Recent shifts in the state of the North Pacific

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[1] The winters of 1999–2002 for the North Pacific were characterized by spatial patterns in sea level pressure anomaly (SLPA) and sea surface temperature anomaly (SSTA) with little resemblance to those of the leading pattern of North Pacific climate variability, the Pacific Decadal Oscillation (PDO). In essence, the southeastern (northern) portion of the North Pacific was subject to atmospheric forcing characteristic of that before (after) the major regime shift of 1976–77. Recent major changes in the ecosystems off the west coast of the United States and continued conditions similar to those of the early 1990s in the Gulf of Alaska, Bering Sea, and Sea of Okhotsk are consistent with these SLPA and SSTA patterns. Our result illustrates that a single indicator such as the PDO is incomplete in characterizing North Pacific climate. *INDEX TERMS:* 1635 Global Change: Oceans (4203); 1610 Global Change: Atmosphere (0315, 0325); 4215 Oceanography: General: Climate and interannual variability (3309); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504). **Citation:** Bond, N. A., J. E. Overland, M. Spillane, and P. Stabeno, Recent shifts in the state of the North Pacific, *Geophys. Res. Lett.*, *30*(23), 2183, doi:10.1029/2003GL018597, 2003.

1. Introduction

[2] The objective of this note is to critically assess the state of the North Pacific over the previous 5 years (1999–2003) in the context of the historical record beginning in 1950. The Pacific Decadal Oscillation (PDO) has served as a model of North Pacific climate variability on multidecadal scales in the 20th century. It is well recognized that there were major atmospheric, oceanographic, and ecological changes near 1976/77, with a shift from the "negative" to the "positive" phase of the PDO. Recent discussion is often centered on whether such a shift, with a return to PDO negative conditions, occurred in 1999 [*Greene*, 2002; *Minobe*, 2002; *Chavez et al.*, 2003; *Peterson and Schwing*, 2003]. We offer an alternative hypothesis that recent conditions in the North Pacific do not lie on a continuum between PDO+ and PDO− states, but manifested as different spatial patterns in sea level pressure (SLP) and sea surface temperature (SST).

2. Comparison of Recent SLP and SST Anomaly Fields to the 1970s Regime Shift

[3] It is instructive to compare SLP and SST anomalies for the recent five winters (November–March) of 1999–2003 with their counterparts prior (1972–1976) and following (1977–1981) the last major shift of the PDO. Winter seasons are labeled for the year corresponding to January. Our analyses are based on the NCEP/NCAR Reanalysis as made available by the Climate Diagnostic Center (www.cdc.noaa.gov) and the SST fields of *Rayner et al.* [2003].

[4] The SLP and SST anomalies (hereafter SLPA and SSTA) for the mean of four winters (November–March) of 1999 through 2002 are shown in Figure 1. The primary feature in the SLPA field (Figure 1a) is a NNW-SSE oriented dipole in the eastern Pacific with lower pressure in the north, implying strong westerly wind anomalies across 45°N. The corresponding SSTA pattern (Figure 1b) consists of a cold anomaly extending from off California across the Pacific to the western Bering Sea and Sea of Okhotsk in the far northwest Pacific, with a prominent warm anomaly south of 40°N extending from the coast of Asia to about 150°W. All four years individually support these two patterns; maps for individual years are available over the web at http://www.cdc.noaa.gov/cgi-bin/PublicData/getpage.pl.

[5] In contrast, the five winters before the regime shift (1972 through 1976) tended to have anomalously high SLP in a NW-SE oriented strip extending from far eastern Siberia to off the coast of California (Figure 2a), and anomalously warm SST in the central North Pacific, especially north of Hawaii, with cold anomalies along the entire west coast of North America (Figure 2b). Similar patterns, but in an opposite sense, occurred in the five winters (1977 through 1981) after the shift (Figures 3a and 3b). Essentially, these two 5-year periods characterize canonical examples of the negative and positive phases of the PDO.

[6] The winter of 2003 is considered separately from those of 1999–2002 because of the probable impacts of the El Niño of 2002–03. The SLPA for the winter of 2003 (Figure 4a) was dominated by a single negative center south of Alaska; the SSTA (Figure 4b) featured a three-pole pattern (warm in the SW and NE, and cold in the central North Pacific). It remains to be seen whether this winter represents a temporary response to El Niño or long-lasting return of warmer SST along the west coast of North America.

[7] Tight coupling between the atmosphere and ocean is seen in all four sets of maps. In general, cold (warm) SST anomalies are co-located with anomalous north through west (south through east) winds. Different forcings can yield similar SST signals in particular locations. For example the SST was cold off the west coast of North America both before the regime shift (Figure 2b) and from 1999 through 2002 (Figure 1b), but in the first case SSTA were associated with anomalous northerlies and hence cold air accompanying a weak Aleutian low, and in the second case in association with enhanced west winds and presumably greater mixing of cold water from depth. On a basin-wide basis, the winter mean SLP and SST fields for the recent 4-year period 1999–2002 as a whole resemble neither the period before nor after the

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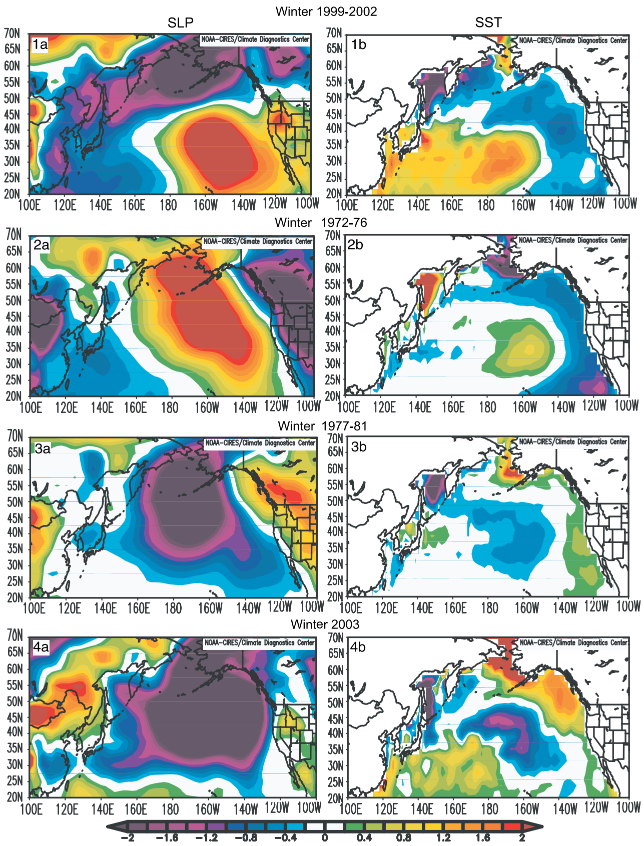

Figures 1–4. Spatial anomaly fields of (a) SLP and (b) SST for winter (November–March) covering 1999–2002, 1972–1976, 1977–1981, and 2003.

1976/77 regime shift. Our interpretation is that climate variations other than those strictly associated with the PDO characterize the recent state of the North Pacific.

[8] The north/south dipole nature of the recent SLP fields accounts for much of the recent trends in coastal conditions. For example, the high SLPA off of the coast of California (Figure 1a) is similar to the high SLPA for the period before the 1976/77 regime shift (Figure 2a). Both periods have cold SSTA along this coast. Thus the report of major changes after 1998 in the oceanography and biology of this region [*Peterson and Schwing*, 2003] is entirely consistent with the local SLP field, despite the fact that the Pacific-wide SLP fields substantially differ in detail. The recent SLPA field (Figure 1a) also explains conditions in northern waters. The late 1990s show a continuation of low SLPA centered near 55°N from earlier in the decade, which is also consistent with the SLPA for the local region after the 1976/77 regime shift. Thus the Bering Sea shows a continuing tendency after the turn of the century for reduced sea ice extents and early ice retreats. Likewise temperatures in the Sea of Okhotsk remain cold throughout the decade (Figure 1b). Also of interest are the warm SSTA across the western Pacific south of 40°N (Figure 1b) which are not present before or after the regime shift (Figures 2b and 3b).

3. PCA of the Winter North Pacific

[9] Further characterization of the state of the North Pacific can be made based on Principal Component Analysis (PCA) decomposition of the winter SSTA. The first two principal components (PC) and corresponding EOFs for the winter (November–March) SSTA fields north of 20°N with a base period 1950–2003 are shown in Figure 5. Data are SSTA on a 5 × 5 degree grid from the Hadley Centre of the UK Meteorological Office (www.cru.uea.ac.uk). The percent variance explained by the first six modes are 28.2, 15.3, 9.3, 7.3, 5.4, 5.2; thus there is some separation in the amount of variance explained between modes 1 and 2, and between modes 2 and 3. Note that the structure of EOF1 closely resembles the SSTA patterns before and after the shift of 1976–77 (Figures 2b and 3b). PC1 essentially tracks the PDO, as defined by *Mantua et al.* [1997], with large autocorrelation in the periods before and after the 1976/77 regime shift. The correlation between PC1 and the Mantua PDO series (www.jisao.washington.edu/pdo) is 0.95. The amplitude of PC1 after 1998 is generally small except for 2000 and 2003. While the PDO or PC1 exhibits considerable variability on decadal scales, large and systematic shifts can occur rapidly, as in 1957 and 1976. The amplitude of PC2 was relatively large from the 1950s through the early 1960s, generally small for the next two decades, and then substantial from the mid-1980s to the present.

[10] The structure of EOF2 is similar to the SSTA field for the recent years (Figure 1a). Thus the recent SSTA

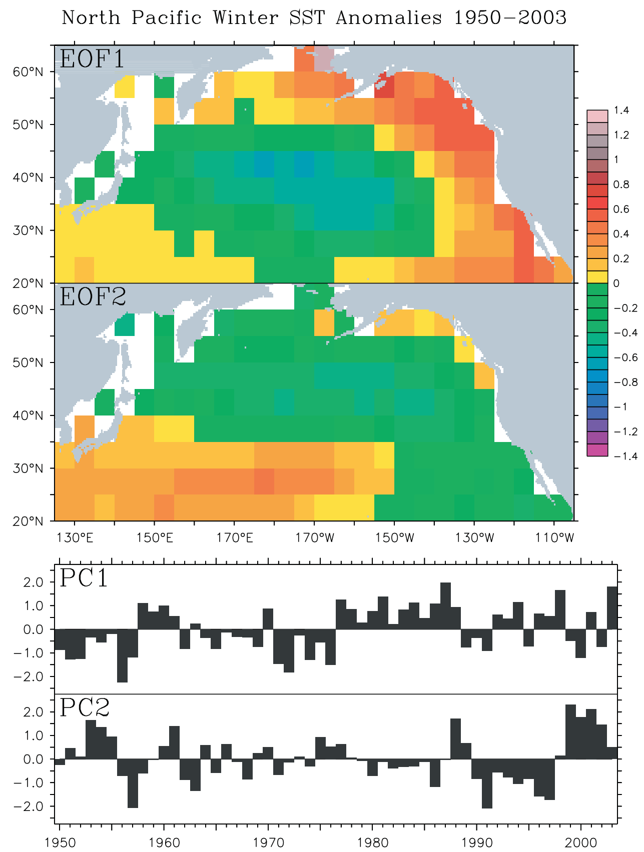

Figure 5. Principal Component Analysis of North Pacific winter (November–March) SST fields north of 20°. The first EOF (top) corresponds to the PDO pattern and its time evolution is given by PC1. The evolution of the second EOF pattern shows large magnitudes since the 1990s with a shift to large positive values for 1999–2002.

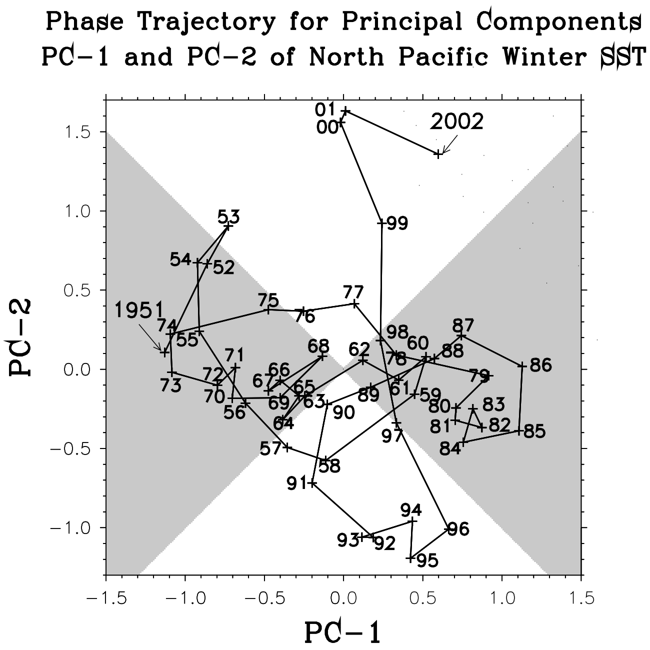

Figure 6. Trajectory of the state of North Pacific SSTA in the phase space of the first two principal components, PC1 (abscissa) and PC2 (ordinate). Labels showing years represent 5-year running means except at endpoints, which represent 3-year running means.

pattern is nearly orthogonal to the standard PDO SSTA pattern; it is not consistent to consider this recent period as being on the continuum of states between PDO+ and PDO−. In fact, the strongest shift in recent years is a strongly negative phase of PC2 in the 1990s followed by a positive phase beginning in 1999.

[11] A complementary perspective on the time evolution of SSTA in the North Pacific is provided by Figure 6. The trajectory of the system in the phase space of PC1 and PC2 (using 5-year running means) demonstrates the dominance of PC1 up until the end of the 1980s, followed by the dominance of PC2 since the early 1990s. The end of the dominance of the PC1 pattern roughly coincides with the 1989 shift examined by *Hare and Mantua* [2000]. The primary change in the late 1990s was a shift from negative to positive in the phase of PC2.

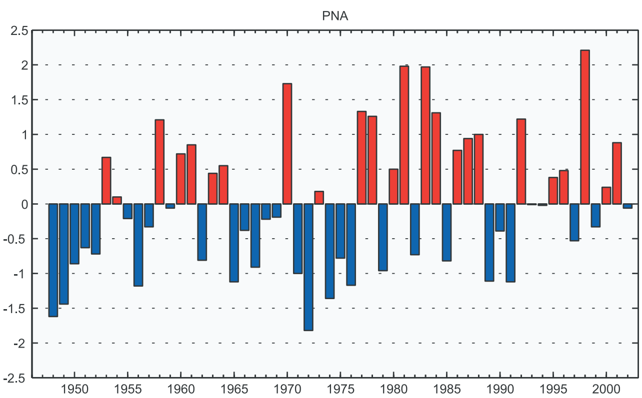

Figure 7. The time series of the Pacific North American (PNA) teleconnection pattern for 500 hPa [*Wallace and Gutzler*, 1981]. Amplitudes have been normalized by the standard deviation. The PNA was small |<0.4| for three of the four years: 1999–2002.

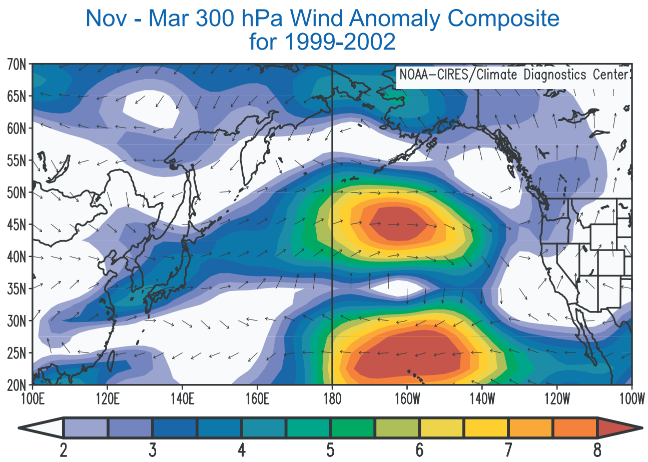

Figure 8. 300 hPa wind anomalies for 1999–2002. Note stronger magnitudes of westerlies in the eastern North Pacific along 45°N.

4. Meteorological Interpretation of Recent North Pacific Forcing

[12] The PDO based on SSTA is associated with the strength of the Aleutian low at the surface and the Pacific North American (PNA) pattern in the troposphere [*Wallace et al.*, 1992]. Based on the 500 hPa definition of *Wallace and Gutzler* [1981], the PNA had small magnitude and inconsistent sign during 1999–2002 (Figure 7). All values were less than 0.4 standard deviation units except for 2001. The 300 hPa wind anomalies for the winter mean (November–March) 4-year period (1999–2002) are shown in Figure 8. This pattern shows the presence of an anomalously strong westerly jet at 45°N in the eastern North Pacific; this pattern of anomalous winds is different from the patterns associated with the positive or negative PNA, El Niño, or La Niña.

[13] The lack of a consistent sense to the PDO since 1998 can be attributed, at least in part, to the concurrent fluctuations in El Niño/Southern Oscillation (ENSO). As discussed by *Newman et al.* [2003] among others, ENSO impacts the PDO through the former's influences on the atmospheric circulation and ultimately air-sea interactions in the North Pacific. The transition from the very strong El Niño in the winter of 1998 to the moderate La Niña of 1999 continuing into 2000 is presumed to be at least partially responsible for the PDO changing from positive in 1998 to slightly negative in 1999 and then somewhat more negative in 2000. The following two winters were ENSO-neutral and the PDO was first slightly positive and then slightly negative. Finally, the winter of 2003 featured a moderate El Niño and the response included a significantly positive phase for the PDO.

5. Conclusion

[14] All four years for the recent period of 1999–2002 had SLPA and SSTA patterns different than those associated with before or after the regime shift of 1976/77. Based on PCA,

the pattern of SSTA for the winters of 1999–2002 is nearly orthogonal to that for the leading mode of variability, the PDO. Instead, the SSTA for this period projects strongly positive on the second mode, EOF2. In addition, the upper-tropospheric winds across the North Pacific for 1999–2002 featured strong westerly anomalies at 45°N, unlike those accompanying either phase of the PDO. The PDO was significantly positive during the winter of 2003; it is uncertain whether this is just a temporary condition due to the moderate El Niño of 2003 or the beginning of a sustained positive PDO state.

[15] The recent manifestations of a north/south dipole in SLPA has allowed the Gulf of Alaska and Bering Sea to continue to experience atmospheric forcing characteristic of that after the regime shift of 1976/77, while the portion of the North Pacific south of 40°N and east of the dateline has resembled the forcing before the regime shift. The marine ecosystem of the North Pacific has responded with major changes along the west coast of the United States with increased productivity and the return of sub-Arctic species [e.g., *Peterson and Schwing*, 2003], while oceanographic conditions in the Gulf of Alaska, Bering Sea, and Sea of Okhotsk have remained in a state associated with an anomalously strong Aleutian low.

[16] The development in recent years of a north/south dipole SLPA and a PC2-type SSTA pattern contrasts with the PNA/PDO type variability that dominated much of the 20th century. The limitations of the PDO paradigm are consistent with the concept that indicators of the North Pacific climate system appear fundamentally stochastic [*Percival et al.*, 2001], and the potential predictability of the North Pacific climate system on multi-year time scales is small.

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