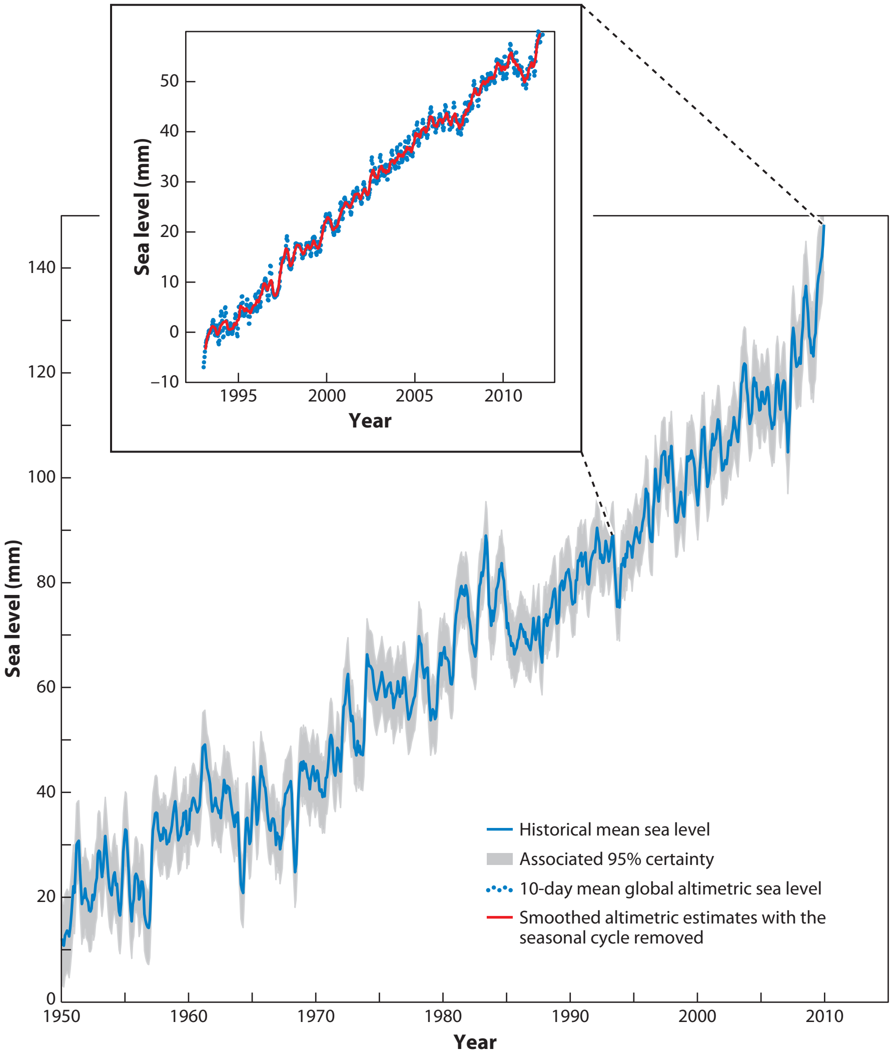


Figure 2

Historical mean sea level since 1950 (*blue line*) and associated 95% certainties based on the standard deviations of the different analyses (*gray shaded area*), using data from Church & White's (2011) reconstruction. The inset shows the global sea level curve from satellite altimetry since 1993 (*blue dots*) and a smoothed curve with the seasonal cycle removed (*red line*), using data from Aviso (**http://www.aviso.oceanobs.com**); in both cases a glacial isostatic adjustment correction of -0.3 mm year^{-1} has been applied.

uncertainty in the altimetry-based rate of sea level rise results from errors in the geophysical corrections applied to the altimetry data as well as an imperfect account of instrument drifts (e.g., Ablain et al. 2009, Masters et al. 2012).

Figure 2 gives an example of a state-of-the-art estimate of global sea level change since 1950, along with an inset highlighting the altimetric era. The main factors contributing to the GMSL increase are thermal expansion of seawater, land ice loss, and freshwater mass exchange between oceans and land water reservoirs (discussed in more detail below). Although none of these components evolve linearly with time, on average across the 1993–2010 time span, ocean thermal expansion and glaciers have each contributed roughly 30% to the observed rate of sea level rise, and the ice sheets explain approximately 20%–25%. The rationale for the contributions made by these three components to GMSL rise is briefly discussed below.

3.1. Ocean Warming

In situ ocean temperature data have been collected over the past 50 years by ships and more recently by Argo profiling floats (Argo Data Manag. Team 2008), mostly in the upper layers (i.e., to depths of 700–2,000 m). Analyses of these data indicate that ocean heat content has increased significantly during the past few decades, leading to a positive ocean thermal expansion, especially since 1970 (e.g., Domingues et al. 2008, Ishii & Kimoto 2009, Levitus et al. 2009). A steep increase was observed during 1993 and 2003 (e.g., Lyman et al. 2010), but the rate of thermal expansion has subsequently been slower (Lyman et al. 2010, von Schuckmann & Le Traon 2012). During the satellite altimetry era (1993–2010), the contribution of ocean warming to the GMSL rise amounted to $\sim 1 \pm 0.3$ mm year^{-1} (Cazenave & Llovel 2010, Church et al. 2011).

3.2. Land Ice

From mass balance studies (e.g., Kaser et al. 2006, Meier et al. 2007, Cogley 2009), the contribution of the melting of glaciers and ice caps to sea level rise for the period 1993–2010 has been estimated as ~ 1 mm year^{-1} (e.g., Cogley 2009, Church et al. 2011). Although little is known about the mass balance of the ice sheets before the 1990s because of inadequate and incomplete observations, modern remote sensing techniques—notably airborne and satellite radar and laser altimetry, interferometric synthetic aperture radar, and Gravity Recovery and Climate Experiment (GRACE) space gravimetry—suggest an acceleration of ice mass loss in recent years (e.g., Rignot et al. 2008a,b, 2011; Chen et al. 2009; Velicogna 2009). For the period 1993–2003, $<15\%$ of the rate of GMSL rise was due to the ice sheets (Intergov. Panel Clim. Change 2007), but their contribution has nearly doubled since 2003–2004 (e.g., Van den Broeke et al. 2011, Jacob et al. 2012). On average, ice sheet mass loss explains ~ 0.6–0.7 mm year^{-1} of the rate of sea level rise during 1993–2010 (e.g., Steffen et al. 2010, Van den Broeke et al. 2011).

3.3. Land Waters

Changes in land water storage due to natural climate variability and human activities (e.g., anthropogenic changes in the amount of water stored in soils, reservoirs, and aquifers as a result of dam building, underground water mining, irrigation, urbanization, deforestation, etc.) also contribute to sea level change. Model-based estimates of land water storage change caused by natural climate variability suggest no long-term contribution to sea level for the past few decades, although interannual/decadal fluctuations may have been significant (Milly et al. 2010). Although dam building during the second half of the twentieth century has lowered the sea level by ~ 0.5 mm year^{-1} (Chao et al. 2008), groundwater pumping has increased it during the same period on the order of ~ 0.3–0.5 mm year^{-1} (e.g., Wada et al. 2010, Konikow 2011). Thus, these two processes have essentially canceled each other in the past, but this may not be true in the future because of increasing groundwater mining and declining dam building (Wada et al. 2012).

In addition to the linear trend shown in **Figure 2**, the GMSL shows significant interannual to decadal variability. For example, positive and negative sea level anomalies have been observed during El Niño and La Niña, respectively (e.g., Nerem et al. 2010), and have been related to

ENSO-driven variations in the global water cycle (Llovel et al. 2011), in particular ocean mass variations (Chambers 2011, Cazenave et al. 2012).

4. REGIONAL SEA LEVEL CHANGES AND OCEAN DYNAMICS

4.1. Spatial Patterns of Contemporary Sea Level Changes

Historical tide gauge measurements reveal substantial spatial variations in sea level (e.g., Douglas 2001, Woodworth et al. 2011). However, to a large extent they provide only relative sea level information, with significant contributions originating from the vertical motions of the gauge stations (e.g., Wöppelmann et al. 2009). Putting tide gauge measurements into a global context and inferring long-term regional trends from them requires correcting them for many local effects. Thus, our information about past regional sea level changes based on tide gauge measurements is incomplete. Nevertheless, corrected tide gauge time series indicate substantial regional differences in long-term trends and demonstrate significant interannual-to-decadal variability not related to long-term trends (**Figure 3**).

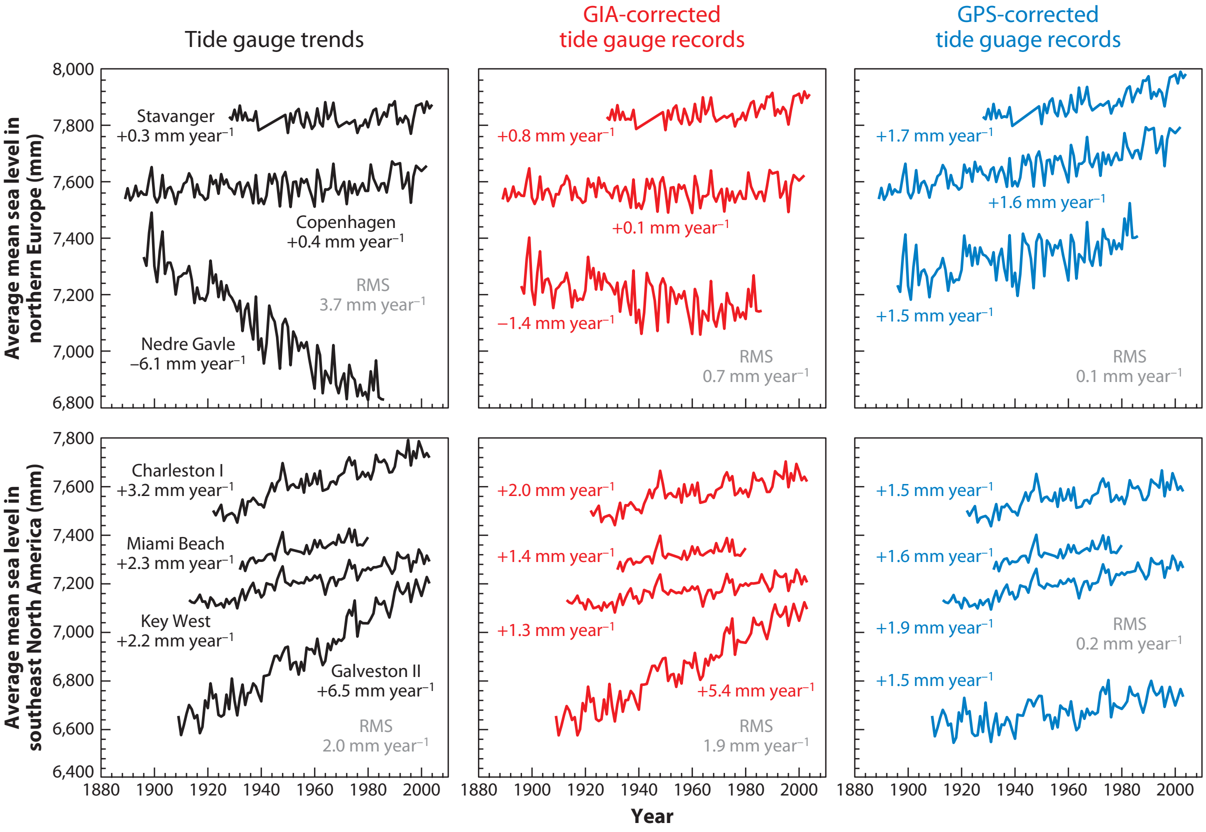


Figure 3

Time series of annual mean sea level values from (*left*) tide gauges, (*middle*) tide gauges corrected for the glacial isostatic adjustment (GIA) using Peltier (2004) ICE-5G (VM2) model predictions, and (*right*) GPS-corrected tide gauge records in the International Terrestrial Reference System 2005 reference frame in (*top*) northern Europe and (*bottom*) southeast North America. The time series are displayed with arbitrary offsets for presentation purposes. Adapted from Wöppelmann et al. (2009).

Quality observations of regional sea level, continuous in time and with quasi-global coverage, exist only since the start of precise satellite altimetry in 1993. Those measurements have revealed a complete picture of the global variations. Today, altimetric satellite measurements of sea surface height together with in situ (subsurface) density (temperature and salinity) measurements for steric height variability, along with satellite measurements of gravity (e.g., from the GRACE mission; Tapley et al. 2004) for mass changes, form a nearly complete set of observations enabling the study of large-scale sea surface height variations (e.g., Wilson et al. 2010). Together with output from numerical ocean models, these observations allow us to understand sea level change in terms of ocean variability and its underlying causes in ocean mass, density, and circulation, which will in turn permit more accurate projections of future sea level rise.

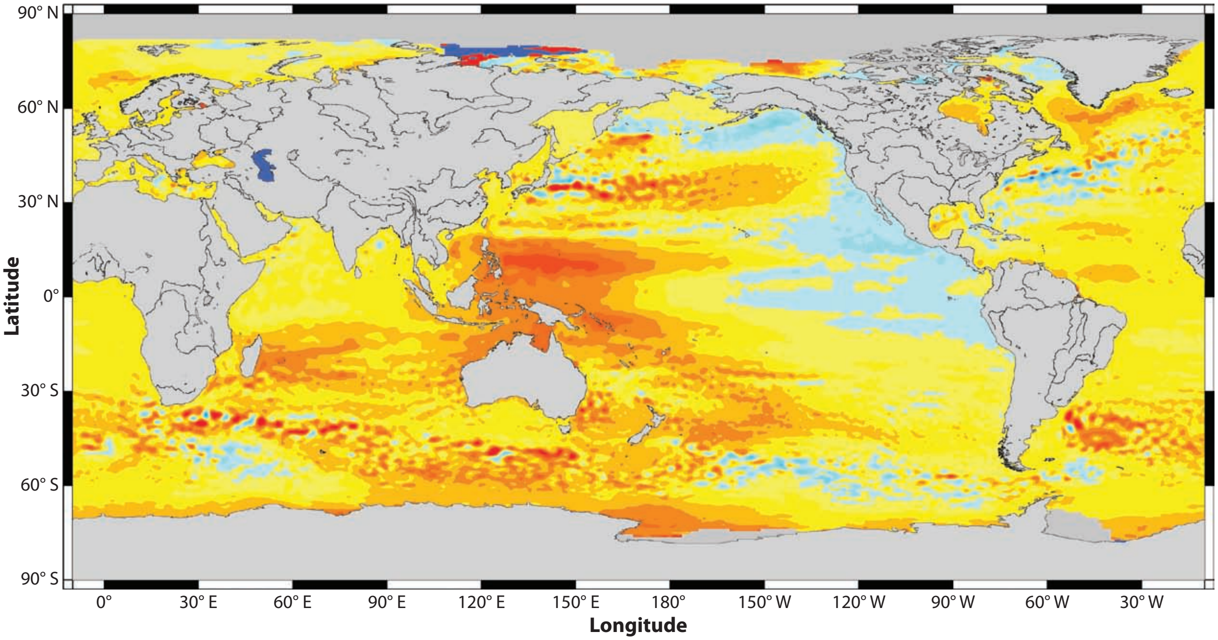
Figure 4 illustrates example regional sea level changes estimated from altimeter data for the period 1993–2010. In some regions, rates of sea level rise during this period are higher than the global mean rate by up to a factor of three. Rates higher than the global mean can be observed particularly in the western tropical North Pacific, in the North Atlantic, around Greenland, and in the Southern Ocean. Rates lower than the global mean can be observed in the eastern Pacific. For comparison, **Figure 4** also shows observed sea level changes for the period 1993–2001. Although some geographic regions show similar trends, the results are quantitatively different in the trend estimate for the shorter period, suggesting that regional sea level is highly variable in time and that observed changes to first order do not represent long-term trends. As an example, the Indian Ocean changes the sign of its trend over the longer period, whereas the eastern Pacific becomes quasi-neutral. Only a long-term continuation of the required measurements will allow us to understand ongoing sea level changes and distinguish secular regional changes from natural variability.

Comparisons of satellite altimetry–based sea level observations with available in situ temperature and salinity data (primarily for the upper ocean) indicate that past and ongoing regional sea level changes appear to be mostly steric in nature and are primarily thermosteric during the altimetry era (Levitus et al. 2005, 2009; Ishii & Kimoto 2009). However, in many regions (e.g., the Atlantic), halosteric effects are also important and often reduce or enhance thermosteric changes in sea level (e.g., Durack & Wijffels 2010). **Figure 5** illustrates the relationship between sea level and upper-ocean steric height, showing spatial trend patterns for the period 1993–2010 as inferred from satellite altimetry (uniform global mean trend removed) and from the total steric (thermosteric plus halosteric) contribution. Apart from data noise and data exploitation (i.e., incomplete sampling), differences in observed patterns in both fields can be due to unaccounted changes in deep steric height and in bottom pressure (ocean mass). Purkey & Johnson (2010) estimated basin-scale decadal steric height trends in abyssal layers at <1 mm year^{-1}, but apparent larger regional trends have been observed (e.g., Johnson et al. 2008). Sutton & Roemmich (2011) used altimetry and hydrography data to infer the presence of relatively large (>1 mm year^{-1}) bottom pressure decadal trends in middle and high southern latitudes.

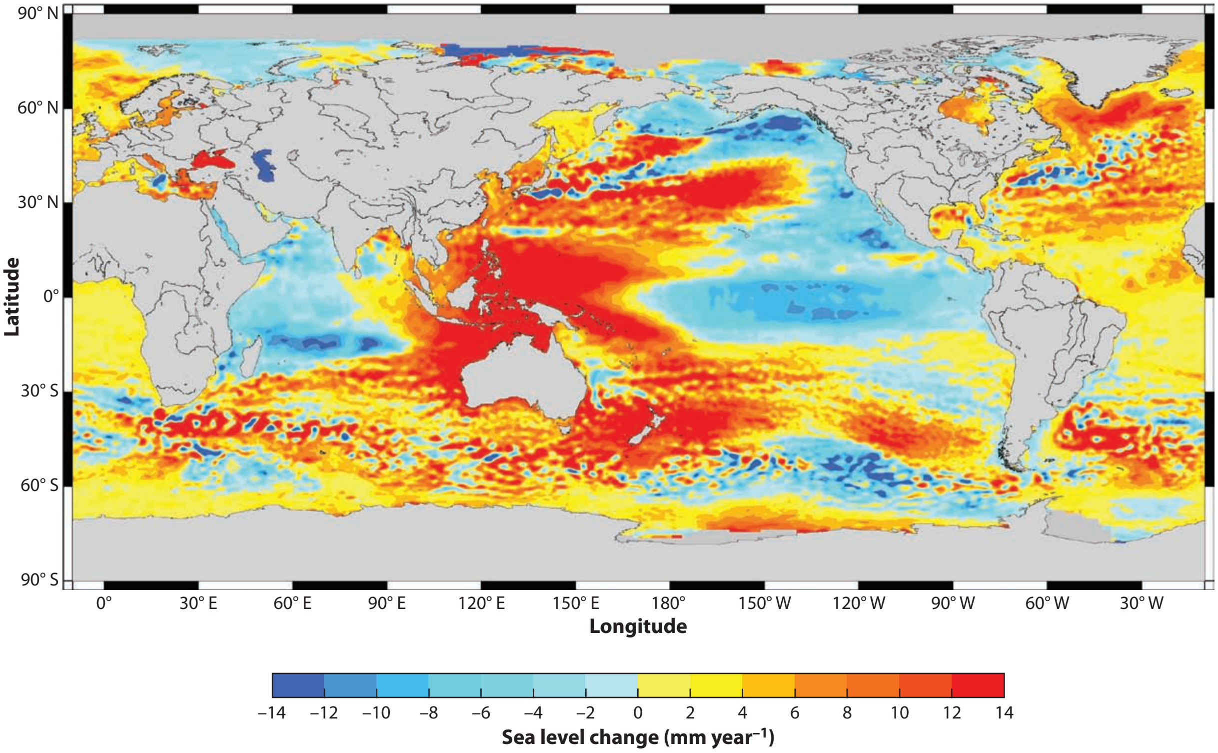
Ocean circulation models that were constrained by observations (Carton et al. 2005, Wunsch & Heimbach 2007, Köhl & Stammer 2008, Stammer et al. 2010) as well as ocean circulation models without data assimilation (Lombard et al. 2009, Song & Colberg 2011) are useful for exploring the processes contributing to sea level changes. Results based on these reanalyses indicate that most of the observed change in regional sea level is steric in nature, including deep contributions, with nonnegligible effects of bottom pressure also possible (e.g., Köhl et al. 2007, Wunsch et al. 2007, Köhl & Stammer 2008, Song & Colberg 2011).

To obtain information on spatial sea level variations prior to the altimetry era, statistical reconstruction techniques have been developed (Wenzel & Schröter 2010, Church & White 2011, Meyssignac et al. 2012a, Ray & Douglas 2012). These techniques combine long tide gauge records

a Mean sea level trends: altimetry, 1993–2010



b Mean sea level trends: altimetry, 1993–2001



of limited spatial coverage with shorter, global-gridded sea level data, either from satellite altimetry or from numerical ocean models. Despite the remaining uncertainties, spatial trend patterns over the past 50 years are likely significantly different from those observed during the recent altimetry era and have a much lower magnitude (three to four times), again highlighting the presence of low-frequency internal dynamic modes of the ocean (White et al. 2005, Meyssignac et al. 2012b). This low-frequency (multidecadal) dynamic ocean variability underlies the sea level spatial patterns visible in **Figure 4** and can strongly affect regional decadal sea level changes [e.g., Becker et al. (2012) argued that total sea level rise since 1950 at the Tuvalu Islands is three times larger than the global mean because of ENSO-related low-frequency sea level variability].

4.2. Sea Level Forcing Factors

For a better understanding of contemporary sea level changes in terms of natural dynamic modes versus anthropogenic influences, it is important to discuss potential underlying forcing factors. In general terms, the forcing for regional patterns of local/regional sea level variability can be associated with (*a*) surface warming and cooling of the ocean; (*b*) exchange of freshwater with the atmosphere and land through evaporation, precipitation, and runoff; and (*c*) changes in the surface wind stress. The complex dynamic response of the ocean to these forcing mechanisms can result in changes in ocean circulation and transports of density and mass, which relate directly to the observed sea level trend patterns (e.g., Köhl & Stammer 2008, Lombard et al. 2009). Moreover, because of the long response time of the ocean to surface forcing, contemporary patterns in sea level change reflect not only ongoing forcing changes but also forcing changes that occurred far in the past (Wunsch et al. 2007).

Figure 6 demonstrates the complexity of the ocean's response to a changing surface forcing, showing observed and simulated sea level patterns along the latitude band 12°–14° N in the Pacific. This figure clearly illustrates the prominence of low-frequency wind-forced variability in basin-scale sea level observations in the form of planetary Rossby waves governed by linear vorticity dynamics (for further details, see Qiu & Chen 2010). **Figure 7** further illustrates the role of low-frequency sea level dynamics in shaping decadal-scale sea level changes, showing a close relationship between sea level variations observed on the western side of the Atlantic and those that occurred on the eastern side 10 years earlier, which is the time it takes for a free, nondispersive Rossby wave to cross the basin at 40° N (see also Sturges et al. 1998, Hong et al. 2000). As ocean climate variability modes are to a large extent driven by winds, these changes are essential for shaping the sea level patterns shown in **Figure 4**, which are inferred from a decadal time series. To fully explain the low-frequency sea level variability, however, other forcing mechanisms like air-sea heat exchanges may have to be considered—e.g., as has been demonstrated for regions in the eastern tropical Pacific (Piecuch & Ponte 2012).

The importance of wind variations for decadal sea level changes was also demonstrated for the global ocean based on an ocean synthesis product resulting from merging observations with a numerical model (Köhl & Stammer 2008). The results suggest that most of the regional sea level changes observed during the past decade are steric in nature and caused by a changing wind-forced ocean circulation. Using tropical and subtropical sea level variability as an example,

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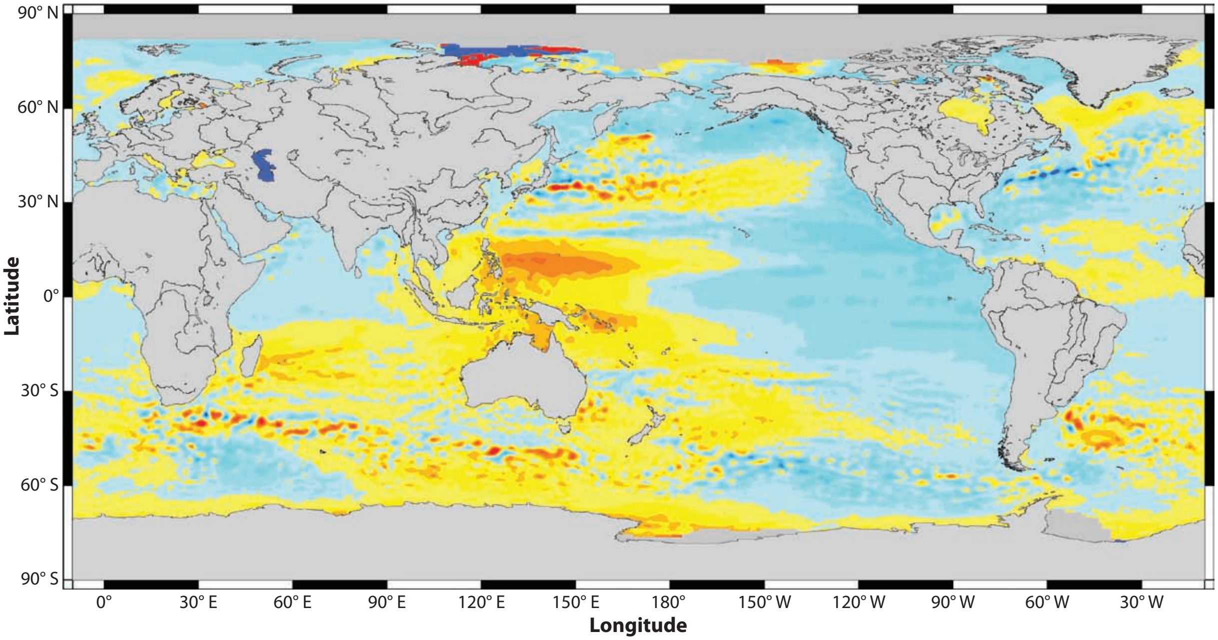
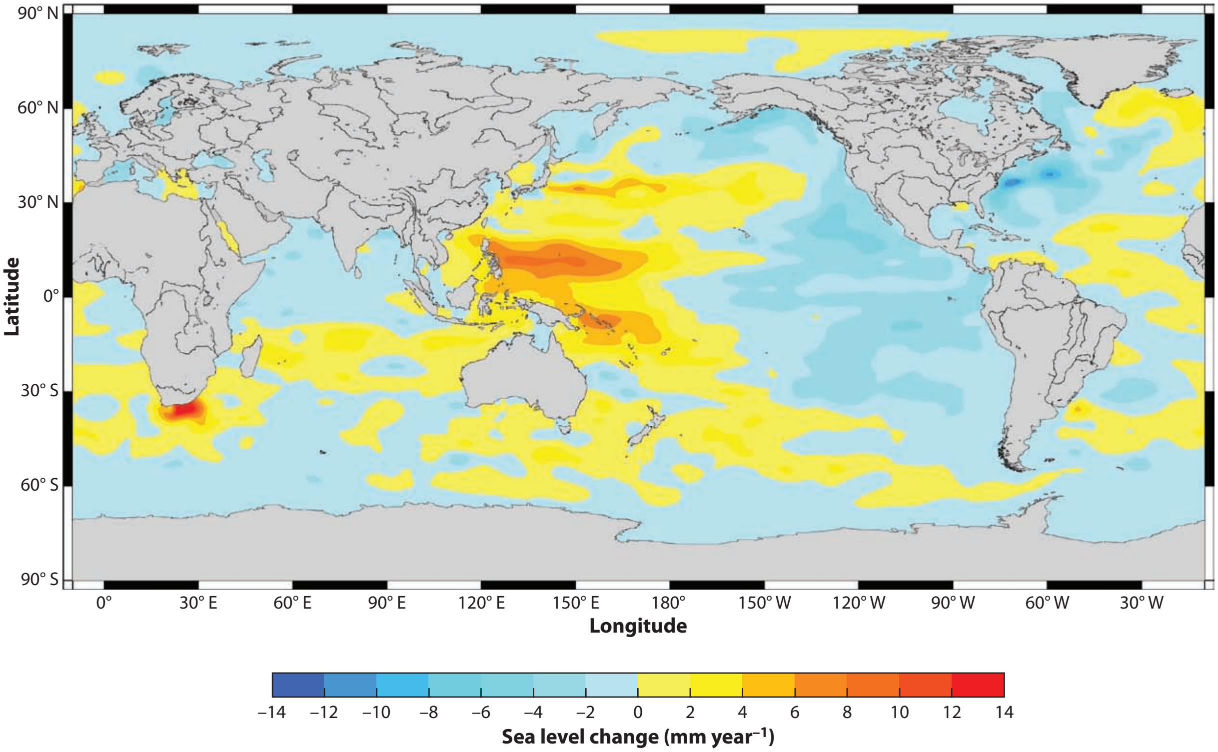
Figure 4

Spatial patterns in sea level trends based on TOPEX/Poseidon, Jason-1, Jason-2, and Envisat satellite altimetry data from Aviso (**http://www.aviso.oceanobs.com**). (*a*) Estimated mean sea level trend for 1993–2010. (*b*) Estimated mean sea level trend for 1993–2001.

a Mean sea level trends: altimetry, 1993–2010



b Steric sea level trends: ocean temperature and salinity, 1993–2010



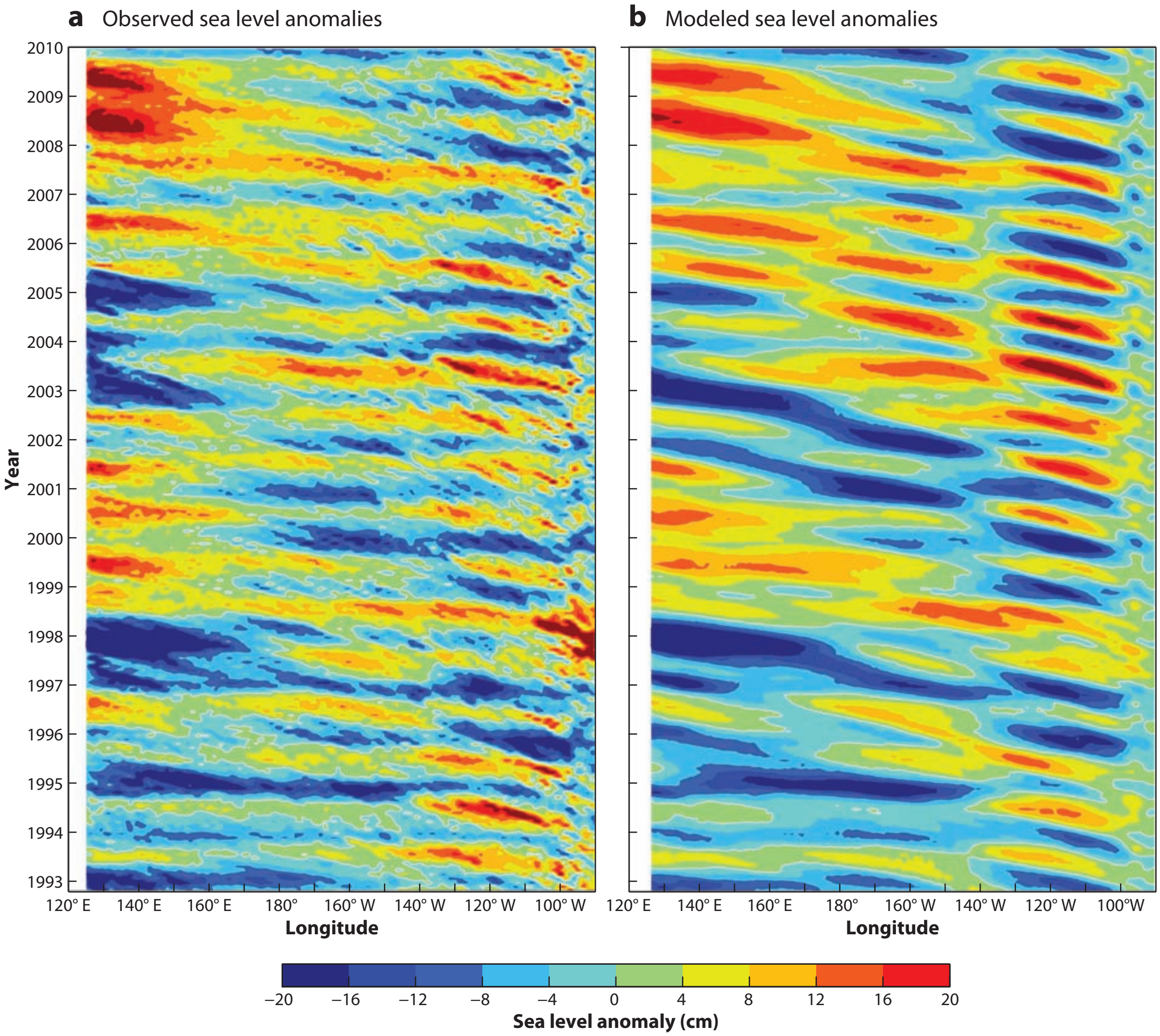


Figure 6

(*a*) Observed and (*b*) simulated sea level anomalies along 12°–14° N associated with a planetary wave adjustment of the Pacific circulation. Adapted from Qiu & Chen (2010, figure 6) with permission from the American Meteorological Society. Copyright © 2010 by the American Meteorological Society.

Figure 5

Spatial patterns in observed and steric sea level trends for the period 1993–2010. (*a*) Patterns from satellite altimetry, using data from Aviso (**http://www.aviso.oceanobs.com**) with the uniform global mean trend removed. (*b*) Patterns from the total steric contribution, using updated ocean temperature and salinity data from Ishii & Kimoto (2009) (version 6.12 of their data) integrated over the 0–700-m depth range with the uniform global mean trend removed.

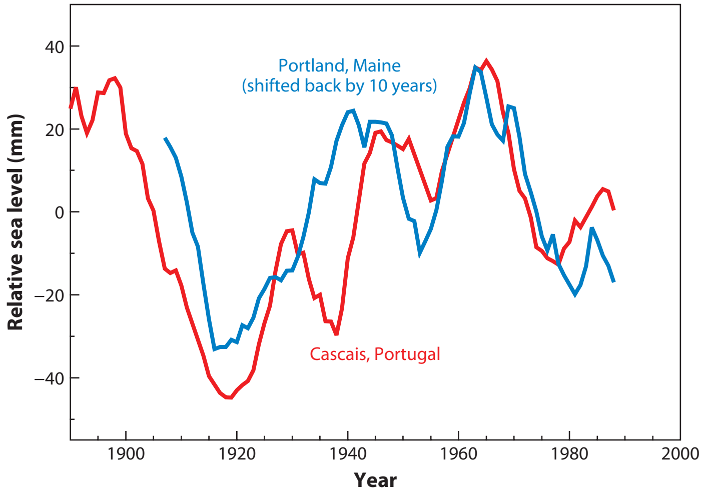


Figure 7

Time series of sea level measurements obtained at Cascais, Portugal (*red*), and Portland, Maine (*blue*), with the latter shifted back by 10 years. Adapted from Miller & Douglas (2007, figure 3) with permission from the American Geophysical Union. Copyright © 2007 by the American Geophysical Union.

Timmermann et al. (2010) and Merrifield & Maltrud (2010) demonstrated that the observed sea level trend from 1958 to 2001 can be explained as the ocean's dynamic response to variations in the wind forcing. In particular, the large rates of sea level rise in the western tropical Pacific and sea level fall in the eastern Pacific during 1993–2009 correspond to an increase in the strength of the trade winds in the central and eastern tropical Pacific during the same period (**Figure 8**).

4.3. Regional Trends: Natural Variability or Anthropogenic Forcing?

Although there is clear consensus that sea level trends in the Indo-Pacific region during the past two decades are closely related to wind stress intensification, one may raise the question of whether the long-term persistence of the recent wind regime is linked with anthropogenic global warming. Merrifield & Maltrud (2011) suggested that the recent trade wind increase and associated high sea level rates in the western Pacific may be the signature of a forced response of the coupled ocean and atmosphere to anthropogenic global warming rather than natural climate variations. Han et al. (2010) drew a similar conclusion, suggesting that regional sea level changes that have emerged in the Indian Ocean since the 1960s are driven by a changing wind forcing associated with a combined enhancement of Hadley and Walker cells. However, their conclusion could be premature, partly because variations of the wind regime and sea level have been reported on a multidecadal timescale in the Indo-Pacific region, with a trend reversal in the early 1990s. Along these lines, Schwarzkopf & Böning (2011) suggested that the late-twentieth-century South Indian sea level decline, which was observed to have reversed in the 1990s, reflects the impact of a regime shift in the tropical Pacific easterlies communicated between both basins via wave transmission through the Indonesian archipelago. These waves subsequently propagate westward as baroclinic Rossby waves.

Using long-term (500-year) control runs from eight coupled climate models without external forcing, Meyssignac et al. (2012b) examined sea level variability in the tropical Pacific. Sea level trend patterns similar to those observed during the altimetry era and the past 60 years occurred at

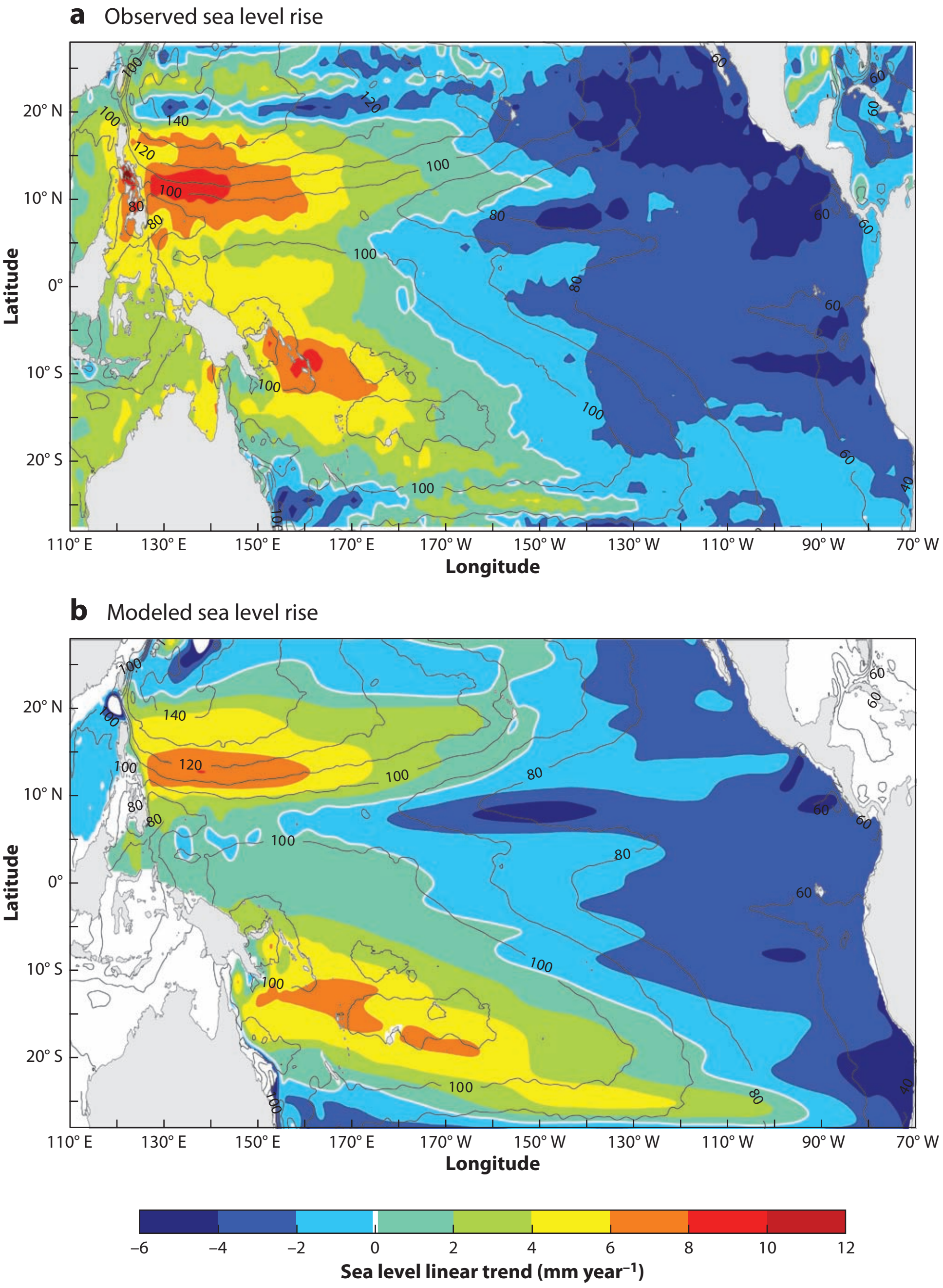


Figure 8

(*a*) Observed (with a rate of 3 mm year^{-1} removed from the field) and (*b*) modeled sea level rise during 1993–2009. Adapted from Qiu & Chen (2012, figure 10) with permission from the American Meteorological Society. Copyright © 2012 by the American Meteorological Society.

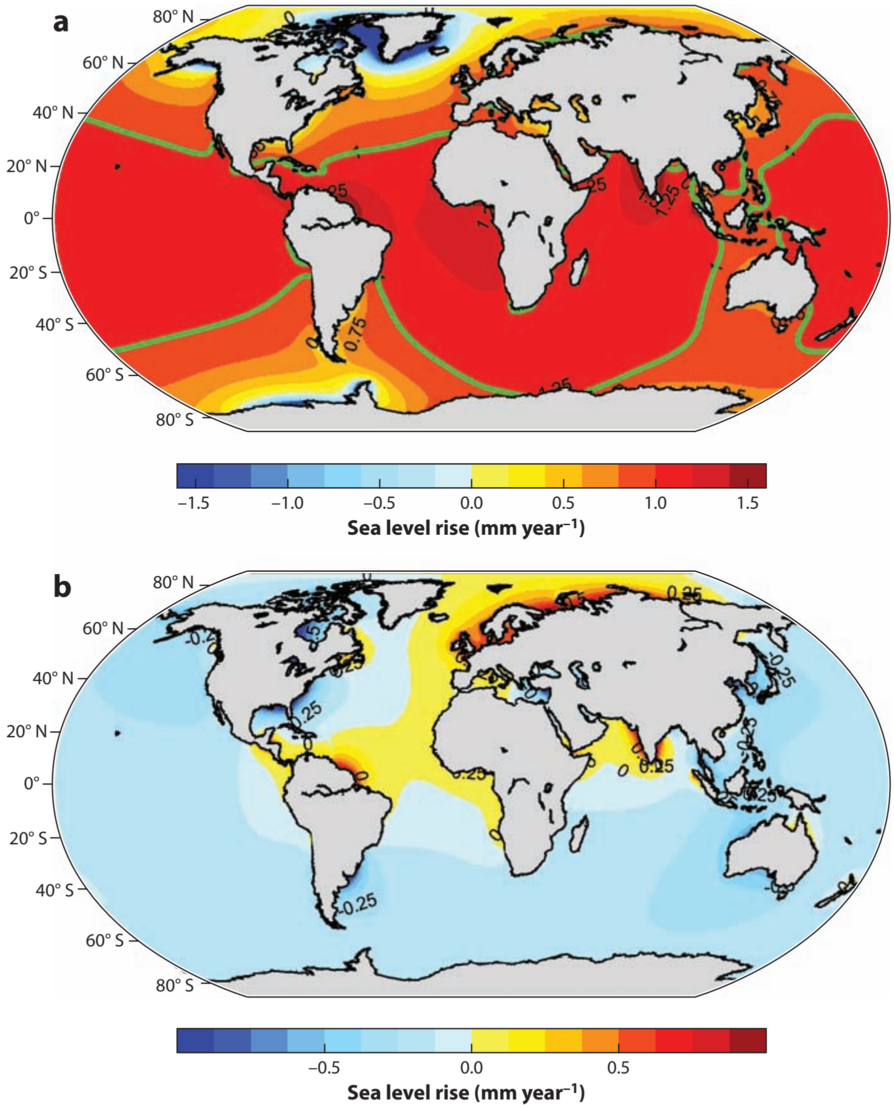


Figure 9

Static relative sea level rise modeled using Gravity Recovery and Climate Experiment (GRACE)–observed mass variations from (*a*) glaciated and (*b*) nonglaciated regions. The global average of panel *a* is 1.0 mm year^{-1} (*green contour*); the global average of panel *b* is -0.1 mm year^{-1}. Adapted from Riva et al. (2010, figures 2 and 3) with permission from the American Geophysical Union. Copyright © 2010 American Geophysical Union.

different periods in the past and were essentially driven by low-frequency (multidecadal) ENSO modes. An extension of this analysis using twentieth-century coupled model runs (with external forcing, in this case anthropogenic greenhouse gas emissions plus aerosols, volcanic eruptions, and solar radiation changes) did not change the conclusion—i.e., the observed regional sea level variability in the tropical Pacific seems to mostly reflect internal modes of ocean variability. Substantial decadal- to centennial-scale sea level variability is also present at mid- and high latitudes in millennium-scale climate simulations (M. Carson, A. Köhl, J. Jungclaus, E. Zorita & D. Stammer, manuscript to be submitted).

A forcing signature of enhanced meltwater supply from the Greenland ice sheet also appears to be hard to detect thus far in terms of the ocean's response. Although an associated increase in ocean mass is communicated quickly around the ocean basins, resulting in global sea level increases (e.g., Ponte 2006b, Lorbacher et al. 2012), the addition of freshwater from Greenland also results in a basin-wide steric response in the North Atlantic on timescales of a few years, communicated via boundary waves, equatorial Kelvin waves, and westward-propagating baroclinic Rossby waves (Stammer 2008, Stammer et al. 2011). A complete baroclinic adjustment of the global ocean might take several hundred years. In addition, sea level changes resulting from meltwater forcing in the subpolar North Atlantic cause changes in the meridional overturning circulation (MOC), which can have wider implications for sea level changes across the North Atlantic. Using hindcast simulations for the period 1958–2004, Lorbacher et al. (2010) suggested that the sea level change pattern is related primarily to the wind-driven variability of the MOC and gyre circulation on interannual timescales. Thus, the pattern is not useful as a fingerprint of longer-term changes in the MOC due to Greenland runoff, because the detectability of such a trend is low along the Gulf Stream owing to a large wind-driven natural variability. More favorable signal-to-noise ratios are found in the subpolar gyre and the eastern North Atlantic, where a significant imprint in sea level is apparent after approximately 20 years.

5. REGIONAL VARIATIONS DUE TO LAND MOTION AND GEOID CHANGES

5.1. Static Effects Due to Contemporary Mass Changes

Besides the simple addition to the GMSL due to freshwater fluxes into the ocean, the loading variations from grounded ice mass changes or continental water storage variations also introduce regional patterns into sea level change; in studies of polar ice melting, these patterns have been called fingerprints. The fingerprints associated with water redistribution are robust, giving similar predictions for both analytical solutions and a number of different numerical methods (Mitrovica et al. 2011). Most studies utilizing fingerprints have focused on relative sea level, as it is the most relevant result for society; for absolute sea level, the pattern would be significantly different because the contribution due to crustal motion would not be included (Conrad & Hager 1997).

Much of the mass-induced regional sea level change is expected to be due to losses from the glaciers and large ice sheets (Riva et al. 2010, Jacob et al. 2012). Thus, regions in the vicinity of the mass loss, such as Greenland, West Antarctica, and Alaska, should experience a net static sea level fall, while many far-field locations of the ocean should experience a larger-than-average static sea level rise (see **Figure 9*a***). Accurate predictions of sea level change in the near field of the glaciers or ice sheets (up to 2,500 km away) will require detailed knowledge of the spatial distribution of the mass loss (Hill et al. 2011). The far-field pattern, however, will be insensitive to the exact distribution of the mass loss within the ice sheet, e.g., due to melting from western or eastern Greenland (Bamber & Riva 2010). Changes in water storage on the continents, whether due to dam impoundment, groundwater extraction, or natural climate variability, will also introduce regional variations in sea level. Historically, it was difficult to assess the land water component, though attempts have been made for the global mean (Llovel et al. 2011) and the regional variations (Vinogradova et al. 2011). Tide gauges along the coasts capture only a fraction of this signal (Fiedler & Conrad 2010). More reliable results are now available through GRACE by observing the total mass change across the continents. Riva et al. (2010) found that nonglaciated regions contributed little to the global average (-0.1 ± 0.3 mm year^{-1}), although there were a few regions near the coasts that experienced relative sea level trend magnitudes as large as 0.9 mm year^{-1} (**Figure 9*b***).

5.2. Contribution of Glacial Isostatic Adjustment to Present-Day Sea Level Observations

GIA contributes differently to each of the observations of sea level change (tide gauges, altimetry, and GRACE). Tide gauges are affected primarily in the near field of the former ice sheets, with falling sea levels near the loading centers and rising sea levels at the collapsing fore bulges near the edges, though systematic effects occur globally, and thus removal of a GIA model is standard in many tide gauge analyses (Douglas 1991). In contrast, GIA causes a large-scale lowering of the sea surface, or absolute sea level, which is associated with the globally averaged subsidence of the crust across the oceans. This contributes a small bias of approximately -0.3 mm year^{-1} (Peltier 2001, 2009; Peltier & Luthcke 2009) to altimetric estimates of sea level change caused by present-day effects, and this value is typically removed from reported global averages. Compared with the value from present-day mass flux, GIA has the largest contribution to GRACE-derived estimates of mass gain in the oceans. Averaged across the oceans, GIA leads to an apparent water-thickness decrease of over 1 mm year^{-1} (e.g., Chambers et al. 2010). However, there is still a large uncertainty in this value due to its dependence upon GRACE analysis procedures and due to uncertainties in Earth's viscosity structure and ice sheet models (Tamisiea 2011).

5.3. Detecting and Fitting Static Sea Level Patterns

Observed mass variations over the continental ice bodies can be used to generate the expected static sea level changes in the oceans (Riva et al. 2010). At current melt rates, static sea level effects due to ice sheet mass loss lie near the detection thresholds of the available data (Kopp et al. 2010). Nevertheless, at accelerated melt rates, they are expected to become more prominent in much of the ocean in the future as total loss reaches the decimeter scale. The static effects will dominate most quickly near melting ice sheets, becoming important in these regions for future projections (Slangen et al. 2011). As noted above, however, the precise pattern of a static sea level effect in this region is sensitive to the detailed melt geometry. High-latitude ocean warming and increased net precipitation will also contribute (Yin et al. 2009).

6. COASTAL PROCESSES

In terms of coastal sea level variations, vertical crustal motions might dominate the effects measured by tide gauges. Vertical ground motion may be caused by natural phenomena acting on a variety of timescales as well as human-induced activities. In several coastal regions of the world, this component is of the same order of magnitude as the absolute sea level change. Mechanisms causing ground subsidence amplify the GMSL rise. Moreover, in addition to the large-scale crustal deformations discussed in Section 5, other natural vertical motions result from tectonic and volcanic activity and surface loads. Coastal sites and islands located in active tectonic areas can be subject to strong horizontal and vertical crustal deformations associated with the seismic cycle, i.e., interseismic motion resulting from strain accumulation, coseismic motion during an earthquake rupture, and postseismic relaxation, each occurring on different timescales.

It is worth highlighting the importance of crustal motions when discussing local sea level changes to avoid interpreting the observations as being due to factors related only to the climate. To illustrate this, Ballu et al. (2011) reported large earthquake-related ground subsidence at the Torres Islands (Vanuatu) between 1997 and 2009 that was of the same order of magnitude as the absolute climate-related sea level rise, leading to an effective doubling of sea level rise. Large earthquakes that occurred before and after this period also caused sudden vertical motions of several decimeters, generating further apparent sea level rise. In addition, many islands are affected by crustal deformation associated with volcanic activity or simply subside on geological timescales because of the aging lithosphere (Parsons & Sclater 1977).

River deltas are another type of coastal environment that is impacted by ground subsidence. Deltas are dynamic systems linking fluvial and coastal ocean processes. Although agriculture has accelerated the growth of many world deltas (McManus 2002), dam and reservoir construction (e.g., Chao et al. 2008) and river diversion for irrigation have considerably decreased the sediment supply along numerous world rivers, destroying the natural equilibrium of many world deltas (Ericson et al. 2006). Although the evolution of delta morphology under these changing factors is very complex (e.g., Bianchi & Allison 2009, Edmonds & Slingerland 2010), most deltas are currently sinking at rates many times faster than that of climate-related GMSL rise (Syvitski & Saito 2007, Syvitski et al. 2009). The case of the Mississippi delta is particularly noteworthy because ground subsidence there results from multiple factors, including Holocene sediment compaction (Tornqvist 2008) and oil and gas mining (Morton et al. 2006), which together cause ground subsidence along the Gulf Coast in the range of 5–10 mm year^{-1} (Ericson et al. 2006).

Accelerated ground subsidence due to local groundwater withdrawal is another problem that affects several coastal megacities. During the twentieth century, several near-coastal megacities have suffered ground subsidence of a few meters because of groundwater withdrawal (e.g., Phien-wej et al. 2006). For example, during the twentieth century, Tokyo subsided by 5 m, Shanghai by 3 m, and Bangkok by 2 m (Nicholls 2010).

Total relative sea level rise (i.e., absolute sea level rise minus vertical ground motion) acts as an additional stress to the coastal systems (e.g., Nicholls & Cazenave 2010). It interacts with other phenomena such as tides, storms, waves, currents, and winds (the latter being partly driven by climate variability) and thus contributes to sediment transport and shoreline morphology changes. Moreover, the sediment budget is also affected by direct human coastal activities such as coastal infrastructures (harbor, dikes, artificial beaches, dam building along rivers, etc.) and land use practices that today generally prevent inland sediments from migrating to the coast.

To better identify climate-related factors of sea level change, recent tide gauge analyses have removed these local effects by deriving independent estimates of crustal motion from GPS time series (Wöppelmann et al. 2009) (see also **Figure 3**). The resulting trends demonstrate a much greater regional consistency and are directly comparable to altimetry observations. However, these results with the crustal motion removed are not appropriate for coastal planning.

7. DISCUSSION AND OUTLOOK

Modern observations have revealed substantial regional deviations in sea level from the global mean and have demonstrated that those regional patterns vary on a broad range of spatial and temporal scales. Variations in regional sea level observed during the altimeter era are largely steric in nature, i.e., caused by changes in the ocean density field driven mostly by changes in the heat content. However, evidence has emerged that freshwater changes can also be essential in changing regional sea level. The underlying regional temperature and salinity changes are caused by variations of the ocean circulation driven by surface wind forcing. As a result, ongoing regional sea level changes may not be related to anthropogenically forced long-term trends, and may instead represent natural modes of climate variability superimposed on a global trend. However, this situation might change substantially in the future, as longer periods are considered and the relative magnitudes of natural and anthropogenic contributions evolve over time.

When considering coastal regions, it is the relative sea level changes that are of importance for planning and mitigation issues. There are many climate- and non-climate-related processes that cause contemporary relative sea level to vary, especially along coastlines; these processes include changes in the regional circulation, land ice and water redistribution, ground subsidence, and earthquakes. The mix of factors controlling relative sea level differs from place to place, and climate effects may not be the largest (e.g., present ground subsidence outweighs any climate-related effects in some regions). In any case, it is important for the future protection of coastal populations to take into account all factors contributing to the regional nature of sea level change.

7.1. Projections of Regional Variability

There is no reason to believe that natural climate variability will cease in the future, although various climate modes might change their character in a warming climate. Therefore, future regional sea level patterns will continue to be influenced by a complex mix of natural and anthropogenic climate processes with multiple spatial and temporal scales. Accordingly, geographic patterns of future sea level changes will continue to show nonuniform steric effects and variability on a range of timescales (e.g., Intergov. Panel Clim. Change 2007, Pardaens et al. 2011, Suzuki & Ishii 2011, Yin et al. 2010). The presence of natural variability is a considerable challenge for projections of future regional sea level change, as the basis for predicting many major climate modes (ENSO, the Pacific Decadal Oscillation, the Indian Ocean Dipole, etc.) is not fully developed and understood on interannual and longer timescales.

Pronounced differences in projected regional sea level variability remain between different Coupled Model Intercomparison Project (CMIP)–type climate projections (A.B.A. Slangen, M. Carson, C.A. Katsman, R.S.W. van de Wal & D. Stammer, manuscript submitted). However, ensemble means indicate higher sea level rise (with respect to the global mean) in some regions—for example, in the Arctic Ocean due to halosteric height increases caused by freshwater input in that region (from sea ice and Greenland melting, increased precipitation, and Arctic river runoff). Strong compensation between thermosteric and halosteric effects is predicted in the Atlantic, with a slight dominating effect from thermal expansion. In the Southern Ocean, at latitudes centered near 60° S, there is a tendency for sea level fall compared with the global mean just south of a band of sea level rise; such a dipole-like behavior is associated with changes of the Antarctic Circumpolar Current. In the Indian Ocean, projections generally indicate the sea level rising at rates slightly higher than the global mean. The Intergovernmental Panel on Climate Change (2007), Pardaens et al. (2011), Suzuki & Ishii (2011), and others drew similar conclusions for the steric effects.

Regional sea level projections are fundamentally dependent on the behavior of the ice sheets. For example, a larger influx of freshwater from Greenland ice sheet melting into the high-latitude Atlantic will cause a highly dynamic regional sea level response in terms of steric long-term adjustments, but will also have an effect on the Atlantic MOC (Stammer 2008, Lorbacher et al. 2010, Stammer et al. 2011). Pardaens et al. (2011) showed a correlation between MOC weakening and North Atlantic sea level change in the CMIP3 ensemble. A weakening of the MOC could have a great impact on coastal sea level, with rapid rises at the northwestern corner of the North Atlantic, including the coastal region north of Cape Hatteras. The superposition of such a dynamic sea level signal on the GMSL rise exposes northeastern North America to some of the fastest and largest sea level rise projected during this century (Yin et al. 2009). Projections for other coastlines, e.g., along the European shelf, also show a regional effect, but do not result in nearly as large a dynamic regional increase as that along the east coast of North America.

With increasing greenhouse gas forcing and an associated warming, anthropogenically forced static changes in sea level, presently not clearly detectable in regional sea level patterns, will gain importance and will become prominent toward the end of the twenty-first century (Slangen et al.

2011). This will be due to gravitational effects and the solid Earth's elastic response, leading to large-scale water mass redistribution with characteristic regional static patterns. Slangen et al. (2011; A.B.A. Slangen, M. Carson, C.A. Katsman, R.S.W. van de Wal & D. Stammer, manuscript submitted) have modeled relative regional sea level changes to 2100, accounting for steric effects plus the last deglaciation-induced GIA and additional deformational and gravitational effects due to future land ice melt. The past and ongoing land ice melt leads to strong deviation from the GMSL rise in the vicinity of the melting bodies where a sea level fall occurs. In some parts of the Arctic Ocean, the static factors compensate for sea level rise due to freshening.

7.2. Required Long-Term Observations

Long-term measurements are required to understand ongoing and future sea level changes and attribute them to natural variability or anthropogenic effects. This holds for global as well as regional sea levels. To obtain these measurements, a number of observational requirements must be met (e.g., Wilson et al. 2010), including the continuation of coastal tide gauge measurements as well as measurements of full-depth temperature and salinity, use of altimeter satellites for measurements of geometric sea level, and use of space gravimetry for measurements of ocean mass change, ice sheet mass balance, and land water storage change. Most of these data sets already exist and provide an initial basis for present sea level studies. For a more accurate assessment of global and regional sea level changes and their relationship to changes in the hydrological cycle and Earth's energy budget, these data sets need to be expanded to allow for truly global and continuous coverage.

In addition to long altimetry time series and Argo measurements, the GRACE satellites have been invaluable for measuring changes in water mass storage across the planet. A better understanding of the large-scale mass redistributions in the entire Earth system associated with climate change and variability requires continuous, long-term measurements of gravity and an ongoing series of GRACE-type satellites. The Argo measurements have provided good geographic coverage only since 2004. However, a system must be devised to observe changes in temperature and salinity below 2,000-m depths and under sea ice. Deep ocean temperature changes have been observed in every ocean basin (e.g., Johnson et al. 2007, 2008; Purkey & Johnson 2010), but the contribution of these deep steric changes to global and regional sea level rise remains poorly understood. In addition, we need to continue and expand high-quality tide gauge measurements. Although useful for calibration purposes, they also allow for monitoring regional sea level effects that are difficult to observe via satellites and for assessing different behaviors between the coastal and deep oceans.

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LITERATURE CITED

Ablain M, Cazenave A, Valladeau G, Guinehut S. 2009. A new assessment of the error budget of global mean sea level rate estimated by satellite altimetry over 1993–2008. *Ocean Sci.* 5:193–201

Argo Data Manag. Team. 2008. 9th Argo Data Management Meeting. *Argo Data Manag. Meet. Rep.*, Honolulu, HI, Oct. 29–31. **http://www.argo.ucsd.edu/DM9report.pdf**

Ballu V, Bouin MN, Simeoni P, Crawford WC, Calmant S, et al. 2011. Comparing the role of absolute sea level rise and vertical tectonic motions in coastal flooding, Torres Islands (Vanuatu). *Proc. Natl. Acad. Sci. USA* 108:13019–22

Bamber J, Riva R. 2010. The sea level fingerprint of recent ice mass fluxes. *Cryosphere* 4:621–27

Becker M, Meyssignac B, Llovel W, Cazenave A, Delcroix T. 2012. Sea level variations at tropical Pacific islands during 1950–2009. *Glob. Planet. Change* 80–81:85–98

Bianchi TS, Allison MA. 2009. Large river delta-front estuaries as natural recorders of global environmental change. *Proc. Natl. Acad. Sci. USA* 106:8085–92

Bindoff N, Willebrand J, Artale V, Cazenave A, Gregory J, et al. 2007. Observations: oceanic climate and sea level. See Intergov. Panel Clim. Change 2007, pp. 385–432

Bingham RJ, Hughes CW. 2012. Local diagnostics to estimate density-induced sea level variations over topography and along coastlines. *J. Geophys. Res.* 117:C01013

Carton JA, Giese BS, Grodsky SA. 2005. Sea level rise and the warming of the oceans in the Simple Ocean Data Assimilation (SODA) ocean reanalysis. *J. Geophys. Res.* 110:C09006

Cazenave A, Dominh K, Guienhut S, Berthier E, Llovel W, et al. 2009. Sea level budget over 2003–2008: a reevaluation from GRACE space gravimetry, satellite altimetry and Argo. *Glob. Planet. Change* 65:83–88

Cazenave A, Henry O, Munier S, Delcroix T, Gordon A, et al. 2012. Estimating ENSO influence on the global mean sea level. *Mar. Geod.* In press

Cazenave A, Llovel W. 2010. Contemporary sea level rise. *Annu. Rev. Mar. Sci.* 2:145–73

Chambers DP. 2011. ENSO-correlated fluctuations in ocean bottom pressure and wind-stress curl in the North Pacific. *Ocean Sci.* 7:685–92

Chambers DP, Wahr J, Tamisiea ME, Nerem RS. 2010. Ocean mass from GRACE and glacial isostatic adjustment. *J. Geophys. Res.* 115:B11415

Chao BF, Wu YH, Li YS. 2008. Impact of artificial reservoir water impoundment on global sea level. *Science* 320:212–14

Chen JL, Wilson CR, Blankenship D, Tapley BD. 2009. Accelerated Antarctic ice loss from satellite gravity measurements. *Nat. Geosci.* 2:859–62

Church JA, White NJ. 2011. Sea-level rise from the late 19th to the early 21st century. *Surv. Geophys.* 32:585–602

Church JA, White NJ, Konikow LF, Domingues CM, Cogley JG, et al. 2011. Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. *Geophys. Res. Lett.* 38:L18601

Church JA, Woodworth PL, Aarup T, Wilson WS, eds. 2010. *Understanding Sea-Level Rise and Variability*. Oxford, UK: Wiley-Blackwell. 428 pp.

Clark JA, Primus JA. 1987. Sea-level changes resulting from future retreat of ice sheets: an effect of CO_2 warming of the climate. In *Sea-Level Changes*, IBG Spec. Publ. Ser. 20, ed. MJ Tooley, I Shennan, pp. 356–70. Oxford, UK: Blackwell

Clarke PJ, Lavallée DA, Blewitt G, van Dam TM, Wahr JM. 2005. Effect of gravitational consistency and mass conservation on seasonal surface mass loading models. *Geophys. Res. Lett.* 32:L08306

Cogley JC. 2009. Geodetic and direct mass balance measurements: comparison and joint analysis. *Ann. Glaciol.* 50:96–100

Conrad C, Hager BH. 1997. Spatial variations in the rate of sea level rise caused by present-day melting of glaciers and ice sheets. *Geophys. Res. Lett.* 24:1503–6

Domingues C, Church J, White N, Glekler PJ, Wijffels SE, et al. 2008. Improved estimates of upper ocean warming and multidecadal sea level rise. *Nature* 453:1090–93

Douglas BC. 1991. Global sea level rise. *J. Geophys. Res.* 96:6981–92

Douglas BC. 2001. Sea level change in the era of the recording tide gauge. In *Sea Level Rise: History and Consequences*, ed. BC Douglas, MS Kearney, SP Leatherman, pp. 37–64. San Diego: Academic

Durack PJ, Wijffels SE. 2010. Fifty-year trends in global ocean salinities and their relationship to broad-scale warming. *J. Clim.* 23:4342–62

Edmonds DA, Slingerland RL. 2010. Significant effect of sediment cohesion on delta morphology. *Nat. Geosci.* 3:105–9

Ericson JP, Vorosmarty CJ, Dingman SL, Ward LG, Meybeck L. 2006. Effective sea level rise and deltas: causes of change and human dimension implications. *Glob. Planet. Change* 50:63–82

Farrell WE, Clark JA. 1976. On postglacial sea level. *Geophys. J. R. Astron. Soc.* 46:647–67

Fiedler JW, Conrad CP. 2010. Spatial variability of sea level rise due to water impoundment behind dams. *Geophys. Res. Lett.* 37:L12603

Giles KA, Laxon SW, Ridout AL, Wingham DJ, Bacon S. 2012. Western Arctic Ocean freshwater storage increased by wind-driven spin-up of the Beaufort Gyre. *Nat. Geosci.* 5:194–97

Han WQ, Meehl GA, Rajagopalan B, Fasullo JT, Hu AX, et al. 2010. Patterns of Indian Ocean sea-level change in a warming climate. *Nat. Geosci.* 3:546–50

Hill EM, Davis JL, Tamisiea ME, Ponte RM, Vinogradova NT. 2011. Using a spatially realistic load model to assess impacts of Alaskan glacier ice loss on sea level. *J. Geophys. Res.* 116:B10407

Hong BG, Sturges W, Clarke AJ. 2000. Sea level on the US East Coast: decadal variability caused by open ocean wind-curl forcing. *J. Phys. Oceanogr.* 30:2088–98

Hu AX, Meehl GA, Otto-Bliesner BL, Waelbroeck C, Han WQ, et al. 2010. Influence of Bering Strait flow and North Atlantic circulation on glacial sea-level changes. *Nat. Geosci.* 3:118–21

Intergov. Panel Clim. Change. 2007. *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Ed. S Solomon, D Qin, M Manning, Z Chen, M Marquis, et al. Cambridge: Cambridge Univ. Press

Ishii M, Kimoto M. 2009. Reevaluation of historical ocean heat content variations with varying XBT and MBT depth bias corrections. *J. Oceanogr.* 65:287–99

Jacob T, Wahr J, Pfeffer WT, Swenson S. 2012. Recent contributions of glaciers and ice caps to sea level rise. *Nature* 482:514–18

Jevrejeva S, Moore JC, Grinsted A, Woodworth PL. 2008. Recent global sea level acceleration started over 200 years ago? *Geophys. Res. Lett.* 35:L08715

Johnson GC, Mecking S, Sloyan BM, Wijffels SE. 2007. Recent bottom water warming in the Pacific Ocean. *J. Clim.* 20:5365–75

Johnson GC, Purkey SG, Bullister JL. 2008. Warming and freshening in the abyssal southeastern Indian Ocean. *J. Clim.* 21:5351–63

Kaser G, Cogley JG, Dyurgerov MB, Meier MF, Ohmura A. 2006. Mass balance of glaciers and ice caps: consensus estimates for 1961–2004. *Geophys. Res. Lett.* 33:L19501

Köhl A, Stammer D. 2008. Decadal sea level changes in the 50-year GECCO ocean synthesis. *J. Clim.* 21:1876–90

Köhl A, Stammer D, Cornuelle B. 2007. Interannual to decadal changes in the ECCO global synthesis. *J. Phys. Oceanogr.* 37:313–37

Konikow LF. 2011. Contribution of global groundwater depletion since 1900 to sea level rise. *Geophys. Res. Lett.* 38:L17401

Kopp RE, Mitrovica JX, Griffies SM, Yin J, Hay CC, Stouffer RJ. 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. *Clim. Change* 103:619–25

Lambeck K. 1988. *Geophysical Geodesy: The Slow Deformations of the Earth*. Oxford, UK: Oxford Univ. Press. 710 pp.

Levitus S, Antonov JL, Boyer TP. 2005. Warming of the world ocean, 1955–2003. *Geophys. Res. Lett.* 32:L02604

Levitus S, Antonov JL, Boyer TP, Locarnini RA, Garcia HE, Mishonov AV. 2009. Global ocean heat content 1955–2008 in light of recently revealed instrumentation. *Geophys. Res. Lett.* 36:L07608

Levitus S, Antonov J, Boyer TP, Stephens C. 2000. Warming of the world ocean. *Science* 287:2225–29

Llovel W, Becker M, Cazenave A, Jevrejeva S, Alkama R, et al. 2011. Terrestrial waters and sea level variations on interannual time scale. *Glob. Planet. Change* 75:76–82

Lombard A, Garric G, Penduff T. 2009. Regional patterns of observed sea level change: insights from a $^1/_4$° global ocean/sea-ice hindcast. *Ocean Dyn.* 59:433–49

Lorbacher K, Dengg J, Böning CW, Biastoch A. 2010. Regional patterns of sea level change related to interannual variability and multi-decadal trends in the Atlantic meridional overturning circulation. *J. Clim.* 23:4243–54

Lorbacher K, Marsland SJ, Church JA, Griffies SM, Stammer D. 2012. Rapid barotropic sea level rise from ice sheet melting. *J. Geophys. Res.* 117:C06003

Lowe JA, Gregory JM. 2006. Understanding projections of sea level rise in a Hadley Centre coupled climate model. *J. Geophys. Res.* 111:C11014

Lyman JM, Godd SA, Gouretski VV, Ishii M, Johnson GC, et al. 2010. Robust warming of the global upper ocean. *Nature* 465:334–37

Masters D, Nerem RS, Choe C, Leuliette E, Beckley B, et al. 2012. Comparison of global mean sea level time series from TOPEX/Poseidon, Jason-1, and Jason-2. *Mar. Geod.* In press

McManus J. 2002. Deltaic responses to changes in river regimes. *Mar. Geochem.* 79:155–70

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, et al. 2007. Global climate projections. See Intergov. Panel Clim. Change 2007, pp. 748–845

Meier MF, Dyurgerov MB, Rick UK, O'Neel S, Pfeffer WT, et al. 2007. Glaciers dominate eustatic sea-level rise in the 21st century. *Science* 317:1064–67

Merrifield MA, Maltrud ME. 2011. Regional sea level trends due to a Pacific trade wind intensification. *Geophys. Res. Lett.* 38:L21605

Merrifield MA, Merrifield ST, Mitchum GT. 2009. An anomalous recent acceleration of global sea level rise. *J. Clim.* 22:5772–81

Meyssignac B, Becker M, Llovel W, Cazenave A. 2012a. An assessment of two-dimensional past sea level reconstructions over 1950–2009 based on tide gauge data and different input sea level grids. *Surv. Geophys.* 33:945–72

Meyssignac B, Salas Y, Melia D, Llovel W, Cazenave A. 2012b. Spatial trend patterns in observed sea level: internal variability or anthropogenic signature? *Clim. Past* 8:787–802

Miller L, Douglas BC. 2007. Gyre-scale atmospheric pressure variations and their relation to 19th and 20th century sea level rise. *Geophys. Res. Lett.* 34:L16602

Milly PCD, Cazenave A, Famiglietti J, Gornitz V, Laval K, et al. 2010. Terrestrial water storage contributions to sea level rise and variability. See Church et al. 2010, pp. 226–54

Milne GA, Gehrels W, Hughes C, Tamisiea M. 2009. Identifying the causes of sea-level change. *Nat. Geosci.* 2:471–78

Milne GA, Mitrovica JX. 1998. Postglacial sea-level change on a rotating Earth. *Geophys. J. Int.* 133:1–19

Mitchum GT, Nerem RS, Merrifield MA, Gehrels WR. 2010. Modern sea level change estimates. See Church et al. 2010, pp. 122–42

Mitrovica JX, Gomez N, Morrow E, Hay C, Latychev K, Tamisiea ME. 2011. On the robustness of predictions of sea level fingerprints. *Geophys. J. Int.* 187:729–42

Mitrovica JX, Tamisiea ME, Davis JL, Milne GA. 2001. Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. *Nature* 409:1026–29

Morison J, Kwok R, Peralta-Ferriz C, Alkire M, Rigor I, et al. 2012. Changing Arctic Ocean freshwater pathways. *Nature* 481:66–70

Morton RA, Bernier JC, Barras JA. 2006. Evidence of regional subsidence and associated interior wetland loss induced by hydrocarbon production, Gulf Coast region, USA. *Environ. Geol.* 50:261–74

Nerem RS, Chambers DP, Choe C, Mitchum GT. 2010. Estimating mean sea level change from the TOPEX and Jason altimeter missions. *Mar. Geod.* 33:435–46

Nicholls RJ. 2010. Impacts of and responses to sea level rise. See Church et al. 2010, pp. 17–51

Nicholls RJ, Cazenave A. 2010. Sea level change and the impacts in coastal zones. *Science* 328:1517–20

Okumora YM, Deser C, Hu A. 2009. North Pacific climate response to freshwater focring in the subarctic North Atlantic: oceanic and atmospheric pathways. *J. Clim.* 22:1424–45

Pardaens AK, Lowe JA, Brown S, Nicholls RJ, de Gusmao D. 2011. Sea-level rise and impacts projections under a future scenario with large greenhouse gas emission reductions. *Geophys. Res. Lett.* 38:L12604

Parsons B, Sclater JG. 1977. An analysis of the variation of the ocean floor bathymetry heat flow and with age. *J. Geophys. Res.* 82:803–27

Peltier WR. 2001. Global glacial isostatic adjustment and modern instrumental records of relative sea level history. In *Sea Level Rise: History and Consequences*, ed. BC Douglas, MS Kearney, SP Leatherman, pp. 65–95. San Diego: Academic

Peltier WR. 2004. Global glacial isostasy and the surface of the ice-age Earth. *Annu. Rev. Earth Planet. Sci.* 32:111–49

Peltier WR. 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. *Quat. Sci. Rev.* 28:1658–74

Peltier WR, Luthcke SB. 2009. On the origins of Earth rotation anomalies: new insights on the basis of both "paleogeodetic" data and Gravity Recovery and Climate Experiment (GRACE) data. *J. Geophys. Res.* 114:B11405

Phien-wej N, Giao PH, Nutalaya P. 2006. Land subsidence in Bangkok. *Eng. Geol.* 82:187–201

Piecuch CG, Ponte RM. 2012. Buoyancy-driven interannual sea level changes in the southeast tropical Pacific. *Geophys. Res. Lett.* 39:L05607

Ponte RM. 1993. Variability in a homogeneous global ocean forced by barometric pressure. *Dyn. Atmos. Oceans* 18:209–34

Ponte RM. 2006a. Low-frequency sea level variability and the inverted barometer effect. *J. Atmos. Ocean. Technol.* 23:619–29

Ponte RM. 2006b. Oceanic response to surface loading effects neglected in volume-conserving models. *J. Phys. Oceanogr.* 36:426–34

Ponte RM. 2012. An assessment of deep steric height variability over the global ocean. *Geophys. Res. Lett.* 39:L04601

Purkey SG, Johnson GC. 2010. Warming of global abyssal and deep Southern Ocean waters between the 1990s and 2000s: contributions to global heat and sea level rise budgets. *J. Clim.* 23:6336–51

Qiu B, Chen S. 2010. Interannual-to-decadal variability in the bifurcation of the North Equatorial Current off the Philippines. *J. Phys. Oceanogr.* 40:2525–38

Qiu B, Chen S. 2012. Multidecadal sea level and gyre circulation variability in the northwestern tropical Pacific Ocean current off the Philippines. *J. Phys. Oceanogr.* 42:193–206

Ray RD, Douglas BC. 2012. Experiments in reconstructing twentieth-century sea levels. *Prog. Oceanogr.* 91:496–515

Rignot E, Bamber JL, Van den Broecke MR, Davis C, Li Y, et al. 2008a. Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. *Nat. Geosci.* 1:106–10

Rignot E, Box JE, Burgess E, Hanna E. 2008b. Mass balance of the Greenland ice sheet from 1958 to 2007. *Geophys. Res. Lett.* 35:L20502

Rignot E, Velicogna I, van den Broeke MR, Monaghan A, Lenaerts J. 2011. Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophys. Res. Lett.* 38:L05503

Riva REM, Bamber JL, Lavallée DA, Wouters B. 2010. Sea-level fingerprint of continental water and ice mass change from GRACE. *Geophys. Res. Lett.* 37:L19605

Schwarzkopf FU, Böning CW. 2011. Contribution of Pacific wind stress to multi-decadal variations in upper-ocean heat content and sea level in the tropical south Indian Ocean. *Geophys. Res. Lett.* 38:L12602

Slangen ABA, Katsman CA, van de Val RSW, Vermeersen LLA, Riva REM. 2011. Towards regional projections of twenty-first century sea level change based on IPCC SRES scenarios. *Clim. Dyn.* 38:1191–209

Song YT, Colberg F. 2011. Deep ocean warming assessed from altimeters, Gravity Recovery and Climate Experiment, in situ measurements, and a non-Boussinesq ocean general circulation model. *J. Geophys. Res.* 116:C02020

Stammer D. 2008. Response of the global ocean to Greenland and Antarctica melting. *J. Geophys. Res.* 113:C06022

Stammer D, Agarwal N, Herrmann P, Köhl A, Mechoso R. 2011. Sea level response to Greenland ice melting in a coupled climate model. *Surv. Geophys.* 32:621–42

Stammer D, Köhl A, Awaji T, Balmaseda M, Behringer D, et al. 2010. Ocean information provided through ensemble ocean syntheses. *Proc. OceanObs'09 Sustain. Ocean Obs. Inf. Soc. Conf.*, Vol. 2, Venice, Sept. 21–25, 2009, ESA Publ. WPP-306, ed. J Hall, DE Harrison, D Stammer. Paris: Eur. Space Agency. **http://www.oceanobs09.net/proceedings/cwp/cwp85**

Steffen K, Thomas RH, Rignot E, Cogley JG, Dyurgerov MB, et al. 2010. Cryospheric contributions to sea level rise and variability. See Church et al. 2010, pp. 177–225

Sturges W, Hong BG, Clarke AJ. 1998. Decadal wind forcing of the North Atlantic subtropical gyre. *J. Phys. Oceanogr.* 28:659–68

Sutton P, Roemmich D. 2011. Decadal steric and sea surface height changes in the Southern Hemisphere. *Geophys. Res. Lett.* 38:L08604

Suzuki T, Ishii M. 2011. Regional distribution of sea level changes resulting from enhanced greenhouse warming in the Model for Interdisciplinary Research on Climate version 3.2. *Geophys. Res. Lett.* 38:L02601

Syvitski JPM, Kettner AJ, Overeem I, Hutton EWH, Hannon MT, et al. 2009. Sinking deltas due to human activities. *Nat. Geosci.* 2:681–89

Syvitski JPM, Saito Y. 2007. Morphodynamics of deltas under the influence of humans. *Glob. Planet. Change* 57:261–82

Tamisiea ME. 2011. Ongoing glacial isostatic contributions to observations of sea level change. *Geophys. J. Int.* 186:1036–44

Tamisiea ME, Hill EM, Ponte RM, Davis JL, Velicogna I, Vinogradova NT. 2010. Impact of self-attraction and loading on the annual cycle in sea level. *J. Geophys. Res.* 115:C07004

Tamisiea ME, Mitrovica JX. 2011. The moving boundaries of sea level change: understanding the origins of geographic variability. *Oceanography* 24(2):24–39

Tapley BD, Bettadpur S, Watkins M, Reigber C. 2004. The gravity recovery and climate experiment: mission overview and early results. *Geophys. Res. Lett.* 31:L09607

Timmermann A, McGregor S, Jin F. 2010. Wind effects on past and future regional sea level trends in the southern Indo-Pacific. *J. Clim.* 23:4429–37

Tornqvist TE. 2008. Mississippi delta subsidence primarily caused by compaction of Holocene strata. *Nat. Geosci.* 1:173–76

Van den Broeke MR, Bamber J, Lenaerts J, Rignot E. 2011. Ice sheets and sea level: thinking outside the box. *Surv. Geophys.* 32:495–505

Velicogna I. 2009. Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. *Geophys. Res. Lett.* 36:L19503

Vinogradova NT, Ponte RM, Tamisiea ME, Quinn KJ, Hill EM, Davis JL. 2011. Self-attraction and loading effects on ocean mass redistribution at monthly and longer time scales. *J. Geophys. Res.* 116:C08041

von Schuckmann K, Le Traon PY. 2012. How well can we derive Global Ocean Indicators from Argo data? *Ocean Sci.* 7:783–91

Wada Y, van Beek LPH, van Kempen CM, Reckman JWTM, Vasak S, Bierkens MFP. 2010. Global depletion of groundwater resources. *Geophys. Res. Lett.* 37: L20402

Wada Y, van Beek LPH, Weiland FCS, Chao B, Wu YH, Bierkens MFP. 2012. Past and future contribution of global groundwater depletion to sea level rise. *Geophys. Res. Lett.* 39:L09402

Wenzel M, Schroeter J. 2010. Reconstruction of regional mean sea level anomalies from tide gauges using neural networks, *J. Geophys. Res.* 115:C08013

White NJ, Church JA, Gregory JM. 2005. Coastal and global averaged sea level rise for 1950 to 2000. *Geophys. Res. Lett.* 32:L01601

Wilson WS, Abdalati W, Alsdorf D, Benveniste J, Bonekamp H, et al. 2010. Observing systems needed to address sea-level rise and variability. See Church et al. 2010, pp. 376–401

Woodworth PL, Gehrels WR, Nerem RS. 2011. Nineteenth and twentieth century changes in sea level. *Oceanography* 24(2):80–93

Wöppelmann G, Letetrel C, Santamaria A, Bouin M-N, Collilieux X, et al. 2009. Rates of sea-level change over the past century in a geocentric reference frame. *Geophys. Res. Lett.* 36:L12607

Wunsch C, Heimbach P. 2007. Practical global oceanic state estimation. *Physica D* 230:197–208

Wunsch C, Ponte RM, Heimbach P. 2007. Decadal trends in sea level patterns: 1993–2004. *J. Clim.* 20:5889–911

Wunsch C, Stammer D. 1997. Atmospheric loading and the oceanic “inverted barometer” effect. *Rev. Geophys.* 35:79–107

Yin JJ, Griffies SM, Stouffer RJ. 2010. Spatial variability of sea level rise in twenty-first century projections. *J. Clim.* 23:4585–607

Yin JJ, Schlesinger ME, Stouffer RJ. 2009. Model projections of rapid sea-level rise on the northeast coast of the United States. *Nat. Geosci.* 2:262–66

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Errata

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