Gyre-scale Atmospheric Pressure Variations and their Relationship to 19th and 20th Century Sea Level Rise

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Abstract

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 between the late 19th - early 20th century compared to the latter half of the 20th century. The rates of rise are lower in the 19th compared to the 20th century. We show that this behavior is closely related to gyre-scale atmospheric pressure variations, suggesting that regional re-distribution of water plays a role in this difference.

1. The Problem: Estimating Trends & Accelerations in Sea Level Rise in the Presence of Low Frequency Variability.

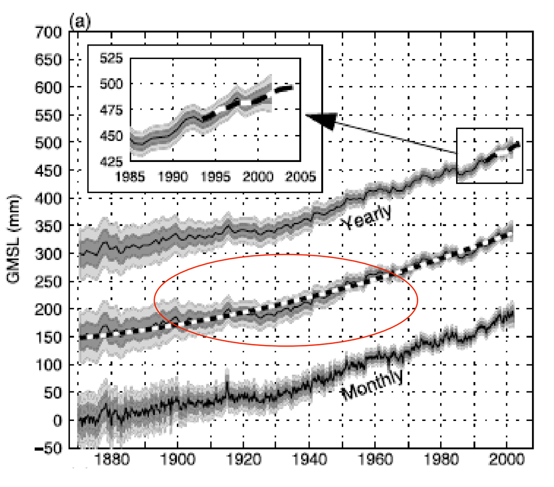

Figure 1. Global mean sea level from the 1870-2002 reconstruction by Church & White (2006), *A 20th century acceleration in global sea-level rise*, GRL, **33**, L01602. Monthly global average (lower curve); yearly global average with quadratic fit (middle curve); yearly global average with satellite altimeter data superimposed (upper curve).

In a recent paper, Church & White (2006) provide evidence of a 20th century acceleration in Global Sea-Level Rise (GSLR). Using tide gauge data to determine the amplitude changes in a set of EOF's derived from 12 years of satellite altimeter data, they produce a reconstruction of global sea level from which they estimate 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 1900 and 1940 (Figure 1). Since the number & distribution of statistically independent gauges prior to this pivotal time period is very limited (perhaps less than 5) it's important to understand the low-frequency characteristics of the gauge time series in the late 19th/early 20th century. Do they show the same type of behavior as during the late 20th century, especially during the period of the satellite altimetry record? Can we distinguish a mass change from volume (steric) change, or simply the redistribution of mass on a regional scale?

2. Northeastern Atlantic Relative Sea Level Rise

Relative Sea Level at Brest & Cascais

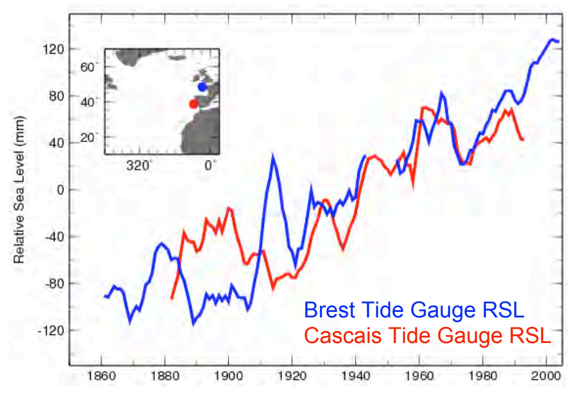

Figure 2. RSL records from the eastern North Atlantic appear "flatter" in the late 1800's/early 1900's than later in the 20th century.

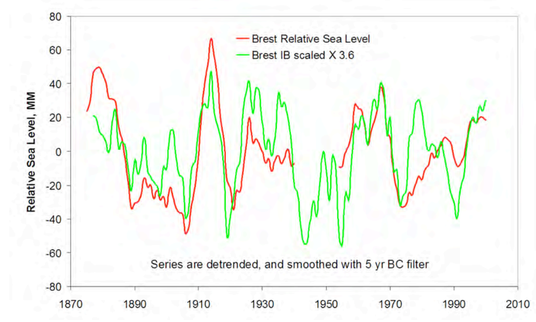

Figure 3. Detrended Brest RSL and scaled (-3.6x) local sea level pressure. Agreement is excellent on decade and longer time scales.

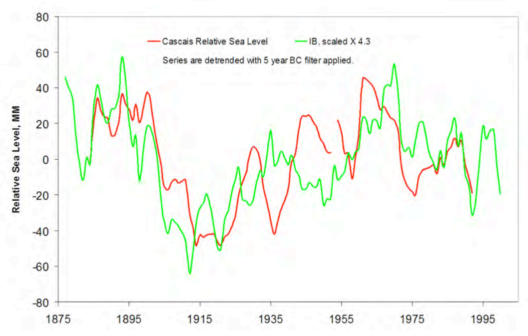

Figure 4. Detrended Cascais RSL and scaled (-4.3x) local sea level pressure. Agreement is good on multi-decade time scales.

The tide gauge records from Brest & Cascais (Figure 2), two of the longest in Europe, both show a distinctly different character between early and late 20th century. *The two appear flatter prior to 1900-1920, compared to later.* At Brest, this causes the calculated trend for the 20th century (1.8 mm/yr) to be about 20% greater than that for the entire record (1.5 mm/yr). However the two time series are not identical in the early 1900's: note the spike in the Brest record in 1910-1920.

Are these variations related to local sea level pressure?
In Figure 3 we compare detrended RSL at Brest with detrended surface pressure at Brest scaled by -3.6, a factor corresponding to the ratio of the normalizing standard deviations. *The phase agreement is generally good at all time scales longer than a decade, including the interval between 1860 and 1910 when the undetrended RSL appears relatively flat.*

Figure 4 shows a similar plot for detrended RSL at Cascais compared with detrended surface pressure at Cascais scaled by the ratio of the normalizing standard deviations, -4.3 in this case. *The decadal agreement isn't as good as at Brest, but the multi-decadal agreement is quite good, especially in the late 19th/early 20th century when the undetrended RSL appears relatively flat.*

However the scaling is all wrong for these signals to be explained by a local Inverted Barometer (IB) effect. A local IB would have a scale factor of -1, not -3.6 or -4.3.

Are these variations related to basin-scale sea level pressure?
Figure 5 shows a comparison between detrended RSL at Cascais and the 1st EOF time function of sea level pressure in the region 0 to 80N, 280 to 360E. The map inset shows the 1st EOF amplitude function which, combined with the time function, accounts for 41% of the total variance. As a check on the ERSLP analysis, which is largely based on ship observations, we also plot actual, not analyzed, sea level pressure observations from Ponta Delgada Azores, detrended and scaled.by a factor of -4. *The excellent agreement between the Cascais RSL and both pressure time series suggests that multidecade variability at Cascais, including the difference between the early and late 20th century trends is closely related to gyre-scale changes in the atmosphere.*

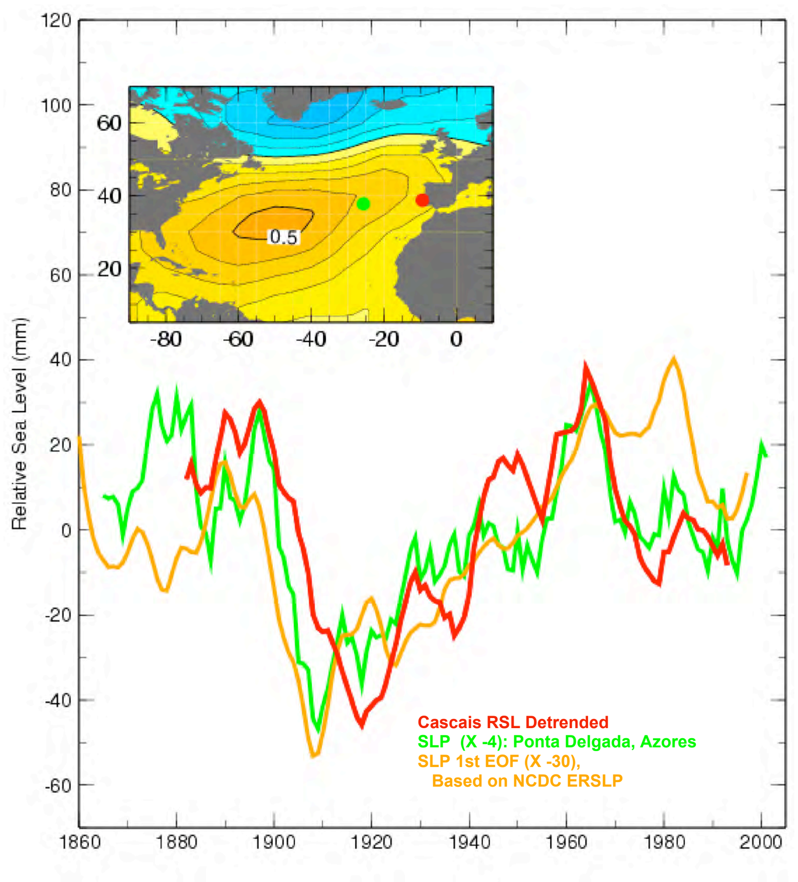

Figure 5. Detrended Cascais RSL compared with time amplitude of 1st EOF of North Atlantic SLP and detrended & scaled SLP time series from Ponta Delgada, Azores.

3. Western Boundary Response

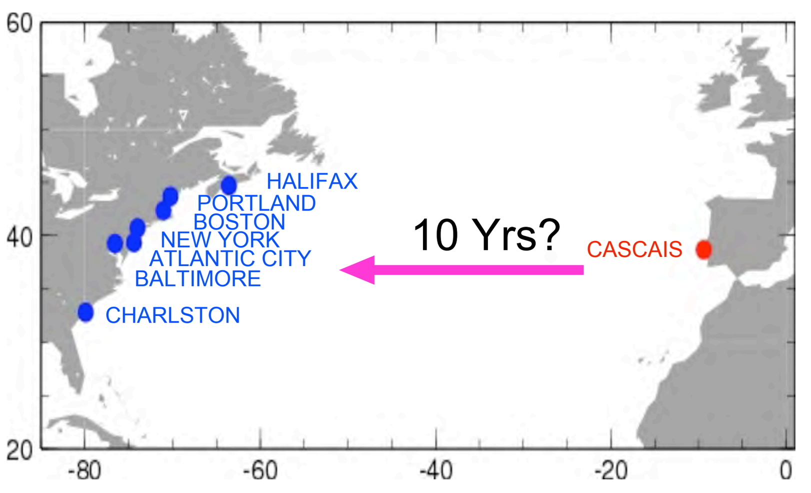

Figure 6. Tide gauge locations along eastern & western boundary. At 40N, the theoretical phase speed for a freely propagating, non-dispersive Rossby wave in the absence of any background mean flow is roughly 2 cm/sec. Assuming a basin width of 6600 km, it should take about 10 years for sea level signal to propagate from the eastern to western boundaries.

Local or Remotely Forced Response?

Sea level along the western boundary is known to respond to *decadal* variations in the gyre winds via baroclinic Rossby waves (Sturges et. al, 1998; Hong et.al, 2000). The question is: is there a link between the *multi-decadal* signals at the eastern & western boundaries? At 40N (Fig. 6), assuming a theoretical Rossby phase speed of 2 cm/sec, it should take about 10 years for a signal to propagate across the basin. Figure 7a shows in fact excellent agreement between the detrended RSL at Cascais and that at Portland plotted with a negative 10 year offset. Looking at all of the long gauge records between Halifax and Charlston (Fig. 7b) we see similar behavior, but also some significant differences.

RSL: Cascais vs Portland

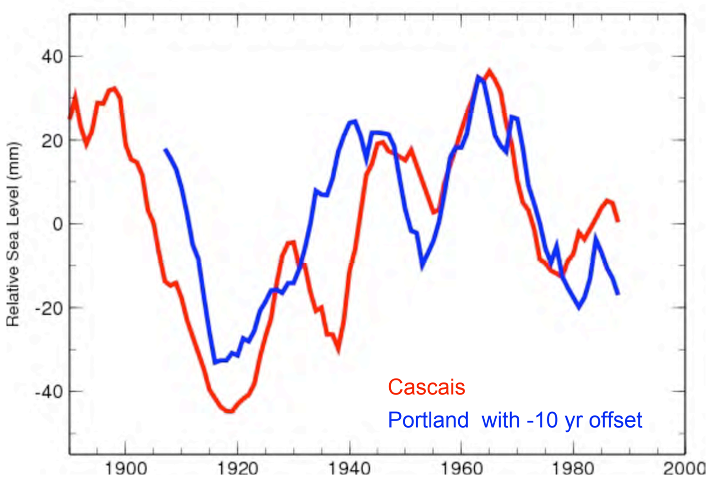

Figure 7a. Detrended Cascais RSL compared with detrended Portland RSL offset by -10 years.

RSL: Cascais vs Halifax to Charlston

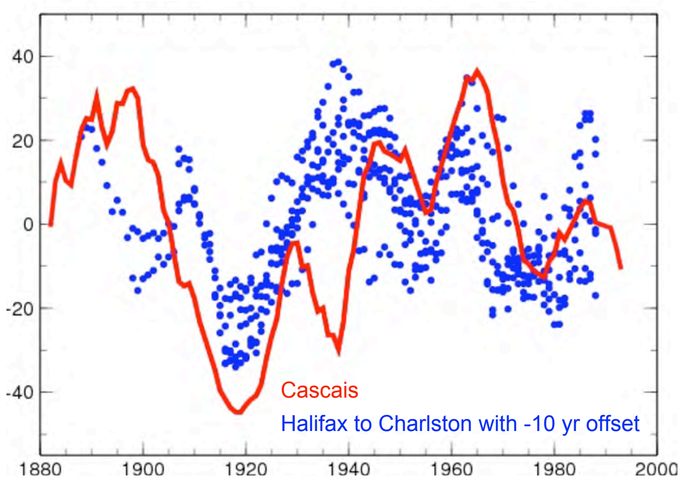

Figure 7b. Detrended Cascais RSL compared with detrended RSL at Halifax, Portland, Boston, New York, Atlantic City, Baltimore, Charlston, all offset by -10 years.

4. Northeastern Pacific Relative Sea Level Rise

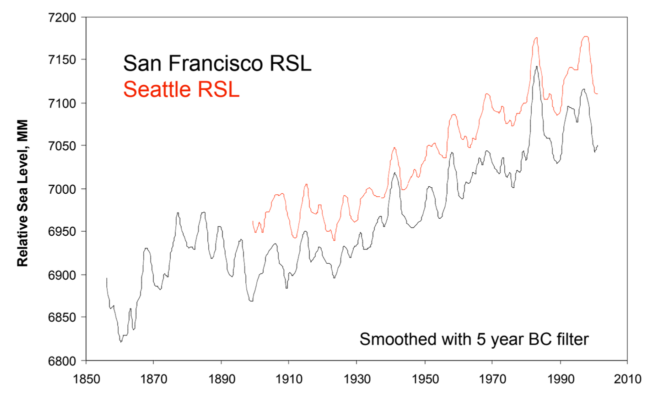

Figure 8. Relative sea level at San Francisco and Seattle. Agreement is excellent at all frequencies during their common time interval. Neither shows a significant increase during 1900-1930.

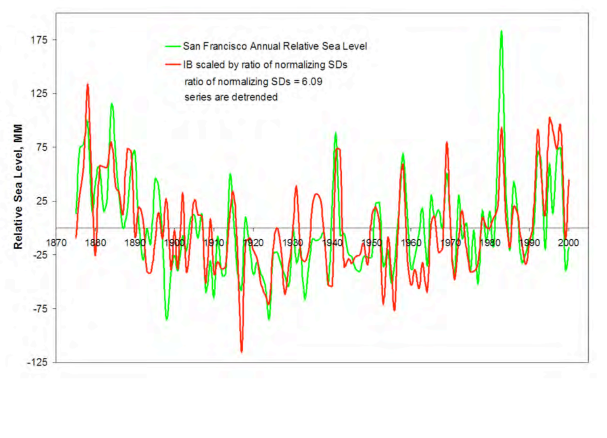

Figure 9. Relative sea level at San Francisco and scaled local inverted barometer correction.

San Francisco (Figure 8) 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, however the Seattle record offers some corroboration of the San Francisco record. Both show little increase between 1900 to1930, followed by a mostly uniform rise from 1930 onward.

Are these variations related to local sea level pressure?
The agreement of interannual variability at San Francisco and Seattle is striking. These 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), but the Darwin sea level pressure (SLP) is a good proxy for it, and it correlates well with San Francisco and Seattle RSL at interannual frequencies as far back as it goes, to 1875. The Darwin SLP does not, however, agree with the very low frequency oscillation of RSL during the latter 19th and early 20th century. *But the local inverted barometer (IB) correction is strongly correlated with San Francisco RSL at all frequencies, as seen in Figure 9.*

Are these variations also related to basin-scale sea level pressure?
Figure 10 shows a comparison between detrended San Francisco RSL and the 1st EOF time function of sea level pressure in the region 30 to 60N, 140 to 230E. The map inset shows the 1st EOF amplitude function which, combined with the time function, accounts for 50% of the total variance. *The agreement among the three time series suggests that the San Francisco RSL record is valid as far back as the 1870's and that the difference between the early and late 20th century trends is closely related to gyre-scale changes in the atmosphere.*

San Francisco Relative Sea Level vs. Sea Level Pressure

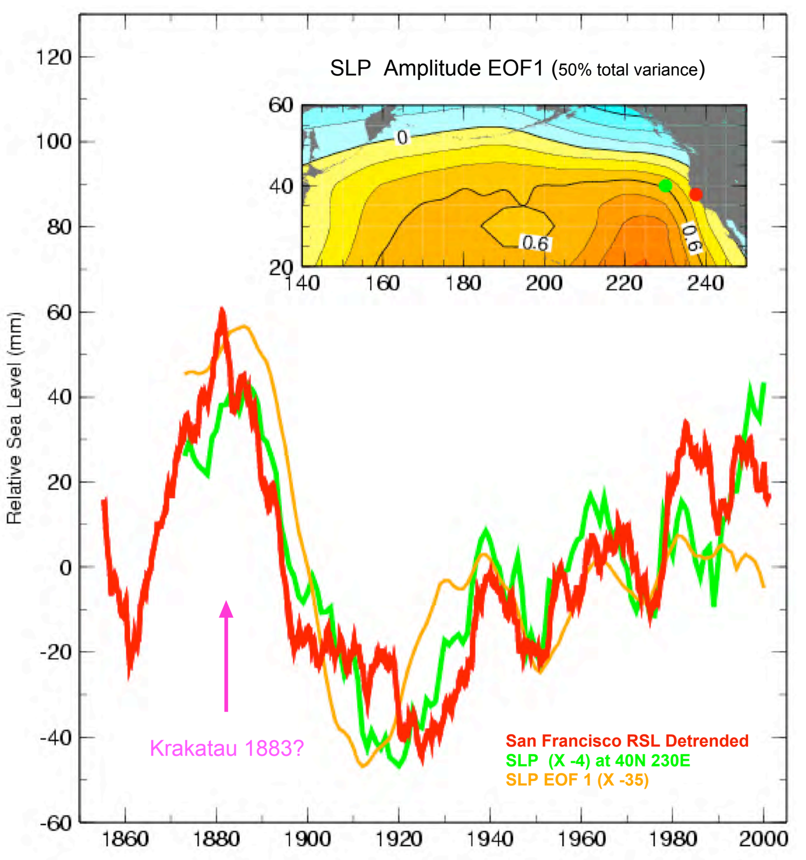

Figure 10. Detrended San Francisco RSL compared with 1st EOF of North Pacific SLP and detrended & scaled SLP time series from analyzed field at 40N 230E.

Caveat: This analysis was carried out using the CRU (U of East Anglia) SLP gridded data set. Similar analyses using the HadSLP2 and NCDC ERSLP data sets do not show a large quadratic term in their 1st EOF time functions.

- **The few gauge records which extend back into the 1800's tend to show a marked difference in behavior, showing little increase in sea level between 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 time scales. But the scaling factors, -3 to -6, are much too large to be true inverted barometer responses.**
- **Basin-scale wind forcing may be a factor. The low-frequency variations in the eastern Atlantic (Brest & Cascais) and eastern Pacific (San Francisco) are strongly correlated with the 1st EOF time function of SLP in each basin. This suggests that an ocean gyre adjustment process is involved.**
- **There is substantial evidence of a Rossby wave response along the western boundary of the subtropical 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 actually reflect density changes unrelated to global heat or fresh water budgets.**
- **What caused the difference in behavior between the late 19th/early 20th century & late 20th century? One possible explanation could be the influence of volcanic eruptions as climate forcing functions. It's interesting to note that the start of the flat period in the San Francisco gauge record, in the 1880's, coincides roughly with the eruption of Krakatua (1883) and subsequent volcanic activity.**