

Patterns and Mechanisms for Climate Change in the North Pacific: The Wind Did It

Franklin B. Schwing

Pacific Fisheries Environmental Laboratory, Southwest Fisheries Science Center, NOAA NMFS, Pacific Grove, CA

Abstract. The observed changes in atmospheric pressure and the associated wind stress field over the North Pacific following the 1976 climate shift appear to have had major effects on conditions in the underlying ocean. The Kurishio Extension, North Pacific Current, and most of the central water mass regions became cooler whereas the California Current, Alaska Current and the westward flow regions of the Alaska Stream were warmer after 1976. The large-scale atmospheric changes had a significant impact on the wintertime circulation of the North Pacific as well. At mid-latitudes, the increase in zonal wind stress led to (1) a doubling of southward Ekman transport; (2) a 3-4-fold increase in upwelling due to Ekman pumping; (3) 30% more turbulent mixing; (4) a 7-fold rise in poleward Sverdrup transport, and (5) a doubling in zonal Sverdrup transport. The North Pacific Current increased by 10 Sv (1 Sv = 10^6 m³/s); southward transport in the subtropical gyre increased by 18 Sv. All of these modifications are consistent with cooler SSTs observed in the central North Pacific and are likely to be associated with a significant change in the advection and distribution of heat, nutrients, and organic material throughout the basin. The geostrophic adjustment to the convergent poleward Sverdrup transport created a westward return flow in the subarctic gyre, which would alter the inflow of heat and material into the Kurishio/Oyashio Current complex. After 1976, the Gulf of Alaska experienced less export in the surface Ekman layer and a broader transport into the Gulf compared to the narrow coastal current prior to 1976. While the California Current appears to have featured less upwelling and mixing, the difference in transport into and through the system before and after this climate shift was insignificant.

1. Introduction

“We cannot control the seas, but we can steer the boat.” This Hawaiian adage applies to climate change and its effects. Interannual to decadal variability in the environment is associated with natural “cycles” (not necessarily periodic) in the atmosphere and oceans. It is important to understand what mechanisms drive these variations and how they trigger responses at the ecosystem level. From this, we can consider ways to mitigate the socioeconomic effects of climate change. Climatic fluctuations on decadal time scales have been linked to ecosystem perturbations that affect the major exploited fish stocks in the mid-latitude North Pacific [Brodeur and Ware, 1992; Hollowed and Wooster, 1992; Lluch-Belda *et al.*, 1992; Beamish, 1993; Francis and Hare, 1994; Polovina *et al.*, 1994; Mantua *et al.*, 1997]. An improved ability to forecast “regime shifts,” or merely to recognize recent shifts in the environment, will allow resource managers to adjust commercial fishing quotas, as well as enable the industry to prevent overcapitalizing on a reduced fishery.

There is much to learn about the scales of climate variability and the physical mechanisms that lead to climate change. Because much of this variability occurs on decadal time scales, we do not have the luxury of documenting it with long-term field studies. A more satisfying alternative is to interpret the large data base of historical measurements. Thoughtful retrospective analysis of these data allows us to describe past changes in the environment, develop hypotheses about what led to these observed changes, and serve as forcing fields for numerical models that can more fully tell us

what conditions were prevalent in past climate regimes. From reconstructions of past environmental conditions, we can relate known fluctuations in marine populations, specifically changes in commercial fishing yields, to the physical parameters and processes most likely to have impacted them on the ecosystem level.

The best known example of decadal climate change is the 1976 shift documented by Nitta and Yamada [1989], Trenberth [1990], Graham [1994], Trenberth and Hurrell [1994], and others. This shift is associated with variations in 40 environmental quantities [Ebbesmeyer *et al.*, 1991]. Its most obvious signal in the North Pacific Ocean was a substantial redistribution of thermal energy in the upper ocean (Figure 1). The central part of the basin, including the Kurishio Extension and North Pacific Current, became relatively cooler. The eastern and northern extent of the North Pacific, incorporating the California Current, Gulf of Alaska, and Bering Sea, warmed after 1976.

Sea surface temperature (SST) is the most accessible ocean parameter available in the historical record. Another relatively available quantity, wind velocity, displays considerable change on decadal scales. Other critical observations, including current velocity, mixed layer depth, and subsurface temperature and salinity, are less common, but fluctuations in these are likely to be more closely coupled to biological variability. Wind measurements are very useful for explaining less completely known circulation fields, by using straightforward fluid dynamical theory to derive lateral and vertical currents. In this paper, we estimate the changes in wind-forced ocean transport in the decade following the 1976 cli-

mate shift. Knowing the response of ocean circulation to climate change is important because of its role in advecting and redistributing heat, salt, and buoyancy, nutrients, plants and animals, including many fish and their prey, and in generating new patterns and features (e.g., eddies, fronts) that alter fish habitats. Decadal environmental changes may also be a reasonable model for future climate changes due to anthropogenic influences.

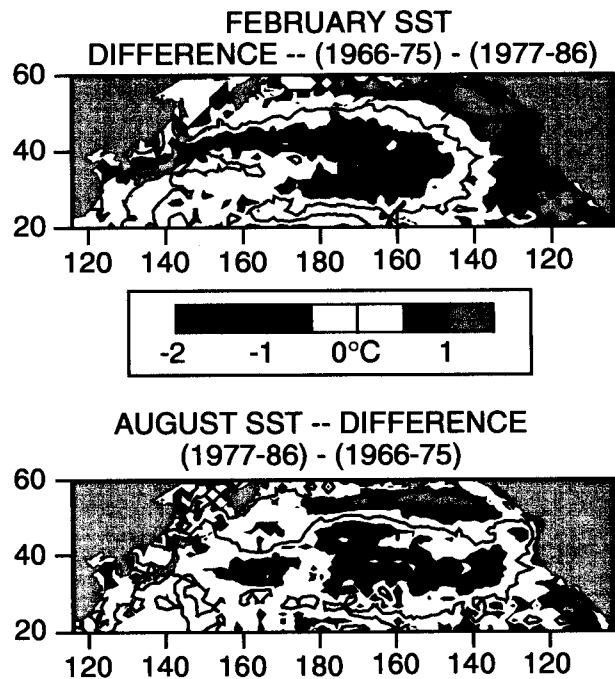


Figure 1. Difference in SST between averaged fields for two decades (1977-86 less 1966-75), for winter (Dec.-Feb.) and summer (June-Aug.). Contour interval is 0.5°C . Bold contour denotes zero anomaly. Light (dark) shades denotes greater than 0.5°C (less than -0.5°C) anomalies.

2. Background

Ocean-atmosphere coupled models [Latif and Barnett, 1994, 1996] suggest that decadal climate variability over the North Pacific is associated with varying rates and distributions of air-sea heat flux and stress driven by interactions between subtropical ocean circulation in the North Pacific and the Aleutian Low-pressure system, and is greatest at mid-latitudes. The deepening and eastward displacement of the winter Aleutian Low that commenced in 1976 led to stronger zonal winds over the central North Pacific and a cyclonic rotation of wind stress to a more poleward direction in the Gulf of Alaska [Deser et al., 1996; Parrish, 1997; Yasuda and Hanawa, 1997] (Figure 2).

The central North Pacific subsequently cooled by a degree and more at the surface, while increasing by a similar amount along the North American coast and in the Gulf of Alaska (Figure 1). Decadal temperature anomalies were evident to at least 400 m, and were strongest below the influence of inter-annual variability (150 m and greater) [Deser et al., 1996; Zhang and Levitus, 1997]. Model [Miller et al., 1994] and

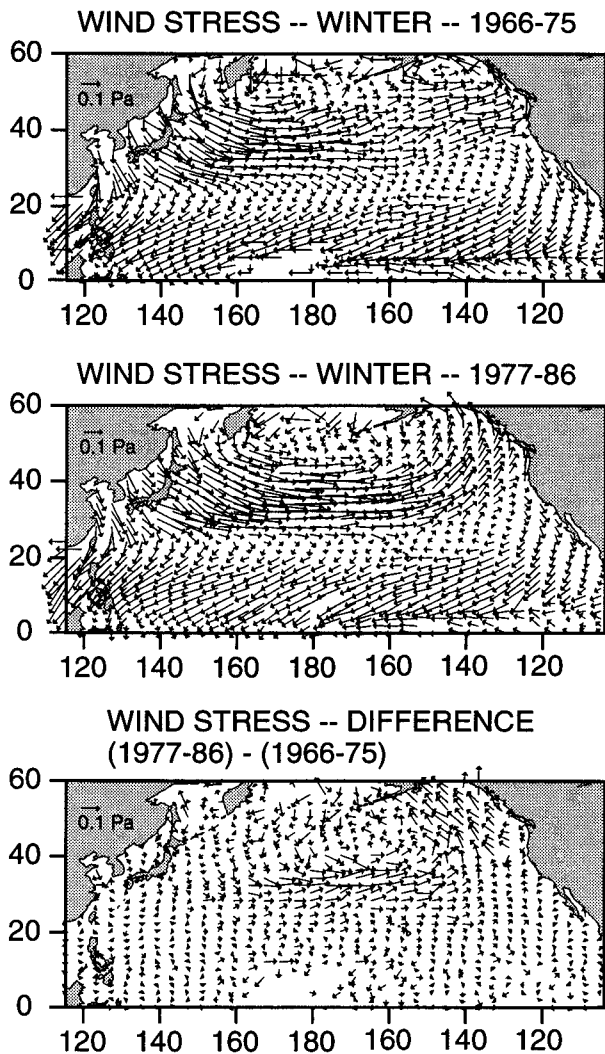


Figure 2. Winter wind stress vector fields for two decades (1966-75 and 1977-86) and their difference. Scaling vector shown in upper left of each panel.

observational [Polovina et al., 1995; Deser et al., 1996] studies indicate a 20 m and more shoaling of the mixed layer depth (MLD) in the subarctic gyre after 1976, and a simultaneous deepening in the subtropical gyre by a similar amount.

SST anomalies in the North Pacific are connected to heat flux anomalies, which in turn are controlled by large-scale atmospheric circulation anomalies [Cayan, 1992; Miller et al., 1994; Yasuda and Hanawa, 1997]. However many ocean circulation quantities (e.g., Ekman divergence, vertical mixing, Sverdrup transport) appear to have changed in a way that contributed to the shift to cooler SSTs in the central North Pacific after 1976 [Haney, 1980; Miller et al., 1994; Yasuda and Hanawa, 1997]. Latif and Barnett [1994, 1996] suggest that heat anomalies rotate anticyclonically around the North Pacific on a ~ 20 -year period and that a substantial portion of the variability in ocean temperature is due to coupling between the subtropical gyre and Aleutian Low. Others [Trenberth, 1990; Graham, 1994; Trenberth and Hurrell, 1994] believe atmospheric teleconnections between the tropics and midlatitudes were the cause of the shift in the Aleutian Low

beginning in 1976. Transports in the gyres themselves are likely to fluctuate on decadal scales as well [Trenberth *et al.*, 1990; Yasuda and Hanawa, 1997]. The subject of heat transport on decadal scales is addressed further by Miller *et al.* [1998] and Schneider *et al.* [1998].

Chelton and Davis [1982] were among the first to show that basin-wide rather than local aspects of wind dynamics are responsible for interannual fluctuations in the California Current System (CCS). Since coastal sea level fluctuates in phase along the entire west coast, geostrophic transports must be out of phase in the Alaska and subtropical gyres. They theorize that during periods of anomalously high (low) coastal sea level, relatively more flow enters the Alaska (California) Current. Their analysis suggests the changes in large-scale forcing after 1976 should be consistent with a reduced equatorward CCS transport and a greater flow into the Alaska Current.

The observed cooling in the central North Pacific after 1976 was accompanied by warming in much of the California Current [Roemmich and McGowan, 1995; Schwing *et al.*, 1997]. Statistical analyses of observations and model simulations indicate that these coastal SST anomalies are negatively correlated with surface temperatures in the central Pacific [Miller *et al.*, 1994]. The concurrent increase in equatorward wind stress and mixing over the CCS south of 40°N [Schwing and Mendelssohn, 1997; Schwing *et al.*, 1997] suggests that decadal SST variations are not associated with locally forced processes. In fact, monthly wind stress and SST time series are not correlated throughout the entire CCS. Miller *et al.* [1994] attribute warming in the CCS to an anomalous heat flux input associated with large-scale shifts in the atmospheric heat and momentum fields.

The northern portion of the CCS was cooler after 1976 and features a ~50-year cooling trend, opposite the tendencies off southern California [Schwing and Mendelssohn, 1997; Schwing *et al.*, 1997]. The shift in the northern CCS was linked to large-scale cool anomalies in the central North Pacific rather than changes in local wind forcing. Various combinations of wind-forced advection, mixing and direct heating lead to distinct regional responses of the coastal ocean on decade scales, which in turn may have substantial consequences for marine populations.

SSTs in the Gulf of Alaska increased dramatically in concert with dynamic height following the 1976 shift [Lagerloef, 1995]. Ekman [Lagerloef, 1995] and geostrophic [Tabata, 1991] transports into the Gulf changed after 1976, and the Alaska Gyre developed a more relaxed circulation with a center that was displaced to the southwest from its previous location. Tabata's [1991] analysis of sea level along the US west coast indicates relatively weaker transport in the California Current in the years following 1976. He also notes that interannual variations in transport into the Alaska and California Currents appear to be out of phase, although not in a statistically convincing way.

3. Results

To assess the effect of the 1976 climate shift in the North Pacific Ocean, conditions during two ten-year periods are

compared; 1966-75 and 1977-86. Monthly means of several quantities—surface atmospheric pressure, wind stress vectors, wind speed cubed, and SST—were compiled from the Comprehensive Ocean-Atmosphere Data Set (COADS) for 2° latitude/longitude squares [Mendelssohn and Roy, 1996]. From this, decadal means were computed for each season, with winter being December-February, etc., such that each seasonal field described here is the average of thirty monthly means. Difference fields are also examined, taking the latter from the earlier period.

From these basic fields, a number of wind-driven ocean circulation characteristics were derived using relatively simple dynamical balances. Surface Ekman transports were derived from observed wind stress fields and Ekman theory. Vertical velocity was estimated from the equation for Ekman pumping, using wind curl estimates. Transport streamfunctions were computed by integrating meridional transports, which were derived from the Sverdrup relationship, west from the eastern ocean boundary. Sea level was found by integrating the geostrophic transport, defined as the difference of the total and Ekman transports.

One of the most apparent effects of the 1976 climate shift was in the surface wind field. Over most of the North Pacific, the decadal intensification of low pressure altered wind speed but had little effect on the mean direction (Figure 2). However, the eastward expansion of the winter Aleutian Low resulted in a more widespread cyclonic atmospheric flow over the subarctic Pacific and a major shift in wind direction over the Gulf of Alaska. In the pre-1976 decade the winter wind stress over the Gulf was primarily eastward; post-1976 it had a very strong northeastward component.

Basin-scale ocean circulation is linked closely to planetary-scale atmospheric forcing, in particular the curl of the wind stress. Therefore changes in ocean transport throughout the North Pacific can be expected to accompany the observed decadal shifts in atmospheric pressure and wind stress. An increase in positive (cyclonic) wind curl, as seen after 1976 over the majority of the North Pacific north of 30°N, has two major effects. First, it generates divergence in the ocean surface layer, leading to Ekman pumping, or upward vertical flow of water, to replace surface water. Second, it leads to poleward ocean transport, based on the Sverdrup relationship [Sverdrup, 1947], by which the additional vorticity imparted to the water column by the curl is balanced through a poleward movement of water to a latitude of greater planetary vorticity. The Sverdrup transport dwarfs the Ekman transport; however the latter is concentrated in the upper ocean (~50 m) and is generally a greater contributor to near-surface flow.

The consequences of the alteration in the winter wind stress pattern over the central Pacific are several and inter-related. Typically the mid-latitude surface Ekman transport is to the south, in association with the predominantly eastward wind stress. The intensification of eastward stress over most of the North Pacific implies an increase in southward Ekman transport south of 42°N, and more eastward (westward) surface transport east (west) of the dateline (Figure 3).

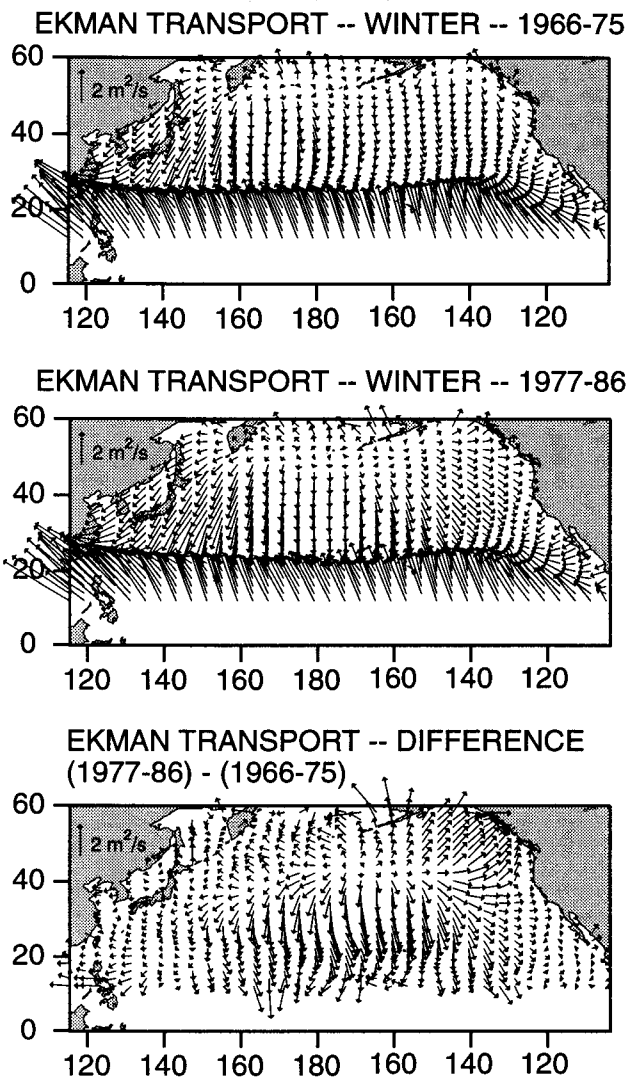


Figure 3. Winter surface Ekman transport fields for two decades (1966-75 and 1977-86), and their difference. Scaling vector shown in upper left of each panel.

The pattern of surface Ekman divergence in the upper ocean, equivalent to the wind curl and roughly proportional to the meridional gradient of the east wind stress component over the central North Pacific, is greatly altered as well (Figure 4). During both decades, a near-zonal line of zero divergence near 35°N separated a region of upwelling to the north from downwelling south of this line. Specific regions of upwelling exceeding 10 cm/day are seen east of the Kamchatka Peninsula, in the Gulf of Alaska, and along the California coast. Xie and Hsieh [1995] derived a similar pattern of upwelling for the North Pacific, with a winter mean of 5.2 cm/day for the area 39-61°N, and 13.5 cm/day downwelling from 5-39°N. After 1976, the magnitude of divergence increased north of about 38°N, and the upper ocean switched from a convergent (downwelling) to divergent (upwelling) state over the region 34-38°N. Winter frontal formation was therefore shifted about 450 km to the south in the post-1976 decade. Downwelling increased slightly in the subtropics.

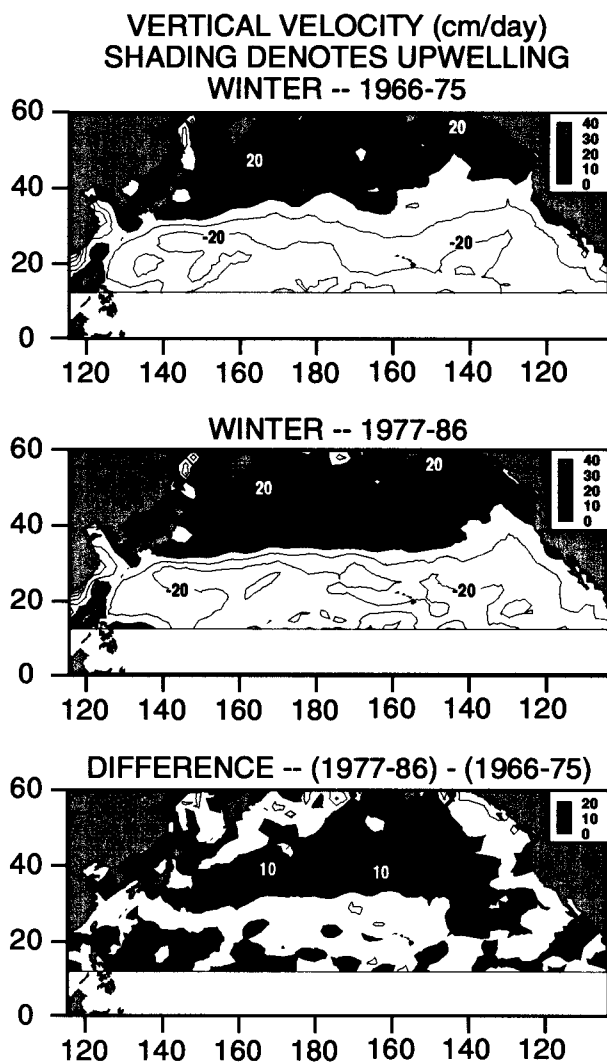


Figure 4. Winter vertical velocity fields for two decades (1966-75 and 1977-86), and their difference. Contour interval is 10 cm/day. Shading denotes areas of upwelling.

In the central North Pacific (166°E-146°W), the average southward Ekman transport (Figure 5a) grew by about 70% over an area from 32-42°N (-1.0 to -1.9 m²/s, or -4.9 to -8.2 Sv). The result is an increased surface transport of presumably colder, nutrient-rich water to the subtropical side of the North Pacific Current. This is despite the fact that the centers of the subarctic and subtropical atmospheric cells (near 50°N and 25°N, respectively) were virtually identical during both decades.

Upwelling due to Ekman pumping (Figure 5b) increased in the region 32-50°N by an average of over 360%, from 2.0 cm/day (2.3×10^{-7} m/s) to 9.1 cm/day (10.6×10^{-7} m/s). Xie and Hsieh [1995] indicate that upwelling is enhanced in this region during El Niño events, when a stronger Aleutian Low develops that is analogous to the pressure fields seen after 1976. They also suggest there is a long-term trend toward greater winter upwelling (downwelling) north (south) of about 30°N, a pattern that agrees closely with the one seen in Figure 4.

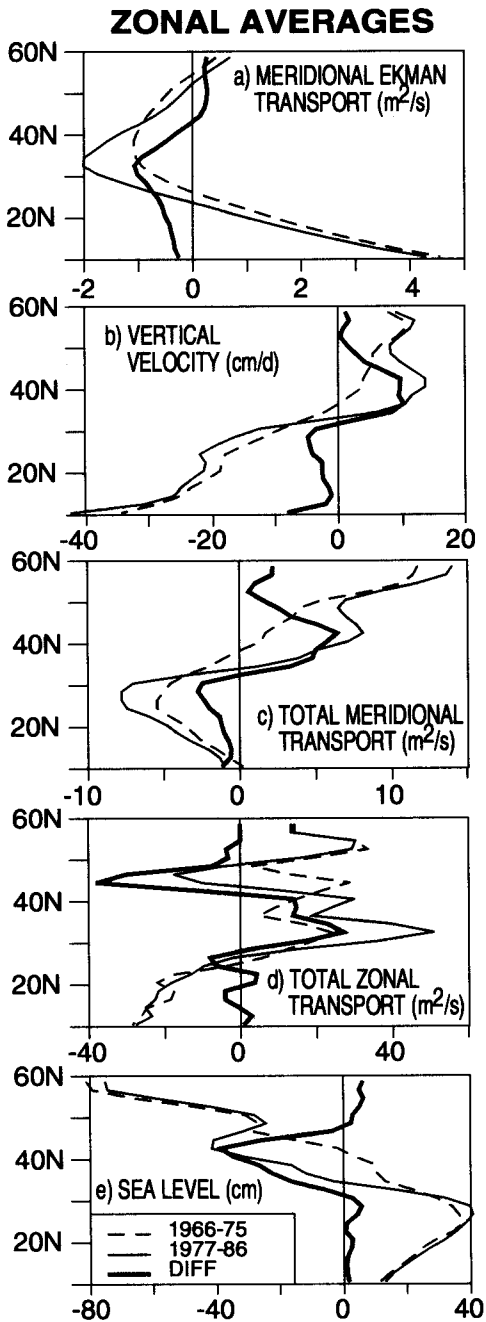


Figure 5. Winter zonally averaged values for key circulation variables, for two decades (1966-75 and 1977-86), and their difference. Variables averaged over 166°E - 146°W for each 2° latitude box. Panels show (a) meridional Ekman transport (positive denotes northward), (b) vertical velocity (positive denotes upwelling), (c) total meridional transport (positive denotes northward), (d) total zonal transport (positive denotes eastward), and (e) sea level height (positive denotes higher sea level).

The aforementioned region of increased winter wind stress also experienced greatly increased turbulent mixing after 1976 (Figure 6). The average of the wind speed cubed, an index of vertical mixing of near-surface water, increased from

1840 to $2371 \text{ m}^3/\text{sec}^3$ (29%). This would act to entrain cooler water into the ocean's surface mixed layer. The estimated changes in Ekman transport, Ekman divergence and pumping, and vertical mixing are consistent with, and likely contribute to, the 30-80% deepening of the winter and spring upper mixed layer in the central North Pacific [Miller *et al.*, 1994; Polovina *et al.*, 1995; Deser *et al.*, 1996]. All of these factors have the same effect on local SST, namely cooler conditions in the North Pacific Current region since 1976.

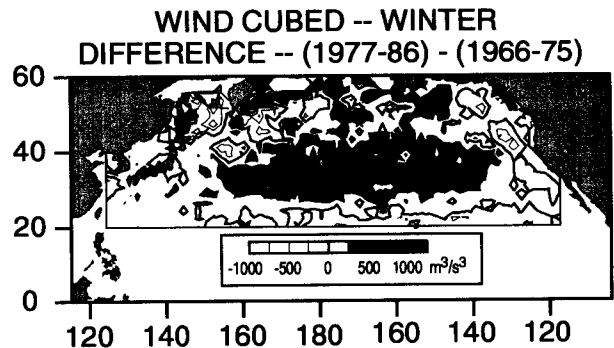


Figure 6. Decadal difference in winter wind speed cubed (1977-86 less 1966-75). Contour interval is $250 \text{ m}^3/\text{s}^3$. Bold contour denotes zero difference; shading denotes areas greater than $250 \text{ m}^3/\text{s}^3$.

Transports computed from the decadal winter fields replicate the anticipated North Pacific Ocean circulation (Figure 7). An anticyclonic subtropical gyre spanning about 10 - 40°N is bracketed by cyclonic subpolar and subtropical gyres. The integrated transports are comparable to winter climatologies based on analyses of other wind data sets (Table 1). Noteworthy are the substantially larger winter transports from this study and Trenberth *et al.* (1990), relative to annual-averaged estimates [White, 1975; Trenberth *et al.*, 1990; Burkov, 1993].

The total integrated transport in the West Wind Drift region between the subpolar and subtropical gyres increased from 130 to 140 Sv (+8%) between the two time periods described here (Table 1, Figure 7). The circulation of the North Pacific subtropical gyre increased from 72 to 90 Sv (+25%). This accounts for most of the increase in the westward North Equatorial Current. However the circulation of the subarctic gyre decreased from 58 to 50 Sv (-13%). The decadal difference in the North Pacific Current corresponds with an increase in the average January geostrophic transport of the Kuroshio Current from 43 to 52 Sv (derived from Qui and Joyce, 1992, their Table 2).

Greater positive wind curl increased the average poleward Sverdrup transport over 32 - 50°N , 166°E - 146°W from 2.7 Sv to 20.8 Sv (+670%) (Figures 5c, 7). Just as the change in wind curl varied meridionally, the increase in the Sverdrup transport was not uniform with latitude, but peaked at about 43°N . Convergence and divergence in the Sverdrup transport sets up significant zonal currents. Although the total transport between the subpolar and subtropical gyres increased by only 8% between the two time periods (Table 1), the distribution of transport changed dramatically within this region

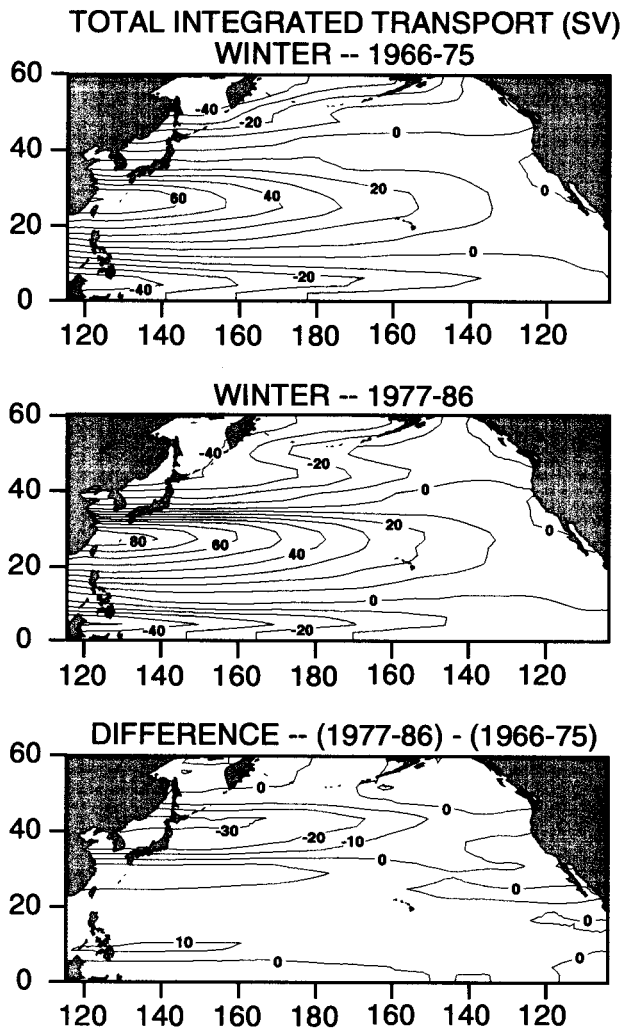


Figure 7. Winter integrated Sverdrup transport fields for two decades (1966-75 and 1977-86), and their difference. Transport between streamlines is given by their difference, and is parallel to the lines. Contour interval is 10 Sv.

(Figure 5d). The ocean adjusted geostrophically to the divergence in poleward transport with a more than doubling of eastward transport between 32-42°N (16.3 to 38.3 Sv), but a reversal in zonal transport over 42-50°N (from 15.5 Sv eastward to 4.7 Sv westward) corresponding to the reduced subarctic gyre circulation. The impressive changes in transport are likely to have an associated equally important impact on the advection of heat, nutrients and organic matter.

The redistribution of mass in the upper ocean associated with the alteration of the wind stress field resulted in a modification of the meridional gradient of the sea level surface (Figure 5e). The drop in sea level over 32-48°N, with a minimum at about 43°N (Figure 5e), corresponded roughly with an area characterized by isopycnal shoaling since 1976 [Miller *et al.*, 1994; Polovina *et al.*, 1995; Deser *et al.*, 1996]. This was balanced by an increase in eastward geostrophic flow on the subtropical side of the North Pacific Current (34-42°N), but a decrease, and in some areas a reversal, in geostrophic transport on the subarctic side (34-54°N).

Table 1. Total integrated transports in the North Pacific Ocean

	66-75	77-86	EC ¹	HR ¹	B ²
GYRE MERIDIONAL TRANSPORTS (SV)					
SUBPOLAR	-58	-50	-75	-55	
SUBTROPICAL	72	90	100	100	
SUBEQUATORIAL	-48	-54	-40	-60	
ZONAL TRANSPORTS (SV)					
N. PACIFIC	130	140	175	155	89
N. TROPICAL	-120	-144	-140	-160	-76

Based on winter wind stress forcing from 1966-75 and 1977-86 periods. For comparison, transports from literature for winter and annual averages are shown. Sources are ¹Trenberth *et al.* [1990], derived from ECMWF (EC) and HELLERMAN and ROSENSTEIN (HR) wind climatologies; and ²Burkov [1993].

Conversely, the higher sea level north of 48°N agrees with observations of a deeper mixed layer [Miller *et al.*, 1994; Polovina *et al.*, 1995; Deser *et al.*, 1996].

Changes in ocean circulation over the central North Pacific in association with the 1976 climate shift are reflected in the transports of the eastern boundary currents as well. Surface Ekman transport out of the Gulf of Alaska decreased by a factor of two during 1977-86 (Figure 8a). The pattern of Ekman divergence changed as well, with an area of maximum upwelling due to Ekman pumping expanding west through the Gulf after 1976 (Figure 4). The meridional Ekman component through the California Current remained the same (Figure 8a). Seaward of the CCS, the southward Ekman transport doubled as part of the basin-scale intensification in wind stress described above. Winter Ekman transport away from the coast, responsible for upwelling in the CCS, decreased slightly after 1976 south of Monterey (Figure 3). Onshore transport increased in the northern portion of the CCS and along coastal British Columbia and Alaska, enhancing downwelling. The summer pattern (not shown) suggests a decline in coastal upwelling north of about San Francisco (to near-zero in some areas), but greater upwelling in the south.

Meridional Sverdrup transports in the Alaska and California Currents for both time periods display a similar pattern; a poleward (equatorward) transport north (south) of about 40°N, with a countercurrent near the coast (Figure 8b). However the distribution of transport into the Gulf of Alaska changed profoundly. Prior to 1976, the flow across 50°N was constrained in a strong, relatively narrow current along the eastern edge of the Gulf. Transport in 1977-86 was weaker in the east, but extended across the entire southern edge of the Gulf. The integrated transport east of 135°W changed from about 3 Sv northward to 1 Sv out of the Gulf. Transport between 135°W and 160°W was about 5 Sv prior to 1976, increasing to about 9 Sv thereafter. For comparison, Tabata [1991] estimated the average total transport between the coast

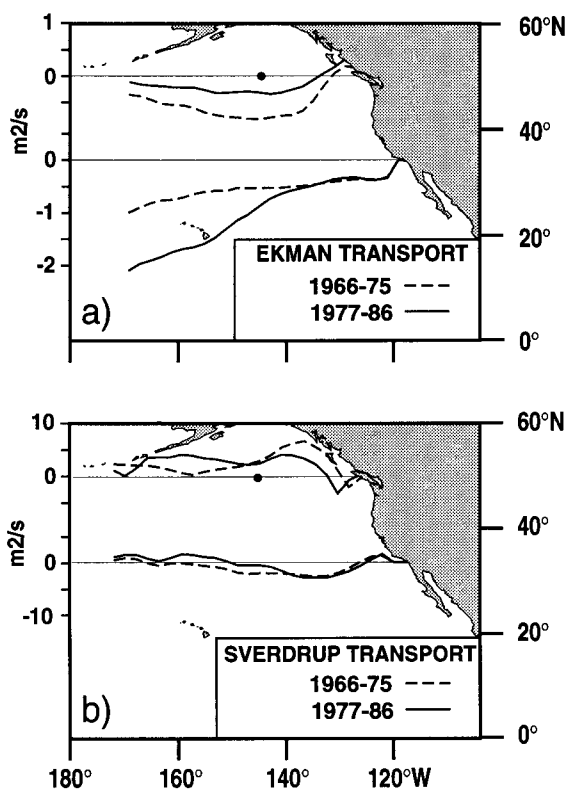


Figure 8. Winter meridional (a) Ekman and (b) Sverdrup transport (m^2/s) across 50°N and 34°N latitude, for two decades (1966-75 and 1977-86), representing transport into Gulf of Alaska and through California Current. Scales shown to left of each panel. Location of Ocean Station P (50°N , 145°W) denoted by dot.

and Ocean Station P (50°N , 145°W) is about 5 Sv, with 2 Sv of this entering the Gulf east of 135°W .

In contrast, equatorward Sverdrup transport in the California Current was only slightly weaker after 1976. It has been suggested that during El Niño years the transport of the California Current is weaker and the Alaska Current strengthens [Chelton and Davis, 1982; Chelton et al., 1982; Tabata, 1991]. A similar relationship is implied when comparing indices of transport in these two boundary currents before and after 1976; the Alaska Current became relatively stronger, particularly west of 135°W , while the California Current was reduced [Tabata, 1991]. However the results presented here indicate the California Current's transport was not significantly changed following the 1976 shift.

4. Concluding remarks

These transports and circulation patterns are estimated from simplified theory and do not include the effects of thermohaline circulation. However the consistency of these results and the magnitude of the differences before and after 1977 clearly indicate that the regime shift characterized by

the intensified Aleutian Low led to substantial and widespread changes in ocean circulation and presumably to the redistribution of heat and material throughout the North Pacific. These changes are very likely to have had significant effects on the ecosystems of the North Pacific as well. Future, more realistic numerical models will examine the impact of this and similar climate shifts on ocean circulation, incorporating ocean density effects as well. From these, we can examine the true effect of climate change in transporting heat, salt, nutrients, and organisms throughout the basin, and ultimately assess its role in modifying ecosystem structure.

Acknowledgments. I am grateful to my colleagues Richard Parrish, Roy Mendelssohn, and Tom Murphree, who contributed greatly to this manuscript through their scientific discussions and collaborations and their assistance in preparing the data sets. Thanks to Peter Müller and Greg Holloway for their invitation to the 'Aha Huliko'a Workshop. This research was supported in part by the US GLOBEC Northeast Pacific Program, sponsored by NSF and NOAA.

References

- Beamish, R. J., Climate and exceptional fish production off the west coast of North America, *Can. J. Fish. Aquat. Sci.* 50, 2270-2291, 1993.
- Brodeur, R. D., and D. M. Ware, Long-term variability in zooplankton biomass in the subarctic Pacific Ocean, *Fish. Oceanogr.* 1, 32-38, 1992.
- Burkov, V. A., *General Circulation of the World Ocean*, translated from Russian, Amerind Publ. Co., New Delhi, 199 pp., 1993.
- Cayan, D. R., Latent and sensible heat flux anomalies over the northern oceans: driving the sea surface temperature, *J. Phys. Oceanogr.*, 22, 859-881.
- Chelton, D. B., and R. E. Davis, Monthly mean sea-level variability along the west coast of North America, *J. Phys. Oceanogr.* 12, 757-784, 1982.
- Deser, C., M. A. Alexander, and M. S. Timlin, Upper-ocean thermal variations in the north Pacific during 1970-1991, *J. Climate* 9, 1840-1855, 1996.
- Ebbesmeyer, C. C., D. R. Cayan, D. R. McLain, F. H. Nichols, D. H. Peterson, and K. T. Redmond, 1976 step in the Pacific climate: Forty environmental changes between 1968-1975 and 1977-1984, in *Proc. 7th Ann. Pacific Climate Workshop, Interagency Ecol. Stud. Prog. Tech. Rep. 26*, edited by J. Betancourt and V. L. Sharp, pp. 129-141, Calif. Dept. of Water Resources, 1991.
- Francis, R. C., and S. R. Hare, Decadal-scale regime shifts in the large marine ecosystems of the Northeast Pacific: a case for historical science, *Fish. Oceanogr.*, 3, 279-291, 1994.
- Graham, N. E., Decadal-scale climate variability in the 1970s and 1980s: observations and model results, *Climate Dyn.*, 10, 135-162, 1994.
- Haney, R. L., A numerical case study of the development of large-scale thermal anomalies in the central North Pacific Ocean, *J. Phys. Oceanogr.*, 10, 541-556, 1980.
- Hollowed, A. B., and W. S. Wooster, Variability of winter ocean conditions and strong year classes of Northeast Pacific fish stocks, *ICES mar. Sci. Symp.*, 195, 433-444, 1992.
- Lagerloef, G. S. E., Interdecadal variations in the Alaska Gyre, *J. Phys. Oceanogr.*, 25, 2242-2258, 1995.
- Latif, M., and T.P. Barnett, Causes of decadal climatic variability over the North Pacific and North America, *Science*, 266, 634-637, 1994.
- Latif, M. and T. P. Barnett, Decadal climate variability over the North Pacific and North America: dynamics and predictability, *J. Climate*, 9, 2407-2423, 1996.
- Lluch-Belda D., R., A. Schwartzlose, R. Serra, R. Parrish, T. Kawasaki, D. Hedgecock, and R., J., M. Crawford, Sardine and anchovy regime fluctuations of abundance in four regions of the world oceans: a workshop report, *Fish. Oceanogr.*, 1, 339-347, 1992.

- Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Amer. Meteor. Soc.*, **78**, 1069-1079, 1997.
- Mendelssohn, R., and C. Roy, *Comprehensive Ocean Data Extraction Users Guide*, U.S. Dep. Comm., NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-228, La Jolla, CA., 67 pp., 1996.
- Miller, A. J., D. C. Cayan, T. P. Barnett, N. E. Graham, and J. M. Oberhuber, Interdecadal variability of the Pacific Ocean: model response to observed heat flux and wind stress anomalies, *Clim. Dyn.*, **9**, 287-302, 1994.
- Miller, A. J., D. R. Cayan, and W. B. White, A westward intensified decadal change in the North Pacific thermocline and gyre-scale circulation, *J. Climate*, in press, 1998.
- Nitta, T., and S. Yamada, Recent warming of tropical sea surface temperature and its relationship to the northern hemisphere circulation, *J. Met. Soc. Japan*, **67**, 375-383, 1989.
- Polovina, J. J., G. T. Mitchum, N. E. Graham, M. P. Craig, E. E. DeMartini, and E. N. Flint, Physical and biological consequences of a climate event in the central North Pacific, *Fish. Oceanogr.* **3**, 15-21, 1994.
- Polovina, J.J., G.T. Mitchum, and G.T. Evans, Decadal and basin-scale variation in mixed layer depth and the impact on biological production in the Central and North Pacific, 1960-88, *Deep-Sea Res.*, **42**, 1701-1716, 1995.
- Qui, B. and T. M. Joyce, Interannual variability in the mid- and low-latitude western North Pacific, *J. Phys. Oceanogr.*, **22**, 1062-1079, 1992.
- Roemmich, D., and J. McGowan, Climatic warming and the decline of zooplankton in the California Current, *Science*, **267**, 1324-1326, 1995.
- Schneider, N., A. J. Miller, M. A. Alexander, and C. Deser, Subduction of decadal north Pacific temperature anomalies: Observations and dynamics, *J. Phys. Oceanogr.*, in press, 1998.
- Schwing, F. B., and R. Mendelssohn, Increased coastal upwelling in the California Current System, *J. Geophys. Res.*, **102**, 3421-3438, 1997.
- Schwing, F. B., R. H. Parrish, and R. Mendelssohn, Recent trends in the spatial variability of the SST and wind fields of the California Current System, in *Global Versus Local Changes in Upwelling Systems: Proc. First Intl. CEOS Workshop*, edited by M. H. Durand et al., ORSTOM, Paris, France, 1997.
- Sverdrup, H. U., Wind-driven currents in a baroclinic ocean; with application to the equatorial currents of the eastern Pacific, *Proc. Natl. Acad. Sci. USA*, **33**, 318-326, 1947.
- Tabata, S., Annual and interannual variability of baroclinic transports across Line P in the northeast Pacific Ocean, *Deep-Sea Res.*, **38**, S221-S245, 1991.
- Trenberth, K. E., Recent observed interdecadal climate changes in the Northern Hemisphere, *Bull. Amer. Meteor. Soc.*, **71**, 988-993, 1990.
- Trenberth, K. E., and J. W. Hurrell, Decadal atmospheric-ocean variations in the Pacific, *Clim. Dyn.*, **9**, 303-319, 1994.
- Trenberth, K. E., W. G. Large, and J. G. Olson, The mean annual cycle in global ocean wind stress, *J. Phys. Oceanogr.*, **20**, 1742-1760, 1990.
- White, W. B., Secular variability in the large-scale baroclinic transport of the North Pacific from 1950-1970, *J. Mar. Res.*, **33**, 141-155, 1975.
- Xie, L., and W. W. Hsieh, The global distribution of wind-induced upwelling, *Deep-Sea Res.*, **68**, 1239-1250, 1995.
- Yasuda, T., and K. Hanawa, Decadal changes in the mode waters in the midlatitude north Pacific, *J. Phys. Oceanogr.*, **27**, 858-870, 1997.
- Zhang, R.-H., and S. Levitus, Structure and cycle of decadal variability of upper ocean temperature in the North Pacific, *J. Climate*, **10**, 710-727, 1997.