Mass & Volume Contributions to 20th Century Global Sea Level Rise

Laury Miller
Laboratory for Satellite Altimetry, NOAA/NESDIS

Bruce Douglas
Laboratory for Coastal Research, Florida International University

Both the rate and causes of 20th century global sea level rise (GSLR) are the subjects of intense controversy. Most direct estimates from tide gauges give 1.5-2 mm/yr, while indirect estimates based on the two processes responsible for GSLR --mass increase (primarily meltwater from continental ice) and volume increase (expansion due to ocean warming) -- fall far below this range. Either the gauge estimates are too high, or one (or both) of the component estimates is too low. In order to monitor and understand future changes in GSLR, it is essential that this dilemma be resolved. Here we present an analysis of gauge and hydrographic (*in-situ* temperature and salinity) observations in the Pacific and Atlantic Oceans showing that gauge-measured sea level rates (which reflect both mass & volume change) are 2-3 times higher than hydrographic based rates (which only reflect volume change). We find no evidence that the gauges are located in regions of abnormally high warming. Our analysis supports earlier studies that put 20th century GSLR in the range of 1.5 to 2 mm/yr, but more importantly it provides clear evidence that mass contributions play an important, perhaps dominant role in GSLR.

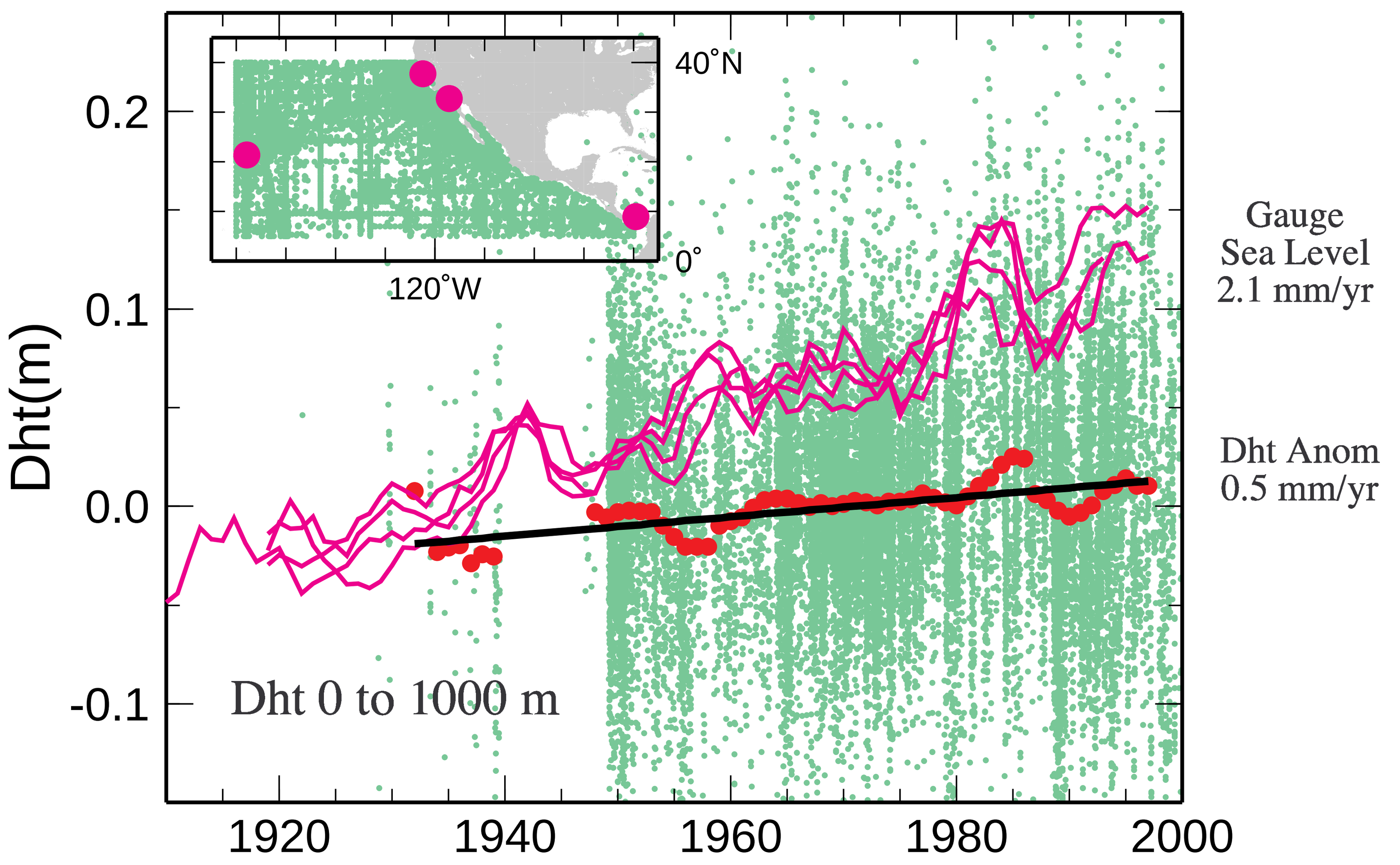
1. BACKGROUND

At the time of the second IPCC assessment in 1998, there seemed to be little controversy regarding GSLR. Most gauge estimates fell in the range 1.5-2 mm/yr. Most of this rise was thought to result from ocean warming, with the rest due to melting of continental ice. However, by the time of the 2001 IPCC assessment, this consensus view had collapsed. New and better estimates of ocean warming had reduced the volume increase component to about 0.5 mm/yr (Levitus et al., 2000) and the mass component was thought even smaller. This left a large unexplained gap between direct and indirect estimates of GSLR, now known as the "attribution problem".

Two recent studies offer opposing solutions to this dilemma. Cabanes, Cazenave and Le Prevost, 2001 (hereafter CCL) argue that gauge rates are 2-3 times too high because the gauges happen to be located in areas of abnormally high ocean warming. They arrive at this result by comparing gauge derived sea level trends with those obtained from objectively interpolated hydro measurements, concluding that the true rate of GSLR is actually 0.5 -1 mm/yr. due mostly to ocean warming. This solution provides a way out of the attribution problem, but implies a huge acceleration of GSLR in the 1990's if recent satellite altimetric estimates of ~2.5 mm/yr are to be believed Alternately, Antonov, Levitus and Boyer (2003) suggest that the problem may be solved by revising upward the mass component estimate. They show the oceans are freshening at a rate equivalent to the addition of 1.4 mm/yr of fresh water, approximately the number needed to bring the mass plus volume rate close to the gauge rate. However, this solution assumes a continental ice source rather than floating ice, a key point that they are unable to demonstrate.

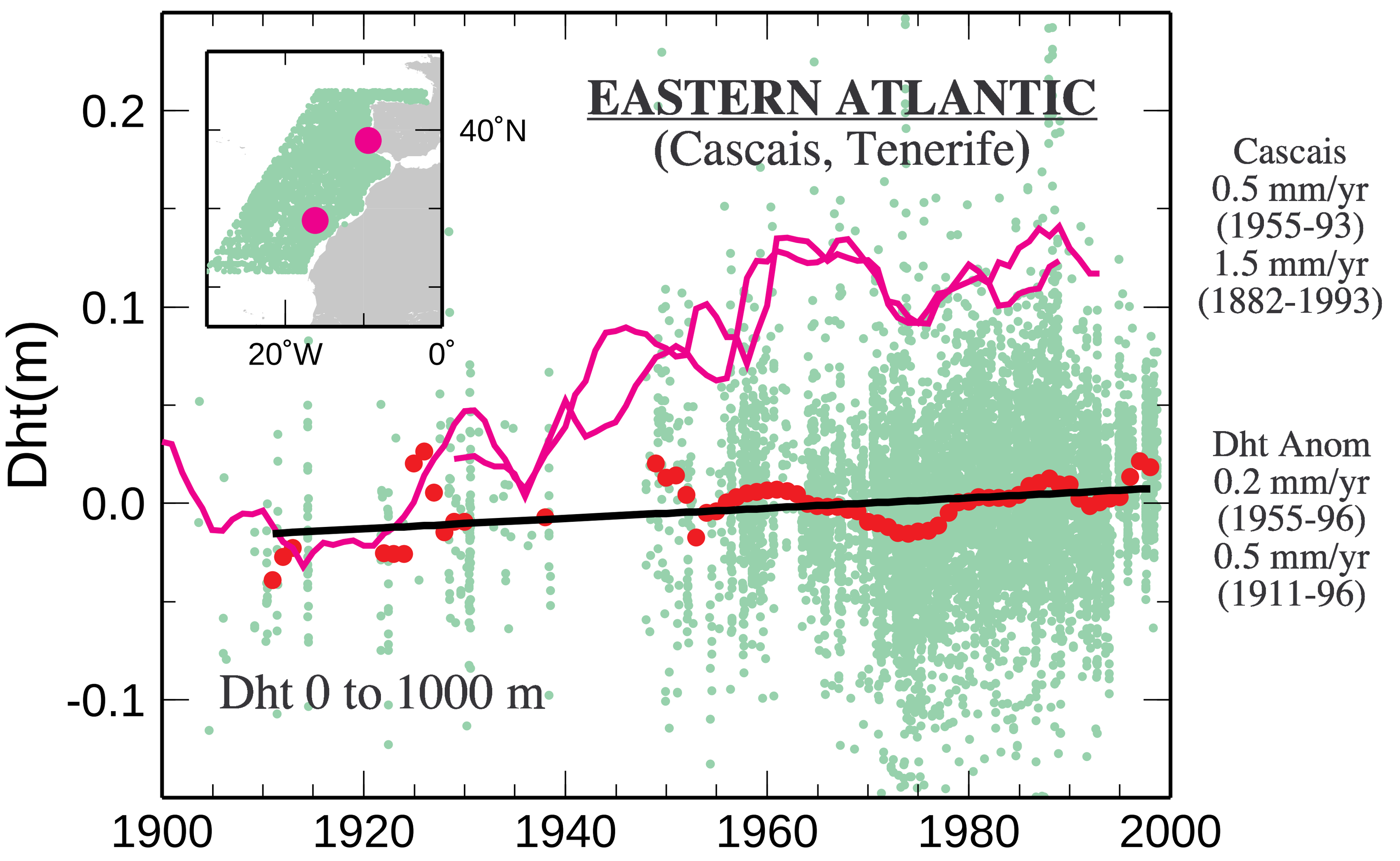
Here we present a simple approach to the problem of distinguishing between mass & volume contributions to GSLR. We identify large areas in the Pacific and Atlantic Oceans that are either bounded by, or adjacent to, several gauge sites exhibiting similar trends and variability. For those regions, we compare average gauge trends with average dynamic height trends computed from actual rather than interpolated hydrographic data.

EASTERN PACIFIC
(San Francisco, San Diego, Honolulu, Balboa)



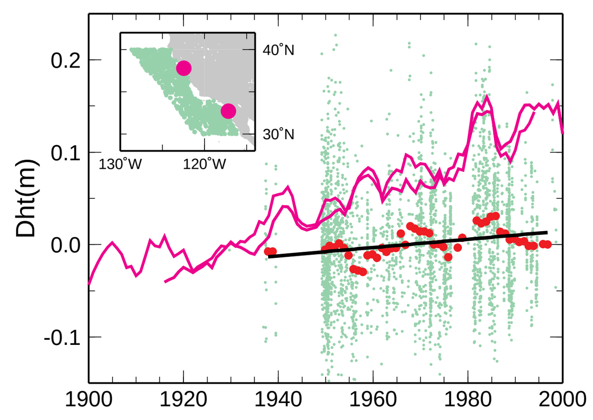
2. WHY IS SEA LEVEL RISING?

If GSLR is largely the result of steric heating effects, then one should expect to find reasonably close agreement between tide gauge measurements (which reflect both mass & volume change) and hydro measurements (which reflect only volume changes). A regional analysis of observed (as opposed to interpolated) hydrographic profiles and gauge records in the eastern Atlantic and Pacific (see above & below) suggests otherwise. In both oceans, the dynamic height anomalies (mean topography and seasonal signals removed) exhibit trends of about 0.5 mm/year, whereas the surrounding tide gauges show sea level rising at about 2 mm/yr. The problem is complicated by the presence of regional and time dependent variations (note the "flat" periods in the Atlantic tide gauges in the early 1900's and after 1960). However, 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 & salinity) changes alone. Mass change must play a large role.**



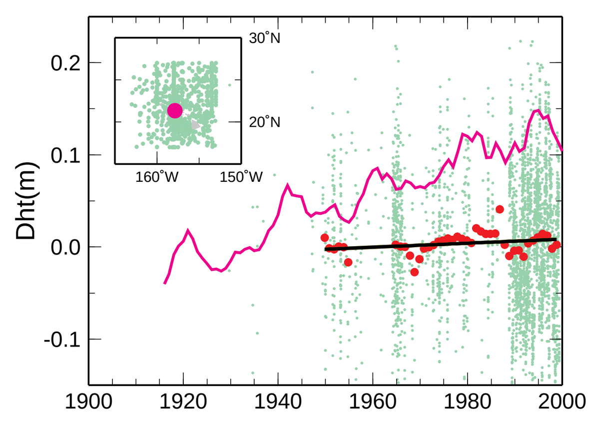
3. ARE THE GAUGES BIASED HIGH BY LOCAL WARMING EFFECTS?

San Francisco & San Diego

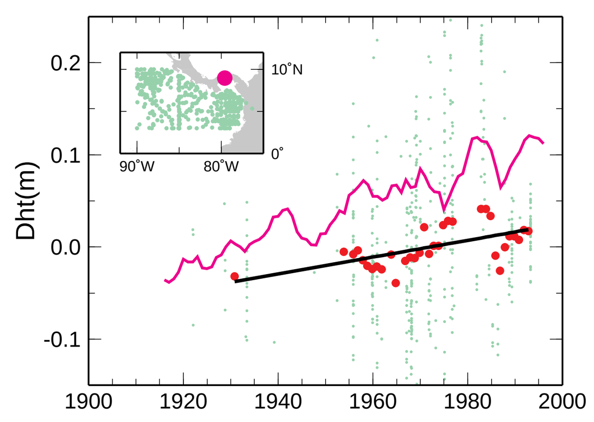


The figures to the left & below show gauge and hydrographic comparisons for three local areas encompassing or adjacent to the Pacific gauge sites. Because of strong similarities between the San Francisco and San Diego gauge records, the California coast is treated as one region. California and Honolulu show dynamic height trends of 0.5 mm/yr and 0.3 mm/yr from 1938 to 1996 and 1950 to 1999, respectively. Extending the hydrographic analysis in either of these locations to 2000 m does not significantly change the results (there are insufficient hydrographic data in either region to go to 3000 m). Balboa exhibits a larger dynamic height trend, 0.9 mm/yr, but still only half the matching gauge trend of 1.7 mm/yr over the interval 1930-1993. **We find no evidence that the gauges are located in regions of abnormally high warming.**

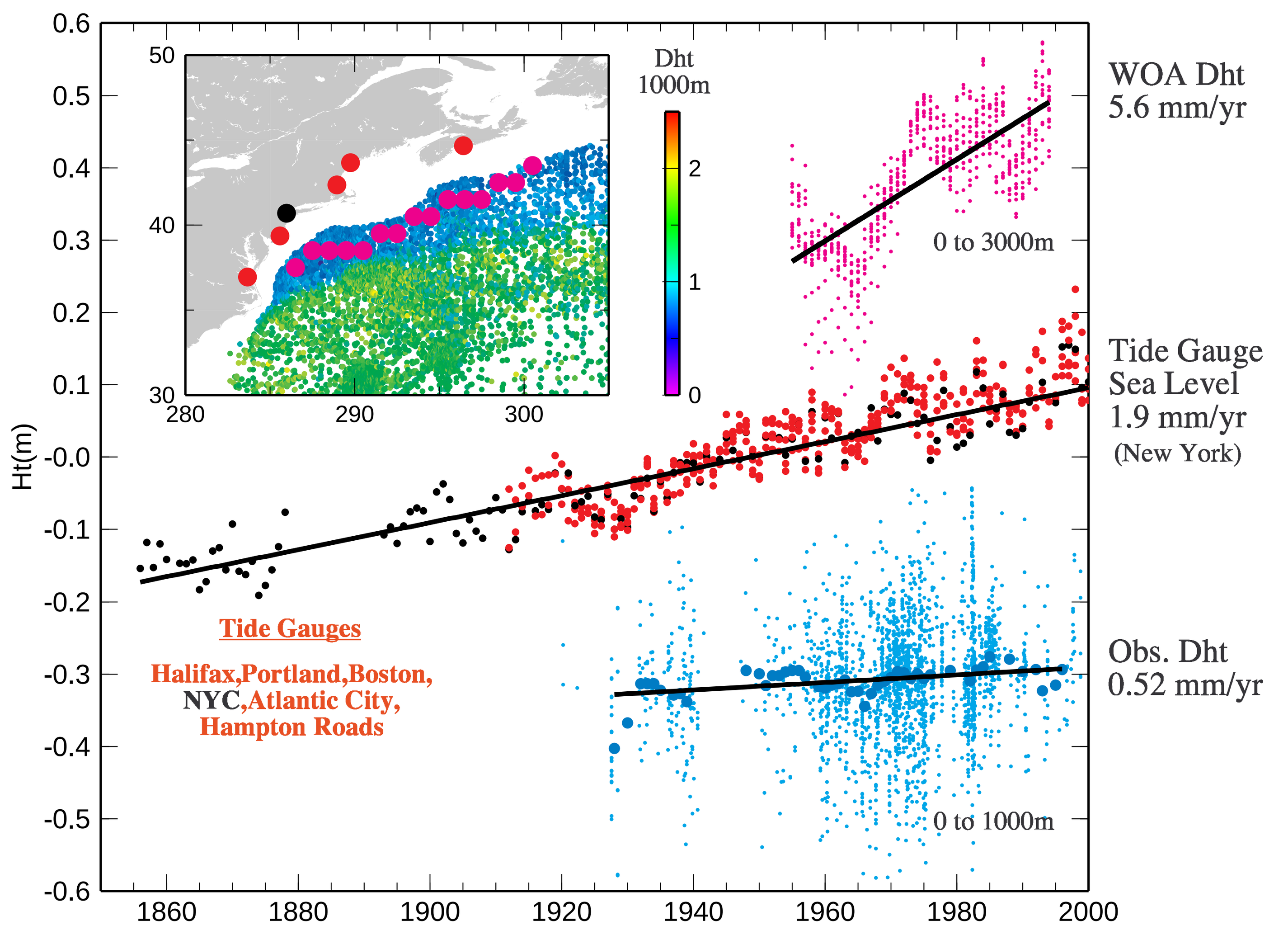
Honolulu



Balboa



WESTERN NORTH ATLANTIC



4. PROBLEMS WITH THE WOA NEAR THE GULF STREAM

The figure on the left presents an analysis of the Slope Water region in the western North Atlantic, adjacent to the gauges between Halifax, Nova Scotia and Hampton Roads, Virginia. Two types of dynamic height data are shown. The light blue dots, and their 5-year means in dark blue, represent dynamic height anomalies computed for all Slope Water temperature & salinity profiles defined as having deviations < 1.0 dynm. The purple dots represent anomaly values computed from the World Ocean Atlas 2000 (WOA), the objectively interpolated hydrographic data set employed by CCL, at the 1°x1° grid points closest to the coast

As in the eastern Pacific and Atlantic, the gauge trends are substantially higher than the observed hydrographic trends. The NYC gauge indicates a trend of 1.9 mm/yr from 1856 to the present and the trend on all of the gauges from 1910 to the present is 2.3 mm/yr. The trend on the observed hydrographic 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 hydrographic observations or gauge records. Over the 1955-1996 interval used by CCL, 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 (444 to 888 km) radius of influence used in the objective analysis. Between the mid 1960's and early 1970's, the mean position of the Gulf Stream shifted northward by about 50 km as a result of gyre-scale changes in the surface wind field (Joyce et al., 2000). The actual hydrographic observations taken during this period show a rise of about 20 cm confined to a zonal band about 100 km wide, i.e. the width of the Gulf Stream, and negligible change to the north or south. However, the WOA analysis shows this 20 cm signal covering all of the Slope Water shoreward of the Gulf Stream, between Cape Hatteras and Newfoundland. In contrast, none of the gauges along the east coast of North America show a 20 cm rise in the 1970's. To assess the impact of this error on CCL's calculation of the average warming induced rise for their nine study areas, assuming a minimal rate of 0.5 mm/yr for eight of their regions and 5.6 mm/yr for the northeast coast of North America, yields an average rate of 1.1 mm/yr, which is 2 times greater than global estimates of the warming effect (Levitus et al., 2000). **Thus nearly all of the alleged anomalous local effects in CCL's study can be explained by errors in the WOA analysis.**