1976 Step in the Pacific Climate: Forty Environmental Changes Between 1968-1975 and 1977-1984

Curtis C. Ebbesmeyer, Daniel R. Cayan, Douglas R. McLain,
Frederic H. Nichols, David H. Peterson, and Kelly T. Redmond

Abstract: Examination of 40 time series of multidisciplinary environmental variables from the Pacific Ocean and the Americas, collected in 1968 to 1984, demonstrated the remarkable consistency of a major climate-related, step-like change in 1976. To combine the 40 variables (*e.g.*, air and water temperatures, Southern Oscillation, chlorophyll, geese, salmon, crabs, glaciers, atmospheric dust, coral, CO_2, winds, ice cover, Bering Strait transport) into a single time series, standard variants of individual annual values (subtracting the mean and dividing by a standard deviation) were averaged. Analysis of the resulting time series showed that the single step in 1976, separating the 1968-1975 period from the 1977-1984 period, accounted for 89% of variance within the composite time series. Apparently, one of the Earth's large ecosystems occasionally undergoes large abrupt shifts.

Introduction

The numerous time series of environmental variables are becoming increasingly valuable as concerns arise from human influence on the Earth's ecosystem, particularly as the variables may be critical to comprehensive models describing the Earth's dynamics. Forecasts of global climate change often predict smoothly varying temporal fluctuations; however, some variables have shown fairly abrupt changes over time (McLain 1983, Trenberth 1990). We thought that by combining a large number of environmental variables, the temporal variability could be clarified, thereby providing guidance to modelers.

Through our interest in the temporal structure of environmental variables and our participation in a 7-year series of climate meetings (Peterson 1989), we became aware of the broad diversity of Pacific Ocean environmental variables for a variety of disciplines for which long data sets are available.

The variables for which we found appropriate data sets (covering the same time span and bracketing the environmental change in 1976) included an array of atmospheric and oceanic characteristics from the broader Pacific basin and from a more localized Northeast Pacific region including Puget Sound (Figure 1; Table 1). If, as we suspected from initial inspections, many variables underwent a sharp change in a single year, plans for dealing with future environmental change would have to include rapid, perhaps unexpected shifts.

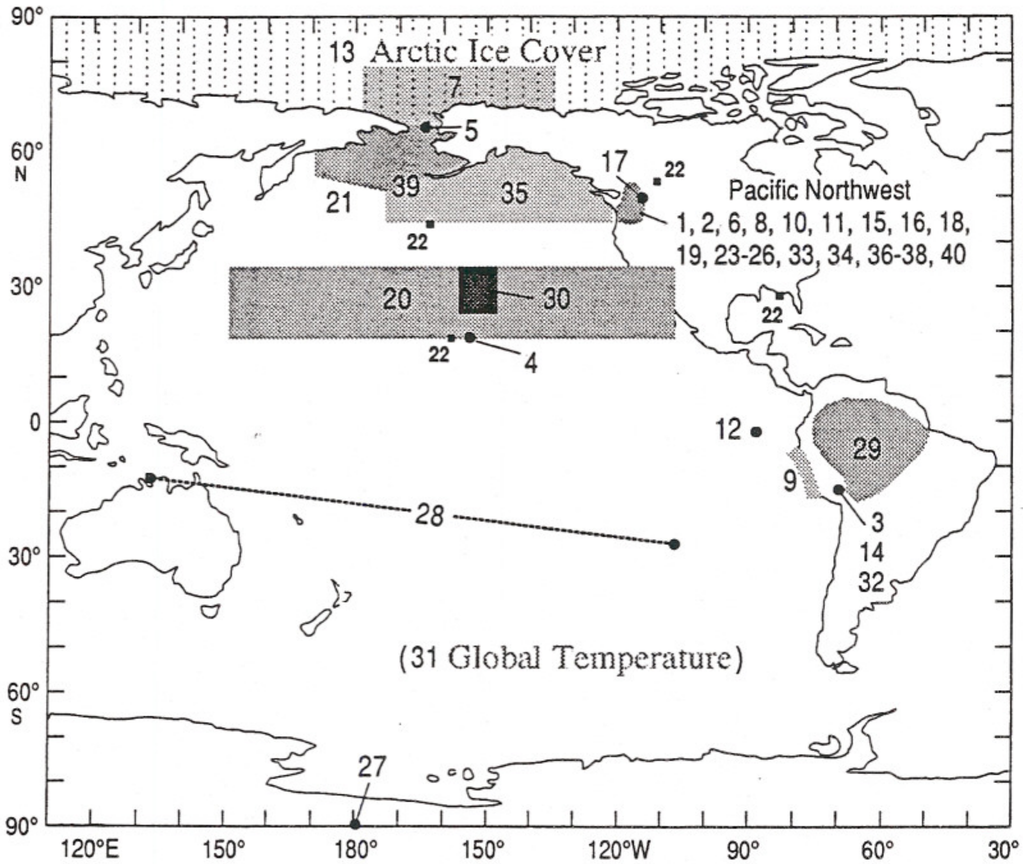
Approach

A number of previous studies were structured using three elements of an experiment — subject, stimulus, response (Aitchison and Brown 1969, Benjamin and Cornell 1970, Montroll and Badger 1974). We adopted a similar approach.

In: J.L. Betancourt and V.L. Tharp, editors. 1991. *Proceedings of the Seventh Annual Pacific Climate (PACLIM) Workshop, April 1990*. California Department of Water Resources. Interagency Ecological Studies Program Technical Report 26.

Figure 1
LOCATIONS OF THE 40 ENVIRONMENTAL VARIABLES

Circled numbers indicate the rank (lowest to highest) of the step's magnitude for each variable *(d)*: average standard deviate of 1977-1984 minus that for 1968-1976 (see Table 1)



Subject

The data sets we examined fall in two categories:

- Those obtained in several comparatively small regions of the Pacific ecosystem because of practical concern about urban effects.
- Those collected at the Pacific basin scale with reference to the natural variability of the climate.

Consequently, we were able to examine the response of the overall Pacific Ocean, as well as that of one small portion, the Pacific Northwest including Puget Sound. By these selections, variability was characterized over a range of spatial scales, from variability in a single estuary (Puget Sound) to variability over the entire Pacific Ocean and some adjacent areas.

Stimulus

A number of Pacific Ocean environmental variables changed abruptly during 1976 (McLain 1983, Trenberth 1990). In the middle latitudes of the North Pacific, notable large-scale changes were observed in the atmospheric circulation (*e.g.,* a preponderance

Table 1

40 ENVIRONMENTAL VARIABLES RANKED ACCORDING TO THE DIFFERENCE ACROSS THE STEP BETWEEN AVERAGES COMPUTED FOR 1968-1975 AND FOR 1977-1984

Ranked smallest to largest.
In the Step Magnitude column, asterisks (*) denote variables from the Pacific Northwest and plus signs (+) denote variables for which signs were reversed (k=1).

Rank	Step Magnitude (*d*)	Environmental Variable	Notes
1	0.18*	Salinity, Puget Sound, 150-m	Annual average salinity at 150-m depth in Puget Sound's main basin (47.7-47.9°N; 122.4-122.5°W). Ebbesmeyer *et al.* (1989).
2	0.19*	Conductivity, Snake River	Annual average specific conductivity of the Snake River at King Hill (43°0.17'N; 115°12.08'W). US Geological Survey, Water Res. Div.
3	0.24+	Ice accumulation, Quelccaya ice core	Thompson and Mosley-Thompson (1989).
4	0.36	Atmospheric CO_2 anomaly, Hawaii	Annual anomaly in concentration of atmospheric CO_2 at Mauna Loa Observatory, HI. Keeling *et al.* (1989).
5	0.40+	Transport, Bering Strait	Annual mean volume transport through Bering Strait. Coachman *et al.* (1988).
6	0.43*	Goose nests, Columbia River	Number of Great Basin Canada goose *(Branta canadensis mofitti)* nests found annually on islands of the Hanford Reach, Columbia River. L.E. Eberhardt (pers. comm.) and Hanson *et al.* (1971).
7	0.46+	Sea ice extent, Beaufort and Chukchi seas	Area covered by ice in the Beaufort and Chukchi seas. Manak and Mysak (1987).
8	0.57*+	Water density, Puget Sound	Annual average sigma-t units computed from temperature and salinity at 150-m depth in Puget Sound's main basin. Ebbesmeyer *et al.* (1989).
9	0.61	Wind stress, Peru	April-September wind stress off Peru. Bakun (1990).
10	0.65*+	Peak water storage, Columbia River basin	Annual maximum total water storage in the basin above The Dalles, OR. Tangborn (1990).
11	0.73*+	Discharge, Fraser River, British Columbia	Annual average (January-December) discharge at Hope, BC (49°22.83'N; 121°27.08'W). Environment Canada (1989).
12	0.74+	Coral, Cd/Ca ratio, Galapagos Islands	Cd/Ca ratio in coral in the Galapagos Islands. Baumgartner, *et al.* (1989).
13	0.83+	Sea ice extent, Arctic total	Manak and Mysak (1987).
14	0.83	Oxygen isotope, Quelccaya ice cap, Peru	$\delta^{18}O$ annual value from Quelccaya summit ice core (13.93°S; 70.83°W). Thompson and Mosley-Thompson (1989).
15	0.97*	Solar radiation, Puget Sound	May-July average at the University of Washington and Lake Washington. Unpublished data, M. Albright (pers. comm.), U. of Wash., Seattle.
16	0.98*+	Upwelling index, winter	Upwelling index for winter at 42°N off Washington. Norton *et al.* (1985).
17	1.01	Mass balance, Peyto glacier, Canada	Annual mass balance for Peyto glacier (51.67°N; 116.55°W). Walters and Meier (1989).
18	1.03*+	Snow depth, Mount Rainier, Washington	Snow depth on March 15 at Paradise Ranger station (46.78°N; 121.73°W). Unpublished data, National Weather Service.
19	1.06*+	Wind speed, 500 mb, Medford, Oregon	Annual mean wind speed at 500 mb, Medford, OR (42.38°N; 122.88°W). Unpublished data, Archives of Oregon Office of State Climatologist .
20	1.08	Wind speed, winter westerlies, 20-35°N; 110°W 150°E	West-to-east geostrophic wind component at 700 mb averaged during winter overarea bounded by 20-30°N by 150°E-110°W.
21	1.15+	Sea ice extent, Bering Sea	Manak and Mysak (1987).

Table 1 (continued)
40 ENVIRONMENTAL VARIABLES RANKED ACCORDING TO THE DIFFERENCE ACROSS THE STEP BETWEEN AVERAGES COMPUTED FOR 1968-1975 AND FOR 1977-1984

Ranked smallest to largest.
In the Step Magnitude column, asterisks (*) denote variables from the Pacific Northwest and plus signs (+) denote variables for which signs were reversed (k=1).

Rank	Step Magnitude (*d*)	Environmental Variable	Notes
22	1.17	Pacific North American Index	December-February average (Wallace and Gutzler 1981) computed as the linear combination of normalized 500 mb height anomalies (z^*) at four locations: $PNA = \frac{1}{4}[z^*(20°N,160°W) - z^*(45°N,165°W) + z^*(55°N,115°W) - z^*(30°N,85°W)]$.
23	1.31*+	Precipitation, Cedar Lake, Washington	Annual (January-December) total at 47.42°N; 121.73°W. Climatological data for Washington, NOAA.
24	1.36*	Salinity, Puget Sound, surface	Average of monthly salinity values (May-July) near the sea surface in Puget Sound's main basin (47.7-47.9°N; 122.4-122.5°W). Unpublished data, University of Washington and Municipality of Metropolitan Seattle.
25	1.36*+	Discharge, Skagit River, Washington	Annual average discharge (January-December) at Concrete, WA; Monthly reports of Dept. of Interior, US Geological Survey.
26	1.49*+	Oxygen saturation, Puget Sound, surface	Percentage of average monthly dissolved oxygen values (May-July) near the sea surface in Puget Sound's main basin (47.7-47.9°N; 122.4-122.5°W). Unpublished data, University of Washington and Municipality of Metropolitan Seattle.
27	1.42	Atmospheric CO_2 anomaly, South Pole	Annual anomaly in concentration of atmospheric CO_2 at the South Pole. Keeling *et al.* (1989).
28	1.43+	Southern Oscillation Index	Standardized atmospheric pressure difference (annual average) at sea level between Darwin, Australia, and Easter Island. Climate Analysis Center, National Weather Service, NOAA, Washington, DC.
29	1.50+	Discharge, Amazon River, Manacapuru	Richey *et al.* (1989).
30	1.65	Integrated chlorophyll *a*, central North Pacific Ocean	Venrick *et al.* (1987).
31	1.70	Global mean annual air temperature	Jones *et al.* (1986).
32	1.76	Particle concentration, Quelccaya ice cap, Peru	Concentration greater than 0.63µ from Quelccaya summit ice core (13.93°S; 70.83°W). Thompson and Mosley-Thompson (1989).
33	1.95*	Wind frequency, southerly, Tacoma, Washington	Average frequency of southerly wind (102-258°T) for May-July at Tacoma, WA (47.27°N; 122.52°W). Unpublished data, Puget Sound Air Pollution Control Agency.
34	2.08*	Crab, Dungeness, Puget Sound	Commercial Dungeness crab *(Cancer magister)* production. Bumgartner *et al.* (1989).
35	2.05	Water temperature, sea surface, northeastern Pacific	Sea surface temperature over the northeast Pacific Ocean averaged from 175°W eastward and 45°N northward to the coast. Royer (198*).
36	2.34*	Salmon migratory route, Vancouver Islands, Canada	Fraction of Fraser River sockeye salmon *(Oncorhynchus nerka)* returning around the northern end of Vancouver Island. Hamilton (1987).
37	2.47*+	Secchi disk depth, Puget Sound	Deepest depth observed of a 0.3-m diameter white (Secchi) disk beneath the water surface (May-July average). Unpublished data, Municipality of Metropolitan Seattle.
38	2.77*	Mollusk abundance, Puget Sound, 200 m depth	Abundance of *Macoma carlottensis* at 200-m depth at station 2 (47°42.0'N; 122°27.2'W) in Puget Sound's main basin off West Point. Nichols (1988).
39	2.81	Salmon catch, Alaska	Alaska salmon catch. NOAA (1988).
40	4.39*	Water temperature, Puget Sound, 150-m	Annual average at 150-m depth in Puget Sound's main basin. Ebbesmeyer *et al.* (1989).

of deepened Aleutian lows in winter) and in the distribution of sea surface temperature (*e.g.*, cooler in the west and central sectors and warmer in the east along the coast of North America).

In the tropics, there was a shift toward more frequent El Niño conditions, evident in the reduced gradient of atmospheric pressure from east to west across the Pacific basin, as well as in a tendency for warmer sea surface temperature in the central-to-eastern Pacific. Associated changes in physical and biological variables indicate several regions and disciplines followed this large-scale shift.

Therefore, we examined all the data sets for equivalent periods before and after this 1976 change (hereafter called the "step"). The 1976 step change was taken as the stimulus.

Response

To characterize the response, differences were computed between the mean of the variables before and after the step.

Methods

Data were available in the literature for a wide range of variables, but only up to 1984. Therefore, to equally weight the years before and after the step, we examined the eight years before the step (1968-1975) and the eight years after the step (1977-1984), yielding a total interval of 17 years including the year of the step (1976). By averaging over two 8-year blocks of time, we were able to estimate changes between two intervals that were approximately decadal.

To describe the Pacific environmental system, about equal numbers of variables were selected from each of the regional- and oceanic-scale data sets, yielding a total of 40 variables. To reduce bias, we tried to select variables with broad coverage of geographic and environmental disciplines and to include no more than a few of the same kind of variable. Both the dimensions and signs of the variables were eliminated.

To remove dimensions, we computed a standard deviate for each value in a time series by subtracting the mean of the time series and dividing by a standard deviation. Realizing a step was contained in the observations, we normalized with parameters not biased by the size of the step in a given time series. To do this, we subtracted the mean of the entire 17-year time series from each annual value, then divided the annual values prior to the step with the standard deviation of the first eight annual values (1968-1975) and divided those after the step with the standard deviation of the last eight annual values (1977-1984). As we found that the standard deviations were not correlated with step size and were almost identical for the first and the last eight years, bias toward the decades before or after the step was reduced.

Regarding elimination of variable signs, our sample of 40 variables is about equally divided; 22 increased and 18 decreased over the step. However, because we were most interested in magnitude of change, we reversed the signs of the 17 annual values of those variables that decreased so that prior to the step, the average value of each variable lies below the 17-year average and afterward, the average value lies above the 17-year average.

This operation enabled us to combine the 40 time series, thereby illustrating the step's average magnitude.

The computations may be expressed mathematically as follows. Given that x_i is the estimate of environmental variable x in the i^{th} year, the x_i is normalized as $v_i = (x_i - x_m)/\sigma$, where x_m(1968-1984), (σ1968-1975) if i=1968-1975, s(1977-1984) if i=1977-1984, the subscript m denotes the mean of the associated variable, and σ the standard deviation computed over the years in parentheses, inclusively. The signs of v_i are rectified as $v_{ri}=(-1)^k v_i$, where k=1 if $v_m(1968\text{-}1975)>v_m(1977\text{-}1984)$, and k=2 if $v_m(1968\text{-}1975)<v_m(1977\text{-}1984)$. Then the magnitude of the step (d) may be expressed as the difference $d=|[v_m(1968\text{-}1975)-v_m(1977\text{-}1984)]|$.

Results

Our methods described the temporal structure of the environmental time series and the step's magnitude, as follows.

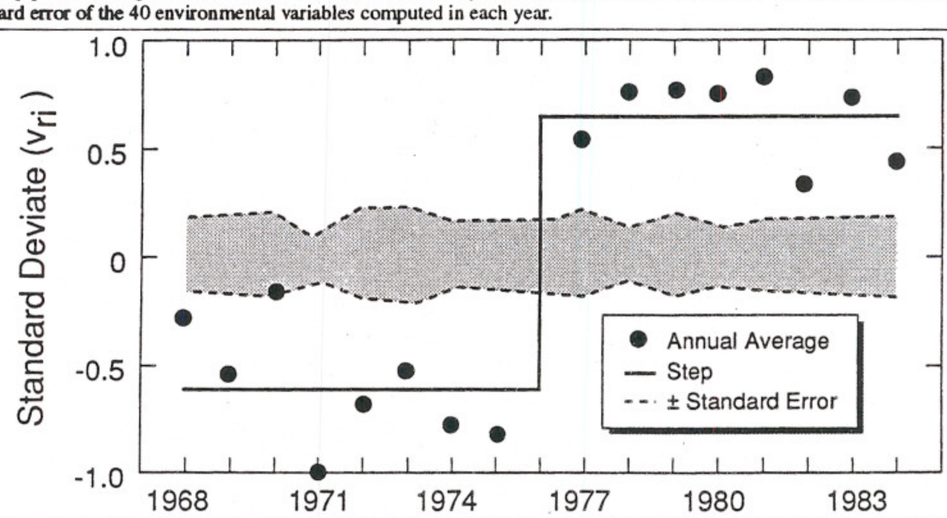
Temporal Structure of Composite Time Series

The time series of the 40 variables were superimposed by calculating for each year the mean and standard deviation of the standard deviates (v_{ri}). Standard errors of the annual mean values were computed as $\pm s/\sqrt{n}$, where s the standard deviation and n is the sample size (equaling 38 variables in the average year; a few values were missing in some years). Before the step, the deviates were an average of 3.6 times below the standard error; after the step, the deviates were an average of 3.9 times above the standard error. Therefore, the deviates before and after the step were large.

Dimensions were eliminated using standard deviations computed from data before and after the step. Therefore, the step may have been influenced by temporal fluctuation of the standard deviation of the environmental variables. Since the sample size was nearly constant from year to year, the standard errors, shown in Figure 2, are indicative of the

Figure 2
17-YEAR TIME SERIES OF THE STANDARD DEVIATE AVERAGED BY YEAR FOR 40 ENVIRONMENTAL VARIABLES

The step passes through the mean standard deviate for two 8-year intervals (1968-1975 and 1977-1984) and the shaded area, the standard error of the 40 environmental variables computed in each year.



variation of environmental variables within a given year. The lack of an apparent trend suggests that within-year variability was not a contributing factor to the step.

Further calculations were made to ascertain whether a "step" is an appropriate description of the temporal structure of the composite time series. Three kinds of variation were considered: uniform change (a line with a slope), near-step (rapid, but not instantaneous, change computed as a 3-year moving average), and the step (instantaneous change as described above). These descriptions accounted for the following percentages of the variance:

Uniform change — 59%;
Near-step — 90%; and
Step — 89% (v_{ri}=–0.609, 1968-1975; v_{ri}=+0.634, 1977-1984).

Since observations with step explained most of the variance of the composite time series, we deemed it an appropriate description.

Variability of Step Magnitude

To explore the magnitude of the step, estimates of magnitude were ranked. From previous studies of natural variability, we thought logarithms of the differences across the step might be distributed with about normal probability, an hypothesis that would be supported if the logarithms occurred as a straight line on normal probability paper. The difference across the step for each environmental variable was expressed as $ln(d+1)$, where 1 has been added to avoid negative logarithms. The values of $ln(d+1)$ were ranked from smallest to largest and the rank (j) converted to cumulative probability (p), using the convention $p=(j-0.5)/40$ (Mann *et al.* 1974). In the graph of $ln(d+1)$ *versus* p (Figure 3), the abscissa corresponds to the non-exceedance probability for a normal distribution.

To explore the ranking of the step magnitudes, three inquiries were made.

- Variables drawn from the Pacific Northwest and Pacific Ocean areas were combined, then inspected to determine whether variables from both areas occur at intervals throughout the ranking for the combined data sets (Table 1 and Figure 3). If data from the two areas were different, values for one of the areas might be expected to cluster in a portion of the overall ranking. Also, the clustering might be evident in abrupt changes in the slope of the probability distribution. Since neither clustering (Table 1) nor obvious changes of slope (Figure 3) is present, we infer that responses from the two areas are similar.

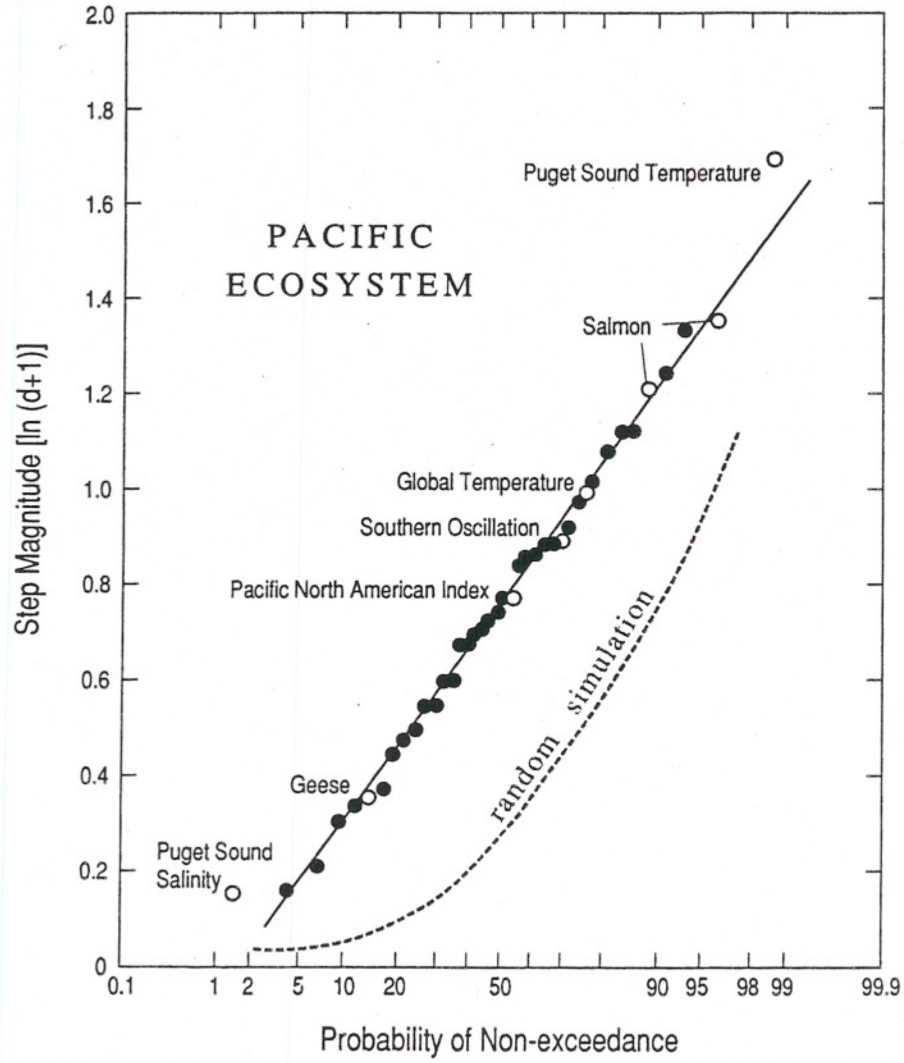
- Quantitative tests, following the method of Aitchison and Brown (1969) for log-normal distributions, showed that means and variances of the Pacific Northwest and Pacific Ocean variables were not different at the 95% limit. The foregoing analyses suggest that distributions at the two spatial scales are not substantially different.

- The distribution for the combined data was compared with a distribution constructed using random numbers (Figure 3) by simulating the time series of the variables with trials of 17 numbers drawn at random from a table of random numbers (Table 26.11, Abramowitz and Stegun 1965).

As described above, standard deviates were computed for each random number series as if it were an environmental variable. The average step magnitude for the random numbers (0.50 deviates) differed from the mean of the environmental variables (1.29 deviates) by 6-9 times the standard errors of the samples (0.10 for random numbers; 0.13 for environmental variables). The magnitudes of the step for the environmental variables appear to be substantially larger than the simulations with random numbers.

Figure 3
DISTRIBUTION OF 40 ENVIRONMENTAL VARIABLES AND SIMULATION WITH RANDOM NUMBERS

Circles illustrate selected variables. The vertical axis represents a logarithmic transformation of the step's magnitude between 1968-1976 and 1977-1984. The horizontal axis is the probability of non-exceedance for the normal distribution.



Discussion

We are in agreement with the statement of McGowan (1989):

> *We have very little in the way of conceptual models that provide testable predictions of the behavior of complex pelagic systems, especially how they may or may not respond to climate forcing.*

Our analysis of a 17-year time series of many variables characterizing the Pacific ecosystem suggests that, after a number of years of minor interannual variability, the ecosystem may undergo a substantial shift followed by a return to secondary variability. In this sample, variables shifted in 1976 by an amount averaging 4-7 times interannual variability during the preceding and succeeding eight years.

In our sample a number of environmental variables do not show substantial change. For example, 16 of the variables had steps less than the mean-plus-one standard deviation for the random numbers (one deviate). Nevertheless, they are part of the continuum of changes associated with the overall step. Consequently, they deserve as much attention as the variables that changed substantially.

In a study of the variable at the lowest percentile (salinity in deep water in Puget Sound at the first percentile, Table 1), salinity changed by only a small amount, because influences at the oceanic scale tended to cancel those at the regional scale (Ebbesmeyer *et al.* 1989). Specifically, as the Aleutian low pressure center shifts toward the west, storm tracks shift to the south and more frequently intersect drainage basins in the Pacific Northwest. The increased runoff to Puget Sound tends to lower the deep salinity. However, as the storm tracks shift, so do the advective oceanic processes that influence the oceanic source of water for Puget Sound. While Puget Sound salinity tends to decrease as streamflow increases, the oceanic source becomes saltier, with the net result that, when averaged over a decade, the deep salinity tends to not change by significant amounts.

The foregoing example suggested to us that variables at lower percentiles are controlled by linkages that have the net effect of canceling one another, whereas linkages for the variables at higher percentiles tend to amplify one another. When viewed this way, the linkages that tend to cancel become as informative as those that greatly amplify.

Although we have focused on the Pacific Northwest, where variables range between ranks of 1 and 40, environmental variables in our sample also cluster around other regions of the Pacific ecosystem. For example, variables near Hawaii range between ranks of 4 and 30, and in northern South America they between 3 and 32. These three areas illustrate that even if an area is small compared with the overall Pacific Ocean, variability of the response remains nearly as large as that for the entire environmental system.

Conclusions

As many environmental variables describing the Pacific Ocean environmental system changed abruptly in 1976, a single step between constant values during the periods 1968-1975 and 1977-1984 accounted for 89% of the variance of a composite time series derived from annual values of 40 multidisciplinary environmental variables. Regional and large-scale environmental variables changed by similar degrees within the overall probability distribution.

Available time series covering decades are unevenly distributed among the disciplines. Therefore, to adequately describe the Pacific system and its statistics and dynamics, many more time series of biological/chemical/physical variables spanning decades must be obtained.

Acknowledgments

We thank the sponsors and participants of the Pacific Climate (PACLIM) workshops for their encouragement and suggestions. We also thank the following colleagues for sharing unpublished data: Mark Albright and Jack Rensel (University of Washington), Wendell Tangborn (Hymet, Inc.), and Paul R. Olson (City of Seattle). We are also grateful to Dora P. Henry for editing and Jeanne Delio-Stevens for preparing the figures.

References

Abramowitz, M., and I.A. Stegun. 1965. *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables.* National Bureau of Standards, Applied Mathematics Series 55.

Aitchison, J., and J.A.C. Brown. 1969. *The Lognormal Distribution.* Cambridge University Press.

Bakun, A. 1990. "Global Climate Change and Intensification of Coastal Ocean Upwelling", *Science*, 247:198-201.

Baumgartner, T.R., J. Michaelsen, L.G. Thompson, G.T. Shen, A. Soutar, R.E. Casey. 1989. "The Recording of Interannual Climatic Change by High-Resolution Natural Systems: Tree Rings, Coral Bands, Glacial Ice Layers, and Marine Varves" in *Aspects of Climate Variability in the Pacific and the Western Americas*. Ed. D.H. Peterson. American Geophysical Union. Geophysical Monograph 55:1-14.

Benjamin, J.R., and C.A. Cornell. 1970. *Probability, Statistics, and Decision for Civil Engineers.* McGraw-Hill.

Bumgartner, R.H. 1989. "Puget Sound Crab and Shrimp Management" in *Status and Management of Puget Sound's Biological Resources.* Ed. J.W. Armstrong and A.E. Copping. Proceedings from the Forum on Puget Sound's Biological Resources — Status and Management, September 11-12, 1989. p. 32-47.

Coachman, L.K. and K. Aagaard. 1988. "Transports Through Bering Strait: Annual and Interannual Variability". *J. Geophys. Res.*, 93(C12):15535-15539.

Ebbesmeyer, C.C., C.A. Coomes, G.A. Cannon, and D.E. Bretschneider. 1989. "Linkage of Ocean and Fjord Dynamics at Decadal Period" in *Aspects of Climate Variability in the Pacific and the Western Americas*. Ed. D.H. Peterson. American Geophysical Union. Geophysical Monograph 55:399-417.

Environment Canada. 1989. *Historical Streamflow Summary, British Columbia.* Inland Waters Directorate, Water Resources Branch, Water Survey of Canada. Ottawa.

Fitzner, R.E. and W.H. Rickard. 1983. "Canada Goose Nesting Performance Along the Hanford Reach of the Columbia River, 1971-1981". *Northwest Science*, 57(4):267-272.

Hamilton, K. 1987. "Interannual Environmental Variation and North American Fisheries". *Bulletin American Meteorological Society*, p. 1541-1548.

Hanson, W.C. and L.L. Eberhardt. 1983. "A Columbia River Canada Goose Population 1959-1970". *Wildlife Monograph* No. 27, The Wildlife Society.

Jones, P.D., T.M.L. Wigley, and P.B. Wright. 1986. "Global Temperature Variations Between 1861 and 1984". *Nature*, 322:430-434.

Keeling, C.D., R.B. Bacastow, A.F. Carter, S.C. Piper, T.P. Whorf, M. Heimann, W.G. Mook, and H. Roeoffzen. 1989. "A Three-Dimensional Model of Atmospheric CO_2 Transport Based on Observed Winds: 1. Analysis of Observational Data" in *Aspects of Climate Variability in the Pacific and the Western Americas*. Ed. D. H. Peterson. American Geophysical Union, Geophysical Monograph 55:165-236.

Manak, D.K., and L.A. Mysak. 1987. *Climatic Atlas of Arctic Sea Ice Extent and Anomalies, 1953-1984*. Climate Research Group Report 87-8.

Mann, N.R., R.E. Schafer, and N.D. Singpurwalla. 1974. *Methods for Statistical Analysis of Reliability and Life Data*. John Wiley and Sons.

McGowan, J.A. 1989. "Pelagic Ecology and Pacific Climate". in *Aspects of Climate Variability in the Pacific and the Western Americas*. Ed. D.H. Peterson. American Geophysical Union, Geophysical Monograph 55:141-150.

McLain, D.R. 1983. "Coastal Ocean Warming in the Northeast Pacific, 1976-83". in *The Influence of Ocean Conditions on the Production of Salmonids in the North Pacific*. Ed. W.G. Pearcy, Oregon State University, Sea Grant College Program, ORESU-W-83-001, pp. 61-86.

Montroll, E.W., and W.W. Badger. 1974. *Introduction to Quantitative Aspects of Social Phenomena*, Gordon and Breach Science Publishers.

Nichols, F.H. 1988. "Long-Term Changes in a Deep Puget Sound Benthic Community: Local or Basinwide?" in *Proceedings First Annual Meeting on Puget Sound Research,* Vol. 1, pp. 65-71.

National Oceanic and Atmospheric Administration. 1988. "The Role of Sea Ice in Controlling Arctic Ecosystems" in *Ocean System Studies NOAA/OAR Research Strategy I, The Ocean System — Prediction and Resources*.

Norton, J., D. McLain, R. Brainard, and D. Husby. 1985. "The 1982-83 El Niño Event Off Baja and Alta California and Its Ocean Climate Context" in El *Niño North: Niño Effects in the Eastern Subarctic Pacific Ocean*. Ed. W.S. Wooster and D.L. Fluharty. Washington Sea Grant Program, WSG-W0 85-3. p. 44-72.

Peterson, D.H. Ed. 1989. *Aspects of Climate Variability in the Pacific and the Western Americas*. American Geophysical Union, Geophysical Monograph 55.

Richey, J.E., C. Nobre, and C. Deser. 1989. "Amazon River Discharge and Climate Variability: 1903 to 1985". *Science*, 246:101-102.

Royer, T.C. 1989. "Upper Ocean Temperature Variability in the Northeast Pacific Ocean: Is It an Indicator of Global Warming?" *J. Geophys. Res.*, 94(C12):18175-18183.

Tangborn, W. 1990. "A Basin Water Storage Model for Forecasting Columbia River Runoff". Presented at Northern Hydrology Symposium, Saskatoon, Saskatchewan.

Thompson, L.G., and E. Mosley-Thompson. 1989. "One-Half Millennia of Tropical Climate Variability as Recorded in the Stratigraphy of the Quelccaya Ice Cap, Peru". in *Aspects of Climate Variability in the Pacific and the Western Americas*, Ed. D.H. Peterson. American Geophysical Union, Geophysical Monograph 55:15-31.

Trenberth, K.E. 1990. "Recent Observed Interdecadal Climate Changes". American Met. Soc. Special Session on Climate Variations and Joint Session on Hydrology and Climate Variations, Anaheim, CA, February 4-9.

Venrick, E.L., J.A. McGowan, D.R. Cayan, and T.L. Hayward. 1987. "Climate and Chlorophyll *a*: Long-Term Trends in the Central North Pacific Ocean". *Science,* 238:70-72.

Wallace, J.M., and D.S. Gutzler. 1981. "Teleconnections in the Geopotential Height Field During the Northern Hemisphere Winter". *Monthly Weather Review,* 109(4):784-812.

Walters, R.A., and M.F. Meier. 1989. "Variability of Glacier Mass Balances in Western North America" in *Aspects of Climate Variability in the Pacific and the Western Americas*. Ed. D.H. Peterson. American Geophysical Union, Geophysical Monograph 55:365-374.

CL/PACLIM-IATR/91-26

PROCEEDINGS OF THE SEVENTH ANNUAL PACIFIC CLIMATE (PACLIM) WORKSHOP

Asilomar, California – April 1990

Edited by
Julio L. Betancourt and Vera L. Tharp

Technical Report 26
of the
Interagency Ecological Studies Program
for the
Sacramento-San Joaquin Estuary

April 1991