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Reconstruction of Sea Level Change from Tide Gauges and TOPEX/POSEIDON EOF Modes

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Introduction

The 70-year record of sea level from tide gauges clearly shows a rise in the sampled mean sea level of over 10 cm since the early part of the century [*Douglas*, 1991]. Although the tide gauge record is long, it does not represent a homogeneous sample of the global oceans. Most gauges tend to be in the northern hemisphere and along coastlines. The results of *Douglas* [1991] were based on only 21 tide gauge sites, all north of the equator, and predominately along the Atlantic coastline. Using the tide gauge data alone, it is impossible to study sea level variability in many parts of the ocean. It is also uncertain how well the "global" mean of the tide gauge data represents the true global mean sea level variations, because of the sparseness of the data. A better measurement of global mean sea level variations can be made with satellite altimetry, since the satellite samples nearly all of the Earth's oceans every 10 to 30 days. The measurement of sea level variability from the TOPEX/POSEIDON (T/P) altimeter has been shown to be quite accurate on both local and global scales but it only measures the sea level rise from late 1992 to the present.

A re-examination of the tide gauge sites used by Douglas in his earlier study shows a significantly different mean sea level (MSL) variation than that determined from T/P, even after the annual variation caused by the predominately northern gauges is removed, suggesting the data are less accurate for determining interannual sea level variability, and possibly long-term trends.

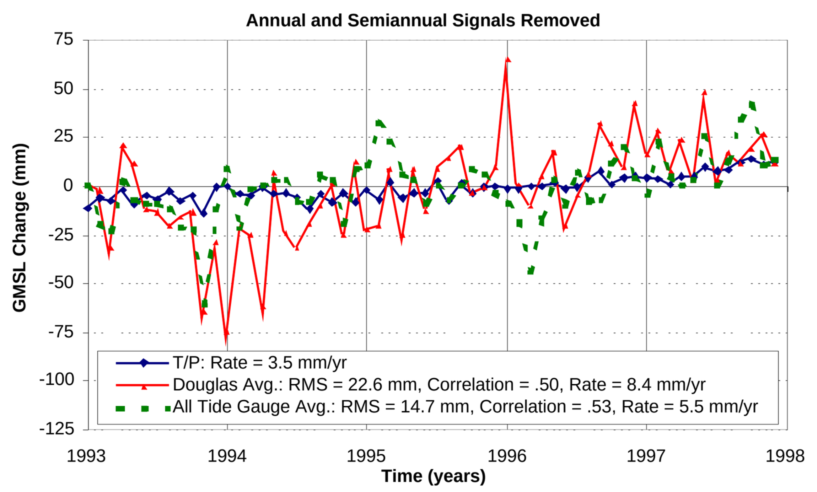

Figure 1. GMSL variations from T/P, Douglas [1990] tide gauge set, and all available tide gauges (1993-1997). Annual and semiannual signals have been removed.

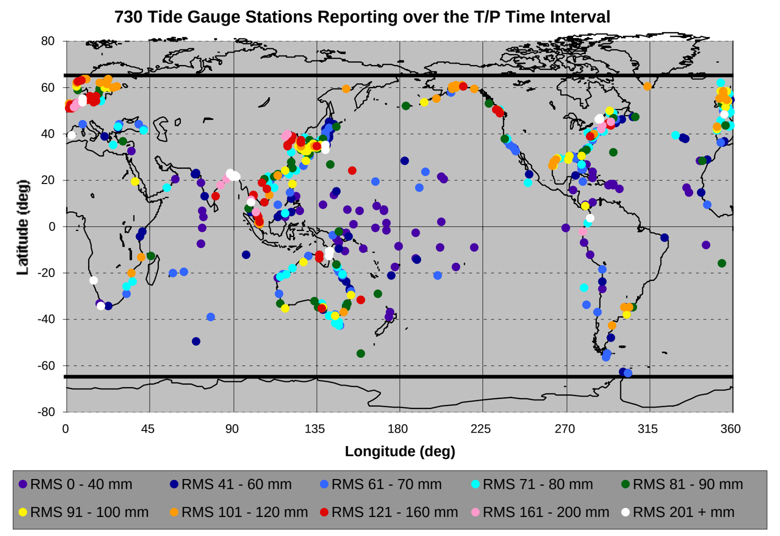

Figure 2. Tide gauge stations reporting observations between January 1993 and December 1997. Stations are color coded by the RMS difference between monthly tide gauge observations at the station and the corresponding T/P data at the location over the same time interval. Thick black lines represent the latitudinal T/P data boundaries.

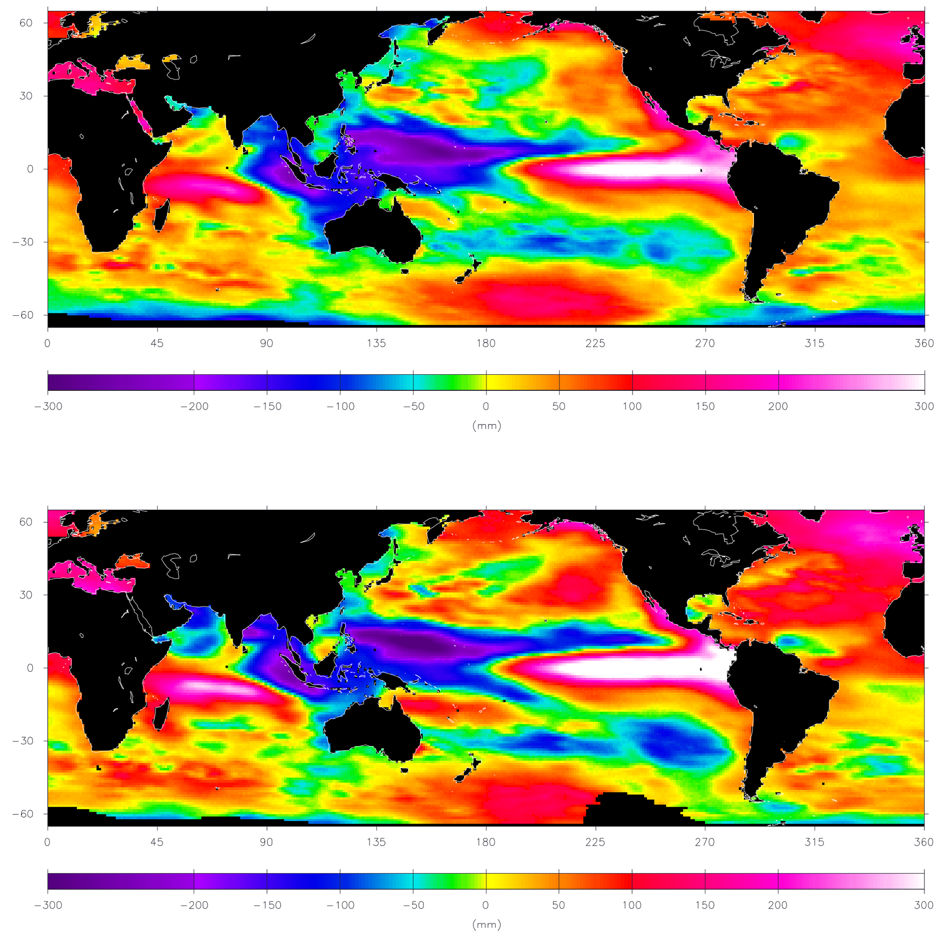

Figure 3. Sea level anomalies for November, 1997 for TOPEX/Poseidon (top) and reconstructed from tide gauge data with 11 EOF modes.

EOF Reconstruction

We have used a method called empirical orthogonal function (EOF) reconstruction to interpolate historical tide gauge data to global, evenly spaced maps in order to better estimate the GMSL change. The method is described by Smith et al [*J. Climate*, 1996]. The idea behind EOF reconstruction is that spatial EOF modes from recent, global satellite data sets are used used as a set of basis functions in a least squares fit to sparse in situ data to estimate the time dependence of each mode. Then global maps at each time step can then be reconstructed from the spatial modes and estimated temporal coefficients. In this manner global grids of sea level anomaly can be interpolated from sparsely populated tide gauge measurements and T/P determined EOF modes. We use EOF modes from T/P for 1993-1998 to reconstruct sparse tide gauge measurements. The preliminary research has focused on quantifying the accuracy of the method using tide gauge data commensurate with the T/P mission, although some initial results for previous periods are presented. Details may be found in *Mehlhaff* [Thesis, UT-Austin, 2000], which is available upon request.

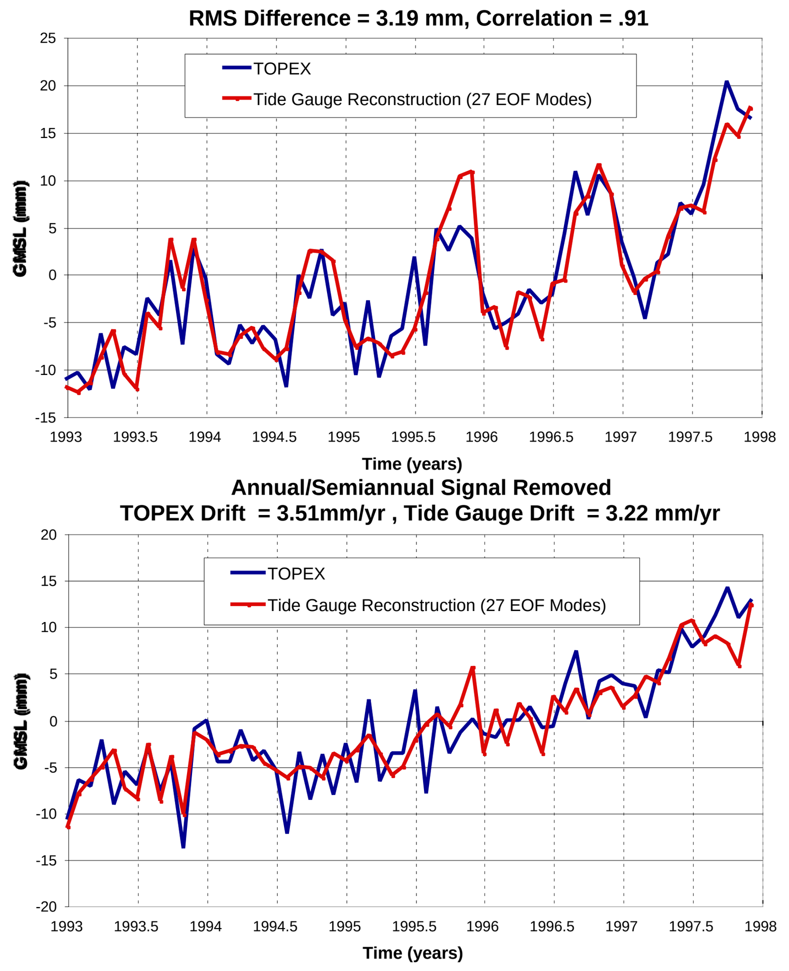

Figure 4. Comparison of GMSL change between December 1993 and December 1997 as determined by T/P and the tide gauge reconstruction. The annual and semi-annual signals have been removed from the lower plot.

Results (1993-1997)

Various numbers of modes ranging from 3 to 29 were used to reconstruct the tide gauge data. It was found that using more than 10 modes gave similar results, and the lowest differences compared to TOPEX/Poseidon measurements. **Figure 3** shows the reconstructed sea level anomaly map for November 1997 using only 11 modes, and the "true" map measured by TOPEX/Poseidon. The average RMS difference is 3.5 cm, which is comparable to the comparison between T/P sea level at specific tide gauge locations. However, these results assume that all the available tide gauge data are used. If data are restricted to only the small number of gauges that have very long records, then only 10-15 modes should be used.

When the monthly reconstructed maps are averaged globally and compared to the T/P measurement (**Figure 4**) the rate difference is 0.5 mm/yr and the standard deviation of the difference between the two time series is less than 5 mm. The overall error in reconstructing GMSL variation from tide gauge observations and TOPEX EOF modes is estimated to be 10 mm at the 95% confidence level.

The reconstructed tide gauge time series suggests a rate of sea level rise of 3.2 mm/yr from January 1993 through December 1997 as compared to 3.5 mm/yr observed by T/P over the same time period.

Data Processing

T/P altimeter data come from the MGDR-B release for Cycles 10-195. Sea level anomalies are computed and averaged over months from January, 1993 to December, 1997, then gridded into 1degree global grids between 65N and 65S latitudes and smoothed with a long wavelength filter [Chambers et al, *JGR*, 1997]. The inverted barometer (IB) correction is not applied here so that the altimeter data can be compared with the non-IB-corrected tide gauge observations. Data are corrected for the TMR drift.

Tide gauge data are obtained from the Permanent Service for Mean Sea Level (PSMSL) which holds a data record of monthly mean values of sea level for over 1800 globally distributed tide gauge stations. Tide gauge observations exist for as early as 1807 and extend through 1998. Due to a latency in reporting tide gauge observations to PSMSL few observations exist past 1997, thus restricting the current analysis to observations between January 1993 and December 1997.

Tide gauge observations are corrected for post-glacial rebound [Peltier, *Science*, 1994] and have the long-term equilibrium tides removed in a similar manner to the T/P data. A long-term mean is then calculated over the entire data record for each tide gauge station and removed, and benchmark shifts of 1000 mm or greater are estimated and removed. The resulting tide gauge sea level anomalies are then gridded to a 1degree grid similar to T/P, but not smoothed.

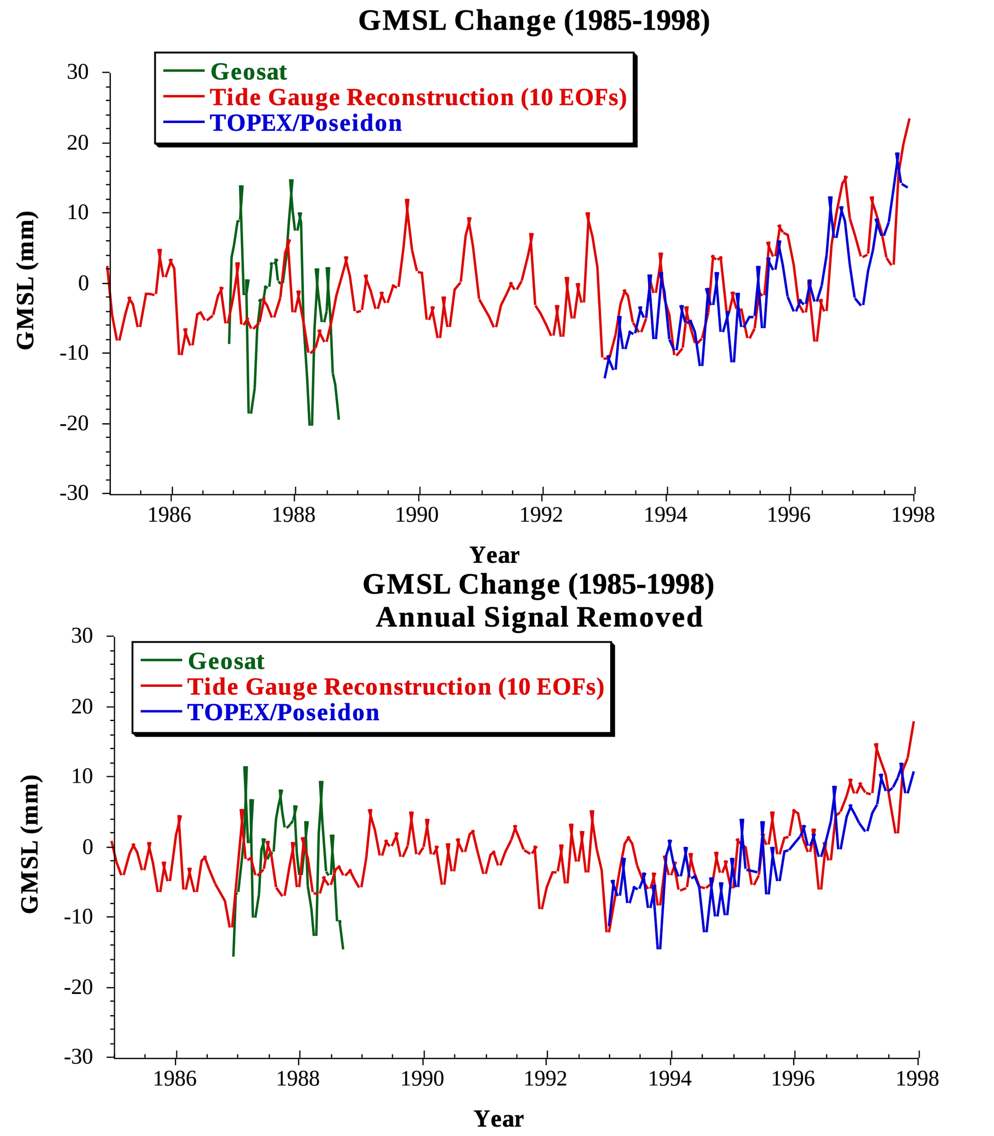

Figure 5. Comparison of GMSL change between 1985 and 1997 as determined by the tide gauge reconstruction, T/P, and Geosat. The tide gauge GMSL series is reconstructed only from observations of tide gauge stations reporting near continuously from 1985 through 1997.

Results (1985-1993)

The results for 1993-1997 suggest that the tide gauge data can be effectively interpolated with EOF reconstruction to an accuracy comparable to that of T/P over long-wavelengths. However, are the results as good for earlier periods? Smith et al [1996] assume spatial stationarity of the EOF modes; that is, it is assumed that the areas of variability do not change, even though the periodicity may not. With this assumption, they interpolated sea surface temperature data back to 1950.

This is not exactly valid. For instance, it is known that ENSO varies both in time and shape. What this means is that an estimate of a particular mode may be incorrect. However, when the estimates of a series of modes are added together in the reconstruction, the may represent the signal adequately. To examine this, we looked at an earlier global record of mean sea level, the record from the Geosat Exact Repeat Mission. These data have been reprocessed from late 1986 to 1988 [Urban, dissertation, UT-Austin, 2000]. A relative bias was applied to the Geosat data by Urban [2000] of 79 mm. The bias is in the sense to lower the normal Geosat measurement of sea level. We found that that bias placed the Geosat curve below the tide gauge reconstruction curve by about 17 mm. Therefore, an additional 17 mm bias has been applied to the Geosat data to raise the curve shown in **Figure 5**. This suggests a total relative bias between Geosat and T/P of 62 mm.

The tide gauge reconstruction curve does not disagree with the Geosat curve significantly, and the differences are just as likely to be from the Geosat data as from the tide gauge reconstruction. Note that the variance of the Geosat time-series is 75-100% greater than the variance of the tide gauge and T/P data, The tide gauge and T/P GMSL have nearly identical variance between 1993 and 1998.

This suggests that non-stationarity of the EOF spatial modes may not negatively affect the reconstruction in the past. We will examine this more as the investigation continues.

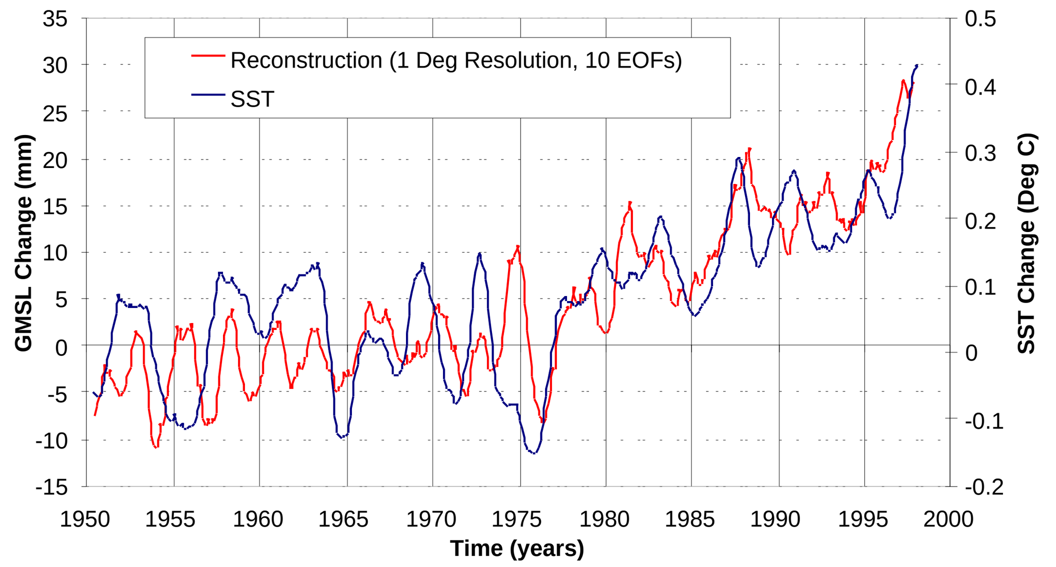

Figure 6. Reconstructed GMSL variations and SST variations during 1950-1997. Only near complete tide gauges records are used in the reconstruction. A 13-month running-mean filter has been applied to both time-series.

Results (1950-1997)

Figure 6 shows the GMSL calculated from reconstructed grids back to 1950, along with the reconstructed SST calculated by Smith et al [1996]. The tide gauge reconstruction has not been verified against any other data, or predictions of GMSL. Recently, Levitus et al [*Science*, 2000] has demonstrated significant changes in ocean heat storage to the 1000 m level and deeper. Such heat changes would affect sea level, and we plan to examine whether our reconstructed sea level is correlated with the steric sea level changes measured detected by Levitus et al [2000]. Also, the tide gauges have not been rigorously checked for benchmark shifts uplift and subsidence, all of which may influence the reconstruction.

With those caveats, it is encouraging that both data sets show similar trends, such as a relatively slow change from 1950-1975, then a more rapid increase. However, we are hesitant to reach any conclusions until we can do more analysis.

Acknowledgments

This investigation is funded in part by NASA Grant NAG5-9144.