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Quantifying recent acceleration in sea level unrelated to internal climate variability

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[1] Sea level observations suggest that the rate of sea level rise has accelerated during the last 20 years. However, the presence of considerable decadal-scale variability, especially on a regional scale, makes it difficult to assess whether the observed changes are due to natural or anthropogenic causes. Here we use a regression model with atmospheric pressure, wind, and climate indices as independent variables to quantify the contribution of internal climate variability to the sea level at nine tide gauges from around the world for the period 1920–2011. Removing this contribution reveals a statistically significant acceleration (0.022 ± 0.015 mm/yr^2) between 1952 and 2011, which is unique over the whole period. Furthermore, we have found that the acceleration is increasing over time. This acceleration appears to be the result of increasing greenhouse gas concentrations, along with changes in volcanic forcing and tropospheric aerosol loading. **Citation:** Calafat, F. M., and D. P. Chambers (2013), Quantifying recent acceleration in sea level unrelated to internal climate variability, *Geophys. Res. Lett.*, *40*, 3661–3666, doi:10.1002/grl.50731.

1. Introduction

[2] Recently, there has been significant interest in the question of whether sea level (SL) rise is accelerating, either regionally or globally. This question has typically been addressed by adding quadratic terms to the linear regression model and estimating their value and uncertainty, either for global mean SL (GMSL) reconstructions [*Jevrejeva et al.*, 2008; *Church and White*, 2011, hereinafter CW2011; *Rahmstorf and Vermeer*, 2011] or at individual tide gauges (TGs) [*Woodworth et al.*, 2009; *Houston and Dean*, 2011; *Watson*, 2011; *Woodworth et al.*, 2011; *Boon*, 2012; *Sallenger et al.*, 2012], and for quite different time scales, some as short as 40 years.

[3] On a regional scale, the main difficulty with estimating accelerations over short periods of time is that such estimates are dominated by decadal and multidecadal variability, which can largely mask a possible underlying mean acceleration due to global warming. Decadal and multidecadal variations in SL exist in many regions of the world ocean. They are caused primarily by changes in atmospheric forcing and can be as large as 20 cm or more [*Hong et al.*, 2000; *Miller and Douglas*, 2007; *Bromirski et al.*, 2011; *Merrifield and Maltrud*, 2011; *Chambers et al.*, 2012; *Calafat et al.*, 2012; *Calafat et al.*, 2013]. Nevertheless, none of the regional studies that have attempted to determine a mean quadratic parameter in their SL rise model have accounted for these large decadal and multidecadal variations by including them in their model despite their substantial contribution to short-term accelerations in SL rise. Consequently, and because current estimates of regional SL accelerations reflect a superposition of accelerations due to natural and anthropogenic causes, it is not possible to assess whether the observed accelerations are in response to global warming or whether they are part of a multidecadal variation.

[4] In studies of GMSL, reconstruction techniques are often used to account for the internal variability. Consequently, decadal and multidecadal variations are much weaker in GMSL reconstructions, and acceleration estimates are, therefore, more robust, especially if long records (>100 years) are used [*Jevrejeva et al.*, 2008; CW2011; *Ray and Douglas*, 2011, hereinafter RD2011; *Rahmstorf and Vermeer*, 2011]. Note, however, that GMSL reconstructions are not without their problems and they still show significant decadal and multidecadal variability [*Jevrejeva et al.*, 2008; CW2011; RD2011; *Chambers et al.*, 2012]. The poor spatial sampling of the TG data set used in the reconstruction, the way in which the TG distribution changes over time, and the fact that the SL variability at the TGs is often dominated by coastal processes that are not captured by altimetry, all can introduce spurious signals in the GMSL.

[5] Here, we explore a model of variable SL rise to account for internal climate variability in order to assess whether there has been an acceleration over the last century that can be attributed to causes other than internal climate variability. We make use of results from previous studies on the mechanisms responsible for the observed SL variability to model the response of SL to atmospheric forcing at nine long TG records from around the world for the period 1920–2011. The model is a multiple linear regression (MLR) with SL as the dependent variable and sea level pressure (SLP), wind, and climate indices as independent variables. The paper is arranged as follows. Section 2 will describe the data used, including climate indices. Section 3 will explore the performance of the MLR model and present the results of the SL accelerations. Finally, Section 4 will discuss the implications of the results.

2. Data and Methods

[6] TG records of monthly averaged time series of SL were obtained from the Revised Local Reference data archive of the Permanent Service for Mean Sea Level [*Woodworth and Player*, 2003]. We first selected 13 nearly continuous TG records: Trieste (1875–2011), Newlyn (1915–2011), New York

Additional supporting information may be found in the online version of this article.

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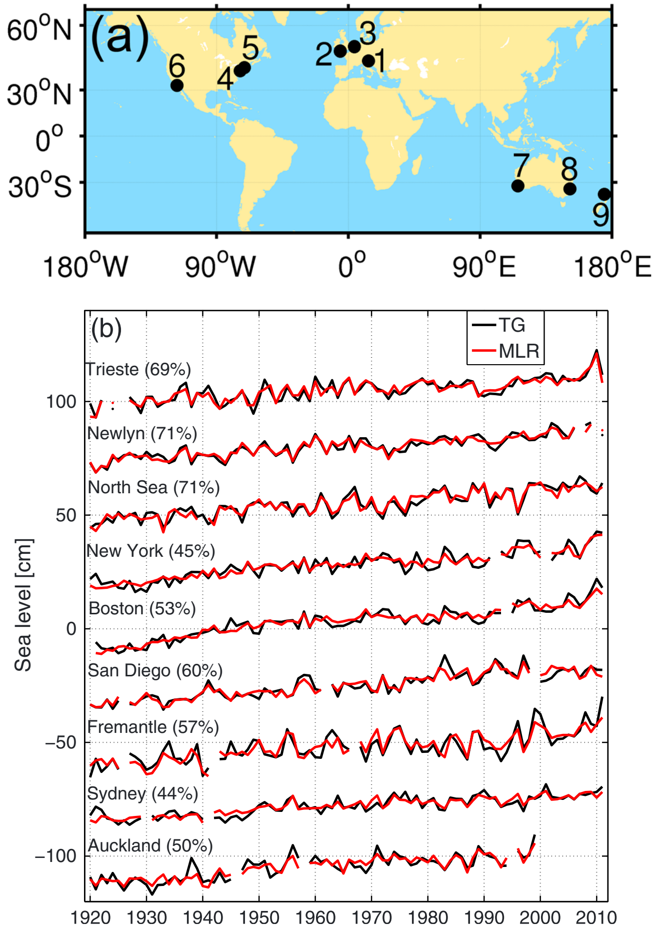

Figure 1. (a) The location of the nine TGs used in this study: (1) Trieste, (2) Newlyn, (3) North Sea, (4) New York, (5) Boston, (6) San Diego, (7) Fremantle, (8) Sydney, and (9) Auckland. (b) A comparison of annual values of SL (black) from the 9 nine TG records with an estimate of the atmospheric contribution (red) calculated using a MLR model with SLP, wind, and climate indices as independent variables. The numbers within parentheses indicate percentage of variance, which has been calculated for detrended time series.

(1856–2011), Boston (1921–2011), San Diego (1906–2011), Fremantle (1897–2011), Sydney (1914–2011), Auckland (1903–1999), Esbjerg (1889–2011), Hoek Van Holland (1864–2011), Ijmuiden (1871–2011), Den Helder (1865–2011), and Vlissingen (1862–2011). The last five stations are all located in the North Sea and are highly correlated. These five stations were, therefore, averaged to produce a single record for the North Sea. The location of the resulting nine TG records is shown in Figure 1a. This set of selected stations ensures that all major oceans (except for the Arctic Ocean) as well as both hemispheres are represented.

[7] Gaps of 1 or 2 months were filled using cubic spline interpolation. Note that this is a very minor correction since no record has more than 5% of missing data over the period 1920–2011. Annual averages of SL were then calculated by averaging the available monthly values, noting that if more than 2 months during the year had a missing monthly value, the annual value was rejected. Note that since we are interested in detecting departures from long-term trends, linear signals such as glacial isostatic adjustment do not affect our analysis.

[8] The SLP data used here were obtained from the near-real-time update of the Hadley Centre Sea Level Pressure (HadSLP2r with reduced variance) data set [*Allan and Ansell*, 2006]. HadSLP2r combines marine and land pressure observations using a reduced-space optimal interpolation analysis and is available on a 5° latitude-longitude grid from 1850 to the present. Monthly mean wind observations (we use wind instead of wind stress because, at low frequencies, observations suggest a linear response [*Cragg et al*., 1983]) were obtained from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS, Release 2.5) [*Woodruff et al*., 2011]. The ICOADS data set contains marine surface observations spanning the period from 1800 to the present and is provided on a global 2° × 2° grid. As for the tide gauge data, annual averages were rejected if more than 2 months in a year had a missing monthly value. It is important to note that because wind observations are really sparse before the 1920s, we decided to restrict our analysis to the period 1920–2011.

[9] The time series of the North Atlantic Oscillation (NAO) index is computed here as the first leading principal component (PC) of the SLP from HadSLP2r over the North Atlantic sector (90°W–40°E, 20°N–80°N) [*Hurrell et al*., 2003]. The variability associated with the El Niño-Southern Oscillation (ENSO) is represented by the Multivariate ENSO index (MEI, available at http://www.esrl.noaa.gov/psd/enso/), which is computed as the first unrotated PC of six observed atmospheric and oceanic variables combined over the tropical

Table 1. SLRDs for Eight TG Records Calculated Using a 60 Year Window From 1952 to 2011[a]

	SLRD	
	Total SL	Residual
	(mm/yr)	(mm/yr)
Trieste	1.5 ± 2.0	0.2 ± 1.0
Newlyn	1.2 ± 1.7	-0.1 ± 1.1
North Sea	0.9 ± 2.0	0.9 ± 1.0
New York	2.8 ± 2.1	0.6 ± 1.1
Boston	3.6 ± 1.9	1.2 ± 1.4
San Diego	-1.3 ± 1.9	0.6 ± 1.4
Fremantle	3.9 ± 3.3	1.6 ± 1.9
Sydney	0.6 ± 1.4	0.2 ± 1.0

[a]SLRDs are shown for both the total SL and the residual (total SL-MLR model). Uncertainties represent the 90% CI, and they account for serial correlation.

Pacific [*Wolter and Timlin*, 1998] and spans the period 1950–2011. For the years before 1950, we use the extended MEI index [*Wolter and Timlin*, 2011]. Finally, the Pacific Decadal Oscillation (PDO) index (available at http://jisao.washington.edu/pdo/) is defined as the leading PC of North Pacific monthly sea surface temperature variability poleward of 20°N [*Mantua et al.*, 1997].

[10] The contribution of the internal variability to coastal SL is modeled by means of MLR, with SLP, meridional (*U*) and zonal (*V*) wind, and climate indices (NAO, MEI, and PDO) as independent variables (see the supporting information). Note that the model is regional, and thus, global ocean mass may not be strictly conserved. Finally, SL accelerations are investigated using SL rate differences (SLRDs) [*Sallenger et al.*, 2012]. Briefly, for a window of size τ, which is divided in two halves, the SLRD between the two half-window series can be calculated as

$$\mathrm{SLRD}(t_c, \tau) = \hat{\beta}_1^{\mathrm{HW2}}\left(\frac{\tau}{2}\right) - \hat{\beta}_1^{\mathrm{HW1}}\left(\frac{\tau}{2}\right), \tag{1}$$

where t_c denotes the central year of the window (taken as the first year of the second half record for even values of τ), and $\hat{\beta}_1^{\mathrm{HW1}}$ and $\hat{\beta}_1^{\mathrm{HW2}}$ represent estimates of the trend coefficient for the first and second half-window series (HW1 and HW2), respectively. A more detailed description of how the SLRDs and their uncertainty are calculated is presented in the supporting information. Unless otherwise noted, all uncertainties represent the 90% confidence interval (CI) and account for serial correlation.

3. Results

[11] A comparison between the MLR model and the SL for each TG is shown in Figure 1b. The interannual SL variability is considerable at all stations with fluctuations of up to 20 cm and is very well captured by the MLR model, although with a varying degree of agreement depending on the TG. The variance explained by the MLR model ranges from 44% at Sydney to 71% at both Newlyn and the North Sea. It should be noted that stations located on the western boundaries of the major oceans, such as New York and Boston, are affected by intense boundary currents and by the delayed response of the ocean to earlier open-ocean atmospheric forcing [*Hong et al.*, 2000; *Miller and Douglas*, 2007]. Such effects are difficult to quantify and are only partly captured in our MLR model by the inclusion of lagged values of the wind in the model and through the link between climate indices and large-scale ocean circulation. Nevertheless, the MLR model performs very well at all TGs, including New York and Boston, and thus, it provides a useful means to quantify the contribution of the internal variability to the observed SL accelerations.

[12] We begin by addressing recent accelerations at individual TGs, such as those remarked on by [*Sallenger et al.*, 2012] in the northeastern United States. Table 1 lists the SLRDs for eight TGs (Auckland ends in 1999) calculated using a 60 year window from 1952 to 2011 for both the total SL and the residual (total SL-MLR model). We find that only New York, Boston, and Fremantle show statistically significant (90% CI) SLRDs, with values that are larger than 2.8 mm/yr at all three locations. SLRDs from all other records are not statistically different from zero. After subtracting our estimate of the internal variability from the total SL, SLRDs are not statistically different from zero at any TG (Table 1). This indicates that a substantial fraction of the recent increase in the rate of SL rise observed at these TG stations can be explained as a response to changes in atmospheric forcing.

[13] A question now arises as to whether this considerable contribution of internal variability to the SLRDs is also observed in other periods in the past. To answer this question, we calculate SLRDs for each year of the TG record by shifting the regression window through the entire record at intervals of 1 year. A comparison of the SLRDs from total SL with those from the MLR model is shown in Figure 2 for a 60 year window and for all TG records. Overall, there is a very good agreement between the two time series of SLRDs at all stations. The MLR model explains on average 75% of the SLRD variance, with maximum values of 97%, 93%, and 91% at Boston, Trieste, and New York, respectively. Note also that SLRDs fluctuate between negative and positive values. However, while the amplitude of the fluctuations is similar among stations, their phases differ significantly. In some extreme cases, such as between San Diego and Fremantle, SLRDs fluctuate completely out of phase with each other (correlation = −0.77).

[14] SLRDs at the nine TGs can be averaged to give a time series of global coastal mean SLRDs (CM SLRDs). A comparison between the CM SLRDs before and after the removal of the internal variability is shown in Figure 3 for a 60 year window. For the total SL (black line), CM SLRDs exhibit statistically significant negative values from 1950 to 1968, with a minimum value of -1.4 ± 0.6 mm/yr (90% CI) for the record centered around 1958, and positive and statistically significant values from 1978 to 1982, with a maximum of 1.7 ± 0.8 mm/yr for the 60 year record centered around 1981.

[15] If the effect of the internal variability is ignored, one might (erroneously) conclude from the most recent CM SLRDs quoted above that SL rise is accelerating at a substantial rate (note that a SLRD of 1.7 mm/yr for a 60 year window corresponds to an acceleration of ~0.06 mm/yr^2, which if continued over the next 100 years would result in a SL rise of ~30 cm in addition to the rise due to the linear rate). However, we have seen that internal variability is important at individual TGs, and thus, it must be accounted for to properly estimate the fraction of the accelerations that is due to external forcing. After removing our estimate of the internal variability, the curve of CM SLRDs is much flatter, with almost all values being not statistically different from zero (Figure 3, red line). We find, however, that the two most recent

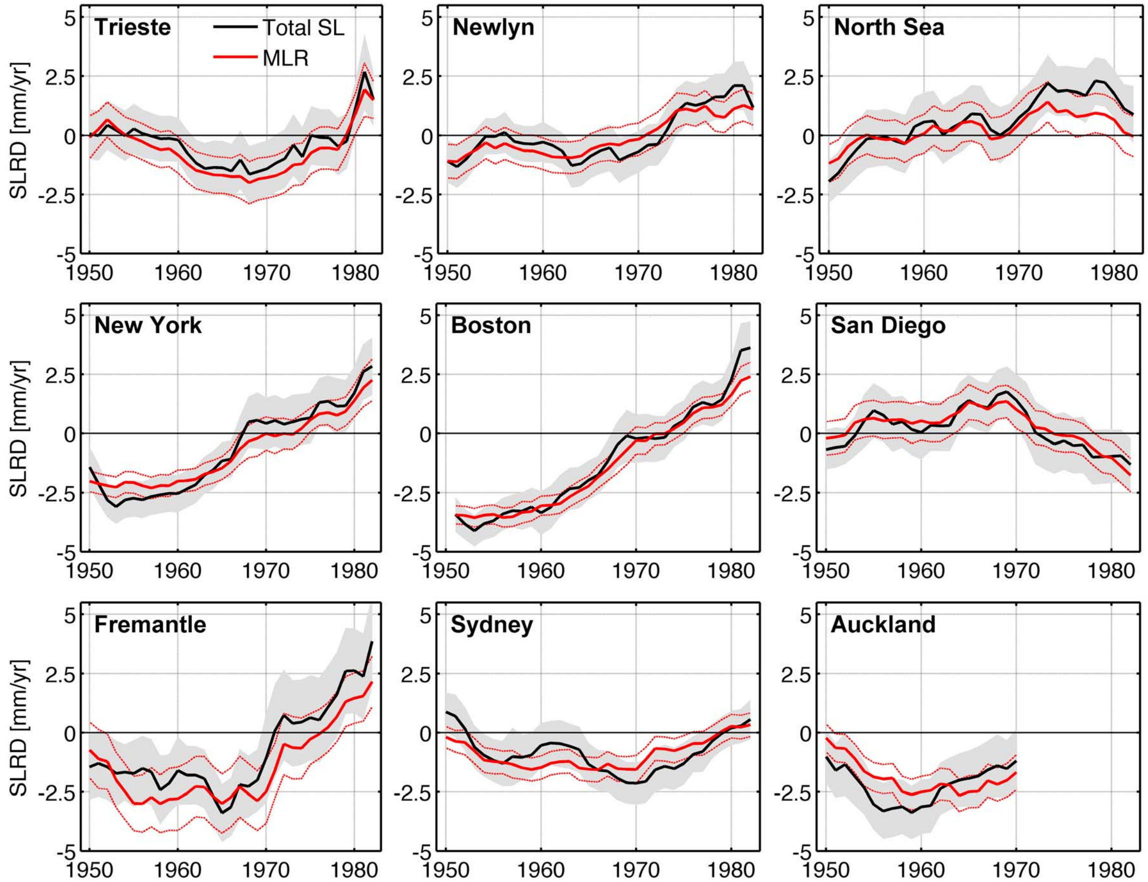

Figure 2. A comparison between the SLRDs (60 year window) from total SL (black) and those from the MLR model (red) at nine TGs: Trieste, Newlyn, North Sea, New York, Boston, San Diego, Fremantle, Sydney, and Auckland. The gray shaded area represents the uncertainty (±1σ) associated with the black line, whereas the dashed red lines represent the uncertainty (±1σ) associated with the red line. Uncertainty accounts for serial correlation.

CM SLRDs from the residual (centered around 1981 and 1982) are statistically significant (0.65 ± 0.45 mm/yr for the most recent record). Note that all other values are not statistically different from zero in spite of the fact that the CM SLRDs from the total SL exhibit large negative and positive values. It is also interesting to note that while the CM SLRDs from the total SL started to increase remarkably from 1966, the residual CM SLRDs remained close to zero (although with a slightly positive trend) until 1973 and only then started to increase significantly. Hence, in the most recent record, there is a statistically significant acceleration in SL of 0.022 ± 0.015 mm/yr^2 (90% CI), which is unique over the whole period, and which, assuming that the internal variability has been adequately removed, is due to external forcing (anthropogenic and/or natural).

[16] In order to ensure that no single TG biased the overall results of the CM SLRDs from the residual, each TG was removed one at a time and the CM SLRDs recalculated. Removal of each TG did not alter our results, and all the recalculated CM SLRDs showed statistically significant values for the most recent record centered around 1982 (from 1952 to 2011) and nonsignificant values for all other records.

[17] Another remarkable feature from Figure 3 is the linear increase in the residual CM SLRDs from 1973 onward, which suggests that the acceleration is increasing over time. Fitting a linear trend to this section of the curve shows that, since 1973, CM SLRDs from the residual have been

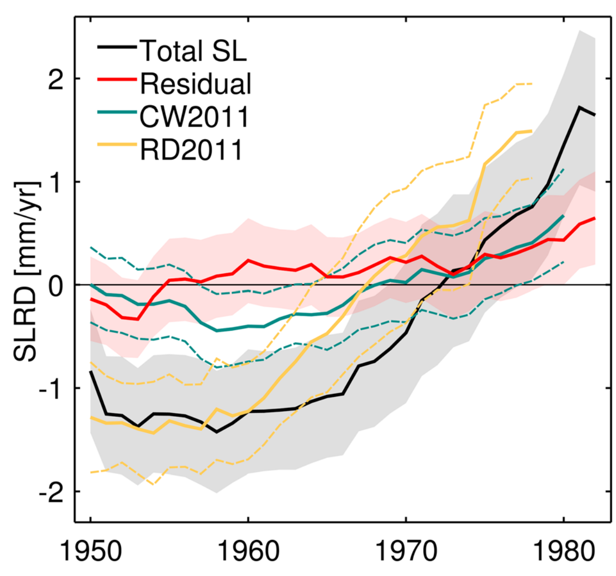

Figure 3. Comparison between the CM SLRDs (from the nine TGs) from total SL (black) and from the residual (total SL-MLR model) (red) for a 60 year window. The SLRDs from the GMSL reconstructions of CW2011 (green) and RD2011 (orange) are also shown. Shading and dashed lines represent the uncertainty (90% CI), which accounts for serial correlation.

increasing at a significant rate of 0.06 ± 0.03 mm/yr^2 ($\pm 1\sigma$, accounts for errors in the SLRDs). If the linear trend is fitted over the whole period, we find a rate of 0.021 ± 0.005 mm/yr^2, which is also statistically significant.

[18] We have also compared our CM SLRDs to the SLRDs from the GMSL of CW2011 (green line) and RD2011 (orange line) (Figure 3). In principle, one would expect SLRDs from GMSL to show much less decadal-scale variability than the uncorrected CM SLRDs, since, in such studies, the effect of internal climate variability is minimized. We note, however, that this is not the case for RD2011, the variability of which is comparable to that of the CM SLRDs from total SL and much larger than the variability of the CM SLRDs from the residual. Conversely, the global SLRDs from CW2011 agree quite well with the residual CM SLRDs, although their variability is slightly larger (standard deviation of 0.29 mm/yr as compared to 0.22 mm/yr for the residual CM SLRDs). They show a statistically significant SLRD at the end of the record (0.67 ± 0.45 mm/yr) and a significant linear increase in the SLRDs from 1973 onward. Both features are consistent with those observed in the residual CM SLRDs. Some differences are observed, however, during the period 1957–1962, when the global SLRDs from CW2011 show statistically significant negative values, whereas the residual CM SLRDs suggest that such values are not statistically different from zero. This may be an indication of a small contribution from internal variability in either the global SLRDs or the CM SLRDs, or both.

4. Discussion and Conclusions

[19] In this study we have found that SLRDs at nine individual TGs from around the world exhibit significant decadal and multidecadal variability over the period 1920–2011, fluctuating between periods of negative and positive values (ranging from -4.1 mm/yr to 3.6 mm/yr for a 60 year window). We have demonstrated that a significant fraction (up to 97%) of these fluctuations can be explained as a response to changes in atmospheric forcing related to modes of natural variability. In regional studies, such fluctuations can largely mask a possible underlying mean acceleration due, for instance, to global warming, and thus, they need to be accounted for to avoid drawing incorrect conclusions.

[20] By modeling the contribution of the atmospheric forcing to each TG and removing it from the total SL, we have been able to detect a statistically significant acceleration in the coastal average SL from the nine TGs of 0.022 ± 0.015 mm/yr^2 (90% CI) for the most recent record (1952–2011). This acceleration in the residual SL is unique over the whole time period considered here. Furthermore, our curve of coastal average SLRDs (Figure 3) shows that, since 1973, SL accelerations have been increasing at a significant rate of 0.002 mm/yr^3 until reaching its present value of 0.022 ± 0.015 mm/yr^2 for the 60 year record centered around 1982. A similar increase in the SL acceleration is also evident in the reconstructed GMSL of CW2011.

[21] We can conclude that, since the residual CM SLRDs reflect mostly changes unrelated to internal climate variability, the detected SL acceleration is likely not part of a natural cycle. Note that, in this study, internal climate variability includes not only the barotropic response to SLP and wind but also other less local processes such as coastal steric changes induced by the longshore wind, Rossby wave propagation, and changes in ocean currents and circulation. We, of course, admit that some fraction of the acceleration may be due to internal climate variability that has not been properly captured by the MLR model. Nevertheless, the fact that the residual CM SLRDs show less variability than the SLRDs from GMSL suggests that our MLR model does indeed a good job in minimizing the effect of internal climate variability. Also note that external forcing, such as anthropogenic climate change, might also influence modes of natural variability. This contribution, as far as it is reflected in the model, will likely have been removed with the MLR model. Thus, the detected acceleration can only be that due to external forcing that is not reflected in changes in modes of natural variability in the model. We also note that changes in SL from addition of water mass from ice sheets, continental glaciers, and depletions of hydrological reservoirs will not be reflected in this model.

[22] In a recent paper, *Church et al.* [2013] explored the relative contribution of different processes to changes in the rate of GMSL rise during the period 1900–2010. Consistent with our results, they identified an increase in the rate of GMSL rise from about 1980 to 2010. They found that most of this increase can be explained as the sum of the ocean thermal expansion, glacier, and land-water storage contributions, with thermal expansion being the dominant contribution, especially after 1986. The contribution from the Antarctica and Greenland ice sheets appears to be relatively small. Furthermore, they concluded that the increase is the result of continued increases in greenhouse gas concentrations, along with changes in volcanic forcing and tropospheric aerosol loading, and thus the result of anthropogenic and natural external forcing.

[23] Our study corroborates the work of *Church et al.* [2013] that SL rise has accelerated significantly over the last several decades and that it does not appear to be related to internal variability. In addition, we have shown that the acceleration is increasing over time. Due to its link with anthropogenic activities, this acceleration may continue to grow as greenhouse gas concentrations increase.

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References

Allan, R. J., and T. J. Ansell (2006), A new globally complete monthly historical mean sea level pressure data set (HadSLP2): 1850–2004, *J. Climate*, *19*, 5816–5842.

Boon, J. D. (2012), Evidence of sea level acceleration at U.S. and Canadian tide stations, Atlantic Coast, North America, *J. Coast. Res.*, *28*, 1437–1445.

Bromirski, P. D., A. J. Miller, R. E. Flick, and G. Auad (2011), Dynamical suppression of sea level rise along the Pacific coast of North America: Indications for imminent acceleration, *J. Geophys. Res.*, *116*, C07005, doi:10.1029/2010JC006759.

Calafat, F. M., D. P. Chambers, and M. N. Tsimplis (2012), Mechanisms of decadal sea level variability in the eastern North Atlantic and the Mediterranean Sea, *J. Geophys. Res.*, *117*, C09022, doi:10.1029/2012jc008285.

Calafat, F. M., D. P. Chambers, and M. N. Tsimplis (2013), Inter-annual to decadal sea-level variability in the coastal zones of the Norwegian and Siberian Seas: The role of atmospheric forcing, *J. Geophys. Res. Oceans*, *118*, 1287–1301, doi:10.1002/jgrc.20106.

Chambers, D. P., M. A. Merrifield, and R. S. Nerem (2012), Is there a 60-year oscillation in global mean sea level?, *Geophys. Res. Lett.*, *39*, L18607, doi:10.1029/2012GL052885.

Church, J. A., and N. J. White (2011), Sea-level rise from the late 19th to the early 21st Century, *Surv. Geophys.*, *32*, 585–602.

Church, J. A., D. Monselesan, J. M. Gregory, and B. Marzeion (2013), Evaluating the ability of process based models to project sea-level change, *Environ. Res. Lett.*, *8*, 014051.

Cragg, J., G. T. Mitchum, and W. Sturges (1983), Wind-induced sea-surface slopes on the West Florida Shelf, *J. Phys. Oceanogr.*, *13*, 2201–2212.

Hong, B. G., W. Sturges, and A. J. Clarke (2000), Sea level on the U.S. East Coast: Decadal variability caused by open ocean wind-curl forcing, *J. Phys. Oceanogr.*, *30*, 2088–2098.

Houston, J. R., and R. G. Dean (2011), Sea-level acceleration based on U.S. tide gauges and extensions of previous global-gauge analyses, *J. Coast. Res.*, *27*, 409–417.

Hurrell, J. W., Y. Kushnir, G. Ottersen, and M. Visbeck (Eds.) (2003), *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, Geophys. Monogr. Ser., vol. *134*, 279 pp., AGU, Washington, D. C., doi:10.1029/GM134.

Jevrejeva, S., J. C. Moore, A. Grinsted, and P. L. Woodworth (2008), Recent global sea level acceleration started over 200 years ago?, *Geophys. Res. Lett.*, *35*, L08715, doi:10.1029/2008GL033611.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079.

Merrifield, M. A., and M. E. Maltrud (2011), Regional sea level trends due to a Pacific trade wind intensification, *Geophys. Res. Lett.*, *38*, L21605, doi:10.1029/2011GL049576.

Miller, L., and B. C. Douglas (2007), Gyre-scale atmospheric pressure variations and their relation to 19th and 20th century sea level rise, *Geophys. Res. Lett.*, *34*, L16602, doi:10.1029/2007GL030862.

Rahmstorf, S., and M. Vermeer (2011), Discussion of: Houston, J.R. and Dean, R.G., Sea level acceleration based on U.S. tide gauges and extensions of previous global-gauge analyses, *J. Coast. Res.*, *27*, 784–787.

Ray, R., and B. Douglas (2011), Experiments in reconstructing twentieth-century sea levels, *Prog. Oceanogr.*, *91*, 496–515.

Sallenger, A. H., Jr., K. S. Doran, and P. A. Howd (2012), Hotspot of accelerated sea-level rise on the Atlantic coast of North America, *Nat. Clim. Change*, *2*, 884–888.

Watson, P. J. (2011), Is there evidence yet of acceleration in mean sea level rise around mainland Australia?, *J. Coast. Res.*, *27*, 368–377.

Wolter, K., and M. S. Timlin (1998), Measuring the strength of ENSO events: How does 1997/98 rank?, *Weather*, *53*, 315–324.

Wolter, K., and M. S. Timlin (2011), El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext), *Int. J. Climatol.*, *31*, 1074–1087.

Woodruff, S. D., et al. (2011), ICOADS Release 2.5: Extensions and enhancements to the surface marine meteorological archive, *Int. J. Climatol.*, *31*, 951–967.

Woodworth, P. L., and R. Player (2003), The Permanent Service for Mean Sea Level: An update to the 21st century, *J. Coast. Res.*, *19*, 287–295.

Woodworth, P. L., N. J. White, S. Jevrejeva, S. J. Holgate, J. A. Church, and W. R. Gehrels (2009), Evidence for the accelerations of sea level on multi-decade and century timescales, *Int. J. Climatol.*, *29*, 777–789.

Woodworth, P. L., M. Menéndez, and W. R. Gehrels (2011), Evidence for century-timescale acceleration in mean sea levels and for recent changes in extreme sea levels, *Surv. Geophys.*, *32*, 603–618.