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Is there a 60-year oscillation in global mean sea level?

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[1] We examine long tide gauge records in every ocean basin to examine whether a quasi 60-year oscillation observed in global mean sea level (GMSL) reconstructions reflects a true global oscillation, or an artifact associated with a small number of gauges. We find that there is a significant oscillation with a period around 60-years in the majority of the tide gauges examined during the 20th Century, and that it appears in every ocean basin. Averaging of tide gauges over regions shows that the phase and amplitude of the fluctuations are similar in the North Atlantic, western North Pacific, and Indian Oceans, while the signal is shifted by 10 years in the western South Pacific. The only sampled region with no apparent 60-year fluctuation is the Central/Eastern North Pacific. The phase of the 60-year oscillation found in the tide gauge records is such that sea level in the North Atlantic, western North Pacific, Indian Ocean, and western South Pacific has been increasing since 1985–1990. Although the tide gauge data are still too limited, both in time and space, to determine conclusively that there is a 60-year oscillation in GMSL, the possibility should be considered when attempting to interpret the acceleration in the rate of global and regional mean sea level rise.
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1. Introduction

[2] Over the last decade, numerous papers have commented on the appearance of decadal and longer period fluctuations in select tide gauge records [e.g., *Feng et al.*, 2004; *Miller and Douglas*, 2007; *Woodworth et al.*, 2009; *Sturges and Douglas*, 2011]. Multi-decadal fluctuations also appear in reconstructions of global mean sea level (GMSL) that are computed from the tide gauge records, using quite different techniques [*Holgate*, 2007; *Jevrejeva et al.*, 2008; *Merrifield et al.*, 2009; *Wenzel and Schröter*, 2010; *Church and White*, 2011; *Ray and Douglas*, 2011]. The nature of the multi-decadal fluctuations in GMSL reconstructions is not well understood. Authors have suggested they are linked to changes in the volcanic aerosols [*Church et al.*, 2005; *Domingues et al.*, 2008], global surface temperature [*Rahmstorf*, 2007], radiative forcing [*Jevrejeva et al.*, 2009], and land water storage [*Ngo-Duc et al.*, 2005]. Another plausible explanation is that the fluctuations may be an artifact of the sparse sampling of large regional sea level variations caused by volume redistribution within the ocean that does not change GMSL.

[3] The multi-decadal variations have often been described in terms of "inflexions" [e.g., *Woodworth et al.*, 2009], with the main signal being an increase in the rate of sea level rise in the early part of the 20th Century, a decrease beginning in about 1960, and a return to high rates in recent decades. On the other hand, several studies have found that the approximate period of this multi-decadal oscillation is between 50 and 60 years, based on analysis of two gauges in the North Atlantic [*Sturges and Douglas*, 2011] or a GMSL reconstruction from numerous gauges, the majority of which are in the North Atlantic before 1950 [*Jevrejeva et al.*, 2008; *Wenzel and Schröter*, 2010]. All the GMSL reconstructions exhibit significant 50 to 60 year fluctuations, although there are differences in the details (Table 1). A quasi 60-year oscillation explains anywhere from 31% to 62% of the residual variance in the time-series after removing a trend.

[4] Near 60-year oscillations in North Atlantic sea surface temperature (SST) have been identified and named the Atlantic Multidecadal Oscillation (AMO) [e.g., *Delworth and Mann*, 2000], and more recently there is evidence of a phase-locked fluctuation in the Pacific Decadal Oscillation at a similar frequency [*d'Orgeville and Peltier*, 2007]. Studies have found strong peaks near 60-year periods in numerous other data, including global-mean surface temperature [*Schlesinger and Ramankutty*, 1994], geomagnetic activity, Earth rotation, North American air temperature, northern hemisphere atmospheric pressure [e.g., *Mazzarella*, 2007], precipitation in numerous continents [*Enfield et al.*, 2001; *McCabe et al.*, 2004; *Knight et al.*, 2006] as well as North Pacific SST [e.g., *Minobe*, 1997]. *Jevrejeva et al.* [2008] speculated that the signal in their GMSL reconstruction was due to the AMO, but this was based solely on the appearance of the 60-year oscillation in the time-series.

[5] Is there is a 60-year oscillation in global sea level? This study will examine this issue by considering the longest, nearly continuous tide gauge records around the world (most extending back to 1900) and fitting ~60-year sinusoids to the records. We will then assess regional patterns of sea level based on averages of multiple gauges in the same ocean basin, and evaluate the amplitude and phase of the quasi 60-year variability around the globe. We also will examine how these variations relate to the known climatic large-scale variations that exhibit a 60-year fluctuation.

2. Analysis

[6] We use yearly-averaged tide gauge data from the archive at the Permanent Service for Mean Sea Level (PSMSL) [*Woodworth and Player*, 2003; *PSMSL*, 2012]. Only data from the revised local reference (RLR) database are used. The exact tide gauges examined with their range of

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Table 1. Estimated Parameters for Two Different Models Fit to GMSL Reconstruction Time-Series[a]

Series	Start/Stop	Trend (mm/year)	Oscillation Period (Years)	Amplitude (mm)	Phase (deg)	Residual Variance Reduction (%)	Effective Degrees of Freedom (N^*)
C&W, 2011	1900/2010	1.7 ± 0.2	–	–	–	–	15
C&W, 2011	1900/2010	1.7 ± 0.2	50	6.0 ± 1.6	59.5 ± 15.6	30.7%	19
J, 2008	1900/2003	1.9 ± 0.2	–	–	–	–	10
J, 2008	1900/2003	2.0 ± 0.2	54	14.5 ± 2.6	39.9 ± 5.8	48.8%	20
R&D, 2011	1900/2008	1.7 ± 0.2	–	–	–	–	3
R&D, 2011	1900/2008	1.7 ± 0.2	59	8.1 ± 1.1	-34.7 ± 10.4	62.4%	7

[a]The models are: 1) bias + trend, 2) bias + trend + long-period sinusoids, where the period is found via a search to minimize residuals. Uncertainty is 90% confidence level, and accounts for serial correlation in the residuals to the fit based on the effective degrees of freedom from the Lag-1 autocorrelation (r) of the residuals and the number of observations (N) as $N^* = N(1 - r)/(1 + r)$ minus the number of parameters estimated. The period of the long-period sinusoid is treated as a free parameter. Parameters for long-period sinusoids are expressed as Amplitude (A) and phase (ϕ) of the equation $A\cos(\omega(\text{t-1990}) - \phi)$, where ω is the frequency.

dates used are shown in Table 2. We also show the effective degrees of freedom (N^*), computed from the Lag-1 autocorrelation (r) of the residuals to the fit and the number of observations (N) as $N^* = N(1 - r)/(1 + r)$ minus the number of parameters estimated.

[7] Although many of the gauges utilized extend for more than 100 years and have few gaps, we have also included several gauges that have shorter records (e.g., Buenos Aires, Bermuda, Mumbai), or significant gaps (Dunedin II). The rationale for including these gauges will be discussed later. Uncertainty of the estimated parameters is given as the 90% confidence interval, and computed by inflating standard errors from the fit by a factor depending on N*, assuming a two-tailed t-distribution. The fit was computed using linear least squares assuming a model of a bias + trend + cosine and sine terms with a period of 55 years, but expressed in terms of amplitude and phase relative to 1900. 55 years was selected as the mean of the best-fit period to the GMSL reconstruction time-series (Table 1). Although this may not be the optimal period for all gauges (based on the minimal residual variance), it is representative of an oscillation around 60 years. The percentage of variance reduction is computed relative to the variance after removing the trend only.

[8] The North Atlantic and its adjacent seas have the majority of the long records. All except Brest (on the coast of France) have a significant amplitude at a period of 55-years with a minimum between 1922 and 1932 and a peak between 1949 and 1959. The oscillation explains anywhere from 2% of the residual non-linear variance of the annual averaged data (at Trieste) to as much as 29% at Cascais, where *Sturges and Douglas* [2011] previously noted a near 60-year variation. The average is around 10%. The fluctuation may not be as apparent in Brest as the other gauges because it has a gap between 1944 and 1953, right at the peak of the fluctuation. Brest also has the longest record of sea level in the North Atlantic, going back to 1807. The earlier part of the Brest record also does not show a significant 55-year oscillation (Table 1). The tide gauge at Bermuda, although short and gappy has been included, as it is the only site in the North Atlantic that is not along a coast. The phase of the 55-year period at Bermuda is reasonably consistent with that of the New York, Baltimore, Cascais, and Marseille (within the 90% confidence), which suggests a large-scale correlated rise/fall of sea level over the North Atlantic. The 55-year signal in gauges in the southwest North Atlantic (Key West and Fernandina) peaks ~10 years earlier. This phase difference is just outside the 90% confidence interval of the other phase estimates, but would overlap at the 99% confidence level. Only one gauge extends back to 1905 in the South Atlantic, Buenos Aires, and it stopped reporting in 1987. Although highly uncertain due to the short record, there is a significant 55-year oscillation, although with a phase about 17 years earlier than the North Atlantic.

[9] We have broken the gauges in the North Pacific into two distinct regions: The Western North Pacific (dominated by Japanese gauges) and the Central/Eastern North Pacific, which include Honolulu and gauges along the North American West Coast. The reason for the partitioning is based on the fits. There is no obvious sign of a 55-year oscillation in the Central/Eastern North Pacific gauges, while there is a significant oscillation in the Japanese gauges, both in the one that extends back to 1900 and the three that start in 1930.

[10] The number of long records south of the equator in the South Pacific and Indian Ocean are extremely limited. However, analysis of the records that are there (primarily around Australia and New Zealand) indicates the existence of a quasi 60-year fluctuation. Amplitudes of the fit are high and significant at all 5 gauges examined, and the fit explains anywhere from 4% to 32% of the residual variance. There is a noticeable shift in the phase, however, between the Indian Ocean and South Pacific gauges. The phase of the oscillation in the Indian Ocean (based on only 2 gauges, it must be noted) is similar to that in the Atlantic and Western North Pacific (within the uncertainty), while that in the South Pacific lags the other basins by about 10 years.

[11] The coherent ~60-year oscillation is even more obvious if we remove the estimated trends from each tide gauge record, and average records for each basin. We require that there be at least two tide gauges to compute an average, which means we cannot do the calculation in the South Atlantic, in the Western North Pacific before 1930, or in the Indian Ocean after 1988. However, even with these limitations, the appearance of a ~60-year fluctuation is obvious in all basins except the Central Eastern North Pacific (Figure 1). The North Atlantic variation, which is the most robustly determined due to the number of gauges, has an optimal period of 64-years (based on minimizing residual variance). It explains 55% of the variance of the 5-year smoothed residuals. Fitting this same period to the Indian Ocean and western North Pacific gauges explains 61% and 65% of the variance, respectively, while the fit to the western

Table 2. Estimated Amplitude, Phase, and Implied Trend for 1993–2011 of a 55-Year Oscillation for Long-Tide Gauge Records[a]

	Start/End	Amplitude (mm)	Phase (deg)	Residual Variance Reduction (%)	Effective Degrees of Freedom (N^*)
			North Atlantic/Gulf of Mexico/Mediterranean Sea		
New York	1900/2011	15.4 ± 4.0	5.7 ± 10.9	13.4%	69
Baltimore	1903/2011	15.6 ± 3.9	3.1 ± 11.0	14.0%	54
Brest	1807/1910	7.5 ± 7.2	127.8 ± 66.3	2.9%	32
Brest	1900/2011	5.1 ± 4.9	−63.9 ± 69.4	0.9%	38
Cascais	1900/1993	22.3 ± 3.8	−4.4 ± 9.0	28.7%	25
Marseille	1900/2011	18.4 ± 4.1	0.7 ± 10.9	17.4%	46
Trieste	1905/2011	6.8 ± 5.0	46.8 ± 31	1.9%	67
Key West	1913/2011	8.5 ± 3.5	−44.3 ± 30.2	5.7%	48
Fernadina	1900/2011	12.4 ± 5.6	−60.6 ± 37.1	6.0%	51
Bermuda	1933/2009	20.3 ± 13.9	28.6 ± 39.4	10.5%	21
Average	1900/2011	10.5 ± 2.1	−8.2 ± 9.2		
			South Atlantic		
Buenos Aires	1905/1987	15.3 ± 12.4	−118 ± 47	5.2%	39
			Central/Eastern North Pacific		
San Diego	1906/2011	5.1 ± 4.2	−145.4 ± 240.2	1.5%	61
San Francisco	1900/2011	0.4 ± 5.1	−154.9 ± 203.9	0.1%	69
Honolulu	1905/2011	4.7 ± 5.0	−130 ± 170	0.9%	56
Balboa	1908/2006	8.4 ± 6.0	−5.2 ± 24.8	2.0%	63
Average	1905/2011	1.3 ± 3.6	−66.5 ± 176.6		
			Western North Pacific		
Tonoura	1900/1983	22.1 ± 8.1	−95.7 ± 23.8	21.5%	66
Aburatsubo	1930/2011	15.2 ± 6.5	−9.7 ± 23.3	17.4%	35
Wajima	1930/2011	25.2 ± 7.0	−42.4 ± 21.8	31.9%	56
Hosojima	1930/2011	27.8 ± 9.3	−8.1 ± 18.6	25.1%	28
Average	1930/2011	19.9 ± 4.4	−24.3 ± 12.6		
			South Pacific (Southwestern Only)		
Sydney	1900/1993	20.3 ± 5.2	70.0 ± 5.2	22.6%	46
Auckland	1904/1998	15.8 ± 5.2	33.9 ± 5.2	10.9%	46
Dunedin II	1900/2010	20.8 ± 11.0	85.9 ± 20.4	13.6%	21
Average	1900/1998	16.1 ± 3.8	55.1 ± 14.6		
			Indian Ocean		
Fremantle	1900/2010	12.5 ± 6.7	−0.3 ± 20.7	3.9%	56
Mumbai	1900/1988	26.7 ± 6.9	−52.1 ± 20.9	31.9%	33
Average	1900/1988	18.2 ± 4.4	−46.2 ± 13.4		

[a]Uncertainty is 90% confidence. Tide gauges are grouped by regions and the fits to the regional averages of the tide gauge records are also shown. Time-series plots of the detrended tide gauge records and the corresponding sinusoid fit are in the auxiliary material (Figures S1 and S2).[1]

South Pacific gauges explains 42% of the variance. There is no obvious 64-year fluctuation in the Central Eastern Pacific gauges. The phase of the oscillation is nearly the same in the western North Pacific and Indian Ocean and slightly later in the North Atlantic gauges. The minimum is around 1915–25, with a peak around 1950–60, and another minimum around 1980–90. The phase of the South Pacific gauges around Australia/New Zealand is approximately 10 years later.

3. Discussion

[12] We have demonstrated that a quasi 60-year oscillation exists in long tide gauge records around the world and that the gauges in the North Atlantic, western North Pacific, and Indian Ocean have similar phase (within 10 years, or 55°) and amplitude when regionally averaged. The western South Pacific gauges around Australia and New Zealand also have a significant 60-year oscillation, although one that lags by 10–15 years. There is no obvious 60-year cycle in Hawaii or on the west coast of the U.S. Similar conclusions were reached by *Woodworth et al.* [2009], although in the context of two inflexions during the 20th century, not an oscillation. We use the harmonic fit primarily as a tool for characterizing the phasing of the recent sea level variations in the different regions. We do not claim that the 60-year harmonic is a better model for the recent regional or global sea level behavior than some other model, for example a sequence of inflexions as described by *Woodworth et al.* [2009]. A higher level of statistical testing is needed to ascertain the "best" model, and it is doubtful that 120 years of data are sufficient to resolve such an issue.

[13] We return to our initial question - is there a 60-year cycle in GMSL? We know that there are 60-year oscillations in several climate indices that attempt to represent the patterns and timing of large-scale atmosphere-ocean climate couplings, such as the AMO and PDO, as well as in output from climate models [*Andronova and Schlesinger*, 2000; *Delworth and Mann*, 2000; *Zhang et al.*, 2007]. Some climate model experiments have found that forcing with combinations of external forcing (greenhouse gases, solar variations, volcanic aerosols) cannot reproduce the observed multi decadal variation in surface temperature [*Andronova and Schlesinger*, 2000], but that a coupled climate model forced with only

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL052885.

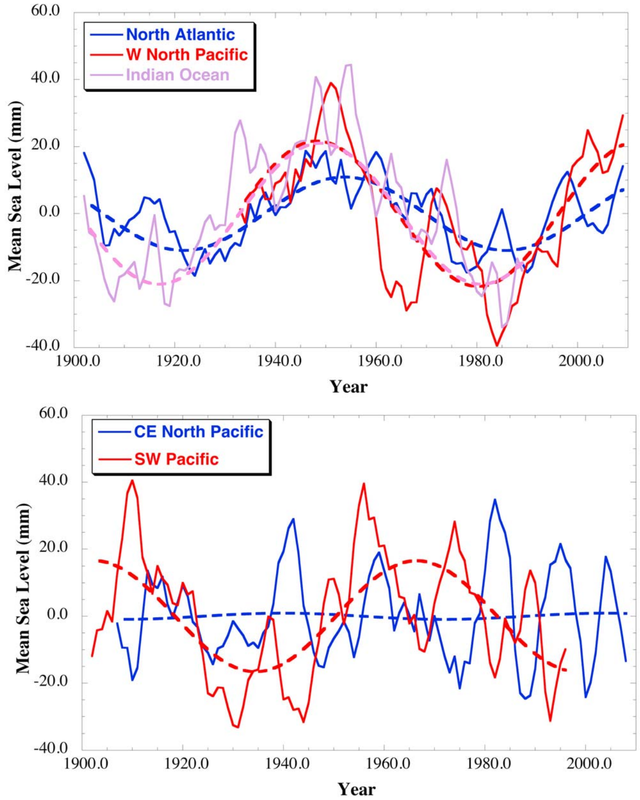

Figure 1. Average sea level over basins defined in Table 2. Calculation is described in text. Data have been smoothed with a 5-year running mean. Dashed lines are best-fit 64-year sinusoid.

climatological fluxes and run over 1000 years will reproduce a quasi 60 year oscillation in surface temperature that is related to fluctuations in the thermohaline circulation in the model [*Delworth and Mann*, 2000]. This suggests the multi decadal oscillation is an internal mode, and not externally forced. Moreover, a coupled model experiment where the Atlantic surface temperatures were forced to correspond to observations resulted in multi decadal surface temperature oscillations throughout the Northern hemisphere, similar to observations [*Zhang et al.*, 2007], again with no external forcings other than climatology. Output of these coupled climate model experiments have also shown regular multi decadal fluctuations with a peak around 60 years going back to the mid-1600s or earlier [*Delworth and Mann*, 2000], which is also seen in tree-ring reconstructions [*Delworth and Mann*, 2000; *Biondi et al.*, 2001; *Gray et al.*, 2004], and more recently ice cores from Greenland [*Chylek et al.*, 2012].

[14] While there is growing evidence of a near 60-year natural climate oscillation and our analysis indicates that some regions have a strong, quasi 60-year variation in sea level, this alone does not mean that there is a detectable GMSL signal. It is likely that a significant fraction of the multi decadal fluctuations in local and regional sea level represent dynamical adjustments to winds, and resulting fluctuations in the strength of the circulation, propagation of Rossby and/or Kelvin waves, or other effects that when averaged globally do not cause a significant amplitude in GMSL. This likely explains some of the phase differences between gauges within the same basin, notably the earlier phase in tide gauges south of Bermuda in the Atlantic Ocean (Key West, Fernandina) and the phase differences in the western North Pacific. Moreover, if the GMSL fluctuation were as large as that found in some of the reconstructions (Table 1), then to explain the weak (Brest) or nearly absent (Honolulu) 60-year cycle at other locations would mean that the regional signals would have to cancel or nearly cancel out the large GMSL fluctuation. Although possible, it would require an extraordinary synchronization between regional winds and whatever process or processes may be driving GMSL fluctuations at these time scales, which again are not understood.

[15] One mechanism that could cause a detectable change in GMSL is variations in the ocean mass related to multi decadal changes in cycling of water between the oceans and land. Near 60-year oscillations have been observed in precipitation in North America [*Enfield et al.*, 2001; *McCabe et al.*, 2004], as well as Africa and South America [e.g., *Knight et al.*, 2006], all of which have been shown to be significantly correlated with the AMO. We know that the mass component of sea level variability is connected with changes in this water cycling, and has large interannual variations [e.g., *Ngo-Duc et al.*, 2005; *Syed et al.*, 2010]. Although it is probable that 60-year oscillations in precipitation over land will have measureable effects on global mean sea level, the magnitude is impossible to compute without comparable long-term, global measurements of evaporation and river runoff, which do not exist.

[16] Our overarching view is that it is difficult to tell if there is a 60-year oscillation in GMSL based on the tide gauge dataset alone without a better understanding of the redistribution signal. Ignoring the issue of land motion at the tide gauges, which in most locations can be treated as a contribution to the long-term relative sea level trend, we take the view that each tide gauge provides a measure of GMSL fluctuations plus regional sea level variations that do not contribute to GMSL. In that context, it seems most likely that the high amplitude 60-year fluctuations in some of the regions, such as the western North Pacific, the South Pacific, the North Atlantic, and the Indian Ocean (Figure 1 and Table 2) represent wind driven changes associated with an internal climate mode. This would be consistent with recent findings that suggest that multi-decadal sea level variation in the western tropical Pacific is due primarily to trade wind forcing [*Merrifield and Maltrud*, 2011; *Becker et al.*, 2012]. Other regions also exhibit multi decadal sea level variations that appear to be largely wind-driven and not due to GMSL, such as Fremantle [*Feng et al.*, 2004] and the U.S. East coast [*Sturges and Douglas*, 2011].

[17] We do note, however, that an upturn in GMSL rise due to a 60-year oscillation with a minimum between 1980 and 1990 is consistent with the increased GMSL trend obtained from satellite altimetry [e.g., *Nerem et al.*, 2010] and the reconstructions since 1993. Does this mean that the earlier notable inflexion in GMSL in the 1920s and 1930s is also real? Not necessarily. The recent high rates of sea level rise are due in part to what appears to be an enhanced ice melt contribution, particularly from the ice sheets [*Rignot et al.*, 2011], which presumably is a response to increasing global surface temperatures over the same period. Whether or not a similar increase in ice melt, global ocean heat content, or increased water mass exchanges from land occurred

during the earlier inflexion has not been established. Given the small number of tide gauges available during the earlier inflexion, it may be that GMSL reconstructions were more susceptible to poor sampling of regional multi decadal variability than during the altimeter period when the global tide gauge network coverage is relatively high. The long records examined in this study are from regions that are featured heavily in all GMSL reconstruction analyses [e.g., *Jevrejeva et al.*, 2008; *Church and White*, 2011; *Ray and Douglas*, 2011] before 1950.

[18] It is important to point out that even if a 60-year oscillation is occurring in GMSL, it is still a small fluctuation about a highly significant rate of rise. Modeling a 60-year oscillation does not change the estimated trend in any reconstruction time-series of GMSL by more than 0.1 mm yr^{-1} (Table 1), which is lower than the uncertainty. Thus, it does not change the overall conclusion that sea level has been rising on average by 1.7 mm yr^{-1} over the last 110 years. The 60-year oscillation will, however, change our interpretation of the trends when estimated over periods less than 1-cycle of the oscillation. Although several studies have suggested the recent change in trends of global [e.g., *Merrifield et al.*, 2009] or regional [e.g., *Sallenger et al.*, 2012] sea level rise reflects an acceleration, this must be re-examined in light of a possible 60-year fluctuation. While technically correct that the sea level is accelerating in the sense that recent rates are higher than the long-term rate, there have been previous periods were the rate was decelerating, and the rates along the Northeast U.S. coast have what appears to be a 60-year period [*Sallenger et al.*, 2012, Figure 4], which is consistent with our observations of sea level variability at New York City and Baltimore. Until we understand whether the multi decadal variations in sea level reflect distinct inflexion points or a 60-year oscillation and whether there is a GMSL signature, one should be cautious about computations of acceleration in sea level records unless they are longer than two cycles of the oscillation or at least account for the possibility of a 60-year oscillation in their model. This especially applies to interpretation of acceleration in GMSL using only the 20-year record of from satellite altimetry and to evaluations of short records of mean sea level from individual gauges.

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