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CHAPTER 4

VARIABILITY AND STABILITY OF CLIMATIC/OCEANIC REGIMES IN THE PACIFIC NORTHWEST

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INTRODUCTION

This chapter addresses the variability and stability of climatic / ocean regimes of the Pacific Northwest. A physical template is first presented that consists of a set of principles and a set of conceptual models. Within the template, conceptual models include the consideration of a nested hierarchy of scales, spatial and temporal scales, and geographic / temporal gradients in Pacific Northwest coastal ecosystems. A scale treatment is applied to both the atmospheric and the oceanic regimes of the Pacific Northwest and is also used in Chapters 5 and 6. Some of the more important linkages between the atmosphere and the ocean are emphasized, and comments are made regarding the development of comprehensive models for the Pacific Northwest Coastal Ecosystems Regional Study (PNCERS). The chapter concludes with some of the questions that have arisen from the body of the chapter and the PNCERS workshop. Appendices include some technical information and a list of data sources.

During the PNCERS workshop (see also Chapter 7) participants suggested improvements to this chapter. First, more attention would be given to large scale models of the atmosphere and ocean and their usefulness. More emphasis would be given to the operation of the climate and ocean in the Pacific Northwest within a larger geographic framework. The region immediately encompassed by the PNCERS program is the coastal terrestrial ecosystem, from about Vancouver Island to Cape Mendicino in northern California, and marine ecosystem out to the edge of the continental shelf. However, it is important to recognize that the region should be extended northwards to include British Columbia and southern Alaska, and that the extended concept of the Pacific Northwest is affected by events within a hemispheric and, most likely, on a global scale. Treatment of these large scales would reveal teleconnections other than El Niño-Southern Oscillation (ENSO)-related ones that should be taken into account. Second, this paper probably does not do justice to the richness and importance of all the phenomena acting on time scales of a year or less by dealing with them in a single section. A truly comprehensive treatment would

examine these scales separately. Third, the mesoscale features of the ocean are particularly important. Fourth, a comprehensive treatment would also give more attention to the past, present, and potential future, use of technology such as satellite use and electronic tracking. Finally, and very important for a program that attempts to provide information to managers, it should be emphasized that, although a certain amount of predictability is possible, an inescapable fact is that the atmosphere and ocean are inherently variable and their non-linear dynamics makes them a system about which perfect predictions are not possible.

CONCEPTUAL FRAMEWORK: PHYSICAL TEMPLATE AND SCALES OF VARIABILITY

Principles

Variability in Pacific Northwest Coastal Ecosystems Reflects Interaction of Multiple Scales of Processes. Pacific Northwest coastal ecosystems display an enormous amount of variability. By definition, these ecosystems lie at the interface of the planet's largest ocean and one of its largest continents. A wide variety of atmospheric, oceanic, hydrologic, and biospheric processes intersects at this location. The richness of the resulting land- and ocean-scape reflects the operation of all of these processes through time scales ranging from billions of years to seconds, and space scales ranging from planetary to sub-millimeter. Scientists attempt to make sense of this complex reality in a number of ways. Two of the most common are first, to recognize the existence of these scales and endeavor to sort out their interaction, and second, to apply the concepts of general systems theory. The first of these approaches is emphasized in the following discussion.

Hierarchy Theory. Hierarchy theory was introduced in the 1980s to address linkage between scales and general complexity in ecological systems. The theory, which sees different scales of ecosystem operation forming a hierarchy, was introduced in great detail by Allen and Starr (1982) and is frequently applied to ecosystems. Among others, O'Neill (1988) has outlined some important practical applications of the theory. He suggests that the understanding of one hierarchical level in a system is enhanced by reference to those immediately above and below it, but not so much by those a long way from it. An important principle of hierarchy theory for the PNCER study is that higher levels set constraints, and in some cases provide control, for lower levels of the hierarchy. The application of this principle is implicit in much that follows.

Heterogeneity in Basinwide Processes. The manner in which oceanic and atmospheric processes function across the whole Pacific Ocean basin has important results for both aquatic and terrestrial ecosystems. There is a continual shifting of habitat conditions. Occasionally successional and developmental processes are reset by high impact events. Often, in marine ecosystems, there are found opposing regions of abundance and scarcity. These phenomena make it impossible to understand coastal ecosystems without a good knowledge of its larger planetary setting and the way that biophysical processes work on all scales.

Nonlinear Behavior and Feedback Systems. Many, if not most, processes in the abiotic and biotic parts of the coastal ecosystems are nonlinear. This fact makes it difficult to understand the processes, to model them, and to fit together the various pieces of sub-models, and finally to make predictions from the resulting comprehensive models. Although there can be some certainty about the way in which a particular part of the ecosystem functions, there is increasing uncertainty when fitting the operation of that part with the functioning of related parts. Furthermore, there are important feedback mechanisms at work. There are many feedbacks between the ocean and the atmosphere in terms of mass, energy, gas, and momentum exchange. There are also many feedbacks of the same properties between the land surface and the atmosphere. These feedbacks also frequently do not act in linear ways.

Interfaces Between Adjacent Ecosystems. A further complexity in Pacific Northwest coastal ecosystems is introduced by the interfaces between the many sub-ecosystems, which are themselves often very distinct and complex. Such interfaces exist between the upland and lowland terrestrial ecosystems, between the terrestrial and freshwater aquatic ecosystems, between the freshwater and marine ecosystems, and between the land and the ocean systems. These interfaces offer discontinuities in abiotic and biotic fluxes and *the degree to which the various sub-ecosystems are coupled or decoupled at the interfaces is a major topic for investigation.*

Press and Pulse Disturbances. Although this review concentrates on processes that work more-or-less continuously in time it recognizes that certain events, which might be regarded on some scales as either directional or discontinuous, are sometimes very important to the ecosystem. Press disturbances, such as increasing toxicity of an estuary due to an anthropogenic cause, may occur in a directional sense. Pulse disturbances, such as a high magnitude, low frequency floods or wind storms, are discontinuous but sometimes have repercussions that filter through all the related parts of the sub-ecosystems.

Models

The complexity of coastal ecosystems demands that rather than one model, a suite of models and modeling approaches is necessary. Such a suite includes the following:

Nested Hierarchy of Scales. Critical biological and physical processes act at different scales of reference; the smaller of these scales are nested within increasingly larger scales. This relates closely to basic hierarchy theory and has many other advantages discussed in the climate section below. Figure 4.1 illustrates how this concept may be applied to the oceanic and atmospheric systems and to understanding some other systems as well.

Spatial and Temporal Scales. A number of authors have investigated the organization of biophysical and even anthropogenic processes as they co-vary across spatial and temporal scales. One of the first investigations, and still one of the most helpful, was the concept of Delcourt et al. (1983) shown in Figure 4.2. The hierarchy relates a large number of environmental disturbance regimes, which includes far more than climatic disturbance, through biotic responses and into resulting vegetation patterns. The investigators are careful to quantify the scales involved by

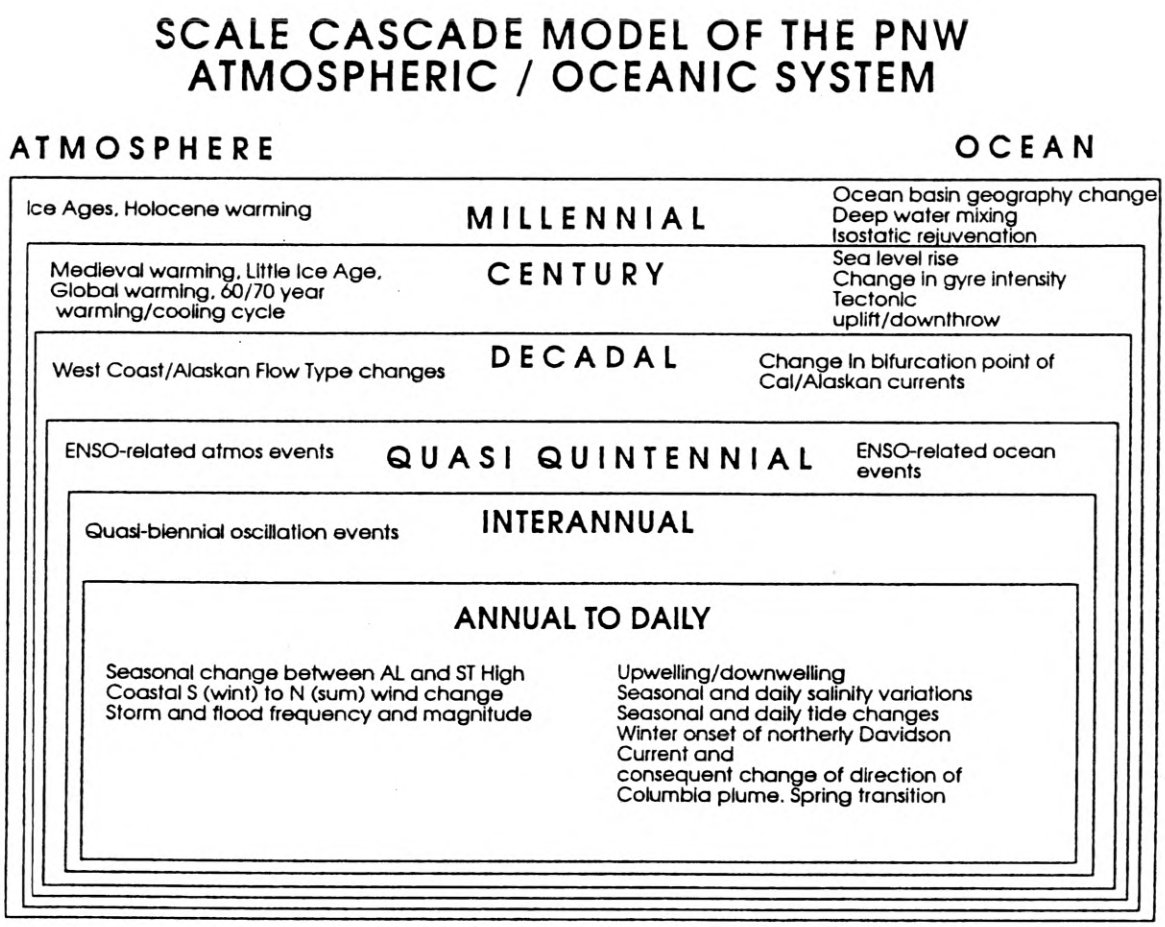


Figure 4.1. Concept of nested hierarchies of scales as applied to the atmospheric and oceanic systems. AL = Aleutian Low pressure, ST High = SubTropical High pressure, S = southerly winds, N = northerly winds.

giving specific limits for mega, macro, and micro scales, their sub-scales, and related vegetation units. The overall pattern is one in which the larger the temporal scale of the disturbance, the larger is the spatial scale of the disturbance, its associated biotic processes, and vegetation response. There is a general semi-linear pattern of increase along both the logarithmic scales of time (in years) and space (in meters). Similar patterns are found in a later study by McDowell et al. (1990) that concentrates more on climatic forcing functions. The McDowell et al. study, unlike others, uses equally-spaced logarithmic units on both time and space axes. The relationships in time and space of climatic episodes and events, on the one hand, and ecological and evolutionary units, on the other hand, show the different phenomena tend to be located towards the spatial, as opposed to the temporal, axis, and thus demonstrate that the temporal scale of the climate-vegetation system is virtually unlimited, but the spatial scale hierarchy is bounded by the finite size of the Earth. Additional scale diagrams have been provided by Graetz (1990) and by Clark (1985), who brings in an anthropogenic component. Exciting new

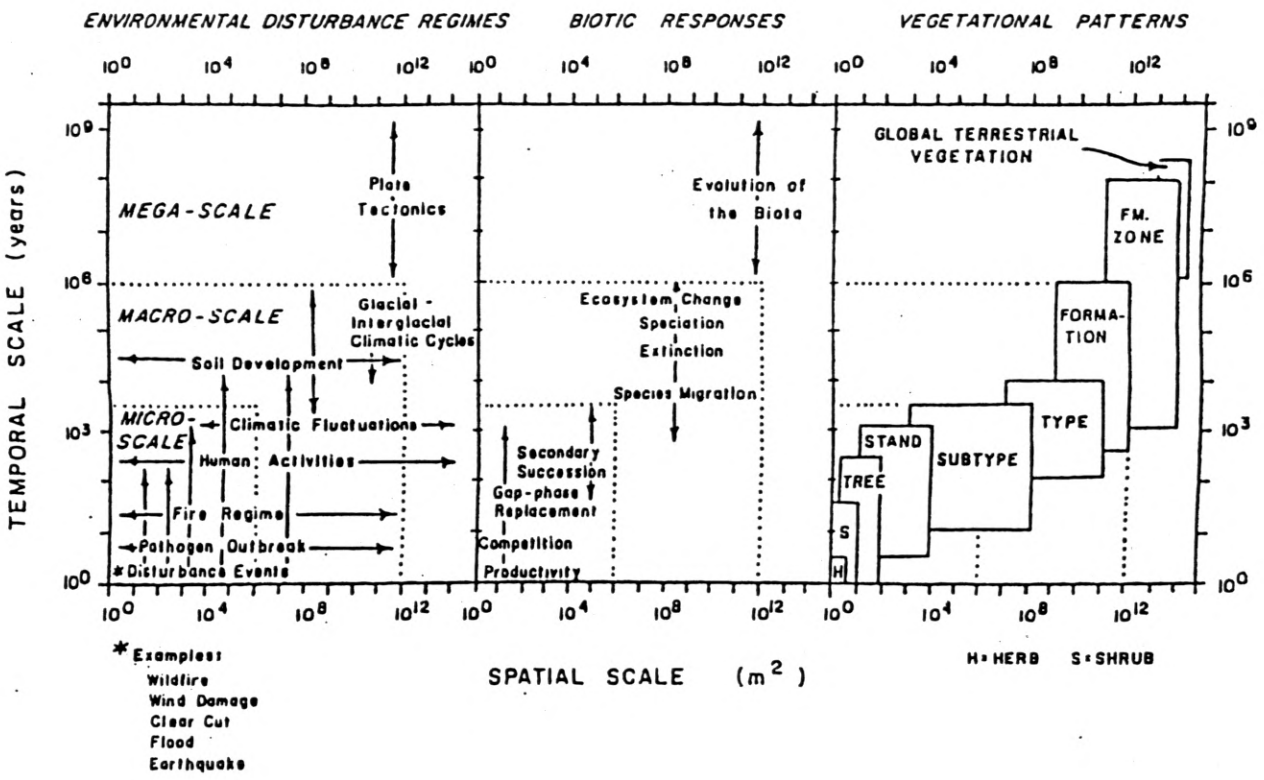


Figure 4.2. Environmental disturbance regimes, biotic responses and vegetational patterns viewed in the context of space-time domains in which the scale for each process or pattern reflects the sampling intervals required to observe it. The time scale for the vegetational patterns is the time interval required to record their dynamics. (Source: Delcourt, H.R., P.A. Delcourt, and T. Webb. 1983. Dynamic plant ecology: the spectrum of vegetational change in space and time. *Quaternary Science Reviews* 1:153-175. Reprinted with permission, courtesy Elsevier Science.)

semivariance analysis and fractal techniques are becoming available in order to link different biophysical phenomena together at mutually important scales (Bian and Walsh 1993).

Geographic/Temporal Gradients in Pacific Northwest Coastal Ecosystems. The geography of the Pacific Northwest gives rise to well-marked gradients in values of biophysical variables in both the latitudinal (north-south) direction and in the longitudinal (west-east) direction. In addition, a third dimension of time is conceived as running perpendicular to these spatial dimensions. Within this three-dimensional view we can imagine "temporal time-dependent slices" of variability in one or more biophysical variables at any geographic point on the plane formed by the two spatial dimensions (Figure 4.3). This is somewhat analogous to the world line or Feynman diagram

concept used by particle physicists (Zukav 1979: p. 232). In the reality of the Pacific Northwest, some of these "temporal slices" are known and it is probable that there are others about which we do not yet know.

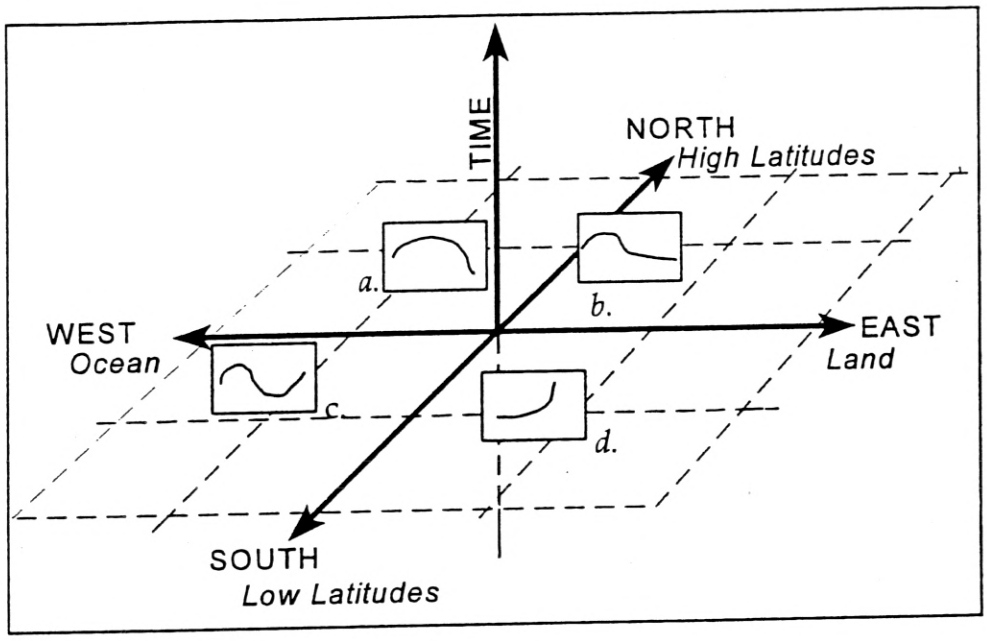


Figure 4.3. Conceptualization of geographic/temporal gradients in Pacific Northwest Coastal Ecosystems. A plane of geographic gradients is formed by the horizontal East-West and North-South axes. A vertical Time axis forms the temporal gradient. Four conceptual examples of "temporal slices" of biophysical variability across geographic gradients are shown as graphs a, b, c and d.

CLIMATIC AND OCEANIC REGIMES IN THE PACIFIC NORTHWEST

Background

DEFINITION OF THE THEME TOPIC

Overview of the Atmosphere/Ocean System in the Region. The Pacific Northwest Region is defined for the purposes of this review as generally including the Washington and Oregon coasts and the California coast to Cape Mendocino. The coastal ecosystem at the center of attention includes the linked components of rivers and streams in coastal watersheds; estuaries including Puget Sound, and the Pacific Ocean to the seaward edge of the continental margin (PNCERS

1995). The coastal ecosystem is nested within the larger oceanic and atmospheric setting of the northeast Pacific Ocean and because of the way in which the atmosphere and ocean operate, this setting itself can extend to large parts of the planet as a whole.

Climatography/Oceanography. The climate of the Pacific Northwest is mostly marine West Coast climate but includes some Mediterranean climate in the south (central and northern California) and sub-arctic climate in Alaska. East of the Cascade Range, where lies a large part of the Columbia-Snake river drainage area, the climate is mainly one of Middle Latitude Steppe (Akin 1991). The ranges of monthly mean temperatures and monthly total precipitation demonstrate both the north-south latitudinal gradient and the west-east, coast to interior gradient for the greater Pacific Northwest area (Figure 4.4). The terrestrial part of the Pacific Northwest climate has a precipitation maximum in winter, much of it falling as snow in the higher elevations. Snowmelt potentially leads to a June maximum of discharge for the Columbia River but since the damming of the river its flow has much less seasonal variation. Papers in Small (1990) show that the peak flow of the Columbia at Astoria can now occur in January. The other coastal rivers have a maximum discharge to the ocean in December and January (Landry et al. 1989). The summer tends to be hot and dry in all areas of the Pacific Northwest.

Winter sea surface temperatures range from 8°C in the north to 10°C in the south. Summer sea surface temperatures range from 17°C well off shore to 11°C near the coast in areas of upwelling (Figure 4.5). Values of summer and winter distributions of salinity and density (Figures 4.6 and 4.7) show the huge impact that the Columbia river discharge has on large areas of water over the continental shelf, especially in summer (Landry et al. 1989). The winter storms give intense vertical mixing and alongshore northward advection which, for the most part, is not impeded by the straight coastline of much of the Pacific Northwest. The Columbia provides about 80% of the river discharge to the ocean between San Francisco and the Strait of Juan de Fuca (Hickey 1989). The Fraser river, which has fewer dams than the Columbia, is also a major contributor of fresh water to the ocean off Washington and Oregon (Huyer 1983). The important features of the ocean/atmosphere system in this region are the frequent and strong winter storms, strong wind stress, seasonal wind reversals, moderate upwelling in spring and summer, significant freshwater input, relatively smooth coastline, major estuaries and nursery grounds, moderate advection, and mesoscale oceanic activity (GLOBEC 1994).

The atmosphere/ocean system in NE Pacific and Pacific Northwest is extremely dynamic. Driven initially by solar energy, the system plays its part in the general planetary circulation of atmosphere and ocean that attempts to balance heat energy between low and high latitudes. The system is composed of a variety of atmospheric and oceanic currents together with interrelated processes of heat, mass, moisture, and momentum flows and exchanges. Typical ocean and atmospheric movement throughout the year is summarized by a schematic diagram of surface atmospheric pressure and ocean currents (Figure 4.8). The summer atmosphere of the North Pacific and Pacific Northwest is dominated by a subtropical high pressure system (termed the North Pacific High in Chapter 5) with accompanying clockwise-flowing anticyclonic winds that brings a northerly (southward) air flow over the region. During winter, the high pressure system is much reduced in size and replaced in the north by the Aleutian Low pressure system with its associated counter-clockwise, cyclonic winds that bring air from the west, southwest and

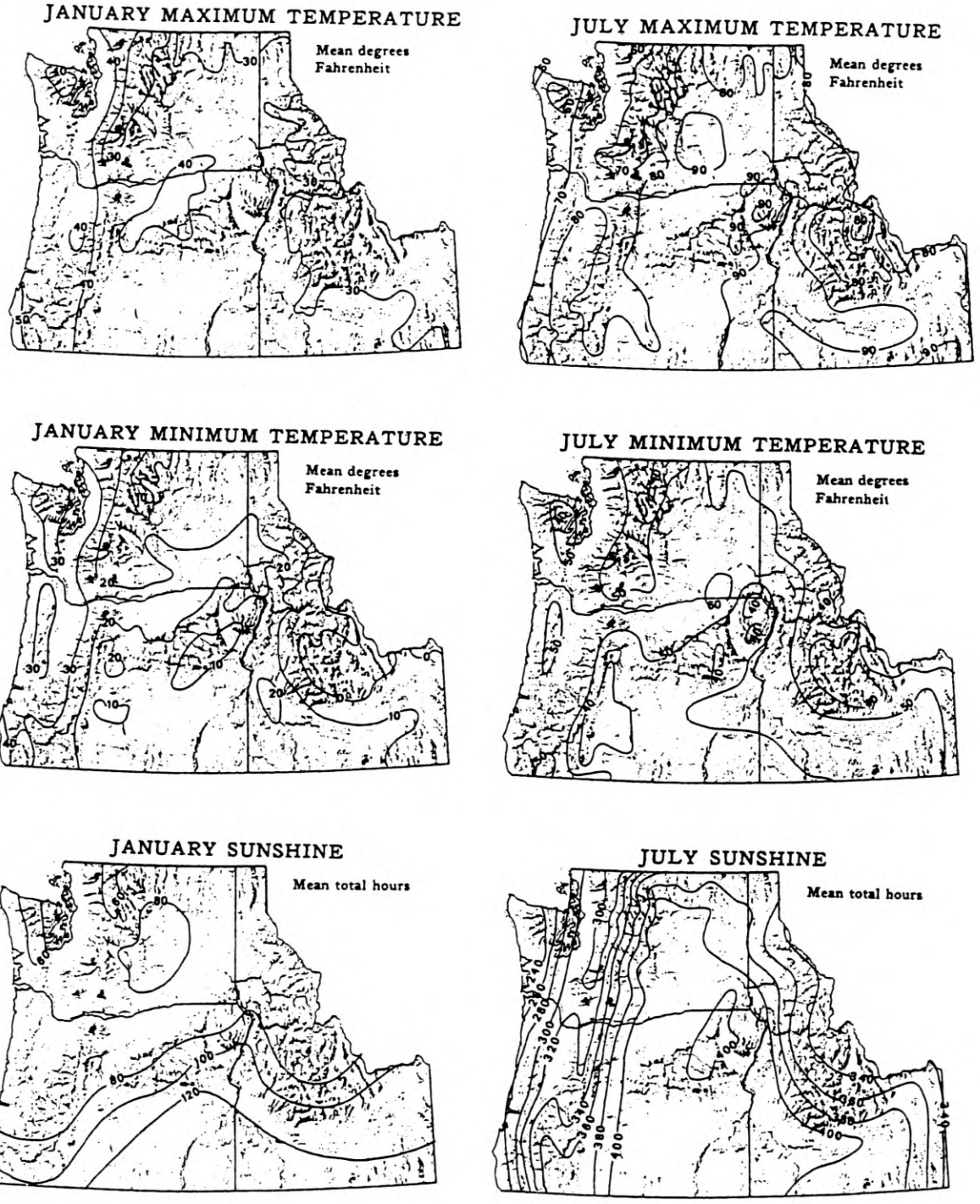


Figure 4.4. Maps of selected climate variable values for the Pacific Northwest. (Source: Jackson, P.L., and A.J. Kimerling. 1993. *Atlas of the Pacific Northwest*, 8th Ed. Corvallis: Oregon State University Press. Reprinted with permission, courtesy OSU Press.)

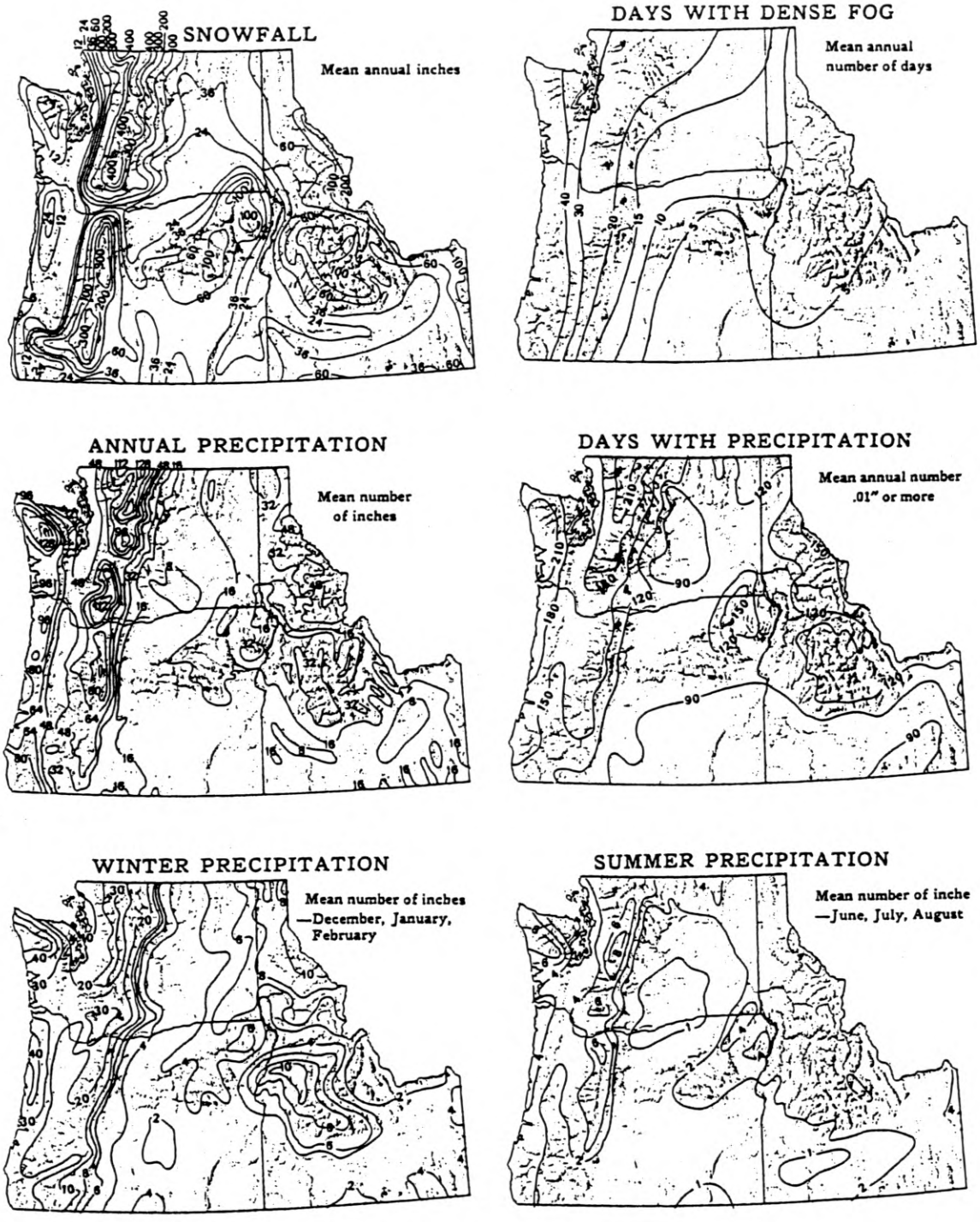


Figure 4.4 (continued). Maps of selected climate variable values for the Pacific Northwest. (Source: Jackson, P.L., and A.J. Kimerling. 1993. *Atlas of the Pacific Northwest*, 8th Ed. Corvallis: Oregon State University Press. Reprinted with permission, courtesy OSU Press.)

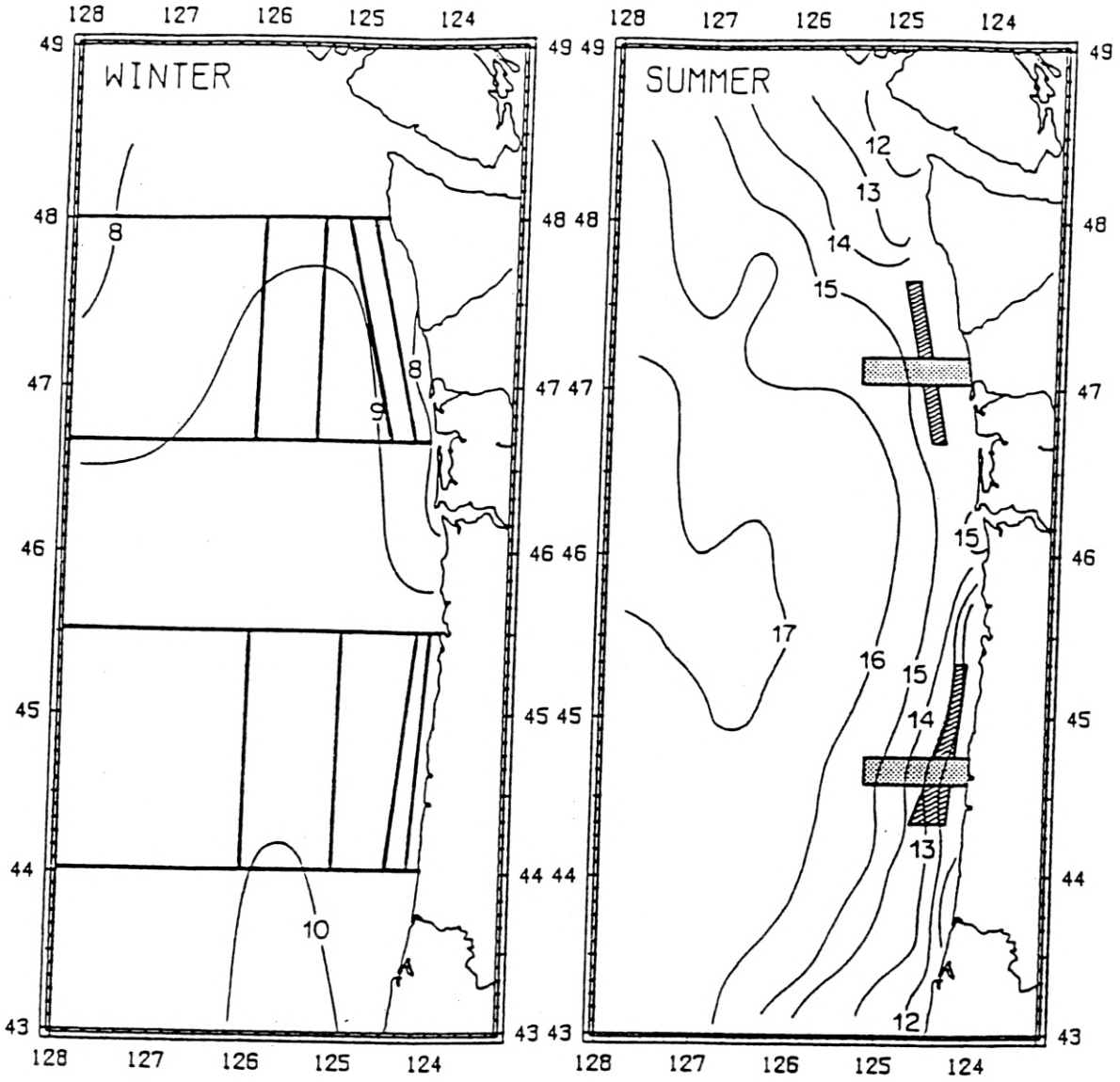


Figure 4.5. Summer and winter distributions of sea surface temperature in °C over the ocean of the Pacific Northwest. Also shown are areas of previous intense study. (Source: Landry, M.R., J.R. Postel, W.K. Peterson, and J. Newman. 1989. Broad-scale distributional patterns of hydrographic variables on the Washington / Oregon shelf. In *Coastal Oceanography of Washington and Oregon*, eds. M.R. Landry and B.M. Hickey, 1-40. New York: Elsevier. Reprinted with permission, courtesy Michael Landry.)

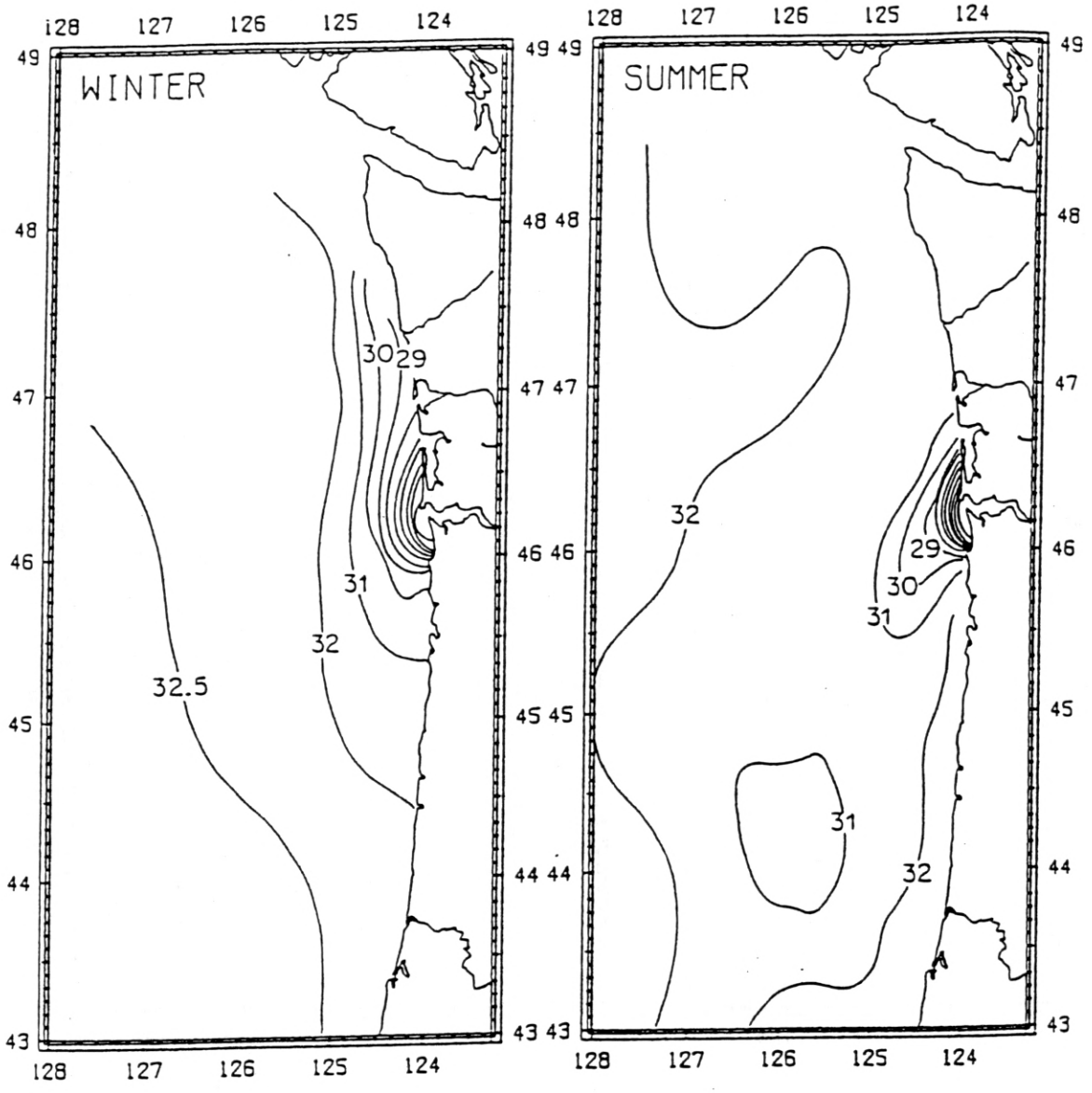


Figure 4.6. Summer and winter distributions of salinity over the ocean of the Pacific Northwest. (Source: Landry, M.R., J.R. Postel, W.K. Peterson, and J. Newman. 1989. Broad-scale distributional patterns of hydrographic variables on the Washington / Oregon shelf. In *Coastal Oceanography of Washington and Oregon*, eds. M.R. Landry and B.M. Hickey, 1-40. New York: Elsevier. Reprinted with permission, courtesy Michael Landry.)

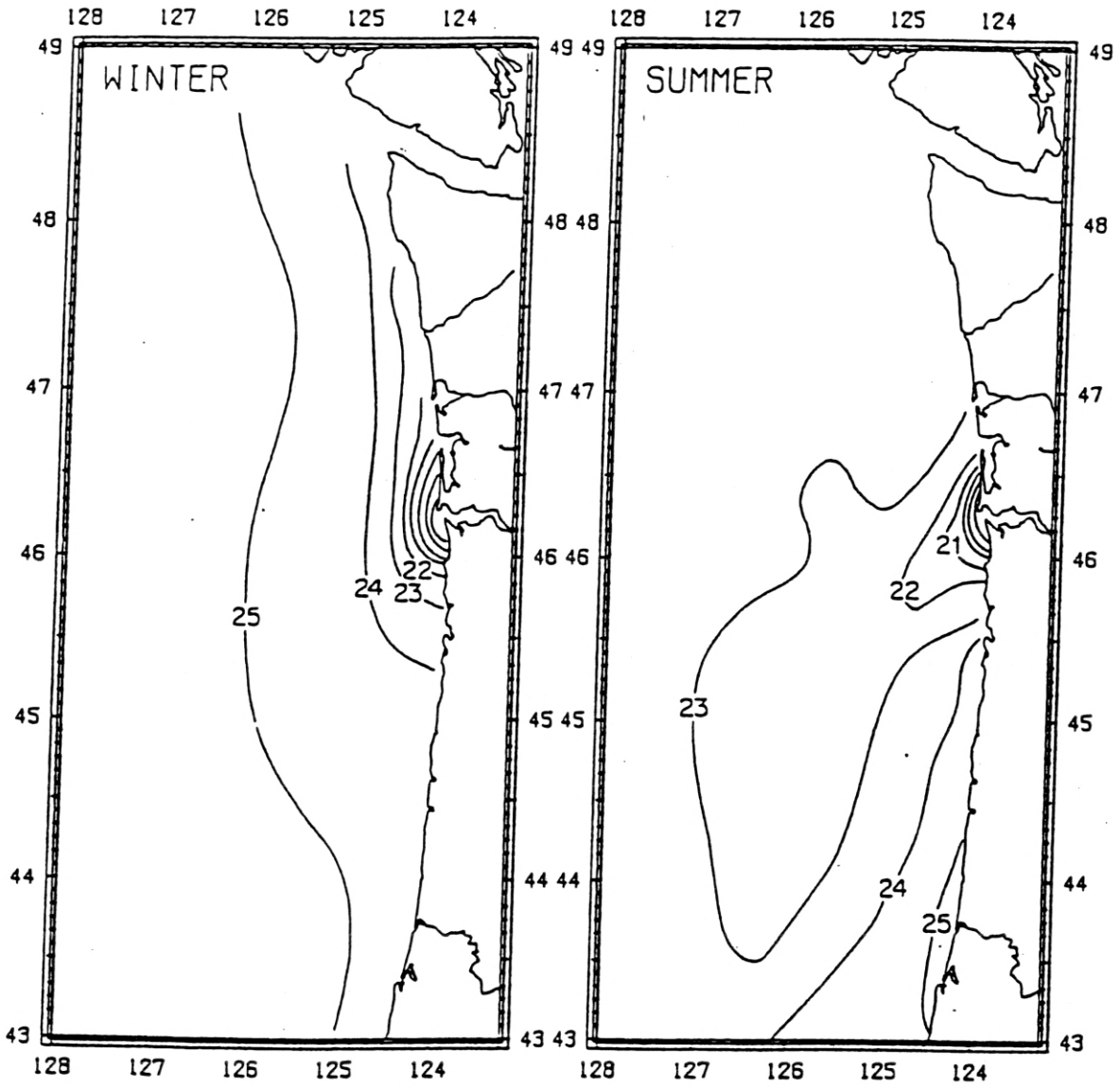


Figure 4.7. Summer and winter distributions of density (σt) over the ocean of the Pacific Northwest. (Source: Landry, M.R., J.R. Postel, W.K. Peterson, and J. Newman. 1989. Broad-scale distributional patterns of hydrographic variables on the Washington / Oregon shelf. In *Coastal Oceanography of Washington and Oregon*, eds. M.R. Landry and B.M. Hickey, 1-40. New York: Elsevier. Reprinted with permission, courtesy Michael Landry.)

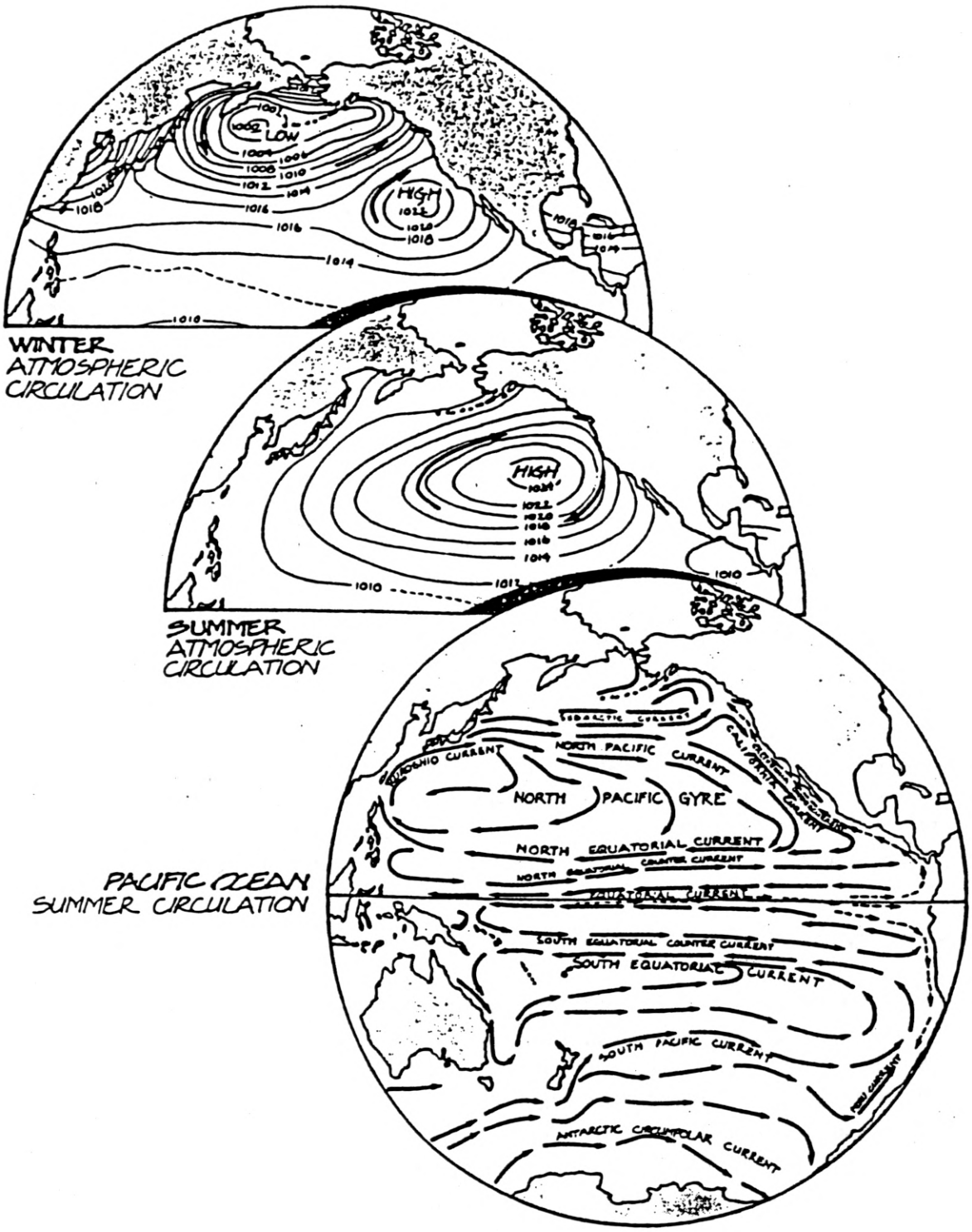


Figure 4.8. Major circulation patterns in the atmosphere and the ocean. (Source: Parmenter, T., and Bailey, R. 1985. *The Oregon Ocean Book*. Salem: State Printing Office. Reprinted with permission, courtesy Robert Bailey.)

south to the region. In the upper atmosphere, generally westward flowing air in the mid- to high-latitudes comprises the northern hemisphere circum-polar vortex. This vortex is marked by the presence of long or planetary (Rossby) waves that can guide surface storms, and by geographic expansion and greater vigor in the winter season compared to the summer. The surface winds associated with the Aleutian low and subtropical high pressure provide the principal force that drives the major ocean currents shown in Fig. 4.8. The North Pacific Current (sometimes called the West Wind Drift) and the Sub-Arctic Current flow eastward across the North Pacific and bifurcate to form the northward flowing Alaskan Current and the southward flowing California Current in the NE Pacific. Both currents continue to become parts of oceanic gyres (basin-wide horizontal circulations).

SCOPE OF VARIABILITY

An effective way of approaching the complexity of this system is to identify the principal temporal scales on which phenomena operate. These scales actually range from the instantaneous to the lifetime of the planet but for this review are identified as including the daily, monthly and seasonal, annual (calendar and water year), interannual, quasi-quintennial (here defined as 3-7 years), decadal, century, and millennial. The range between seasonal to century scales is particularly important to the goals of the PNCERS because larger temporal scales are related to larger spatial scales and *vice versa*. The identification of the scale of a process is very important because phenomena at different scales often have different processes operating and different causes for changes of rates or manner of operation. In addition, variability of biophysical phenomena at different scales frequently carries different implications for the way in which an ecosystem is managed. Scale is so important as an organizing framework that the bulk of this review is taken up by a consideration of atmospheric and oceanic phenomena on the scales listed above.

The Atmosphere

The principal processes operating in the atmosphere are ones of *physical climatology*, which involves the transfer and exchange of heat and moisture within the atmosphere and between the atmosphere and the Earth's surface, and *dynamic and synoptic climatology*, which treats the movement of air and its properties in the atmosphere and across the surface. These types of climatology assume varying degrees of emphasis on the different time scales outlined above. Atmospheric processes and phenomena are reviewed according to the scale most appropriate for them. In some cases there is a certain degree of sharing of scales as, for example, changes in intensity over a period of a century of the quasi-quintennial scale El Niño-Southern Oscillation (ENSO).

ATMOSPHERIC VARIABILITY AT THE MILLENNIAL SCALE

The millennial time-scale, which here focuses on the Holocene but which can also involve the Pleistocene and some preceding geological epochs, does not play such an important role for

present-day ecosystem managers. But it does help to be aware of changes on this time scale for three reasons. First, the changes on the millennial scale can give information concerning the extremities to which the system can move and provide some feel for the degree of homeostasis of the system. Millennial-scale changes set the "limiting values" on the natural system changes in a practical and hierarchical sense. It is conceivable that human influence can help exceed these limits but it is useful to have some idea for where they are or have been in the past. Second, many of the floral and faunal species presently found in the ecosystem, or close relations of current species, have survived throughout all these extremities, thus indicating the degree of resilience of the ecosystem to natural changes. Third, it helps to recognize that many atmospheric phenomena that are important today have been present for a long time. Radiolarian records from the Santa Barbara basin, for example, indicate that El Niños have been occurring for at least 5.5 million years (Casey et al. 1989).

The occurrence of the major ice age of the Pleistocene epoch [approximately 2 million to 10,000 years before present (BP)] may be due to the changing geography of land and ocean distribution related to the continental drift forced by plate tectonics. Within the Quaternary period [i.e., the Pleistocene plus the Holocene (10,000 years BP to present)] variations of solar radiation reaching the Earth are important and are generally believed to be a major cause of continent-scale waxing and waning of ice sheets and cold and warm periods. The major orbital variations of the Earth include changes in the eccentricity of the planet's orbit around the sun (100,000 years periodicity), changes in the tilt (obliquity) of the Earth's axis to the plane of orbit (40,000 years periodicity), and changes related to a 'wobbling' of the Earth's axis (20,000 years periodicity). The combined effects of the three orbital parameters can cause variation in seasonal insolation as large as ~ 30% in high latitudes (Hartmann 1994). At the millennial time scale solar input at 45°N (the approximate latitude of the Pacific Northwest) can vary by about 70 Watts per square meter (Wm^{-2}) during the summer solstice, which may be compared to a present day mean of about 475 Wm^{-2} arriving at the top of the atmosphere and approximately 225 Wm^{-2} (Landry et al. 1989) which arrives at the surface of the Pacific Northwest in June.

Warona and Whitlock (1995) used pollen analysis from Little Lake in the central Oregon Coast Range and climatic reconstructions (COHMAP 1988) to determine five major climate periods during the past 42,000 years. The period between 42,000 and 24,770 years BP, a nonglacial interval, was cooler and wetter than today. From 27,770 to about 16,000 BP there was a full glacial period in the area marked by parkland, lodgepole pine, fir and mountain hemlock. During this period, the mean annual temperature was likely to have been 7°C lower than today with the January temperature 14°C lower. Conditions were also probably drier than today with the jet stream flowing well to the south. The Late Glacial period occurred between 16,000 BP to 10,000 years BP and was marked by an increase in temperature and effective moisture. There is some evidence for a reversal to a Younger Dryas climate between 11,000 and 10,000 years BP but this is not certain. Between 10,000 and 5,600 years BP (Early Holocene) temperature is believed to have increased and effective moisture decreased as summer droughts became a climatic feature associated with an expansion of the subtropical high pressure area in the eastern Pacific Ocean. The Cooperative Holocene Mapping Project (1988) noted that the time between 12,000 and 6,000 years BP was one of enhanced solar radiation in summer which would lead to a greater

thermal contrast between land and sea. If the line of reasoning of Bakun (1990) is correct then this would also have increased coastal upwelling during this period. The Late Holocene, 5,600 years BP to the present, showed a trend toward cooler, moister conditions. Most of these changes are echoed to some extent by evidence from the Olympic Peninsula and the Puget Sound area and in the Cascades (Sea and Whitlock 1995).

ATMOSPHERIC VARIABILITY ON THE CENTURY SCALE

Apart from approximately the last 150 years, which are treated in the next section, not much is known concerning century-scale climate variability in the Pacific Northwest. During the last 1500 years the general climate of the northern hemisphere saw a warm period in Medieval times from about 1000 to 1300 AD, and a colder period variously described as occurring somewhere between 1300 and 1900 AD and known as the Little Ice Age (Lamb 1995). It is reasonable to assume that the Pacific Northwest was subject to these trends but in a less extreme way owing to its maritime location. The small amount of available evidence is either consistent with this suggestion or does not contradict it.

A tree ring chronology for Lost Forest (northeastern Lake County, eastern Oregon) from 1460 clearly shows that interannual variability is the norm on the century scale (Hatton 1989). Graumlich (1987) performed an excellent analysis for whole of the Pacific Northwest and concentrated on precipitation. A principal component analysis of the precipitation record identified three regions: Southern Valleys, Columbia Basin, and Western Lowlands. There are some north-south contrasts, especially in 19th Century. Between 1810-1838 it was wet in the Columbia Basin and dry in Southern Valleys while between 1850-1890 it was wet in Southern Valleys and dry in the Columbia Basin. Graumlich suggests that: 1) cool season droughts occur when there is a blocking high pressure sending storm tracks north of the Pacific Northwest; 2) cool season precipitation occurs when the polar front jet stream is over the Pacific Northwest; and 3) summer drought is due to expanded influence of subtropical high pressure ridge. Leavett et al. (1991) looked at tree rings near the Collier Glacier in the Oregon Cascades and found the glacier had not moved very far down the valley in the last 500 years. Sorenson (1983) found evidence for smaller advances in the Little Ice Age about 500 BP when new and high moraines occurred in the Cascades. The most exciting dendrochronological work related to PNCERS is the coastal tree ring and density records of Buckley et al. (1992) and Wiles et al. (1995) that extend records of both Pacific Northwest and Alaskan coastal air temperatures and Gulf of Alaskan and coastal sea surface temperatures back to about 1750. The Graumlich, Buckley et al. and Wiles et al. records display high variability but do not seem to have been examined for trends or cyclicities some of which can be seen in the latter (Figure 4.9).

Beyond the issues of the Medieval warming (1000-1300 AD) and the Little Ice Age (1300-1900 AD) some investigators have concentrated on cycles and on shorter time scales. Sediment cores from anoxic basins reveal a 60-70 year cycle of warming and cooling over the past 1500 years (GLOBEC 1994). The last cycle in this pattern, which ecologically is associated with sardine dominance over anchovy and *vice versa*, is seen with warming around 1925, cooling at 1948, and a return to warming about 1977. Ware and Thompson (1991) regard the 60 year cycle in

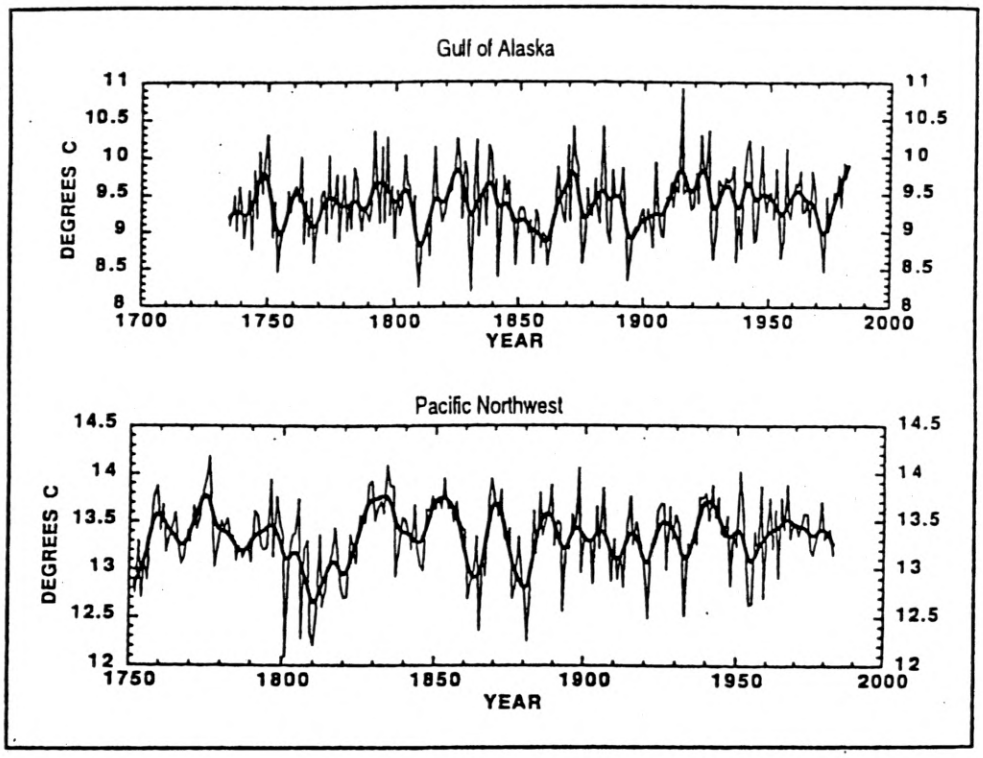


Figure 4.9. Summer temperature reconstructions from dendrochronological data for the Gulf of Alaska and the Pacific Northwest. (Source Wiles, G.C., R. D'Arrigo, and G.C. Jacoby. 1995. Modeling North Pacific temperatures and pressure changes from coastal tree-ring chronologies. In Proceedings of the Eleventh Annual Pacific Climate (PACLIM) Workshop, eds. K.T. Redmond and V.L. Tharp, 67-78. California Department of Water Resources, Interagency Ecological Studies Program for the Sacramento-San Joaquim Estuary. Technical Report 40. Reprinted with permission, courtesy California Department of Water Resources.)

Southern California data as being consistent with their belief that pelagic fish are responding to a 40-60 year oscillation in primary and secondary production that, in turn, is being forced by a long-period oscillation in wind-induced upwelling. They report evidence, some of which goes back to 1910, and several findings in other investigations, that is consistent with an approximate 50 year cycle. *A search for cyclic behavior in the range 40 to 70 years should be a research topic of some importance.* On yet another temporal scale, Sharp (1992) uses the evidence from fish scales buried in sediments in the Santa Barbara basin to identify a 250-350 year climatic cycles and a major change, at or near, the end of the Medieval Warm period (which he dates at 1050-1100 AD) tending away from warmer and wetter conditions with greater upwelling activity.

Trenberth (1993) reviewed coupled General Circulation Model output and suggested, under current projections of CO_2 increase, that the western coast of North America is expected to warm

by about 1.0-1.5 °C by the year 2030 and that northern regions will warm more rapidly than southerly regions. The hydrologic cycle is expected to intensify by about 10%, leading to greater amounts of evaporation and precipitation. Trenberth (1995) has also suggested that the relative frequency of the El Niño mode in the past decade "may well be one of the primary manifestations of anthropogenic global warming". Some analyses have shown the possibility of century-scale oscillations in El Niño frequency (Endfield 1988; Anderson 1992). Anderson's (1992) analysis reveals a pattern in which El Niños are more frequent in cycles of about 90, 50, and 24 to 22 years periodicity. El Niño events were most frequent around AD 800 and least frequent during the Medieval Warm period (1100 to 1300 AD) when they had a periodicity of about 90 years.

It seems that there is a good opportunity to re-examine old proxy data and acquire new proxy data in an attempt *to learn more about climatic variability in the Pacific Northwest on the century scale* and this should be taken as a research task of some importance. In contrast to the century scale, the decadal scale has been given a great deal of attention in the last few years.

ATMOSPHERIC VARIABILITY ON THE DECADAL SCALE

Initial studies on the decadal scale concentrated on investigating whether there had been any 100 year-long warming or cooling trends in temperature data (precipitation data have been somewhat neglected in terms of trends on this scale). Roden (1989) found no such trends except for significant warming at large city stations which he attributed to heat island effects. Some other studies support this conclusion for parts of the Pacific Northwest (Greenland 1994a). More importantly, a highly sophisticated study by Dettinger et al. (1995) for the US as a whole for the period 1910-1987 concluded that the first three factors in a mulitvariate analysis (called empirical orthogonal functions), which collectively explain 75% of the spatial temperature variability of the US, had less importance in the Pacific Northwest area indicating relatively low temporal variability. They found, however that the Pacific Northwest did share somewhat in a general national trend for a warming from 1910 to the 1940s and a cooling to minimum in the 1970s. A nationwide study of 10- to 20-year climatic fluctuations showed that such fluctuations were frequent between 1931-1982 (Karl and Riebsame 1984). This national trend pattern and the tendency for marked interdecadal variation is part of a pattern noted by Wallace et al. (1996), that the best-marked interdecadal variation in temperature is a land (continental) -based, cold season phenomenon. Wallace et al. also found that the mixed-layer of the ocean has a "memory" (at least 12 months long) that masks warm season/cold season changes. This "memory" masking implies that interdecadal changes in temperature in the Pacific Northwest are likely to be rather smaller in size than those in continental interiors.

A great deal of attention has been given to the possibility of a certain degree of regularity in the operation of the atmosphere on the interdecadal scale and the possibility of fast changes between one decadal regime and another. Initial time series studies, although sometimes displaying these changes, did not emphasize them (Roden 1966, 1987; Bradley 1982). However, the remarkable winter of 1976-77 stimulated climatologists to pay more attention to the climatic conditions before and after this time. Several investigators (Trenberth 1990; Ebbesmeyer et al. 1991) noticed a "step" change, and in some cases, recognized that there had been earlier such changes of

this kind in the observed environmental records of about 100 years in length (Ebbesmeyer et al. 1989).

Trenberth and Hurrell (1994) concentrated on the atmospheric part of the interdecadal change. Compared to the decadal-scale period preceding it, they found the troposphere over the North Pacific during the period 1976-1988 displayed a deeper and eastward shifted Aleutian low system in the winter half of the year, which advected warmer and moister air along the west coast of North America and into Alaska and advected colder air over the North Pacific Ocean. This period was also associated with a southward shift in storm tracks. Cayan and Peterson (1989) showed that when the Aleutian low was deep, storm tracks were guided northwards towards Alaska tending to result in anomalously high stream flows in Alaska and anomalously low stream flows in the Pacific Northwest (Figure 4.10). It seems reasonable to generalize these processes and their hydrological implications as being integral parts of regime shifts. Thus, during a West Coast flow regime (see below, Francis 1993) the Pacific Northwest has above-average precipitation values and is cooler while during an Alaskan regime the region has above-average temperatures and below-average precipitation leading to persistent droughts such as those of the late 1980s. This regime shift has recently been termed the Pacific Decadal Oscillation (PDO; Mantua et al. 1997).

Teleconnective or circulation indices are used on a number of scales to summarize the state of the atmosphere at a given time period on a quasi-hemispheric spatial scale. A number of these indices has been defined for the Pacific Northwest. The most relevant ones for the Pacific Northwest include the North Pacific Index, Pacific North American Index, Central North Pacific Index, and the Southern Oscillation Index. (SOI) These are defined and their operations explained in Appendix 4.1. The values of most of the indices are well correlated among each other (Cayan and Peterson 1989; Trenberth and Hurrell 1994). Figure 4.11 clearly identifies four decadal-scale periods, centered at about 1925, 1940, 1962, and 1984, of anomalously low values of the North Pacific Index, indicating a strong Aleutian low at these times. Other investigators have used their own indices (e.g., Beamish and Bouillon 1993), but most time series results of this kind are quite similar.

Ebbesmeyer et al. (1989) developed a very interesting measure called the Pacific Northwest Index (PNWI), composed of information on: 1) the coastal ocean temperature anomaly; 2) the annual average Puget Sound main basin temperature; and 3) the March 15 snow depth in the Cascades. The PNWI is extended back to 1916 and shows well the interdecadal pattern with 4 cycles in the period 1915-1987 (Figure 4.12). Spectral analysis of these data showed that 40 % of the variance could be explained by a peak with a period of about 16 years. Ebbesmeyer et al. (1989) suggest that there may be approximately five cycles in the period from 1889 to 1987. Different variables were used to develop an index called the PNI (Ebbesmeyer et al. 1995), made up of the annual precipitation at Cedar Lake, Washington, snow depth on Mount Ranier, air temperature at Olga, Washington, the percentage of salmon returning to the Fraser river around the northern end of Vancouver Island, the oyster condition index in Willapa Bay, and the maximum PSP toxin concentrations in June in butter clams in Sequim Bay. The PNI can be extended back to about 1946 (Figure 4.13) and, according to Ebbesmeyer et al. (1991), equals the average of the standard normal deviates (also called standardized anomalies) of the 1989 PNWI.

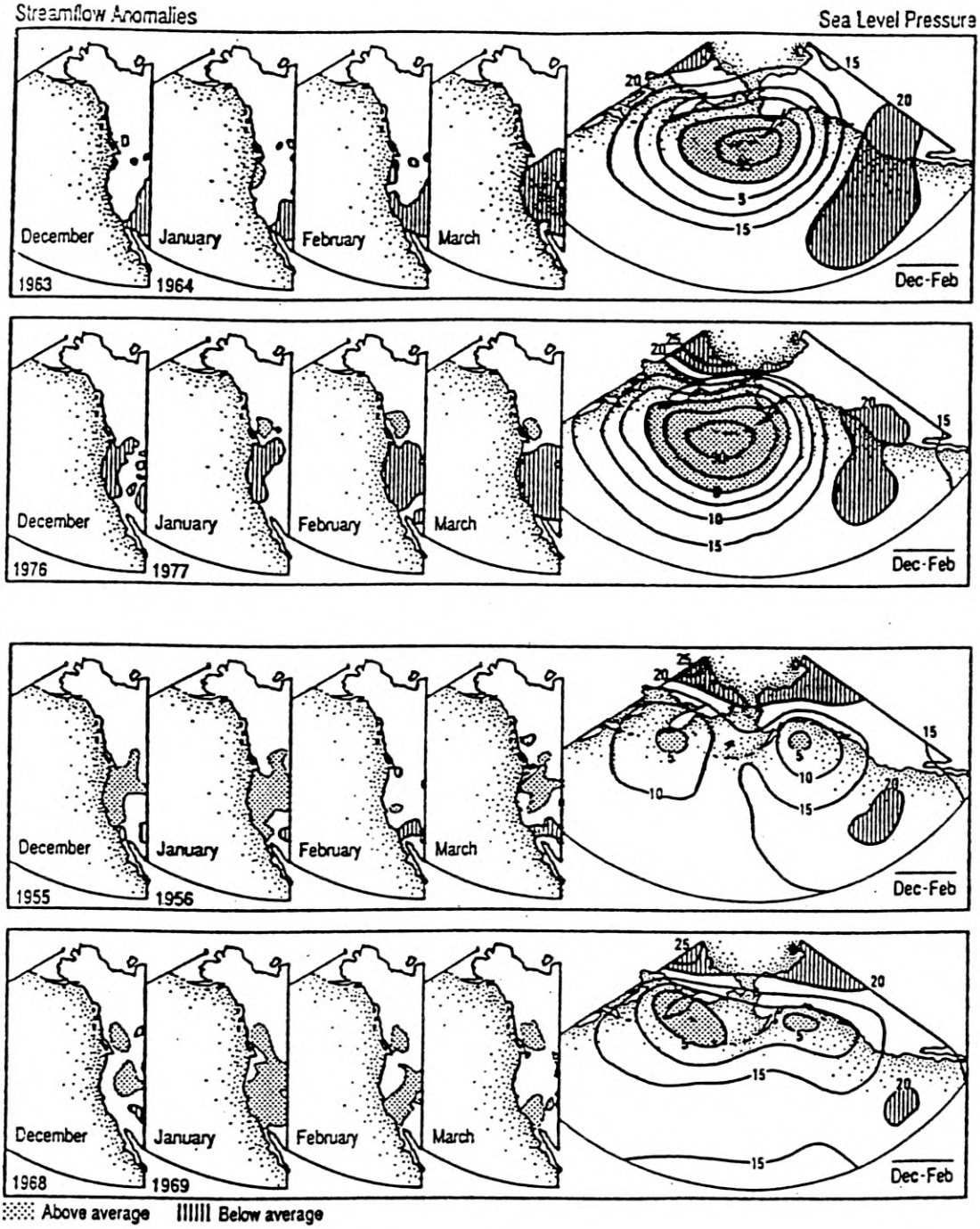


Figure 4.10. Stream flow anomalies under different atmospheric flow patterns. Upper panel are Alaska flow regimes; lower panels are West Coast flow regimes. (Source: Cayan, D.R., and Peterson, D.H. 1989. The influence of North Pacific atmospheric circulation on streamflow. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 375-397. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

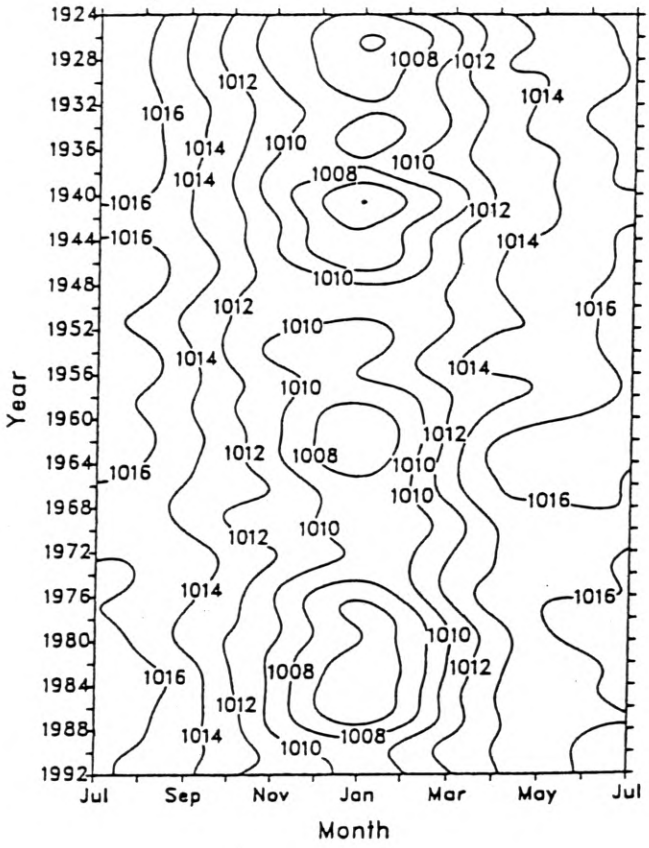


Figure 4.11. Changes in the North Pacific Index over the last century. Time series of the mean North Pacific sea level pressures (in millibars) averaged over the area between 30°N to 65°N, 160°E to 140°W as a function of month and year. Note four decadal-scale periods centered on 1925, 1940, 1962, and 1984 of very low values for the Aleutian low. (Source: Trenberth, K.E., and J.W. Hurrell. 1994. Decadal atmosphere-ocean variations in the Pacific. *Climate Dynamics* 9:303-319. Reprinted with permission, courtesy Springer-Verlag, New York, Inc.)

Regime changes may occur suddenly. Ebbesmeyer et al. (1991) identified 40 environmental variables from the ocean, atmosphere and biosphere and demonstrated a significant difference, which they called a step jump, in their deviate values between the periods 1968-1975 and 1977-1984. It is important to examine the nature of the cycles seen in the PNWI and PNI, and the strength of the evidence for them to determine whether or not they are cycles rather than modal regime changes separated by step jumps. Step jumps have been suggested by Francis (1993) who, following a model of Hollowed and Wooster (1991), only used one index, the Central North Pacific Index (CNP), to propose four modal changes between what he calls a West Coast Type and Alaskan Type circulation pattern (Figure 4.14). Greenland (1996) showed how the CNP was well-related to other atmospheric indices for the two circulation patterns (Figure 4.15). In particular, the Alaskan Type is a form of the positive Pacific North American Index (PNA) pattern and the West Coast Type is related to negative PNA values. The existence of regime changes is now well established for the last hundred years in the Pacific Northwest. Dell'Arciprete et al. (1996) assembled a comprehensive data set of Pacific Northwest air temperature, precipitation, streamflow, snowpack, and sea surface temperatures and found that 79% of the multi-variance could be explained by two statistical factors. The first factor (principal component, PC1) they called the "cool-and-wet / warm-and-dry" winter mode with values that parallel the PNW index. The second factor was labeled the "cool-and-dry /warm and wet" winter climate mode and is

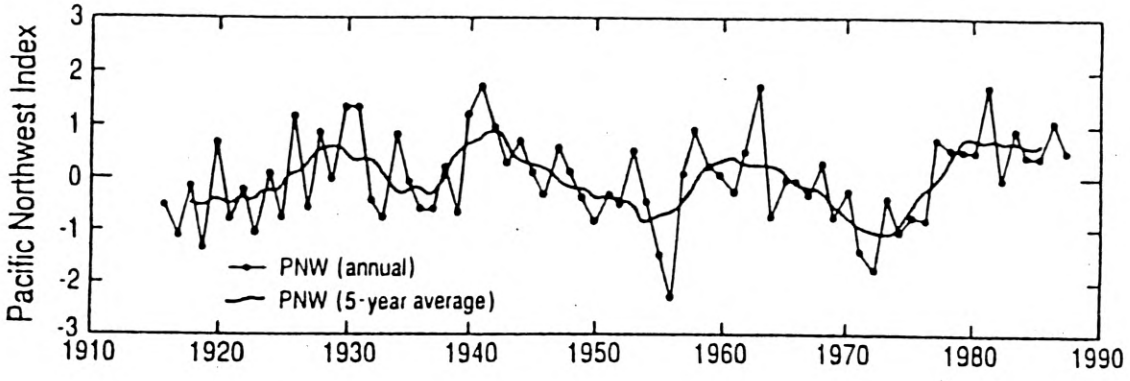


Figure 4.12. Changes in the PNW Index over the last century. The 5-year average shows four cycles of oceanic-atmospheric circulation between 1916 and 1987. (Source: Ebbesmeyer, C.C., C.A. Coomes, G.A. Cannon, and D.E. Bretschneider. 1989. Linkage of Ocean and Fjord Dynamics at Decadal Period In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 399-417. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

dominated by interannual variability. Principal component 1 was well correlated with the Pacific Basin-wide variables of North Pacific sea surface temperature, North Pacific Index, and SOI. Re-examination of earlier comprehensive investigations (Roden 1989) of coastal air temperatures and sea surface temperatures demonstrates decadal changes well (Figures 4.16 and 4.17). Roden has also found some discontinuous West Coastal station data that could be used to establish a hypothesis of how the decadal regimes might be extended back into the beginning of the 19th Century. Royer (1993) found a clear 18.6 nodal (lunar tide) signal in Sitka, AK, air temperatures, and presumably, sea surface temperatures, going back to 1828. He suggests that this lunar signal is best found in high latitudes. A possible research task would be to *use discontinuous early coastal air and sea surface temperature data to build a suggested picture of decadal regime behavior extending back to the early 1800s.* Such a picture might tell us important information about the degree of "stationarity" of this type of change.

Since interdecadal changes seem to be related to the catch of some fish species (Francis and Sibley 1991; Francis 1993; Greenland 1996) it is important to find out more about them. Unfortunately the instrumental record is not long enough to ensure that the time-series is stationary. Because of this an important *research area would be to look at longer time-series of proxy data* (possibly the dendrochronological data going beyond that of Graumlich and Brubaker 1986; Graumlich 1987; Wiles et al. 1995) to see if these phenomena persist beyond the last century.

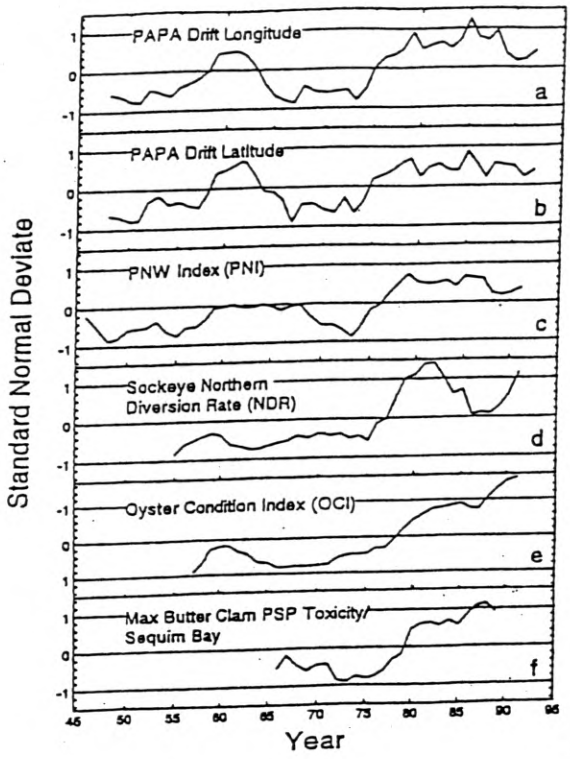


Figure 4.13. Changes in the PNI (c) back to 1945, along with five other environmental parameters. (Source: Ebbesmeyer, C.C., R. Chiang, A. Copping, G.M. Erickson, R. Horner, W.J. Ingraham, and L. Nishitani. 1995. Decadal covariations of Sequim Bay paralytic shellfish poisoning (PSP) with selected Pacific Northwest environmental parameters. *Puget Sound Research* '95:415-421.)

Schwing (1994) has pointed out that the variations in coastal temperature and salinity time-series could be interpreted as either decadal periods of slightly increasing (or decreasing) temperature followed by rapid increases (or decreases) of temperature, *or* as a series of "regime shifts" where the mean annual temperature over a short period makes a rapid shift following a decadal period of relatively level temperature. This is consistent with the ideas of Francis (1993). Another research area, then, is *to determine whether the changes are quasi-cyclic in form or quasi-modal punctuated by step functions*. Dettinger et al. (1995) found peaks in spectra of US air temperatures at 10 and 7.4 years with strongest oscillation in the Western US and with noticeably step-like transitions. Another research area is to find out *what causes the change between one part of the cycle or modal type and another*. Francis (1993) has implied a relationship between shifts from West Coast Type to Alaskan Type (now being termed the Pacific Decadal Oscillation) and the occurrence of El Niño winters that have the highest sea surface temperatures in the far western Pacific. Trenberth (1995) and Trenberth and Hoar (1996) have suggested that the decadal time-scale variations are linked to recent changes in the frequency and intensity of El Niño versus La Niña events and related forcing from the anomalous sea surface temperatures of the tropics. An intense investigation on this general topic is justified, and is all the more urgent since other studies have shown well-marked decadal variation in the Atlantic sector of the Northern Hemisphere (Hurrell 1996) and the fact that the North Atlantic Oscillation has remained in one extreme phase over the last decade (Hurrell 1995). Another research question related to all these issues is, *given the fact that the changes are somewhat statistical in nature (i.e., they show up best when the data are aggregated for the whole winter and in standardized anomalies rather than 'raw' data), how can this knowledge best be transferred to, and used by, decision makers?*

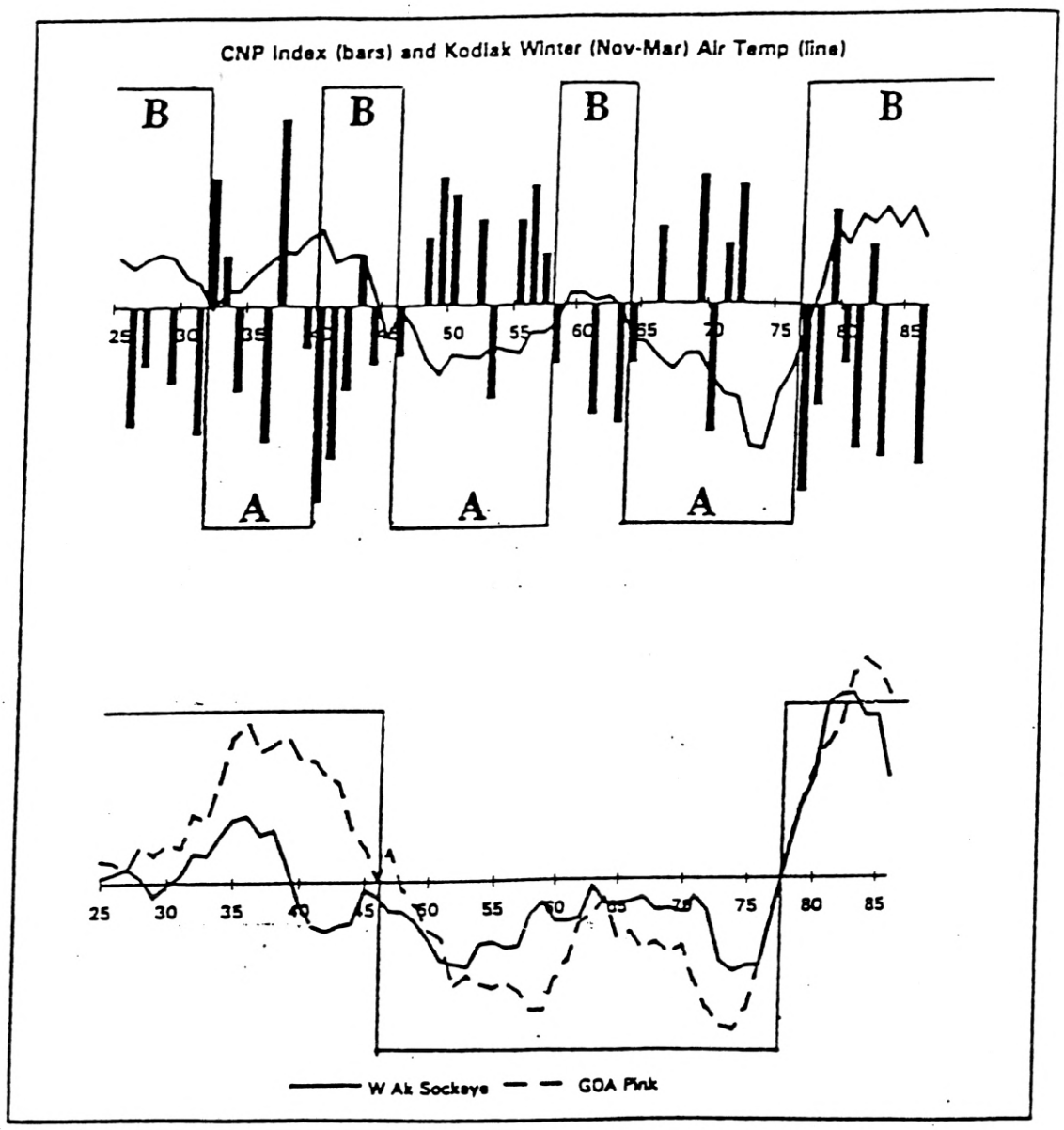


Figure 4.14. Changes and possible regimes in the Central North Pacific (CNP) over the last century. The upper graph plots the CNP Index and the winter air temperature in Kodiak, Alaska, to suggest West Coast Type (A) and Alaska Type (B) circulation regimes between 1925 and 1985. The lower graph shows distinct, related shifts in abundance of Alaska sockeye salmon and Gulf of Alaska pink salmon. Note the "regime shift" apparent in both graphs in 1976. (Source: Francis, R.C. 1993. Climate change and salmonid production in the North Pacific Ocean. In Proceedings of the Ninth Annual Pacific Climate (PACLIM) Workshop, April 21-24, 1992, eds. K.T. Redmond and V.L. Tharp, 33-43. California Department of Water Resources, Interagency Ecological Studies Program, Technical Report 34. Reprinted with permission, courtesy California Department of Water Resources.)

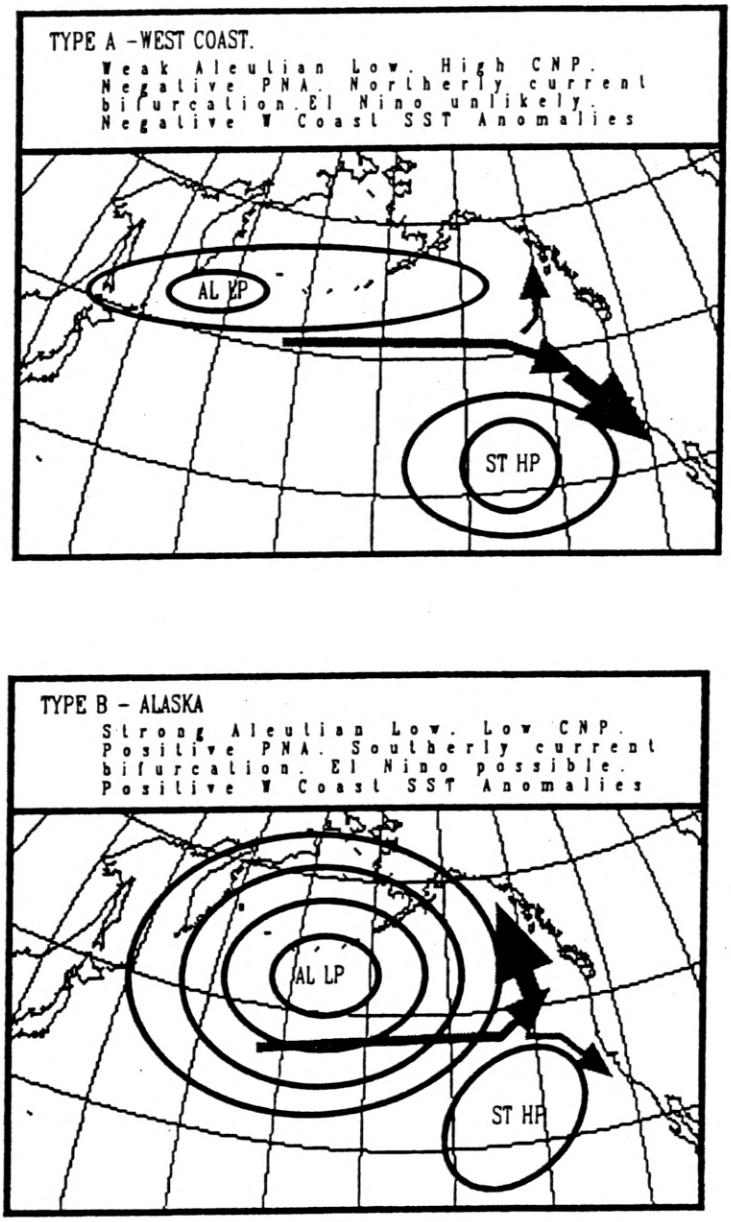


Figure 4.15. Schematic diagram of the West Coast and Alaskan flow types with their relation to several teleconnective indices. AL LP is Aleutian low pressure; ST HP is subtropical high pressure; arrows show relative magnitude of strength of oceanic surface currents. This suggests the relationship between atmospheric conditions and ocean currents. (Source: Greenland, D. 1996. Offshore coho salmon populations near the Pacific Northwest and large scale atmospheric events. In Proceedings of the Twelfth Annual Pacific Climate (PACLIM) Workshop, May 2-5, 1995, eds. C.M. Isaacs and V.L. Tharp, 109-119. California Department of Water Resources, Interagency Ecological Program. Technical Report 46. Reprinted with permission, courtesy California Department of Water Resources.)

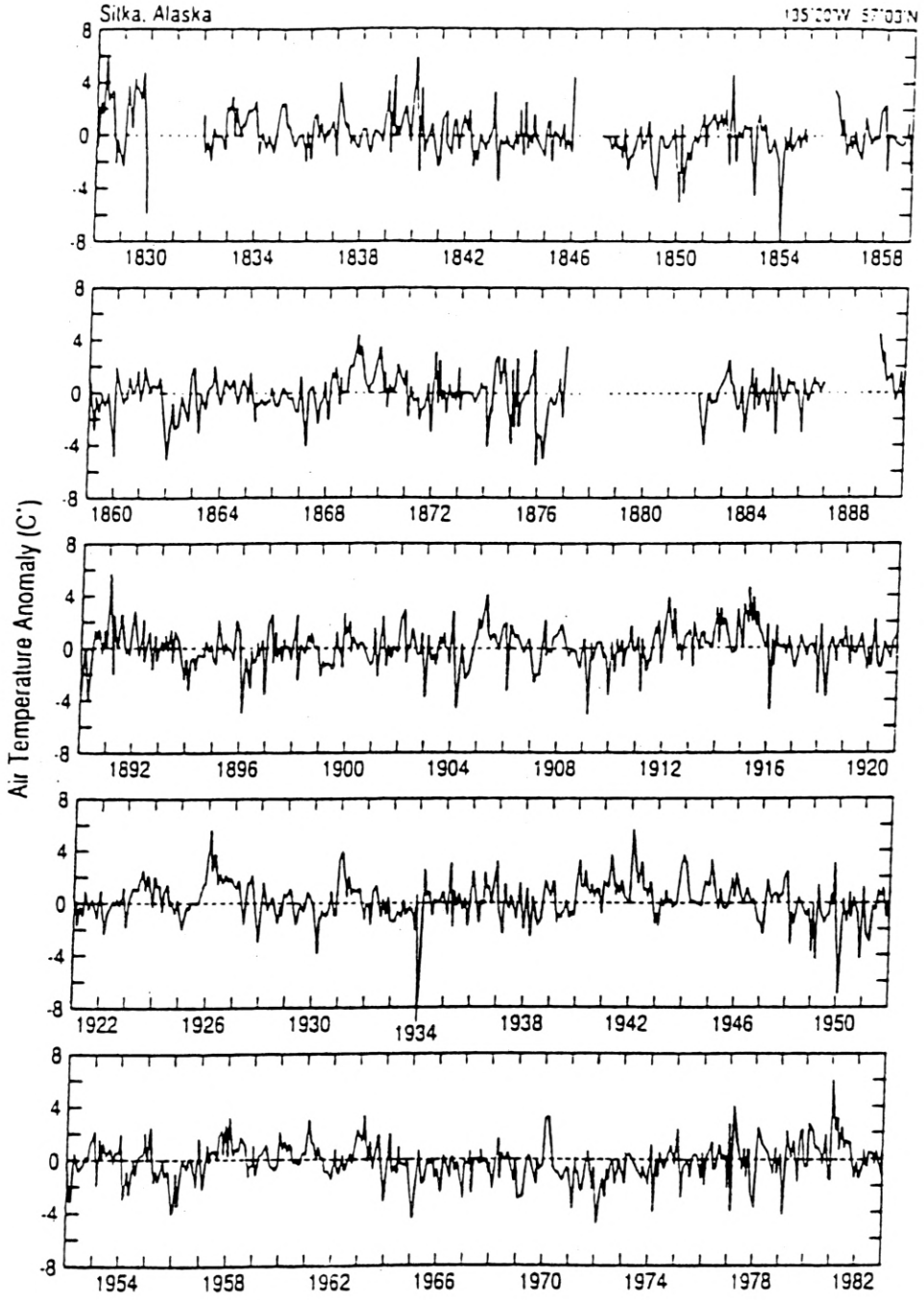


Figure 4.16. Air temperature anomalies from long-term monthly means at Sitka, Alaska. (Source: Roden, G.I. 1989. Analysis and interpretation of long-term climatic variability along the West Coast of North America. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 93-111. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

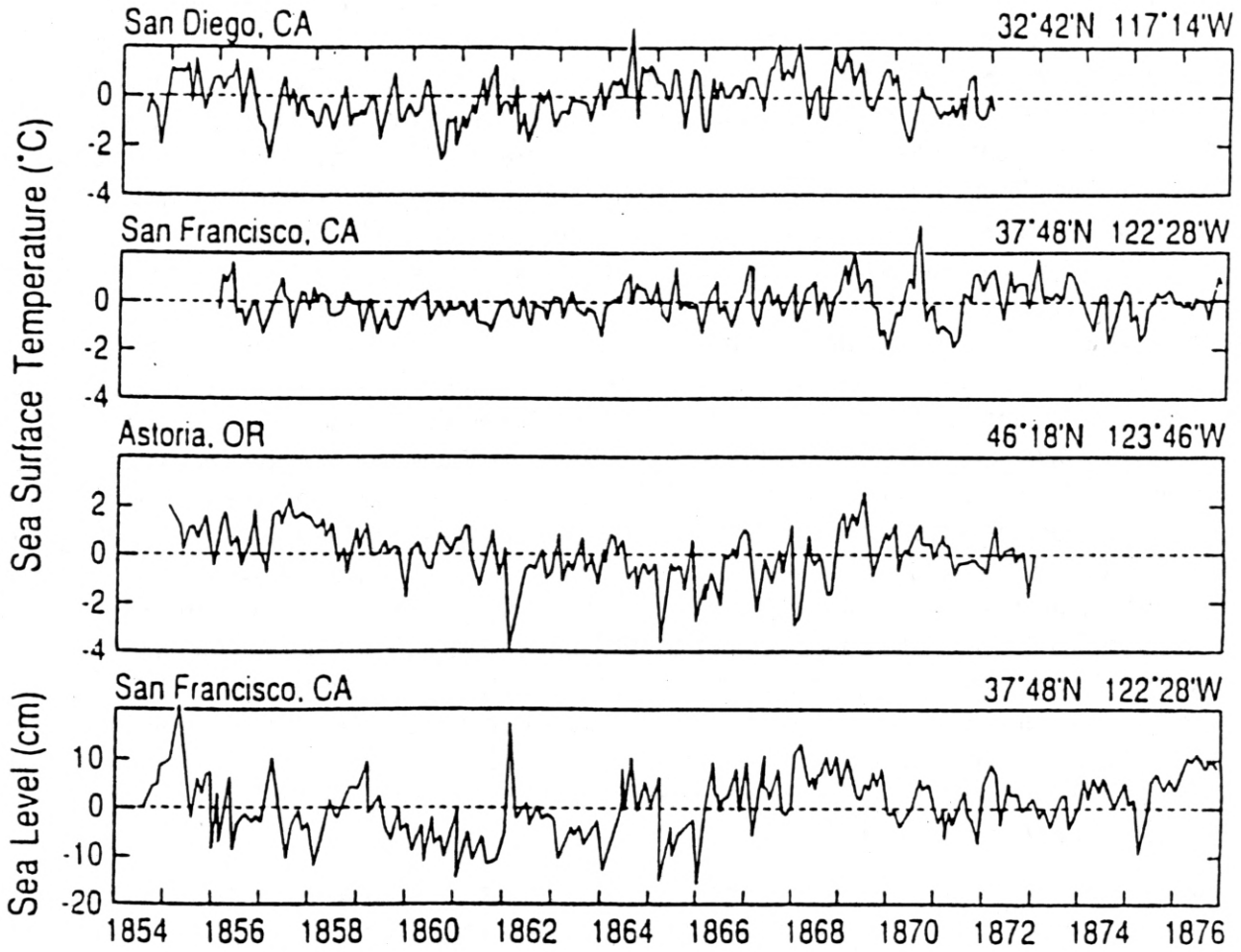


Figure 4.17. Sea surface temperature anomalies from 1854-1876 at California and Oregon tide stations. (Source: Roden, G.I. 1989. Analysis and interpretation of long-term climatic variability along the West Coast of North America. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 93-111. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

ATMOSPHERIC VARIABILITY ON THE QUASI-QUINTENNIAL SCALE - ENSO

The dominant source of variation on the quasi-quintennial scale is related to the El Niño-Southern Oscillation (ENSO). El Niño refers strictly to a warming of sea surface temperatures in the eastern tropical Pacific Ocean but is usually associated with a basin-scale warming extending from the coast of South America to the International Dateline. An important hypothesis suggests that the ENSO system, which is primarily driven by the ocean, is a natural result of interactions between oceanic Kelvin and Rossby waves in the tropical part of the Pacific Ocean (Graham and White 1988). El Niño is linked in the atmosphere to times of low sea level pressure in the area of Tahiti and high sea level pressure near Darwin, Australia. The atmospheric part of El Niño is embedded in the Southern Oscillation in which the difference of pressure between these two places oscillates between high and low on a 2-7 year time scale. The Southern Oscillation is itself part of a larger oscillation in the strength and direction of flow of the "Walker Cell", which is a cell of air with rising and falling limbs near Tahiti and Darwin, respectively, and surface and upper air flows moving either east or west to provide continuity of mass. Most commonly, the state of the Southern Oscillation is measured by the departure from the long-term monthly mean sea level pressures at Tahiti minus those at Darwin in an index called the Southern Oscillation Index (SOI). However, there are many other ways of measuring the phenomena of the oscillation. Indeed, Murphree (1996) has pointed out that the SOI may not be the most appropriate measure of the ENSO phenomena as they are related to the Pacific Northwest. He has identified monthly mean 200 millibar (mb) pressure anomalies over the North Pacific as a useful tool because it is at this level where much of the tropical-extra tropical ENSO-scale connection may be found (Murphree and Reynolds 1995). Other measures of ENSO more applicable for the Pacific Northwest than are tropical sea surface temperatures, may be available for the ocean as well. McGowan et al. (1996) have suggested the use of North American West Coastal sea surface temperatures and changes in sea level heights. Consequently, an important research topic is *what are the most appropriate measures of both the atmospheric and the oceanic manifestations of ENSO in relation to the Pacific Northwest?*

The SOI is not the only measure of El Niño phenomena. Cayan and Webb, (1992) following earlier workers, grouped years into El Niño and La Niña years from 1901. Quinn (1992) made a classic reconstruction of El Niño years classified in five classes of strength, three classes of time within the year, and five classes of confidence in the data used for any particular year. The record goes back five centuries to 1497 and encompasses both large-scale and regional El Niños. Quinn has also extended the record back to 622 AD using data on Nile River flooding. Tree-ring records have been employed to reconstruct SOI values back to 1607 by Lough (1992). The ENSO signal is also the dominant signal in a 1500 year ice-core record from Peru (Thompson et al. 1992). The major El Niño (warm event) and La Niña (cold event) episodes between 1877 and 1988 have been identified by Diaz and Kiladis (1992) as shown in Table 4.1. The atmospheric manifestation of El Niño and La Niña in the Pacific Northwest, as measured by SOI values, is well marked. Low SOI values (El Niños) are correlated with reduced precipitation (Redmond and Koch, 1991), snowpack and streamflow in the region (Cayan and Webb 1992; Figures 4.18, 4.19 and 4.20). The Pacific Northwest also tends to display warmer winter temperatures and drier than usual conditions (Redmond and Koch 1991). Redmond and Koch (1991) used a four month

lag to correlate June to November SOI values to precipitation and temperature values in the following October to March for western climate divisions. The results for the Pacific Northwest, both east and west of the Cascades in Washington and Oregon, show mostly a very clear ENSO signal (Table 4.2), although the signal on the west is somewhat more clear. This is consistent with results found for the Andrews Forest Long-Term Ecological Research site in the foothills of

Table 4.1. Major El Niño (warm event) and La Niña (cold event) episodes between 1877 and 1988. After Diaz and Kiladis (1992).

Warm Event (El Niño) Years	Cold Event (La Niña) Years
1877	1886
1880	1889
1884	1892
1888	1898
1891	1903
1896	1906
1899	1908
1902	1916
1904	1920
1911	1924
1913	1928
1918	1931
1923	1938
1925	1942
1930	1949
1932	1954
1939	1964
1951	1970
1953	1973
1957	1975
1963	1988
1965	
1969	
1972	
1976	
1982	
1986	
Total = 27	Total = 21

the Cascades in Oregon (Greenland 1994a). Ropelewski and Halpert (1996) demonstrated the most consistent El Niño response is decreased precipitation at 4 to 12 months after the peak of the ENSO warm event with the largest response occurring in the November after the June in which the El Niño peaked. The highest El Niño-related temperatures in the Pacific Northwest

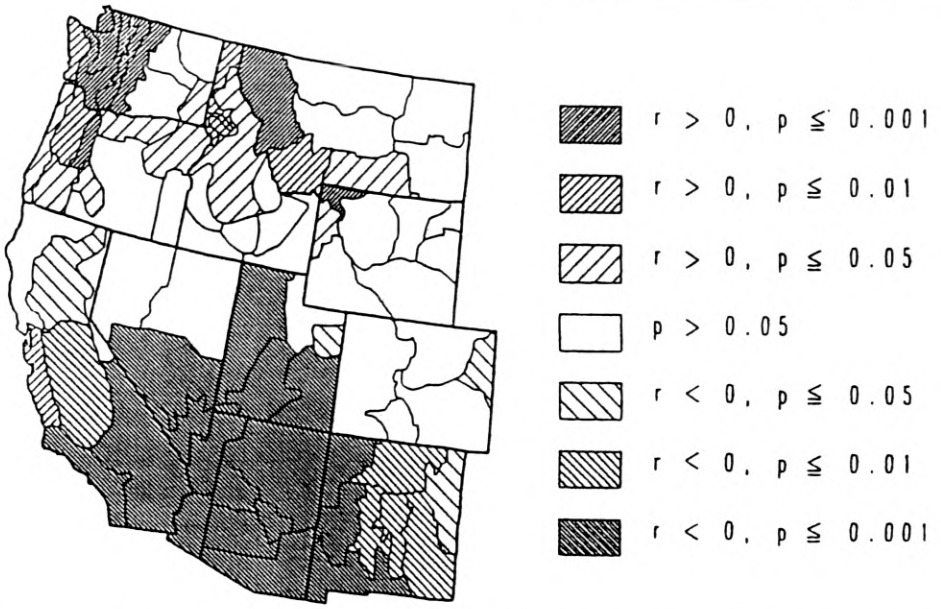


Figure 4.18. Relationship of Southern Oscillation Index (SOI) to precipitation values in the western US. r is the correlation coefficient and p is the probability of random occurrence. (Source: Redmond, K.T., and R. Koch. 1991. ENSO vs. surface climate variability in the western United States. *Water Resources Research* 27:2381-2399. Reprinted with permission, courtesy American Geophysical Union.)

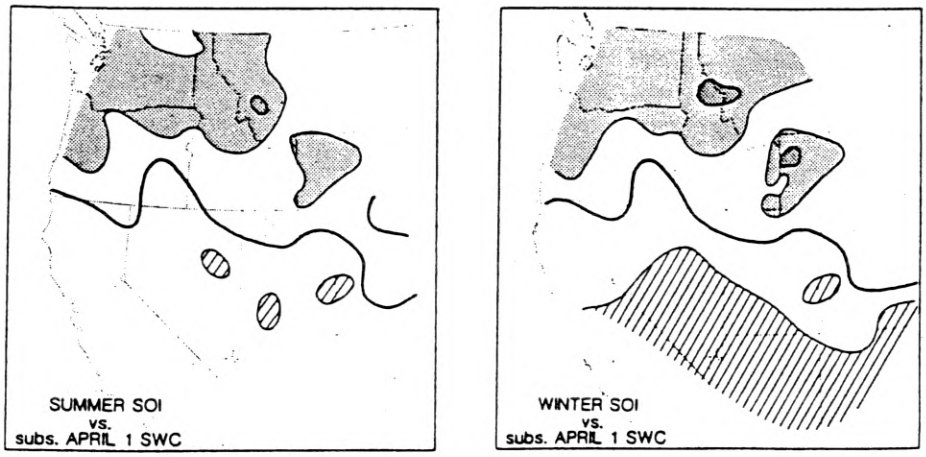


Figure 4.19. Relationship of Southern Oscillation Index (SOI) with snow water content (SWC) in the western US. Stippling represents positive correlation and hatching represents negative correlation. (Source: Cayan, D.R., and R.H. Webb. 1992. El Niño/Southern Oscillation and streamflow in the western United States. In *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*, eds. H.F. Diaz and V. Markgraf, 29-68. Cambridge: Cambridge University Press. Reprinted with permission, courtesy Cambridge University Press.)

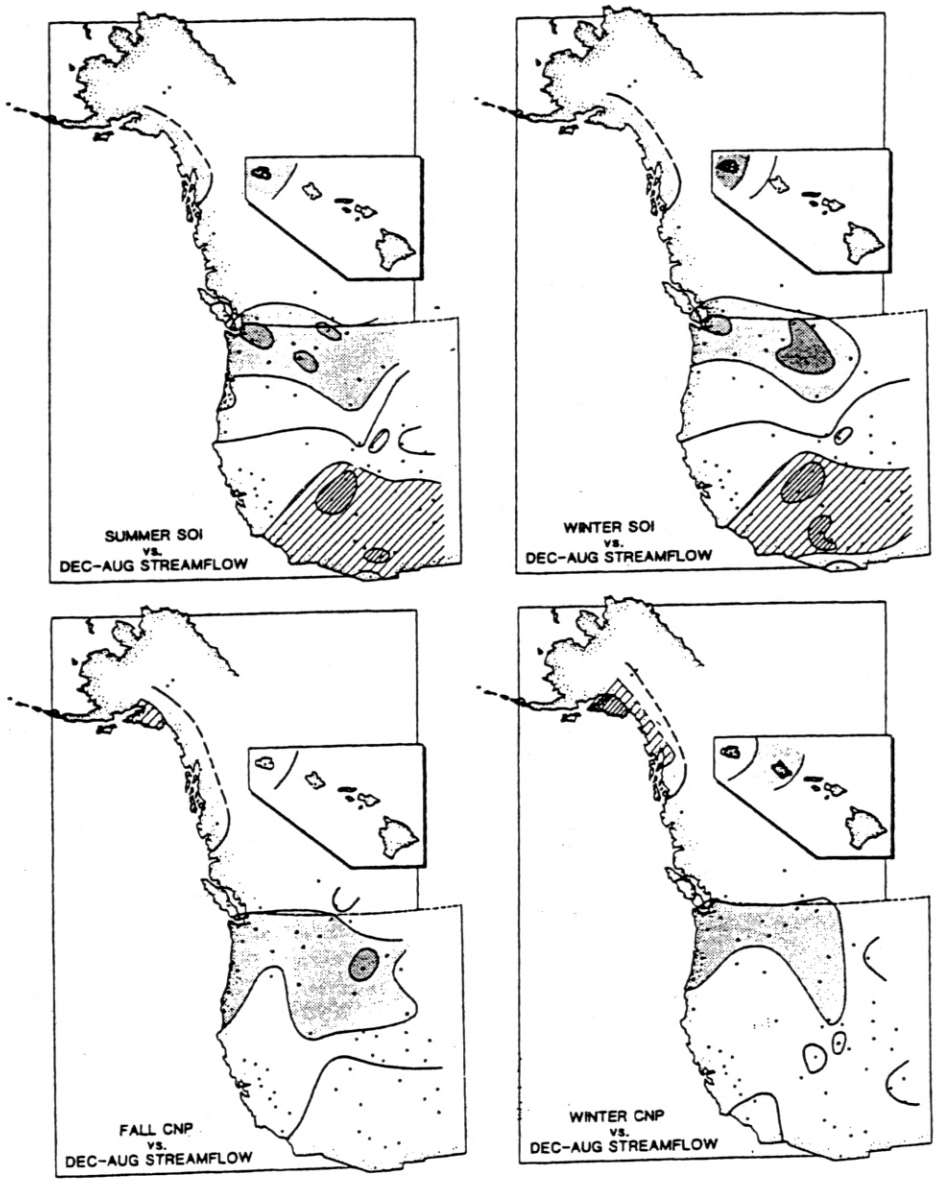


Figure 4.20. Relationship of Southern Oscillation Index (SOI) and Central North Pacific Index (CNP) with streamflow in the western US. Stippling represents positive correlation and hatching represents negative correlation. (Source: Cayan, D.R., and R.H. Webb. 1992. El Niño/Southern Oscillation and streamflow in the western United States. In *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*, eds. H.F. Diaz and V. Markgraf, 29-68. Cambridge: Cambridge University Press. Reprinted with permission, courtesy Cambridge University Press.)

Table 4.2. Statistics from analyses of June-November Southern Oscillation Index (SOI) and October-March Climate Divisional Precipitation and Temperature. The correlation coefficient, r, shows positive correlations between SOI and precipitation, and negative correlations between temperature and SOI. Ratio is the quotient of the average precipitation for years with SOI > 0.5 divided by that for years with SOI < 0.5. Difference in temperature is the average difference also between years with SOI > 0.5 and those for years with SOI < 0.5 (from Redmond and Koch 1991).

Division	Precipitation	Ratio	Temperature	Difference °C
	r		r	
Washington				
West Olympic Coast	0.363	1.22	-0.399	-1.1
NE Olympic San Juan	0.455	1.36	-0.384	-1.0
Puget Sound Lowlands	0.416	1.27	-0.357	-1.0
E Olympic-Cascade Foothills	0.481	1.30	-0.355	-1.0
Cascade Mts. west	0.512	1.35	-0.344	-1.1
E Slope Cascade	0.428	1.42	-0.246	-0.9
Okanogan-Big Bend	-0.007	1.06	-0.254	-1.2
Central Basin	0.125	1.19	-0.171	-0.8
Northeast	0.183	1.14	-0.265	-1.1
Palouse-Blue Mts.	0.301	1.23	-0.165	-0.7
Oregon				
Coastal area	0.268	1.19	-0.304	-0.8
Willamette Valley	0.341	1.25	-0.229	-0.6
Southwest Valleys	0.261	1.29	-0.186	-0.6
Northern Cascades	0.471	1.38	-0.203	-0.9
High Plateau	0.252	1.23	-0.083	-0.3
North central	0.239	1.22	-0.112	-0.5
South central	0.171	1.16	-0.080	-0.3
Northeast	0.301	1.26	-0.185	-0.7
Southeast	-0.047	1.01	-0.028	-0.2

occur between November and June, peaking in March, following an El Niño of the previous June. Yarnal and Diaz (1986) also determined that the west coast temperature and precipitation anomalies during warm ENSO events are associated with a strong Pacific North American Index (PNA) pattern, while during cold events there is a reversed-polarity PNA pattern. More recently Ropelewski and Halpert (1996) showed the value of expressing ENSO-related shifts in median precipitation amounts expressed as percentiles with respect to climate normal values. This approach can be potentially useful for managers interpreting ENSO forecasts but the authors did not apply the approach to the Pacific Northwest. Consequently a research question would be

what are the sizes of ENSO-related shifts in precipitation and temperature median values to climatic normal values in the Pacific Northwest?

The 1982/83 El Niño is the largest one recorded (this was written before the 1997/98 El Niño). It was more noteworthy for its oceanic effects in the Pacific Northwest than for those in the atmosphere. Even so, the SOI value was the lowest recorded since modern records began in 1935. There was the greatest negative 700 mb seasonal mean height anomaly since the beginning of records in 1948 (see Appendix 4.1) and the second lowest monthly mean sea level pressure for February in the NE Pacific since records started in 1899. Temperature anomalies in the Pacific Northwest for the winter of 1982/83 ranged between 1 and 2°C above the 30 year mean. But instead of being dry, the precipitation for the winter was between 100-150% above normal in the Pacific Northwest mainly because of a wet February (Quiroz 1983). Although this year appears as an outlier in a scattergram of winter water-year precipitation at the H. J. Andrews Forest, Oregon, it is more an outlier because of its SOI value rather than its climatic value (Greenland 1994a).

La Niña events also have important effects on the Pacific Northwest climate. Kahya and Dracup (1993) are among several investigators to demonstrate that high precipitation and high streamflow values in the Pacific Northwest are often associated with La Niña years. We mention below that severe floods may also be associated with such years. A more systematic investigation of La Niña climate in the Pacific Northwest is justified.

Whatever measure is used, the nature, intensity, and geographic extent of effects vary from one El Niño to another. Nevertheless, the similarities between one event and another are large enough to permit model predictions and seasonal forecasts. Emery and Hamilton (1985) noted empirically that not only are ENSO episodes often coincident with a well developed Aleutian low, but also that the episodes often follow a year of poorly developed Aleutian low pressure. Graham and Barnett (1995) used 6 month lead forecasts of tropical Pacific sea surface temperatures to predict 700 mb height-anomalies for the Northern Hemisphere. The forecast worked best for extreme episodes but had substantial success in 23 consecutive winter predictions; however the results for the Pacific Northwest were not as good (Figure 4.21; Graham and Barnett). The National Center for Environmental Prediction (NCEP) uses a combination of a number of different forecast methods to provide long-range forecasts for the US. As an example of the wording used in the forecast we present the following:

> The forecast issued December 1995 for the period January, February, and March, 1996 using statistical methods called for cold temperatures in the Pacific Northwest, forecasts of temperatures from dynamical methods did not mention the Pacific Northwest. Dynamical methods called for wetness in the Pacific Northwest while statistical methods called for a dry Pacific Northwest.
>
> The forecast issued March 1996 for the period April, May, and June 1996 using statistical methods called for warm temperatures in the Pacific Northwest, forecasts of temperatures from dynamical methods called for "cool on northern tier for spring and summer 1996". Dynamical methods said nothing about the Pacific Northwest while

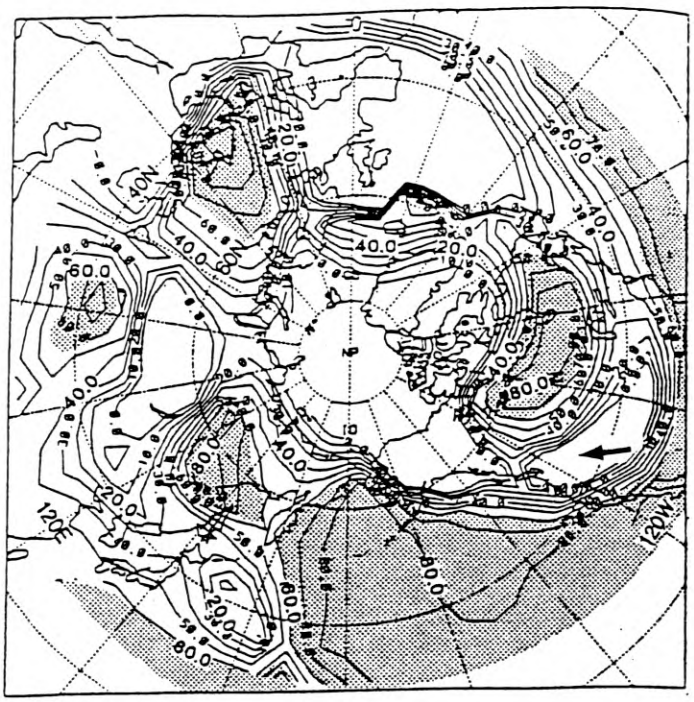


Figure 4.21. Polar-view global map showing areas (shaded) of 90% success in predicting winter weather conditions (700 mb) using 6-month lead forecasts of tropical sea surface temperature. The Pacific Northwest (arrow) is at the edge of areas where this technique is successful. (Source: Graham, N.E., and T.P. Barnett. 1995. ENSO and ENSO-related predictability. Part II: Northern hemisphere 700 mb height predictions based on a hybrid coupled ENSO model. *Journal of Climate* 8:544-549. Reprinted with permission, courtesy American Meteorological Society.)

statistical methods called for wetness in the Pacific Northwest for April, May, and June.

Both forecasts generally believed La Niña conditions would continue through the summer but some (of 12) forecasting methods suggested that it would end by fall and winter would see rising sea surface temperatures in the equatorial Pacific (NOAA 1996).

Two potential research projects arise from these efforts. First, model forecasting studies should be reviewed, and their efficiency assessed, with regard to their specific Pacific Northwest area forecast. Second, the best methods for use of National Weather Service (NWS) Long-lead forecasts by Pacific Northwest managers should be determined. At the same time NOAA should work on educating the forecast users on how to assess the forecasts, particularly at times when different forecast methods render different prognostications. Because an El Niño event leads to warming in the Pacific Northwest area, there is a belief that it can, to some extent, be used as an analog for global climate warming conditions. This may be true in some areas but Bakun (1990) has pointed out that this may not be true as far as coastal upwelling is concerned.

As mentioned above, Francis (1993) has implied a relationship between shifts from West Coast Type flow mode to Alaskan Type flow mode and the occurrence El Niño winters that have the

highest sea surface temperatures in the far western Pacific. He points out that three of the four hypothesized shifts from West Coast to Alaskan flow regimes occurred during the high west Pacific sea surface temperature El Niño times of 1925/26, 1941/42 and 1976/77. An interesting research topic would be *to see if this West Coast to Alaskan Type flow regime switch also occurred in earlier decades.* The earlier data of Roden (1989) and earlier El Niño occurrence data (see Diaz and Markgraf 1992) could be used to test this hypothesis. A related question would be to find out *what causes the switch back from Alaskan to West Coast Type flow regimes*?

Wang (1995) has shown that atmospheric and oceanic conditions prior to an El Niño event have changed since the 1970s. Prior to this, the onset was preceded by a large anomalous cyclone (low pressure) over Australia and a relaxation of the easterly Trade Winds leading to an increase of sea surface temperature off the South American coast prior to an increase in sea surface temperatures in the central tropical Pacific. Instead, from 1980, the onset phase of El Niño has been preceded by an anomalous cyclone over the Philippines Sea, enhanced Trade Winds in the southeast Pacific, and central Pacific sea surface temperatures warming before those on the South American coast. Recent studies have also suggested that the unusually long El Niño event of the early 1990s is related to anthropogenic-induced global climate change since it is statistically unlikely to be part of decadal time scale variation (Trenberth and Hoar 1996). It is certain that ENSO related phenomena will be the focus of much research attention for many years to come.

ATMOSPHERIC VARIABILITY AT THE INTERANNUAL SCALE

Preliminary analyses of precipitation variations by Greenland (unpublished) indicate considerable variability at a biennial scale for the Northern Cascade Climate Division of Oregon. But on a national scale Dettinger et al. (1995) found that biennial scale variability in air temperature is much more marked in many other parts of the country. Dettinger et al. explain how the temperature variations across the country are associated with the Quasi-Biennial Oscillation (QBO). The QBO is best seen in the mean zonal-winds of the equatorial stratosphere, which have zonally symmetrical easterly and westerly regimes alternating regularly with periods varying from about 24 to 30 months (Holton 1992). Atmospheric circulation patterns in the North America area related to the QBO include stationary centers at about 40° latitude off both coasts that fluctuate in phase opposition. The centers bring warm air to the Southwest and cool air to the Northeast and *vice versa* about 12 months later (Dettinger et al. 1995). Barnston et al. (1991) have postulated a relationship between ENSO and the QBO such that during a warm ENSO event there is a preference in January and February for a strong Pacific North American Index circulation pattern in the west QBO phase.

Another feature that should be considered at this scale is the effect of major explosive volcanic eruptions. Such events tend to be stochastic and time-scale independent but their effects play out on a biennial scale. Portman and Gutzler (1996) have shown that at various times in the two years after a major eruption the Pacific Northwest tends to be anomalously cool in winter and spring and wet in summer. Based on the work of these authors and Lamb (1995) the most significant eruptions in recent times are listed in Table 4.3.

Table 4.3. Important volcanic eruptions which have effected the atmosphere. After Portman and Gutzler (1996) and Lamb (1995). MA and MI indicate major and minor eruptions, respectively.

Volcano	Year	Severity
Krakatau	1883	MA
Pelée	1902	MA
Soufrière	1902	MA
Santa Maria	1902	MA
Ksudach	1907	MA
Katmai	1912	MA
Hekla	1947	MI
Bezymyannyy	1956	MI
Agung	1963	MA
Awu	1966	MI
Fernandina Island	1968	MI
Fuego	1974	MI
Mount St. Helens	1980	MA
El Chichón	1982	MA
Mount Pinatubo	1991	MA

ATMOSPHERIC VARIABILITY AT THE ANNUAL SCALE

The seasonal changes of the Pacific Northwest include a long winter rainy season and a hot, dry summer. Alsop (1989) has identified the seasons of Oregon as follows. On the average, the winter season runs from November 5 to March 12. Spring is between March 19 and May 14. Summer lasts from May 21 to September 17 while the short fall season is between September 24 and October 29.

Monthly and Seasonal. More detail of the principal changes in the typical seasonal variations in surface pressure are provided in Figure 4.22 (Terada and Hanzawa 1984). Between latitudes 42-46°N is found the greatest poleward energy flux in the northern hemisphere. The Pacific Northwest lies, on the average, in the latitude of the main Polar Front Jet Stream (PFJ) in summer and just north of PFJ in winter. While the surface pressure is dominated by subtropical high pressure in summer and a mixture of high and Aleutian low in winter, the upper air (700 mb) over the Pacific Northwest is dominated by a zonal jet in January with a ridge over western Alaska. In July the influence of upper air high pressure is seen. The climate in the coastal region is markedly maritime with lower temperatures than the interior continent in July and higher than the interior continent in January. There is a very marked gradient of annual temperature range between maritime and continental areas that makes climatic modeling difficult in this part of the world. Most cyclonic centers in winter track north of the Pacific Northwest but trailing fronts affect the

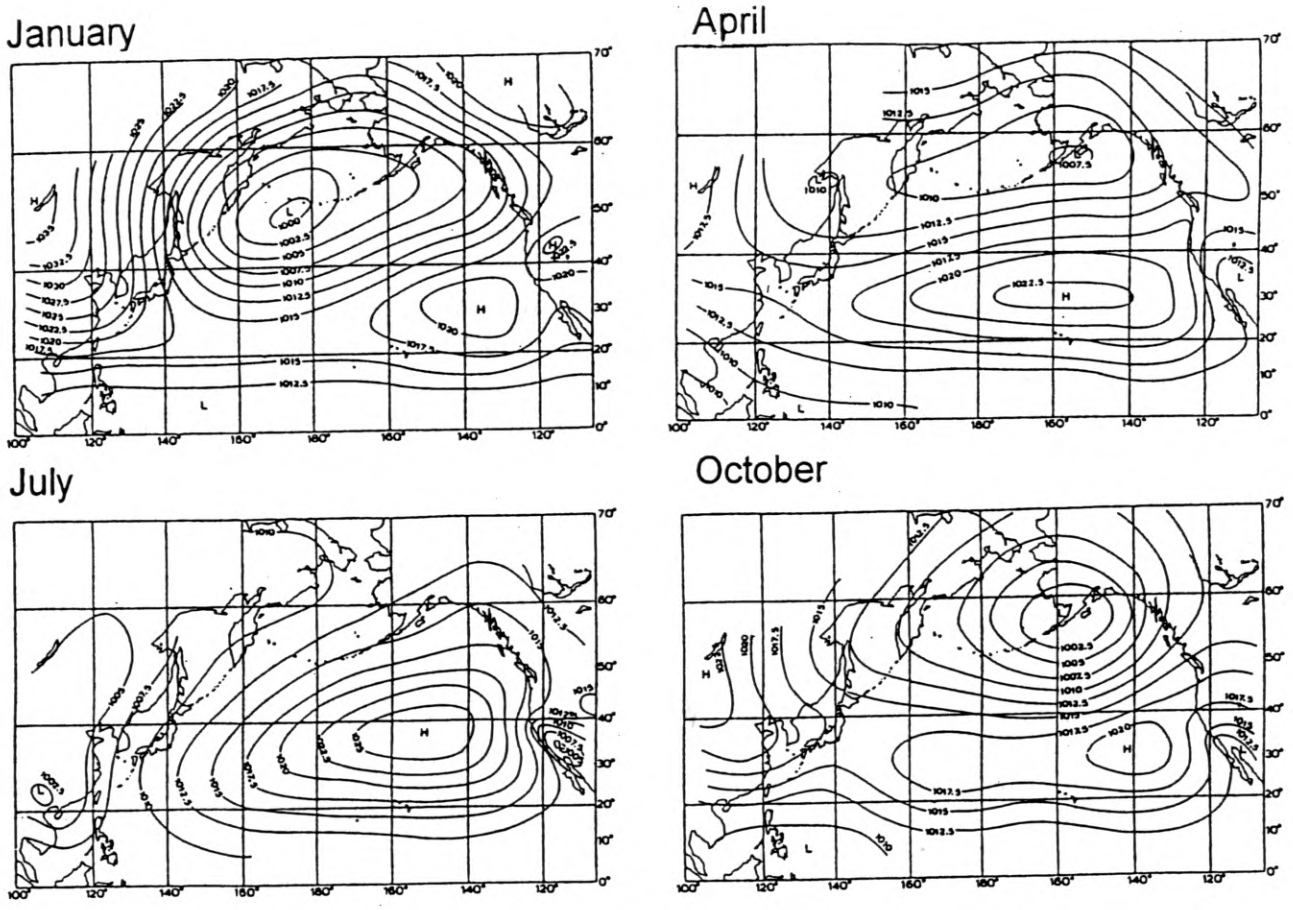


Figure 4.22. Mean sea level pressure (millibars) over the North Pacific Ocean in January, April, July, and October. Note the strong Aleutian low and weak subtropical high in January compared to the dominance of the high pressure in July. April and October show transitions between theses extremes. (Source: Terada, K., and M. Hanzawa. 1984. Climate of the North Pacific Ocean. In *World Survey of Climatology,* ed. H.E. Landsberg Vol. 15, 431-477. *Climates of the Oceans*, ed. H. Van Loon. Amsterdam: Elsevier. Reprinted with permission, courtesy Elsevier Science - NL.)

area. In July, storm tracks are in the latitude of Alaska. Pacific airmasses dominate all year round (Barry and Chorley 1992; Bryson and Hare 1974).

Within the Pacific Northwest the warmest month near the coast is August. This delay is due to the peak of cold offshore currents in July and the associated fog. The annual average snow fall is between 2.5 and 7.5 cm. Several times each year winds may exceed 33 m s^{-1} (74 miles per hour, or hurricane force). Higher elevations in the Coastal Ranges have little effect on temperature because maritime air masses in winter are not much colder at 1000 m compared to sea level while in summer continental heating balances an expected altitudinal cooling (Sternes 1960).

Teleconnective Indices. Wallace and Gutzler (1981) provided the first "type description" of the Pacific / North American Pattern (PNA). They described it as one in which "...(winters are) characterized by below normal temperatures over the eastern United States and strong ridges in the 700 mb height field extending from the Pacific Northwest of the United States to the Alaska-Canada border." Greenland (1994a) noted that when the PNA index is positive and high, a meridional circulation in the westerlies with a ridge of high pressure shunts storms to the north of the Pacific Northwest giving rise to relatively dry and warm winters. When the PNA is negative, the zonal circulation in the westerlies brings in storms from the Pacific Ocean giving rise to wetter and cooler weather. Cayan and Peterson (1989) found that streamflow fluctuations show correlations (0.3-0.6) with sea level pressure anomaly patterns over the North Pacific. For streams on the West Coast, positive streamflow is associated with low pressure off the coast (to the west or northwest) leading to increased west and southwest winds and storms. Higher interior streamflow is associated with a positive sea level pressure anomaly over the central North Pacific.

Stream and River Discharges. As mentioned above, snowmelt potentially leads to a June maximum of discharge for the Columbia river but the existence of dams has smoothed out this seasonal pattern. The Columbia provides about 80% of the river discharge to the ocean between San Francisco and the Strait of Juan de Fuca (Hickey 1989) and the Fraser is also a major contributor. The other coastal rivers have a maximum discharge to the ocean in December and January (Landry et al. 1989). The amplitude and phase of the annual cycle of monthly precipitation and streamflow varies markedly along the West Coast and the strict Pacific Northwest area is just part of this gradient of variation.

In, and south of the San Francisco Bay area, maximum stream flow occurs between April and July following maximum precipitation (falling as snow) in January and February (Figure 4.23; Cayan and Peterson 1989). This pattern is followed in the Pacific Northwest by the Columbia River but coastal rivers peak with coastal precipitation maxima in January and February. In British Columbia and Alaska, summer, fall or early winter precipitation tends to give rise to streamflow peaks in various parts of the summer. Further details on stream and river discharges are provided in Chapter 6.

Stream and River Temperatures. Few reports exist of systematically collected long-term stream and river temperatures. This is partially because of the large natural spatial variability of stream temperatures, which are a function of solar radiation and other energy inputs and outflows, advection, convection, evaporation rates, and tributary inflow (Fuhrer et al. 1996). However, Fuhrer et al. (1996) report a general uniformity in the lower Columbia River with daily mean water temperatures for the period 1968 to 1994 ranging between 6°C and 18°C with a median value of approximately 12°C. August is the month of highest values and either January or February has the lowest. An Oregon Department of Environmental Quality (1995) report shows selected samples of Oregon stream temperatures in summer ranging from 15.4°C to 28.9°C and temporal changes from May to November with a range of approximately 17°C and a maximum annual range in mean monthly temperatures of about 15°C in eastern Oregon with smaller values in western Oregon. The rivers tend to warm as they flow downstream. Stream temperatures may potentially be strongly affected by a wide variety of human activities.

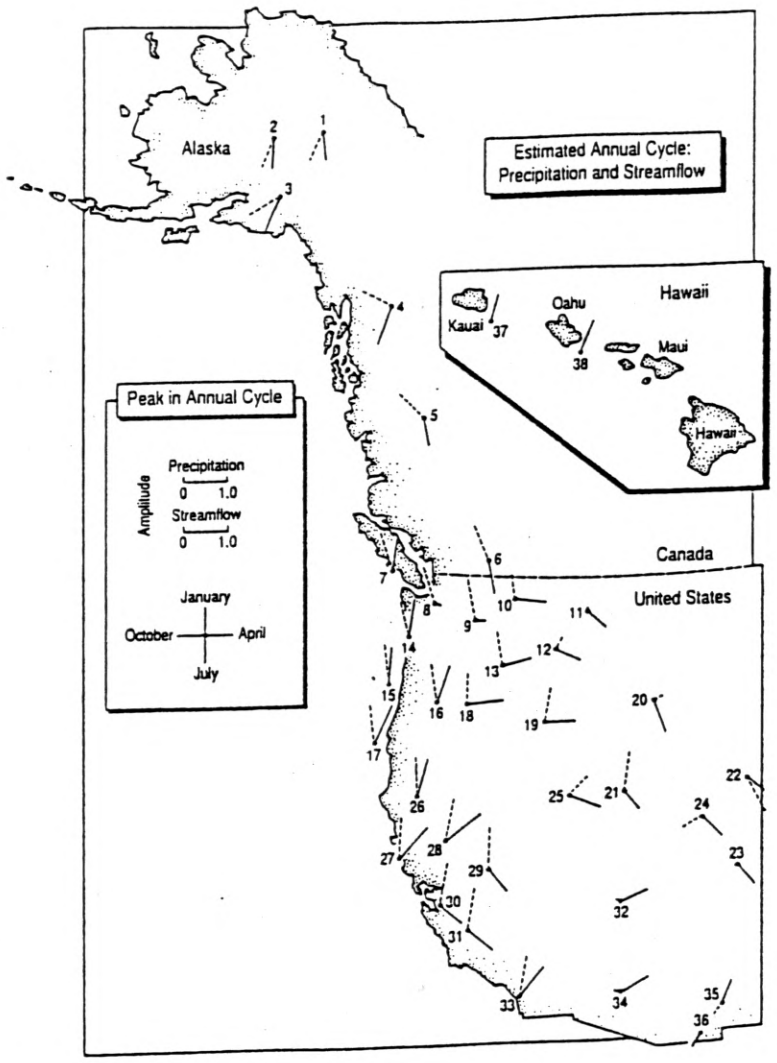


Figure 4.23. Amplitude and phase of the annual cycle of monthly precipitation and streamflow along the West Coast and in the West. Numbers indicate station identification; the direction and length of the vectors indicate the season and amount, respectively, of maximum rainfall (dotted) and streamflow (solid). For instance, at Boise (19), most precipitation falls during January/February and sreamflow peaks during late March. (Source: Cayan, D.R., and Peterson, D.H. 1989. The influence of North Pacific atmospheric circulation on streamflow. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 375-397. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

Daily. Usually any extremes of temperature are of small duration and associated with continental air flows. Low temperatures are found when the air flow is from the northeast and high temperatures occur when air flow is from the southeast. Very extreme seasonal values occasionally occur related to unusual situations. An example of this is the extreme winter of 1861-62 when temperatures reached - 30°C at the Dalles, Oregon, and both the Fraser River at Vancouver and the Columbia River at Vancouver, Washington, froze over. Floods of great magnitude occurred in California at the time and the Sacramento River took on the appearance of "an inland sea" (Roden 1989). These events are believed to be associated with a large jet stream meander that caused a blocking high pressure zone over the Pacific Northwest and allowed Arctic air to penetrate into the region and forcing storm tracks southward into California. This is also the scenario that led to widespread flooding in 1964. According to Sternes (1960), major floods

have occurred at the coast in 1861, 1890, 1909, 1927, 1953, 1955. A further major flood occurred in February 1996 which was due to a rain-on-snow event accompanied by a large stream of atmospheric moisture arriving from the direction of Hawaii that flowed over a long strip of positive sea surface temperature anomalies in the Pacific. *The role of extreme events such as floods and droughts on the ecosystem should be identified as well as the relation between extreme events and longer term cycles.*

Wind storms are also a feature of the Pacific Northwest area. Two of the largest wind storms to affect the Pacific Northwest this century occurred on October 12, 1962 and December 12, 1995. The former, named the Columbus Day Storm was more severe than the latter in virtually every respect (Knight, 1996). Peak wind gusts were recorded at 75 m s^{-1} (170 miles per hour) for the former and 53 m s^{-1} (119 miles per hour) for the latter. Over 51 mm (2 in.) of precipitation were recorded for the former and almost twice as much was observed for the latter. Forest blow-downs were large in both storms, particularly the former. Similar storms affected the area in 1880, 1921, and 1951.

Published data on the magnitude and frequency of severe storms are lacking. One of the most useful data sources is that of Brunengo (unpublished, 1989) who examined the record of the largest 48 hr precipitation events at five sites in the Cascades from 1940 to 1987. He found 47 events during this period with a mean precipitation of 107 mm. The greatest storms were concentrated in the November to February period. Storms of this kind generally affect most of the Pacific Northwest. He identified a tendency for winters in the Pacific Northwest to be stormy at time of low values of the North Pacific Index. Brunengo developed a "Storminess Index" (SI) that reflects the number of storms and the amount of precipitation. Cumulative values of the SI index show some parallels to interdecadal variations noted in other sections of this report and are worthy of further investigation. *More data sets like Brunengo's SI data set should be developed and analyzed for short-term and interdecadal variability.*

Both wind storms and high precipitation events can have the effect of "resetting the ecosystem clock". February 1996 saw a fairly large flood event in the Pacific Northwest with over 305 mm (12 in) of rain in many coastal locations between February 3-9. Similar flood events occurred in 1933 and 1964. Local residents in the coastal town of Waldport, Oregon blame the February 1996 flood for a very low clam catch in their estuary area. It might take some species of clams up to 7 years to reach previous population levels (R. Malouf pers. comm. 1996). Thus short period events may have long-lasting ecological consequences. Evidence (Cayan and Redmond 1994; Greenland 1994a) suggests that some of the largest precipitation values in the Pacific Northwest, and by implication large storms, are associated with La Niña events. This, in turn, suggests once more that further attention should be given to the La Niña- related climatic events in the Pacific Northwest and to answer such questions as *are flood events more likely to occur in the Pacific Northwest during La Niña times?*

Ocean

OCEANIC VARIABILITY AT THE MILLENNIAL SCALE

Paleoclimatic estimates from proxy data suggest that at the height of the last ice advance at 18,000 year Before Present (BP), the majority of the North Pacific had approximately the same temperatures as at present but that areas off Mexico and in a zone between latitudes 45°N to 60°N across the ocean had sea surface temperatures about -2°C or more lower than at present (Hartmann 1994 p. 316; CLIMAP 1981). Radiolarian data from the Santa Barbara basin tend to suggest a decrease in ocean temperatures at 5400 BP that lasted with minor interruptions until 1,500 BP (Pisias 1979), but Roden (1989) has questioned how spatially representative this finding may be.

Generally there seems to be a dearth of information on ocean changes in the Pacific Northwest on this time scale. A general research area would be to improve the information base of ocean data on the millennial time scale.

OCEAN VARIABILITY ON THE CENTURY SCALE

One of the more important potential changes on the century scale are those of coastal sea level rise and fall. Within the general global warming hypothesis of this century it might be expected that there would be a gradual sea level rise along the West Coast. However, partly because of tectonic and isostatic activity, recorded sea levels vary widely from region to region and according to Roden (1989) and others, "any global sea level change, if it occurred at all, is small and masked by land uplift and subsidence." The corollary of this is that tectonic changes are potentially important for future sea level changes at coastal areas and such changes should be recognized as a random variable in any future model that includes sea level. Some investigations performed after Roden's warning about interpretations of sea level data have provided interesting results. Ware and Thompson (1991) report a fall in sea level for Victoria, British Columbia, between 1915 and 1940 followed by a rapid rise at the time of the 1940-41 El Niño. They attribute the fall between 1915 and 1940 to be mainly a function of intensifying northerly winds.

An increase in sea surface temperature is the most commonly expected century scale result of 20th Century global warming. No direct evidence of this is so far reported for Washington and Oregon. But south of the PNCERS study area, along the southern US West Coast, Roemmich (1992) has documented a general ocean warming of about 0.8°C and a rise in sea level. According to Barry et al. (1995) the central California coast has seen a 0.75°C rise in sea surface temperature between the early 1930s and 1994.

It has been suggested that potential global climate warming will increase land-sea temperature differences (Trenberth 1993), intensify equatorward winds in summer and lead to stronger coastal upwelling (Bakun 1990). An examination of West Coast nearshore sea surface temperatures and salinity (Schwing 1994) and sea level change at Vancouver island (Ware and Thompson 1991) is consistent with this suggested increase in upwelling. Bakun (1990) has noted that several major

coastal upwelling areas of the world have been growing in intensity. Bakun also makes the very important point that it is not always possible to project direct physiological effects of climatic warming on organisms. In this case, a simple projected increase in coastal sea surface temperatures would neglect the biological effects of increased upwelling. On the larger spatial scale, Manabe et al. (1991) suggest that carbon dioxide-related warming in the northeast Pacific would be on the order of 1-2 °C at the sea surface. The warming is projected to increase by half that amount at a depth of 700m.

GLOBEC (1994) planners make the following hypotheses regarding projected global warming: boundaries between distinct physical and biological regions will move; there may be a change in strength, timing or even occurrence of the spring transition; greater upwelling and increased stratification will create stronger upwelling fronts and jets as well an increased vertical shear within these jets; global warming will cause the thermocline and nutricline to be depressed. The overall hypotheses of GLOBEC (1994) planners are summarized in Table 4.4.

Table 4.4. Hypothesized physical changes in the California Current-PNCERS region under a global warming scenario (from GLOBEC 1994).

Physical Process	Hypothesized Change
West wind drift intensity	decrease
West wind drift location	shifted north
Freshwater input	increase
Coastal wind stress	increase summer, no change or decrease winter
Mean sea surface temperature	increase all months
Stratification	increase
Mean transport of CCS	decrease
Alongshore transport upwelling jets	increase
Turbulent mixing	increase summer, no change or decrease winter
Transport in eddies and meanders	increase
Offshore transport	increase
Upwelling (vertical transport)	increase
Mixed layer depth	unknown
Winter storm frequency	decrease
Winter storm intensity	decrease
Timing of spring transition	unknown

Apart from global warming issues, the 60/70 year cycle mentioned in the atmosphere section was first found through its effect on the ocean in terms of the relative abundance of sardines and

anchovies. This particular cycle has continued for at least 1,500 years (Baumgartner et al. 1992). *The 60/70 year cycle is an important cycle and deserves to be studied much more closely.*

OCEANIC VARIABILITY AT THE DECADAL SCALE

As was the case in the atmosphere, a great deal of attention has been given recently to decadal variability in the Pacific Ocean. Several studies investigated the spatial variability of ocean parameters at this scale, especially concentrating on sea surface temperatures. Also parallel to the atmospheric case, attention is focused on the changes centered on 1976 but then is also expanded to a longer time period. Trenberth and Hurrell (1994) and several others have pointed out that, in terms of dynamics, there is a fairly sluggish response of the mid-latitude ocean to changes in the ocean forcing through the surface momentum and heat fluxes. This effectively serves as a low-pass filter for short-term variability, and emphasizes the longer time scales. Many features of the interdecadal fluctuations in ocean climate have been modeled by Miller et al. (1994 a, b).

The spatial variation of sea surface temperatures across the Pacific from 1961 to 1989 was subjected to a multivariate analysis by Wang (1995). He found that one principal component (having the most power in the north eastern tropical Pacific) explained 62% of the variance at the interdecadal time scale, and also made a major change from negative to positive values around 1976. An ocean circulation model demonstrated the 1976-77 oceanic regime shift was caused by a unique concurrence of sustained heat flux anomalies during a multi-month period preceding the shift both in the central Pacific and in the California coastal region (Miller et al. 1994b). Graham (1994) suggests that the 1976-77 regime shift is best regarded as a change in the background mean state of the tropical Pacific.

As a result of atmospheric changes, after 1976 sea surface temperatures increased along the west coast of North America and Alaska but decreased over the central North Pacific (Trenberth and Hurrell 1994). Associated changes in wind stress on the ocean altered the transport associated with major surface currents, which relate directly to one of the key features in Francis' (1993) modal-decadal model (Fig. 4.15) of the Eastern Pacific. This feature is the proposed decadal shift of the point where the Sub-Arctic Current (sometimes called the North Pacific Current; Pickard and Emery 1990) bifurcates to form the Alaskan and California currents. The bifurcation point varies on an annual scale between 45°N in the winter and 50°N in the summer (Pickard and Emery 1990: p. 253). According to the Francis model, during the Alaskan flow mode the bifurcation point is further to the south and more water goes into the Alaskan current with the opposite being the case in West Coast flow years (see also Figure 5.10). The movement of the bifurcation point is critical both on an annual scale and a decadal scale. Francis notes that some investigators (e.g. Chelton 1983) suggest that the north-south shift is due to physical factors at or upstream from the bifurcation point but that Tabata (1991) suggests the shift may be due to in-phase coastal currents along the western coast of North America. Trenberth and Hurrell (1994) demonstrate that during the period 1976-1988 (an Alaskan flow regime period) storm tracks in the North Pacific were shifted southwards (Figure 4.24). Cyclonic circulation around these storms would probably increase the velocity and mass of the flow of the Alaskan current.

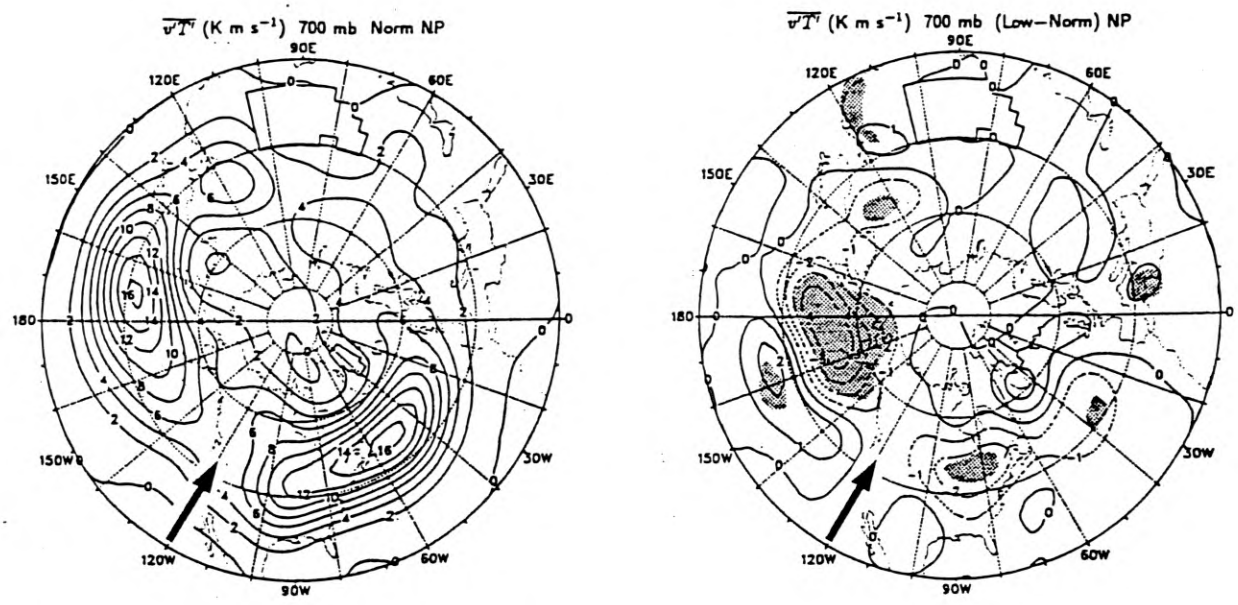


Figure 4.24. Location of storm tracks in the 1976-1988 period (an Alaskan flow regime period) compared to the preceding period. Negative values are dashed; values significantly different from zero are stippled on the right panel. Pacific Northwest region is indicated by arrows. (Source: Trenberth, K.E., and J.W. Hurrell. 1994. Decadal atmosphere-ocean variations in the Pacific. *Climate Dynamics* 9:303-319. Reprinted with permission, courtesy Springer-Verlag, New York, Inc.)

Since the shift of this bifurcation is critical both on the annual and the decadal scale, a prime research topic is *to find out what controls the position of the bifurcation point on scales from the annual to the decadal.* Realizing the importance of this, Ebbesmeyer et al. (1995) used a winter drift latitude and longitude end point (modeled by an ocean current simulation model) in the construction of their PNI index. The decadal changes (as well as El Niño effects) in sea surface temperatures can be seen in a time series of Eastern North Pacific winter sea surface temperatures constructed by Wooster and Hollowed (GLOBEC 1994; Figure 4.25). Tabata's study of baroclinic transports across Line P (145°W) indicated that there was a small out-of-phase relationship between the Alaska Current and the coastal component of the California Current which was consistent with the bifurcation proposal, but he thought the relationship was more likely to be due to an in-phase relationship of coastal currents along the Pacific coast (Tabata 1991). *More research is needed and it would seem a fruitful area for more investigations of the Ocean Weather Ship P data as well as remote sensing studies.* On a more local spatial scale, Ebbesmeyer et al. (1989) link decadal changes in the atmosphere to phenomena of the marine water of Puget Sound. At times when the Aleutian low is eastwards (positive PNA Index), storms deposit less precipitation in the Cascades. The decreasing freshwater input controls a rearrangement of the distribution of water density in the Strait of Juan de Fuca and increases the

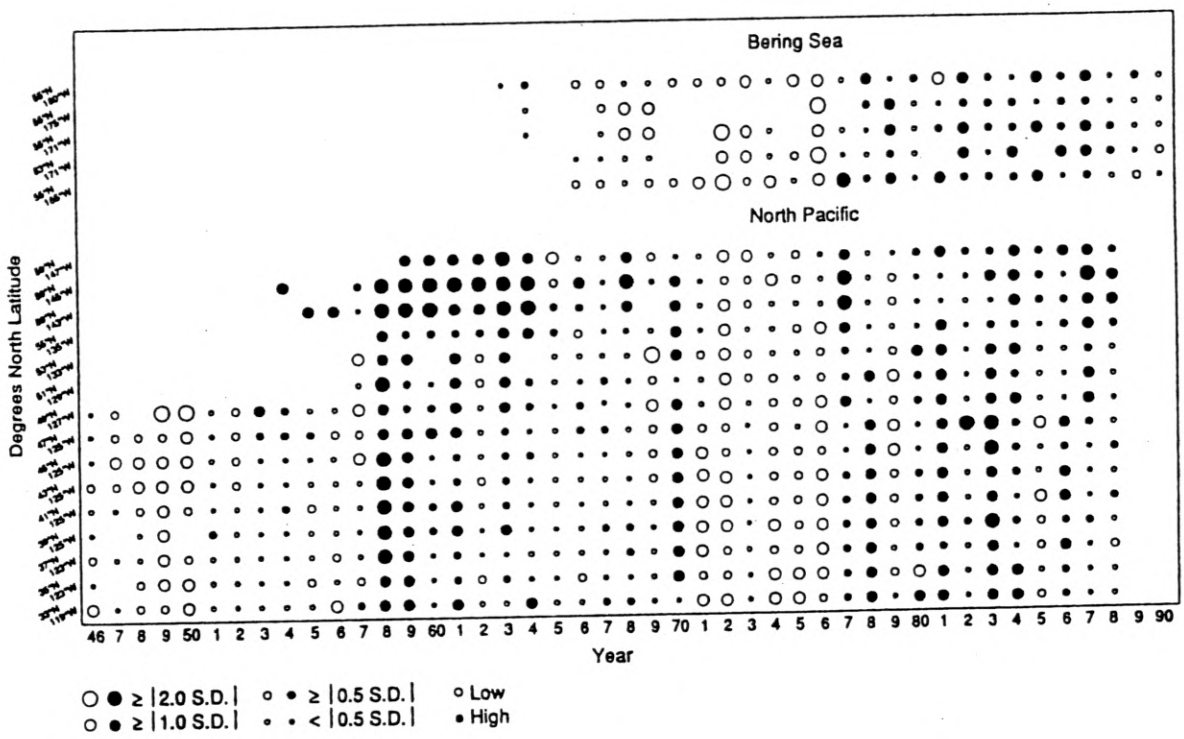


Figure 4.25. Time series of Eastern North Pacific winter sea surface temperatures. Dark circles indicate temperatures higher than normal; open circles indicate temperatures lower than normal. Size of circles shows departure from normal in terms of standard deviations (S.D.) from the mean. The 1976-77 transition from cooler to warmer is readily apparent. (Source: constructed by Wooster and Hollowed in: US GLOBEC. 1994. Eastern boundary current program: A science plan for the California Current. US Global Ecosystems Dynamics. Report Number 11. Reprinted with permission, courtesy US GLOBEC.)

density difference across the entrance sill zone of the Puget Sound main basin. The increased density difference drives the fastest inflow in the basin from mid-depth to bottom. The basin waters of Puget Sound are very sensitive to the decadal changes and thus could be used as an indicator of such changes. The data of Ebbesmeyer et al. show the decadal regime changes going back to the turn of the century. It may be seen from Fig. 4.17 that decadal regimes in sea surface temperatures quite possibly existed in the last century.

Decadal shifts, however, are not necessarily seen along the whole of the West Coast. Considering the shifts centered around 1941 and 1975, Schwing (1994) concluded that there was considerable inter-regional difference in the timing (or even presence) of the shifts. Marked latitudinal variations in such variables as poleward wind stress and sea surface temperature trends have been

identified by Schwing et al. (1996). They note the high variability of the California Current and the danger of oversimplifying present climate change as a constant linear trend or in terms of records from a single location. Similar spatial variability has been found with the values of upwelling indices (Parker 1996). Schwing (1994) suggests an important research task that *future studies should focus on what mechanisms may be responsible for such shifts and how the effect spreads along the coast (i.e., how a sudden shift off southern California "diffuses" northward).*

The fact that these decadal changes do not just occur at the surface was demonstrated in the classic study by Tabata (1989) on 27 years of data (1956 to 1983) on the properties of ocean water at Ocean Weather Station P. Despite not being interpreted as such at the time, these data taken at depths of 400m and below, clearly show evidence for the last two regime shifts with colder water temperatures between the early 1960s and the mid-1970s and warmer water after that to the mid-1980s (Figure 4.26). Comparable changes occur in salinity values but somewhat

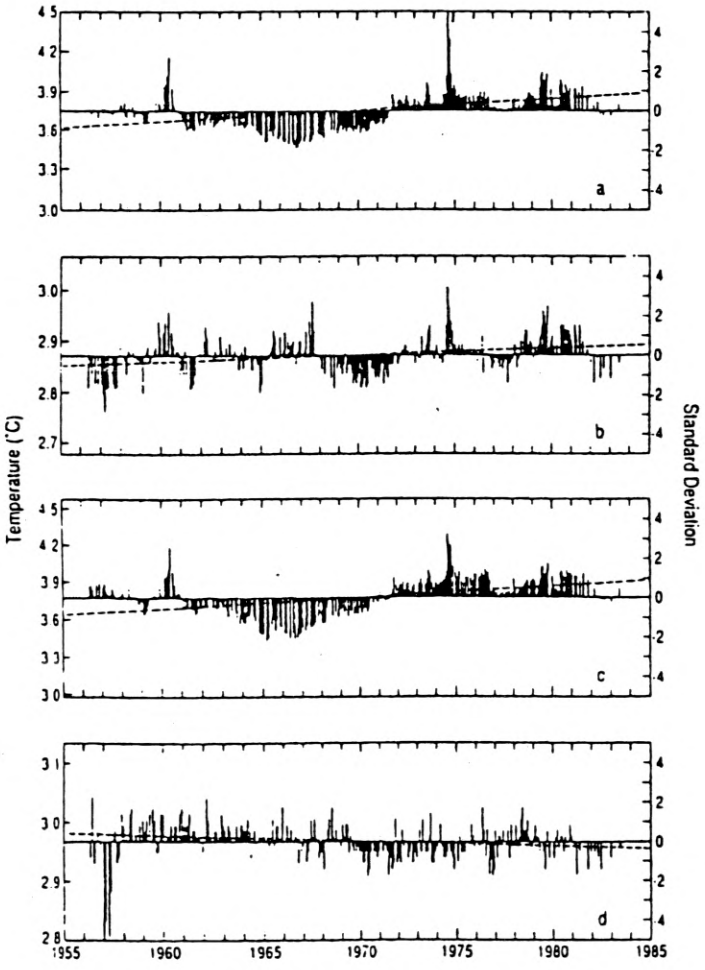


Figure 4.26. Ocean temperature data taken four depths at Ocean Weather Station P (50°N 145°W). Panel (a) 400 decibars, (b) 1000 decibars, (c) $\sigma_t = 27.0$, (d) $\sigma_t = 27.4$. All but the bottom panel show a warming trend over the 27 year time period. (Source: Tabata, S. 1989. Trends and long-term variability of ocean properties at ocean station P in the northeast Pacific Ocean. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 113-132. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

different decadal changes are seen in dissolved oxygen concentration and the depth isopycnal surfaces. It is interesting to note that the length and particular time of the data period investigated by Tabata leads him to conclude that the ocean was warming over the period. Although he is careful to point out the need for an even longer data record before making more firm conclusions. Tabata concluded that the changes taking place at this scale were mainly due to vertical motion in the water and were not influenced much by shifts in the position of the center of the Alaskan gyre.

While keeping in mind the variations in timing or presence of decadal shifts, further long-term retrospective studies of coastal sea surface temperature could take advantage of the spatial coherence of temperature. Roden (1989) has suggested that the sea surface temperature records of La Jolla, California, and Langara, British Columbia, could be used as benchmark stations to investigate changes in the California and Alaskan Current thermal properties, respectively. GLOBEC (1994) planners also noted the spatial representativeness of the Scripps Pier (La Jolla) record. From about 1920, this record shows a period of warm sea surface temperatures ending about 1945, a cool period (with the exception of the 1957-1958 El Niño) up to 1976, and a warm period from 1977 to the present. Abrupt transitions of about one to two years took place between these periods (Roden, 1989; Figure 4.27). During the part of this period for which observations are available, high temperatures coincide with diminished northerly winds. The interior of the central North Pacific Ocean area has cooled between 1968 and at least 1985 (Venrick et al. 1987). In addition, Royer (1993) has drawn attention to long period tides that may affect sea surface temperatures and be related to their quasi-20 year cyclicity. *The relation of these long period tides should also be investigated in the context of interdecadal regime change.*

OCEANIC VARIABILITY ON THE QUASI-QUINTENNIAL SCALE (ENSO)

Following the phase of warm sea surface temperatures in the tropics the observed effects of an El Niño arrive on the West Coast by both oceanic and atmospheric paths (GLOBEC 1994). GLOBEC planners describe how the oceanic path occurs along the eastern margin of the Pacific Ocean basin, when Kelvin waves propagate poleward (i.e., northward along the Pacific Northwest coast), depress the thermocline (i.e., push cold water deeper), and result in anomalously warm waters. The atmospheric path follows later when the Aleutian Low is displaced to the south and/or west, and winds enhance the flow of water from the south, thus trapping upwelling conditions nearer to the coast.

The effects of El Niño events are more marked in the coastal ocean of the Pacific Northwest than in its atmosphere. Several investigators have noted that positive anomalous changes in sea surface temperatures of the California Current take place virtually simultaneously along the whole north-south area of the coast (Roden 1989; McGowan et al. 1996). An analysis by Breaker (1989) using sea surface temperature off Monterey showed that between 1971 and 1985 there had been four El Niño-related warming events. The warming is strongest in the fall and winter and weakest in the spring. The warming can be up to about 4°C higher than the long-term average sea surface temperature (Figure 4.28). The oceanic manifestation of the large 1982/83 El Niño off the Pacific Northwest coast was initially in the form of poleward-propagating Kelvin waves, followed by onshore transport of low-salinity California Current waters from increased southerly

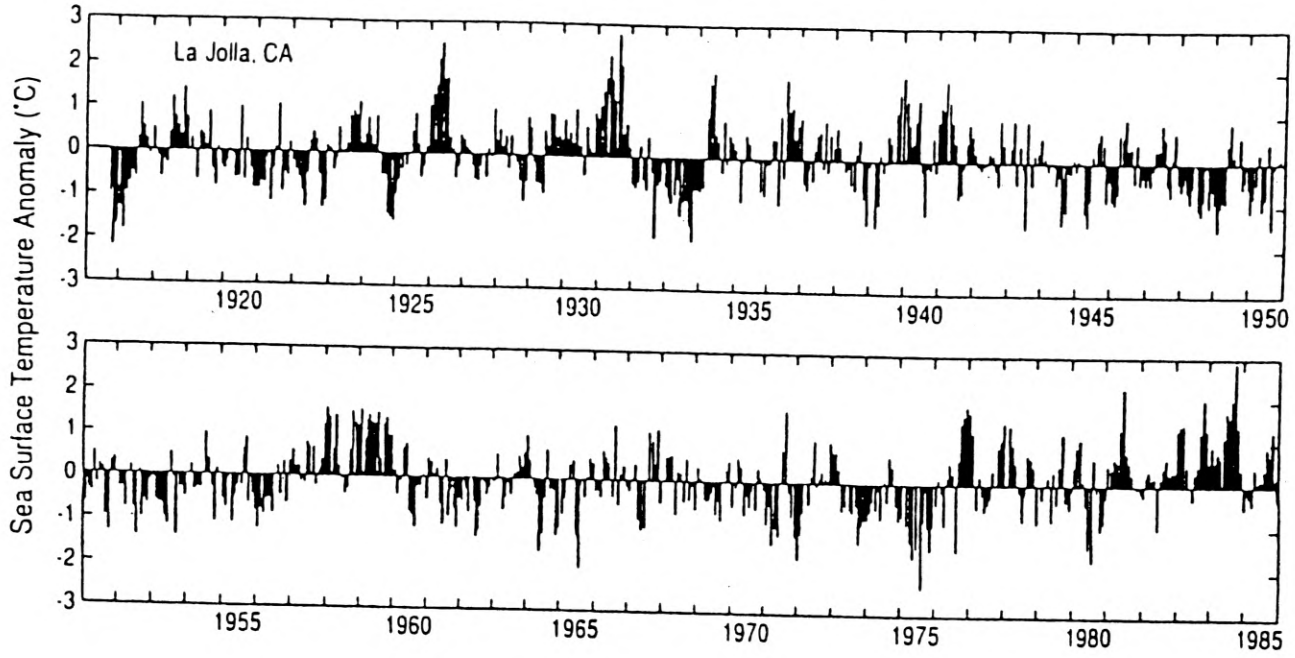


Figure 4.27. Sea surface temperature anomalies at Scripps Pier (La Jolla) from about 1917. The vertical bars show the deviation of the observed temperatures from the long term average. See text for explanation. (Source: Roden, G.I. 1989. Analysis and interpretation of long-term climatic variability along the West Coast of North America. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 93-111. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

winds associated with the intensified Aleutian Low and the intensified poleward California Counter Current. The result was a depression of the thermocline - nutricline inshore and ineffective upwelling (Pearcy 1992). The waters became anomalously warm and the sea level was raised. Thermal and salinity anomalies were greatest about 80 to 100 m below the surface (Rienecker and Mooers 1986). These effects occurred within one month of the El Niño appearance off Peru and 2 to 3 months *before* any atmospheric effect in the North Pacific. Later oceanic effects of the El Niño were enhanced by the atmospheric effects (Huyer and Smith 1985). The onset was probably also accompanied by an increased poleward flow in a 30 km wide undercurrent at 130 dbar depth with an increased subsurface temperature 50 km off the coast. Eventually temperature anomalies penetrated to 300 m and could be found 270 km off the coast (Huyer and Smith 1985). Newton (1995) has identified clear El Niño effects during the years 1991-1993 in the Puget Sound area. Here salinities, sea surface temperatures, and air temperatures increase during a moderate El Niño year. From a basin-wide perspective Trenberth and Hoar (1996) have shown that the SOI is well related to sea surface temperature anomalies both in the tropics and off the coasts of North and South America.

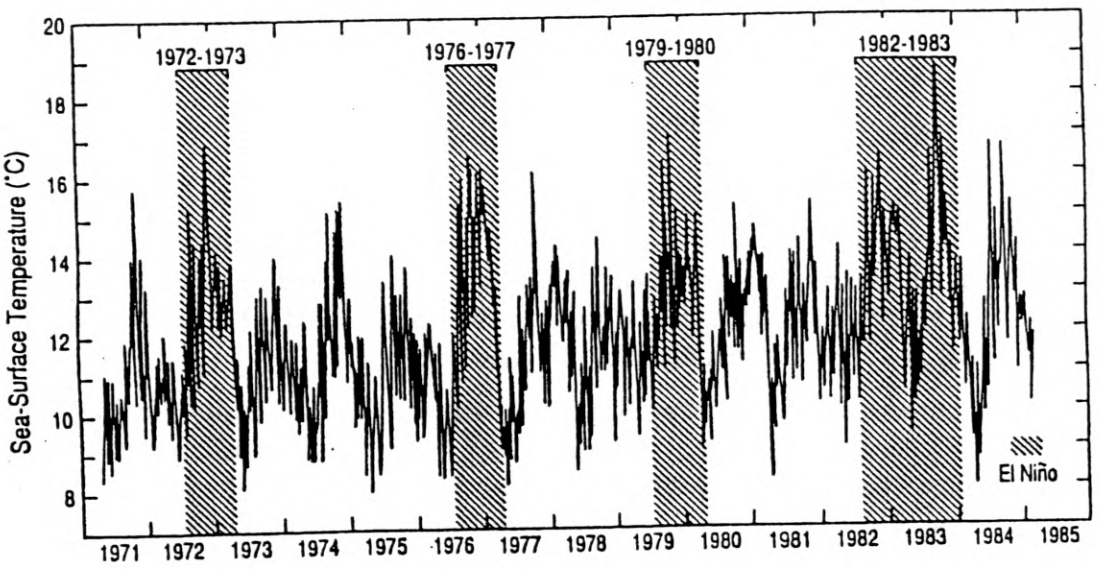


Figure 4.28. Ocean warming during El Niño events (shaded). (Source: Breaker, L.C. 1989. El Niño and related variability in sea-surface temperature along the central coast. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 133-140. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

As with the case of the atmosphere it has been shown that ENSO phenomena in the ocean are not stationary. Gu and Philander (1995) demonstrated that the amplitude of ENSO, as judged by tropical sea surface temperatures, is found to be large between 1885 and 1915 and small between 1915 and 1950 increasing rapidly again after 1960. Also parallel with the atmosphere, ENSO phenomena have existed in the ocean for millions of years.

Efficient methods now exist for forecasting tropical Pacific sea surface temperatures six months ahead and researchers are optimistic that the ability to predict lead times of a year or more can be achieved. The leading groups in this field are the Lamont-Doherty Group (Zebiak and Cane 1987) and the Scripps Institution of Oceanography Group (Graham and Barnett 1995). Combination forecasts of tropical Pacific sea surface temperatures are published monthly in the NOAA Climate Diagnostics Bulletin. Both groups use a coupled ocean/atmosphere model which is much simpler than full-scale general circulation models. *A major research project is to investigate how the information contained in these forecasts can be applied to practical use by ecosystem managers.*

A periodicity of 6-7 and 2 years in ocean events in the North Pacific, which may or may not be associated with ENSO type events, is believed to be related to atmospheric forcing on the same scale (Tabata 1991). Tabata believes that *information on the barotropic component of the*

circulation is lacking and that such data are needed to understand the coupling between the atmosphere and the ocean in both annual and interannual scales.

OCEANIC VARIABILITY AT THE INTERANNUAL SCALE

There does not seem to have been so much attention given to ocean variations at this time scale. However, with the greater availability of satellite-derived data it is likely that this situation will be rectified in the future. Ocean-based measurements tend to be limited to those made by research vessels and the Comprehensive Ocean-Atmosphere Data Set (COADS) data (see Appendix 4.2 for description) has not been fully exploited at this time scale.

A permanently moored weather and ocean observing station, Ocean Weather Station P, provides a rich source of oceanographic data. Tabata (1989) notes temperature and salinity changes throughout the mixed layer at Ocean Weather Station P varying with a periodicity of about 2.5 years. Levitus et al. 1994 (quoted by Levitus and Antonov 1995) have documented the spatial changes in temperatures at 125 m depth in the North Pacific. These investigators suggest that the interior mid-latitude of the North Pacific Ocean seems to be characterized by an anomaly that is opposite in sign to an anomaly in the periphery of the Subtropical Gyre. The maximum temperature change between the periods 1960-1962 and 1965-1969 was about 0.5°C but shorter period changes can also happen. Levitus and Antonov (1995) noted an increase in temperatures of up to 1.5°C between 1986 and 1989. They identify an important research problem as an attempt *to determine what, if any, air-sea interactions are involved in these changes.* They also point to the various ideal components of a comprehensive subsurface ocean observing system.

The "memory effect" of the ocean is important on the interannual and annual time scales. Davis (1976) and others have found the temporal persistence of sea surface temperature anomalies in the North Pacific such that sea surface temperature anomalies could be predicted from previous anomaly conditions.

The bifurcation point of the Sub-Arctic Current varies on an annual scale between 45°N in the winter and 50°N in the summer (Pickard and Emery 1990). Another important annual change is in the southern boundary of Ekman upwelling (see Glossary) in the North Pacific Ocean. Pickard and Emery (1990: p. 163) show this boundary to be at about 30°N in the winter and almost 50°N in the summer. This is important since the upwelling can provide nutrients which are the first step in the food chain. According to Brodeur and Ware (1992) upwelling occurs especially in the core of the Alaskan Gyre because of wind-induced divergence in the upper oceanic layer. Presumably this upwelling would be intensified at times of a well-developed Aleutian Low.

Considerable interannual variability over the continental shelf has been noted in the relatively few years of data that have been gathered. Figure 4.29 shows the current variations for the spring time in the years 1973 to 1978 (Hickey 1989). Although the timing of the spring transition was within 1 or 2 weeks of March 25 for three of the four years, the conditions that lead up to it were highly variable. The transition occurs simultaneously in the Pacific Northwest region. *The timing of the spring transition and its relation to atmospheric conditions on a variety of scales is a fertile research area.*

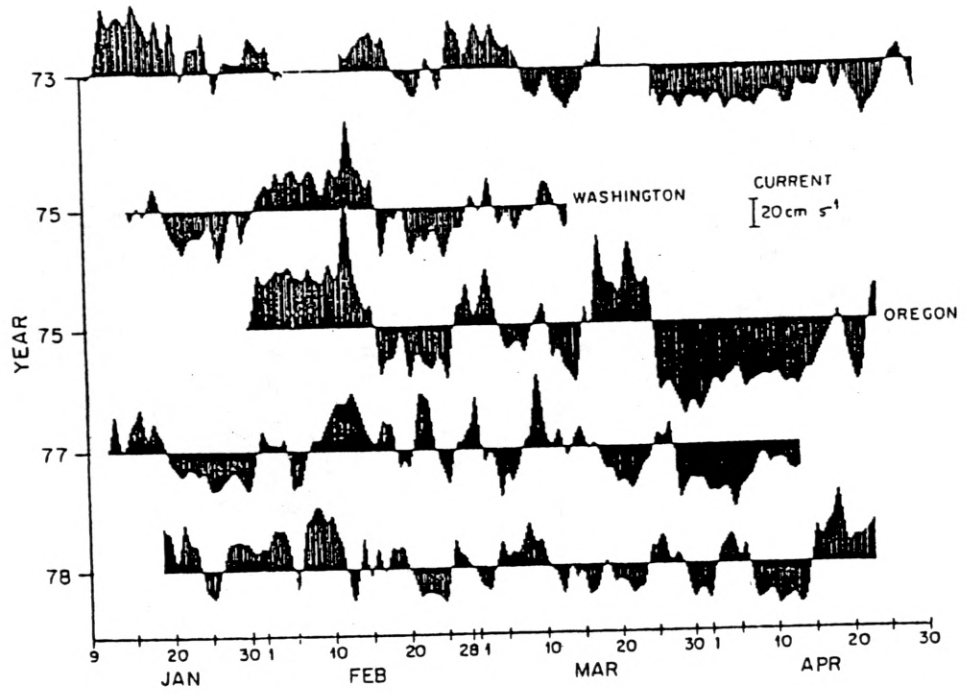


Figure 4.29. The current variations for the spring time in the years 1973 to 1978. Lines above the abscissa indicate flow to the north; below the abscissa to the south. The figure shows the year-to-year differences in the overall transition from a north-flowing to a south-flowing nearshore current in spring. (Source: Hickey, B.M. 1989. Patterns and processes of circulation over the coastal shelf off Washington. In *Coastal Oceanography of Washington and Oregon*, eds. M.R. Landry and B.M. Hickey, 41-115. New York: Elsevier. Reprinted with permission, courtesy Barbara Hickey.)

ANNUAL SCALE

Summary of Typical Seasonal Changes Throughout the Year. A simple description of seasonal changes in currents over the continental shelf was given by Parmenter and Bailey (1985; Figure 4.30). The summer circulation is comprised of the California Current moving under the influence of the northerly summer winds while below it the California Undercurrent travels northwards. In winter the California Current is found offshore but close to the shore the northward-flowing Davidson Current appears. The change from winter to summer conditions occurs very abruptly and is called the spring transition. The change back in the fall is much more gradual. GLOBEC (1994) planners describe extremely dynamic seasonal changes in the California Current in a little more detail. After the onset of northerly winds in spring, upwelling raises isopycnals next to the

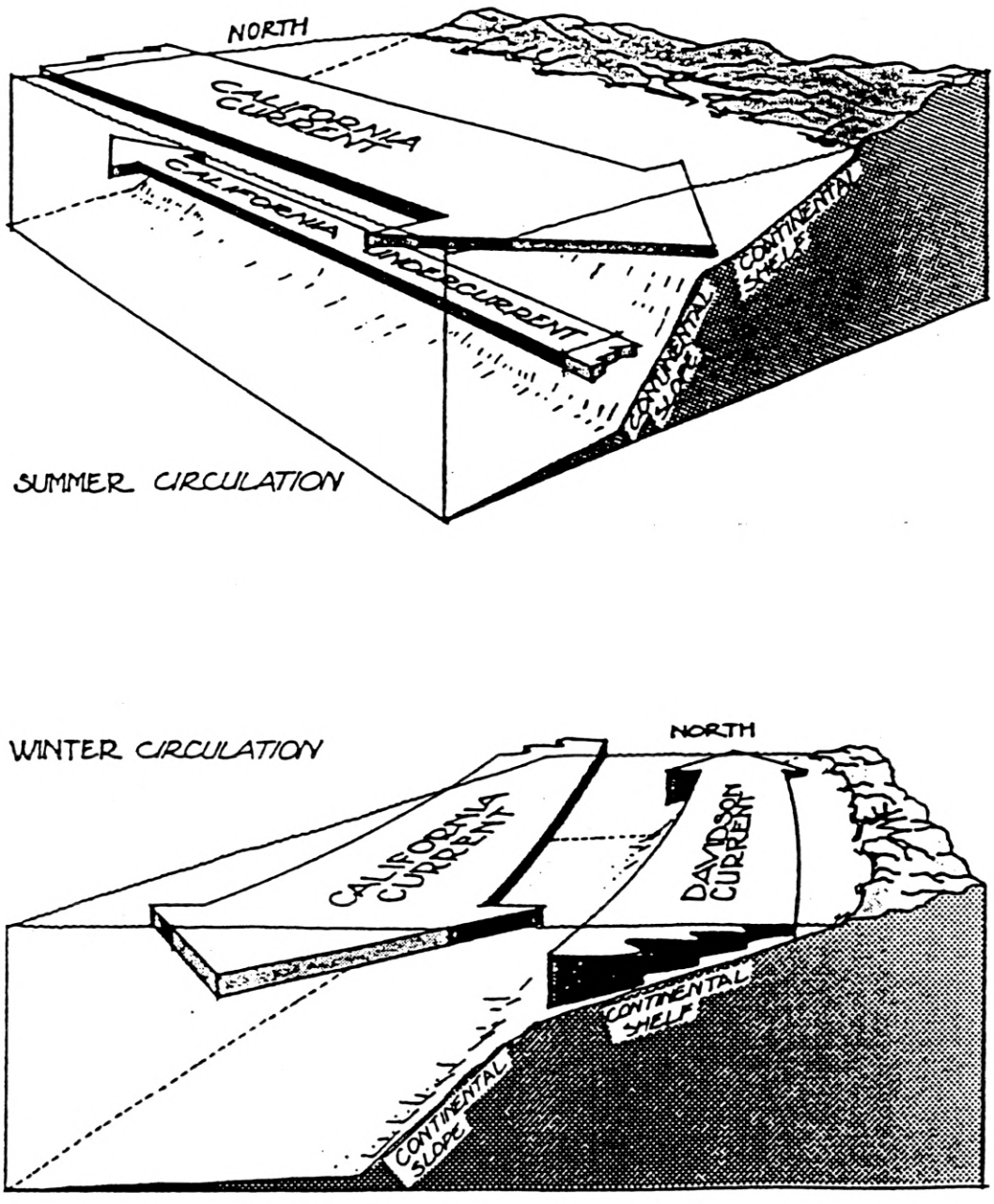


Figure 4.30. Summer and winter ocean currents off the coast of Oregon. (Source: Parmenter, T., and Bailey, R. 1985. *The Oregon Ocean Book*. Salem: State Printing Office. Reprinted with permission, courtesy Robert Bailey.)

coast (i.e., denser, saltier water moves upwards), creating a density front and an equatorward (southward-flowing) jet over the continental shelf. The front and the jet move further offshore in response to stronger northerly winds and return onshore when the wind relaxes or reverses. The southward jet moves further offshore to about 100 km in mid-summer and poleward nearshore counter-currents are often found. During winter, eddies are found offshore and the poleward Davidson current develops over the shelf and slope.

The rather linear and laminar concept of the flow of the California and Davidson currents (and presumably the Alaskan Current also) has been, in recent years, replaced by one of a very turbulent flow with jets, filaments and eddies superimposed on the slow, generally southward flow of the Californian Current. One of the most remarkable advances in recent years is the use of satellite imagery to show the rich structure of the coastal upwelling and eddy formation (Figure 4.31; GLOBEC 1994: p. 15). Present day concepts of the seasonal changes in the California Current System (Figure 4.32; GLOBEC 1994: p17; see also Lynn and Simpson 1987) diverge greatly from our initial laminar conceptualization (Fig. 4.30). Whereas some of these flow phenomena may be geographically anchored by topographic features of the coastline or seabed morphology, other flow phenomena may change with time and changing atmospheric conditions.

Monthly and Seasonal Ocean Currents and Their Boundaries. The most detailed and authoritative review of the circulation over the continental shelf of the PNW area has been provided by Hickey (1989). She and other investigators used a series of models and observations to establish the fundamental features of the circulation and, in many cases, their causes. They investigated: 1) seasonal patterns over the slope, which they divide into inner, middle and outer sections; 2) forcing mechanisms; 3) event - scale variability and forcing; 4) the existence of eddies meanders, squirts, and jets; 5) coastal upwelling; 6) interannual and tidal variability; and 7) the effects of submarine canyons and circulations associated with them. Denbo and Allen (1987) have also provided an insightful discussion of this topic.

Hickey and others have discovered that 70 to 90 % of the fluctuation in alongshelf flow at the mid-shelf, and of coastal sea level, can be explained as "first-mode" coastal trapped waves. The percentage falls to 50% for the outer shelf. Denbo and Allen (1987) find that the fluctuations in alongshore currents occurring on the time scale of about 4 days and longer are more highly correlated with the wind stress value 100 to 300 km to the south than with local winds but short period fluctuations are better correlated with local winds. In the mid and outer shelf, event-scale fluctuations are of the same magnitude as the seasonal mean-scale flow change.

The timing and duration of the periods of equatorward or poleward flow are not constant across the shelf or with depth. As mentioned above, the equatorward coastal jet moves progressively offshore in spring and summer as the upwelling season proceeds. The maximum velocity of the California Undercurrent and the large-scale California Current occurs in the late summer. In the Washington inner shelf, flow in the summer is equatorward to depths of about 100 m and poleward at deeper depths with a subsurface maximum of about 10 to 20 cm s^{-1} in the California Undercurrent. Poleward seasonal mean flow decreases with depth and occasionally reverses to equatorial seasonal mean flow, sometimes called the Washington Undercurrent. According to Hickey (1989) the dynamics of the mean and fluctuating currents on the inner shelf have not received so much attention. *A possible research task is therefore to understand better the*

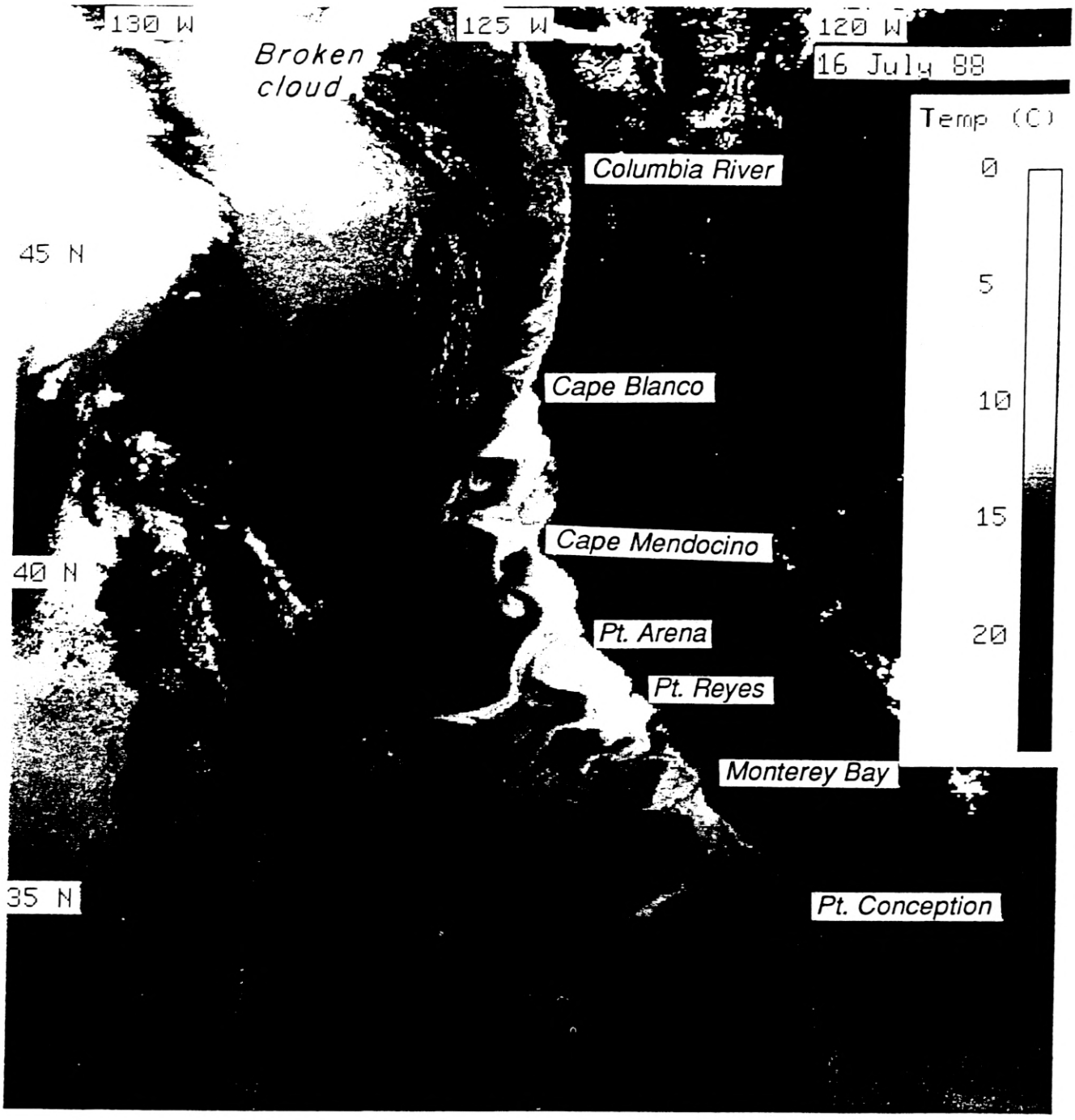


Figure 4.31. Satellite imagery indicating the rich structure of the coastal upwelling and eddy formation in the California Current system. (Source: US GLOBEC. 1994. Eastern boundary current program: A science plan for the California Current. US Global Ecosystems Dynamics. Report Number 11. Reprinted with permission, courtesy US GLOBEC.).

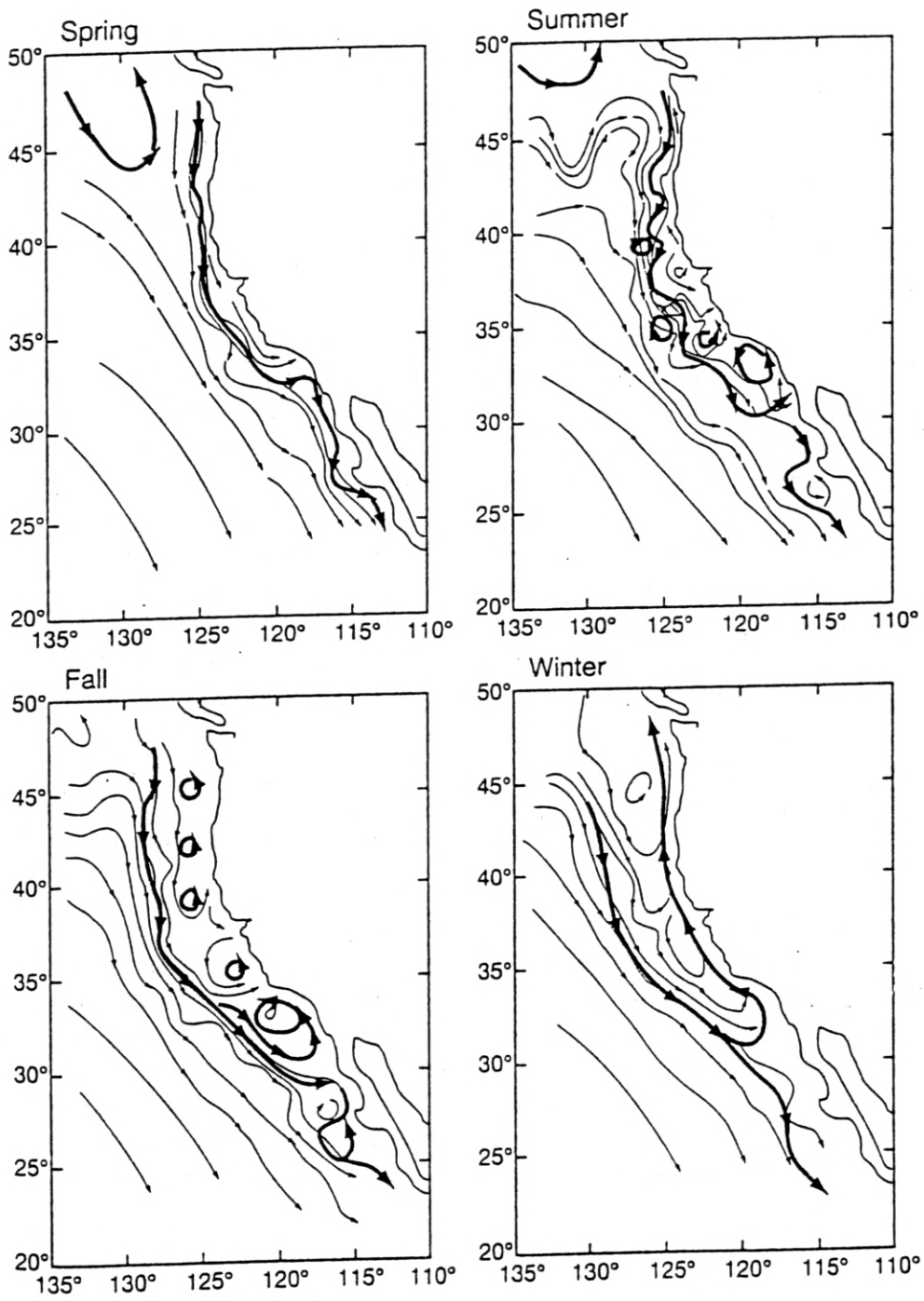


Figure 4.32. Schematic diagram of present day concepts of the seasonal changes in the California Current System (CCS). (Source: US GLOBEC. 1994. Eastern boundary current program: A science plan for the California Current. US Global Ecosystems Dynamics. Report Number 11. Reprinted with permission, courtesy US GLOBEC.).

dynamics of the inner continental slope flows. The principal local forcing mechanisms for the seasonal currents over the Washington shelf and upper slope are combinations of the alongshelf wind stress and a poleward alongshelf pressure gradient force. The principal forcing mechanisms for the seasonal and long-term pressure gradient force are generated by remote wind stress particularly in spring. The effect of submarine canyons is to: enhance upwelling in their vicinity, especially on the downstream side; amplify internal tides; encourage axial (i.e., circular) flow; and, within 50 m of the shelf bottom for narrow canyons (< 6 km), induce counterclockwise eddies when there is equatorward flow.

The spring transition is of interest on the interannual, annual, and daily time scales because it is about a week in length and is often accompanied by a sharp decrease in sea surface temperatures of about 3°C (Breaker 1989). Holtby et al. (1990) have noted that early and abrupt transitions not only produce conditions favorable to upwelling but also delay the formation of, and weaken, the northward flowing coastal current. Future studies on the timing of the spring transition may be informed by the suggestion of Huyer et al. (1979) that the transition is the result of a large cumulative offshore Ekman transport caused by local wind stress. Strub and James (1988) identified the atmospheric pattern associated with the spring transition. The sea level pressure pattern that most often coincides with the spring transition is the formation of a high pressure system centered at 45°N and 140°W together with the development of a low pressure over the southwestern continental US. After transition this is followed by a ridging pattern and diffluent (i.e., not convergent) flow off the western US. The less abrupt fall transition involves the development of a low pressure system off western North America centered at 50°N and 140°W associated with the development of storms in the region. These patterns were based on 9 years of data. Further studies of these weather patterns could show the interannual variability of the sea level pressure situations.

The sum of all the annual events causes regional differences in the ocean. Francis (1993) reviews four of the Northeast Pacific Ocean domains (specified by Ware and McFarland 1989; Figure 4.33) where water properties influenced by seasonal heating and cooling, precipitation and evaporation, and by wind mixing, are critical to fish production. Physical ocean phenomena in some of these domains is discussed in other sections. However, Francis (1993) defines a research question for the Coastal Downwelling Domain. He implies that we should investigate *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.*

With respect to the larger geographic scale, Roden (1989) has documented how extreme seasonal variations of atmospheric pressure in the area normally occupied by the Aleutian Low are accompanied by a consistent pattern of sea surface temperature anomalies across the North Pacific (Figure 4.34). In January 1931, when a -31 mb sea level pressure anomaly occurred centered on the Alaskan Peninsula, large negative sea surface temperature anomalies were found over the northern and northwestern Pacific. In January 1937, when a +24 mb "Aleutian High" occurred, large positive anomalies took place in the subarctic central Pacific and off Japan while large negative sea surface temperature anomalies appeared off the North American coast. Emery and Hamilton (1985) have argued strongly and presented evidence that sea surface temperature anomalies on seasonal time scales are maintained largely by anomalous wind-driven advection in

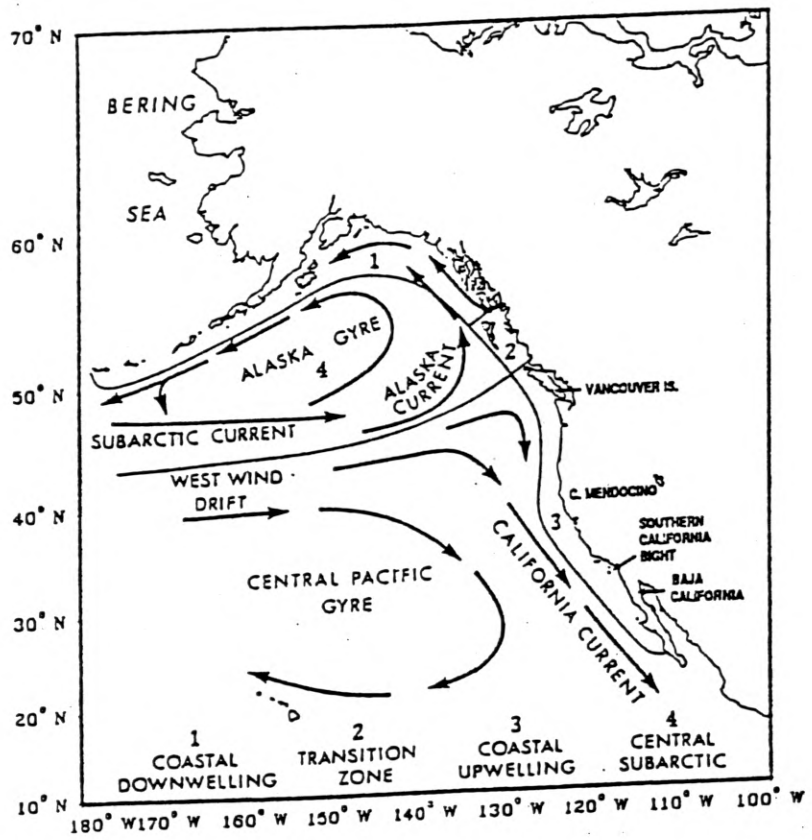


Figure 4.33. Northeast Pacific Ocean domains, showing that the California Current off much of the Pacific Northwest is a domain of coastal upwelling. (Source: Ware, D.M, and G.A. McFarlane. 1989. Fisheries production domains in the Northeast Pacific Ocean. In *Effects of ocean variability on recruitment and an evaluation of parameters used in stock assessment models*, eds. R. J. Beamish and G. A. McFarlane, 359-379. *Canadian Special Publication in Fisheries and Aquatic Sciences* 108. Reprinted with permission, courtesy of National Research Council of Canada.)

the near surface waters of the ocean. Sea level high pressure in the northeast Pacific may also be controlled by the wind circulation over the ocean and this, in turn, may well be controlled by atmospheric changes in the tropical ocean.

When wind blowing across the ocean surface drives ocean movement there are also dynamic cells of water movement formed perpendicular to the surface. These are known as Langmuir cells and start to be generated at wind speeds of 1.5 m s^{-1} (about 3 miles per hour). The convergence part of these cells at the surface can cause local downwelling jets of 2 to 7 cm s^{-1} (Leibovich 1983). Downwind and downcurrent, the downwelling jet speeds reach a maximum at depths between 6 and 20 m beneath the convergence (Shanks 1995). The corresponding associated upwelling is much slower.

Upwelling and Filaments. The simplest conceptual model of two-dimensional coastal upwelling calls for vertical movement of water adjacent to vertical topographical boundaries (the shore), driven by alongshore wind stress from northerly winds and the consequent advection of surface water offshore. Smith (1995) has provided a comprehensive review of upwelling in the region and identifies upwelling as having inherent scales on the order of days and tens of kilometers while the interaction of coastal upwelling with the offshore ocean occurs over of seasons and

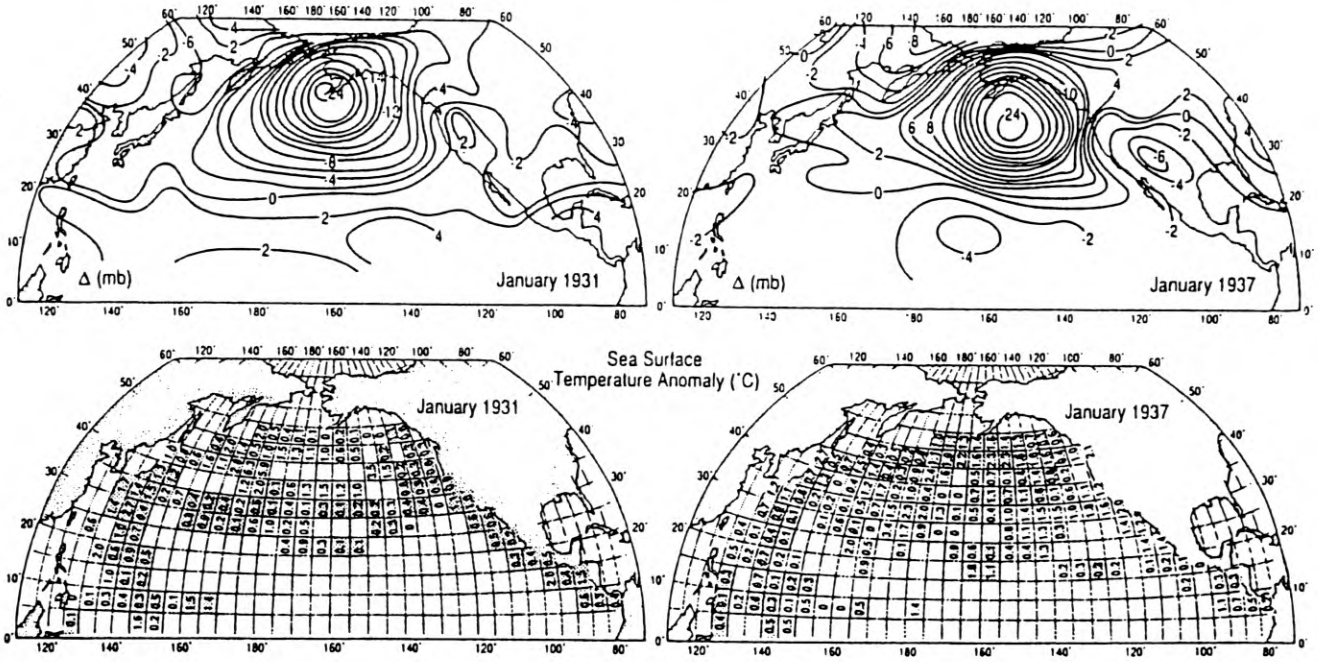


Figure 4.34. Examples of seasonal basin-wide sea surface temperature anomalies and associated atmospheric pressure relations. (Source: Roden, G.I. 1989. Analysis and interpretation of long-term climatic variability along the West Coast of North America. In *Aspects of Climate Variability in the Pacific and the Western Americas*, ed. D. H Peterson, 93-111. Washington, DC: American Geophysical Union. Reprinted with permission, courtesy American Geophysical Union.)

hundreds of kilometers. It is observed that offshore flow during upwelling is confined to a shallow layer at the surface less than 10 m thick.

Hickey (1989) notes observed departures from the strictly two-dimensional classic upwelling model. Two dimensional mass balance has not been observed. Much of the cross-shelf flow beneath the pycnocline occurs in or just beneath the pycnocline rather than deeper in the bottom boundary layer. Alongshore divergence is invoked to explain the lack of mass balance in the cross-shelf plane. Satellite imagery has shown that stronger upwelling occurs at and downstream from capes and promontories (Hickey 1989). Modeling studies have demonstrated that the existence of cape geometry as well as southward surface flow appears to be necessary to produce filament generation (Haidvogel et al. 1991). The topographically-anchored upwelling centers appear to generate jets that carry filaments of coastal water several hundred km offshore (see Fig. 4.31). The Pacific Northwest has fewer marked promontories than California. Satellite and surface observations have shown that the filaments have small-scale horizontal eddies superimposed on them (Flament et al. 1985). Maximum dynamic height ranges and velocities of the filaments occur in summer while minimum height ranges and velocities occur in late winter or early spring. Between May and July in the latitudinal band between 36° and 43°N, a meandering

surface jet intersects with an eddy field (Strub et al. 1991). Larger-scale horizontal eddies can focus upwelled water into streams/filaments as schematically represented by Roughgarden et al. (1988; Figure 4.35). Several investigators have noted an optimal velocity of water and air velocity in upwelling situations with respect to biological recruitment. Ware and Thompson (1991), for example, mention a wind speed of 7-8 m s^{-1}. *An interesting research topic would be to investigate the frequency and controlling factors for biologically optimal upwelling conditions.*

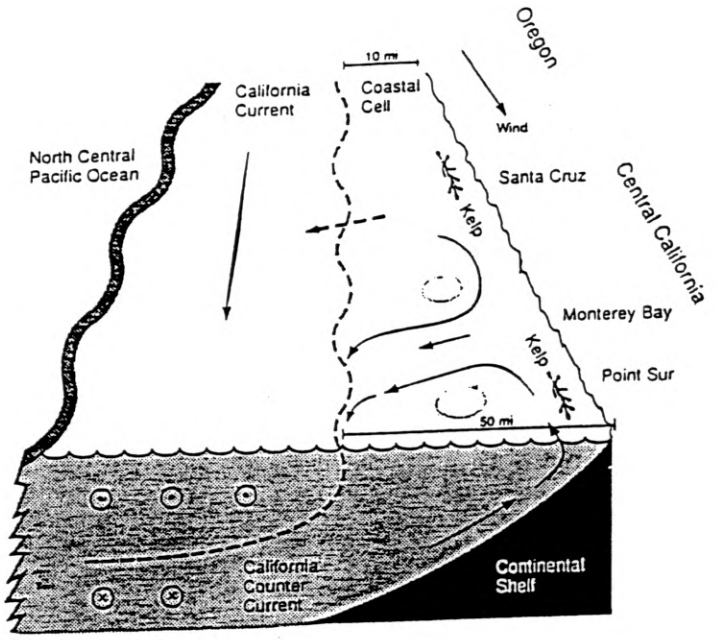


Figure 4.35. Schematic diagram of two dimensional upwelling system with horizontal eddies and streams/filaments. (Reprinted with permission from Roughgarden, J., S. Gaines, and H. Possingham. 1988. Recruitment dynamics in complex life cycles. *Science* 241:1460-1466. Copyright 1988 American Association for the Advancement of Science.)

It is useful to outline the terminology employed for the various mesoscale features. Davis (1985) provided some useful definitions for a variety of mesoscale features. The *eddies* are swirling flows. *Convergences* are regions to which drifters coalesce and frequently coincide with fronts. *Jets* are narrow high speed flows and squirts are localized energetic off-shelf flows often associated with cold-water plumes extending off the shelf. More recently, Strub et al. (1991) used the term *filament* to include many types of surface, cross-shelf, usually cold water flow. They suggested three conceptual models of the filaments (Figure 4.36). First, *squirts* are defined as-one way jets that transport coastally-upwelled water to the deep ocean, sometimes terminating in a counter-rotating vortex pair. The ideal squirt is caused by near-shore convergence. Second, a number of mesoscale eddies embedded in the generally southward-moving current can entrain coastally-upwelled water and move it away from the coast. A third model is one of a continuous southward jet meandering onshore and offshore.

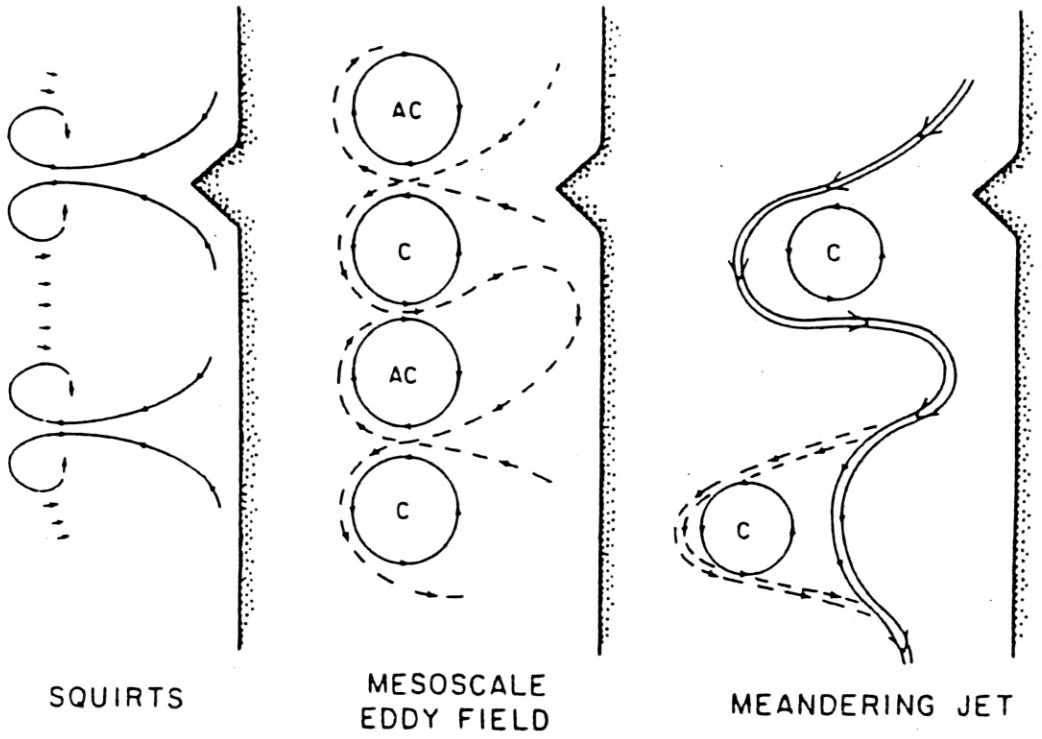


Figure 4.36. Conceptual models considered for the flow structure associated with cold filaments. (Source: Strub, P.T, and C. James. 1988. Atmospheric conditions during the spring and fall transitions in the coastal ocean off the western United States. *Journal of Geophysical Research* 93:15,561-15,584. Reprinted with permission, courtesy American Geophysical Union.)

Eddies and Jets. A very obvious feature of the satellite imagery of the Pacific Northwest ocean (Fig.4.31) is the turbulent flow in the CCS and its mesoscale eddies. Although these are best observed off California and have been described off Vancouver Island, they also exist in the PNCERS study area. They have not been well-studied off Washington and *the study of mesoscale eddies in the Pacific Northwest area is an important research topic.* Hickey (1989) discovered that small-scale eddies are not the principal source of variance at mid-shelf, mid-water column locations but are expected to be of greater significance in the near-surface layers and in the outer shelf. *The relative importance of eddies in the outer shelf should be determined.* Smith (pers. comm. 1996) has pointed out that the major source of current variance is not eddies but is wind-driven. He believes the eddies over the shelf are probably a result of instabilities in a coastal jet. Drifters have been used to make accurate determinations of the paths of the eddies. Davis (1985) gives some very good examples of the eddy phenomena off Northern California. *The specification of spatial and temporal changes of upwelling filaments, eddies, and jets should be a research topic both of PNCERS and GLOBEC.*

Columbia River Plume. Since the Columbia River provides a large amount of the freshwater entering the ocean from Washington and Oregon, its plume obviously plays a major role (Landry et al. 1989). The impact of the plume on salinity and density was shown in Figs. 4.6 and 4.7. Hickey (1989) believes a significant equatorward undercurrent may occur on the Washington inner shelf associated with the Columbia River plume. The construction of dams on the Columbia River has had the effect of increasing the amount of fresh water discharged into the northward flowing coastal current in winter (Ebbesmeyer and Tangborn 1992). This, in turn has given rise to an increase in fresh water intrusions into local bays and estuaries north of the Columbia River mouth and also into the Juan de Fuca Strait. Ebbesmeyer and Tangborn estimate that the new winter discharge to the north is the equivalent in magnitude of adding two rivers the size of the Fraser River. A comprehensive review of the situation in the post-dammed Columbia River is given by a set of papers edited by Small (1990).

Daily. The general effect of semi-diurnal and diurnal tides is twofold. They cause large changes in the volume of water at coasts twice a day and promote vertical mixing which breaks down the stratification of the coastal ocean water (Pickard and Emery 1990). Details on the different harmonic constituents of the tides may be found in Bowden (1983). The essence of the tidal response off the Washington and Oregon coasts is similar but the details depend upon exact bottom slope and water stratification (Hickey 1989). Tidal flows are naturally accelerated when constricted by topographic features such as estuaries. Ocean water movement can also be generated by internal waves formed through the interaction of tidal currents with bottom topography. Such movement may be focused by submarine canyons (Shanks 1995). When internal waves break they are manifested as tidal bores.

Possibly unrelated to tides is the fact that Breaker (1989) found a 40- to 50-day oscillation in the sea surface temperature off the California coast with an amplitude of as much as 1.5°C. *If it has not been performed already, a search for this oscillation should be undertaken for sea surface temperature off the Pacific Northwest coast.*

Other events such as "sneaker waves" and tsunamis occur but are relatively rare in the Pacific Northwest. The last major tsunami that affected the region was on March 17, 1964, when waves of between 3 and 6m (10 and 20 feet) high were reported. Flooding extended several miles up rivers. There is much evidence of past marsh burials in the Pacific Northwest region associated with tsunamis and previous tectonic events. The most recent extremely large tsunami in the Pacific Northwest occurred around 1700 AD (Jarman 1995).

Summary of Linkages between Ocean and Atmosphere

REVIEW AND EXTENSION OF MAIN LINKAGES FROM PREVIOUS SECTIONS

The foregoing discussion has revealed innumerable linkages between the atmosphere and the ocean in, and in the regions affecting, the PNCERS study area. The most predominant are first, the linkages between the basin-wide operation of the systems; second, the phenomenon of coastal

upwelling; and third, the enhancement of coastal ocean El Niño effects by later atmospheric effects. The issue of atmosphere - ocean linkage particularly demands a scale-related treatment and is dominated by questions of identification of causal and resulting factors and the degree of temporal lead and lag.

Wind-driven ocean currents at the basin scale are critical across virtually every time scale. On the longer time scale, the cooling of sea surface temperatures in the central North Pacific is believed to be associated with the post-1976 eastward shift and deepening of the Aleutian Low (Trenberth and Hurrel 1994). In addition, Miller et al. (1994a) have demonstrated that the mid-latitude part of the 1976-77 regime shift in the ocean was driven by the atmosphere, although feedback effects are not ruled out. Indeed, they identify the research question *to what extent do ocean thermal anomalies, once initiated, act to modify the air-sea heat exchange and subsequently affect the atmospheric circulation?* The model, developed by Miller et al. (1994a) points up the important fact that the temperatures of the mixed layer of the ocean off the coast of California are controlled much more by heat-flux input anomalies than by advection. Further interesting associations on the decadal scale were found by Namias et al. (1988) in correlations between the persistence of sea surface temperature in the North Pacific during January, the amplitude of the first principal component of sea surface temperatures in the North Pacific, and Pacific North American Index and Southern Oscillation Index values.

We believe the feedback between sea surface temperatures and the atmosphere on interannual and lower scales is also important. Namias (1969) and his co-workers performed intensive work in the 1960s and 1970s in attempting to identify such feedbacks. They investigated a number of different situations including the possibility of cyclogenesis in the presence of anomalously warm sea surface temperatures (Pickard and Emery 1990). Davis (1976) however, made an in-depth study of the statistical relationship between atmospheric pressure and sea surface temperature and found only slight skill in forecasting atmospheric pressure from sea surface temperature anomalies. He concluded that the statistical connection between sea level pressure and sea surface temperature is more likely due to the driving of the ocean by the atmosphere. Davis did find that sea level pressure anomalies could be specified statistically from simultaneous sea surface temperature conditions. Walsh and Richman (1981) found significant correlations between North Pacific sea surface temperature anomalies and temperature fluctuations in the West Coast states. In more recent studies, Trenberth and Hurrell (1994) discovered that, on the monthly scale, in the North Pacific atmospheric changes lead sea surface temperatures by one to two months. They attribute this to changes in surface-sensible and latent heat fluxes combined with mixing in the ocean and entrainment (Trenberth 1995). At the same time, changes in the tropical Pacific sea surface temperatures lead those in the North Pacific by three months. Changes in the storm tracks in the North Pacific help to reinforce and maintain the anomalous circulation in the upper troposphere of the atmosphere.

The relationships between wind and upwelling have been treated above. However, as mentioned previously, there seems to be a need for a more comprehensive climatology of the upwelling phenomenon and one which also includes biologically-important wind and water velocities.

The ocean/atmosphere relations surrounding ENSO phenomena are some of the most closely integrated and difficult to unravel. Trenberth and Hurrell (1994) hypothesize that the deepened

Aleutian Low in ENSO events results in a characteristic sea surface temperature anomaly pattern that, on average, is enhanced through positive feedback effects from: 1) effects of the extratropical sea surface temperature itself; and 2) changes in momentum (and vorticity) fluxes associated with high frequency storm tracks. On the decadal time scale, changes in ocean currents reinforce the sea surface temperature changes. Changes in the ocean currents and Sverdrup circulation are slow and add persistence to the extratropical system which, together with heat storage in the upper 500m, helps to emphasize the decadal over the interannual scale relative to the tropics. *A research topic would be to flesh out this hypothesis and test it more thoroughly.* Emery and Hamilton (1985) support this idea. They found that the relationship between the North Pacific sea level pressure and the Southern Oscillation, together with the relationships between the North Pacific sea level pressure and oceanic conditions in the NE Pacific, could account for the observed general tendency for sea surface temperature and sea level high pressure along the west coast of North America to be anomalously high during tropical warm ENSO episodes, although not all ENSO events were accompanied by warming of the Northeast Pacific. On a more local scale we have mentioned that for 1982 -1983 El Niño initial ocean appearance of high sea surface temperature along the West Coast was later enhanced by the atmospheric manifestations of the warm ENSO event (Huyer and Smith 1985).

There are other important ocean/atmosphere links. One is the determination of ocean salinity as a result of variation in winter coastal and interior precipitation. This was considered in the development of the PNI. Interesting statistical relations exist in yet another arena. Dettinger et al. (1995), for example, find a 3.3 year periodicity in one of their principal components of US temperature variation. This periodicity is found mainly in the western US and coincides with an identical periodicity in North Pacific sea surface temperatures and boundary current flow. *Such statistical associations should be examined to see if a physical cause or relationship might be at work.* Indeed, Dettinger et al. explicitly say that *"connections of the 3.3- and 10 year oscillations (in US air temperature) to the oceanic sea surface temperatures and flow patterns in the North Pacific's double-gyre circulation ... are certainly worth pursuing."* Finally, one of the most intriguing ocean/atmosphere linkages is that related to the spring transition. *An important research task would be to investigate if there are interdecadal cycles and/or other kinds of long term variability in this transition. Also, what is the threshold that exists which leads to the onset of the transition?*

THE IMPORTANCE OF TIMING OF OCEAN/ATMOSPHERE EVENTS WITH RESPECT TO SELECTED BIOTIC ACTIVITIES

The importance of timing of ocean/atmosphere events with respect to biotic processes is discussed in Chapters 5 and 6. It needs to be emphasized here that oceanographers and climatologists should be sensitive to the fact that not all events of the atmosphere and ocean have equal importance to biota. Some events and phenomena can be quite critical to biota. Upwelling situations are one, and the ocean and atmospheric conditions when salmonids first leave the estuary and enter the marine environment are another. A review of some of these linkages and critical times has been provided by Greenland (1996). A critical point in this general context is

that *the important times in the life cycles of biota should be recognized explicitly and these times and their related spatial and temporal scales, should be used to set priorities in PNCERS research in the ocean/atmosphere arena.*

TOWARDS MODEL DEVELOPMENT

The PNCERS program has started with a simple conceptual model focused on management decision-making with input from biophysical, and social and economic systems. The implicit underlying idea is that there are, or could be developed, more detailed sub-models of various parts of the biophysical and socioeconomic systems that can be used to extend the PNCERS conceptual model and make it more useful for ultimate management decision making. The whole approach leans towards being mechanistic and deterministic, which may be appropriate to a certain extent, but has some profound limitations. The limitations relate to the wide variety of existing or potentially new models that could be conceived, the difficulties of linking biophysical models together, the importance of recognizing the role of history and the larger context surrounding individual models, and also the very real difficulties of linking human and biophysical systems. The following discussion gives some idea of the different kinds of models already available and then expands upon the difficulties of linking human and biophysical systems.

Existing and Potentially New Models that Would Extend the PNCERS Conceptual Model

Existing models may be simplistically classified into conceptual models and deterministic numerical models. An example of the conceptual model is the "HWFS" model, an acronym for the interdecadal regime shift conceptual model developed by Hollowed, Wooster, Francis, and Sibley (Hollowed and Wooster 1991; Francis and Sibley 1991). It was discussed in earlier sections and diagrammed in Fig. 4.15. It is used in the present context as an example of the kind of conceptual model that brings together a number of cross-disciplinary features, has the potential for explaining a number of disparate observations, and can stimulate new research questions and data gathering programs. As such, it is a good example of a model lying between the extreme physical and mathematical complexities of the numerical models and overly simplistic conceptual models that are more descriptive than either diagnostic or prognostic.

There is a wide variety of deterministic numerical models. Numerical models are models that use equations of motion, hydrostatics, state, and radiative transfer in a three-dimension grid system space, and that use time-dependent, finite-difference computer solutions to model processes, particularly those of movement in both the atmosphere and the ocean. Usually there are separate models for the atmosphere and ocean but sometimes coupled models are used. Most commonly the models are employed on a global, coarse grid, but in many instances fine grid, or very fine mesh grid models are used separately or as nested models within a global grid. There are many versions of numerical models, the most well known being the global circulation models.

Physical models are best when they deal with relatively small, well specified parts of the physical system. A two-dimensional numerical model of coastal upwelling is a good example of this. The coupling together of different types of deterministic numerical models is no easy task. Nevertheless, GLOBEC (1995) planners have pointed out that many efforts to date have sought to incorporate basic ecological process formulations into regional scale transport models. They advocate the development of a series of multiscale nested models that will have a great deal of sophistication in their ecological parts and also be open to data assimilation techniques. It is conceivable that some future PNCERS models may be incorporated into this framework. Coupled ocean/atmosphere global circulation models will be the basis of large scale modeling for a long time to come. These global circulation models continue get better at bringing in realistic physical and biophysical processes but their spatial resolution will probably be coarse so as to necessitate nested, higher resolution models.

The Important Role of History in Models

Models are not very good at incorporating history and feedbacks into situations. When cyclic phenomena are being treated (as in the case of interdecadal variability in the Pacific Northwest) it is important to recognize that it is likely that when the time series returns to the point at which a new cycle begins, it is often the case that both biophysical and human-related situations have changed since the similar point was reached in the previous cycle. Consequently, the new cycle is operating on new background conditions and predictions of what will happen next cannot necessarily be made with confidence. Additionally, directional changes may also have taken place. For example, a century-long global climate-warming trend would mean that a cyclic phenomenon with a 20 year periodicity would start at different point every time the cycle repeated. This and analogous sets of events have caused severe problems in population ecology models (Kingsland 1995). Thus individual models must not be conceived as acting without a context. Francis and coworkers have argued this point eloquently with respect to biotic changes in the North and Northeast Pacific Ocean (Francis and Hare 1994; Francis 1996).

The role of the history of models is also instructive. Ecologists found in the 1960s that it was unwise to try to model everything into a large comprehensive model (e.g., an ecosystem). Problems of model-emergent properties and nonlinearity made the approach untenable. Huge, comprehensive models of individual ecosystems met with only very limited success with the result that it was found more effective to design smaller models of certain parts of the ecosystem and make sure these kinds of models worked well within the quite tightly prescribed limits that were set up for them. A later stage of development has seen increasing attempts to link the individual models but this procedure is performed cautiously and on a limited basis.

Currently it is generally found more effective to have a suite of individual efficient models than to aim for a large all-encompassing modeling system. It is likely that this kind of approach will work best for the PNCERS program as well.

Difficulties in Linking Biophysical and Social Science Models

Investigators in the natural sciences are not generally aware of the huge difficulties existing in attempts to link biophysical and social science models. The principal reason for these difficulties is that biophysical and social scientists generally work within totally different research paradigms. Biophysical scientists work mostly in the logical positivist paradigm where empirical observation, inductive and deductive processes are paramount. This framework is also used by social scientists, and to the extent that it is, then there is some possibility that natural and human-related systems can be linked. However, social scientists have found the logical positivist framework to be extremely limiting and have performed a great deal of their work under other paradigms. We will very briefly describe these paradigms and then re-state the difficulties that they represent for a program such as PNCERS.

Some of the more important social science paradigms that have found favor in the last four decades are as follows. Phenomenology is a philosophy that seeks to disclose the world as it shows itself *before* scientific inquiry, as that which is pre-given and pre-supposed by the natural sciences. Realism is the identification and abstraction of causal powers (as opposed to empirical regularities) acting under specific conditions, recognizing that all social science systems are open systems. Structuralism is a set of principles and procedures seeking to expose the basic structural logic underlying human actions and activities. Structuration is an approach concerned with the intersections between human agents and wider social systems and structures (agencies). More details of these can be found in many books (e.g., Johnston 1991). Post-Modernism is an approach assuming that "truth" and "explanation" has many equally possible, and often simultaneous, forms (e.g., Harvey 1989).

Most of these paradigms either present severe challenges to the logistical positivistic approach used in the sciences or are mutually exclusive of it. The only short-term pragmatic way to resolve this is to recognize that studies such as PNCERS, that seek to bring together biophysical and human systems, must be very carefully limited to specific subject areas where it is believed that some, albeit limited, progress can be made.

Use of Climate Forecasts in Decision-Making

In the 1960s, and following that time, there were many techniques developed for taking meteorological forecasts made in probability terms and using them within quantitative, operational, decision-making frameworks. The fact that a recent study has shown that salmon managers use only a very small part of the information available to them suggests that decision making methodology should be improved (Pulwarty and Redmond 1997).

The most suitable operations for applying decision-making theory, much of which is based on probability theory, are operations that are repetitive (such as deciding every year what salmon catch may be permitted). Once a solution or set of strategies has been established for a repetitive operation then they can be used repetitively. Classic early examples of techniques such as the cost/loss ratio were provided by Thompson (1950) and Thompson and Brier (1955). Naturally, advances have been made in this field since that time, particularly in the area of agricultural

climatology. Thus a general research area for PNCERS would be *to review and apply current methods of operational decision making to the management problems of the Pacific Northwest given the availability of current weather and marine forecasting methods.*

DISCUSSION AND RESEARCH QUESTIONS

It is not easy to review the whole of the two very specialized fields of atmospheric science and oceanography even when consideration is limited to a particular region of the Earth. The Pacific Northwest region happens to be a very complex area because it is an interface between two of the world's great land and ocean masses. Consequently, there are severe limitations to this review. Many items have been omitted.

A little over a hundred years ago the first climate maps of the area were published (Secretary of War 1889) and they were based on less than a score of reporting stations. The complexity of the coastal ocean currents was discovered by noting the terminal points of the wreckage of ships and cargo lost at sea (Garfielde 1871). Just as there are trends in the biophysical time series, progress in the development of knowledge has been marked by trends and fashions in areas of research concentration. Early studies naturally tended to be descriptive. During the latter part of this century we have been reacting to *features* of the system. The 1982-83 El Niño was a wake-up call to the entire ENSO phenomena and was followed by intense study of that field, a study that is by no means complete. The late 1980s saw the discovery of the importance of interdecadal cycles/regime shifts and a great deal of effort has since been devoted to them. Similarly, oceanography has undergone a comparable pathway with concentrations, for example, on current flow and upwelling phenomena. Concentration on trends in study such as these are necessary and important. It is essential to thoroughly mine a research theme. But these focuses should not be permitted to take attention away from other important areas. In the Pacific Northwest region such items as paleoclimate and paleo-oceanography, the influence of extreme events, 40-70 year cycles, and techniques such as remote sensing and geographic information systems, all need further work and application.

Extent and Quality of Data Supporting the Conceptual Model

Available data on biophysical systems in the Pacific Northwest are abundant and many of them may be used to support the PNCERS conceptual model. The principal data shortages lie in the century and millennial time scales and in the ocean. Only new sources, and thorough re-examination of paleo-proxy data, can be used to redress the former need. Oceanography will continue to require large resources to be devoted to ship and other surface-based observation systems. The continuing and rapidly developing deployment of remote sensing systems will be of immense value in the larger spatial scale studies of both the atmosphere and the oceans. The Earth Observing System (EOS) will likely play a critical role in this development.

Research Questions

Research questions in the fields of atmospheric science and oceanography arising from this review may be categorized into ones dealing with general broad areas of study and research, specific questions of high priority, and other important specific questions. These questions are conceptually rather limited to the areas already studied. It is likely that there are whole suites of very important questions related to areas such as remote sensing which have not received attention in this review. Finally, five general discussion questions were provided for use at the PNCERS workshop.

GENERAL QUESTIONS AND RESEARCH AREAS

What is the degree to which the various sub-ecosystems such as upland and lowland terrestrial, freshwater, and marine, are coupled or decoupled at the interfaces with respect to abiotic and biotic fluxes?

To what extent are there cycles in the range 40 to 70 years periodicity in biophysical time series in the Pacific Northwest area and how important are these compared to other cycles?

It is necessary to learn more about climatic variability in the Pacific Northwest area on the century and on the millennial scale especially with regard to the oceans.

The specification of spatial and temporal changes of upwelling filaments, eddies, and jets is of great interest.

The important times in the life cycles of biota should be recognized explicitly and these times and their related spatial and temporal scales should be used to set priorities in PNCERS research in the ocean/atmosphere arena.

We need to review and apply current methods of operational decision making to the management problems of the Pacific Northwest given the availability of present weather and marine forecasting tools.

Discussion Questions

Five general questions are provided for this theme. They are:

1) What are the relationships existing between phenomena and processes occurring on all of the different scales considered in this theme?

2) How stationary (i.e., faithfully replicable over long periods of time) are the various cyclic and quasi-cyclic phenomena in the Pacific Northwest atmospheric and oceanic systems?

3) How best can information on our knowledge of the variability of climatic/oceanic regimes in the Pacific Northwest and their predictability be transmitted to ecosystem managers?

4) What are the most important research needs on scales of century and greater and annual and lesser?

5) What new and existing observing systems and data bases are required and exist for answering PNCERS-related questions and meeting its goals?

Specific Questions

Are forecasting models useful to managers? Specifically: 1) model forecasting studies should be reviewed with regard to their specific Pacific Northwest area forecast and their efficiency should be assessed; 2) the best methods for use of NWS Long-Lead forecasts by Pacific Northwest managers should be determined.

What are the most appropriate measures of both the atmospheric and the oceanic manifestations of ENSO in relation to the Pacific Northwest?

What causes the change between one part of an interdecadal scale cycle or modal type and another ? Specifically, has the HWFS model of West Coast to Alaskan flow regime switch also occurred in earlier decades. What causes the switch back from Alaskan to West Coast flow regimes?

What detailed set of events, such as the sea level pressure patterns found by Strub and James, determines the timing of the spring transition and how is the transition related to atmospheric conditions and atmospheric and oceanic cycles on a variety of scales especially the decadal?

To what extent can we use discontinuous historic coastal air and sea surface temperature data extending back to the early 1800s to assess the degree of 'stationarity' of decadal regime behavior?

In what ways can dendrochronological or other proxy data be best used to investigate interdecadal and century scale periodicity?

Can we determine whether the interdecadal scale changes are quasi-cyclic in form or quasi modal punctuated by step functions ?

Given the fact that interdecadal changes are statistical in nature (i.e. they show up best when the data are aggregated for the whole winter and in standardized anomalies rather than raw data) how can knowledge of them best be transferred to, and used by, decision makers?

What controls the position of the bifurcation point of the Alaskan and Californian ocean currents on scales from the annual to the decadal? To what extent can OWSP data and remote sensing be used to answer this question?

What mechanisms may be responsible for decadal scale shifts in the coastal ocean and how the effect spreads along the coast (i.e. how a sudden shift off southern California "diffuses" northward)?

Are long period tides with quasi 20 year cyclicity related to interdecadal regime change?

Can an observational framework be designed to gain information on the barotropic component of the ocean circulation in the NE Pacific?

What, if any, air-sea interactions are involved to give rise to changes of temperature in the order of 1.5 °C over a three to four year period in the interior mid latitude of the North Pacific Ocean?

What are the mean and fluctuating current dynamics of the inner continental slope flows ?

How do the dynamics and intensity of the Alaska current respond to a very large annual signal in wind and precipitation in the Gulf of Alaska ?

What is the frequency and what are the controlling factors of biologically optimal upwelling conditions (i.e, upwelling conditions with certain water velocity ranges)?

What is the role of mesoscale eddies in the Pacific Northwest area and what is their relative importance compared to other dynamic features in the outer shelf. In particular what is the relative importance of eddies in the outer shelf ?

Is there a 40 to 50 day oscillation in sea surface temperature off the Pacific Northwest coast ?

Expand and test the hypothesis that on the decadal time scale a deepened Aleutian low in ENSO events results in a characteristic sea surface temperature anomaly pattern which, on average, is enhanced through positive feedback effects from: 1) effects of the extratropical sea surface temperature itself; and 2) changes in momentum (and vorticity) fluxes associated with high frequency storm tracks.

What are the sizes of ENSO-related shifts in precipitation and temperature median values to climatic normal values in the Pacific Northwest?

To what extent do ocean thermal anomalies on the interdecadal scale, once initiated, act to modify the air-sea heat exchange and subsequently affect the atmospheric circulation?

Is there a physical causal relationship for the 3.3 and 10 year periodicity in a principal component of US temperature variation found mainly in the Western US and an identical periodicity in North Pacific sea surface temperatures and boundary current geometries ?

To what degree are the periodic and random components in the time series of biophysical data in the Pacific Northwest area not independent of each other and does this lead to non-linear interactions between the components? Is there evidence for linkage between processes occurring at shorter and longer time scales?

To what degree can models of fluctuations at different time scales be put together so as to know the state of any particular cycle at any given time and its quantitative relation to simultaneous cycles of other lengths ?

What is the role of extreme events such as floods and droughts on the ecosystem and what is the relation between extreme events and longer term cycles ?

More data sets like Brunengo's Storminess Index data set should be developed and analyzed for short and interdecadal variability.

More attention should be given to the La Niña- related climatic events in the Pacific Northwest and to answer such questions as are flood events more likely to occur in the Pacific Northwest during La Niña times?

WORKSHOP-GENERATED QUESTIONS

During the course of the workshop the following areas were identified as being important for climatic/oceanic research for the PNCERS program:

- Characterization of temporal/spatial environmental (climate and ocean) variability;
- Long-term climate history;
- Monitoring the salmon's physical environment;
- Linkages between the physical environment and biota; and
- Air - sea - land - dynamics.

More details of these questions are contained in Chapter 7. It was the view of many participants that an effective monitoring program was essential to begin to solve some of the problems which are the focus of the PNCERS. Participants believed the monitoring program should be integrated and comprehensive (see for example, Sharp and McClain 1992).

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APPENDICES

Appendix 4.1. Teleconnective/Circulation Indices

CNP Central North Pacific. The average sea level pressure over the region 35° to 55° N, 170° E - 150° W. The CNP measures the intensity and area of the Aleutian Low and is available from 1899. (Cayan and Peterson 1989).

NP North Pacific Index. Area-weighted mean sea level pressure (mean sea level pressure) over the region 30° - 60° N, 160°E - 140°W (Trenberth and Hurrell 1994). Measures the intensity of the Aleutian low pressure. See also Emery and Hamilton (1985).

PNA Pacific North American Index. ¼[z^* (20° N, 160° W) - z^* (45° N, 165°W)

z^* (55° N, 115° W) - z^* (30° N, 85° W)] where z^* is the 500 mb mean monthly geopotential height anomaly at the points identified (Wallace and Gutzler 1981). A three node PNA at 700 mb was also designed by Yarnal and Diaz (1986) and Leathers and Palecki (1992). This index effectively measures the degree to which the general circulation over the Pacific and North America is meridional and adopts a pattern with a well developed Aleutian low and a low over eastern North America together with a high pressure ridge over western North America. These pressure patterns collectively make up what is called the PNA pattern. Ebbesmeyer et al. (1989) conceive a negative PNA value as representing the Aleutian Low being located more to the west and *vice versa*.

SOI Southern Oscillation Index. The standardized sea level pressure difference between Tahiti and Darwin, Australia. Low values of the index tend to indicate El Niño conditions while high values suggest La Niña events.

Appendix 4.2. Data Sets

CRITERIA FOR INCLUSION

There are a large number of data sets already collected and maintained that are useful for studies related to the PNCERS. Although there is need for more, particularly with regard to the ocean, it is useful to list and partially review some of the data sets that already exist. Such is the purpose of this section. Criteria for inclusion in this report are: 1) the data have been used previously in a Pacific Northwest coastal ecosystems-related study; and 2) the data have a clear potential for future use in the PNCERS program. Some of the data sets listed below are also included in the other data sets. There has only been enough time and resources to do a cursory examination of these data sources. PNCERS workshop members were invited to add to and improve upon this list.

RELEVANT DATA SETS

NATIONAL WEATHER SERVICE LAND SURFACE CLIMATE DIVISIONAL DATA

The US National Weather Service, the prime atmospheric data collecting agency in the US, collects a wide variety of data. Particularly useful for PNCERS are the Climate Divisional data. Each state is divided into up to about 10 or 12 Climate Divisions and data on temperature and precipitation values from stations within the division are averaged to form the divisional data sets. Climatic data from the individual stations are also available. Climate Divisional data and data from some individual sites are easily accessible from the World WeatherDisc (1994). The data sets of other national meteorological services may also be useful. Canadian data are available from Atmospheric Environment Canada which is located at Downsview, Ontario, Canada. The Hadley Centre for Climate Prediction and Research of the United Kingdom Meteorological Office has produced time series of monthly mean hemispheric-mean surface air temperature and sea surface temperature anomalies for the years 1890 to 1993 (Wallace et al. 1996).

NOAA CLIMATE DIAGNOSTICS CENTER PRODUCTS

The NOAA Climate Diagnostics Center (CDC) produces a large array of data sets and products that concentrate on climatological summaries of raw data and derived variables. They are also responsible for issuing the Long- Lead Forecasts which give forecasts for several months ahead. CDC products are disseminated in both hard copy and electronic form and include values of teleconnective indices and sea surface temperature data. The NCEP/CDC has a useful monthly averaged climatology of sea surface temperature (Reynolds 1982 quoted by Graham and Barnett 1995). The electronic address for the CDC is http://www.cdc.noaa.gov/.

COADS

The development of the Comprehensive Ocean/Atmosphere Data Set (COADS) is described by Woodruff et al. (1987). Elms et al. (1993) have reported aspects of the digitization of the data set. The COADS data are discussed comprehensively in the COADS web site at http://www.cdc.noaa.gov/coads. The COADS project collected global weather observations since 1854 taken near the Earth's surface primarily by merchant ships. Statistical summaries for each month were made using a 2° latitude by 2° longitude grid from 70 million original observations up to 1979. Monthly summary products give 14 statistics for each of 8 observed variables (air and sea surface temperatures, scalar and vector wind, pressure, humidity, and cloudiness) and 11 derived variables. Periodic updates of the data sets are made. Several subsequent data sets have been prepared from the COADS. An often used one is that of Pan and Oort (1990) which has a 1° latitude by 1° longitude spatial resolution and a temporal span of 119 years from 1870 to 1988.

COASTAL AND OCEANIC UPWELLING (BAKUN INDICES)

There is a lack of direct measurements of coastal upwelling. Because of this Bakun developed a series of upwelling index data based on the derivation of northerly wind stress along the West Coast obtained from meteorological data. The Bakun indices, sometimes called PFEG indices, are regularly updated and are often used. They are available in electronic form from The Pacific Fisheries Environmental Group, Southwest Fisheries Center, National Marine Fisheries Service, NOAA, P.O. Box 831, Monterey, CA.

PACIFIC CLIMATE WORKSHOPS (PACLIM) DATA SET

This data set was established out of the first years of operation of the PACLIM workshops. A key reference to it is Cayan et al. 1991. The data take the form of standardized monthly anomaly time series for several climatic variables for locations in the eastern Pacific Ocean and the western Americas. Variables include air temperature, barometric pressure, precipitation, streamflow, sunshine, sea level height, sea surface temperature, sea surface salinity, atmospheric teleconnective/circulation indices and biological variables, and miscellaneous ocean subsurface temperature and salinity factors. The data are available in an electronic form. The set and documentation can be obtained by writing for the Cayan et al. 1991 reference, USGS, Books and Open File Reports Section, Federal Center, Building 810, Box 25425, Denver, CO 80225.

SPECIFIC DATA SETS OF INDIVIDUAL INVESTIGATORS AND INSTITUTIONS

Specific data sets exist of individual investigators and institutions such as state Department of Fish and Wildlife in Oregon and the state Department of Ecology in Washington, the School of Fisheries at the University of Washington and the Scripps Institution of Oceanography (SIO).

Mr. Daniel Bottom at the state Department of Fish and Wildlife in Oregon and co-workers have assembled a Pacific Basin-wide data base of information related to salmonids. This data base is in a GIS framework. Ms. Patricia Dell'Arciprete and coworkers at the School of Fisheries at the University of Washington are working on an integrated assessment of the dynamics of climate variability, impacts and policy response strategies for the Pacific Northwest, and in doing so have assembled a very useful multidisciplinary data set for the Pacific Northwest that concentrates on the Puget Sound but which also addresses Pacific Basin wide issues (Dell'Arciprete et al. 1996). SIO has used COADS data to provide a set of monthly sea surface temperatures for the global ocean between 1950 and 1979 (Barbour 1986; Graham and Barnett 1995). SIO possesses many large atmospheric and oceanographic data sets.

Two other potentially useful data CDs are available: 1) the "US Navy Marine Climatic Atlas of the World" version 1.0 released in March 1992 from the Naval Oceanography Command Detachment, Ashville, N.C.; and 2) "A Daily Stream Discharge Data Set for the Continental US" version 1.0, released in February 1991 by J.R. Wallis, IBM Thomas J. Watson Research Laboratory, D.P. Lettenmaier, Department of Civil Engineering, University of Washington, and E.F. Wood, Department of Civil Engineering and Operations Research, Princeton University.

SELECTED SATELLITE DATA SETS

Heavily under-represented in this review is the potential for the use of satellite-derived data for the PNCERS study. It is likely that many themes of the study can benefit from such data. Up to the present the most commonly used data type for PNCERS-related studies has been Advanced Very High Resolution Radiometer (AVHRR) data for oceanic use. The frequency of use is because of the daily availability and relative high resolution of this data source. LANDSAT and Satellite Pour l'Observation de la Terre (SPOT) data have some potential for use but suffer from the approximate 16 day interval return overpass. In the future, Earth Observing System (EOS) program platforms and sensors will be of immense use for both oceanic and terrestrial parts of the PNCE area. The use of satellite-derived data for land surface climatology has been reviewed in detail by Greenland (1994b). There are a number of remotely-sensed precipitation data sets for the North Pacific which have used microwave and other technologies.

HISTORICAL GRIDDED SURFACE PRESSURE AND CLIMATE NETWORK SETS

The Department of Energy (DOE) houses and distributes a wide range of climatological data sets from the Oak Ridge National Laboratory in Tennessee. At least two of these are of potential use for the PNCERS. A first is the historical gridded-surface pressure data set for the North American continent. This set provides monthly mean surface pressure on an approximately 250 km grid back to 1858. The area also covers parts of the NE Pacific Ocean. The data are available in hard copy and electronic form (Jones et al. 1987). A second data set distributed by DOE is the Historical Climate Network (HCN) data set (Karl et al. 1988). This is composed of temperature and precipitation data from a large number of individual recording stations. The data have been processed so as to remove errors due to such things as time of observer bias, and are especially

useful for analysis of long-term climate variability. There are approximately 80 HCN stations in Washington, Oregon and Northern California. A new version of the US HCN was recently released and information concerning it can be found at the following URL: http://cdiac.esd.ornl.gov/ndps/ndp019r3.html.

NCEP GRIDDED PRESSURE SET

NOAA through its National Centers for Environmental Prediction (NCEP) provides a useful CD ROM entitled "National Meteorological Center Grid Point Data (Version II)" (1990) containing gridded surface and upper air atmospheric pressure data sets for the northern hemisphere. These have been widely used in synoptic climatological studies and are potentially of great value to future PNCERS investigations. The CD is available from the National Center for Atmospheric Research (NCAR) Data Support Section (303-497-1215) or Atmospheric Sciences at the University of Washington (206-543-0448). NCEP (along with the European Centre for Medium Range Weather and the Fleet Numerical Meteorology and Oceanography Center) also provide model "initial condition" wind fields over the North Pacific.

MOODS SUBSURFACE DATA SET

GLOBEC (1994) planners also have drawn attention to the Master Oceanographic Observations Data Set (MOODS), from the Fleet Numerical Meteorology and Oceanography Center (FNMOC), Naval Research Laboratory, which consists of sub-surface ship data from conductivity/temperature/depth (CTD) observing instruments, bathythermographs (BTs), and expendable bathythermographs (XBTs) which extends back into the 19th century. Sharp and McLain (1993) have made excellent use of these data to provide mean monthly depths of the 14°C isotherm from 60°N to 60°S along the coast of the W Americas from 1943-1991.

PHYSICAL PARTS OF CALCOFI DATA SET

The California Cooperative Oceanic Fisheries Investigations (CalCOFI) sampling program occurs along the California coast. It was initiated in 1950 and is still being continued. There were some data gaps in the 1970s. Stations in the sampling grid are typically 30 to 60 km apart and sampling is performed down to 500 m. Variables sampled include temperature and steric height (Roemmich 1992).

WASHINGTON DEPARTMENT OF ECOLOGY MARINE WATERS DATA BASE

Dr. Jan Newton of the state Department of Ecology in Washington has assembled a large collection of data related to the Puget Sound area. The data include 21 variables of physical, chemical, and biological significance (Newton et al. 1995).

NEWPORT HYDROGRAPHIC (NH) LINE

Temperature and salinity with depth observations taken at stations off Newport, Oregon, originally to 25 nautical miles offshore, and later to 165 nautical miles. The observations were started in 1959 by Oregon State University investigators. Quite good coverage exists for all seasons for the years 1960 to 1970. Partial coverage is available from 1971 to 1975 after which time the coverage is sporadic. These data are described by Huyer (1977) and have been used in several papers (e.g., Huyer and Smith 1985).

HYDROLOGY DATA SETS

Comprehensive hydrologic data are represented by the US Geological Survey stream flow/gage records and the US Department of Agriculture Soil Conservation Service (and Canadian) snow course and snow sensor records.

Science for Solutions

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Pacific Northwest Coastal Ecosystems Regional Study (PNCERS)

Edited by Gregory R. McMurray
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PNCERS

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