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Separating Long-Term Sea Level Trends and Interannual Climate Variations

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Abstract

Sea level variability can be measured by tide gauges and satellite altimeters very accurately. The variability is caused by a variety of signals, including short period tides, eddies, storm surges, seasonal warming/cooling and wind changes, interannual fluctuations such as El Niño, and long term climate change. Although satellite altimetry measures sea level very precisely over most of the global oceans, highly accurate data extend back only for the past decade. Thus, it is difficult to separate long-term climate change signals from shorter interannual and decadel signals. Shorter period fluctuations can be averaged while regular variations (such as seasonal warming) can be modeled with sinusoids of a known frequency. Interannual signals with a changing frequency are more difficult to model and remove from sea level time series. The goal of this study is to investigate a method to model interannual signals using climate indices, and then remove these periodic climate fluctuations from sea level variations in order to detect the rate of long-term sea level rise change.

Introduction

Accurate measurements of global mean sea level and its variability have long been sought. 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. 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.

Better measurements 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 [*Born et al*. 1986; *Tapley et al*., 1992; *Nerem*, 1995]. 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 [*Cheney et al*., 1994; *Mitchum,* 1994; *Chambers et al*., 1998; *Nerem et al*., 1997], but it only measures the sea level rise from late 1992 to the present.

The rate measured by T/P from 1993 is slightly higher than the historical tide-gauge rate of 1.8 mm/year determined by *Douglas* [1991], which has been attributed in part to the El Niño of 1997 [*Nerem et al*., 1999]. However, 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. The linear trend in MSL from 1993-1998 for T/P is 3.5 mm/year, while for the gauges used by Douglas it is 8.4 mm/year. The accuracy of the T/P results is 1-2 mm/year [*Nerem et al*., 1997; *Mitchum* 1998]. Because the tide gauge MSL change is significantly different from that measured by the global sample of T/P, one must question whether 21 gauges can measure MSL change as precisely as has been assumed, or if the measurement is affected by climate signals present mainly in the Atlantic and/or Northern Hemisphere.

However, it is also dangerous to infer a long-term rate of MSL change from a relatively short altimeter record, as deviations away from a century-long rate can be caused by decadal variations. Based on the frequency of previous El Niño events *Nerem et al* .[1999] find that more than 11 years of T/P-quality altimetry will be needed to resolve a 2 mm/year linear trend in sea level to an accuracy of 1 mm/year. The actual time to resolve the answer can be even longer if there are other decadal variations. Even if there are not, and assuming that the Jason-1 altimeter follows T/P with no interruption in the MSL time-series, the long-term trend can not be expected to be resolved until the post 2003 time frame.

Methodology

This investigation begins to utilize current altimeter measurements of MSL to determine a more accurate measure of long-term sea level change before 2003. This is accomplished by modeling interannual and decadal climate variations with frequencies higher than 1-per-century and estimating coefficients to remove similar fluctuations from sea level measurements. This method will effectively filter out interannual and decadal fluctuations from existing MSL measurements, so that long-term change can be determined.

Typically, sinusoids with frequencies of 1 cycle/year and 2 cycles/year along with a bias and linear trend are used to model sea level variations, η as

$$\eta(t) = a + b(t-t_o) + C_a\cos(2\pi(t-t_o)) + S_a\sin(2\pi(t-t_o)) + C_{sa}\cos(4\pi(t-t_o)) + S_{sa}\sin(4\pi(t-t_o)) \quad (1)$$

where t is in years, and to is some epoch. The coefficients Ca, Sa, Csa, Ssa, a, and b are estimated using least squares estimation to observations of η. Where the coefficients are large, there is a strong signal at that particular frequency. A similar technique could be applied to other climatic signals, if their pattern were known.

The main problem with climate signals other than the annual and semi-annual is that they are quite irregular. For example, the power spectrum of the Southern Oscillation Index (SOI) (the atmospheric relation to El Niño in the ocean) shows peaks at multiple frequencies, and the frequencies vary depending on the time span used (**Figure 1**).

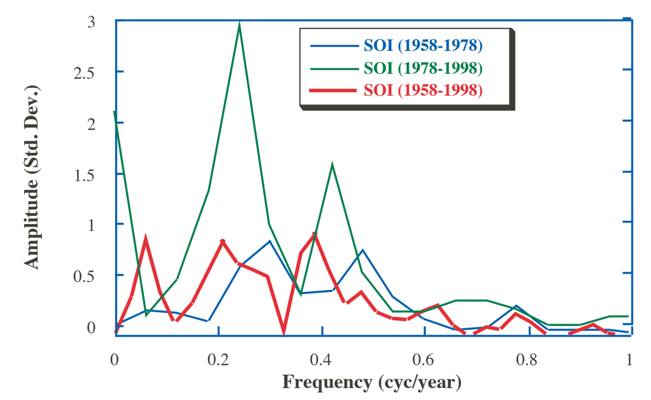

Figure 1. Power spectrum of the SOI time-series, computed over different time spans. While similarities exist in the distribution of dominant frequencies (roughly three, spaced ~0.2 cyc/year apart), the exact frequencies vary depending upon which decades are examined.

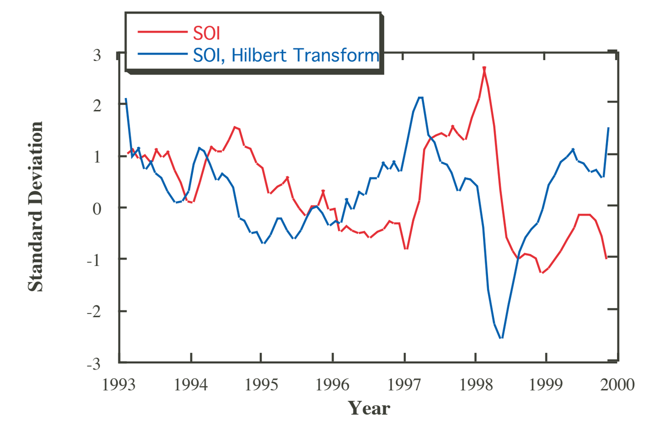

Figure 2. The SOI time-series and its Hilbert transform during the T/P time-frame. Note that the SOI has been inverted so that the time-series is positive at the same time sea level is positive (e.g, during the 1997/1998 El Niño).

Hilbert Transform

Instead of using sinusoid representations of the climate signal as in Equation (1), a discrete time-series of the climate signal ($f_{clim}(t)$) is used along with its Hilbert transform ($f^H_{clim}(t)$) in the model, such as

$$\eta(t) = a + b(t-t_o) + C_a\cos(2\pi(t-t_o)) + S_a\sin(2\pi(t-t_o)) + C_{sa}\cos(4\pi(t-t_o)) + S_{sa}\sin(4\pi(t-t_o)) + A_{clim}f_{clim}(t) + B_{clim}f^H_{clim}(t) \quad (2)$$

where the coefficients A_{clim} and B_{clim} are estimated along with the others.

The Hilbert transform is calculated by Fast Fourier Transform (FFT) methods (in this research using IDL). Whereas the Fourier time-series may be represented by **(3)**, the Hilbert transform is represented by **(4)**, which swaps the coefficients and shifts the climate signal 90 degrees in phase (**Figure 2**).

$$f(x) = a_o/2 + \Sigma(a_n\cos(n\pi x/L) + b_n\sin(n\pi x/L)) \quad (3)$$

$$f^H(x) = a_o/2 + \Sigma(b_n\cos(n\pi x/L) + a_n\sin(n\pi x/L)) \quad (4)$$

By including the phase-shifted spectrum, the model is able to account for phase-shifted propagating signals with the same frequency as the climate index. More than one climate variation can be included in the model, and solutions can be obtained simultaneously for all coefficients.

Climate Indices

For this investigation, we examined three well-known, well-defined climate indices to model interannual sea level variability. We used monthly time-series of the indices and estimate coefficients to each index and its Hilbert transform. These climate indices are:

1) the Southern Oscillation Index (SOI), based on pressure differences between Darwin and Tahiti, which is known to be related to El Niño [*Philander*, 1990],

2) the North Atlantic Oscillation (NAO), based on pressure differences between Portugal and Iceland [*Jones et al*., 1997], and

3) the Pacific Decadal Oscillation (PDO), based on the average sea surface temperature (SST) in the Pacific poleward of 20N [*Hare and Francis*, 1995].

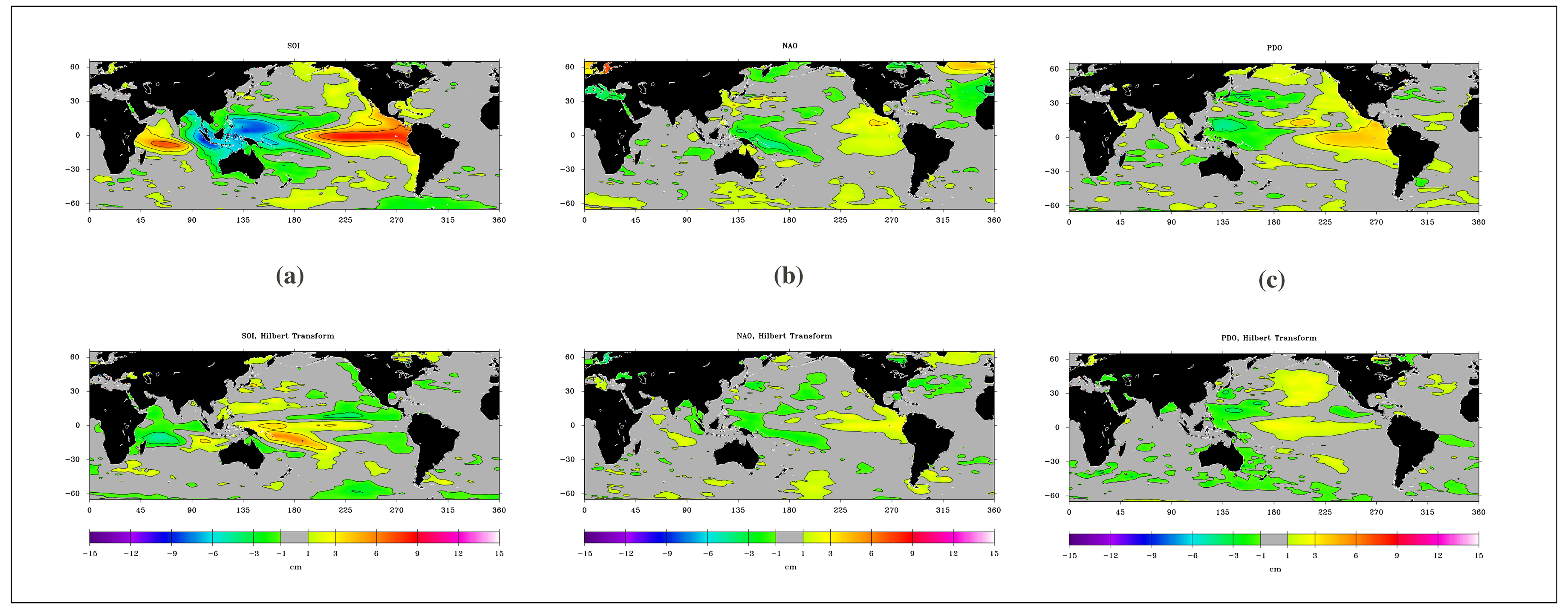

Figure 3. Estimated amplitude coefficients of the interannual model, using (a) SOI, (b) NAO, and (c) PDO, and their Hilbert transforms as the basis functions.

Model Coefficients

The coefficients of each climate index and its Hilbert transform are estimated for each grid of sea level anomalies mapped from satellite altimetry (**Figure 3**). Since we are interested in large-scale signals, the data are gridded to 1-degree grids and are smoothed over long wavelengths (using a Gaussian smoother in IDL). After modeling, the interannual variations can then be removed from the sea level observations, and the adjusted sea level anomalies averaged over the ocean basins in order to compute global mean sea level (GMSL) change.

On a global scale, one can examine the size of the estimated coefficients in each grid and note where there are very strong variations at the SOI frequencies, such as in the Pacific and Indian Oceans, strongly correlated with El Niño. Both the NAO and PDO maps display their stronger signals in the equatorial Pacific also. Note however, in all six maps, that most of the ocean shows relatively little correlation to any of the chosen indices or their Hilbert transforms. If the annual and climate estimates are removed from the sea level variations in each grid, the residuals can be averaged to examine GMSL change without these signals.

Example using SOI in the Niño 3 region

Consider the sea level variations in the eastern Pacific from 1993 to the present, plotted along with the SOI in **Figure 4**. There is an obviously high correlation between the two time-series. If the SOI and its Hilbert transform are used as the interannual signal in the model (**Equation (2)**), then the model fits the data very well, with a standard deviation of less than 3 cm (**Figure 5**), which is comparable to the estimated accuracy of the T/P sea level measurement on this scale. Although the model does not reflect all the interannual variability, it does reproduce the significant components, especially the El Niño of 1997/1998.

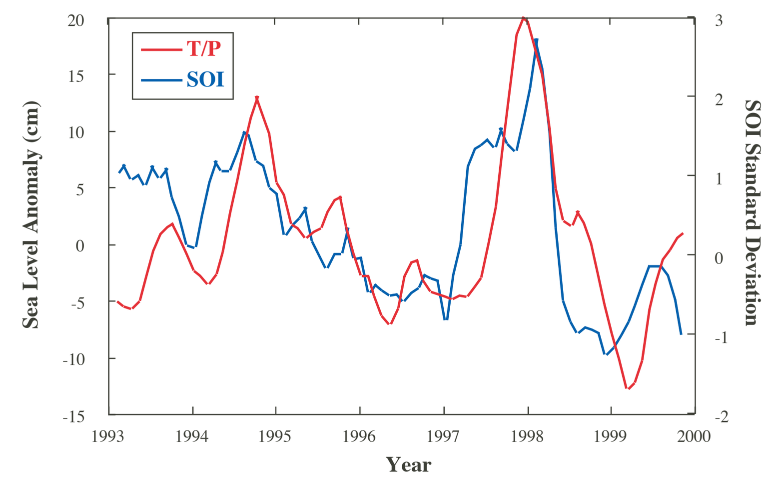

Figure 4. Sea level anomalies from T/P (red) averaged in the Niño 3 region (5S-5N, 210E-290E) and the SOI (blue). Note that the SOI has been inverted so that the time-series is positive at the same time sea level in the eastern Pacific is positive. The two time-series are strongly correlated, especially during the strong El Niño of 1997/1998.

Preliminary Results

The interannual model (**Equation (2)**) including all three climate indices (SOI, NAO, PDO) as basis functions was applied to the T/P GMSL time-series. The time-series before and after the removal of the interannual variations is shown in **Figure 6** .The T/P data have been cycle-averaged (10 days) and smoothed with a 60-day running-mean boxcar filter.

Note that the large rise in sea level associated with the 1997/1998 El Niño has been reduced, as well as the significant fall during the 1999 La Niña. There are still signals other than a long-term trend, indicating further interannual climate signals that need to be removed.

Most importantly for long-term climate change study, the estimated GMSL trend increases from 2.0 mm/year (T/P) to 2.7 mm/year (T/P-model) when interannual signals are removed. While this change is slightly less than the current estimated accuracy of the T/P time-series (1-2 mm/year [*Nerem et al*., 1997; *Mitchum* ,1998]), perhaps interannual variations are a primary cause of the T/P uncertainty. It is obvious from the figure that the model produces a dramatic change in the shape of the time series. In the future, if GMSL time-series are to be determined at the sub-mm/year level, the removal of interannual signals are necessary to reach that level of accuracy.

The T/P GMSL time-series was also examined using each climate index basis individually (**Figure 7**) (in addition to the annual and semi-annual signals). The T/P-PDO curve is nearly the same as the estimate using all three climate indices, indicating that the variability characteristics of the T/P time-series are (mostly)dominated at PDO frequencies. Note that the SOI (blue) curve does not fully remove the sea level drop during the 1999 La Niña, but the PDO curve does. Not also that the PDO curve does not fully remove the variability during 1994/1995, but the NAO (green) curve does. Clearly, all three climate indices are important to the global climate variability of the oceans.

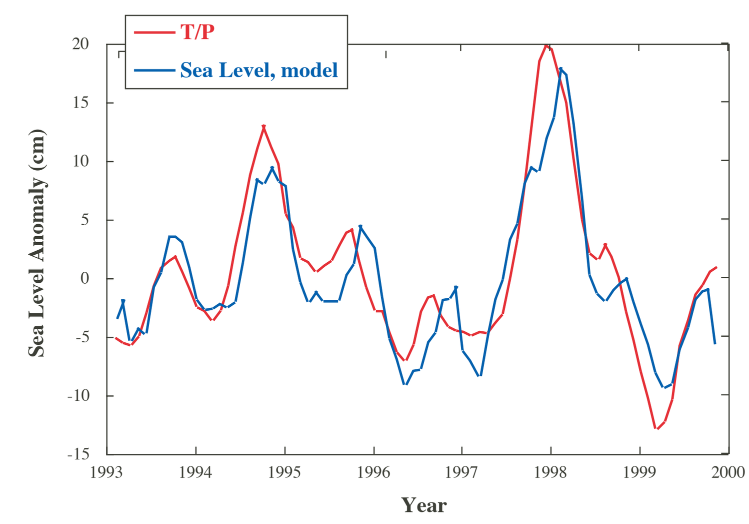

Figure 5. Sea level anomalies in the Nino 3 region from T/P (red) and from a the model based on estimated fits to T/P data using **Equation (2)**, including only the SOI for the interannual signal. The model reproduces much of the interannual variability, although not all. The standard deviation between T/P and the model is less than 3 cm.

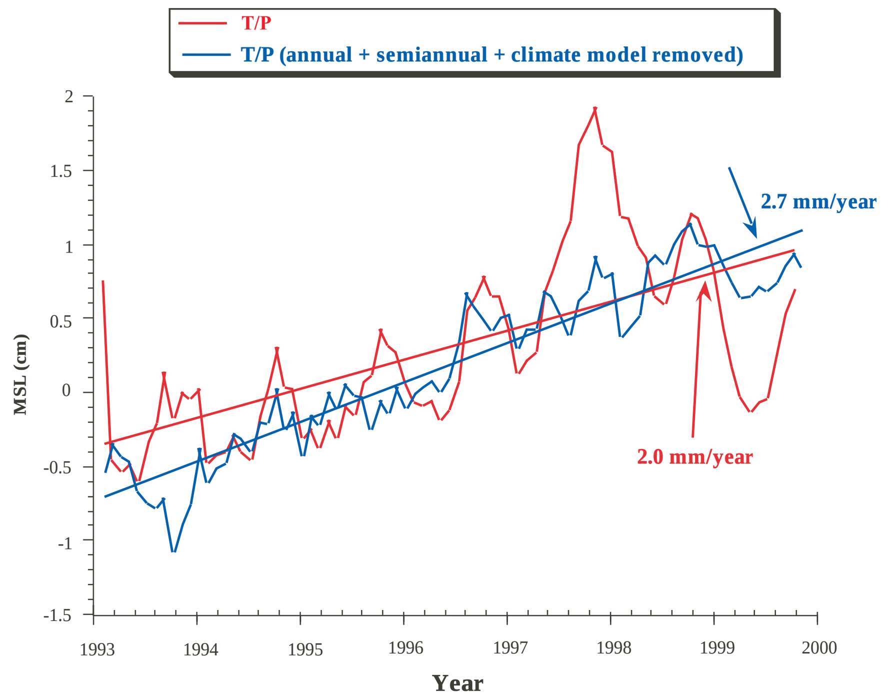

Figure 6. GMSL from T/P (red) and from T/P after removing the interannual model (blue) using the combined SOI, NAO, and PDO as basis functions. A significant reduction in the estimated GMSL trend is obtained when the interannual signals are removed using the model.

To examine the whole ocean, T/P sea level anomaly (SLA) maps were constructed before and after the interannual variability signals where removed. (**Figure 8**) The interannual model removes a great deal of the variability signal, but not all. In the T/P-model map, higher sea level anomalies remain in the equatorial Pacific and Indian oceans, perhaps linked to another El Niño-related climate variable. Further research into the roles of these and other climate indices are ongoing.

Future Work

One advantage to estimating coefficients to multiple signals with the least squares technique is that the covariance matrix may indicate correlations between parameters (and climate signals), which may indicate that climate signals have similar interannual variations and the seasonal and long-term variations. The same technique can also be applied to individual tide gauge stations, and we will examine this in order to determine if we can reconcile the MSL measurements from tide gauges and altimetry. If this can be done, then the technique can be applied to earlier tide gauge data and a very long time series of MSL change excluding interannual signals can be determined.

The examples have been computed using only TOPEX/POSEIDON altimeter data from 1993 to the present. However, altimeter data from the GEOSAT mission exists back to 1985, and data from the ERS-1 mission exists back to 1991. The ERS-1 data, although it is less accurate than T/P, can be used without much difficulty, as the two instruments overlapped in time, so relative biases between the instruments can be computed. We will evaluate such biases for ERS-1, as well as the accuracy of the sea level measurement of ERS-1 relative to T/P before utilizing the data in this investigation.

The GEOSAT data are more problematic, as there were no absolute bias calibrations performed on the instrument, and the data did not overlap with any other mission. Thus, it is difficult to quantify MSL change before 1992, as the GEOSAT data have an unknown bias. Efforts have been made to estimate the bias [*Guman*, 1997; *Urban*, 2000], but the accuracy of the estimate is still on the order of 2-3 cm. Therefore, before using GEOSAT data in this investigation, we will continue to improve the estimate of the relative bias.

In addition to applying this method to altimeter data, we will also investigate applying it to tide gauge data. Although there are fewer tide gauge observations than altimeter observations per month, the tide gauge records do extend back much farther. One would like to determine GMSL change unambiguously from the tide gauge data. However, as noted before, because of the small number and limited locations, this is difficult. For example, the tide gauges used by *Douglas* [1991, 1992] are mainly in the North Atlantic. If the gauges produce a strong correlation with the North Atlantic Oscillation, then the tide gauge record may be indicating a local change, and not a global change. By estimating and removing the effects of the NAO, one might be able to pick out the global long-term change.

After quantifying the correlation between the SOI, NAO, and PDO on sea level variability, we will consider other climate indices such as the solar cycle, carbon dioxide, and precipitation. If sea level change is related to any of these time-series, then there should be a significant correlation with the sea level variations.

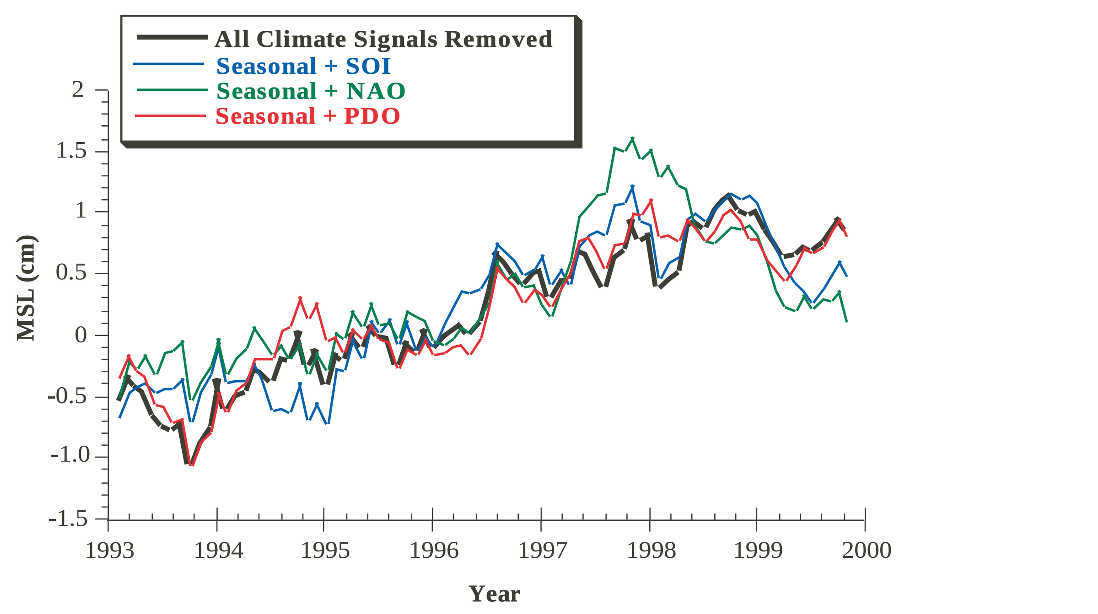

Figure 7. GMSL from T/P using the interannual model with all climate signals removed (black, = blue curve from Figure 6), and from using each climate index basis individually. The PDO (red) curve most closely approximates the black curve, indicating that the PDO basis removes most (but not all) of the interannual signal removed by the complete model.

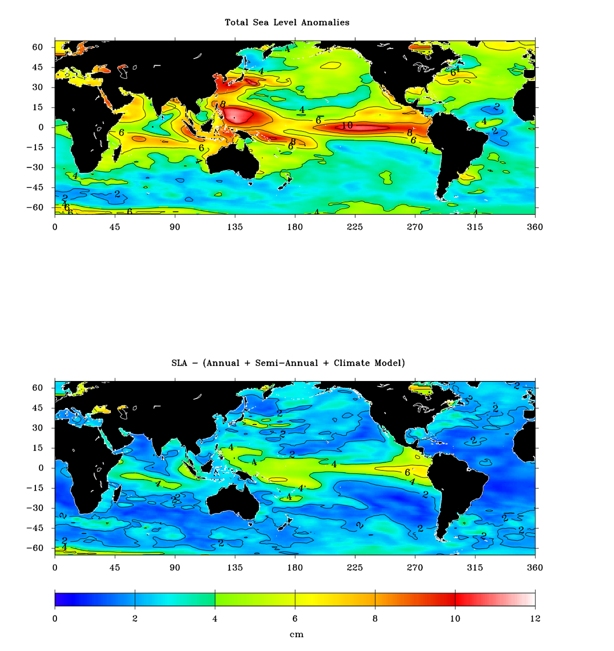

Figure 8. Sea level anomaly (SLA) maps from T/P data before and after all climate signals have been removed by the interannual model. The model removes most (but not all) of the interannual signal. Higher sea level anomalies remain in the equatorial Pacific and Indian oceans, in a few coastal regions, and in areas of naturally high variability.

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