Comparing Global Sea Level Rise Estimates from Satellite Altimetry and a Global Ocean Reanalysis: 1993-2001

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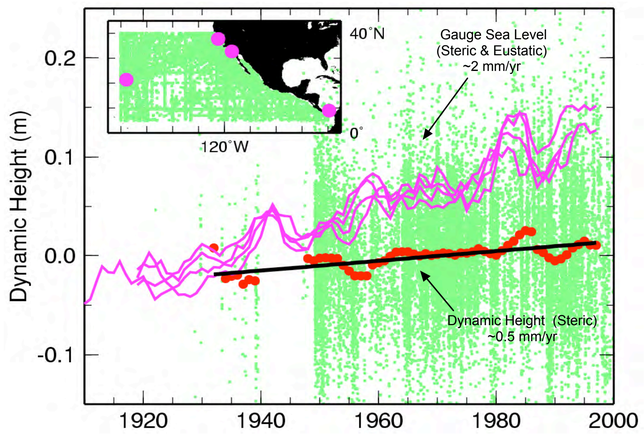
Abstract: Satellite altimeter observations show that global sea level has been rising over the past decade at a rate of about 3 mm/yr, well above the centennial rate of 1.8 mm/yr. This has been occurring despite the presence of large geographical variations, including large areas of falling sea level. Here we investigate the global and regional nature of this signal by comparing satellite altimeter measurements of sea level change between 1993 and 2001 with estimates of the steric component of sea level change for the same period based on the SODA 1.2 reanalysis of global in-situ temperature and salinity (Carton et al., 2005).

A map comparison of the two trend data sets shows broad geographical similarities, including high positive rates (>10 mm/yr) throughout much of the western Pacific and eastern Indian Oceans, negatives in the eastern tropical Pacific, and positives in the North Atlantic. Surprisingly, the reanalysis rates tend to have higher absolute values than the altimeter rates, particularly in the tropical Pacific. Analyzing the data sets in three zonal bands (66N to 30N, 30N to 30S, 30S to 66S) reveals distinct latitudinal differences. The northern and equatorial bands exhibit roughly similar average altimeter rates of sea level rise, at 2.5 and 2.3 mm/yr, respectively, and similar levels of correlation (~0.7) between altimeter trends and reanalysis trends on a local (grid point) basis. The southern band shows the highest average altimeter rate, at 3.9 mm/yr, suggesting that much of the increase between the centennial global rate determined from tide gauges and the 1993-2001 global altimeter-derived rate is due to rapid changes in the Southern Ocean. However, a local comparison shows that the reanalysis trends are poorly correlated with the altimeter trends in this band, making it difficult to distinguish between steric and eustatic contributions in the one band of greatest sea level rise. The poor correlation between the two data sets is probably due the lack of in-situ hydrographic observations in the Southern Ocean, a situation which no longer exists because of the advent of the Argo program, coincidentally in 2001.

1. Background: The 20th Century Problem.

20th Century Sea Level Rise: Eastern Pacific



Analysis suggests 20th century rate ~2 mm/yr, with eustatic increase much larger than steric increase.
(Miller, L. & B.C. Douglas, Mass & Volume Contributions to 20th Century Global Sea Level Rise, *Nature*, **248**, 407-409, 2004)

IF Global Sea Level Rise (GSLR) is largely the result of steric effects, then one should expect to find close agreement between tide gauge measurements, which reflect both steric & eustatic change, and hydro measurements, which only reflect steric change. A regional analysis of 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 2 to 3 times faster than can be accounted for by steric change alone. Eustatic change, presumably due to the addition of fresh water from grounded ice, must play the larger role (Miller & Douglas, 2004; Miller & Douglas, 2006).**

2. Steric & Eustatic Trends Over the Past Decade (1993-2001)

Satellite altimeter observations show that global sea level has been rising over the past decade at a rate of about 3 mm/yr, well above the centennial rate of 1.8 mm/yr. To determine the causes of this apparent increase we expand on the technique used in Miller & Douglas (2004), by carrying out a global comparison of altimeter measured sea surface height (SSH) trends and dynamic height (DHT) trends derived from a data assimilation reanalysis. The SODA 1.2 reanalysis (Carton, et al., 2005) of in-situ temperature and salinity observations (no altimetry), was used to compute DHT trends relative to 1000m, globally, from 1993 to 2001. Altimeter SSH trends were computed from TOPEX and Jason-1 data, gridded and smoothed in a manner similar to the reanalysis DHT data. The figure to the right shows the main results of this analysis.

Sea Surface Height & Dynamic Height Trends

o The trends of SSH (steric + eustatic) and DHT (steric) show good spatial agreement everywhere above 30°S: intense positives in western Pacific and eastern Indian Oceans, negatives throughout much of eastern Pacific.

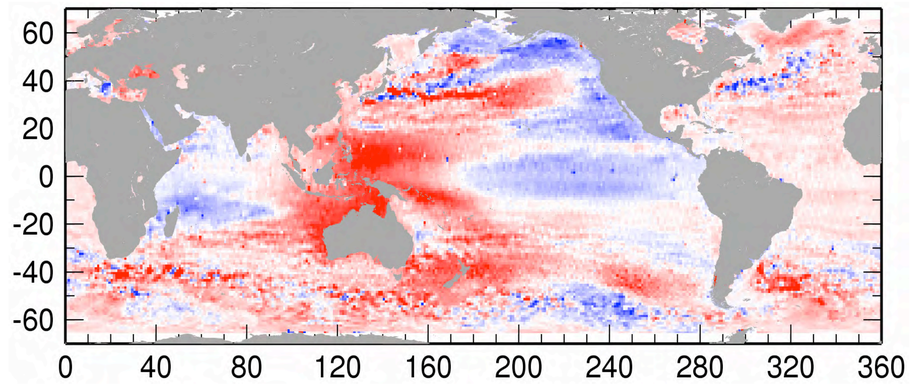
o Below 30°S, the SSH map shows strong positive bands coinciding with axis of Circumpolar Current, while the DHT map shows predominately negatives with no clear pattern.

SSH Trends *Minus* DHT Trends = Eustatic Signal??

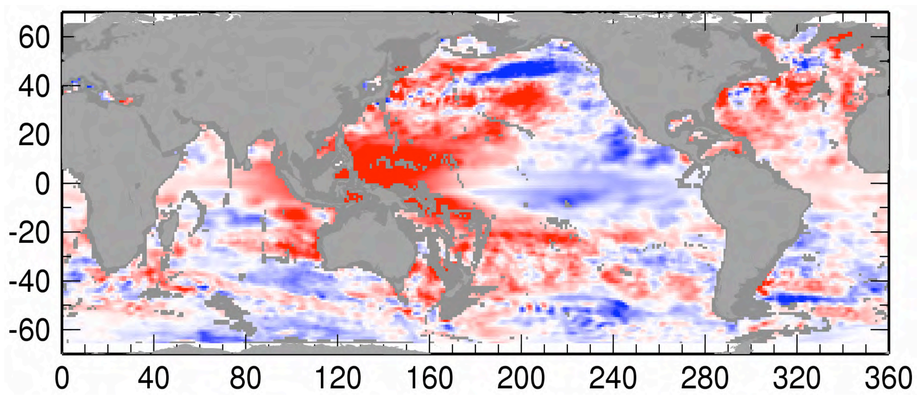
o Above 30°S, the trend differences (SSH - DHT) follow the same pattern as the separate SSH and DHT trends, *but with a reversed sign*, *suggesting DHT trends have been systematically overestimated both positively & negatively*

o Below 30°S, the trend differences are mostly positive, suggesting, at first glance, a *dominant eustatic signal in the one band of greatest average sea level rise*, However, the story is more complicated.

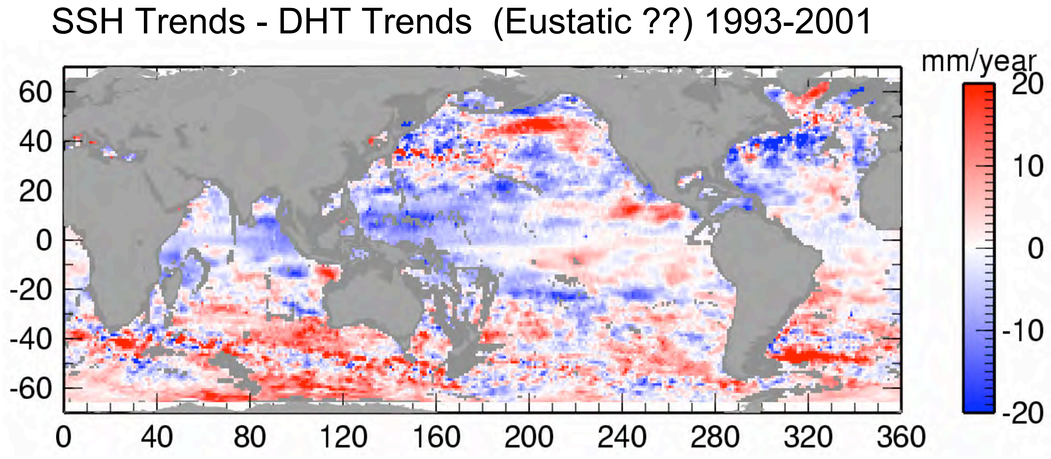
Altimeter SSH Trends (Steric & Eustatic) 1993-2001

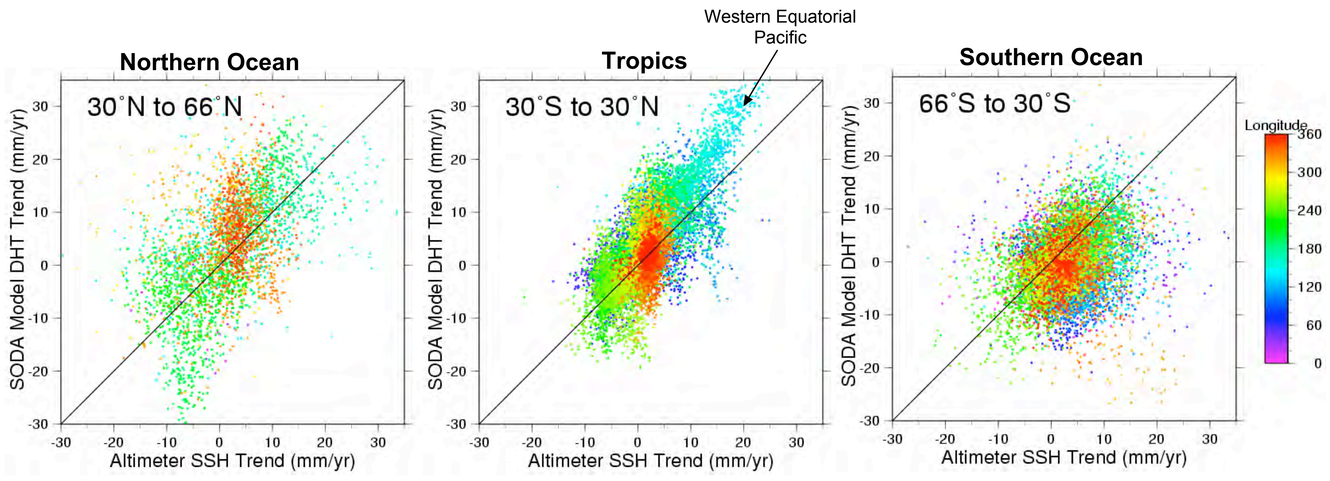


Reanalysis DHT Trends (Steric) 1993-2001

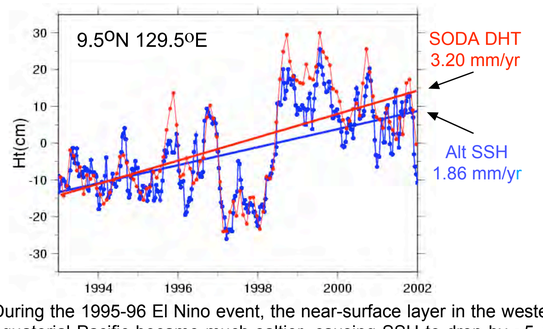


SSH Trends - DHT Trends (Eustatic ??) 1993-2001





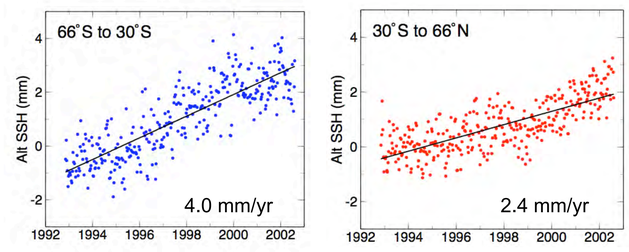
DHT vs. SSH in Western Equatorial Pacific



During the 1995-96 El Nino event, the near-surface layer in the western equatorial Pacific became much saltier, causing SSH to drop by ~5 cm (Ji, et al., 2000). Due to a lack of salinity observations, the reanalysis DHT fails to capture this drop.

4. Importance of Southern Ocean to Global Mean SSH Trend.

The plots below show altimeter measured SSH averaged (1) across the Southern Ocean and (2) everywhere north of 30ºS. These demonstrate that roughly half of the increase in GSLR in the past decade relative to the centennial rate, is due to a high rate of sea level rise between 66ºS and 30ºS.



66ºS to 30ºS 30ºS to 66ºN 66ºS to 66ºN

4.0 mm/yr X 0.30 (area) + 2.4 mm/yr X 0.70 (area) = 2.90 mm/yr

3. Does the Reanalysis Really Work in the Southern Ocean?

The scatter plots (SSH trend vs DHT trend) on the left show markedly different behavior above and below 30ºS.

o In the Tropics & Northern Hemisphere regions, the two trend types are roughly *correlated*, but DHT appears to be mostly biased high compared to SSH (above the 45ºline). [The cause of this bias is not generally understood, however there is an explanation for the extremely high DHT rates (>20 mm/yr) in the western equatorial Pacific. See plot in lower left corner].

o In the Southern Ocean plot (66ºS to 30ºS), the SSH trends are biased high compared to the DHT trends, *but more importantly the two trend types appear largely uncorrelated.*

5. Summary.

o SSH (steric + eustatic) and DHT (steric) trend maps show good spatial agreement everywhere above 30ºS, poor agreement south of 30ºS.

o Above 30ºS, the differences in the trends (SSH - DHT) follow the same spatial patterns as the separate SSH and DHT trends, *but with reversed sign, suggesting DHT trends have been systematically overestimated both positively & negatively*

o Below 30ºS, the trend differences are mostly positive, suggesting at first glance a dominant eustatic signal in the latitude band of greatest sea level rise, but this is unlikely given the poor correlation between SSH and DHT trends below 30ºS and the slow response of eustatic processes.

o A more likely explanation is that the SODA reanalysis does not accurately reflect the steric change in the Southern Ocean due the poor sampling of in-situ hydro data in the 1993-2001 time frame. This situation has been remedied with the advent of the Argo profiler program, beginning in 2001.

References:

Miller, L. & B.C. Douglas, Mass & Volume Contributions to 20th Century Global Sea Level Rise, *Nature*, **248**, 407-409, 2004.
Miller, L. & B.C. Douglas, On the rate and causes of twentieth century sea-level rise, *Phil. Trans. R. Soc. A*, **364**, 805-820, 2006.
Carton, J.A., B.S. Giese,& S.A. Grodsky, Sea level rise and the warming of the oceans in a simple Ocean Data Assimilation (SODA) ocean reanalysis, *J. Geophys. Res.*, **110**, 2005.
Ji, M., R.W. Reynolds, and D.W.Behringer, Use of TOPEX/Poseidon Sea Level Data for Ocean Analyses and ENSO Prediction: Some Early Results, *J. Clim.*, **13**, 216- 231, 2000