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On the Pacific Ocean regime shift

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Abstract. The temporal variability of Pacific Ocean upper ocean heat content is examined for the 1948-1998 period using gridded, objectively analyzed temperature anomaly fields. Results indicate a "regime shift" in upper ocean temperature structure occurred in conjunction with the atmospheric shift in sea level pressure around 1975 leading to warming (cooling) in the eastern (western) equatorial Pacific. The shift is a basin-wide phenomenon affecting the thermal structure from 60°S to 70°N. EOF analysis of the Pacific Ocean heat content (0-125 m) shows a shift from a relatively cool to a warm state in the equatorial Pacific during the mid-1970s. Further analysis of the gridded temperature anomaly fields shows equatorial warming to be as much as 1.5°C and a cooling in the North Pacific of 1°C, down to 250 meters, after the mid-1970s. Overall, the analysis indicates the "regime shift" continues through 1998 with no signs of returning to a cooler phase.

Introduction

Previous studies have described the variability of sea level pressure (SLP), surface air temperature (SAT) and sea surface temperature (SST) of the Pacific Ocean and to a lesser extent subsurface ocean temperature. To understand the role of the ocean in climate change, it is necessary to systematically document the variability of temperature as a function of depth in the world ocean on gyre, basin, and global scales.

The first step in examining the role of the ocean in climate change is to build the most comprehensive database possible and construct data and analysis fields that can be used to describe ocean variability. Ship-of-Opportunity Programs (SOOP) during the past 25 years provide unique sampling of the upper ocean. *Levitus et al.* [1994, 2000] describe the results of projects that have resulted in a large increase in the historical upper ocean thermal data from research and naval ships now available to study the interannual-to-decadal variability of the upper ocean.

Levitus and Antonov [1997] prepared and distributed gridded analyses of upper ocean temperature anomaly fields for individual years for the 1960-1990 period and presented results of multivariate analysis of these fields. We have used data from the more recent and comprehensive *World Ocean Database 1998* [*Levitus et al.*, 1998a,b; *Boyer*, 1998a,b,c] to prepare yearly upper ocean temperature anomaly fields. In this paper we describe the variability of upper ocean heat content, integrated through 125 m depth, of the Pacific Ocean for the 1948-98 period by analyzing the fields using Empirical Orthogonal Function Analysis (EOF - known also as Principal Component Analysis). The EOF analyses we present are only capable of representing "standing" patterns of variability. While advection of surface and subsurface temperature anomalies has been documented in the North Pacific, the standard EOF analyses we utilize are adequate to represent the temporal changes we wish to describe in Pacific Ocean heat content.

Since the pioneering works by *Nitta and Yamada* [1989], *Royer* [1989], and *Trenberth* [1990], a great deal of scientific research has focused on the variability of the North Pacific Ocean [*Zhang and Levitus*, 1996; *Manutua*, 1997]. Shifts in atmospheric SLP, SAT and SST [*Minobe*, 1997; 1999], that last occurred in the mid-1970s, are collectively referred to as a "regime shift", as the Pacific Decadal Oscillation (PDO), and as the Cold Ocean Warm Land (COWL) pattern [*Mantua et al.*, 1997; *Zhang et al.*, 1999]. *Chao et al.* [2000] note that the 1976-1988 event is the largest transition thus far. Many scientists question whether this shift in the mid-1970s is due solely to natural variability, is a unique phenomenon or is related to increased warm events in the Pacific [*Trenberth and Hurrel*, 1994; *Latif and Barnett*, 1994; *Zhang et al.*, 1997]. Most of these studies examine the variability of sea level pressure and/or surface temperatures.

Multivariate analysis results and discussion

We have performed EOF analyses on heat content of the Pacific Ocean integrated through 125 m depth for the 1948-98 period using yearly temperature anomaly fields. *Levitus et al.* [1994] provide detailed information about the objective analysis of the temperature anomaly fields. The spatial loading pattern of the 1st EOF of upper ocean heat content (based on the correlation matrix) is shown in figure 1a with its associated time series (figure 1b). The product of the spatial pattern of an EOF and its time variability give the contribution of the EOF to the actual analysis fields. Therefore the regions of negative polarity associated with this EOF were relatively warm before the mid-1970's and cooled after the mid-1970s. The next two modes of variability are related to phases of El Niño and not shown. We also performed rotation on the EOFs, but the results do not contribute additional information to the EOF analyses.

The 1st EOF represents the spatial distribution of the pattern of variability that accounts for the largest percent variance of the data series. The variance accounted for by this EOF is 13.19%. This EOF shows a pattern that includes regions of maximum (negative) variability centered along 40°N in the Pacific between 140°E and 140°W. Other

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regions of negative variability occur in a region centered along 10°N in the western Pacific and in a region extending from the western equatorial Pacific to the southeast (coincident with the South Pacific Convergence Zone (SPCZ)). The region of positive maximum variability is located in the tropics and subtropics east of the dateline and extends poleward with increasing distance from the western boundary of the Pacific. The time series associated with this EOF is mainly negative before the mid-1970s and then shifts rapidly to a more positive state coincident with the shift in sea level pressure. In addition to the regime shift, this first mode of variability is also characterized by high frequency interannual variability which has increased in magnitude after 1975. The increased magnitudes could be related to a relative lack of data prior to the regime shift or due to stronger warm events that occurred after the regime shift.

The decrease (increase) of heat content in the western (eastern) tropical Pacific after the mid-1970s regime shift is consistent with a decrease in the east to west downward tilt of the tropical thermocline. *Clarke and Lebedev* [1997] estimated zonal wind stress as a function of year for the equatorial Pacific Ocean based on atmospheric sea level pressure differences (to avoid biases in winds from ship data). Their work shows a sudden decrease in the westward wind stress in the mid-1970s consistent with our results that show a decrease in the westward, downward tilt of the equatorial and tropical thermocline.

Temporal variability of temperature as a function of depth

Figure 2(a-b) shows the temperature differences at selected standard depth levels (50 m and 250 m) for the 1978-88 period minus the 1964-76 period. These compositing periods were chosen to represent conditions before and after the mid-1970s shift. At 50 m depth (Fig. 2a), a major feature in the temperature difference fields is the positive anomalies in the eastern Pacific associated with the upward

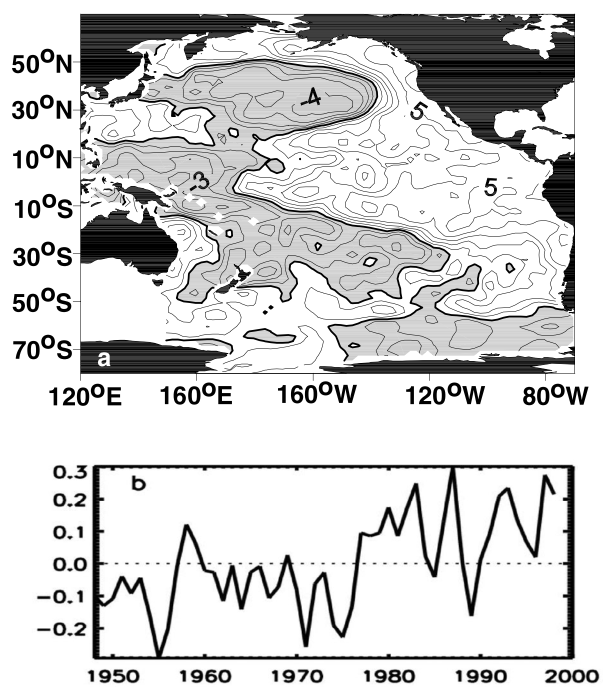

Figure 1. First EOF of the annual Pacific Ocean heat content integrated through 125 meters for the period 1948-1998, accounting for 13.19%; (a) Spatial distribution with a contour interval of 1.0; (b) temporal distribution.

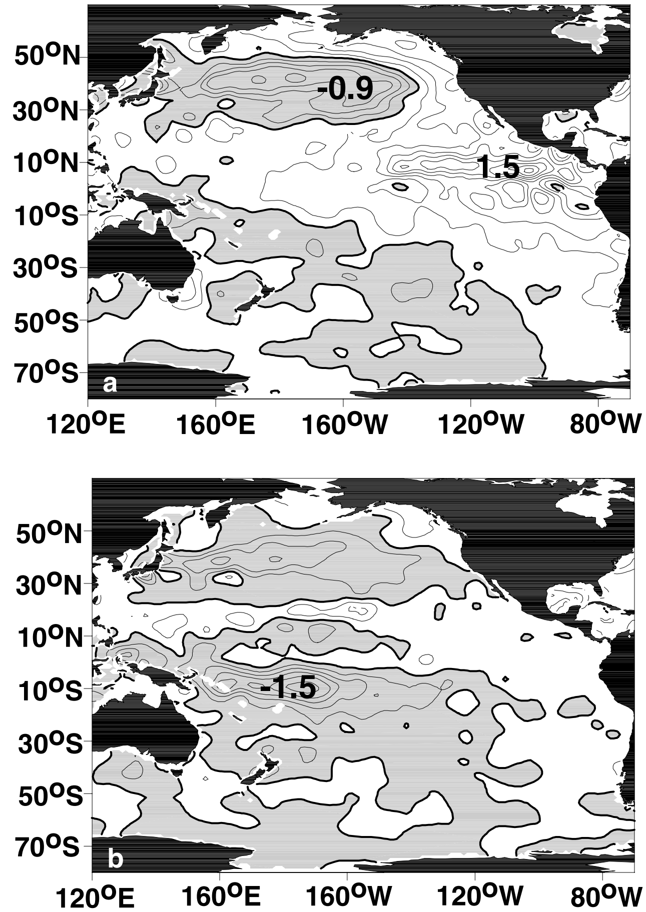

Figure 2. Annual temperature anomaly differences for the period 1978-1988 minus 1964-1976 at (a) 50 meters depth and (b) 250 meters depth. Contour interval is 0.3°C; shading represents negative values.

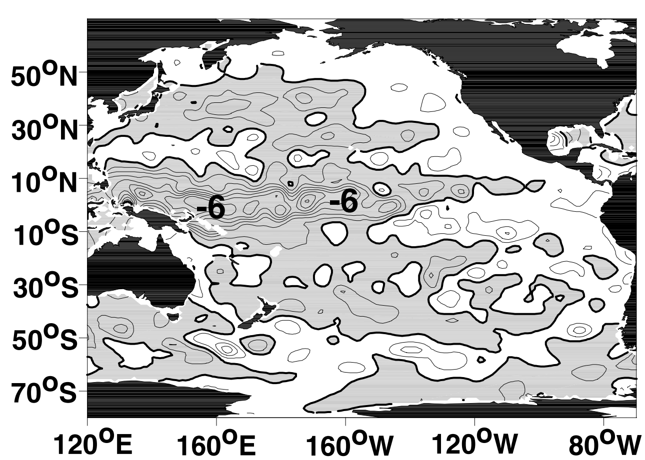

Figure 3. Annual temperature anomaly differences for the period 1987 minus 1989 at 150 meters depth. Contour interval is 1.0°C; shading represents negative values.

displacement of the thermocline in this region. The post-1975 period shows an increase in temperature of as much as 1.5°C. Along 40°N, the cooling reaches a maximum of approximately 1.0°C. This feature is apparent from the sea surface through 250 m depth (Fig. 2b), although the maximum has shifted westward and is approximately 0.8°C. At 250 m depth the western equatorial Pacific exhibits a cooling with a maximum difference of 1.2°C due to upward displacement of the thermocline.

Although a major shift in the subsurface temperature structure occurred in the mid-1970s, high frequency variability of similar nature is observed every three to four years. The temperature difference field for 1987 minus 1989 at 150 m depth is shown in figure 3. The same features, noted in figure 2, dominate the equatorial eastern Pacific and the North Pacific. Debate is ongoing as to whether or not a recent increase in interannual variability is due to natural phenomena or to increasing occurrences of El Niño in the past 15 years. However, the same high frequency variability is also observed prior to 1975 though not as large in magnitude.

Examining the temperature anomalies near the eastern and western equatorial boundaries of the Pacific Ocean we note opposing signs. At 0.5°N, 84.5°W (not shown) just off the western coast of Ecuador, large warm anomalies exist after 1975 with a few minor cool periods in 1985, 1989 and 1994 consistent with known cooling events (La Niñas). The magnitude of these anomalies reach 2°C. Prior to 1975, the eastern equatorial Pacific Ocean was in a cooler phase. Conversely, at 8.5°S, 169.5°E (Figure 4), the years prior to 1975 were dominated by warm anomalies. After 1975, relatively large cool events persisted with the greatest magnitudes occurring between 100 and 250 meters depth. The magnitudes (both positive and negative) of these anomalies are on the order of 2°C. Again, these findings support the occurrence of a regime shift of subsurface temperature structure in 1975 and show the dipole structure, that exists in the thermocline depth across the equatorial Pacific during the warm events, has persisted since the mid-1970s.

To further document Pacific Ocean variability, we present the zonally averaged temperature anomaly field as a function of latitude versus time at 400 m depth (Figure 5). At 400 m depth it is clear that a shift from relatively cool to warm temperatures occurred around 1968 for most of the Pacific between 60°S and 60°N. This occurred prior to the upper

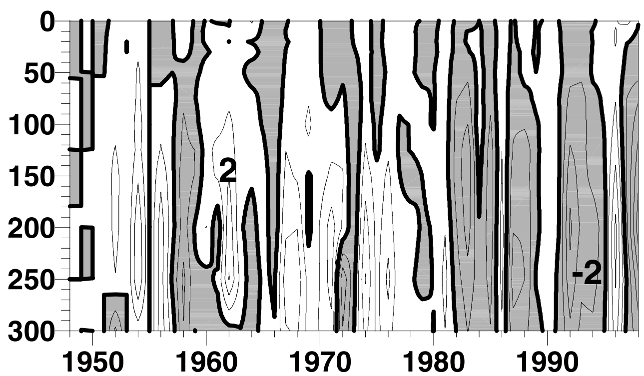

Figure 4. Yearly temperature anomaly (1948-1998) versus depth (0-300 meters) at 8.5°S, 169.5°E . Contour interval is 1.0°C with negative values shaded.

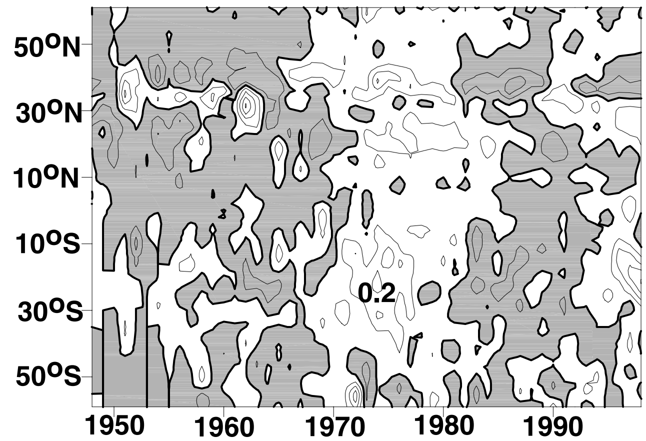

Figure 5. Pacific Ocean zonally averaged annual temperature anomalies at 400 m depth for 1948-1998. Contour interval is 0.2°C with negative values shaded.

ocean shift. A shift back to a relatively cool state occurred during the early 1980s and then perhaps a shift back to a relatively warm state occurred in the late 1980s.

Conclusions

Multivariate analysis of the Pacific Ocean heat content integrated through 125 m depth for the period 1948-1998 indicates the atmospheric regime shift in sea level pressure that occurred in the mid-1970s has a Pacific basin-wide upper ocean counterpart as evidenced by changes in the subsurface ocean temperature structure. Based on our results it has been approximately 28 years since the shift occurred and there is no evidence of a return to pre-1975 conditions as of 1998. High frequency modes of variability similar to the large decadal shift in the 1970s are observed throughout the period. Shifts in temperature occur at 400 m depth but these may or may not be related to the upper ocean regime shift. Finally, the variability of yearly Pacific Ocean heat content described by *Levitus et al.* [2000] exhibits variability that is not consistent with a simple regime shift in the mid-1970s. Hence, causes other than the regime shift must account for the variability in the integrated Pacific Ocean heat content.

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