CITATION

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

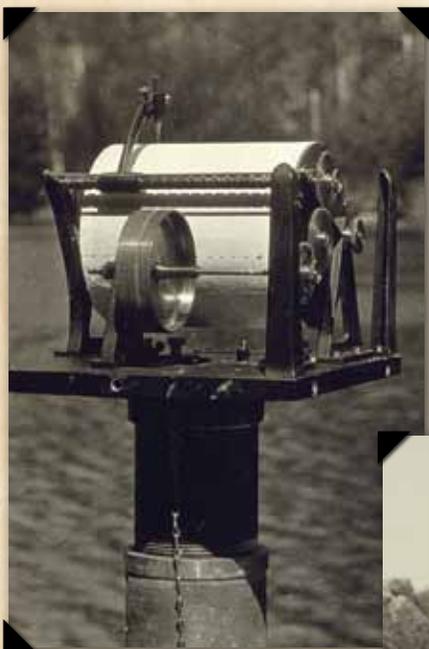# Nineteenth and Twentieth Century
Changes in Sea Level

BY PHILIP L. WOODWORTH, W. ROLAND GEHRELS, AND R. STEVEN NEREM

(top left) Automatic tide gauge mounted on float well off the west coast of Baranof Island, Alaska, 1924. Installed by party off of *Surveyor*. *Photo credit: C&GS Season's Report Sobieralski 1924-93; from http://www.photolib.noaa.gov/ htmls/theb2385.htm*

(top right) Tide gauge in Knik Harbor, Alaska, 1918. Installed by party off of *Eoline Hand*. *Photo credit: C&GS Season's Report Hand 1918-32; from http://www.photolib. noaa.gov/htmls/theb2366.htm*

(bottom left) Tide gauge in the Aleutian Islands, Alaska, 1952. Installed by party off of *Explorer*. *Photo credit: Family of Captain George L. Anderson, C&GS; from http://www. photolib.noaa.gov/htmls/theb2394.htm*

ABSTRACT. Following the Last Glacial Maximum (25,000–20,000 years ago), sea level rose at rates on the order of several tens of millimeters per year at times, and increased overall by over 130 m. However, melting of the great ice sheets was largely complete by 6,000 years ago, and it is believed that sea level did not rise significantly again until recently. The rates of sea level change during the last few centuries and in recent decades can be measured in units of millimeters per year and are particularly important in understanding present-day climate change. We now have a range of techniques with which sea level changes can be measured and thus studied more intensively than before, as a global average and in each region. This article introduces each of the main data sets and presents the primary research findings. It is hoped that a greater understanding of the reasons for past observed sea level change, discussed elsewhere in this issue, will lead to better estimation of the changes likely to occur in the future.

INTRODUCTION

Sea level rise is one of the most important, and most publicized, aspects of climate change. Prerequisites for reliable rise prediction are accurate assessment of past global and regional changes and complete understanding of the causes of these changes. In this article, we address the evidence for sea level changes in the past two centuries, in particular, in the last two decades, while other articles in this issue are concerned with determining the causes (the "sea level budget").

We describe how sea level has been measured in the past with tide gauges and by satellites. We explain why global sea level data derived from tide gauges is limited, both geographically and temporally, and review some of the major research findings derived from it. Salt marsh studies have the potential to extend the tide-gauge data set, both spatially and backward in time, and we provide some examples of this relatively new technique and its complementarity to tide gauges. Then, we describe how precise quasi-global and near-continuous measurements of sea level became possible during the 1990s, thanks to the development of satellite radar altimetry complemented, since 2002, by satellite temporal gravity.

All of these techniques provide evidence for changes in mean sea level (sea level averaged into annual mean values), which is the parameter of most interest to climate researchers. However, the public is mostly concerned with extreme sea level changes, which determine the frequency and severity of flooding and are a major factor in coastal erosion. Consequently, the article closes with pointers to further reading on this important practical topic.

SEA LEVEL MEASUREMENTS BY TIDE GAUGES

The earliest extended sea level measurements were made in Europe during the eighteenth century. These data were visual observations of the heights and times of high and low waters, or sometimes high waters alone. Many entrances to docks (or to "sluices," connections between the sea and inland waters) were equipped with what were then called "tide gauges," graduated markings on their stone walls to indicate water depth over the dock sill. Observations of water level could be made using those markings. Alternatively, wooden measuring rods called "tide-poles" or "tide-staffs" were used.

Visual measurements could have had centimeter-level accuracy in calm weather conditions, but would have been much less accurate in the presence of waves, especially at night during winter. A "stilling well" enables a more accurate measurement of the "still water level" (Moray, 1665). This technique uses a vertical tube with a small opening at the bottom so that the water level inside the tube is the same as that outside. The small opening dampens the water-level fluctuations due to waves. By the 1830s, automatic (or "self-registering") tide gauges had been developed that could record the full tidal curve, not just the high and low waters; the first is often credited to Palmer (1831), with the first in the United States made by Joseph Saxton for the US Coast Survey in 1851. These instruments again employed a stilling well but also contained a float connected by a wire run over pulleys to a pen that moved up and down as the tide rose and fell, thereby drawing a tidal curve on a rotating drum of paper. The resulting continuous water-level measurements could then be expressed

relative to the height of a benchmark on the nearby land. Benchmarks are usually made of brass and are fixed into solid rock, or sometimes buildings, to provide a local height reference level.

By the end of the nineteenth century, similar instruments had been installed at most major ports. Their primary purpose was to obtain sufficient knowledge of the local tide to allow accurate tidal predictions for port operations and coastal navigation. Their data were also used to determine national datums. As their time series extended, it became clear that they had many other scientific and practical applications, including operational flood warning in areas prone to storm surges and tsunamis. New technologies have since replaced float gauges at many locations. However, it is important to note that float gauges have provided the bulk of the historical sea level data set, including the evidence for sea level rise over the past two centuries, and they still constitute a large fraction of the global network.

The Permanent Service for Mean Sea Level (PSMSL; Woodworth and Player, 2003) is the global data bank for long-term sea level information from tide gauges. Figure 1 presents an overview of

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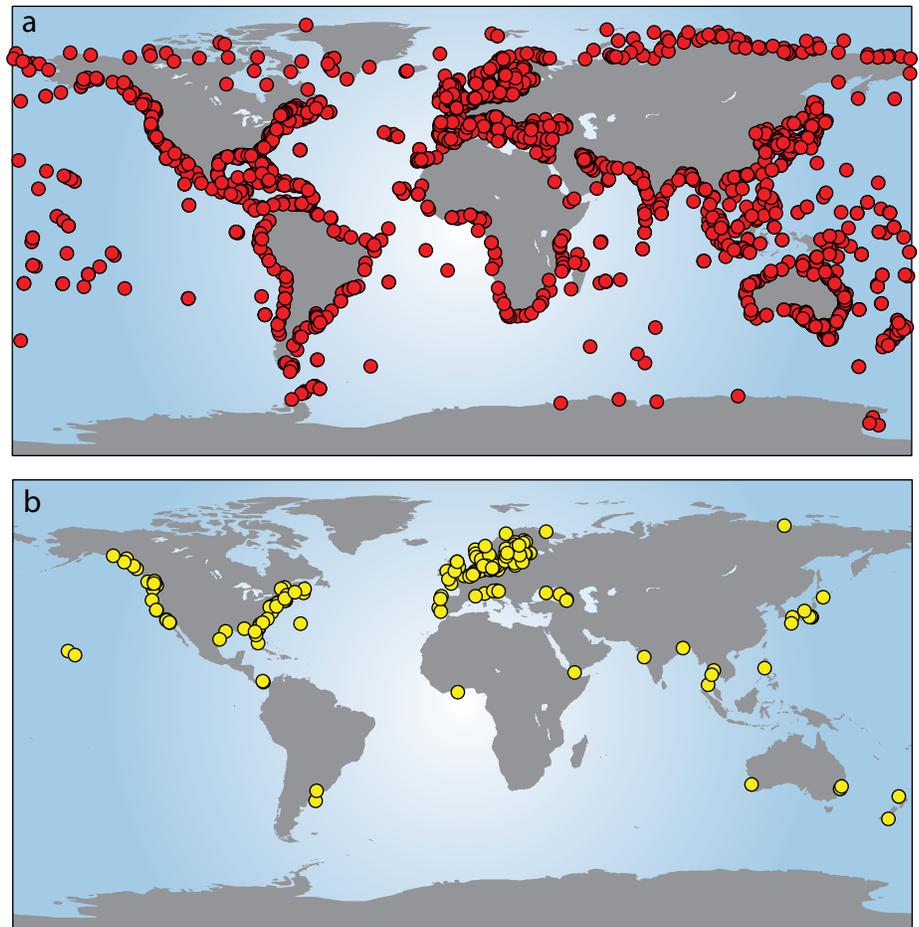
Figure 1. (a) Stations represented in the data set of the Permanent Service for Mean Sea Level (PSMSL). (b) Stations with long records containing more than 60 years of data.

its data holdings. The data set contains much greater contributions from the Northern Hemisphere and for the second half of the twentieth century, and such bias must always be kept in mind when considering time series of "global-average" sea level change. Issues of data quality must also always be considered in the study of historical information, with records subjected to careful inspection prior to analysis; the PSMSL Web site (http://www.psmsl.org) contains detailed information on this aspect while Douglas (2008), for example, contains several examples of data difficulties.

All of the PSMSL tide-gauge data

(and also geological and archaeological measurements of sea level) are "relative" ones (i.e., relative to the local land) unlike the "geocentric" (relative to Earth's center) ones described below for satellite altimetry. Figure 2 presents four representative records from the US component of the PSMSL data set, demonstrating the importance of vertical land movements (VLMs) to the records. San Francisco and New York are the longest, near-continuous records from the United States (Key West is arguably the longest US record, but it contains many gaps; Maul and Martin, 1993). These records indicate rising sea

levels through the twentieth century of approximately 1.4 and 2.8 mm yr^{-1}, respectively, an amount comparable to that seen at mid-latitude stations throughout the world if corrections are made for VLM using a model of glacial isostatic adjustment (GIA). These corrections amount to approximately 0.4 and –1.4 mm yr^{-1}, respectively (e.g., Douglas, 1991), the latter being large and negative as a consequence of New York's location in the forebulge of the North American deglaciation (a region that is still sinking in response to the end of the last ice age, making local sea level rise appear bigger than the global rate in the New York tide gauge; Peltier, 2001; see also Tamisiea and Mitrovica, 2011, in this issue). Evidence such as these two records, and many others worldwide, are the basis of our belief that sea level has risen globally during the twentieth century. However, at Sitka, Alaska, sea level is falling at a rate of over 2 mm yr^{-1} as a result of a combination of GIA and local tectonics. Even higher rates of sea level fall due to GIA can be observed in other records from former glaciated areas (e.g., Hudson Bay, Scandinavia). Meanwhile, the Galveston record shows an extremely high rate of rise (over 6 mm yr^{-1}), which has nothing to do with natural geological processes like GIA, but is a consequence of the removal of groundwater and hydrocarbons (Emery and Aubrey, 1991).

Three methods are often used to correct tide-gauge records for VLMs. The first requires GIA to be the dominant geological process at the tide-gauge location, and employs predictions of present-day VLM due to GIA obtained from geodynamic models of Earth's continued response

to deglaciation (e.g., Peltier, 2001). In the second method, geological data from the Holocene (last 10,000 years) obtained from sites near the tide gauge are used as the basis of an estimate of the present-day rate of sea level change due to geological processes of whatever cause. It is then possible to infer that any excess in the tide-gauge trend compared to the geological value is due to recent climate-change-related processes. One drawback of this method is that it is restricted to tide-gauge locations where geological information is available. In the third method, geodetic techniques are employed to measure directly the rate of any vertical crustal movement, of whatever origin, and so "correct" the tide-gauge data (e.g., Bouin and Wöppelmann, 2010). The main geodetic technique is the Global Positioning System (GPS), with Absolute Gravity and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) also employed. This method also involves an assumption: the vertical rate over the GPS measurement period

(typically a decade) is representative of that over the entire tide-gauge record (typically a century). Measurements of crustal movement as measured by GPS will not, strictly speaking, provide a complete "VLM correction" to the tide-gauge data if the main geological process is large in amplitude and spatial scale (like GIA). This is because an additional correction for the corresponding changes to Earth's gravity field is required. If the process is small in amplitude or spatial scale (e.g., submergence due to water or mineral extraction), then this additional correction will be less important.

Most analysts of twentieth-century sea level trends have employed the first method with GIA corrections applied to individual records, and corrected trends combined into regional and quasi-global averages (e.g., Douglas, 1991, 1997). Church et al. (2001) and Bindoff et al. (2007) provided assessments of this topic for the Intergovernmental Panel on Climate Change (IPCC), while Mitchum et al. (2010) provided a more recent review. A consensus has been achieved
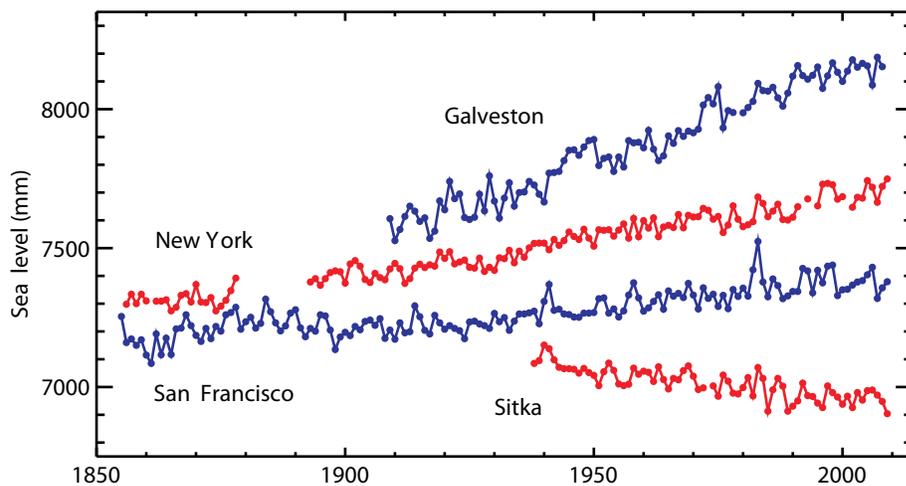

Figure 2. Four long sea level records from the United States indicating different rates of change at each site based on data obtained from the Permanent Service for Mean Sea Level. Each record contains an arbitrary offset for presentation purposes.

that the twentieth-century rise in global sea level was closer to 2 mm yr^{-1} than 1 mm yr^{-1}, with values around 1.7 mm yr^{-1} obtained recently for the past century (Church and White, 2006) or past half century (Church et al., 2004; Holgate and Woodworth, 2004).

Although there may be a consensus regarding twentieth-century global-average sea level change, it is clear that far less is known about century-time-scale regional rates, especially in the Southern Hemisphere. Correction for Earth's long-term GIA goes some way to explaining the large differences between measured trends in each region (Douglas, 1991), though large spatial variations remain. Some could be due to quite recent changes in hydrological and glaciological loads on the solid Earth (e.g., recent melting of ice sheets and glaciers), resulting in modifications to the gravity field and a spatial "sea level fingerprint" (Mitrovica et al., 2001, 2010). Other spatial variations could be due to the way that the ocean adjusts, on many time scales, to changing heat and freshwater fluxes. Two decades of satellite altimeter data have shown that rates can vary considerably regionally on decadal time scales due to changes in the steric (density) composition of the ocean (see below and also Church et al., 2010, and Tamisiea and Mitrovica, 2011, in this issue). In addition, numerical models have demonstrated considerable differences between rates of sea level change in different regions on century time scales due to the ocean's adjustment to climate change. It is likely, therefore, that our appreciation of the true extent of regional variation in twentieth-century sea level change, due to a number of geophysical and oceanographic causes,

has been underestimated because of limitations in the geographical coverage of historical tide-gauge data.

Studying the acceleration of sea level rise is an easier task than studying sea level trends if the VLM rate is constant throughout the record. In that case, the second- (quadratic) and higher-order components of a record can be studied as climate signals. This situation clearly applies to a good approximation if the main geological process is GIA, but does not apply when tectonics or anthropogenic effects dominate the VLM. If one applies a simple second-order fit (a + bt + ct^2, where t is time) to the longest records available, which are from northern Europe, then quadratic coefficients "c" on the order of 0.005 mm yr^{-2} are obtained. These figures provide evidence for long-term acceleration in sea level rise and suggest that twentieth-century rise started at around the end of the nineteenth century (Woodworth et al., 2009, 2011). Slightly shorter records, such as those from San Francisco and New York, yield similar "c" values (0.0069 and 0.0038 mm yr^{-2}, respectively, using data since the 1850s), consistent with the acceleration inferred by Maul and Martin (1993) from the Key West record.

Several studies of "reconstructions" of "global" sea level change have been published, using both long and short records combined in various ways. These studies attempt to make maximum use of the sparse historical sea level data set, with inevitable analysis assumptions that may lead to biases that must always be considered. Figure 3 shows several of these results. For example, Church and White (2011) used empirical orthogonal functions of ocean variability

as observed by satellite altimetry since 1993, together with coastal tide-gauge information for the period between 1880 and 2009, to obtain an acceleration corresponding to "c" = 0.0045 ± 0.0015 mm yr^{-2} since the late nineteenth century. Jevrejeva et al. (2006) used a "virtual station" technique and demonstrated a similar acceleration rate. This long-term acceleration is made up of shorter periods with greater acceleration, or even deceleration. Woodworth et al. (2009) pointed out that most sea level data originate from Europe and North America. Both of these data sets display evidence for a positive acceleration, or "inflexion," around 1920–1930 and a negative one around 1960, and indicate that these inflexions are the main contributors to the long-term "global" acceleration (and to an overall deceleration using twentieth-century data alone). However, all of these characteristic features are not found in records from all parts of the world.

An important question is, what may have caused the long-term acceleration of sea level rise between the nineteenth and twentieth centuries seen in the tide-gauge data and also salt marsh information discussed below? No doubt, an answer has to come from proper appreciation of the changing budget of oceanic steric, cryospheric, and hydrological contributions from natural (e.g., volcanic, solar) and anthropogenic forcings. Budgets have recently been considered extensively by Cazenave et al. (2010) and in the work of John Church, Australian Commonwealth Scientific and Industrial Research Organisation, and colleagues. However, these researchers focus only on the last few decades when most observational

data sets have been of adequate quality. Miller and Douglas (2007) undertook an interesting study of the evidence for a long-term deceleration in North Atlantic gyre strength (spin down), represented by decreasing air pressures near the center of the subtropical gyre, and the evidence for a connection to an acceleration in the rate of sea level change at the eastern boundary. A similar inference was made from the North Pacific data, although the poorer-quality air pressure fields available for that ocean prevented as firm a set of conclusions to be drawn as for the North Atlantic. Their analysis was limited to data sets from the late nineteenth century onward. However, Woodworth et al. (2010) recently showed that the relationship holds at a qualitative level for the North Atlantic for the last two and a half centuries. Sturges and Douglas (in press) also discuss low-frequency redistribution of water in the Atlantic, and similar work in the Pacific is being done by Mark Merrifield, University of Hawaii at Manoa, and colleagues. It is clear that a considerable amount of ocean and climate modeling remains to be performed in order to better understand the various contributors to global average sea level rise and to the low-frequency spatial redistribution of water.

SEA LEVEL MEASUREMENTS FROM SALT MARSHES

Recently, a number of sea level records have been published that use salt marsh sediments, and the fossils contained within them, as indicators of sea level change (e.g., Donnelly et al., 2004; Gehrels et al., 2005; Engelhart et al., 2011, in this issue). These proxy records typically span the last few centuries or

longer and often also cover the twentieth century, providing a useful check on the validity of the reconstructions. The resolution of proxy records depends on sedimentation rates in the marshes and is usually on the order of one data point per decade, considerably lower than observational records. Proxy records, however, can provide data beyond the period that is covered by tide gauges, including the centuries immediately preceding the observational era.

Most proxy records that cover the nineteenth and twentieth centuries show a marked positive inflexion in the late 1800s or the early 1900s. This inflexion

has been interpreted as the transition from late Holocene background rates of sea level change to the fast rates that have become prevalent in the twentieth and twenty-first centuries as recorded by tide gauges and satellite instruments. The inflexion has been dated by various authors to the second half of the nineteenth century (Donnelly et al., 2004), the period 1900–1920 (Gehrels et al., 2005), the start of the twentieth century (Gehrels et al., 2008), the period 1880–1920 (Leorri et al., 2008), and the period 1879–1915 (Kemp et al., 2009). As shown above, tide gauges have documented a slow acceleration between
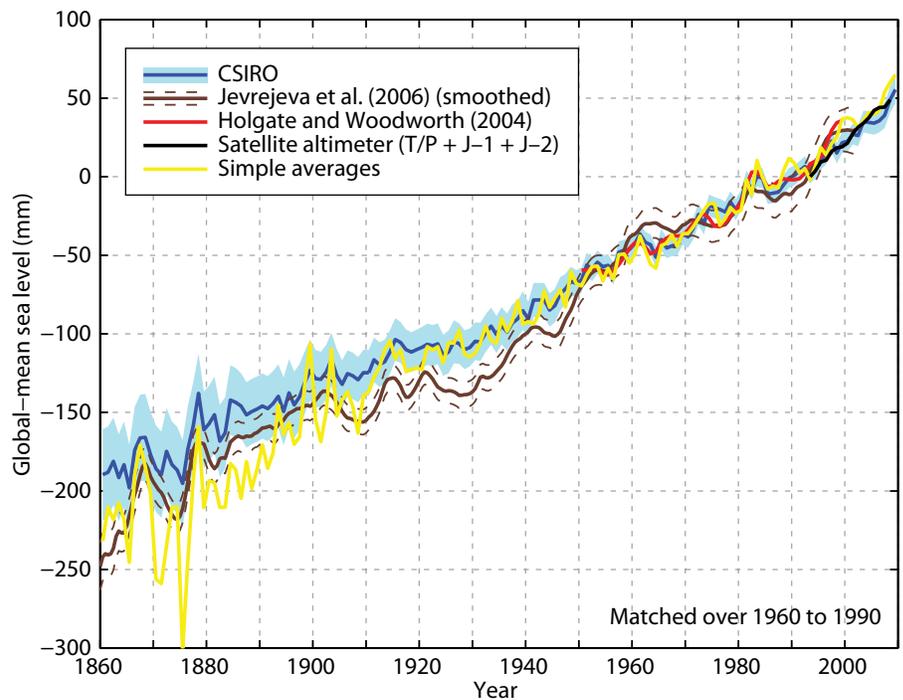

Figure 3. Global average sea level from 1860 to 2009 (in blue) derived from the reconstruction method of Church and White (2011) (denoted CSIRO, the Australian Commonwealth Scientific and Industrial Research Organisation) compared with the estimates of Jevrejeva et al. (2006; brown), Holgate and Woodworth (2004; red), and from a simple average of tide-gauge data (yellow). All of these estimates are based entirely or largely on Permanent Service for Mean Sea Level tide-gauge data. The satellite altimeter record is shown in black. All series are set to have the same average value over 1960 to 1990, and the reconstruction is set to zero in 1990. *From Church and White (2011).* Note that altimeter data in this figure are as computed by CSIRO, whereas those in Figure 5 are from the University of Colorado; the two time series are essentially the same.

the nineteenth and twentieth centuries, with possibly higher rates starting around 1920–1930 (Woodworth et al., 2009), but they do not show the clear inflexion observed in the proxy records. We investigate below the possibility that this discrepancy can be ascribed to the

that usefully can fill in some dating gaps in the nineteenth century (Gehrels et al., 2006; Marshall et al., 2007). Along coasts in the Southwest Pacific and Northwest Atlantic, pollen analyses can provide markers for the eighteenth and nineteenth centuries by revealing a distinct

constructing a best-fit age-depth plot using the dated levels in a sediment core and then interpolating between the measured ages to estimate the ages of intermediate levels in the core. This method results in many more data points, but the quality of the age model depends on the number and precision of available dates. Age-depth models are commonly used in paleoenvironmental studies when sedimentation rates are relatively constant (e.g., peatlands, deep-ocean sediments), but salt marsh sedimentation is notoriously episodic, and resolving changes in accretion rates can require a large number of dates. Furthermore, when sea level rise is very slow, sedimentation rates in salt marshes decrease and dating resolution suffers as a result.

> " IT IS HOPED THAT A GREATER UNDERSTANDING OF THE REASONS FOR PAST OBSERVED SEA LEVEL CHANGE, DISCUSSED ELSEWHERE IN THIS ISSUE, WILL LEAD TO BETTER ESTIMATION OF THE CHANGES LIKELY TO OCCUR IN THE FUTURE. "

limited chronologies of proxy records, and ask whether the accelerations and inflexions observed by the two techniques are consistent.

Dating methods used to provide chronologies for salt-marsh-based sea level reconstructions include radiometric analyses (^{14}C, ^{210}Pb) and stratigraphic marker techniques (e.g., ^{137}Cs, pollen, charcoal, Pb isotopes, metal concentrations). The ^{210}Pb method is suitable to date sediments younger than ~ 120 years. Measurements of ^{137}Cs are used to detect the 1965 level (when nuclear bomb testing was globally at its peak) or local nuclear spill events. High-precision accelerator mass spectrometry (AMS) ^{14}C techniques, in combination with bomb-spike AMS^{14}C dating, can also be used to date recent sediments (Marshall et al., 2007; Kemp et al., 2009). Isotopic ratios of Pb and metal concentrations in the sediment (e.g., Pb, Cu) provide ages for local and regional pollution events

change in vegetation resulting from the first settlement by Europeans (Gehrels et al., 2005, 2008; Kemp et al., 2009).

Proxy sea level records from salt marshes have been presented in two different ways. The first way is to depict proxy records by the "traditional" method and only show established sea level index points in an age-depth plot (Donnelly et al., 2004; Gehrels et al., 2008). A sea level index point is obtained from a sediment sample with a measured age that can be related to a former sea level position. The relationship between a sediment sample and sea level is referred to as the sample's "indicative meaning" and is usually determined by analyzing microfossils (e.g., foraminifera) whose modern counterparts are found in narrow vertical niches within the intertidal zone. The second way of presenting proxy records is to make use of age models (Gehrels et al., 2005, 2006; Leorri et al., 2008; Kemp et al., 2009) by

In Figure 4 we present four published proxy sea level reconstructions. Three of these (from Nova Scotia, North Carolina, and northern Spain) have been published previously using age models, but here we show the records with only the established sea level index points and their age uncertainties. The reconstruction from Nova Scotia (Gehrels et al., 2005) is in excellent agreement with the tide-gauge record from Halifax (Figure 4a). Many dates are available for the twentieth century (these are ^{210}Pb ages), but there are no dates for the nineteenth century. The earlier part of the record is only constrained by a pollen marker dated at 1780 ± 20 years. The proxy record starts to depart from the late Holocene trend in the 1920s. The record from North Carolina (Kemp et al., 2009) is based on two cores taken about 120 km apart (Figure 4b). There are good chronologies for the twentieth century, and each record contains two

dates from the preceding 200 years. The distance between the two sites results in different late Holocene background rates. In one core (Tump Point), the departure from the late Holocene trend appears to occur around 1900, but in the other core (Sand Point), it occurs about 30 years later, although the departure in both records remains within the errors of the data points during these 30 years. This study highlights the value of replicating records from the same area.

The northern Spain record (Leorri et al., 2008) suffers from large vertical uncertainties, but the tide-gauge record of Santander is in general agreement with the proxy reconstruction

(Figure 4c). Figure 4c also shows the tide-gauge record from Brest, about 550 km to the north across the Bay of Biscay, because it is the longest in the world. It is also in reasonable agreement with the proxy record. The chronology of the reconstruction is derived from ^{210}Pb and two industrial Pb markers. The record does not depart from the late Holocene trend (Leorri and Cearreta, 2009) if the vertical error bars are taken into account. The proxy record from New Zealand (Gehrels et al., 2008) contains fewer dates, primarily because ^{210}Pb dating was not possible at this site, so the chronology had to rely on other dating

methods (Figure 4d). Nonetheless, the reconstruction is in reasonable agreement with the tide-gauge record from Lyttelton. Importantly, there are no dates in the proxy record between 1900 and 1940. An inflexion in the proxy record occurs in this period.

In summary, the use of age models in the derivation of proxy sea level records can hide some of the uncertainties that are associated with the time-series reconstruction technique. In particular, the models create "synthetic" points whose ages are only obtained by inter-polation. This method is undesirable when exploring the timing and magni-tude of inflexions in the proxy records.
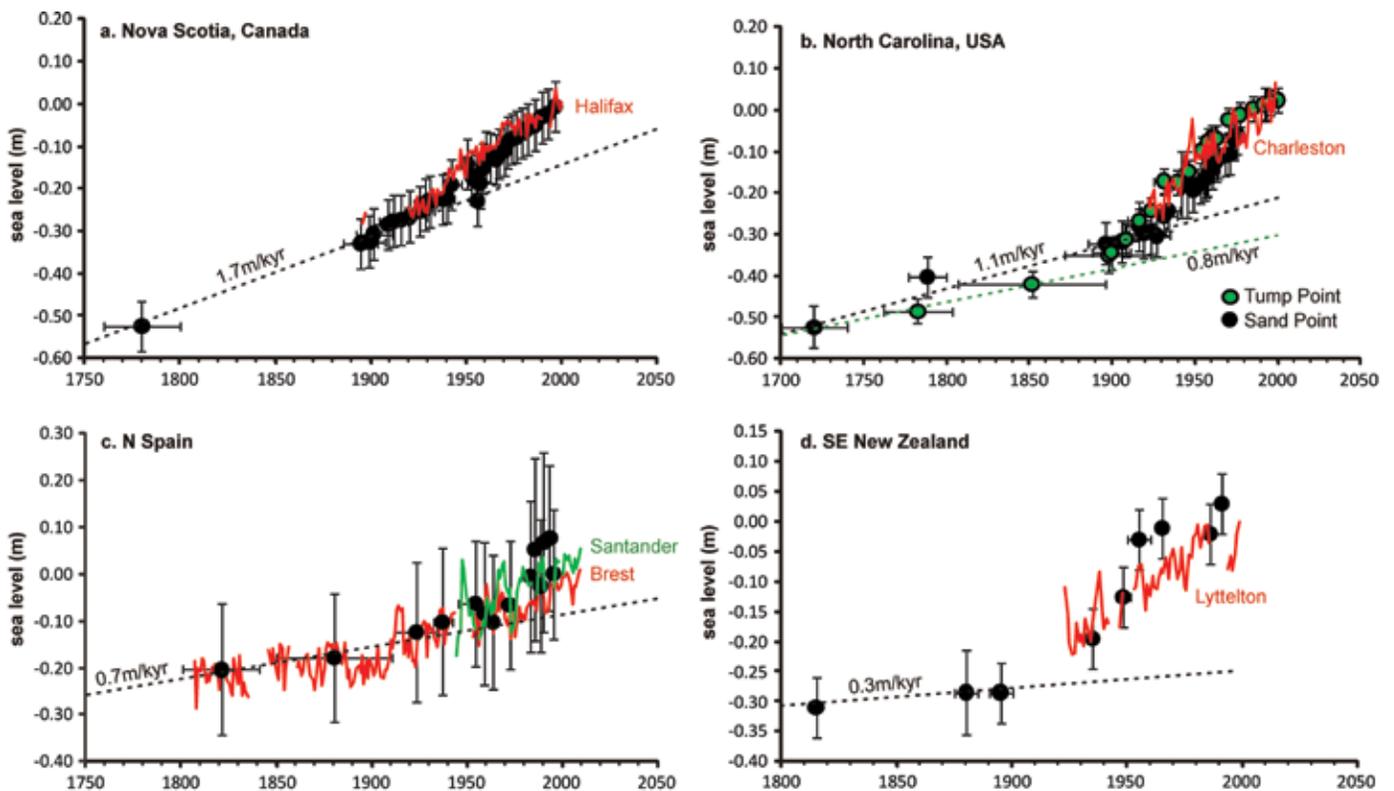

Figure 4. Records of sea level change derived from salt marsh data in different parts of the world. In each plot, the proxy sea level index points are shown as black or green dots with vertical and age error bars. Red and green indicate the nearest tide-gauge records to each site. This figures also depicts as dashed lines the late Holocene millennial rates of sea level change obtained from dates on basal salt marsh sediments buried along a sloping upland surface (most of these dates are older than can be shown on the graphs). A positive departure from this "background" trend reveals an acceleration of sea level rise. Sources of the proxy data: (a) Gehrels et al. (2005); (b) Kemp et al. (2009); (c) Leorri et al. (2008); (d) Gehrels et al. (2008). Tide-gauge data were obtained from the Permanent Service for Mean Sea Level.

Consequently, the most we can say with regard to findings from this relatively new field is that salt marsh (Figure 4) and tide-gauge (Figure 3) data appear to reflect similar features of acceleration between the nineteenth and twentieth centuries, with important details to be resolved by further research.

SEA LEVEL MEASUREMENTS FROM SPACE
Satellite Altimeter Measurements

The era of precision altimetry began with the launch of TOPEX/Poseidon (T/P) in 1992, and was later continued by Jason-1 (2001) and Jason-2 (2008). For these precision missions, great attention was given to the accuracy of the orbit determination (via precise tracking systems such as GPS, DORIS, and satellite laser ranging), the measurement corrections (e.g., ionosphere, troposphere, sea state),

and the orbit selection (to minimize issues with tidal aliasing). Each of these missions was flown in the same identical 10-day repeating orbit with an inclination of 66° and a ~ 300-km track spacing at the equator. In addition, there was an overlap period between each of these missions when the satellites were flown very close together (same orbit, approximately 1 minute apart) to facilitate inter-mission calibration of the measurements. These "tandem" periods resulted in a number of improvements to the measurement corrections and processing. Thus, we now have a precise calibrated continuous record of sea level change between ± 66° latitude from late 1992 to the present. While other altimeter missions have flown during this time period, each had deficiencies that made them less desirable as climate monitoring tools.

Despite these efforts to improve the accuracy and precision of satellite altimetry, there is still the possibility that the instrument might drift after it is on orbit. Tide gauges have proven to be very effective for monitoring the stability of the altimeter instruments after they have been launched (Mitchum, 2000). The basic technique is to difference the altimeter measurements in the local vicinity of a tide gauge with the tide-gauge data. This calculation results in a time series of altimeter minus tide-gauge sea level at many gauges around the world. Once these time series are stacked together, a globally averaged picture of the drift in the altimeter system can be obtained. These techniques have been used to identify a number of issues in the measurement processing that have now been corrected. The drift in any of the systems is now less than 0.5 mm yr^{-1}.

Figure 5 shows a time series of global mean sea level variations derived from T/P, Jason-1, and Jason-2 covering 1993–2010. Over this time period, sea level has risen at an area-weighted average rate of 3.0 ± 0.4 mm yr^{-1}. GIA causes the ocean basins to increase in volume by an amount equivalent to approximately 0.3 mm yr^{-1} (causing a sea level fall unrelated to a change in water volume); thus, the GIA-corrected rate is 3.3 mm yr^{-1}. In addition, there is considerable El Niño-Southern Oscillation (ENSO) related interannual variability in the altimetric global mean sea level record that was not previously detected in the less-accurate tide-gauge record (Nerem et al., 1999, 2010). It is thought that this variability is caused by ENSO-forced variations in land water storage. Global mean sea level tends to be higher during ENSO events because there is
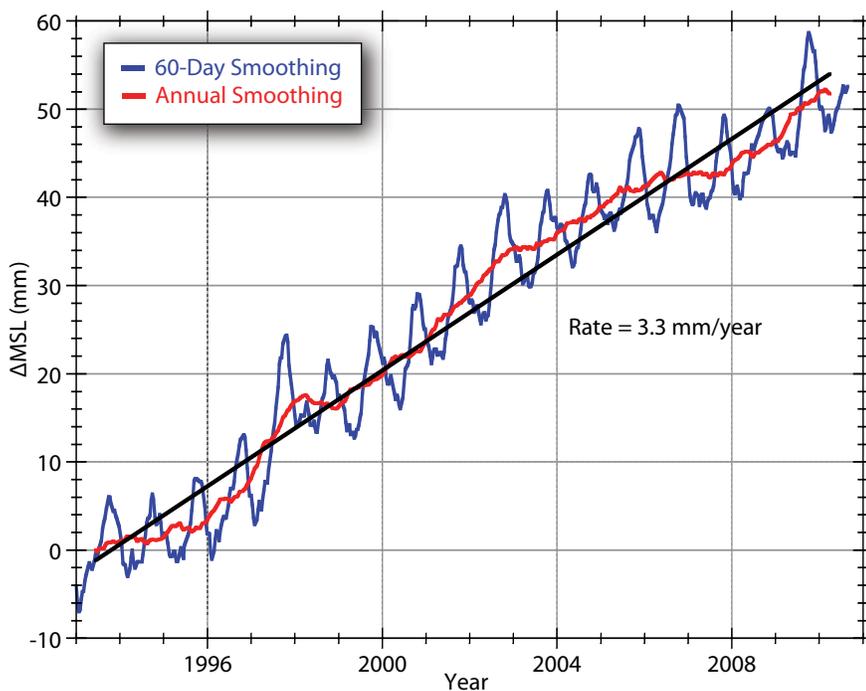

Figure 5. Variations in global mean sea level from a combination of TOPEX/Poseidon, Jason-1, and Jason-2 altimeter measurements, using 60-day and annual smoothing of 10-day average values. A glacial isostatic adjustment correction of 0.3 mm yr^{-1} has been applied.

more precipitation over the ocean (Llovel et al., 2011), which accounts for the higher sea level during 1997–1999. The reverse occurs during La Niña events, which accounts for the downturn in global mean sea level during 2007–2009.

An acceleration of sea level rise has yet to be detected in the altimeter record itself, and it is estimated that 30 years of altimetry will be required before an acceleration can be detected in the presence of the ENSO-related variability (Nerem et al., 1999). However, it may be noted that the rate observed by altimetry over the last two decades, which is comparable to that from tide gauges over a similar period, is nearly double the average sea level trend for the twentieth century. Consequently, there is already some evidence for acceleration relative to the longer term. The acceleration of sea level rise has also been detected in the longer tide-gauge record (Holgate and Woodworth, 2004; White et al., 2005; Prandi et al., 2009; Merrifield et al., 2009).

Regional variations in the rate of sea level rise observed by satellite altimetry are highly variable (Figure 6a). While the global mean rate is 3.3 mm yr^{-1}, departures from this rate of the order of 10 mm yr^{-1} are observed regionally. The patterns reflect variations in the rate of thermosteric sea level rise, changes in the various climate indices (e.g., Southern Oscillation Index, Pacific Decadal Oscillation, North Atlantic Oscillation), and a variety of other factors. Much research is currently ongoing to understand the patterns of regional sea level change and to identify the "fingerprints" of various forcing factors, such as the polar ice sheets (Mitrovica et al., 2001). Maps of thermosteric sea level change

(Figure 6b) constructed from in situ measurements (e.g., expendable bathythermographs, Argo floats) show that much of the spatial variability in sea level rise observed during the altimeter era can be explained by variations in thermosteric sea level. The highest rates of sea level rise are in the equatorial western Pacific where sea level has been rising at ~ 10–15 mm yr^{-1} since the beginning of the altimeter era. Mark Merrifield, University of Hawaii at Manoa, and colleagues have recently analyzed tide-gauge data from this

region, and have determined that sea level was relatively stable prior to the altimeter era, and then began to rise rapidly in the early 1990s. They show the cause of this rise is related to an increase in the speed of the trade winds. It is currently unknown if this has a climate connection.

Satellite Gravity Measurements

The launch of the Gravity Recovery and Climate Experiment (GRACE) mission in 2002 ushered in a new era in satellite sea level measurements.
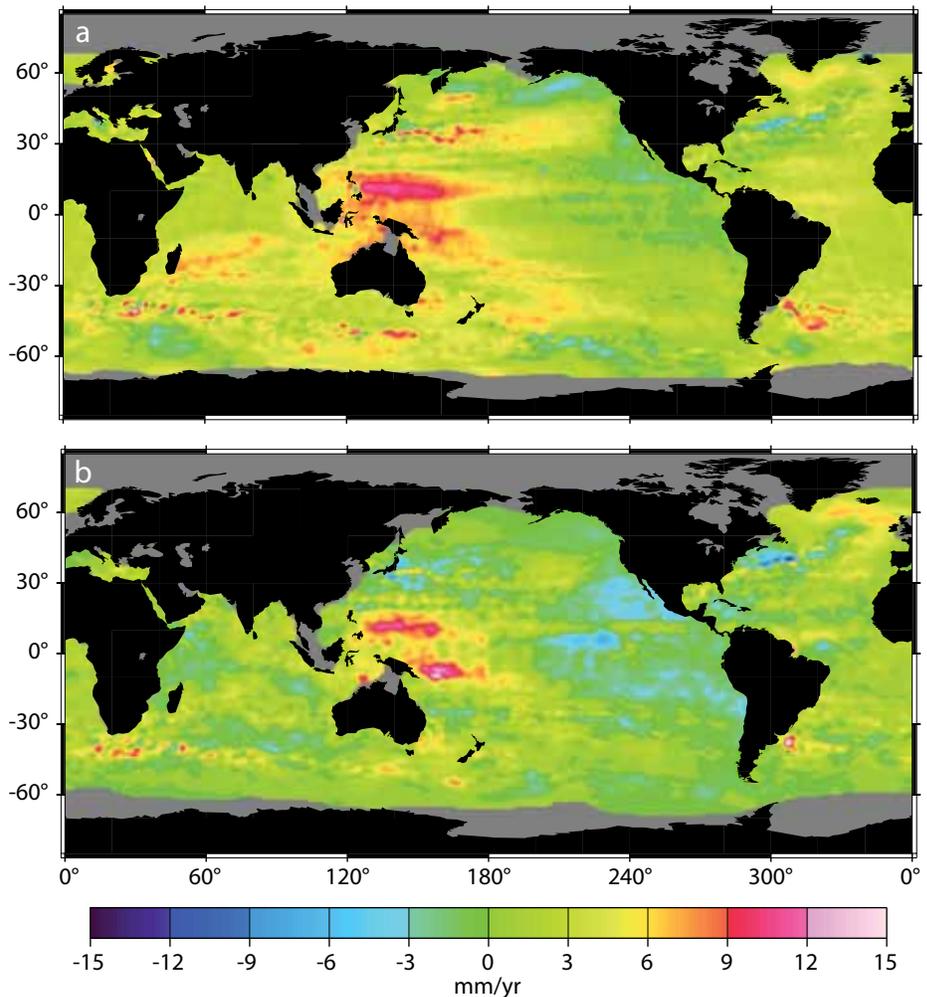

Figure 6. Regional rates of sea level change over 1993–2010. (a) Total sea level change as measured by satellite altimetry. (b) Thermosteric sea level change determined from expendable bathythermograph and Argo in situ measurements.

Over the nine years since its launch, this satellite has proven to be capable of monthly measurements of water-mass distribution with a spatial resolution of ~ 500 km anywhere on the planet. GRACE has been used successfully to monitor changes in Greenland and Antarctic ice masses (Luthcke et al., 2006; Velicogna, 2009), the melting of glaciers in Alaska (Luthcke et al., 2008) and Patagonia (Chen et al., 2007), global ocean mass (Chambers et al., 2004), ocean bottom pressure (Morison et al., 2007), continental water storage (Rodell et al., 2009; Tiwari et al., 2009), and a host of other signals.

Over the last decade, GRACE has become an invaluable tool for studying the effects of climate change on Earth's water reservoirs. GRACE has made an important contribution to studies of sea level change, specifically, that ocean mass has been increasing at a rate of between 1 and 1.5 mm yr^{-1} since 2002 (this range of uncertainty originates from the different GRACE gravity solutions calculated by different analysis centers). However, it is clear from each available GRACE data set that most of this increase is due to melting of ice in Greenland (0.6 mm yr^{-1}) and Antarctica (0.4 mm yr^{-1}) (Velicogna, 2009;

Figure 7). These figures suggest that the contribution of mountain glaciers is less than previously believed or that there are residual errors in the GRACE data. GRACE has for the first time provided a method of monitoring ice mass loss from the polar ice sheets and mountain glaciers. Thus, we can now determine how much of sea level rise observed from satellite altimetry and tide gauges is attributable to melting ice and how much to thermal expansion.

Comparisons between satellite altimeter and gravity measurements can lead to better understanding of the various factors involved in sea
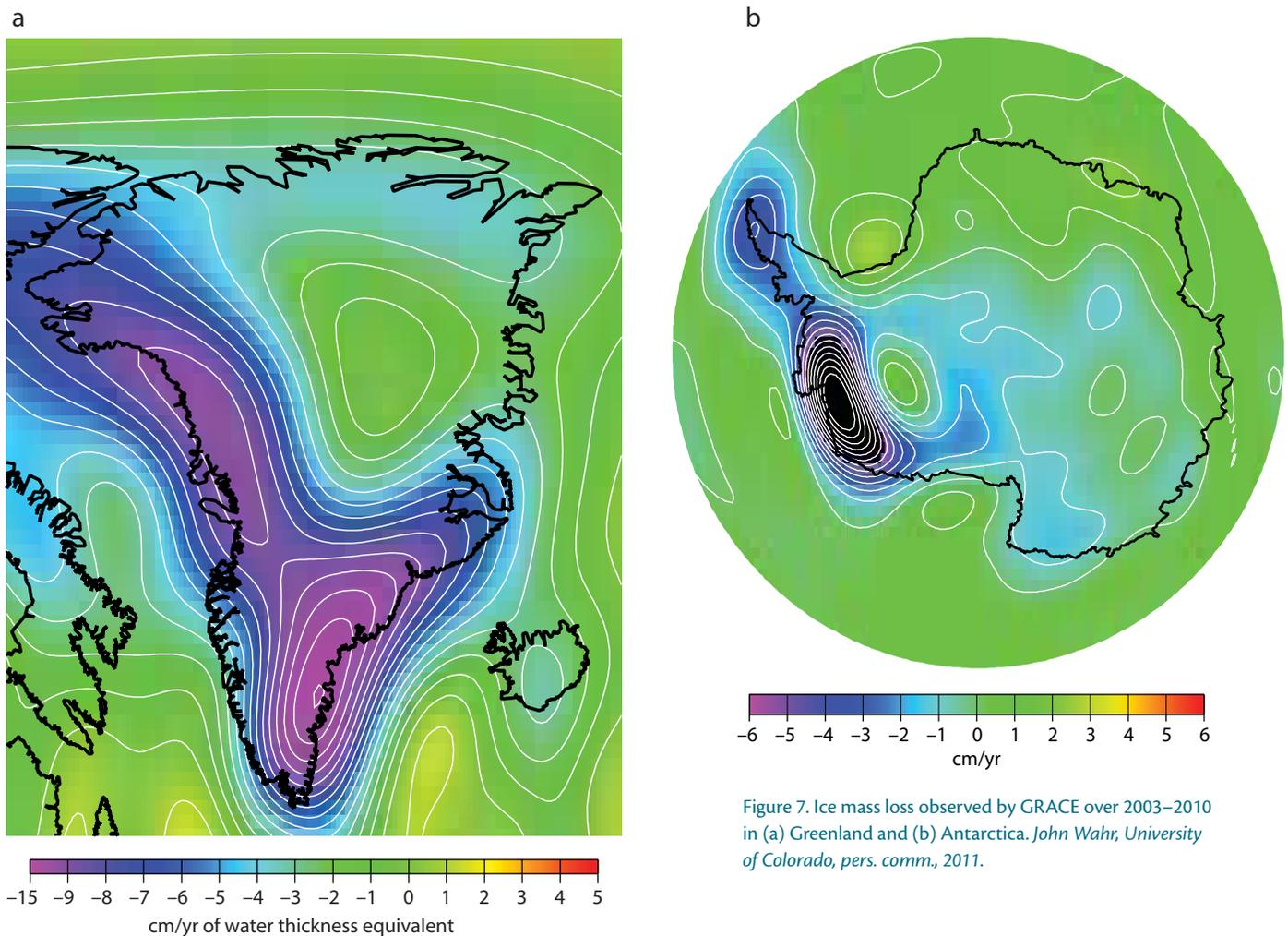
a

b

Figure 7. Ice mass loss observed by GRACE over 2003–2010 in (a) Greenland and (b) Antarctica. *John Wahr, University of Colorado, pers. comm., 2011.*

level change; while altimeter sea level measurements reflect steric (density) changes due to temperature and salinity variations as well as changes in ocean mass, the gravity measurements just see the mass contributions. The Argo network of profiling floats in the ocean has contributed to understanding of these differences (Willis et al., 2008; Leuliette and Miller, 2009; Leuliette and Willis, 2011, in this issue), but the network only became fully robust in the 2004–2005 time frame. Since then, GRACE measurements have led to a better understanding of the seasonal exchange of mass between the continents and the ocean, and to the realization that the interannual variations in this mass exchange dominate the interannual variability in global mean sea level change.

Altimetry and GRACE are two examples of technologies that will revolutionize future sea level research. Wilson et al. (2010) provide an overview of requirements for the ongoing monitoring of sea level change in the twenty-first century, and associated changes in the cryosphere and hydrosphere, using both in situ and space instrumentation.

TWENTIETH-CENTURY CHANGES IN EXTREME SEA LEVELS

Scientists usually focus on changes in mean sea level because changes in mean values are associated closely to climate-related processes, including oceanic steric change, variations in ice sheet, ice cap, and glacier mass balance, and hydrological exchanges between land and ocean. However, people more concerned with impacts of sea level change, including those who live near the coast, tend to be interested primarily in evidence for changes in extreme sea levels.

Studies of extremes present many more problems than those of mean sea level. Particular problems are associated with access to data sets, changes in tide-gauge technology through the years,

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and the fact that gauges sometimes fail to record extreme sea levels during the most violent storms. Woodworth et al. (2011) expand on some of these difficulties, and provide a short overview of this subject that updates the comprehensive review of Lowe et al. (2010).

Among the most recent studies, Menéndez and Woodworth (2010) made use of a quasi-global sea level data set to apply a nonstationary extreme value analysis to the monthly maxima of total elevations and surges from 1970 onward, while a small subset of the data was used to study changes over the twentieth century. Extreme sea levels were found to have increased at most locations around the world, as suggested by many anecdotal reports of increased coastal flooding. However, subtraction from the extreme sea levels of the corresponding annual median sea level was found to result in a reduction in the magnitude of trends at most stations, leading to the conclusion that much of the change in extremes is due to change in the mean values. A related finding was that extreme sea levels have become more frequent at most locations since the 1970s. However, subtracting median sea level values from the extreme values yields much smaller long-term changes in frequency of extreme events. These conclusions are clearly important for coastal planners if they also apply to the future, as predictions of mean sea level change are difficult and uncertain enough (cf. Figure 2 of Willis et al., 2010) without additional uncertainties being introduced with regard to projected extremes.

CONCLUSIONS

Sea level change is one of the most discussed aspects of climate change, as demonstrated by the many recent papers cited by articles in this special issue. We are unlikely to learn more about the reasons for past changes, let alone predict more confidently those of the future, without continued access to the best possible observational data sets. This article has introduced some of the main

data sets used for measuring the changes of the last two centuries, demonstrating the interdisciplinary nature of much of the research. Synthesis of information from the many disciplines involved in sea level science should ensure not only that a vibrant area of research continues but also that it can eventually provide the practical information required by coastal populations. ☑

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