Pacific Sardine Habitat Changes Induced by a Climate Shift

Tim R. Baumgartner[1,2]
Guillermo Auad[1]
and
Arthur J. Miller[1]*****

[1] Scripps Institution of Oceanography, La Jolla, CA 92093, USA
[2] CICESE, Ensenada, Mexico

* *Corresponding author address:*
Climate Research Division
Scripps Institution of Oceanography
La Jolla, CA 92093-0224
phone: (858) 534-8033
fax: (858) 534-8033
ajmiller@ucsd.edu

ABSTRACT

The variability of Pacific sardine populations on interdecadal timescales is studied in the context of habitat changes induced by changing physical oceanographic conditions associated with the 1976-77 climate regime shift. A primitive equation ocean model is forced with atmospheric fields that are meant to represent canonical regime changes which may also apply to past sardine population variations observed in sediment records. The model ocean produces a 40habitat when the ocean climate is in the warm phase in the California Current region. Nutrient enrichment of the upper ocean may also play a role in establishing the favorable habitat, but its effects appears to be small compared to the post-shift expansion of spawning-favorable habitat.

Key words: Pacific sardine, regime shift, ocean circulation, ecosystem, decadal variability

Running title: Pacific sardine habitat climate shift

Pacific Sardine Habitat Changes Induced by a Climate Shift

INTRODUCTION

Large-scale changes in the marine environment are increasingly being recognized as forcing agents in organizing large-scale patterns of oceanic ecosystem response, especially on interannual, decadal and longer timescales (e.g., Hayward, 1997; Francis et al., 1998; Holloway and Müller, 1998; Miller and Schneider, 2000; +other-refs????). This is particularly apparent in sardine and anchovy populations in the Pacific Ocean (Kawasaki, 1991; Lluch-Belda et al., 1992; Beamish, 1995; MacCall, 1996; Klyashtorin, 1998 ; Schwartzlose et al., 1999; Yasuda et al., 1999; +other-refs???). Regionally, sardine and anchovy populations often appear to be anti-correlated. Basinwide, correlations and anticorrelations occur between geographically disparate small pelagic fish populations. Hence, large-scale oceanic response to climate forcing is often invoked to explain these patterns. This has been especially relevant to the 1976-77 climate shift of the Pacific Ocean which has been indirectly linked to many major changes in marine ecosystems (e.g., Ebbesmeyer et al., 1991; Hare and Mantua, 2000).

Other processes may also control small pelagic fish populations such as intrinsic biological variations associated with trophic level interactions (e.g., Bakun and Cury, 1999), fishing pressures (e.g., Beverton, 1990), changes in statistics of mesoscale eddy formation (Logerwell and Smith, 2001), or complicated combinations of physical forcing, trophic interactions and fishing (e.g., Cury et al., 2000). [Add more refs and text here....]

The observational record of both the small pelagic fish populations and the oceanic environmental conditions in the Pacific is too short, however, to draw substantive conclusions regarding the importance of these different mechanisms. Typically, the physical oceanographic observations include sea-surface temperature over the last century and subsurface measurements of temperature over the last half century. Both these datasets are increasingly sparsely sampled for earlier time periods and records of other physical variables are spotty. Fish population changes, too, have only been tabulated for a half century based on fishing hauls.

Long records of the deposition of small pelagic fish scales, on the other hand, are available for certain key regions of the Pacific. These include the Santa Barabara Basin (SBB) where is has been shown that over the last 2000 years sardine and achovy populations generally are anticorrelated. Moreover, the two populations covary on interdecadal timescales with suggestions of enahanced variance at periods of 20?, 30? and 50? years. A major ocean climate event 25 years ago is thought to have coordinated ecosystem response throughout the North Pacific including sardine and anchovy populations in the SBB.

3

What physical ocean conditions prevail during periods of predominance of sardine versus those of anchovies? If physical forcing exerts a strong control on sradine populations, is habitat size or food source availability more likely to be the dominant instigator of these interdecadal changes? Can the 1976-77 climate shift be considered a canonical regime shift in the context of eastern Pacific small pelagic fish populations?

We address these questions by simulating the altered oceanic conditions associated with a smoothed version of the 1976-77 climate shift. We then assess the modeled changes of the ocean along western North America in relation to their effects on Pacific sardine habitat changes and lower trophic level changes. We suggest that this canonical regime shift is consistent with interdecadal climate forcing of habitat changes of sardine and anchovy populations inferred from sediment records.

OCEAN MODEL

The primitive equation ocean model called OPYC was developed by *Oberhuber* [1993] and applied by *Miller et al.* [1994a,b] to study the 1976-77 climate shift as well as other intraseasonal, interannual and decadal-scale ocean variations over the Pacific Basin (Miller et al., 1997; 1998; Auad et al., 1998a,b). We here use an updated version of the model (Auad et al., 2001) which includes higher resolution and a different forcing strategy.

The model is constructed with ten isopycnal layers (each with nearly constant potential density but variable thickness, temperature and salinity) that are fully coupled to a bulk surface mixed-layer model. The grid extends from 119^oE to 70^oW and from 67.5^oS to 66^oN, with periodic boundary conditions along the latitudes of the Antarctic Circumpolar Current. The resolution is 1.5^o in the midlatitude open ocean, with zonal resolution gradually increased to 0.65 ^{o} resolution within a 10° band around the equator. The semi-implicit time step is 0.75 days. Although the model is not eddy resolving, equatorial instability waves occur spontaneously and eddies develop in the west wind drift of the midlatitudes. We only seek to study large-scale patterns in the response and regard this intrinsic variability as noise which must be filtered out by averaging many years together. The semi-implicit time step is 0.75 days.

Surface atmospheric forcing is specified as follows. A monthly mean seasonal cycle forcing and response is first established. Then a canonical climate shift anomalous forcing is computed from NCEP re-analysis fields (Kistler et al., 2001) and added to the seasonal cycle forcing. The monthly mean seasonal cycle forcing is derived from various sources and is the same as used by *Miller et al.* [1994]. The monthly mean wind stress climatology is derived from a combination of monthly mean ECMWF midlatitude fields and monthly mean Hellerman-Rosenstein tropical climatology. The monthly mean seasonal cycle climatology of turbulent kinetic energy (TKE) input to the mixed layer is estimated from the same datasets

4

[*Oberhuber*, 1993]. The surface fresh-water flux is represented as a combination of observed monthly mean rainfall [*Legates and Willmott*, 1992], evaporation computed by bulk formula, plus a relaxation to the annual mean Levitus salinity field over thirty-day timescales. The monthly mean seasonal cycle climatology of total surface heat flux is computed during spin-up (with no anomalous forcing) by determining surface heat flux at each time step with bulk formulae that use evolving model SST with ECMWF-derived atmospheric fields (air temperature, humidity, cloudiness, etc.); the daily mean seasonal cycle of heat flux is then saved (averaged over the last 10 years of a 99-year spin-up) and subsequently used as specified forcing during the anomalously forced hindcasts.

The canonical climate shift anomalous fields of monthly mean wind stress, total surface heat flux and TKE are computed as month-by-month differences of the average six years after the shift less the six years before the shift. For our purposes, November 1976 is consider the last month before the shift and December 1976 is considered the first month after the shift (cf. Trenberth, 1990). We compare the magnitude and structure of the NCEP canonical shift surface heat flux and wind stress forcing to that derived from COADS direct observations. While the structures were very similar (Miller et al., 1994a,b), the amplitude of the NCEP forcing was roughly a factor of two too large. So we reduced the magnitude of the NCEP heat flux and wind stress forcing by a factor of two; the TKE input evaluated from NCEP was roughly consistent with COADS and was unaltered. [DID WE DO THIS?] A 1-2-1 smoothing of the differenced monthly anomalous forcing is done to remove intraseasonal fluctuations of the anomalous forcing. This canonical climate shift anomalous forcing is then added to the monthly mean seasonal cycle.

Because there is no SST feedback to any of the anomalous forcing fields the model is not constrained to reproduce the observed temperature shift (as could be achieved by adapting a relaxation formulation). Near the equator, the anomalous heat fluxes are poorly known due to many gaps in ship weather reports, so a physically motivated Newtonian damping is employed within a 6° e-folding scale around the equator. The SST anomaly there is damped towards the pre-shift model SST climatology. on timescales that depend on a damping coefficient divided by the mixed layer depth (following *Miller et al.* [1994]). Specified surface fresh-water flux anomalies are excluded because of unreliable precipitation estimates from the NCEP Reanalysis [e.g., *Janowiak et al.,* 1998]. This is a potential deficiency of the model canonical shift since long-term changes in salinity can clearly effect the MLD in the higer latitude regions of the Pacific (Freeland et al., 1997). The continuous relaxation to annual mean Levitus salinity, however, does imply that fresh-water flux anomalies occur in the hindcasts; but they have a weak influence on SST and mixed layer depth anomalies.

Initial conditions for this run are from the ninetieth year of the model spin-up with

climatological forcing. Because there is no model SST feedback to the surface heat fluxes (except in a narrow equatorial band) there is a possibility of a drift in the model climatology because the model has not reached a complete equilibrium with mean flux forcing after 90-100 years of spin-up. Hence, we also run with model with no anomalous forcing from the same initial conditions and compute the difference between the anomalously forced run and base run with no anomalous forcing.

RESULTS FROM OCEAN MODEL

We now discuss the modeled canonical climate shift in terms of the physical variables that are relevant to sardine populations of the North American West Coast. We particularly emphasize how the altered atmospheric forcing and oceanic physical processes conspire to induce these modeled changes. Wintertime forcing in the North Pacific controls the model response to a large degree, even in subsequent seasons, and so we concentrate our discussion on the winter season.

Surface heat flux forcing

After the canonical shift, the atmospheric wintertime surface heat fluxes (Figure 1) cool the central North Pacific and warm the eastern, northern and subtropical North Pacific which aids in the the establishment of the 'canonical SST pattern' of the North Pacific. The California Current region is warmed during winter but cooled by surface heat fluxes during the spring and summer. The winter warming is consistent with heat flux forcing of the SST in that region (Miller et al., 1994; Auad et al., 1998). The spring and summer cooling, however, may be indicative of ocean to atmosphere feedback (Norris et al., 1998) since SST anomalies tend to remain positive during these seasons (see below).

Wind stress and wind-stress curl forcing

The strengthened wintertime Aleutian Low after the canonical shift results in positive zonal wind stress anomalies in the central North Pacific and negative zonal wind stress anomalies along the North American West Coast (Figure 2). Much weaker versions of this zonal wind stress pattern occur in spring and fall. Meridional wind stress (Figure 3) is strongly northward in the wintertime northeastern Pacific, along the U.S. West Coast and in the Gulf of Alaska. The fall pattern is also northward there, but weaker. The spring and summer patterns are very weak.

The wind stress curl pattern associated with the canonical shift (Figure 4) is strongest during winter with positive curl north of 35N in the central subpolar gyre region that extends southeastward along the western U.S. coast with weaker amplitude and connects to a strong positive subtropical gyre pattern south of 20N. A region of negative curl occurs in the Gulf of Alaska and north of 45N, with a broad negative curl region between 20N and 35N in the central North Pacific. This curl pattern is associated with a strengthening

and southeastward displacement of the Aleutian Low pressure system and implies increased open-ocean upwelling in the region of the California Current System and downwelling near the Gulf of Alaska coast. The changes near the North American coast persist but weaken in spring and summer and then reverse sign in fall. Increased open-ocean upwelling in the CCS region may contribute to an increased wintertime open-ocean nutrient availability which may persist into the time of the spring bloom. Hence it may favor the presence and development of the Pacific sardine.

The wind stress curl, however, is sensitive to precise measurements of the wind stress and to errors in the analysis model; Parrish et al. (2000) found very small changes in wind stress curl off California using the COADS observations. More accurate direct measurements of wind patterns near the eastern boundaries, e.g., from scatterometer measurement, are needed to better understand these effects.

Sea-surface temperature

Concurrent with the atmospheric forcing changes that took place after the 1976-77 shift, oceanic changes occurred in many observed physical variables. Figure 5 shows the anomalous model SST field driven by the canonical shift in atmospheric forcing. This structure is commonly observed on timescales from monthly to interannual to interdecadal in the Pacific Ocean (e.g., Tanimoto et al., 1991; Zhang et al., 1997; Mantua et al., 1997; Enfield and Mestas-Nuñez, 1999) and can be considered the 'canonical SST pattern' of North Pacific interdecadal variability (Miller and Schneider, 2000). Cooling occurs in the model western central North Pacific (centered between 25N and 40N) surrounded by warming the eastm north and south. The strongest model warming is found between 15^oN and 25^oN and 150^oE and 200^oE. The California Current region warms moderately. Similar SST responses have been studied by others who have modeled this oceanic shift (e.g., Wu and Hsieh, 1999; Xie et al., 2000; Haigh et al., 2001; Seager et al., 2001).

Figure 6 shows the mean state of the SST field before and after the canonical climate shift. The spatial extent of the spawning-favorable temperature range, 17^oC-25^oC, of Lluch-Belda et al. (1991) increased considerably after the climate shift. To quantify the increase we evaluated the change in volume of spawning favorable water between Punta Eugenia to the 17^oC isotherm and from the coast to 600km offshore. (There could be temperatures in the allowed range south of Punta Eugenia but the area to the south is low in nutrients so it is not considered here.) We evaluated the vertical extent of the volume by the thickness of the mixed layer. The results (Figure 7) quantify the increase in sardine spawning-favorable habitat after the canonical climate shift. These estimates are in line with the findings of .....(Tim, who was it ?) Figure 6 also shows that the habitat experiences a northward displacement as a consequence of the northward displacement of the mean isotherms during

all seasons. This calculation, however, does not include information about the quality of the habitat such as available nutrients and primary or secondary productivity. These attributes will be inferred from other physical fields.

Mixed-layer depth

The model mixed layer depth (MLD) change after the canonical climate shift shows structures (Figure 8) that are largely consistent with observed changes north of 20N that were described by Polovina et al. (1995) and Deser et al (1996). Winter mixed layers deepened in the central North Pacific and shoaled in the Gulf of Alaska. Both these changes are consistent with increased productivity since the the central North Pacific is considered to be nutrient limited while the Gulf of Alaska is considered to be light limited. South of 25N, the central North Pacific exhibits a much shallower mixed layer, but that is likely to be an exaggerated effect of the bulk mixed layer model's sensitivity to the combined effects of climatological winter downwelling and turbulent mixing in the subtropical gyre (deSzoeke, 1980). The California Current region shows a slight deepening of the winter MLD but it persists through the spring, summer and fall seasons and may be indicative of additional nutrient supply to the ML.

Surface currents

Model surface horizontal currents (Figure 9) show an enhanced large-scale cyclonic flow pattern over the North Pacific during winter months which generally persists for the subsequent seasons (Miller et al., 1998; Deser et al., 1999). Northward flow along the North American west coast prevails during all seasons except summer when the anomalous flow is weak and disorganized. This represents a general weakening of the California Current and a strengthening of the Alaska Gyre. Flows off Baja California are very weak compared to those off Point Conception, showing that the dynamics effect of the canonical climate shift forcing does not influence the region south of the SCB. project into this region.

The cross-shelf surface layer transport (velocity times the mixed layer depth) changes gives a measure of the altered nutrient enrichment pattern due to upwelling near the eastern boundary. It was calculated by projecting the horizontal velocity field in the direction normal to the coastline. Changes off the southwestern U.S. are generally rather small, especially in the SCB. But there are indications of weakly enhanced upwelling between Point Conception and San Francisco during spring and summer (Schwing and Mendelssohn, 1997). This may bring nutrient rich waters into that portion of the Pacific sardine habitat, thus increasing the quality of its in addition to the already mentioned changes in size. Weakly on-shore flow occurs year-round.

Thermocline (depth of $\sigma_\theta = 25.7$ surface)

Changes in the depth of the thermocline influence the stability of the upper ocean (and,

8

hence, vertical mixing processes) and are usually dominated by Ekman pumping in the midlatitudes (e.g., Auad et al., 1998). We evaluated the change in depth of the third potential density layer in the model ($\sigma_\theta = 25.7$) after the canonical shift. The potential density surface is not level, reaching mean depths of 300-400m in the subtropical gyre, 100-200m in the subpolar gyre and 120-200m along the North American West Coast. The change in the depth after the shift (Figure 10) shows a deepened thermocline in the Gulf of Alaska, which continues southwards, albeit much more weakly, along the U.S. West Coast and south to Punta Eugenia. The pattern is driven partly by the downwelling wind stress curl in the Gulf of Alaska and partly by the anomalous onshore Ekman transport associated with the increased northward wind stress after the shift. Although positive wind stress curl favors open ocean upwelling off the coast of the western U.S., its effect is not evident in the pattern of thermocline depth in that region.

DISCUSSION

Simulation of a canonical regimed shift in the North Pacific Ocean shows that sardine spawning-favorable habitat increases by 30-50after the canonical shift. Changes in the physical mechanisms that lead changes in primary and secondary productivity are small. For example, a slight deepening of the mixed layer in that region and slightly enhanced open-ocean Ekman pumping may enrich the surface layer with nutrients. But onshore transport by Ekman currents will act to counter those effects. So it is likely that expanding habitat is the dominant forcing function for sardine dynamics.

There are alternative ways to define a canonical regime besides computing a smoothed forcing function based on the 6 years before and after the 1976-77 shift. Since the dynamics of possible periodicities of the shift are unknown, various time intervals can be specified as pre- and post-shift. For example, Haigh et al. (2001) used the periods 1952-1975 and 1977-1988 to define a regime shift (see also Wu and Hsieh, 1999). One could also use time-dependent observed forcing through the defined time interval and average the model response for the specified intervals, but that may excite higher-frequency patterns in the model output that can obscure simple dynamics.

The study concentrated on the changes in the mean ocean patterns associated with the canonical shift. However, changes in eddy statistics and the concomitant effect on biological processes may be important. For example, Logerwell and Smith (2001) suggests the number and size of eddies may be important in establishing habitats favorable for sardine survival. These types of studies must be addressed with eddy resolving models that include biological processes in this region (e.g., Miller et al., 2000).

CONCLUSION

References

Auad, G., Miller, A. J., and White, W. B., (1998) Simulation of heat storages and associated heat budgets in the Pacific Ocean - 2. Interdecadal timescale. *J. Geophys. Res.* **103**: 27,621-27,636.

Auad, G., Miller, A. J., Roads, J. O., and Cayan, D. R. (2001) Pacific Ocean wind stresses and surface heat fluxes from the NCEP Reanalysis and observations: Cross-statistics and ocean model responses. *J. Geophys. Res.*, in press.

Bakun, A. and Cury, P., (1999) The "school trap": a mechanism promoting large-amplitude out-of-phase population oscillations of small pelagic fish species. *Ecol. Lett.* **6**: 349-351.

Baumgartner, T. R., Soutar, A., and Ferreira-Bartrina, V., (1992) Reconstruction of the history of Pacific sardine and Northern anchovy populations over the past 2 millennia from sediments of the Santa-Barbara Basin, California. *Calif. Coop. Oceanic Fish. Invest. Rep.* **33**: 24-40.

Beamish, R. J. [ed.], (1995) *Climate Change and Northern Fish Populations*, Canadian Special Publication, Fisheries and Aquatic Sciences, 121, 739 pp.

Beverton, R. J. H. (1990) Small pelagic fish and the threat of fishing - Are they endangered? *J. Fish Biol.* **37**: 5-16.

NEED TO CITE Brodeur, R. D., Frost B. W., Hare S. R., Francis, R. C., and Ingraham, W. J., (1996) Interannual variations in zooplankton biomass in the Gulf of Alaska, and covariation with California current zooplankton biomass. *Calif. Coop. Oceanic Fish. Invest. Rep.* **37**: 80-99.

Deser, C., Alexander, M. A., and Timlin, M. S. (1996) Upper ocean thermal variations in the North Pacific during 1970-1991. *J. Climate* **9**: 1840-1855.

Deser, C., Alexander, M. A., and Timlin, M. S. (1999) Evidence for a wind-driven intensification of the Kuroshio Current Extension from the 1970s to the 1980s. *J. Climate* **12**: 1697-1706.

deSzoeke, R. A. (1980) On the effects of horizontal variability of wind stress on the dynamics of the ocean mixed layer. *J. Phys. Oceanogr.* **10**: 1439-1454.

Ebbesmeyer, C. C., Cayan, D. R., McLain, D. R., Nichols, F. H., Peterson, D. H., and Redmond, K. T. (1991) 1976 step in the Pacific climate: Forty environmental changes between 1968-75 and 1977-1984. In: *Proc. 7th Ann. Pacific Climate Workshop*, Calif. Dept. of Water Resources, Interagency Ecol. Stud. Prog. Rep. 26, pp. 115-126.

Enfield, D. B. & Mestas-Nunñez, A. M. (1999) Multiscale variabilities in global sea surface temperatures and their relationships with tropospheric climate patterns. *J. Climate* **12**: 2719-2733.

Francis, R. C., Hare, S. R., Hollowed, A. B., Wooster, W. S. (1998) Effects of interdecadal climate variability on the oceanic ecosystems of the NE Pacific. *Fish. Oceanogr.* **7**: 1-21.

Freeland, H., Denman, K., Wong, C. S., Whitney, F., and Jacques, R. (1997) Evidence of change in the winter mixed layer in the Northeast Pacific Ocean. *Deep-Sea Res.* **44**: 2117-2129.

Haigh, S. P., Denman, K. L., and Hsieh, W. W. (2001) Simulation of the planktonic ecosystem response to pre- and post-1976 forcing in an isopycnic model of the North Pacific. *Can. J. Fish. Aquat. Sci.* **58**: 703-722.

Hare, S. R., and Mantua, N. J. (2000) Empirical evidence for North Pacific regime shifts in 1977 and 1989 *Progr. Oceanogr.* **47**: 103-146.

Hayward, T. L. (1997) Pacific Ocean climate change: Atmospheric forcing, ocean circulation and ecosystem response. *Trends Ecol. Evol.* **12**: 150-154.

Holloway, G. and Muller, P., [eds.] (1998) *Biotic Impacts of Extratropical Climate Change in the Pacific.* Aha Huliko'a Hawaiian Winter Workshop, University of Hawaii, SOEST Special Publication, 156 pp.

Janowiak, J. E., Gruber, A., Kondragunta, C. R., Livezey, R. E., and Huffman, G. J. (1998) A comparison of the NCEP-NCAR reanalysis precipitation and the GPCP rain gauge-satellite combined dataset with observational error considerations, *J. Climate* **11**: 2960-2979.

Kawasaki, T. (1991) Long-term variability in the pelagic fish populations. In: Long-Term Variability of Pelagic Fish Populations and Their Environment. T. Kawasaki, S. Tanaka, Y. Toba and A. Taniguchi (eds). Oxford: Pergamon Press, pp. 47-60.

Kistler, R., Kalnay, E., Collins, W., Saha, S., White, G., Woollen, J., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R., and Fiorino, M. (2001) The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation *B. Am. Meteorol. Soc.* **82**: 247-267.

Klyashtorin, L. B. (1998) Long-term climate change and main commercial fish production in the Atlantic and Pacific *Fish. Res.* **37**: 115-125.

NEED TO CITE Lavaniegos, B. E., Gomez-Gutierrez, J., Lara-Lara, J. R., and Hernandez-Vazquez, S. (1998) Long-term changes in zooplankton volumes in the California Current System - the Baja California region. *Mar. Ecol.* **169**: 55-64.

Legates, D. R., and Willmott, C. J. (1992) A comparison of GCM-simulated and observed

mean January and July precipitation. *Global Planet. Change* **97**: 345-363.

Lluch-Belda, D., Lluch-Cota, D. B., Hernandez-Vazquez, S. and Salinas-Zavala, C. A. (1992) Sardine population expansion in eastern boundary systems of the Pacific Ocean as related to sea surface temperature. *S. Afr. J. Marine Sci.* **12**: 147- 155.

Logerwell, E. A., and Smith, P. E. (2001) Mesoscale eddies and survival of late stage Pacific sardine (Sardinops sagax) larvae *Fish. Oceanogr.* **10**: 13-25.

MacCall, A. D. (1996) Patterns of low-frequency variability in fish populations of the California current *Calif. Coop. Oceanic Fish. Invest. Rep.* **37**: 100-110.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., and Francis, R. C. (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteorol. Soc.* **78**: 1069-1079.

Miller, A. J., Cayan, D. R., Barnett, T. P., Graham, N. E., and Oberhuber, J. M. (1994a) Interdecadal variability of the Pacific Ocean: Model response to observed heat flux and wind stress anomalies. *Clim. Dyn.* **9**, 287-302.

Miller, A. J., Cayan, D. R., Barnett, T. P., Graham, N. E., and Oberhuber, J. M. (1994b) The 1976-77 climate shift of the Pacific Ocean. *Oceanogr.* **7**: 21-26.

Miller, A. J., White, W. B., and Cayan, D. R. (1997) North Pacific thermocline variations on ENSO time scales. *J. Phys. Oceanogr.* **27**: 2023-2039.

Miller, A. J., Cayan, D. R., and White, W. B. (1998) A westward intensified decadal change in the North Pacific thermocline and gyre-scale circulation. *J. Climate* **11**: 3112-3127.

Miller, A. J., and Schneider, N. (2000) Interdecadal climate regime dynamics in the North Pacific Ocean: Theories, observations and ecosystem impacts. *Progr. Oceanogr.* **47**: 355-379.

Miller, A. J., Di Lorenzo, E., Neilson, D. J., Cornuelle, B. D., and Moisan, J. R. (2000) Modeling CalCOFI observations during El Nino: Fitting physics and biology. *Calif. Coop. Oceanic Fish. Invest. Rep.* **41**: 87-97.

NEED TO CITE Mullin, M. M. (1998) Interannual and interdecadal variation in California Current zooplankton: Calanus in the late 1950s and early 1990s. *Global Change Biol.* **4**: 115-119.

Norris, J. R., Zhang, Y., and Wallace, J. M. (1998) Role of low clouds in summertime atmosphere-ocean interactions over the North Pacific. *J. Climate* **10**: 2482-2490.

Oberhuber, J. M. (1993) Simulation of the Atlantic circulation with a coupled sea ice - mixed layer isopycnal general circulation model. Part I: model description. *J. Phys. Oceangr.* **23**: 808-829.

Parrish, R. H., Schwing, F. B., and Mendelssohn, R. (2000) Mid-latitude wind stress: the energy source for climatic shifts in the North Pacific Ocean *Fish. Oceanogr.* **9**: 224-238.

Polovina, J., Mitchum, G. T., and Evans, G. T. (1995) Decadal and basin-scale variations in mixed layer depth and the impact on biological production in the Central and North Pacific. *Deep-Sea Res.* **42**: 1701-1716.

NEED TO CITE Roemmich, D., and McGowan, J. (1995) Climatic warming and the decline of zooplankton in the California Current. *Science* **267**: 1324-1326.

Schwing, F. B., and Mendelsohn, R. (1997) Increased coastal upwelling in the California Current system. *J. Geophys. Res.* **102**: 12785-12786.

Schwartzlose, R. A., Alheit, J., Bakun, A., Baumgartner, T. R., Cloete, R., Crawford, R. J. M., Fletcher, W. J., Green-Ruiz, Y., Hagen, E., Kawasaki, T., Lluch-Belda, D., Lluch-Cota, S. E., MacCall, A. D., Matsuura, Y., Nevarez-Martinez, M. O., Parrish, R. H., Roy, C., Serra, R., Shust, K. V., Ward, M. N., Zuzunaga, J. Z. (1999) Worldwide large-scale fluctuations of sardine and anchovy populations. *S. Afr. J. Marine Sci.* **21**: 289-347.

Seager, R., Kushnir, Y., Naik, N., Cane, M. A., and Miller, J. A. (2001) Wind-driven shifts in the latitude of the Kuroshio-Oyashio Extension and generation of SST anomalies on decadal timescales. *J. Climate, sub judice.*

Tanimoto, Y., Iwasaka, N., Hanawa, K., and Toba Y. (1992) Characteristic variations of sea surface temperature with multiple time scales in the North Pacific. *J. Climate* **6**: 1153-1160.

Trenberth, K. E. (1990) Recent observed interdecadal climate changes in the Northern Hemisphere, *Bull. Amer. Meteorol. Soc.* **71**: 988-993.

NEED TO CITE Uda, M. (1962) Cyclic, correlated occurrence of World-wide anomalous oceanographic phenomena and fisheries conditions. *J. Ocean. Soc. Japan* **20**: 368-376.

Venrick, E. L., McGowan, J. A., Cayan, D. R., and Hayward, T. L. (1987) Climate and chlorophyll a: long-term trends in the central north Pacific Ocean. *Science* **238**: 70-72.

Wu, J. Q., and Hsieh, W. W. (1999) A modelling study of the 1976 climate regime shift in the North Pacific Ocean. *Can. J. Fish. Aquat. Sci.* **56**: 2450-2462.

Xie, S.-P., Kunitani, T., Kubokawa, A., Nonaka, M., and Hosoda, S. (2000) Interdecadal thermocline variability in the North Pacific for 1958-1997: A GCM simulation. *J. Phys. Oceanogr.* **30**: 2798-2813.

Yasuda, I., Sugisaki, H., Watanabe, Y., Minobe, S. S., Oozeki, Y. (1999) Interdecadal variations in Japanese sardine and ocean/climate. *Fish. Oceanogr.* **8**: 18-24.

Zhang, Y., Wallace, J. M., and Battisti, D. S. (1997) ENSO-like interdecadal variability: 1900-93, *J. Climate* **10**: 1004-1020.