2005

A Regional Index of Northeast Pacific Variability Based on Satellite Altimeter Data

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Received 1 June 2005; revised 10 August 2005; accepted 12 August 2005; published 9 September 2005.

[1] An index of climate variability to monitor the state of the upper ocean is proposed for the northeast (NE) Pacific Ocean based on sea surface height (SSH) data from satellite altimetry. While sea surface temperature (SST) is often used characterize ocean variability, SSH reflects the integrated influence of temperature and salinity anomalies through the water column. A canonical correlation analysis shows that SSH and SST anomalies vary coherently at large spatial scales and low frequencies over the region. SSH anomalies are less subject to short period variability and the temporal components for SSH resemble smoothed, low-pass-filtered versions of the SST components. Also examined is the relationship between the SST-based Pacific Decadal Oscillation (PDO) index and the large-scale, upper ocean variability reflected in the leading principal component of SSH anomalies. The comparison demonstrates that the SSH principal component provides a robust index of regional climate variability that is less noisy than the PDO. The results are used to examine the 1998–2002 climate event over the NE Pacific. **Citation:** Cummins, P. F., G. S. E. Lagerloef, and G. Mitchum (2005), A regional index of northeast Pacific variability based on satellite altimeter data, *Geophys. Res. Lett.*, *32*, L17607, doi:10.1029/2005GL023642.

1. Introduction

[2] Sea surface temperature (SST) anomalies are used routinely to monitor the climatic state of the ocean. This is due, in part, to the availability of long time series with broad spatial coverage for this variable. For example, the Pacific Decadal Oscillation (PDO) index [*Mantua et al.*, 1997; *Mantua and Hare*, 2002], defined as the leading principal component of extratropical SST anomalies, is often used to characterize the state of the North Pacific. The warm (positive) phase of the index is associated with above normal SST adjacent to the North American coast, and an elongated pattern of below normal SST in the central basin of the North Pacific.

[3] The major shift in the state of the North Pacific that occurred in 1976/77 [*Miller et al.*, 1994] was reflected as a generally persistent change to the warm phase of the PDO. However, the PDO index is subject to relatively short-period fluctuations and it has changed sign on a number of occasions since the 1976/77 shift. With the development of tropical La Niña conditions following the large 1997/98 El Niño, the PDO index underwent a transition to predominantly negative values. It has been suggested that this may signal the advent of a climate shift to the PDO cold phase [*Peterson and Schwing*, 2003]. On the other hand, *Bond et al.* [2003] have argued that the changes which occurred over the Pacific basin following 1998 were not consistent with PDO variability.

[4] In this paper, we consider the application of sea surface height (SSH) anomalies from satellite altimeter data to develop an index of regional variability for the northeast (NE) Pacific. The eastern side of the extratropical North Pacific provides the habitat for several commercially important fish stocks. It is also a region where PDO variability is thought to have a major influence on the physical environment and is related to several physical and biological climate indices [e.g., *Mantua et al.*, 1997; *Hare et al.*, 1999]. SSH and SST variability over the NE Pacific are compared for the 12-year period, 1993–2004. While SSH and SST vary coherently, the analysis shows that SSH anomalies are less prone than SST anomalies to short period fluctuations. The 1998 shift is clearly reflected in a large-scale pattern of SSH changes that is related to long period SST changes and to the PDO index. The results demonstrate that an index of variability based on SSH may be developed to monitor the state of the NE Pacific.

2. Data and Results

[5] The analysis makes use of monthly SSH fields from the TOPEX/Poseidon and Jason-1 satellite altimeters, gridded at 1° resolution. A description of the gridding procedure is given in *Lagerloef et al.* [1999]. There are 12 years of data covering the period 1993–2004. The NE Pacific region considered here is bounded by the dateline, the west coast of North America, and has a southern boundary along 25°N. (Results are not very sensitive to these choices.) The Bering Sea is not included in the analysis.

[6] Monthly SST fields are drawn from the analyses produced by the Hadley Centre for Climate Prediction and Research [*Rayner et al.*, 2003]. These data are considered on an identical $1° \times 1°$ grid as that used for the SSH data and were processed in a similar manner. The climatological

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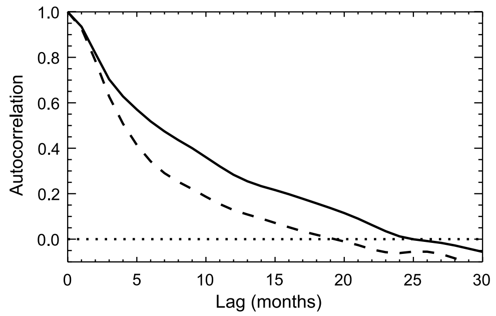

Figure 1. Average autocorrelation functions for SSH (solid line) and SST (dashed line) anomalies from the arithmetic mean of the autocorrelations for all grid points within the NE Pacific domain.

monthly mean was removed from the data and a 3-month boxcar filter was applied to the residual to eliminate high frequency noise, yielding the interannual anomalies.

[7] At low frequencies, extratropical SSH anomalies are due mostly to steric height variability associated with vertically integrated temperature and salinity anomalies,

$$\eta' = \int_{-H}^{0} (\alpha T' + \beta S')dz \qquad (1)$$

with α and β the coefficients of thermal expansion and haline contraction, respectively. While the lower limit of integration in (1) is, in principle, the sea floor, at annual time scales steric variability is dominated by near-surface diabatic processes associated with the seasonal thermocline [*Stammer*, 1997]. For longer periods, SSH variability is thought to be due to adiabatic baroclinic processes below the seasonal thermocline [*Gill and Niiler*, 1973]. Accordingly, *Gilson et al.* [1998] found high correlations along a transpacific section between SSH and temperature anomalies in the core of the thermocline.

[8] Figure 1 shows that the average autocorrelation function for SST decays more rapidly than the SSH autocorrelation, reflecting the greater importance of variability on relatively short time scales in the SST record. SSH anomalies reflect depth-integrated changes extending through the main pycnocline, whereas SST anomalies represent changes confined to the seasonally-varying mixed layer. As a result, SST has a shorter memory and responds more rapidly to atmospheric forcing than SSH. The latter is influenced by variations in pycnocline depth associated with Ekman pumping and baroclinic Rossby waves with a typical adjustment time scale of 1 to 2 years [*Lagerloef*, 1995; *Cummins and Lagerloef*, 2004; *Capotondi et al.*, 2005].

[9] The SSH and SST anomalies were expanded in terms of empirical orthogonal functions (EOFs). A canonical correlation analysis (CCA) was then applied to define and compare the most highly related patterns of SSH and SST variability [*Barnett and Preisendorfer*, 1987]. The three leading EOFs of each variable were used, accounting for a total of 61% and 76% of the SSH and SST variance, respectively. Due to mesoscale variability in the Kuroshio Extension, expanding the analysis region to the west somewhat (for example, to 170°E) leads to a reduction in the fraction of variance associated with the leading SSH modes. The results presented below are otherwise qualitatively unaffected by such a change. They are also insensitive to the inclusion of additional modes in the CCA.

[10] The first two canonical correlations (CCA1 and CCA2) are shown in Figures 2a and 2b. The spatial patterns of SSH and SST associated with CCA1 are remarkably similar with a spatial correlation coefficient of r = 0.92. These canonical maps show the central Pacific varying in

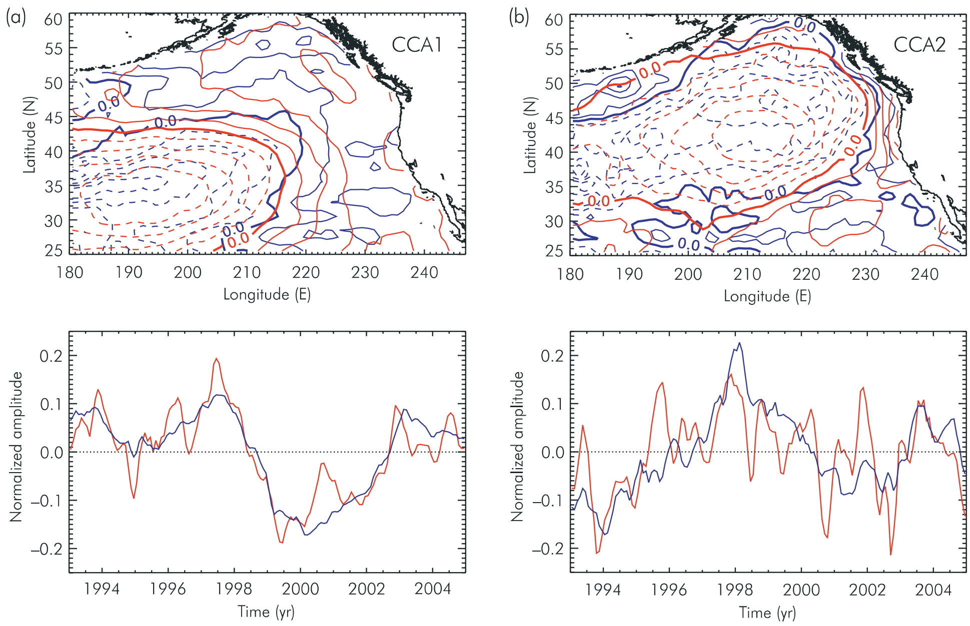

Figure 2. (a) The top panel shows the canonical maps of SSH (blue lines) and SST (red lines) for CCA1. The contour interval is 0.2 and negative contours are dashed. The lower panel gives the temporal components; the canonical correlation is 0.88. CCA1 explains 46% of the SSH variance and 48% of the SST variance. (b) Maps and temporal components (canonical correlation of 0.63) for CCA2, accounting for 12% and 11% of the SSH and SST variance, respectively.

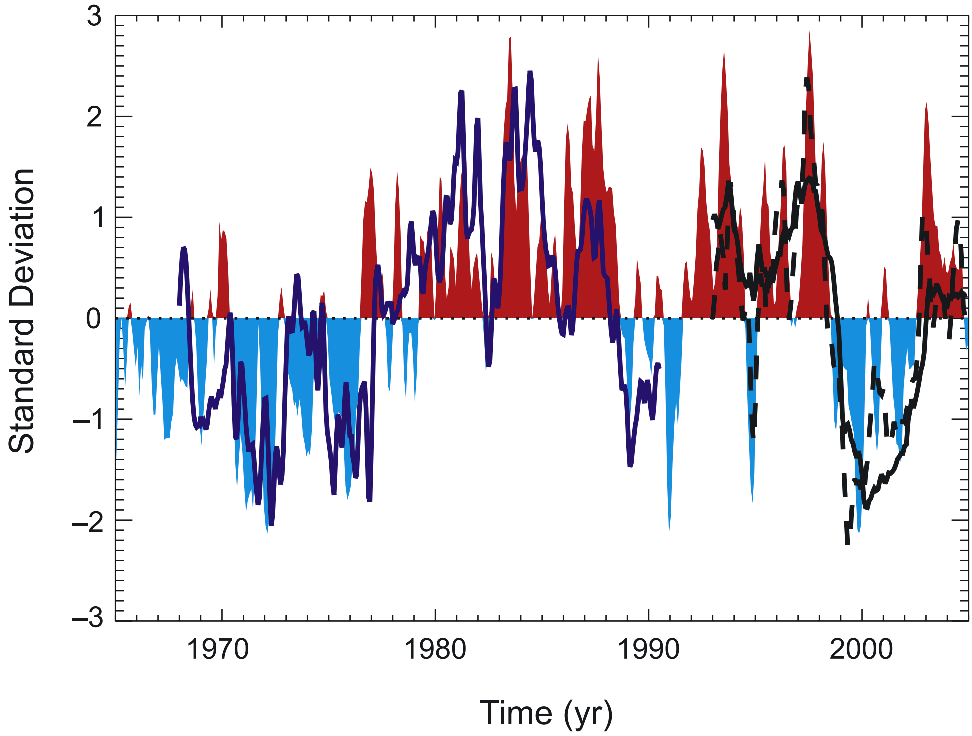

Figure 3. Comparison of the PDO index (red and light blue fill) with the first principal components of NE Pacific SSH (solid black line) and SST (dashed black line) anomalies. The dark blue curve is the first principal component of the Gulf of Alaska dynamic heights [*Lagerloef*, 1995]. The PDO index is from the web site http://jisao.washington.edu/pdo/PDO.latest; for consistency it was smoothed with a 3-month boxcar filter. Each time series has been normalized by its standard deviation.

opposition to a broad region adjacent to the coast in a large-scale pattern that resembles the PDO pattern over the NE Pacific [*Mantua et al.*, 1997]. The temporal component of CCA1 associated with SSH appears as a low-pass-filtered version of the SST component. The results of Figure 2a are consistent with those of *Casey and Adamec* [2002] who demonstrated the co-variability of the leading SSH and SST modes over a region encompassing the equatorial and North Pacific for the period 1993–1999. Inclusion of the tropical Pacific, which dominates the variability of their modes, leads to a tighter correlation between SST and SSH principal components than obtained here for the NE Pacific.

[11] The canonical maps associated with CCA2 (Figure 2b) also show generally coherent spatial patterns ($r = 0.75$). The associated temporal components are less well correlated than with CCA1, due mostly to the presence of strong higher frequency fluctuations in the SST component. CCA3 is not presented as these higher-order spatial patterns are essentially incoherent, and their associated temporal components are poorly correlated.

[12] The spatial maps of SST and SSH associated with CCA1 are virtually identical to the respective leading EOFs of these variables. (Correlation coefficients between the respective CCA1 maps and the EOF1 patterns are greater than 0.98.) As illustrated in Figure 2a, the dominant SST variability is a rapid warming of the surface waters of the central Pacific in 1998, accompanied by a cooling in a broad band around the margin of the basin. CCA1 indicates that these SST changes were associated with a large-scale pattern of rising SSH over the central Pacific and a concomitant lowering of sea level around the basin margin, including the Gulf of Alaska. A relaxation of these conditions followed in 2002.

3. Relation to the PDO Index

[13] As CCA1 is dominated by the leading EOFs, the principal components of these modes have been plotted in Figure 3 where they are superposed against the PDO index. As expected, since the latter is also derived from SST, the first principal component for NE Pacific SST is well correlated with the PDO index ($r = 0.80$). This is a robust result and, for example, a similar correlation ($r = 0.87$) is found for the 55-year period, 1950–2004.

[14] For the earlier 1968–1990 period, Figure 3 includes the first principal component of 0–450 dbar dynamic heights over the Gulf of Alaska [*Lagerloef*, 1995]. Figure 3 demonstrates that principal components of NE Pacific and Gulf of Alaska sea level anomalies are closely related to the low frequency variability displayed by the PDO index. Large-scale SSH anomalies over the region vary as a smoothed version of the dominant SST variability. The major changes in upper ocean conditions in 1998 are particularly evident in the SSH principal component which shows an abrupt sign reversal in near synchrony with the PDO index.

[15] *Bond et al.* [2003] have shown that the basin-wide pattern of atmospheric sea level pressure and SST anomalies which developed following the 1998 shift were different than the anomaly patterns associated with the 1976/77 shift. Discrepancies are particularly evident over the western

Pacific and over marginal seas, such as the Bering Sea and the Sea of Okhotsk. They suggest that the SST anomalies project mainly onto the second basin mode rather than the first (PDO) mode.

[16] To assess the significance of the PDO index for the recent variability over the NE Pacific, regional difference fields for SSH and SST were constructed based on averages over the 4-year periods (1994–1997 and 1999–2002) that preceded and followed the shift. These difference fields were found to be highly correlated spatially (r = 0.97, r = 0.98) with the respective leading EOFs of SSH and SST over the NE Pacific. Thus the patterns of regional change associated with the 1998 shift project almost perfectly onto related SSH and SST modes whose principal components correspond closely to the PDO index (Figure 3). It is worth noting that the regional SST difference field for the 1976/77 shift (based on averages over 1972–1976 and 1977–1981) is also well correlated spatially (r = 0.89) with this same leading NE Pacific SST mode.

[17] These considerations indicate that, with respect to the NE Pacific, the dominant recent SST variability is reasonably described in terms of the PDO index. The SSH data are consistent with this conclusion and indicate that a regional change occurred in 1998 to a state characterized by above-average sea level in the central Pacific and below-average sea level adjacent to the North American coast and in the Gulf of Alaska. In this sense, this state appears as an upper ocean counterpart to the cold phase of the PDO. In contrast to SST-based indices, the SSH principal component shows sustained negative values for the 4-year period, 1999–2002. This episode ended with the onset of the weak El Niño of 2002/03 [*Lagerloef et al.*, 2003] and conditions in 2003 and 2004 remained close to neutral with respect to the dominant mode of upper ocean variability. These events are consistent with the hypothesis of *Newman et al.* [2003] that the PDO represents a reddened response to tropical ENSO forcing and atmospheric noise.

4. Conclusions

[18] Our results demonstrate the value of developing regional indices of climatic variability based on satellite altimeter data. For the NE Pacific, the first SSH principal component provides a robust diagnostic index that may be used to monitor and now-cast the state of the region. As an integral property of the upper ocean, an index of ocean variability based on SSH is less subject to short period fluctuations than one based on SST. This is a desirable property for an indicator of ocean climate changes and it is helpful in the interpretation of the 1998–2002 climate event. In conjunction with the PDO index, the SSH principal component shows that the 1998 shift marked a regional transition to an anomalous state corresponding to the PDO cold phase for the upper ocean. The SSH index shows that these anomalous conditions were maintained until 2002, and that near-neutral conditions prevailed in 2003–2004.

[19] SSH anomalies should find increasing application as a reliable indicator of the climatic state of the upper ocean. This underscores the importance of continuing to collect long time series of high-quality altimeter data.

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