# Climate Change and Salmonid Production in the North Pacific Ocean

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Extreme catches of northeastern Pacific salmon seem to be frequent rather than rare events. Throughout the 1960s and early 1970s, record high catches were realized for stocks originating in streams of Washington, Oregon, and California, while record low catches occurred in the valuable commercial salmon fisheries of Alaska. A major shift in relative fortunes took place beginning in the late 1970s. Recent production of salmon has been so high in Alaska that prices have fallen drastically and much of the product cannot be sold profitably. Conversely, salmon production along the West Coast has fallen so low that the Pacific Fishery Management Council recently considered an option that would eliminate ocean sport and commercial harvest in 1992 from California to Washington. Both sudden declines and increases in salmon production have been either blamed on or credited to a number of natural and anthropogenic factors, "the environment" always being mentioned but in a rather nebulous manner. These recent issues, however, highlight the critical need to understand the long-term effects of the marine environment on the production of northeastern Pacific salmonid stocks and fisheries.

Climate fluctuations and their subsequent oceanic impacts are becoming recognized as important phenomena affecting low-frequency (interdecadal) shifts in large marine ecosystems, resulting in subsequent shifts in marine fisheries production. A recent NOAA plan (NOAA 1989) indicates that, with respect to long-term (interdecadal) shifts in fishery production, a major question that needs to be addressed is: How are large-scale atmospheric and oceanic processes linked to major changes in fish community structure? That is the focus of a research project being conducted, under the support of Washington Sea Grant, by Stephen Riser (University of Washington Department of Oceanography), Warren Wooster (University of Washington School of Marine Affairs) and me. Our specific biological focus is on Pacific salmon for a number of reasons that will be explained later. In general, however, we are attempting to understand the causes and marine biological manifestations of interdecadal shifts in North Pacific atmosphere and ocean regimes.

This paper contains three sections. The first presents an overview of the northeastern Pacific in terms of its component large marine ecosystems and their defining physics and biology. The second attempts to answer the question, why salmon? And the third presents a very rough and

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highly speculative model of how atmosphere, ocean, and marine biological production are linked in the North Pacific, resulting in low-frequency and not necessarily in-phase shifts in fisheries production of the major regions.

## Large Marine Ecosystems of the Northeastern Pacific

Physical oceanographers have identified specific domains in the upper zone of the northeastern Pacific Ocean where water properties are influenced predominantly by seasonal heating and cooling, precipitation, evaporation, and wind mixing (Ware and McFarland 1989). Four of these are critical to the structure and dynamics of northeastern Pacific fisheries production.

The **Transitional Domain** (Figure 1) is one of the main oceanic features of the North Pacific. It lies between the subarctic and subtropical gyres and extends from Japan to North America (Roden 1991). The domain, which lies between the subarctic boundary and the Central Subarctic Domain, is defined on both its northern and southern boundaries by strong salinity and temperature fronts extending from the surface to a depth of about 250 meters (Roden 1975, 1991; Pearcy 1991). The eastward zonal flow in this region is referred to as the Subarctic Current (Figure 1). In the western Pacific this region is defined by the confluence

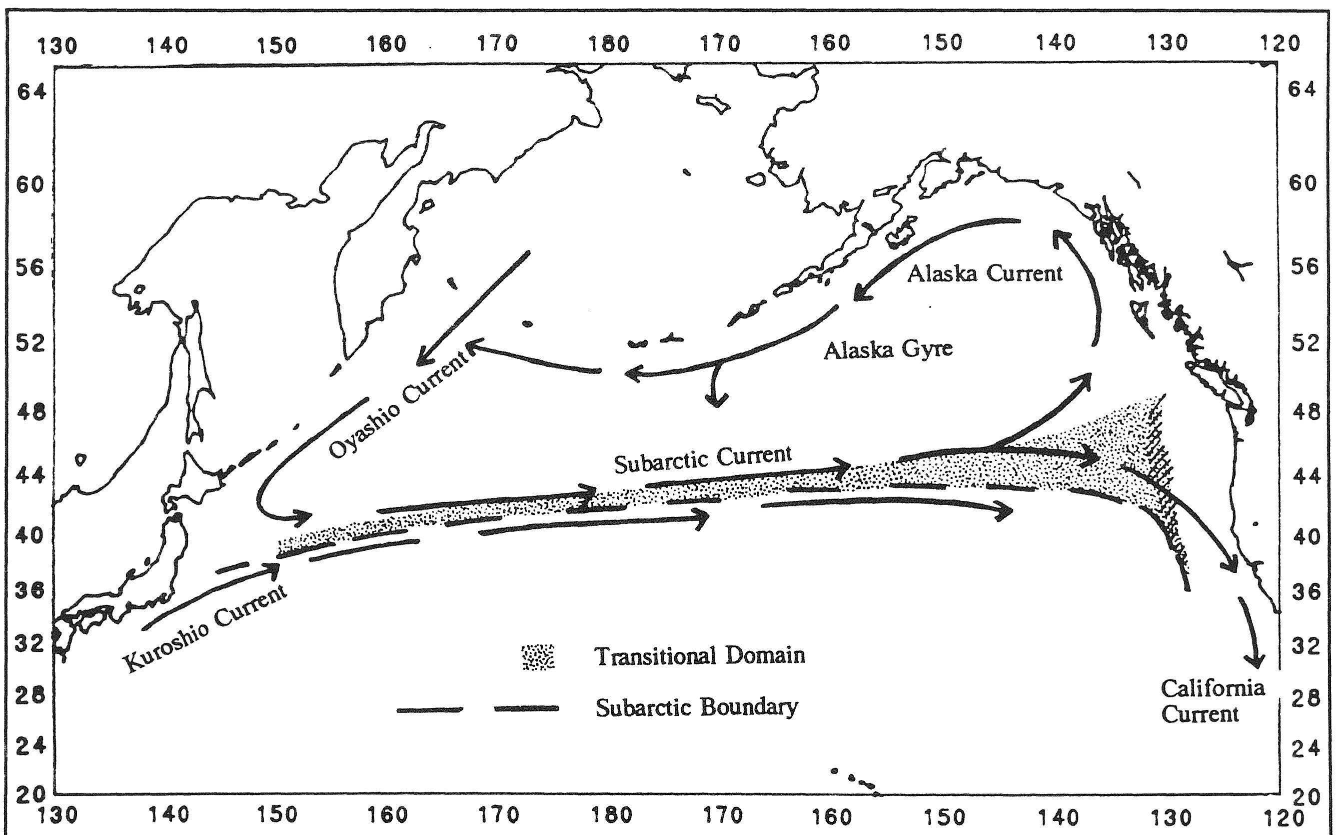


Figure 1. Relevant large-scale upper-level physical oceanography of the Subarctic North Pacific.

of the Oyashio and Kuroshio currents. Conditions influencing formation of the Subarctic Boundary and Subarctic Current are extremely variable (Favorite *et al* 1976; Kawasaki 1983). In the northeastern Pacific, the eastward flowing Subarctic Current separates into two streams about 800 kilometers off shore. One branch (Alaska Current) veers northward and flows into the Gulf of Alaska; the other branch flows southward to form the California Current. This frontal structure, strong eastward zonal flow, and bifurcation at the North American coast are major physical factors that define the other three oceanic domains critical to northeastern Pacific fisheries production (Ware and McFarland 1989). In the summer, large concentrations of flying squid have been harvested by Asian pelagic drift-net fisheries operating in the Transitional Domain.

The **Coastal Upwelling Domain** (California Current) lies off the coast of Washington, Oregon, and California and is a subarctic water mass contained within the southern component of the Subarctic Current bifurcation. This domain is defined by wind-driven equatorward surface flow in the spring and summer resulting in episodic upwelling of cold nutrient-rich water and poleward surface flow in the autumn and winter, during which time downwelling prevails (Pearcy 1991). The transition from poleward to equatorward flow occurs abruptly in the spring and the reverse transition occurs somewhat less abruptly in the autumn. This domain is dominated by a unique assemblage of pelagic species common to most of the major eastern boundary current regions of the world.

The **Coastal Downwelling Domain** ( Alaska Current) lies off the coast in the Gulf of Alaska and is a subarctic water mass contained within the northern component of the Subarctic Current bifurcation. This domain seems to exhibit considerably larger interannual fluctuations than seasonal fluctuations in flow (Reed and Schumacher 1987). At present, it is not clear whether or how the dynamics and intensity of the Alaska Current respond to a very large annual signal in wind and precipitation in the Gulf of Alaska, which is dominated in summer by the North Pacific High and in winter by the Aleutian Low and its accompanying intense cyclonic pressure systems (Royer 1983). Waters contained within the Coastal Downwelling Domain support major salmon, groundfish, crustacean, and herring fisheries.

The **Central Subarctic Domain** lies in the central Gulf of Alaska and is defined by the Alaska Gyre, which rotates in a cyclonic direction. According to Brodeur and Ware (1992), upwelling occurs in the core of the gyre because of a wind-induced divergence in the upper oceanic layer, thus making the domain relatively productive for an oceanic region (Brodeur and Ware 1992). The Central Subarctic Domain serves as an oceanic pasture for many of the Pacific salmon stocks harvested along the northeastern Pacific coast from Alaska to California.

For our research, one of the most striking features associated with the interactions between domains is that a number of physical variables associated with atmospheric conditions (*eg*, temperature, coastal upwelling) and the biological responses of fish in the Alaska and California currents are out of phase (Tabata 1991; Hollowed and Wooster 1991). In our initial work, we have found similar responses in salmonid production (Figure 2). Furthermore, Wickett (1967) and Chelton (1983) speculate that the strengths of the Alaska and California currents apparently fluctuate out of phase. That is, when one of the currents is stronger than normal, the other is weaker. They hypothesize that these north-south shifts in the bifurcation of the subarctic current could be forced by physical factors at or upstream of the bifurcation. Tabata (1991), on the other hand, indicates this "apparent" out-of-phase relationship could be partially due to the influence of in-phase coastal currents that extend from south of the coast of California to Canada. Linked to this is the hypothesis that the fronts that define the Transitional Domain are highly variable in their location. Kawasaki (1983) indicates that in the western Pacific the stream axis of the Kuroshio Current shifts dramatically from year to year and has a significant impact on long-term fluctuations in abundance of Far Eastern sardine. Fulton and LeBrasseur (1985) show evidence of extreme northward shifting of the eastern extension of the Subarctic Boundary in response to anomalous warming events.

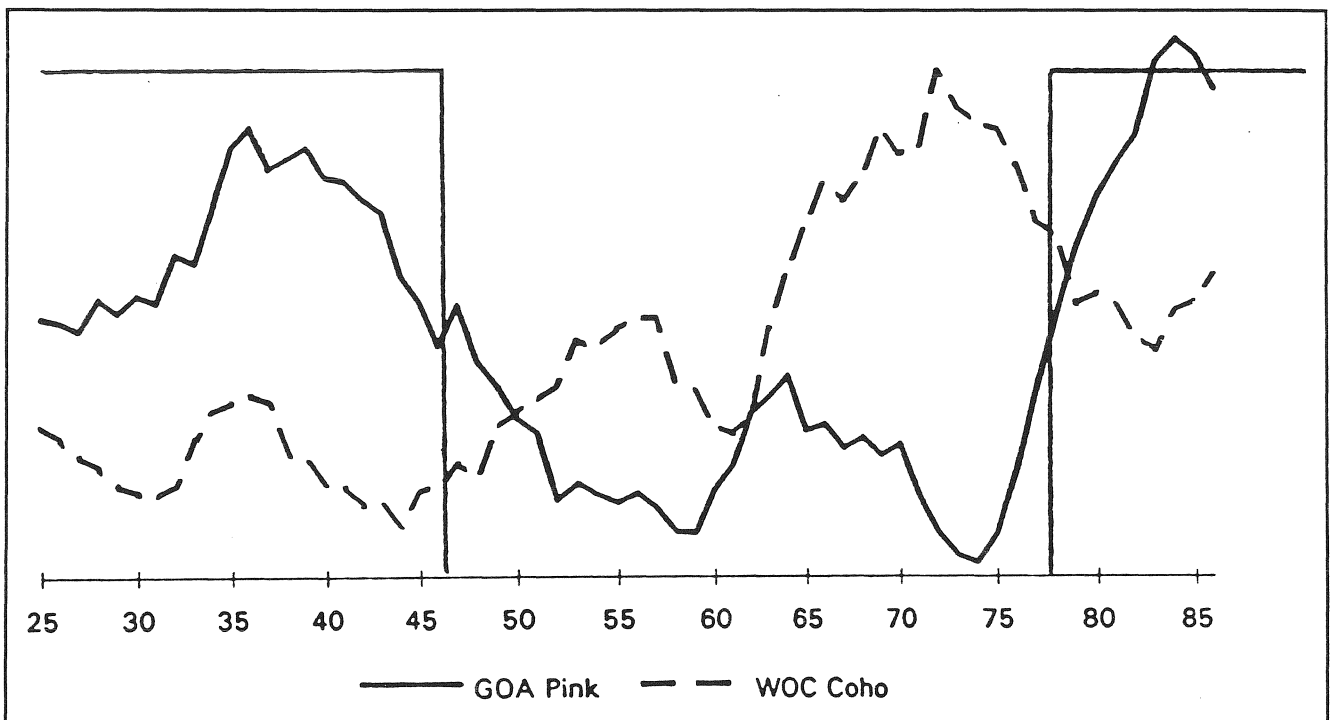


Figure 2. Normalized and smoothed (5-year running mean) pink salmon catch in the Gulf of Alaska and coho salmon catch in the Washington/Oregon/California region.

## Why Salmon?

Pacific salmon are unique in the northeastern Pacific pelagic ecosystem in that their life histories depend on and integrate the physical dynamics of all four of the domains described in the previous section. In addition, the five principal salmonid species (pink, chum, sockeye, coho, and Chinook) have very different marine life histories. Pink, chum, and sockeye are considered oceanic, spending a major part of their marine life histories in the Central Subarctic Domain, whereas some stocks of coho and Chinook may remain in coastal waters for their entire marine life. In addition, because of a long history of high-valued exploitation, accurate records of salmonid harvest exist for most of the region for more than a century.

The most important aspects of biological production, with particular reference to salmonids, involve major long-term (interdecadal) fluctuations and synchrony in these trends between different oceanic domains of the northeastern Pacific, as well as between distant regions of the Pacific. Combined with this is the fact that the dynamics of salmon production for a particular domain seem to reflect low-frequency couplings of atmospheric and oceanic processes. This is described in the next section.

Examination of the time series of total landings of Pacific salmon throughout the North Pacific (Shepard *et al* 1985) shows landings peaked in the late 1930s and early 1940s, dropped off in the late 1940s through early 1970s, and peaked again in the late 1970s and 1980s. Areal breakdowns of Pacific salmon catch statistics reveal these peaks were due mainly to high catches of sockeye salmon in western Alaska (primarily Bristol Bay), pink salmon in central and southeastern Alaska, and Asian chum salmon. All three of these species are considered oceanic, occupying the Central Subarctic Domain for a significant part of their marine life histories. Ware and McFarland (1989) estimate the mean salmonid biomass of the Central Subarctic Domain has increased from a low of 480,000 metric tons between 1956 and 1972 to 820,000 metric tons between 1973 and 1984.

Abundance of coastal salmonid species, including coho and Chinook, which predominate in the coastal region from southeastern Alaska to California, as well as stocks of southern chum, was out of phase with the trends for oceanic salmonids (Figure 2). Catches of coho, Chinook, and southern chum were relatively high during the 1960s and 1970s and then declined beginning in the late 1970s. Rogers (1987) hypothesizes that there is either a competitive interaction between southern and northern stocks or an inverse relationship between oceanic conditions favorable for survival. Similar relationships have been discussed by others (*eg*, Peterman and Wong 1984).

## A Speculative Model

In an attempt to tie together the multidisciplinary nature of our Sea Grant-sponsored research project, we have arrived at a very rough and highly speculative model of how atmosphere, ocean, and marine biological production are linked in the North Pacific, resulting in low frequency and not necessarily in-phase shifts in fisheries production of the major domains. Hollowed and Wooster (1991) hypothesize two mean states of winter atmospheric circulation in the North Pacific — termed Type B and Type A (Figure 3, upper right and lower right panels).

Type B is characterized by (Figure 3, upper right panel):

- A strong winter mean Aleutian Low (AL) with its center located to the east,
- Enhanced southwesterly winds in the northeastern Pacific,
- A more southerly bifurcation of the Subarctic Current,
- Enhanced northward flow at the bifurcation, resulting in increased advection of subarctic water into the Alaska Current,
- Decreased advection into the California Current,
- Positive SST anomalies (+T) throughout the northeastern Pacific and a negative SST anomaly in the central North Pacific (centered on 40°N) (Figure 3, upper left panel).

Type A is characterized by (Figure 3, lower right panel):

- A weak winter mean Aleutian Low (AL) with its center located in the western North Pacific,
- Enhanced westerly winds in the NE Pacific,
- A more northerly bifurcation of the Subarctic Current,
- Enhanced southward flow at the bifurcation resulting in increased advection of subarctic water into the California Current,
- Decreased advection into the Alaska Current,
- Negative sea surface temperature (SST) anomalies (–T) throughout the northeastern Pacific and a positive SST anomaly in the central North Pacific (centered on 40°N) (Figure 3, lower left panel).

The middle panel of Figure 3 shows normalized and smoothed mean Kodiak winter (November-March) air temperature and Gulf of Alaska pink salmon (the dominant species) catches. What is striking is the astounding correlation of overall pattern between these two time series. We hypothesize that abrupt shifts in both winter temperature (winter Gulf of Alaska atmospheric and oceanic temperatures highly correlated) and salmon production (reflected in catch statistics) are related to abrupt shifts between these two mean states of the North Pacific atmosphere and

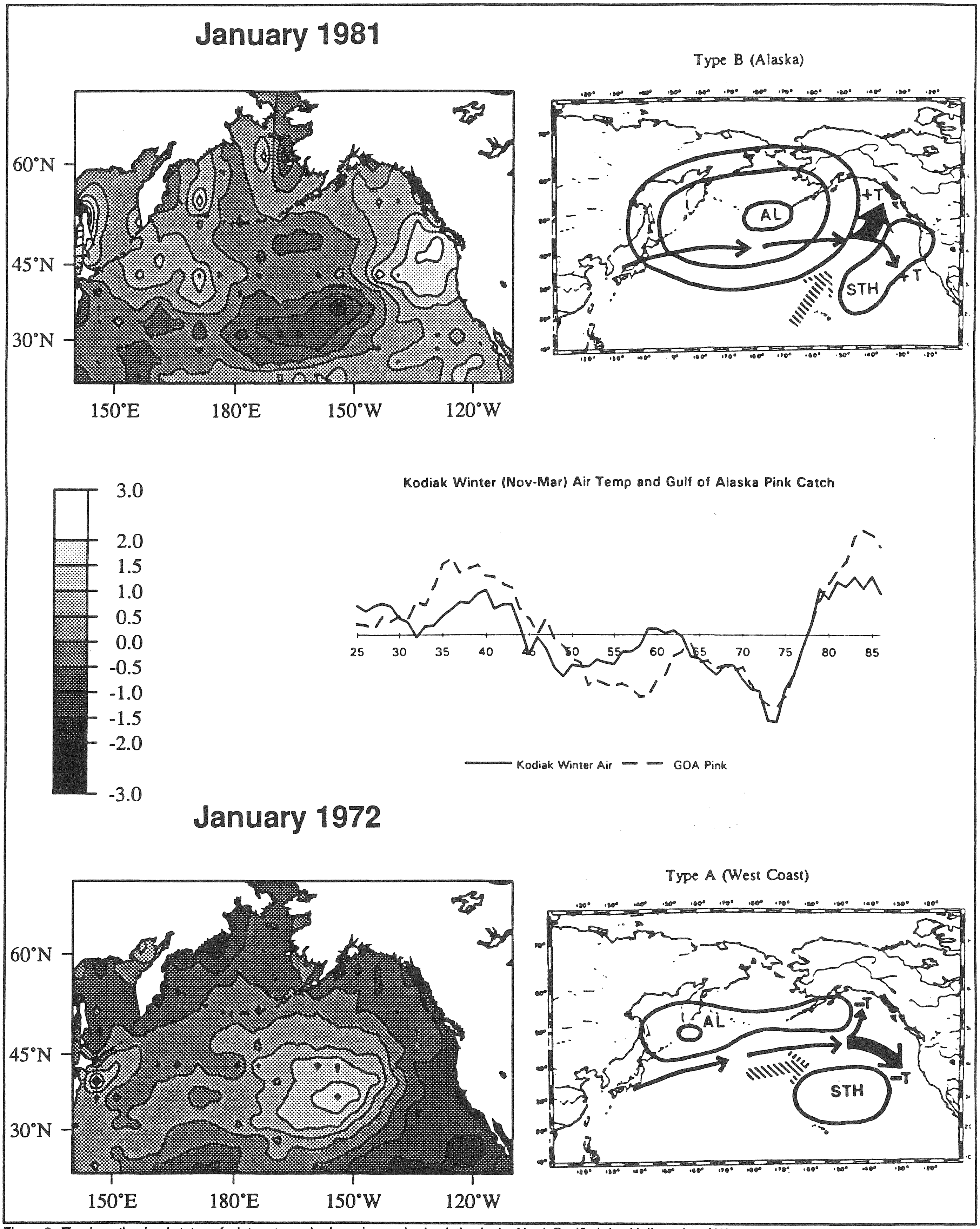


Figure 3. Two hypothesized states of winter atmospheric and oceanic circulation in the North Pacific (after Hollowed and Wooster 1991). (Color copy of this figure is available from the author.)

ocean. Hollowed and Wooster (1991) further point out that over the last 60 years the switch from Type-A state to Type-B state has always occurred at the time of significant El Niño events (*eg,* 1925-26, 1940-41, 1957-58, 1976).

Figure 4 further illustrates how these circulation patterns might relate to long-term trends in northeastern Pacific salmonid production. In the top panel we have plotted:

- Hollowed and Wooster's time series of Type-B and Type-A states from 1925 to 1985,
- Normalized and smoothed Kodiak Island winter air temperature,
- Extreme high and low values of the Central North Pacific (CNP) winter atmospheric pressure index (Cayan and Peterson 1989), which is highly correlated with both the Pacific-North American (PNA) teleconnection pattern (Horel and Wallace 1981) and the intensity of the winter Aleutian Low.

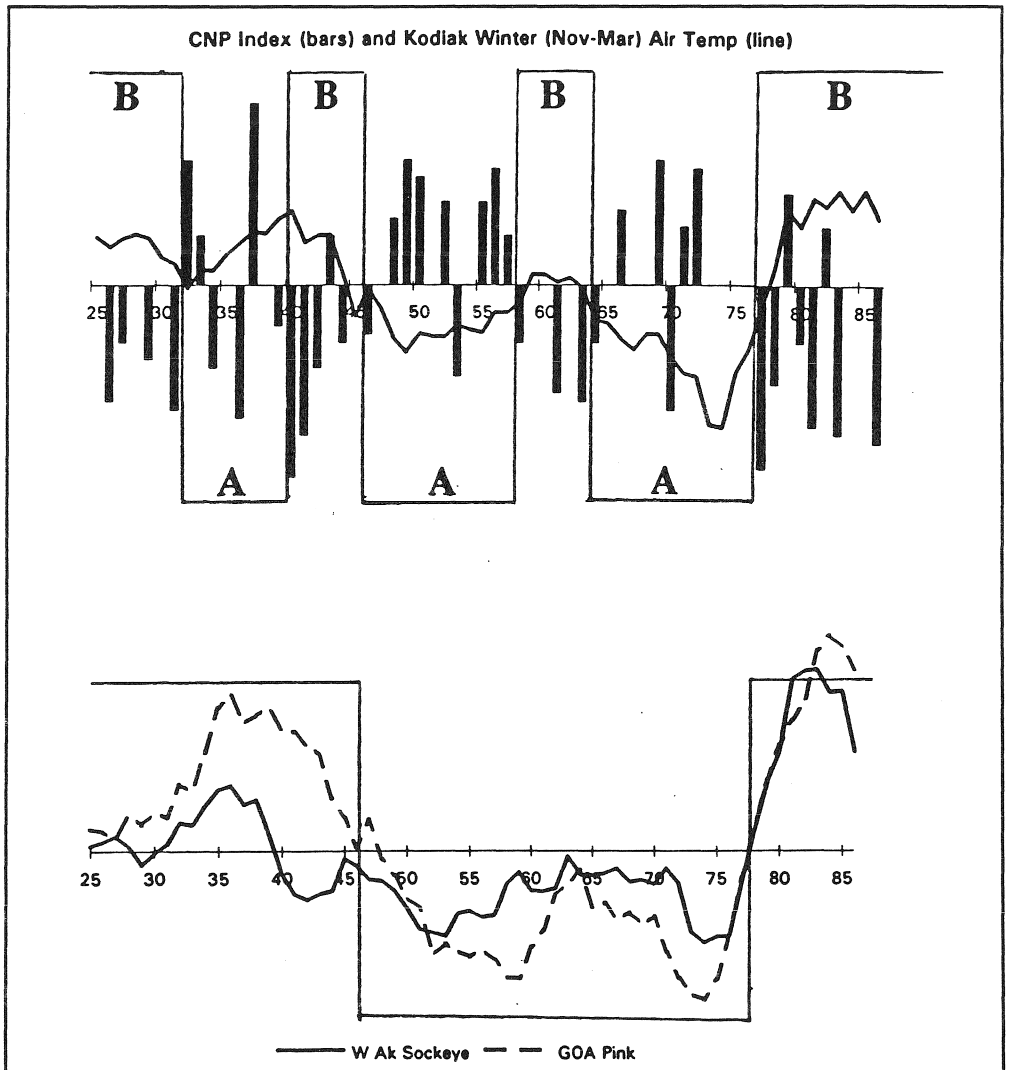


Figure 4. Relationships between Type A/B circulation, Central North Pacific Index, normalized and smoothed Kodiak winter air temperature, western Alaska sockeye salmon catch, and Gulf of Alaska pink salmon catch.

In the bottom panel of Figure 4, we have plotted normalized and smoothed western Alaska sockeye and Gulf of Alaska pink salmon catches, which are the predominant species caught in these two regions. Not only are the long-term patterns similar, but they also show striking correspondence to winter temperature patterns in the upper panel and, in turn, to hypothesized atmosphere/ocean patterns represented by the CNP index and the Type A/B oscillations. Patterns in Alaska salmon production also tend to indicate longer periods of oscillating "warm" and "cool" regimes (early 1920s to late 1940s/early 1950s, early 1950s to mid-1970s, mid-1970s to present). Finally, the hypothesized out-of-phase behavior of the long-term production dynamics of the Alaska Current (GOA Pink) and California Current (WOC Coho) production domains is shown in Figure 2.

## Epilogue

As an epilogue to what I presented at the 1992 PACLIM meeting, I would like to report on some further developments in this research project that resulted directly from having the chance to meet at PACLIM with multidisciplinary scientists working on other aspects of this same problem. This was my first PACLIM meeting and I was impressed with the general theme of a continuous scientific process, with ideas, concepts, and dialogues being carried on between scientists from one year to the next.

Sus Tabata emphasized that I had somewhat misinterpreted his paper (Tabata 1991) concerning possible mechanisms that might cause the relative intensities of the California and Alaska Currents to be out of phase. He pointed my attention to the role of the coastal currents and undercurrents in the California Current system and how their in-phase relationships might affect apparent out-of-phase relationships in the California-Alaska Currents. This, in turn, links to a discussion with Tim Baumgartner who interprets the intensification of these coastal counter currents and weakening of the California Current as "poleward expansions of tropical influences".

Tom Murphree and George Kiladis opened my eyes to atmosphere/ocean connections between the equator and North Pacific and the importance of the Western Pacific Warm Pool and Subtropical Jet to those connections. Based on discussions with Tom and George and readings they suggested, I have now learned that:

- The extratropical atmospheric response to anomalies in the tropical Pacific are strongest and most clearly defined in response to tropical warm episodes during the Northern Hemisphere winter,
- Subtle dynamics of the Western Pacific Warm Pool, associated with the ENSO cycle, may have a profound effect on Northern Hemisphere winter circulation, and

- The strong extratropical teleconnection during ENSO events generally occurs when the SST in the far western Pacific is anomalously warm (or at least not too cold).

Closing the circle somewhat, three of the four hypothesized shifts from Type-A to Type-B states in the North Pacific given in Figure 4 (1925/26, 1941/42 and 1976/77) coincide with ENSO winters reported by Hamilton (1988) to have the highest SST in the far western Pacific.

## References


Brodeur, RD, and DM Ware . 1992. Interannual and interdecadal changes in zooplankton biomass in the subarctic Pacific Ocean. *Fisheries Oceanography* (1).

Cayan, DH,. and DH Peterson. 1989. The influence of North Pacific atmospheric circulation on streamflow in the west. pp. 375-398 in DH Peterson (ed), *Aspects of Climate Variability in the Pacific and Western Americas*. AGU Geophysical Monograph 55.

Chelton, DB. 1983. Commentary: Short-term climatic variability in the Northeast Pacific Ocean. pp. 87-99 in WG Pearcy (ed), *The Influence of Ocean Conditions on the Production of Salmonids in the North Pacific*. OSU Sea Grant Publ. ORESU-W-83-001.

Favorite, F, AJ Dodimead, and K Nasu. 1976. Oceanography of the subarctic Pacific region, 1960-71. *Int. North Pac. Fish. Com. Bull.* 33. 187 pp.

Fulton, JD, and RJ LeBrasseur. 1985. Interannual shifting of the subarctic boundary and some biotic effects on juvenile salmonids. pp. 237-252 in WG Wooster and DL Fluharty (eds), El Niño North. Wash. Sea Grant Publ. WSG-W085-3.

Hamilton, K. 1988. A detailed examination of the extratropical response to tropical EL Niño/Southern Oscillation events. *J. of Climatology* 8: 67-86.

Hollowed, AB, and WS Wooster. 1991. Year class variability of marine fishes and winter ocean conditions in the Northeast Pacific Ocean. ICES Variability Symp. Paper No. 33, Session 3.

Horel, JD, and JM Wallace. 1981. Planetary-scale atmospheric phenomena associated with the Southern Oscillation. *Month. Weath. Rev.* 109: 813-829.

Kawasaki, T. 1983. Why do some pelagic fisheries have wide fluctuations in their numbers? Biological basis of fluctuations from the viewpoint of evolutionary ecology. pp. 1081-1111 in GD Sharp and J Csirke (eds), *Proceedings of the Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Resources*. San Jose, Costa Rica. April 1983. FAO Fish. Rep. 291 (3).

NOAA. 1989. Recruitment Fisheries Oceanography. Program Development Plan.

Pearcy, WG. 1991. Biology of the transition region. pp. 39-56 in J Wetherall (ed), *Biology, Oceanography, and Fisheries of the North Pacific Transition Zone and Subarctic Frontal Zone*. NOAA Tech. Rep. NMFS 105.

Peterman, RM,and FYL Wong. 1984. Cross correlations between reconstructed ocean abundances of Bristol Bay and British Columbia sockeye salmon (*Oncorhynchus nerka*). *Can J. Fish. Aquat. Sci.* 41: 1814-1824.

Reed, RK, and JD Schumacher. 1987. Physical oceanography. pp. 57-76 in DW Hood and ST Zimmerman (eds), *The Gulf of Alaska: Physical Environment and Biological Resources*. Alaska Office, Ocean Assessment Division, NOAA, Washington, DC.

Roden, GI. 1975. On the North Pacific temperature, salinity, sound velocity and density fronts and their relation to the wind and energy flux fields. *J. Phys. Ocean.* 5: 557-571.

______. 1991. Subarctic-subtropical transition zone of the North Pacific: Large-scale aspects and mesoscale structure. pp. 1-38 in J Wetherall (ed), *Biology, Oceanography, and Fisheries of the North Pacific Transition Zone and Subarctic Frontal Zone.* NOAA Tech. Rep. NMFS 105.

Rogers, DE. 1987. Pacific salmon. pp. 461-476 in DW Hood and ST Zimmerman (eds), *The Gulf of Alaska: Physical Environment and Biological Resources.* Alaska Office, Ocean Assessment Division, NOAA, Washington, DC.

Royer, TG. 1983. Annual and interannual variability of temperature and salinity in the Gulf of Alaska with emphasis on coastal waters. pp. 244-255 in WG Pearcy (ed), *The Influence of Ocean Conditions on the Production of Salmonids in the North Pacific.* OSU Sea Grant Publ. ORESU-W-83-001.

Shepard, MP, CD Shepard, and AW Argue. 1985. Long-term trends in the contributions of salmon from different geographical areas to the commercial fisheries of the North Pacific. *Can Tech. Rep. Fish. Aquat. Sci.* 1376.

Tabata, S. 1991. Annual and interannual variability of baroclinic transports across Line P in the Northeast Pacific Ocean. *Deep Sea Research* 38: 5221-5245.

Ware, DM, and GA McFarland. 1989. Fisheries production domains in the Northeast Pacific Ocean. *Can. Spec. Publ. Fish. Aquat. Sci.* 168: 359-379.

Wickett, WP. 1967. Ekman transport and zooplankton concentration in the North Pacific Ocean. *J. Fish. Res. Bd. Can.* 24: 581-594.