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Gyre-scale atmospheric pressure variations and their relation to 19th and 20th century sea level rise

Laury Miller[1] and Bruce C. Douglas[2]

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[1] Most of the long tide gauge records in the North Atlantic and North Pacific commonly used to estimate global sea level rise and acceleration display a marked difference in behavior in the late 1800's – early 1900's compared to the latter half of the 20th century. The rates of sea level rise tend to be lower in the 19th compared to 20th century. We show this behavior may be related to long-term, gyre-scale surface pressure variations similar to those associated with the Northern Annular Mode. As sea level pressure increases (decreases) at decadal and longer timescales at the centers of the subtropical atmospheric gyres, sea level trends along the eastern margins in each ocean basin decrease (increase). This is not an isostatic response; the scaling between local surface pressure and sea level at interannual and longer timescales is 3 to 6 times greater than expected by that mechanism. Rather, it appears to be the result of large, possibly gyre-scale changes in ocean circulation. Some evidence is also presented indicating slow, ~2 cm/sec, westward propagation of sea level changes in the Atlantic from the west coast of Europe to the east coast of the U.S. which produce the decadal variability seen there. **Citation:** 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.

1. Introduction

[2] In a recent paper, *Church and White* [2006] provided evidence of a 20th century acceleration of Global Sea-Level Rise. Using tide gauge data to determine the amplitude changes in a set of empirical orthogonal functions (EOFs) derived from 12 years of satellite altimeter data, they produced a reconstruction of global sea level from which they estimated a 20th century rate of 1.7 ± 0.3 mm/yr and an acceleration of 0.013 ± 0.006 mm/yr^2. In their analysis, much of the acceleration appears to take place between 1910 and 1930. Since the number and distribution of statistically independent gauges prior to this pivotal time period is limited (perhaps fewer than 5), it is important to understand the low-frequency characteristics of the tide gauge records in the late 19th/early 20th century [*Jevrejeva et al.*, 2006]. Do they show the same type of decadal and longer timescale variability as during the second half of 20th century, when the number and distribution of gauges increased greatly? Our interest in this problem stems from a recent paper by one of us [*Douglas*, 2007], in which very low-frequency sea level variations are shown to be highly correlated with local surface atmospheric pressure variations, but not in terms of an isostatic response. Surprisingly, this relationship seems to hold over timescales ranging from interannual to centennial, the latter being the most relevant to estimating accelerations in sea level rise. *Mathers and Woodworth* [2001] have previously documented large variations from isostasy for relative sea levels measured by some tide gauges, although on shorter timescales. In this paper, we relate multi-decadal sea level variations to gyre-scale changes in the atmosphere.

2. Results

2.1. North Atlantic

[3] The tide gauge records of relative sea level (RSL) from Brest & Cascais (Figure 1a), two of the longest in Europe, appear flatter prior to 1900–1920, compared to later. At Brest, this causes the calculated trend for the 20th century (1.4 mm/yr) to be about 40% greater than that for the entire record (1.0 mm/yr). In addition, the early portions of these records also exhibit relatively large (~4 cm) decadal variability. In Figure 1b we compare detrended RSL at Brest with the surface pressure at Brest scaled by −3.6, a factor corresponding to the ratio of the normalizing standard deviations (std of detrended RSL divided by std of detrended SLP). The phase agreement is generally good at all timescales longer than a decade, including the interval between 1860 and 1910 when the undetrended RSL appears relatively flat. Figure 1c shows a similar plot for detrended RSL at Cascais compared with the local sea level pressure scaled by the ratio of the normalizing standard deviations, −4.3 in this case.

[4] The decadal agreement is not as good as at Brest, but the multi-decadal agreement is quite good, especially in the late 1800's–early 1900's. In both examples, the scaling is wrong for the RSL signals to be explained by a local Inverted Barometer (IB) effect, which should scale by −1 cm/mbar [*Gill*, 1982], not −3.6 or −4.3. Since the agreement in Figures 1b and 1c is not the result of local forcing, a reasonable alternative explanation is that it is the indirect result of large scale atmospheric forcing that also happens to be reflected in the local SLP.

[5] To test this idea, Figure 2 shows a comparison between detrended RSL at Cascais and the 1st EOF time function of SLP for the region 0° to 80°N, 280° to 360°E, based on the ERSLP gridded analysis [*Smith and Reynolds*, 2004]. The map inset shows the amplitude of the 1st empirical orthogonal function (EOF) which, combined with the time function, accounts for 41% of the total variance. As

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[1] NOAA Laboratory for Satellite Altimetry, Silver Spring, Maryland, USA.

[2] Laboratory for Coastal Research, Florida International University, Miami, Florida, USA.

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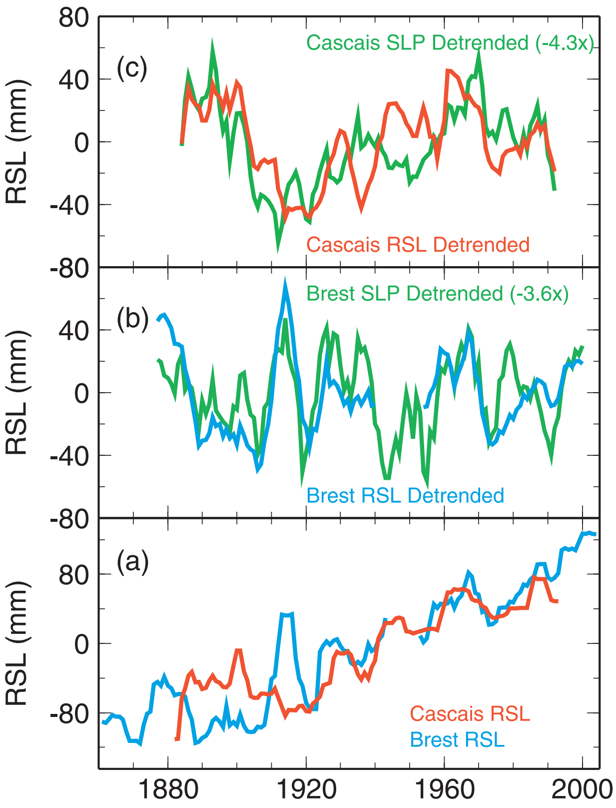

Figure 1. (a) Smoothed (5 year boxcar) RSL records from Brest and Cascais in the eastern North Atlantic appear "flatter" prior to ~1920 than later in the 20th century. (b) Brest RSL detrended and smoothed, local sea level pressure at Brest scaled by −3.6. (c) Cascais RSL detrended and smoothed, local sea level pressure at Cascais scaled by −4.3 (green). Gauge results are based on monthly time series obtained from the Permanent Service for Mean Sea Level (www.pol.ac.uk/psmsl), corrected for GIA [*Peltier*, 2001].

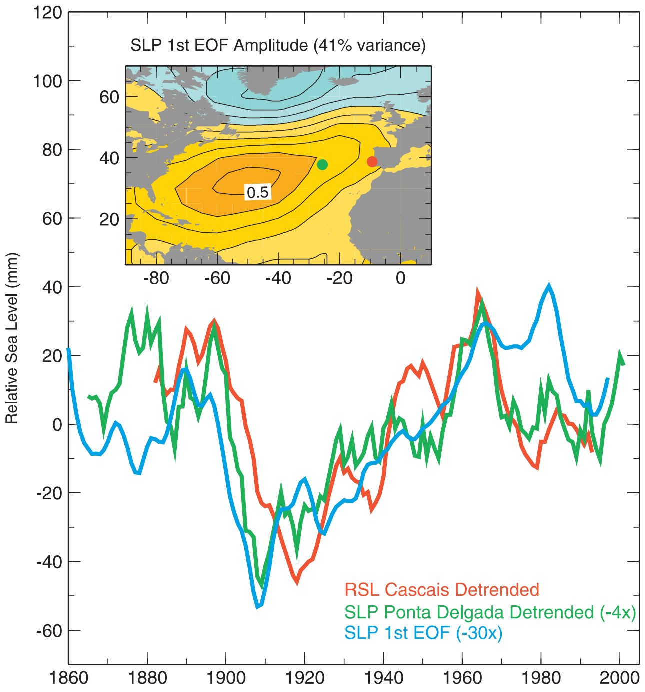

Figure 2. Detrended RSL at Cascais compared with the 1st EOF time function of North Atlantic SLP [*Smith and Reynolds*, 2004] scaled by −30x, and SLP from Ponta Delgada, Azores, detrended and scaled by −4x. All three records show a downturn in 1890–1910 followed by a rise in 1910–1960. Map inset shows dipole pattern in 1st EOF of SLP amplitude characteristic of the North Atlantic Oscillation.

a check on the analyzed SLP field, which is largely based on ship observations, Figure 2 also shows an SLP record from Ponta Delgada, Azores, detrended and scaled by a factor of −4. The excellent agreement between the Cascais RSL and both scaled pressure records suggests that multi-decadal variability at Cascais, particularly the difference between the early and late 20th century trends, is closely related to gyre-scale changes in the atmosphere in the following sense: an increase (decrease) of SLP at the center of the sub-tropical gyre coincides with a decrease (increase) of RSL at the eastern margin of the basin. This inverse relationship suggests that as the atmospheric gyre spins up (down), the oceanic gyre also spins up (down), in response to changes in the wind stress curl, causing RSL at the eastern margin to fall (rise). For example in Figure 2 the atmospheric pressure at the center of the North Atlantic increased during 1890–1910, causing the wind stress curl to become more negative, which in turn forced an increase in southward Sverdrup transport in the ocean interior. This southward transport must be balanced by a zonal sea level gradient, leading to a decrease of sea level along the eastern boundary of the ocean.

[6] However, this simple description gets more complicated if we also consider the decadal variability of RSL along the western margin of the North Atlantic. Figure 3 shows a comparison between detrended Cascais RSL and detrended RSL from the average of 6 tide gauge series between Baltimore and Halifax, each record having been offset by minus 10 years relative to Cascais, the offset of maximum correlation for the ensemble. The decadal agreement is surprisingly good. The correlation between Cascais and Portland is best overall, at 0.78, suggesting that westward wave propagation is responsible for the lagged response along the western margin. Using a simple wind-forced Rossby wave model, *Sturges and Hong* [1995] have

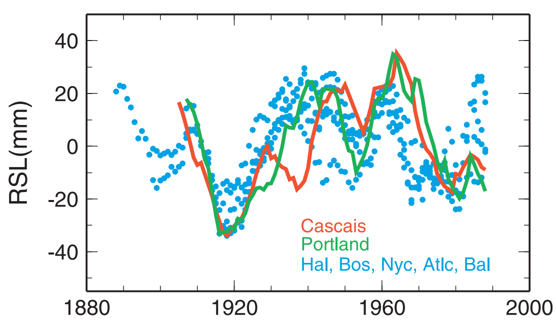

Figure 3. Detrended Cascais RSL (red) compared with detrended RSL at 6 gauge sites along the east coast of North America: Halifax, Boston, New York, Atlantic City, and Baltimore all plotted in blue, Portland in green. All east coast records have been offset by −10 years relative to Cascais, the offset of maximum correlation for the ensemble.

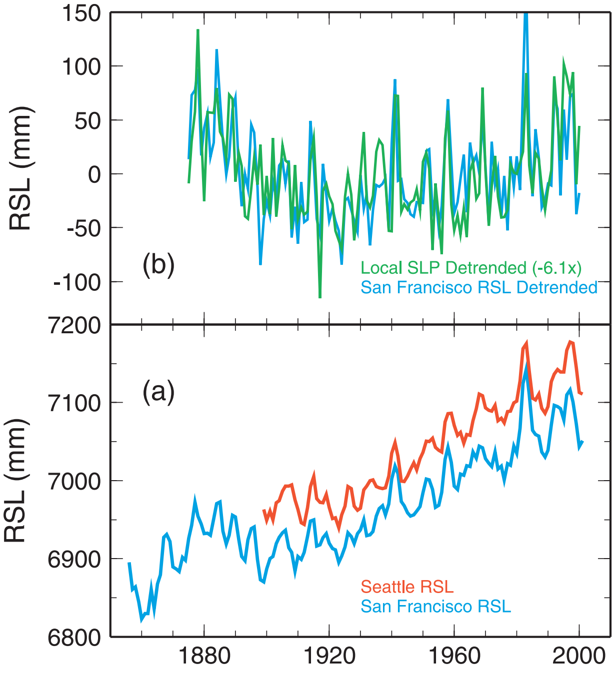

Figure 4. (a) Smoothed (5 year boxcar) RSL at San Francisco and Seattle exhibit good agreement at all timescales, from interannual (ENSO) to multi-decadal. Neither shows a significant increase during 1900–1930. (b) San Francisco RSL detrended and smoothed, local SLP at San Francisco scaled by −6.09.

previously shown that decadal sea level variability at Bermuda is largely explained by the integrated response to wind forcing between Bermuda and the African coast. *Hong et al.* [2000] extended this work by demonstrating that the sea level signals could actually propagate through the Gulf Stream and reach the east coast of the U.S., at least north of Cape Hatteras. However, both of these studies only analyzed the time period after 1950, and thus missed the large change in multi-decadal variability between the late 1800's–early 1900's and the rest of the 20th century.

2.2. North Pacific

[7] San Francisco (Figure 4a) has the longest continuous record of RSL in the U.S. There are no other sites on the west coast that reach into the 1800's, but the Seattle record offers some corroboration of the San Francisco record. Both show little increase between 1900 to 1930, followed by a mostly uniform rise from 1930 onward. However, it is the period prior to 1900 in the San Francisco record which is the most intriguing. Between 1855 and 1900, RSL fluctuated by about 10 cm and between ~1870 and 1930, an interval of 60 years during which there was no net increase of RSL. As a result, the trend computed from 1900 to 2000 is 40% greater (2.03 mm/yr) than that computed from 1855 to 2000 (1.44 mm/yr).

[8] Is this change in RSL trends linked to atmospheric forcing, as seen in the North Atlantic? Figure 4b shows a comparison between de-trended San Francisco RSL and local SLP scaled by −6.09, the ratio of the normalized standard deviations. The centennial-scale agreement is remarkable. The two curves show nearly identical quadratic-shaped curves capturing all of the trend differences before and after the 1910–1930 time period. The inter-annual variations are ENSO-related [*Chelton and Davis*, 1982] and, at least since 1930, are strongly correlated with the Southern Oscillation Index (SOI). The SOI is not very accurate before 1930 [*Trenberth*, 1997; *Douglas*, 2001]. However, the Darwin sea level pressure is a good proxy for the SOI, and it correlates well with San Francisco and Seattle RSL at inter-annual frequencies as far back as it goes, to 1875. The Darwin SLP does not, however, agree with the centennial-scale oscillation of San Francisco RSL between 1860 and 1930.

[9] There is very little wind data available in the North Pacific prior to 1900, however there is some evidence of a quadratic trend in pressure field of the sub-tropical atmospheric gyre similar to that seen in the North Atlantic (Figure 2). Figure 5 shows a comparison between de-trended San Francisco RSL and the 1st EOF time function of SLP for the region 30°N to 60°N, 140°E to 230°E, based on the GMSLP2 gridded analysis [*Basnett and Parker*, 1997]. The map inset shows the 1st EOF amplitude function which, combined with the time function, accounts for 50% of the total variance. The agreement between the two SLP series and the RSL series suggests that: (1) the San Francisco RSL record is valid as far back as the 1870's and (2) the difference between the early and late 20th century trends is closely related to gyre-scale changes in the atmosphere, as was shown for the North Atlantic.

3. Discussion

[10] The fact that decadal variability in certain long gauge records can be explained in some cases by large-scale

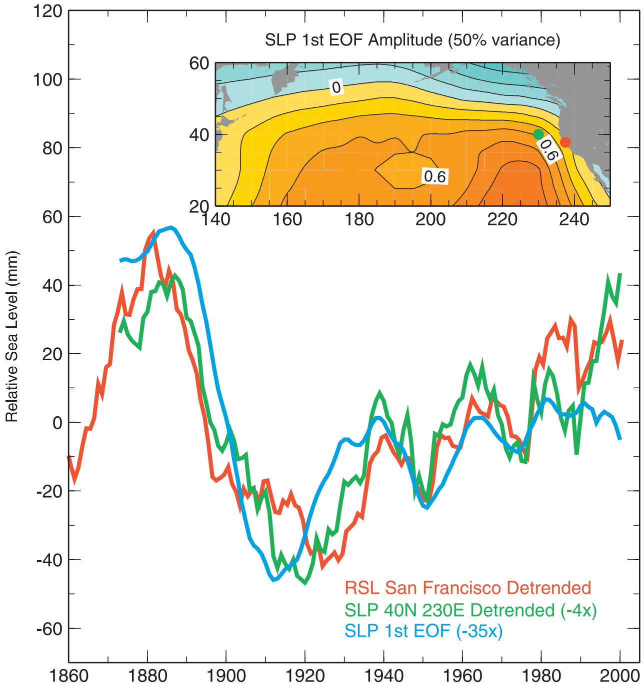

Figure 5. Detrended RSL at San Francisco compared with 1st EOF time function of North Pacific SLP [*Basnett and Parker*, 1997] scaled by −35x, and SLP at 40N 230E from same analysis, detrended and scaled by −4x. Map inset shows 1st EOF amplitude function of SLP.

variations in the surface pressure (and hence wind) field is not a new result. *Sturges and Hong* [1995] and *Hong et al.* [2000] previously demonstrated this for the western North Atlantic. Also, there have been a number of studies relating tide gauge variability at certain North Sea and Baltic sites and in the Mediterranean to changes in the NAO after 1960. What is new here is evidence that multi-decadal variations in atmospheric forcing may be responsible in part for the marked difference in sea level trends along the eastern boundaries of the North Atlantic and Pacific Oceans between 1880 and 1920, and 1920 onward.

[11] This interpretation is reinforced by the remarkable similarity between Figures 2 and 5. The 1st EOF's of de-trended and scaled sea level pressure decline in both oceans in the late 1800's to 1920's, then rise from 1920 to ~1960, as do the de-trended sea levels at Cascais and San Francisco. (From ~1960 onward, the Atlantic shows a decline, but the Pacific continues upward.) It is difficult to discount these changes as coincidental. Some form of atmospheric forcing must have affected both ocean basins simultaneously. The most likely candidate is the Northern Annular Mode (NAM), the leading mode of extra-tropical variability in the Northern Hemisphere. The NAM (also known as the Arctic Oscillation) is characterized by a dipole pattern of SLP variation between the polar region and a surrounding zonal band centered on the subtropics [*Thompson and Wallace*, 1998; *Thompson et al.*, 2000]. The NAM is well correlated with the North Atlantic Oscillation (NAO) which is usually calculated as the difference in normalized SLP between Ponta Delgada in the Azores and either Stykkisholmur or Reykjavik in Iceland. The 1st EOF in Figure 2 has the spatial structure and decadal variability normally associated with the NAO. The quadratic centennial scale signal noted in Figure 2 is readily apparent in long records of the NAO starting in 1860's (cf. http://www.cgd.ucar.edu/cas/jhurrell/nao.stat.winter.html).

[12] The situation in the North Pacific is less clear. The relationship between the Northern Annular Mode and the Pacific Decadal Oscillation [e.g., *Mantua et al.*, 1997; *Minabe*, 1997; *Wallace and Thompson*, 2002], the dominant multi-decadal pattern of sea surface temperature and pressure variability in the North Pacific, is not well established [*Deser*, 2000]. Also there is a question regarding data coverage. In contrast to the North Atlantic, the North Pacific suffers from very sparse SLP data in the late 1800's–early 1900's [cf. *Allan and Ansell*, 2006]. To assess how this affects different gridded SLP analyses, we compared the EOF's computed from the GMSLP2 data set with those from the ERSLP and HADSLP2 [*Allan and Ansell*, 2006] data sets. We found little agreement among any of the three analyses in the interval prior to ~1900, but good agreement afterwards. Only the GMSLP2 showed a prominent quadratic signal in its 1st EOF. Given the close agreement between the 1st EOF of SLP and San Francisco RSL in Figure 5, we believe that the quadratic signal in the GMSLP2 data set is real and that its absence from the other two gridded data sets is likely due to the use of different editing and smoothing procedures.

[13] One important implication of this study is the idea that some large fraction of the multi-decadal sea level variability along the eastern margin of the North Atlantic and Pacific Oceans is due to a redistribution of water, rather than to steric (volume) or global mass changes. Part of this process may take the form of westward propagating waves, as suggested by Figure 3. It is also possible that water may move into/out of the center of the oceanic gyre as the gyre spins up/down, although in an early study [*Miller and Douglas*, 2006] we showed this was not evident in the gauge record from Bermuda, near the center of the North Atlantic subtropical gyre. The Bermuda record shows sea level trending upward at 1.5 mm/yr from 1935 to 2000, at the same time that gauge trends along the east coast of the U.S. show a rise of about 2.0 mm/yr and those along the west coast of Europe a slightly smaller rate of about 1.5 mm/yr. We also determined that the rate of steric rise in the vicinity of Bermuda was ~0.5 mm/yr, i.e. roughly comparable to that found near the margins of the gyre. Note, however, the Bermuda record is relatively short, contains large decadal fluctuations, and does not begin early enough to include the multi-decadal signal of interest. Model simulation experiments are likely to be the only way of resolving the question of how the ocean responds to long timescale changes in the wind field.

4. Conclusions

[14] The few gauge records which extend back into the 1800's show little increase in sea level between about 1900 and 1930, followed by mostly a steady rise from 1930 onward. Comparisons between relative sea level and scaled local inverted barometer corrections at Brest & Cascais in the Atlantic and San Francisco in the Pacific show good agreement at decadal and longer timescales at these eastern ocean boundary locations. But, the observed scale factors, -3 to -6, are much too large to reflect a true inverted barometer (isostatic) response. Gyre-scale wind forcing is most likely responsible. The low frequency sea level variations are strongly correlated with the 1st EOF time function of SLP in each basin. This suggests that a large, possibly gyre-scale adjustment of the ocean is involved, but no evidence presently exists showing that the ocean gyres actually spin up/down on the centennial timescale. (However, there is evidence of a wave response along the western boundary of the North Atlantic.) If the ocean gyres are changing in strength, then the difference in gauge-measured sea level trends between the late 19th/early 20th century and the middle/late 20th century may reflect, to some extent, a redistribution of water in addition to the well documented mass and volume changes [*Miller and Douglas*, 2004, 2006].

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B. C. Douglas, Laboratory for Coastal Research, Florida International University, Miami, FL 33199, USA.

L. Miller, NOAA Laboratory for Satellite Altimetry, 1315 East-West Highway, Silver Spring, MD 20910, USA. (laury.miller@noaa.gov)