Global Sea Level Rise: 100 Years of In-situ Observations versus A Decade of Multi-Satellite Altimeter Observations

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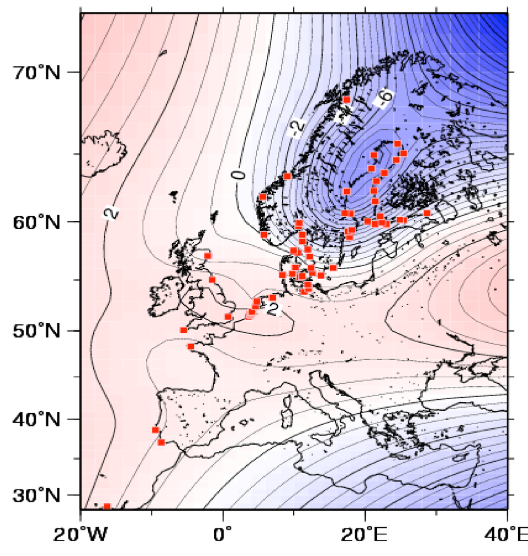
Both the rate and causes of 20th century global sea level rise (GSLR) are controversial. Estimates from tide gauges range from less than one, to more than two mm/yr. In contrast, values based on the processes mostly responsible for GSLR - mass increase (from mountain glaciers and the great high latitude ice masses) and volume increase (expansion due to ocean warming) - fall below this range. Either the gauge estimates are too high, or one (or both) of the component estimates is too low. To further complicate matters, estimates of GSLR based on TOPEX/Poseidon, Jason-1 and four other satellite altimeter missions indicate a rate of about 3 mm/yr over the past decade.

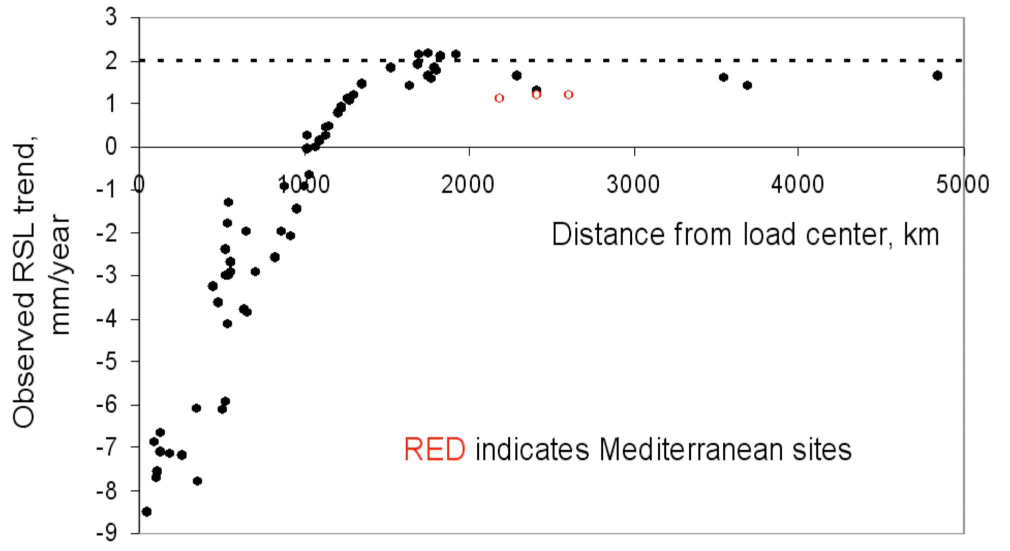
Gauge estimates of GSLR have long been disputed because of vertical land movements, especially due to glacial isotatic adjustment (GIA). More recently the possibility has been raised that coastal tide gauges measure exaggerated rates of sea level rise because of localized ocean warming. Presented here are two approaches to a resolution of these problems. The first is heuristic, based on the limiting values of observed trends of 20th century relative sea level rise as a function of distance from the centers of the ice loads at last glacial maximum. This observational approach, which does not depend on a geophysical model of GIA, supports values of GSLR near 2 mm per year. The second approach involves an analysis of gauge and hydrographic (*in-situ* temperature and salinity) observations in the Pacific and Atlantic Oceans. It was found that sea level trends from tide gauges, which reflect both mass and volume change, are 2-3 times higher than hydrographic based rates which only reveal volume change. These results support studies that put the 20th century rate near two mm/yr, and provide the first clear evidence that mass increase plays a larger role than ocean warming in 20th century GSLR. The question of why the altimetric rate appears to be higher than long-term, gauge-derived rate is discussed in terms of global decadal variability.

Can We Estimate the Current Rate of GSLR Without Resorting to a Complex GIA Model?



Contours of observed RSLR in Europe from long tide gauge records. Mediterranean sites not included. Units are mm per year.

Relative Sea Level Trends As Function of Distance From Center of Maximum Uplift in Scandanavia



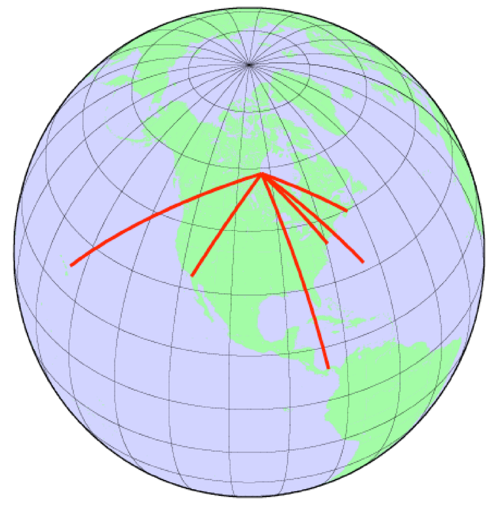
Glacial isostatic adjustment (GIA) is the subject of an extensive literature (see Peltier, 2001). The earth deformed viscoelastically under the immense weight of kilometers-thick ice sheets that covered North America and Europe at last glacial maximum, 21,000 years BP. Mantle material flowed from under the ice sheets to beyond their periphery, producing a subsidence of the land under the ice and a forebulge (uplift) adjacent. By 10,000 years BP the glacial melting that was to occur was essentially complete and sea levels were not far from present values. But the Earth continues to adjust. Even today the surface is still rebounding by nearly 10 mm per year in the areas of greatest ice load, and subsiding in the forebulge regions by as much as 2 mm per year, as mantle material flows back to the formerly ice-covered areas.

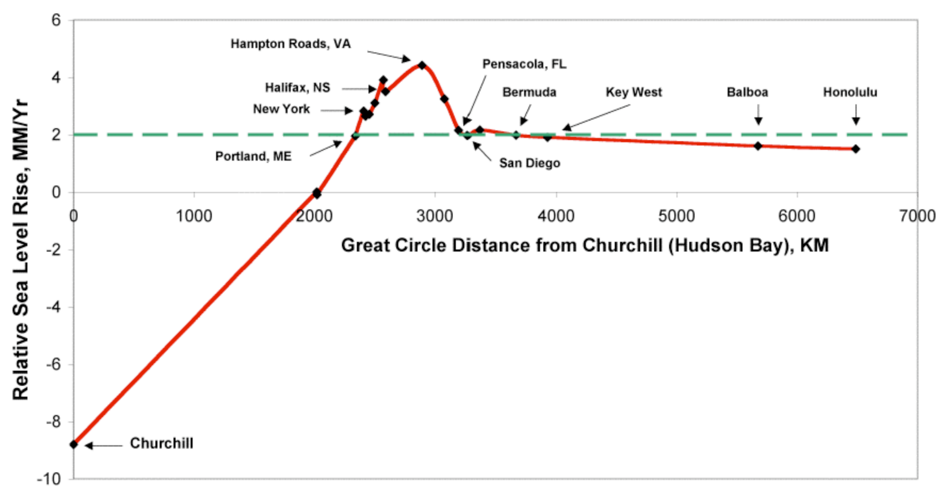
Long tide gauge records clearly show this ongoing process.. The figure to the upper left was obtained by contouring the rates of relative sea level rise (RSLR) for 59 European and UK tide gauge sites (average record length = 84 yrs.). The long Mediterranean records from Marseille, Genoa, and Trieste were not included because of their anomalous behavior from 1960 onward. This familiar elliptical "bulls eye" plot has appeared many times in the literature (e.g., Lambeck et al., 1998; Douglas, 2001), but the figure to the upper right, showing the RSL rates as a function of great circle distance from the point of maximum uplift, is new.

Up to 1000 km from the load center there is some scatter, but at greater distances a more regular pattern emerges. Peak RSLR occurs at about 1800 km distance at neary 2 mm per year (the dotted line) with a subsequent falloff of a few tenths of a mm per year. (The Mediterranean sites at Genoa, Marseille, and Trieste are systematically lower because sea level stopped rising at these sites about 1960). The distance profile suggests that the peak of the residual forebulge is a little less than 2000 km from the load center, and that the magnitude of the "forebulge collapse" is at most about 0.5 mm per year. Much farther away, Cascais, Lagos, and Tenerife are all above 1.5 mm per year. **Far field emergence of a few tenths of a mm per year at low and mid-latitudes is evident from geologic data (Peltier, 2001), and if the effect has even the same sign for the gauges well beyond the forebulge, it's evident that RSLR asymptotically approaches a value near 2 mm per year.**

A similar analysis for gauges in the Western Hemisphere (below, left & right) shows many of the same features although the forebulge collapse is much larger due to a greater ice load. **As with the European results, the addition of a few tenths of a mm per year for far field emergence strongly points to a rate of GSLR much nearer to 2 mm per year than 1 mm per year**.

Relative Sea Level Trends As Function of Distance From Ice Load Center at Churchill



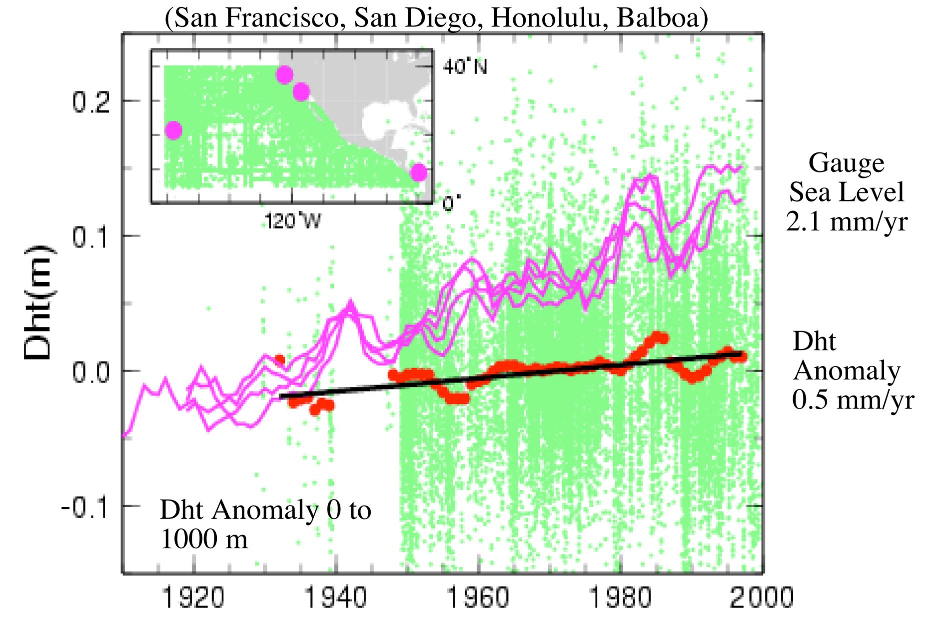


Why Is Sea Level Rising?

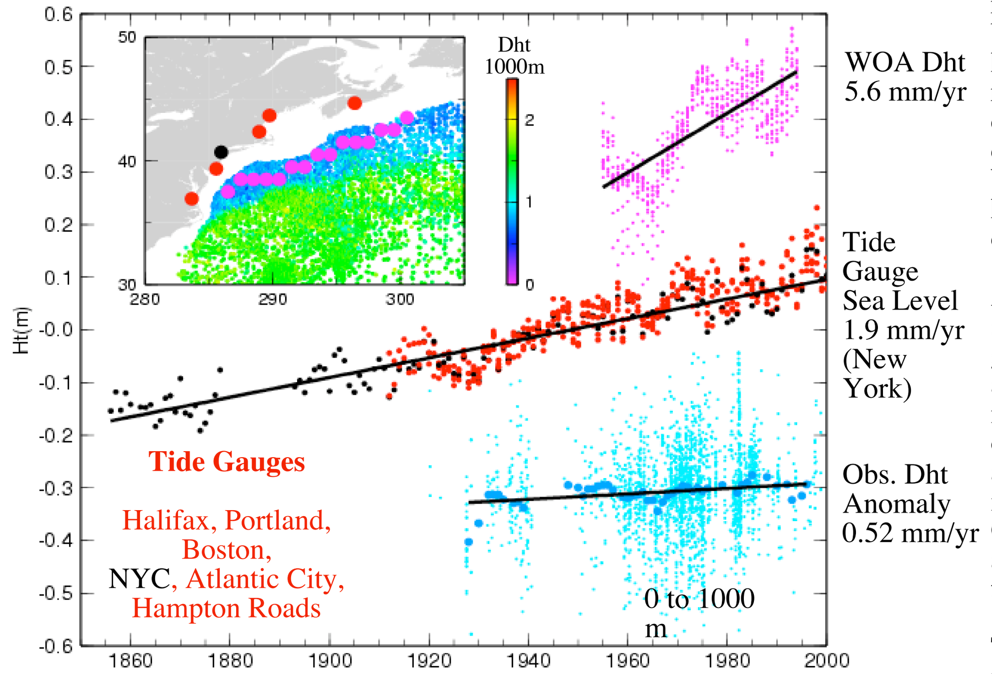
If GSLR is largely the result of steric effects, then one should expect to find close agreement between tide gauge measurements, which reflect both mass & volume change, and hydro measurements, which only reflect volume change. A regional analysis of observed (as opposed to interpolated) hydro profiles and gauge records in the Eastern Pacific (figure to left) suggests otherwise. The dynamic height anomalies (mean topography and seasonal signals removed) exhibit trends of about 0.5 mm/yr, whereas the surrounding tide gauges show sea level rising at about 2 mm/yr. The problem is complicated by regional and time dependent variations, but in general, the results point to one conclusion: **Over the 20th century, sea level rose at a rate several times higher than can be accounted for by volume (temperature and salinity) changes alone. Mass change, presumably due to the addition of fresh water from the melting of continental ice, must play a large role (Miller & Douglas, 2004).**

Eastern Pacific

(San Francisco, San Diego, Honolulu, Balboa)



Western North Atlantic



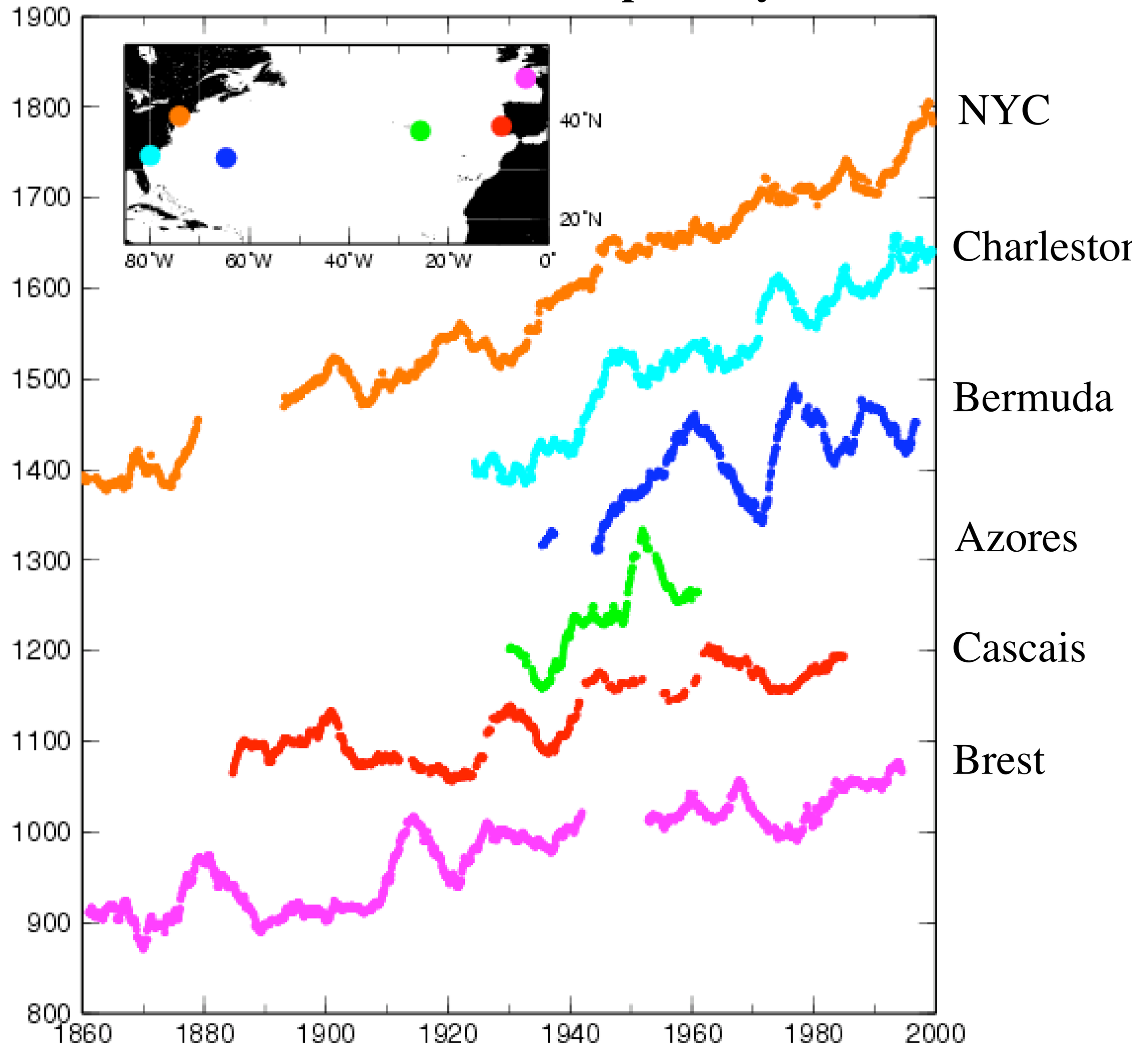
Are The Gauges Biased High By Local Warming Effects?

The figure on the left presents an analysis of the Slope Water region in the western North Atlantic, adjacent to the gauges between Halifax and Hampton Roads. Two types of dynamic height data are shown. The light blue dots, and their 5-year running means in dark blue, represent dynamic height anomalies computed for all Slope Water hydro profiles with deviations <1.0 dynm. The purple dots represent anomalies computed from the World Ocean Atlas 2000 (WOA), the objectively interpolated hydro data set employed by Cabanes et al. (2001) at the 1x1 degree grid points closest to the coast.

As in the Eastern Pacific (figure above), the gauge trends are substantially greater than the observed hydro trends. The NYC gauge indicates a trend of 1.9 mm/yr from 1996 to the present and the trend of all of the gauges from 1910 to the present is 2.3 mm/yr. The trend on the observed hydro data (1929 to 1996) is only 0.52 mm/yr. By contrast, the WOA analysis exhibits an abrupt 20-cm increase between 1965 and 1975 that is not present in either the surrounding hydro observations or gauge records. Over the 1955-96 interval used by Cabanes et al. (2001), the average WOA trend is 5.6 mm/yr, more than 2 times greater than the corresponding gauge trend.

There is good reason to believe that the "jump" in the WOA record is an artifact of the large radius of influence used in the objective analysis. Between the mid 1960's and early 1970's, the mean position of the Gulf Stream (GS) shifted northward by about 50 km as a result of gyre-scale changes in the surface wind field (Joyce, et al., 2000). The hydro observations taken during this period show a rise of about 20 cm confined to a zonal band of about 100 km, i.e. the width of the GS an negligible change to the north and south. However, the WOA analysis shows this signal covering all of the Slope Water region. **Nearly all of the alleged anomalous local warming effects in Cabanes et al. (2001) can be explained by errors in the WOA analysis.**

Tide Gauge Sea Level Measured Across North Atlantic Subtropical Gyre



What About Mass vs Volume Increase Inside The Gyre?

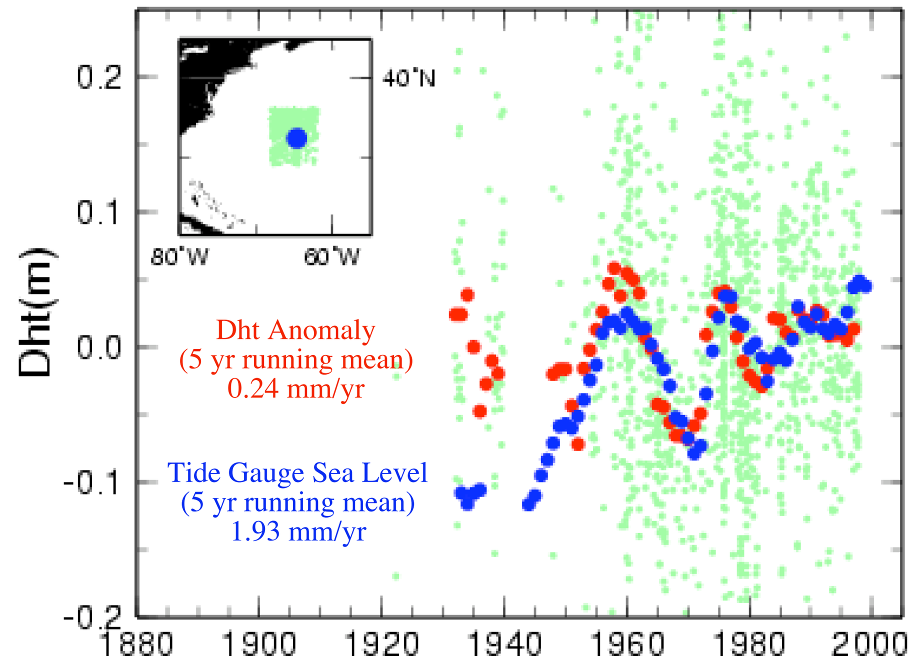
The figure above suggests that sea level rise is more or less uniform across the subtropical gyre in the North Atlantic, which we interpret to mean that there is no significant gyre-scale mass redistribution occurring. But, what about the question of mass versus volume change inside the gyre? To be consistent with the gauge and hydro observations near the coast, we would expect to see a mass change signal 2 to 3 times greater than the volume change signal inside the gyre. To test this proposition, the figure on the right shows a comparison of gauge measured sea level versus dynamic height anomaly for the region immediately surrounding Bermuda. Bermuda is a particularly good site for this type of analysis because of the Panularis series of monthly hydro observations, beginning in 1954. The green dots show the observed dynamic height anomalies (0 to 2000 m), the red dots their 5-year running means, and the blue dots the 5-year running means of the tide gauge data. As in the Eastern Pacific and Western Atlantic, the tide gauge trend is about 1.9 mm/year, as measured over nearly 70 years, whereas the dynamic height trend is considerably smaller, in this case about 0.2 mm/year. **Thus, the mass increase is also greater than the volume increase inside the gyre.**

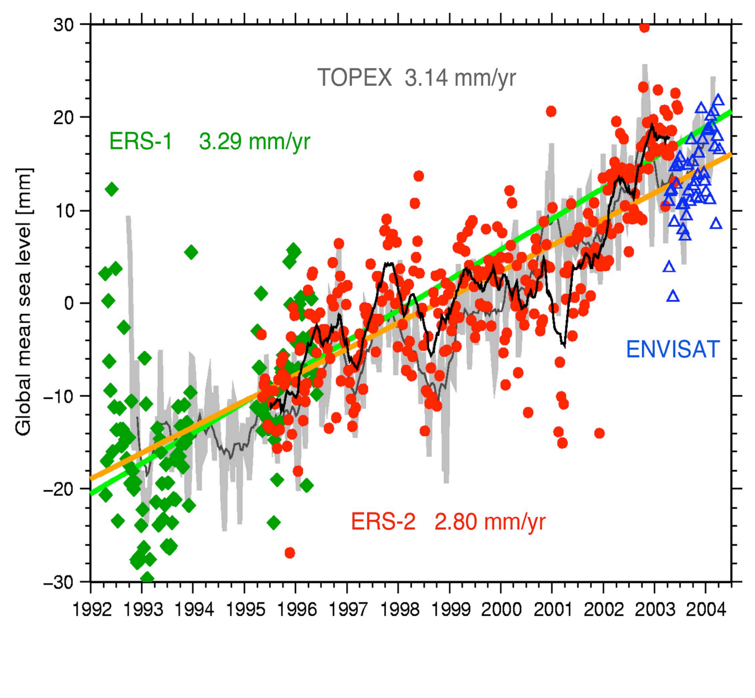
Gyre Spin-down?

Even though we can be confident that the much larger rates of SLR given by GIA-corrected tide gauge data compared to hydrographic observations are real, and not an artifact of some unspecified *steric* sampling problem, such as anomalous local warming, we cannot immediately exclude the possibility that the gauges are subject to a *mass* related sampling problem. For example, since most of the gauges used by Douglas (1991) and others are located along coastlines, and therefore along the peripheries of the major ocean gyres, it's conceivable that the gauges are recording gyre-scale mass redistributions, rather than a mass increase due to addition of fresh water. In this scenario, a portion of the nearly 2 mm per year rise observed along the margins of the North Atlantic might be the result of a century-long spin-down of the sub-tropical gyre, allowing water to spread outward. However, for this to be true, large areas of the gyre interior would have falling sea level for the entire 20th century, and such have not been reported.

In fact, there is some evidence that the gyre interior actually rose during the 20th century. The figure on the left shows coastal gauge records from the eastern and western sides of the Atlantic (Brest, Cascais, and New York, Charleston, respectively), as well as two islands inside the sub-tropical gyre, Bermuda, and San Miguel (Ponta Delgada) in the Azores. The North American records show an increase of about 2.0 mm/yr, while the European records indicate a slightly smaller rate of about 1.7 mm/yr. The record from the Azores is too short (~30 years) to provide a statistically meaningful trend, however at least it does not suggest a falling level. Bermuda is marked by large amplitude (10 cm), decadal fluctuations caused by gyre-scale, wind forced Rossby waves (Sturges and Hong, 1995; Sturges et al., 1998, and Hong, et al., 2000), but it also plainly shows an upward trend of 1.9 mm/yr, as measured by a least squares fit to nearly 70 years of data. While these results are not definitive, they tend to exclude the suggestion that rising sea levels along the margins of the North Atlantic basin are related to a gyre-scale mass redistribution.

Bermuda: Tide Gauge Sea Level vs. Dht Anomaly (0 to 2000 m)





What About The Altimetric Record of GSLR?

To help interpret the altimetric record of GSLR in the context of the historical hydrographic and tide gauge observations, we are using RADS (Radar Altimeter Database System) to develop a consistent, full-corrected, multi-satellite time series. The figures to the left and right show the results of this effort. In these examples, Topex is used as a reference series for vertically offsetting the other records. All of the results fit more or less along the regression line of ~3 mm/yr, as determined from the Topex data. How can we reconcile this result with the our 20th century tide gauge result of ~2 mm/yr, or the claim by others the 20th century figure is closer to 1 mm/yr than 2 mm/yr? It seems unlikely that the difference could be due to a dramatic change in the rate of mass increase, as that would require a very sudden change in the rate of continental ice melt during the 1990's. There is some evidence of a recent acceleration in the movement of glaciers in the Antarctic (e.g Thomas et al., 2004), however a more likely explanation is an increase in the steric rate of change (e.g. Willis et al., 2004).