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A new climate regime in northeast pacific ecosystems

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[1] Following a strong El Niño, the climate of the North Pacific underwent a rapid and striking transition in late 1998. Upwelling-favorable winds strengthened over the California Current (CC), and winds weakened in the Gulf of Alaska (GOA). Coastal waters of the CC and GOA cooled by several degrees, and the Pacific Decadal Oscillation (PDO) reversed sign and remained negative through summer 2002. Zooplankton biomass in the northern CC doubled and switched from warm to cold water species dominance, coho and chinook salmon stocks rebounded, and anchovy and osmeriids increased. Persistent changes in atmosphere and upper ocean fields and ecosystem structure suggest a climate regime shift has occurred, similar (opposite) to shifts observed in 1947 (1925 and 1976). If the 1998 regime shift in the northern CC is completely analogous to earlier shifts, then ecosystem structure should have changed in the GOA. Recent surveys indicate this ecosystem has transformed as well. *INDEX TERMS:* 1635 Global Change: Oceans (4203); 4516 Oceanography: Physical: Eastern boundary currents; 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics; 4215 Oceanography: General: Climate and interannual variability (3309); 4855 Oceanography: Biological and Chemical: Plankton. **Citation:** Peterson, W. T., and F. B. Schwing, A new climate regime in northeast pacific ecosystems, *Geophys. Res. Lett.*, *30*(17), 1896, doi:10.1029/2003GL017528, 2003.

1. Introduction

[2] It is well recognized that the global atmosphere and oceans vary on *interannual* time scales due to the El Niño-Southern Oscillation (ENSO). Through processes related to ENSO, the North Pacific experiences perturbations in its physical state [*Lynn and Bograd*, 2002; *Schwing et al.*, 2002], which are often manifested as ecological changes [*Pearcy and Schoener*, 1987; *Peterson et al.*, 2002]. More recently it has been recognized that these systems also fluctuate on *multidecadal* scales. In the North Pacific, these fluctuations are illustrated by shifts in the strength and position of the Aleutian low pressure system [*Trenberth and Hurrell*, 1994], and large-scale changes in wind patterns, ocean temperatures, and biological productivity [*Mantua et al.*, 1997].

[3] The California Current (CC) and Gulf of Alaska (GOA) ecosystems alternate between anomalous warm and cool states, also known as regimes [*Hollowed and Wooster*, 1992]. The shift toward a warm regime in the 1970s is the best documented [*Trenberth and Hurrell*, 1994; *Mantua et al.*, 1997; *Hare and Mantua*, 2000; *Parrish et al.*, 2000; *Mendelssohn et al.*, 2003]. Since then, zooplankton biomass doubled in the GOA [*Brodeur and Ware*, 1992] and salmon survival increased dramatically [*Francis and Hare*, 1994; *Mantua et al.*, 1997], whereas in the CC zooplankton biomass declined seven-fold [*Roemmich and McGowan*, 1995] and salmonid survival and production declined precipitously [*Pearcy*, 1992]. During the same period, sardine populations expanded into the northern CC [*McFarlane and Beamish*, 2001], a phenomenon not seen since the previous warm regime of ca. 1925–1946.

[4] *Schwing and Moore* [2000] and *Schwing et al.* [2000] suggested that a cool regime in the Northeast Pacific (NEP) began in late 1998. The previous shift to a cool regime in the 1940s coincided with the collapse of the California sardine fishery and an increase in salmon catch in the northern CC [*Mantua et al.*, 1997]. We suggest that the recent climate regime has resulted in changes in ecosystem structure and productivity in the CC and GOA. Here we discuss recent atmospheric and physical oceanographic conditions and highlight some responses of coastal marine ecosystems in the northern CC to the hypothesized regime shift.

2. Methods

[5] Large-scale anomalies (base period 1968–96) in sea surface temperature (SST), 850-hPa (ca. 1000 m) wind velocity, and atmospheric sea level pressure from the National Centers for Environmental Prediction (NCEP) reanalysis fields [*Kistler et al.*, 2001] are presented. The fields were gridded (roughly $2^\circ \times 2^\circ$) as monthly anomaly fields and summarized for winter (November–February). Composite anomalies are compared for periods when the Pacific Decadal Oscillation (PDO) index of North Pacific SST [*Mantua et al.*, 1997] was in its cool (negative, 1970–1976, 1999–2003) and warm (positive, 1977–1983) phase. PDO values are summed annually for the upwelling season (May–September), to match the zooplankton sampling period.

[6] Zooplankton samples were taken at a hydrographic station five miles off Newport, OR. The station was visited ~250 times in 16 years (1969–1973, 1983, 1990–1992, 1996–2002). *Peterson et al.* [2002], and *Mackas et al.* [2003] give details of sample analysis. Annual anomalies are summed for all cruises within the upwelling season (May–September, always >10 cruises), for three "cold water" copepod species, *Pseudocalanus mimus*, *Acartia longiremis*, and *Calanus marshallae.* These species dominate the Bering Sea shelf, coastal GOA, British Columbia coastal waters, and the Washington-Oregon coastal upwelling zone during summer, and serve as an index of ecosys-

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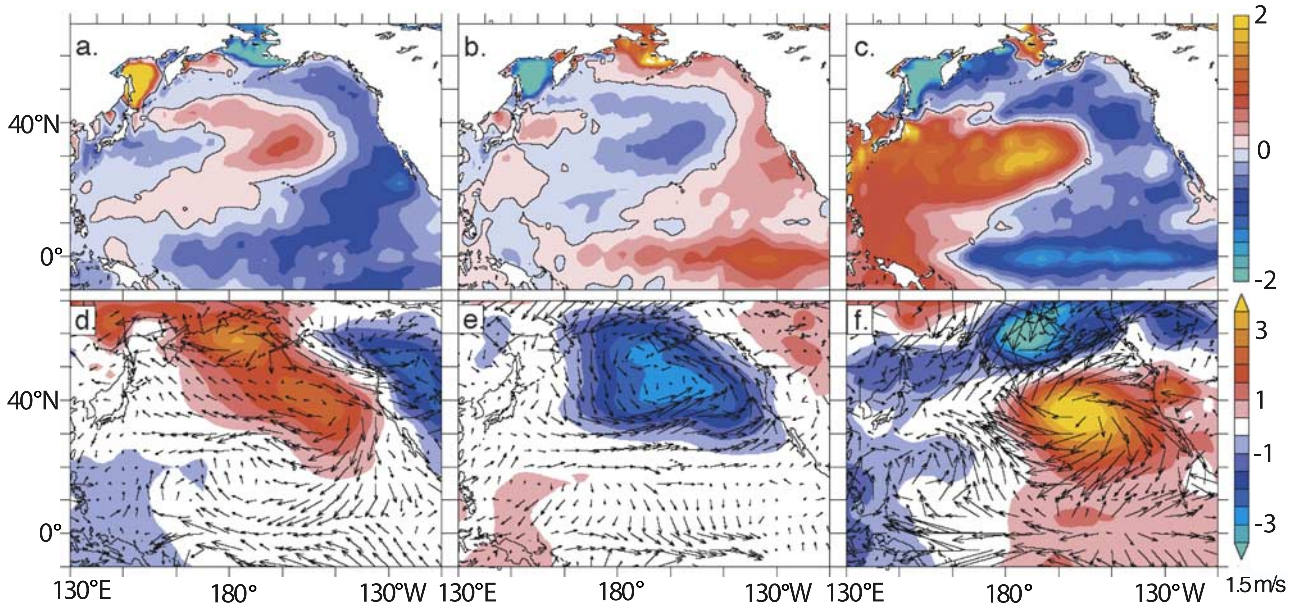

Figure 1. Sea surface temperature (SST) anomalies averaged over November–February from (a) 1970–1976 (b), 1977–1983, and (c) 1999–2003. The first and third periods are during the cool phase of the Pacific Decadal Oscillation (PDO) while the second period is during the warm phase. Anomalies of sea level pressure (colored regions) and winds for the same periods (d,e,f). Strong cyclonic circulation is seen during 1977–1983 (warm phase of PDO) and weak circulation during the cool phase.

tem structure under differing ocean regimes. Annually averaged CalCOFI zooplankton volumes for the California Current region are from the CalCOFI web page. Coho salmon survival data are from *Logerwell et al.* [2003].

3. Results

[7] The transformation in the NEP from the 1997–1998 El Niño to the 1998–1999 La Niña was rapid and strong [*Schwing and Moore*, 2000; *Schwing et al.*, 2002]. By the latter half of 1998, atmospheric and oceanic conditions in the North Pacific clearly exhibited a negative PDO pattern [cf. *Mantua et al.*, 1997]. An unseasonably strong North Pacific High developed, leading to vigorous anticyclonic winds and anomalously strong coastal upwelling-favorable (southward) winds in the CC (Figure 1f). This pattern continued from 1999 through 2002.

[8] Higher than normal SSTs extended from Asia to north of Hawaii, and cooler than normal SSTs stretched across the tropical North Pacific and along the North American west coast into the GOA (Figure 1c). The anomalous winds and SST in the North Pacific since late 1998 are similar to those during years prior to the regime shift in the 1970s (Figures 1a and 1d), and opposite those afterward (Figures 1b and 1e). We speculate that the 2002–2003 moderate El Niño may have weakened this pattern, although warm SST anomalies in the NEP seem to be waning.

[9] The PDO index (Figure 2) was negative for most years during 1948–1976, and positive during 1977–1998. It has been negative for four continuous years since 1998, suggesting that another regime shift may have occurred. The PDO index was not negative (positive) for more than two consecutive years within the previous positive (negative) phase.

[10] The biomass of cold water copepod species is anomalously high during the negative PDO regime (i.e.,

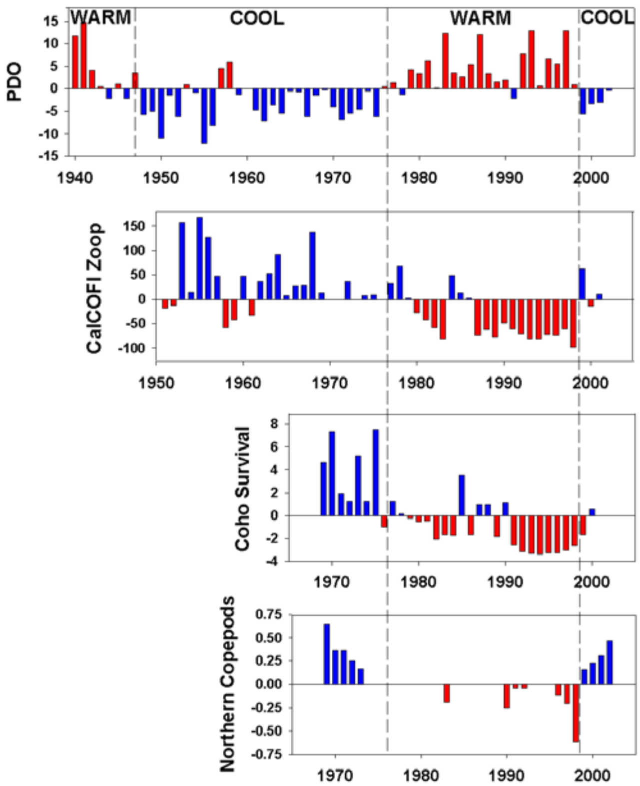

Figure 2. Time series of (a) the PDO index summed annually over May–September (highly correlated with annual averages, R^2 = 0.92); (b) annual anomalies of CalCOFI zooplankton volumes from the California Current region, (c) coho salmon survival, and (d) biomass anomalies of cold-water copepod species. Positive (Negative) PDO index indicates warmer (cooler) than normal temperatures in coastal waters off North America, and vice versa.

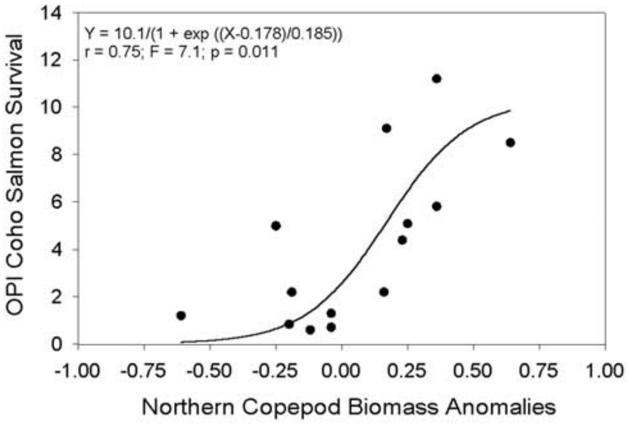

Figure 3. Relationship between coho salmon survival and biomass anomalies for three cold water (northern) copepod species *Pseudocalanus mimus*, *Acartia longiremis*, and *Calanus marshallae*.

1969–1973, 1999–2002), and low when the PDO index is positive (1983, 1990–1992, 1996–1998). The PDO index is highly correlated with cold water copepod species anomalies off Oregon as well as CalCOFI zooplankton volumes off Southern California (Figures 2b and 2d), indicating changes in the ecosystem beginning in 1999. Total copepod biomass off Oregon is significantly higher during cool regimes as well. The average biomass during 1969–1973 was 20.3 ± 3.04 (95% c.i.) mg carbon m^{-3} vs. 9.7 ± 2.89 mg carbon m^{-3} for 1996–1998. Biomass remained low in 1999 (11.0 mg carbon m^{-3}) but doubled after 1999, averaging 19.2 ± 4.47 mg carbon m^{-3} during 2000–2002.

[11] Pelagic fish abundance has also changed. The number of adult chinook salmon returning to the Columbia River system since 1999 has reached levels not seen since the 1950s. Striking changes have also been seen in the ocean survival rate of coho. From 1960–1976, survival ranged from 5–12% [*Logerwell et al.*, 2003]. During the warm phase (1977–1998), survival was much more variable and plummeted to <2% in the 1980s, and <1% in the 1990s. In 1999 the coho salmon populations began to rebound. Returns increased five-fold to 2% in 1999, and to 4% in 2000. Coho survival rates are positively correlated with the copepod biomass anomalies (Figures 2c, 2d, and 3), suggesting a link between salmon, zooplankton, and climate variability reflected by the PDO index.

4. Discussion

[12] The transition between the strong El Niño event in 1997–1998 and the 1998–1999 La Niña was possibly the most dramatic and rapid episode of climate change in modern times [*Schwing et al.*, 2002]. Mean summer ocean temperatures at 50 m off Oregon decreased by 1°C beginning in 1999, while salinity increased by 0.15. Temperatures at some locations off California fell by nearly 10°C between 1998 and 1999 [*Schwing and Moore*, 2000; *Schwing et al.*, 2000]. Coastal sea levels were the lowest in at least 65 years. These changes imply a shift to stronger coastal upwelling and greater than normal southward transport in the CC.

[13] The SST anomaly pattern since 1999 is similar to that seen throughout the North Pacific before the 1976 regime shift [Figure 1; cf. *Mantua et al.*, 1997; *Parrish et al.*, 2000; *Minobe*, 1999]. Based on the persistence of these temperature patterns and related atmospheric and upper ocean fields, we suggest that a regime shift occurred in mid-1998 that has produced striking physical and ecological anomalies in the NEP, such as the development of a cold water copepod community. Several recent studies suggested that this shift was imminent [cf. *Ingraham et al.*, 1998; *Minobe*, 1999].

[14] Changes similar to those observed off Newport have been seen elsewhere. *Mackas et al.* [2001, 2003] show that the copepod community off Vancouver Island during the 1990–1998 warm regime included an anomalously low biomass of cold water species (the same species as reported here), but since 1999 the cold water species have had an anomalously high biomass. Off both Vancouver Island and central Oregon, euphausiid populations have increased during the recent cold regime [*Mackas et al.*, 2001; *Feinberg and Peterson*, 2003]. Since 1998, phytoplankton and zooplankton biomass have doubled off central California [*Chavez et al.*, 2003]. Zooplankton biomass off southern California has increased to values not seen regularly since the 1970s (Figure 2b).

[15] Increased abundances off Oregon and Washington of warm water fish species such as hake (*Merluccius productus*), mackerel (*Scomber japonicus*, *Trachyurus symetricus*), and sardine (*Sardinops sagax*) occurred during the 1977–1998 warm regime, while cold water fish such as anchovy (*Engraulis mordax*) and smelts (Osmeriidae) declined over the same period [*Emmett and Brodeur*, 2000; *Greene*, 2002]. In southern British Columbia waters, these same warm water fish species became abundant, particularly after 1991 [*McFarlane and Beamish*, 2001]. Recent sampling of pelagic fishes off Oregon and Washington has found that sardines have declined, and anchovies and osmeriids have increased by an order of magnitude [*Emmett*, 2002]. The latter are a primary food source for adult chinook and coho salmon.

[16] Other biological changes in the CC at several trophic levels are listed in *Schwing and Moore* [2000] and *Schwing et al.* [2000]. The compilation of observations indicates a shift in 1998 from a warm, low production regime to a cool, highly productive regime. Increased advection of coastal waters out of the GOA would transport cold water species into the northern CC. Stronger upwelling [*Schwing et al.*, 2000] would increase productivity locally. Thus, the biomass of copepods and other zooplankton could be elevated through local production as well as through increased advection from the north. Both processes are favorable for the development and maintenance of all cold water species, including zooplankton, anchovy and osmeriid stocks, and salmonids.

[17] The pattern of past shifts (e.g., 1977) suggests that changes in ecosystem production and structure in coastal CC and GOA ecosystems are coupled but out of phase [*Mantua et al.*, 1997]. GOA zooplankton since 1999 may be transitioning to cold water species, and to a much lower abundance [*Batten and Welch*, 2003]. Pandalid shrimp and lower trophic level fish are apparently returning to dominance in portions of the GOA [*Anderson*, 2003], a status

they held prior to the 1970s, while salmon, cod, and other higher trophic fish appear to be declining. These observations support the idea that a regime shift has changed ecosystem production and structure throughout the NEP. Simultaneous regime shifts in pelagic fisheries have occurred previously [*Schwartzlose et al.*, 1999; *Chavez et al.*, 2003]. Continuing biological surveys are necessary to confirm this idea.

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