An Anomalous Recent Acceleration of Global Sea Level Rise

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ABSTRACT

Tide gauge data are used to estimate trends in global sea level for the period from 1955 to 2007. Linear trends over 15-yr segments are computed for each tide gauge record, averaged over latitude bands, and combined to form an area-weighted global mean trend. The uncertainty of the global trend is specified as a sampling error plus a random vertical land motion component, but land motion corrections do not change the results. The average global sea level trend for the time segments centered on 1962–90 is 1.5 ± 0.5 mm yr^{-1} (standard error), in agreement with previous estimates of late twentieth-century sea level rise. After 1990, the global trend increases to the most recent rate of 3.2 ± 0.4 mm yr^{-1}, matching estimates obtained from satellite altimetry. The acceleration is distinct from decadal variations in global sea level that have been reported in previous studies. Increased rates in the tropical and southern oceans primarily account for the acceleration. The timing of the global acceleration corresponds to similar sea level trend changes associated with upper ocean heat content and ice melt.

1. Introduction

Understanding the response of global sea level to climate change is a prime concern for climate research. Observing systems are in place that can monitor global patterns relevant to the sea level budget, including satellite altimeter and gravity missions, and the array of Argo profiling floats. These systems are essential for determining future changes in global sea level, but at present they provide a snapshot of the current state [see Nerem et al. (2006) for a review]. Since 1993, the current rate of global sea level rise based on altimetry measurements is estimated to be 3.1 ± 0.4 mm yr^{-1} (Leuliette et al. 2004), which includes an added 0.3 mm yr^{-1} to account for crustal changes associated with global isostatic adjustment (GIA; Peltier 2001). An important concern is how the current global rate compares to previous rates.

Estimates of global sea level rise over the past century are based primarily on tide gauges, which provide measurements of sea level relative to nearby land. The problems in using tide gauge data for global estimates include unresolved vertical land motion (VLM) at the tide gauge, which can result in relative sea level trends that are not relevant to the global trend, and an uneven spatial distribution with many more tide gauges in the Northern than the Southern Hemisphere. A common approach for determining global sea level rise is to average linear trends from stations with sufficiently long records [Douglas (2001) recommends at least 60 yr] to account for decadal time-scale sea level variability. Averaging trends from different regions further reduces the influence of decadal variability. To limit spurious VLM trends, stations are chosen to avoid regions with known tectonic activity, and/or VLM corrections are applied to the tide gauge trends, most commonly using GIA models (e.g., Douglas 2001). In the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR), Church et al. (2001) summarize the results of tide gauge analyses and conclude that the global sea level rise rate for the twentieth century falls between 1 and 2 mm yr^{-1}. In the Fourth Assessment Report (4AR), Bindoff et al. (2007) refine the rate estimates as being 1.8 ± 0.5 mm yr^{-1} for

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1961–2003, and 1.7 ± 0.5 mm yr^{-1} for the twentieth century (90% confidence).

To reconcile the nearly factor of 2 difference in the tide gauge and altimeter global rates, reconstructions of global sea level from tide gauges have been made using empirical orthogonal functions (EOFs) obtained from satellite altimeter data (Chambers et al. 2002). Church et al. (2004) and Church and White (2006) compute reconstructions based on the time difference of sea level, rather than sea level itself, so as to include records with changes in the tide gauge datum. Global sea level trends are estimated primarily from a spatially uniform mode, with the EOFs used to account for coherent, residual sea level variability. Church et al. (2004) find a global rise rate of 1.8 ± 0.3 mm yr^{-1} (95%) for 1950–2000, and Church and White (2006) estimate a rate of 1.7 ± 0.3 mm yr^{-1} for the twentieth century. For 1993–2000, Church et al. (2004) determine a rate of 2.9 ± 0.7 mm yr^{-1}, which agrees well with the global trend from TOPEX/Poseidon altimeter data for the same time period. Holgate and Woodworth (2004) find a similar correspondence between tide gauge and altimeter derived rates in an analysis of 177 tide gauges grouped into 13 regions. Holgate and Woodworth (2004) and Church et al. (2004) find that rates as high as the current rate have occurred for other 9-yr segments throughout the 1950–2000 period, indicating that the current rate is not distinguishable from a decadal variation in global sea level.

The importance of decadal fluctuations in global sea level has been debated. Similar time-scale fluctuations have been found in globally averaged upper ocean heat content (Levitus et al. 2005a; Ishii et al. 2006); however, the recent detection of fall-rate errors in historic expendable bathythermograph (XBT) datasets (Wijffels et al. 2008), a major data source for upper ocean heat estimates, has led to a reevaluation of those global estimates. Reanalyses of steric sea level (0/700 m) with XBT-corrected data show a significant reduction of an apparent decadal sea level high during the 1970s and 80s (Wijffels et al. 2008; Domingues et al. 2008). Decadal sea level fluctuations have been simulated in coupled ocean–atmosphere general circulation models, although generally with weaker amplitudes than suggested by the observational estimates (e.g., Gregory et al. 2006). AchutaRao et al. (2006) and others suggest that the observed decadal amplitudes may be overestimated because of the uneven distribution of in situ measurements. Decadal fluctuations in global sea level have been linked to volcanic activity and atmospheric aerosols, which may alter the heat flux to the ocean (Church et al. 2005). Domingues et al. (2008) find that model comparisons to observed steric sea level improve if volcanic forcing is included in the model dynamics.

On multidecadal time scales, there are reports of notable sea level trend changes during the twentieth century and earlier [reviewed by Woodworth et al. (2008)]. Church and White (2006) compute an acceleration of 0.013 ± 0.006 mm yr^{-2} (95%) in global sea level for the period 1870–2001, which is attributed in large part to an increase in the rate of rise beginning around the 1930s. The timing of this transition agrees with an inflexion in tide gauge trends from Europe and North America around 1920–30 (Woodworth et al. 2008). Jevrejeva et al. (2006) also report high global rates from 1920 to 1945 that are comparable to rates from 1993 to 2000. Jevrejeva et al. (2008) extend this analysis to 1700 and report a long-term acceleration since the end of the 18th century of 0.01 mm yr^{-2}, superposed on which are stronger sea level accelerations associated with multidecadal variability. Based on these studies and others, Woodworth et al. (2008) summarize multidecadal changes in global sea level since the latter part of the nineteenth century as a positive acceleration around 1920–30 followed by a deceleration around 1960. Following the 1960s there was a flattening of sea level trends until the recent increase during the altimeter sampling period. One possible explanation for this behavior is that the trend increase that began around 1920–30 was interrupted during the early 1960s because of enhanced volcanic activity (Church et al. 2005). As this forcing has subsided, the recent trend increase since about 1990 can be viewed as a resumption of the generally high rates that began in the early part of the twentieth century.

In this study, we examine the recent acceleration in global sea level rise leading up to the current rate in excess of 3 mm yr^{-1}. Our approach (described in section 2) is to first select stations that provide as uniform a global set as possible while minimizing regional clustering. We compute sea level trends from tide gauge data using 15-yr time segments, which are then zonally averaged and combined into an area-weighted global average. We find that this approach helps to suppress the aliasing of regional decadal variability into the global average. The resulting time series of global sea level trend shows a transition from the late twentieth-century rate to the current rate around the late 1980s–early 1990s (section 3). We attribute the recent acceleration primarily to enhanced and covarying rates in the tropical and southern oceans. These findings are summarized and compared to previous studies, and possible causes for the sea level rise acceleration are considered (section 4).

2. Methods

The tide gauge time series are selected based on record length, the completeness of the record, and station

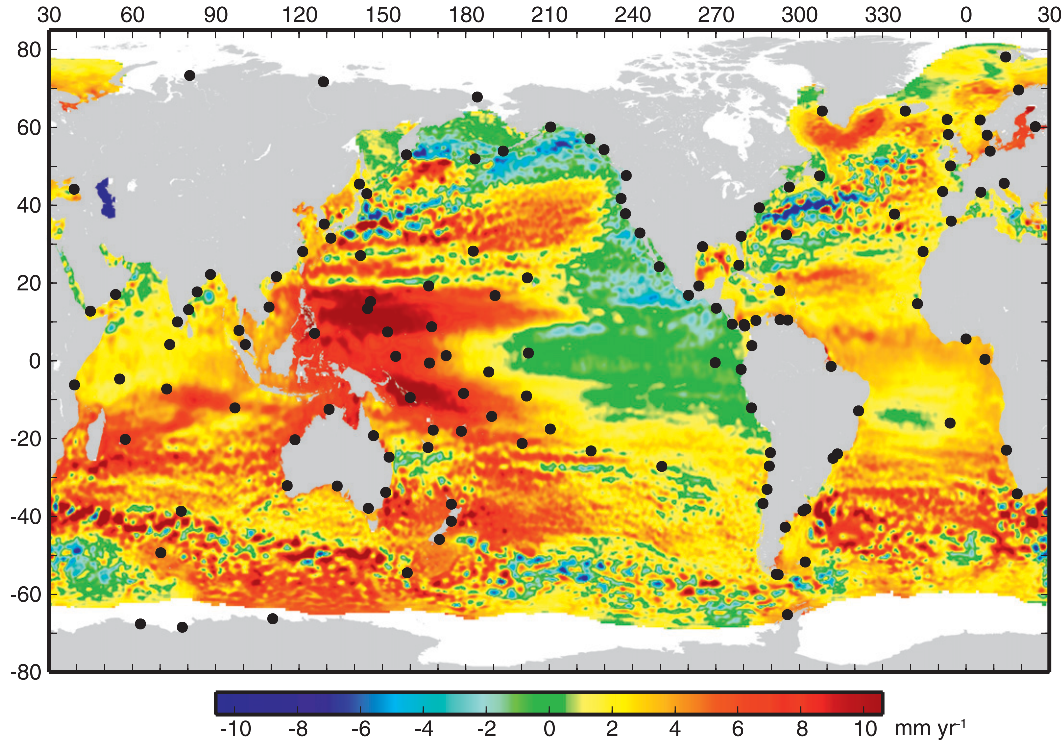

FIG. 1. The location of tide gauges used in this study plotted vs sea level trends (1993–2007) from AVISO multimission gridded sea level anomalies.

location. Priority is given to stations with long, uninterrupted records that span the altimeter period (1993–2007) and extend back preferably to at least 1955. An effort is made to avoid regional clustering; hence, we select a subset of stations that represent sea level trends and variability around Europe, North America, and Japan. Tests indicate that our main findings are not affected by the specific set of stations chosen in these regions. We include some short historic records that may not extend to the present day to give better spatial coverage and to increase the number of degrees of freedom. The resulting dataset includes 134 stations (Fig. 1), with a reduction in the number of available stations going back in time, and the fewest stations in the Southern Hemisphere for all time periods (Fig. 2).

We use annual mean sea level obtained from monthly averaged time series from the Permanent Service for Mean Sea Level (PSMSL; Woodworth and Player 2003). When possible, the PSMSL data are extended through 2007 using fast delivery data from the University of Hawaii Sea Level Center. The data have not been corrected for atmospheric pressure changes, primarily because of concern regarding potential artifacts in the National Centers for Environmental Prediction (NCEP) reanalysis model pressure for the early part of our record. Church et al. (2004) estimate that the pressure correction results in an increase of the global sea level rise rate (1950–2000) of about 0.16 mm yr^{-1}.

Sea level trends are computed every year from 1962 to 2000 over a 15-yr window centered on the year. The 15-yr length matches the available altimeter record. The individual sea level trends are averaged in 10° latitude bands, with the bands centered at $-60°$, $-50°$, . . . , 60°. Tide gauges along Antarctica (Fig. 1) are included in the $-60°$ band. We compute a global average trend using an area-weighted average of the latitude band trends.

Given the limited number of stations used to reconstruct average sea level trends, the sampling error is the major source of uncertainty. We estimate the sampling error by performing Monte Carlo simulations using the multimission gridded sea level anomaly from the Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) Altimetry project. Fifteen-year trends are computed for each $0.25° \times 0.25°$ Cartesian grid cell. Although the grid resolution is 0.25°, the objective mapping decorrelation scales are 100 km and longer. We sample the altimeter trends at random locations within 10° latitude bands and compute a sample average trend to compare with the average trend obtained using all grid points in the band. The random sampling is performed so that no two points in the band are within 500 km of each other, which is approximately

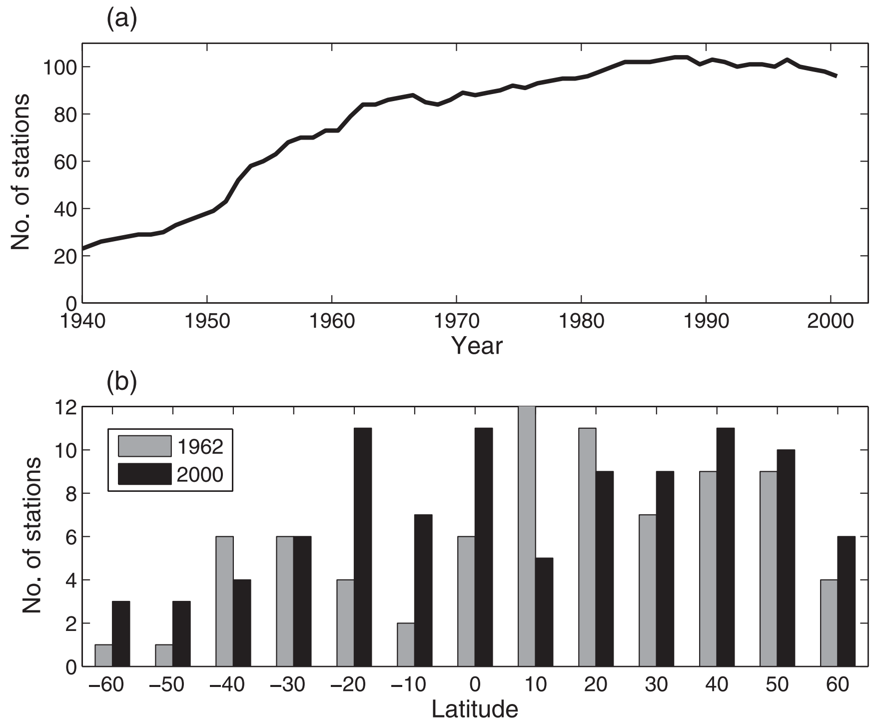

FIG. 2. (a) Number of tide gauges used to construct sea level trends over 15-yr segments, plotted vs the center year of the segment. (b) Number of tide gauges vs 10° latitude band used to construct global sea level for 15-yr segments centered on the years 1962 and 2000.

the minimum separation of the actual tide gauge stations used in the analysis. The simulations are repeated 1000 times and the sampling error is specified as the standard deviation of the trend (the bias error is near zero). We apply this sampling error to the reconstructions of the global trend. For the standard error of the global sea level trend, we treat the latitude bands as statistically independent, which is consistent with Monte Carlo simulations of the global trend.

We will make VLM corrections to the sea level change rates, but we emphasize that the application of these rates does not affect our main results. This is because the VLM rate at each station is assumed to be constant, but our concern is the temporal variation of the sea level rise rates. In addition, the globally averaged rates (see below) do not change significantly whether these rates are applied or not. In brief, following Nerem and Mitchum (2002), we estimate the VLM as the linear trend of the sea level difference between the tide gauge and the nearest altimeter sea level anomaly grid point, assuming that the mismatch in trends is due entirely to ground motion at the tide gauge. We find that the synthetic VLM trends are approximately normally distributed with 2.5 mm yr^{-1} standard deviation and a mean that is not significantly different than zero. As a consistency check, we find that our inferred VLM trends agree qualitatively with direct global positioning system (GPS) based estimates of VLM rates near tide gauge stations (not necessarily the stations used in this analysis) obtained by Woppelmann et al. (2007).

We compute the global sea level trends with and without the VLM correction. A VLM correction is applied by subtracting the synthetic VLM trends discussed above from the tide gauge trends. We assume that this correction reduces the standard deviation of the VLM error at any given station to 1 mm yr^{-1}. Stations that do not have data during the altimeter period are not corrected, and the VLM error at these stations is 2.5 mm yr^{-1}. For estimates of the global sea level trend, we add the 0.3 mm yr^{-1} correction to the tide gauge derived rate, as well as the altimeter rate, to account for the crustal adjustments associated with GIA.

3. Results

We first examine the 1993–2007 time frame to determine whether the tide gauge analysis can reproduce the altimeter trend, which we compute to be 3.2 mm yr^{-1}. The zonally averaged tide gauge and altimeter trends are in reasonable agreement given the uncertainties (Fig. 3a). In general, both the tide gauge and altimeter rates are higher in the southern and tropical bands than

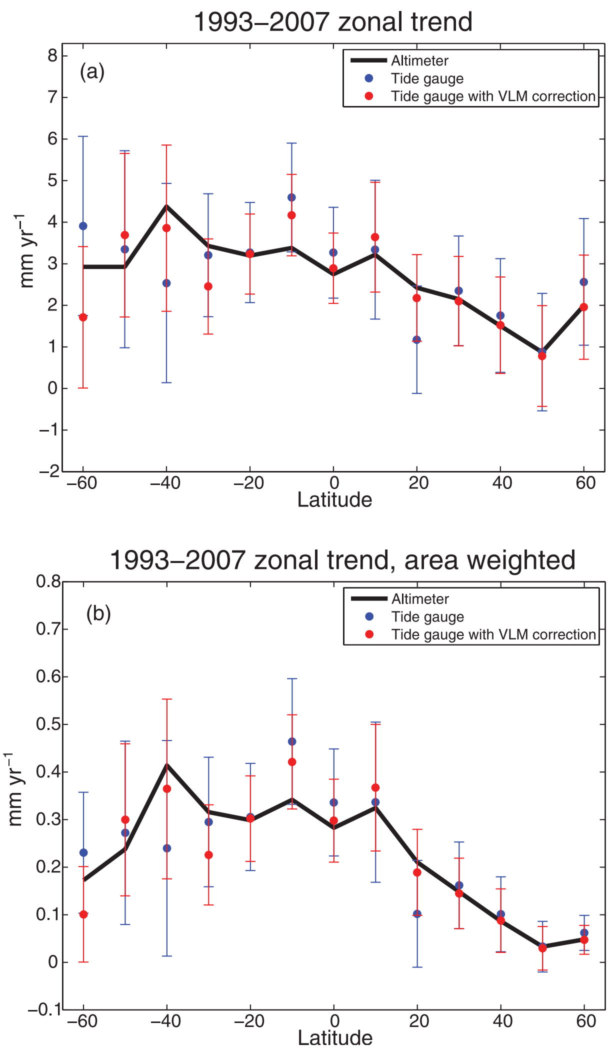

FIG. 3. (a) The average sea level trends in 10° latitude bands for 1993–2007 computed from tide gauges and altimetry (solid line). Tide gauge trends are presented with and without VLM correction. The error bars indicate one standard error. (b) Same as (a) but multiplied by the fraction of total ocean surface area (−65° to 65°) accounted for by each latitude band.

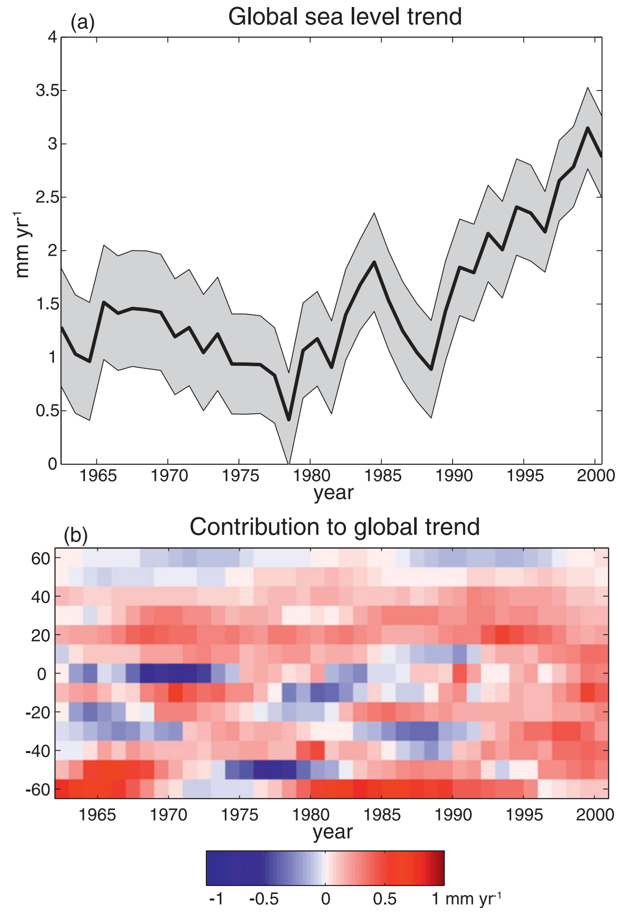

FIG. 4. (a) Tide gauge derived global sea level trends estimated over 15-yr segments and plotted vs the midyear of the segment. The VLM correction and the GIA correction of 0.3 mm yr^{-1} are included. The shaded region indicates one standard error. (b) The average sea level trend in each latitude band as a function of the midyear of the 15-yr window used to compute the trend. The trends are multiplied by the fraction of total ocean surface area (−65° to 65°) in each latitude band.

in the northern bands. Cabanes et al. (2001) report a meridional asymmetry in rates based on Ocean Topography Experiment (TOPEX)/Poseidon data from 1993 to 2000, although their rate difference is more pronounced than depicted in Fig. 3a. Taking into account the fraction of global ocean surface area within each zonal band, the mid- to high-latitude Northern Hemisphere trends contribute a small percentage to the global mean (Fig. 3b). The mean global trend from the tide gauges is 3.2 ± 0.5 mm yr^{-1} without VLM correction, and 3.2 ± 0.4 mm yr^{-1} with the VLM correction, in agreement with the altimeter rate. Our uncertainties represent one standard error.

For earlier time periods, the estimated global sea level trends from the tide gauges, with VLM correction, are less than 2 mm yr^{-1} until the early 1990s (the average for 1962–90 is 1.5 ± 0.5 mm yr^{-1}), followed by a steady increase to the present rate of 3.2 mm yr^{-1} (Fig. 4a). The current rate is over a standard error higher than any rate between 1962 and 1990. The linear increase in trend over time corresponds to an acceleration of 0.09 mm yr^{-2} since the late 1970s, and 0.12 mm yr^{-2} since 1990. We caution that these accelerations are not significantly different than zero given the short record lengths. Contributions to the global trend by latitude band vary in sign prior to about 1990 (Fig. 4b), and tend to cancel out in the global average. In contrast during the recent rate increase, the trends are positive at all latitude bands, with high values in the tropics and Southern Hemisphere.

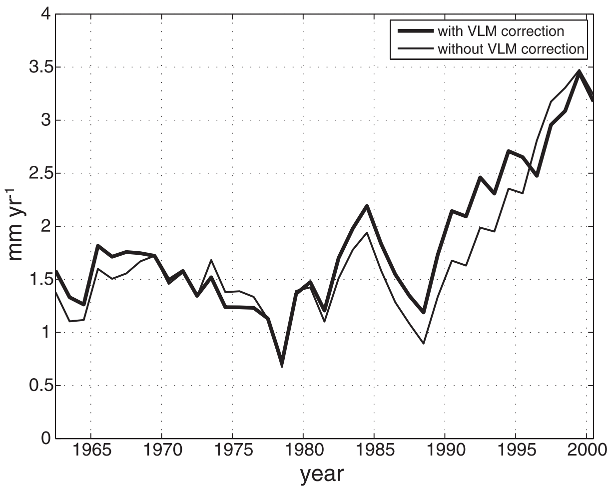

FIG. 5. The estimated global sea level trends for 1962–2000 with and without the VLM correction.

Although VLM corrections certainly are important for determining accurate global sea level rates from tide gauges, for this analysis VLM corrections do not impact our main conclusions regarding the recent increase in sea level rates (Fig. 5). The corrections lead to changes in global trend amplitudes for any given year; however, the overall acceleration is present with or without the correction, which makes sense given that the VLM trends are taken to be constant over time. In that regard, nonlinear VLM signals (e.g., due to tectonic movements and variable groundwater extraction) may impact our results; however, time series of direct VLM measurements generally are not yet long enough to assess this issue.

Because the tide gauge network configuration varies over time, the recent trend acceleration may be a spurious error associated with variations in the number of stations or the geographic coverage (Fig. 2). To assess this potential error, we compute the tide gauge trend for the 1993–2007 time period using tide gauge configurations from past years. If the results were sensitive to the network configuration, we would expect to see changes in the rate over time as the network changes. This is in not the case as all past network configurations predict a similar global rate for 1993–2007 as the present configuration (Fig. 6a). The rates within each latitude band are also fairly consistent for different network configurations (Fig. 6b). This provides some confidence that the trend acceleration observed in Fig. 4a is not a sampling artifact.

Recent increases in the global trend are associated with a sea level rise signal that is not uniform in space (Fig. 3). To examine this further, we compute trends over three regions similar to Cabanes et al. (2001): the northern oceans (25°–65°) for which we are able to compute trends dating back to 1925, and the tropical (−25°–25°) and southern oceans (−65°–25°) (Fig. 7). We examine the average sea level trend in each region (Fig. 7a), as well as the average trend weighted by the fraction of global ocean surface area in each region (Fig. 7b). As shown in Fig. 3, we see a consistency on a regional basis between the tide gauge and altimeter rates (dots in Fig. 7). The regional trends show that the recent rate increase in the global rate (Fig. 4a) is contributed primarily by the tropical and southern oceans (Fig. 7a). The northern oceans experienced high rates around 1940, presumably associated with the sea level inflexion discussed by Woodworth et al. (2008), and a weak long-term trend increase since the 1960s; however, the recent trend increase observed in the tropical and southern oceans is not evident in the north. The contrast between the northern versus the tropical and southern oceans is even clearer when considering the contribution of each region to the total global trend (Fig. 7b). The tropical and southern trends are considerably more variable than the northern trends in general, and both regions contribute equally to the recent global acceleration.

There appear to be two distinct regimes in the global sea level trend. Prior to the mid-1980s or so, the global trend is relatively steady (Fig. 4a), which results because the large trend fluctuations in the tropical and southern oceans are approximately 180° out of phase (Fig. 7b). Trends in the northern oceans do not covary with the other two hemispheres, and given the small area of the northern region, the contribution to the global rate is modest. After the mid-1980s, the global sea level trend increases because the tropical and southern regions both show a steady increase, or the regions now vary approximately in phase instead of out of phase. It appears that the change first occurs in the tropics during the 1980s, when a fluctuation to low rates is interrupted by a steady increase. The southern ocean shift appears to occur later in the decade.

4. Summary and discussion

Time series (1955–2007) from 134 tide gauges are used to assess trends in global sea level, computed over 15-yr time intervals. Uncertainties are assigned to these estimates based on sampling errors derived from altimeter data and vertical land motion errors inferred from trend differences between altimeter and tide gauge data. Our primary results are

1) the global sea level rise rate has accelerated from 1.5 mm yr^{-1} prior to 1990 to a present day rate close to 3.2 mm yr^{-1};
2) the acceleration in global sea level is accounted for primarily by the tropical and southern oceans, because

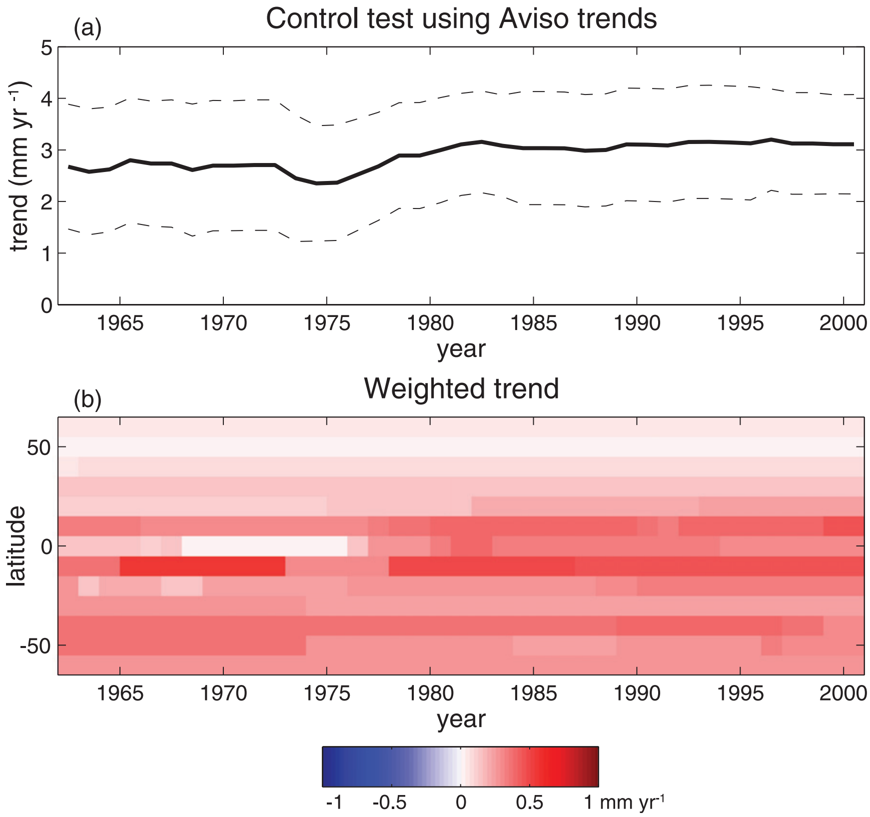

FIG. 6. (a) Estimates of the 1993–2007 global trend using tide gauges available at the time indicated on the abscissa. The error bars are one standard error. For example, the trend for 1980 represents an estimate of the 1993–2007 trend using the tide gauges available from 1973 to 1987. (b) The average sea level trend in each latitude band as a function of the midyear of the 15-yr window used to compute the trend.

of a phase change in the way the two regions covary: out of phase during relatively steady global sea level trends, and in phase during the trend increase;

3) a correction for ground motion at tide gauges changes the absolute levels of the global trend in any given year, but the overall temporal character of the global trend and the recent acceleration are not affected by the VLM corrections.

Previous studies that have examined tide gauge trends over 9–12-yr segments have captured the recent global sea level trend increase leading to the period of satellite altimetry (Church et al. 2004; Church and White 2006; Holgate and Woodworth 2004); however, the uniqueness of the rate change was unclear given the presence of decadal fluctuations in the global sea level reconstructions. Analyses that apply some form of low-pass filter with cutoff periods closer to 20–30 yr (Church et al. 2008; Jevrejeva et al. 2008) have shown that the recent increase is still present on these time scales, and that similar multidecadal variations in sea level trend have occurred throughout the past century and earlier. In both types of studies, the uniqueness of the recent rate increase is questionable given that similar increases apparently have occurred over the tide gauge record.

Our results suggest that the recent trend increase may be unique for several reasons. First, the northern oceans play a surprisingly small role in the acceleration. This was noted by Cabanes et al. (2001) based on only 8 yr of altimeter data; however, to our knowledge a similar conclusion has not been reached based on the tide gauge dataset alone. This would not be easily diagnosed with reconstructions that fit global patterns to the data (e.g., Church et al. 2004). Likewise, we suggest that regional averaging without some sort of area weighting may mask this effect. For example, if we simply had taken the mean of the average trends in the three regions considered (average of the three curves in Fig. 7a), we would arrive at a much different result than obtained by computing the weighted average (sum of the three series in Fig. 7b).

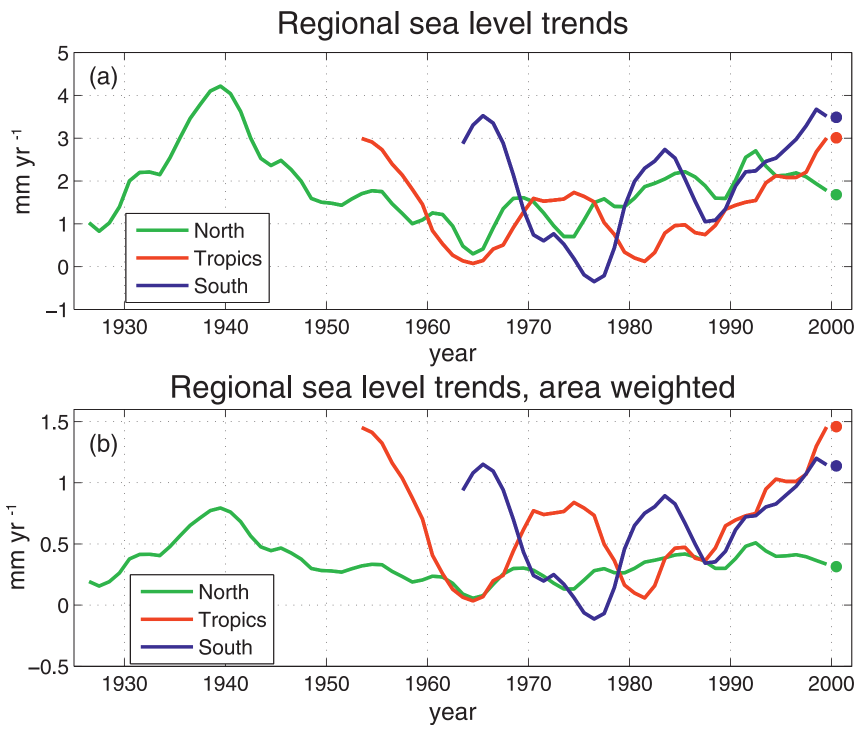

FIG. 7. (a) The average regional sea level trends in the northern (25°–65°), tropical (−25°–25°), and southern oceans (−65°–25°) obtained from the tide gauge analysis. The VLM correction has been made, but not a GIA correction. A three-point running mean is used to smooth the time series. The dots indicate equivalent trend estimates from the AVISO sea level anomaly product. (b) Same as (a) but the trends are multiplied by the fraction of total ocean surface area (−65° to 65°) accounted for by each region.

Second, the importance of the covariation of regional sea level in the tropics and southern oceans leads us to believe that the recent acceleration represents a shift from a state where the two regions once varied out of phase to now apparently more in phase. Understanding the physics of this change in state is necessary for determining whether the simultaneous trend increase in both regions will continue, or whether the fluctuating state will resume.

Third, it is evident how regional fluctuations in sea level may cancel when forming the global average. This makes it difficult to assess previous trend increases associated with multidecadal fluctuations when sufficient tide gauge data are not available in the Southern Hemisphere to assess possible compensating fluctuations. For example, the global trend increase reported in the early twentieth century apparently reflects the state of Northern Hemisphere tide gauges (Fig. 7). This event may well represent the global state; however, that is difficult to verify without better knowledge of the tropical and southern oceans, particularly given the large ocean surface area that these regions represent. If the early twentieth-century acceleration is global in scale, we speculate that it differs from the recent acceleration in that the Northern Hemisphere apparently contributed significantly to the early event but little to the recent event.

A change in the rate of global sea level rise beginning in the late 1980s–early 1990s is consistent with similar trend changes in both upper ocean heat content and glacier and ice sheet melt, the main drivers of sea level change. As summarized in the IPCC 4AR (Bindoff et al. 2007, their Table 5.3; 90% uncertainties), the equivalent global sea level rise rate associated with thermal expansion is estimated to have increased from 0.42 ± 0.12 mm yr^{-1} (1961–2003) to 1.6 ± 0.5 mm yr^{-1} (1993–2003), while the ocean mass contribution associated with ice melt has risen from 0.69 ± 0.5 mm yr^{-1} to 1.19 ± 0.4 mm yr^{-1} for the same periods. The sum of the two components has increased from 1.8 ± 0.5 mm yr^{-1} to 2.8 ± 0.7 mm yr^{-1}. Over the same time periods, we compute average rates from our tide gauge analysis to be 1.8 ± 0.5 mm yr^{-1} and 2.9 ± 0.4 mm yr^{-1}, in close agreement with the inferred rates.

Finally, we note that if the recent increase in the global sea level rise rate represents a long-term change as opposed to a fluctuation, then this is likely to result from ice melt and a subduction of heat below the upper layers of the ocean that interact directly with the atmosphere. There is considerable evidence to suggest the latter, particularly in the Southern Hemisphere. Willis et al. (2004) find that recent ocean warming is enhanced in the southern Indian and Pacific Oceans near 40°S, with thermal anomalies penetrating deep into the water column. Recent studies indicate that the Southern Ocean has warmed over the past several decades (Gille 2002, 2008; Aoki et al. 2005; Robertson et al. 2002; Johnson and Doney 2006; Johnson et al. 2007; Zenk and Morozov 2007; Johnson et al. 2008). Warm anomalies have been detected in intermediate waters penetrating northward toward the equator (Arbic and Owens 2001).

The effect in the Northern Hemisphere appears to be somewhat different. Roemmich and Gilson (2009) compare zonal averages of Argo temperature and salinity data collected from 2004 to 2007 to averages computed from the *WOA 2001* climatology (Conkright et al. 2002). From the surface to 2000 dbar, they find a net warming and freshening in the mid- to high-latitude regions of the Southern Hemisphere in all ocean basins and an increase in steric height (3.5 dyn cm average increase south of −30°). In contrast, a net warming in the Northern Hemisphere is partly density-compensated by an increase in salinity, especially in the northern North Atlantic (Levitus et al. 2005b; Hatun et al. 2005), leading to small changes in dynamic height (0.7 dyn cm north of −30°). Further work is needed to determine if this pattern is related to the north–south asymmetry detected in recent sea level rise rates.

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