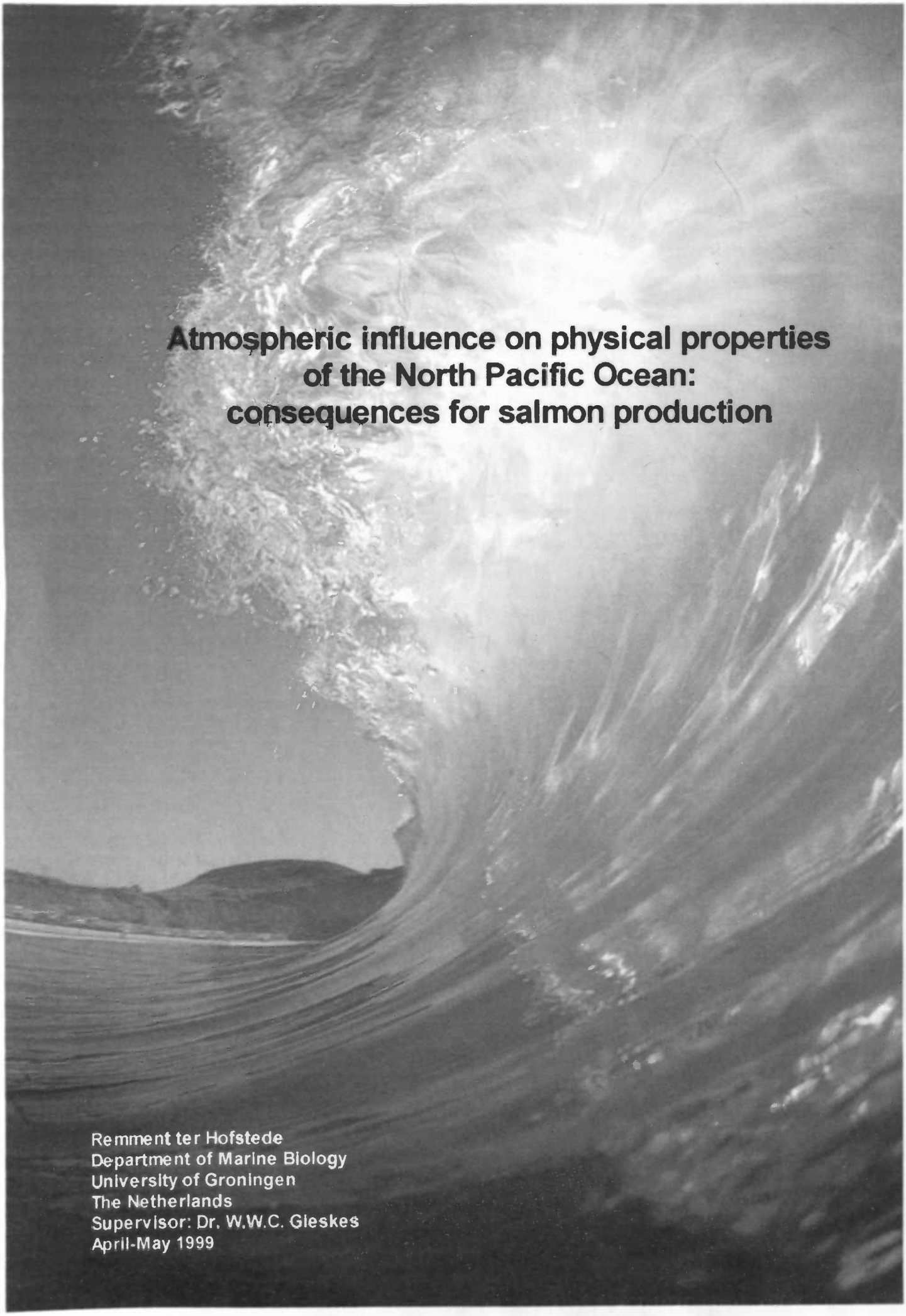

Atmospheric influence on physical properties of the North Pacific Ocean: consequences for salmon production

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April-May 1999

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Abstract

Physical properties of seas and oceans are of major importance to marine ecosystems because they induce the nutrient and light environments that shape their primary production. Physical processes act at all scales, from atmospheric temperatures down to molecular salt diffusivity. A selection of such processes has been made and the most important ones for marine ecosystems will be discussed.
Moving up the food chain from phytoplankton will lead to marine fish stocks such as salmon populations. Salmon is an economically important species because it is intensively fished throughout the world. It has been found in the North Pacific Ocean that in the period 1925-1989 the salmon production correlated with the Aleutian Low pressure system, which is the dominant meteorological feature in the winter and spring atmosphere in this region. The salmon catches appear to be above normal when the Aleutian Low is more intense than average and vice versa.
The trends in salmon production during the period 1925-1989 appeared to be directly related to climate shifts, and were not a result of human activities such as fishing effort, management actions, or artificial rearing. The changes in Northeast Pacific salmon populations are indirectly linked to climate changes through the marine food chain. A new climate shift is expected to occur in the next few years, with probably unfavourable consequences for the abundance of salmon in the North Pacific Ocean.

Contents

1 Preface

An article in Oceanography (1997) by Ann E. Gargett drew my attention and forms the base of this essay. The title of the article covers the issue quite well: "Physics to fish: Interactions between physics and biology on a variety of scales".
In order to execute a solid management strategy for marine fisheries policy, one should be informed of all factors that influence marine fish populations, such as recruitment, pollution and food availability. These factors are primarily determined by the phenomenon of physical processes, because the physical properties of oceans induce the nutrient and light environments that shape their primary production, which forms the base for marine ecosystems

The main aim of this essay is therefore to discuss several physical factors that are mentioned in the literature as being of influence on marine fish stocks. Serving as an example of the influence of physics to marine fish stocks, this essay focuses on the salmon production in the North Pacific Ocean. Salmon is an economically important fish, which increases the usefulness of this essay. The North Pacific Ocean is a well-studied area, so sufficient information exists about this region. However, difficulties occurred while gathering the existing information and the literature that was not available but certainly relevant will be referred to as "non vidi".

The essay starts with the introduction of the most important physical oceanographic processes, both on a large and a small scale. It appears that these processes act upon different levels in the food chain; from the primary production through zooplankton up to fish stocks such as salmon. Therefore, these levels will be discussed with emphasis on the level of salmon. In conclusion, the origination of the main phenomena of physical oceanographic processes that influence the North Pacific salmon production will be accentuated.

2 Physical processes

Physical processes are of major importance to marine ecosystems because they provide the nutrient and light environments that shape them from their base in primary production. Physical processes are three-dimensional and involve interaction of the ocean with the atmosphere. For instance, winds promote mixing and evaporation. Atmospheric temperature influences the density of ocean surface layers through effects on seawater temperature and salinity (through ice formation and melting), which in turn modify the atmosphere. The important physical oceanographic processes act at all scales.

2.1 Large scale physical processes

2.1.1 Wind

The rate at which wind affects the ocean is dependent on its speed; a severe storm can by far outweigh long periods of lighter winds. Generally, on a large scale wind causes upwelling in the subpolar gyres and downwelling in the subtropical gyres (see figure 1). The upwelling in the subpolar gyres positions the nutricline close to the euphotic zone, but primary production can be light limited due to seasonality at the higher latitudes. In the subtropical gyres primary production is not limited by light availability, but the nutrient supply is insufficient because the wind-driven downwelling places the nutricline well below the euphotic zone (Gargett, 1997a).

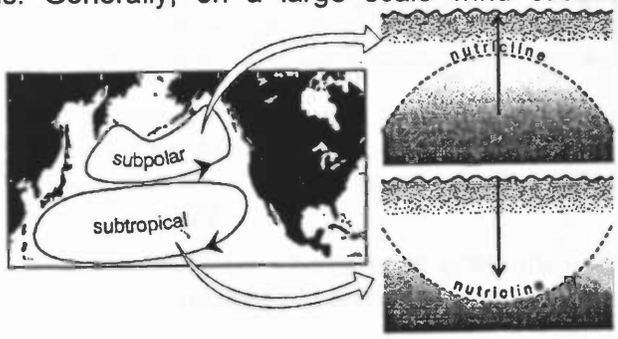

Figure 1: Wind-driven upwelling and downwelling in the major ocean gyres scult the surface of the nutricline, moving it respectively closer to and further from the sea surface within subpolar and subtropical gyres (after: Gargett, 1997a).

In the North Pacific, the ocean circulation consists of the subpolar clockwise-flowing Central Pacific gyre and the subtropical counter-clockwise-flowing Alaskan gyre. The boundary between these two currents, the Subarctic current, divides into two branches as it comes near the coast of North America at about latitude 45-50°N. One branch, the Californian Current, flows south and the other, the Alaskan Current, flows north off the coasts of British Columbia and Alaska (Beamish, 1993).

2.1.2 Sea level pressure

There is a marked annual cycle in atmospheric activity over the North Pacific, with the mid-latitude west-to-east winds (westerlies) and storm tracks reaching their most southerly extent in winter. During the winter months atmospheric forcing most strongly affects a communication between the near-surface waters and those below (Venrick *et al.*,1987).

The sea level pressure field and its spatial gradients are good indicators of storminess and winds over the ocean, and the seasonal mean of the sea level pressure indicates the season's overall conditions.

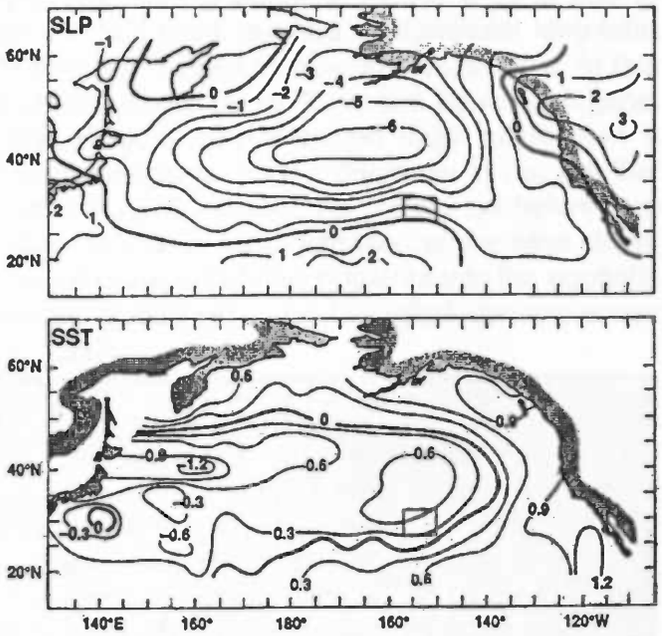

Figure 2: Changes in Sea Level Pressure in millibars (top) and Sea Surface Temperature in degrees Celcius (bottom) over the North Pacific (after: Venrick et al.. 1987).

North of 25°N, average values of winter sea level pressure during 1980 to 1985 (high chlorophyll years) were strikingly significantly lower than during 1968 to 1973 (low chlorophyll years). This decrease was greatest to the north, resulting in an intensification of the north-south gradients of sea level pressure (see figure 2), which can be interpreted as an increase in the strength of westerly winds (Venrick *et al.*, 1987).

2.1.3 Sea surface temperature

Sea surface temperatures are also related to atmospheric conditions and differences between the same periods (see figure 3) show a maximum along the zone of maximum enhanced westerly winds and probably result from more active winter storminess, which has been documented for vigorous winters within the 1980-1985 period. The temperature data of Venrick *et al.* (1987) show a cooling tendency (P ~ 0.20) throughout the upper 100m, but there does not appear to be a concomitant change in salinity. The mechanism of increased latent and sensible heat extraction from the ocean, north-to-south Ekman drift, and wind mixing may have played a role in cooling the upper part of the ocean. Time series of derived wind and sea surface temperatures (see figure 3) indicate that these properties have varied significantly from year to year and forcing mechanisms have probably operated episodically (Venrick *et al.*, 1987).

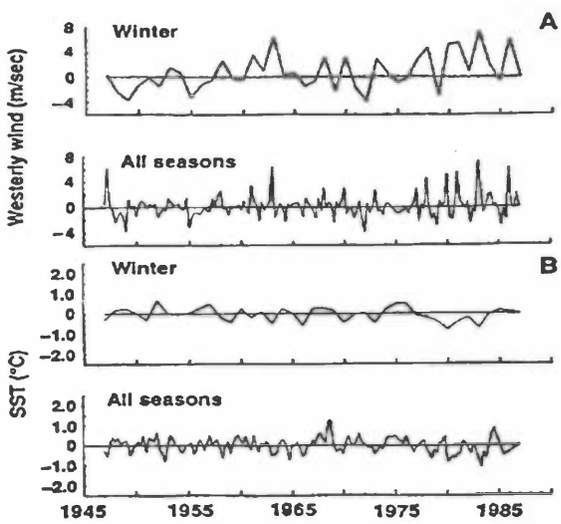

Figure 3: Time series of anomalous west-to-east component of suface winds (A) and Sea Surface Temperatures anomaly (B) (after: Venrick et al.. 1987).

Fluctuations in and sea level pressure and sea surface temperature since 1968 due to atmospheric conditions in the Central North Pacific have resulted in significant long-term changes in the carrying capacity of the Central North Pacific epipelagic ecosystem. In this oligotrophic environment, the majority of nutrients in the upper 150m are bound in organic material. Thus, an increase in the standing stock of phytoplankton must result from a reapportionment of nutrients among organic components, from a decrease in nutrient flux out of the euphotic zone, or from an increase in nutrient input. As mentioned before, the latter would occur if increased surface cooling, combined with increased winter wind stress to increase vertical mixing and enhance upward transport of new nutrients into the euphotic zone. Even if climatic forcing factors operate episodically, the biological consequences appear to be more persistent (Venrick *et al.*, 1987).

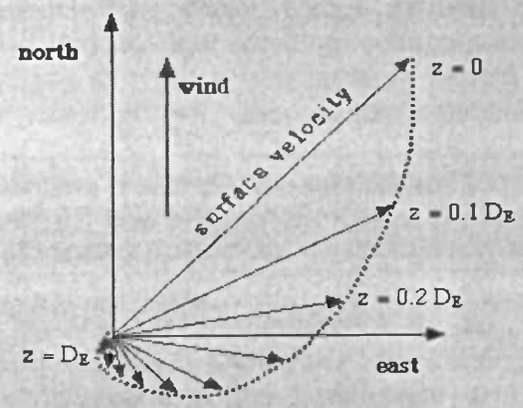

Figure 4: Depth variation of currents in the wind-generated Ekman layer in a deep ocean situation for the Northern Hemisphere, assuming a southerly wind. Current vectors are shown from the surface down in increments of 1/10th of Ekman layer depth (D_E) (after: Ekman, 1905).

Box 1: Ekman Forcing

It is assumed that the principal means for conveying wind stress to the ocean's uppermost layer is in an Ekman layer of ten's to a hundred meters thickness in which the stress is balanced by the Coriolis force. The result is net mass transport to the right of the wind in the Northern Hemisphere. The velocity vectors form a (Ekman) spiral to the right, which decays exponentially with depth if the eddy viscosity is uniform. The principal justification for the theory has been that the ocean's general circulation beneath the Ekman layer is in the proper sense as to be driven by convergent or divergent Ekman transports. In the actual sea, it is necessary to think in terms of the turbulent diffusion rather than the molecular viscosity (Ekman, 1905).

2.1.4 Aleutian Low

The Aleutian Low is a deep extensive low-pressure area that is centred over the Aleutian Islands in the North Pacific Ocean. It typically begins forming during the autumn months and intensifies during the winter. During the winter, the Aleutian Low dominates the climate over the North Pacific Ocean (Trenberth, 1990; Beamish & Bouillon, 1993). The low begins to break down in spring and is replaced in the summer by an area of extensive high pressure. The major ocean currents are generated by the resulting surface winds, with the strength of the currents related to the strength of the winds. Seasonal differences in the direction of the winds determine if surface currents (called Ekman transport) flow inshore or offshore (Freeland *et al.*, 1984).

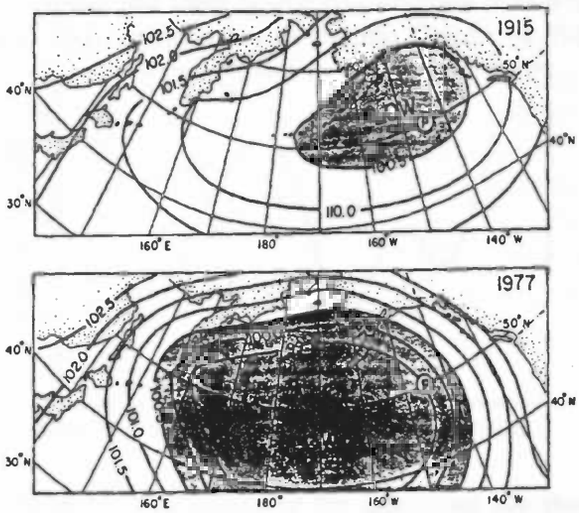

Figure 5: Examples of a weak Aleutian Low pressure system for January 1915 and a typical intense Aleutian Low for January 1977. Sea Surface Pressure gradients are in kilopascals (after: Beamish & Bouillon, 1993).

As the Aleutian Low develops in the fall, the circulation around the Alaska gyre intensifies (Thomson, 1981). During periods of strong Aleutian Lows, there is strong onshore transport of surface currents (the Ekman layer) and intense downwelling along the coast as far south as central California. This mass of water flowing towards the coast must be replaced by water from below. Hence, there is a shallowing of the upper mixed layer to the north in the Central Pacific Ocean bringing cooler, nutrient-rich water to the surface (Thomson, 1981).

A strong Aleutian Low brings intensified flows of moist marine air up against the coastal mountains of Alaska and northern British Columbia, causing an increased precipitation and run-off. These conditions will lead to a stronger stratified coastal ocean in the northern regions. In the southern regions, a strong Aleutian Low causes an increase incidence of winds to the coast of California. This means less upwelling of the coastal ocean, which is usually high because of the subtropical gyre, hence here too leading to a more strongly stratified water column.

Conversely, during periods when the Aleutian Low is weak, there will be a decreased freshwater input in the North and an increased upwelling in the south, both leading to a weaker stratification of the water column along the entire eastern coastal boundary of the North Pacific (Gargett, 1997a).

The Aleutian Low Pressure Index for the years 1900-1989 (see figure 6) indicates that the sea level pressure was high over a vast area of the northern North Pacific Ocean at the turn of the century (low index represents high pressures or less intense lows). The Aleutian Lows intensified steadily until the late 1930s (high index represents low pressures or intense lows). From about 1940 to 1950 the index dropped, indicating a change to higher sea level pressures. The period from 1950 to 1970 was characterised by high pressure or weak lows, except for a small period of intense lows in the late 1950s and early 1960s. Beginning in the early 1970s, the intensity of the Aleutian Lows again increased, reaching the most intensive levels in the time series in the 1980s. In the late 1980s, there was a weakening of the Aleutian Low (Beamish & Bouillon, 1993).

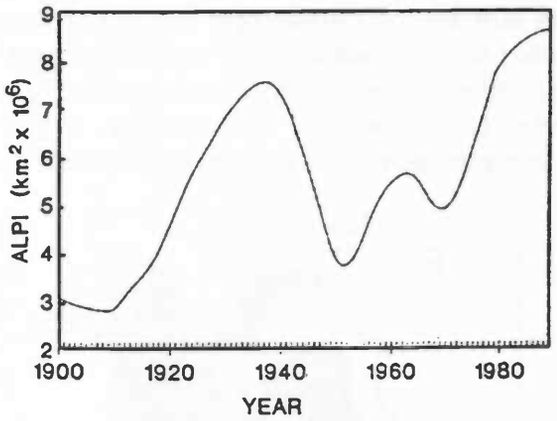

Figure 6: The course of the smoothed Aleutian Low Pressure Index (solid line) for the years 1900-1989 (after: Beamish & Bouillon, 1993).

The Aleutian Low of 1976-1977 (see figure 7) was the most intense low since the winter of 1940-1941 (Beamish & Bouillon, 1993) and it signalled a change in the pattern of winter (November-March) low pressures. The mean sea level pressure over the North Pacific Ocean decreased with 2 millibars from approximately 1012.8 millibars (1956-1976) to 1010.8 millibars (1977-1988) (see figure 8) (Trenberth, 1990).

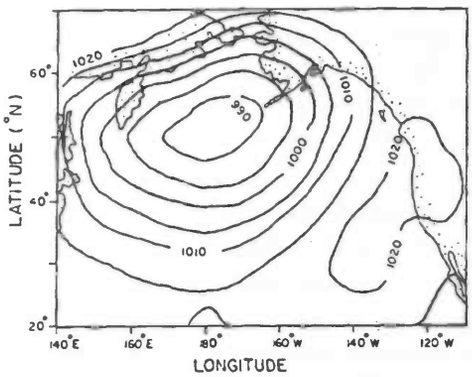

Figure 7: Aleutian Low that formed from December 1976 to February 1977 (after: Beamish, 1993).

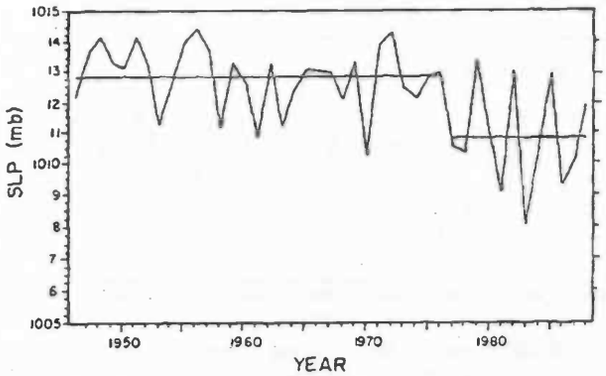

Figure 8: Mean Sea Level Pressure in the North Pacific Ocean from November to March showing the change in the pattern of the winter climate that occurred in 1976 (after: Trenberth, 1990).

Another indication of a climate change over the North Pacific in the late 1970s is the change that occurred in the sea surface temperatures. Sea surface temperatures in the Northeast Pacific Ocean have two general patterns: For the first pattern counts that sea surface temperatures along the coast of North America are below normal when temperatures farther offshore are above normal. The second type is the opposite; sea surface temperatures along the coast of North America are above normal when temperatures farther offshore are below normal. These patterns are also most obvious in winter (see figure 9) (McLain, 1984).

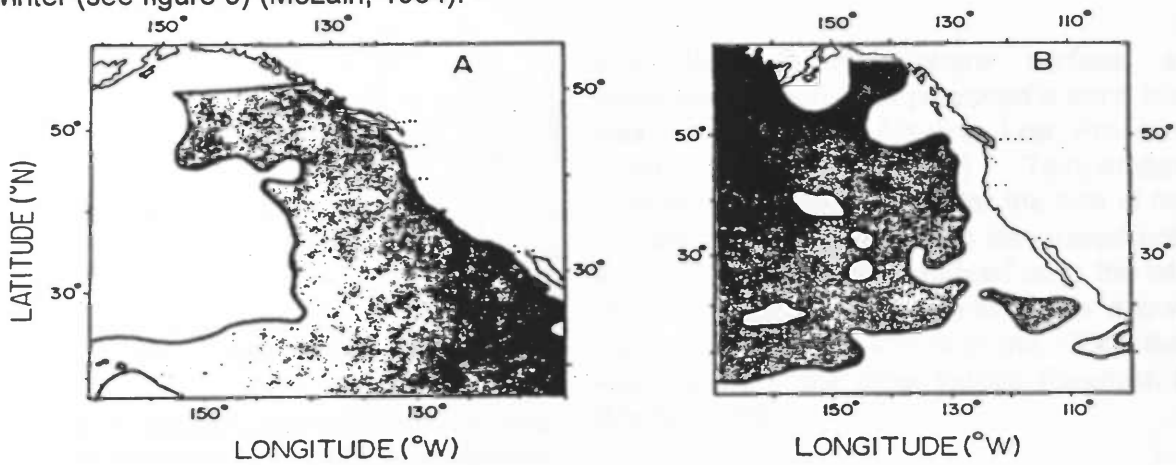

Figure 9: Pattern of Sea Surface Temperature anomaly (°C) for January 1972 showing below-normal temperatures (shaded area) close to shore (left) and January 1983 showing above-average temperatures (unshaded area) close to shore (right) (after: McLain, 1984).

The pattern oscillated over the years 1957-1976. In the summer of 1976, however, it changed from having below-normal sea surface temperatures adjacent to shore to having above-normal sea surface temperatures close to shore (McLain, 1984). The increase in sea surface temperatures lasted until at least the mid-1980s and was most dramatic in the Northeast Pacific Ocean (see figure 10) (Chelton, 1984).

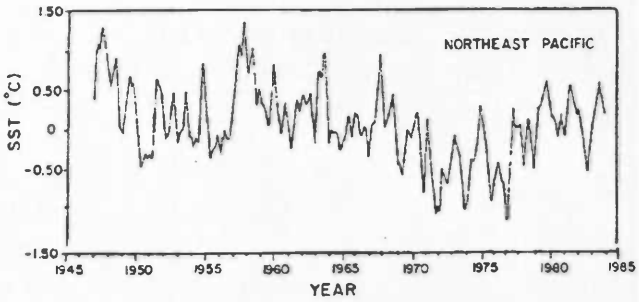

Figure 10: Time series of Sea Surface Temperatures in the Northeast Pacific Ocean (after Chelton, 1984).

The climate shift in 1976 started a new climate regime over a vast area of the Pacific Ocean and North America (Kerr, 1992). In general, the period 1977-1986 featured very large air temperature anomalies in the North Pacific basin. There was a general warming exceeding 1,5 °C over Alaska and a cooling of less than 0.75 °C in the central and western North Pacific (Trenberth, 1990). This pattern would be expected with more intense Aleutian Low because warmer, moister air would be carried along the West Coast of North America into Alaska. At the same time, cooler, southward flowing air would be found in the central and western North Pacific (Beamish 1993).

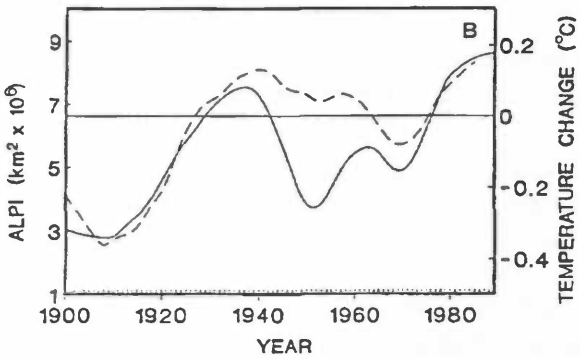

Figure 11: Aleutian Low Pressure Index (solid line) compared with the Northern Hemisphere mean surface air temperature (broken line) (after: Beamish & Bouillon, 1993)

The Northern Hemisphere surface air temperature anomalies produced a trend that was similar to the Aleutian Low Pressure Index (see figure 11). Temperature anomalies increased just after the turn of the century to about 1940, then decreased until about 1970, and then increased up to the late 1980s. The temperature time series shows the small change in trends in the 1950s that was present in the other indices (Beamish & Bouillon, 1993).

Box 2: North versus South Pacific Ocean

The pattern of the smoothed sea level pressure at Darwin (Australia; South Pacific Ocean) was very similar to the trend in the Aleutian Low Pressure Index after the mid-1920s (see figure 12). After the mid-1920s, there were increasing trends in both areas up to about 1940, from the early 1950s to the early 1960s and from the early 1970s until the late 1980s. Decreasing trends occurred from about 1940 to the early 1950s and from the early 1960s to the early 1970s. The similarity in the patterns indicates that sea level pressure trends in the North Pacific were closely related to trends in the tropical South Pacific Ocean but were opposite in phase. The trends at Darwin were actual sea level pressures whereas the Aleutian Low Pressure Index is an index of the area of low pressures. The trends of increasing sea level pressures at Darwin, therefore, were associated with trends of increasing size of the area of low pressure in the North Pacific, i.e. with decreasing sea level pressure. This indicates that the pressure trends in the North Pacific Ocean are similar, but opposite in phase to the trends in the tropical Southern Pacific Ocean (Beamish & Bouillon, 1993).

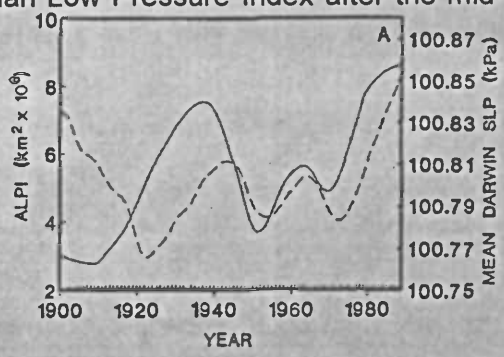

Figure 12: Aleutian Low Pressure Index (solid line) compared with Sea Level Pressure at Darwin (broken line) (after: Beamish & Bouillon, 1993).

2.2 Small scale physical processes

The action of small-scale physical process cause the actual vertical transport of nutrients up into the euphotic zone, whether the nutricline is shallow or deep.
This phenomenon of resuppliance is generalised in the word **turbulence** and incorporates:

- near-surface turbulence driven by winds or breaking waves,
- Langmuir circulation,
- shear instabilities at the mixing layer base,
- free convection driven by surface heat loss or salinisation, and
- double diffusive processes.

The type of small-scale process occurring depends on the relative location of the base of the surface mixing layer and the top of the nutricline (Gargett, 1997).

2.2.1 Near-surface turbulence driven by winds or breaking waves

Wave breaking is an important source of turbulence close to the surface. It causes entrained air that represents an exchange of kinetic for potential energy within the water column. Clouds of bubbles play a role in air-sea gas exchange and can serve as tracers of fluid motion. Large bubbles rise quickly, whereas smaller ones (radius <500 μm) are organised into patterns by the circulation. Smaller bubbles are redistributed by near surface turbulence and the more persistent subsurface motions, Langmuir circulation.
Bubble dissolution depends on the difference in partial pressures of the primary gas constituents N_2, O_2 on either side of the bubble surface. Despite its relevance to the air-sea CO_2 flux, the dissolution of highly soluble trace gases has no perceptible influence on bubble volume and hence buoyancy. Nevertheless, it appears that bubbles may have significant effect on the CO_2 flux, providing added motivation for understanding dissolution of N_2 and O_2 (Farmer, 1997).

2.2.2 Langmuir cells

Langmuir circulations are commonly observed as parallel streaks formed when the wind blows across the surface of the water. Irving Langmuir (1938) was the first who analysed the wind-aligned streaks to be a series of counter-rotating vortices aligned approximately in the direction of the wind. These "Langmuir" circulations (see figure 13) can cause downwelling velocities as high as 1% of the wind speed and therefore represent a potentially important mechanism for the downward mixing of surface waters.
Langmuir circulations act as an efficient heat pump, stirring relatively warm surface waters downwards and cool deeper waters towards the surface, where they may gain heat from the air and sun.
Although similar in form to such thermally driven dynamics as Rayleigh-Bernard convection (see box 2), it is found that thermal forcing is not of particular importance in Langmuir circulation. Instead the instability is forced through an interaction between the wind and the surface wave stokes drift (Hasse & Dobson, 1986).

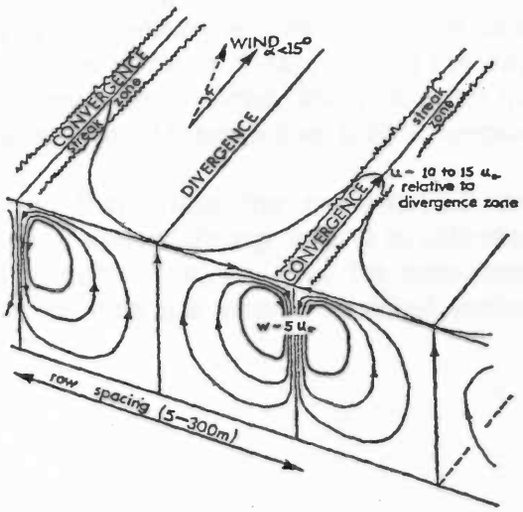

Figure 13: Schematic diagram of the observed structure of Langmuir circulations (after: Hasse & Dobson, 1986).

Box 3: Rayleigh-Benard Convection

Convection is the well-known phenomena of fluid motion induced by bouyancy when a fluid is heated from below. In 1900 Benard investigated a fluid, with a free surface, heated from below in a dish, and noticed a rather regular cellular pattern of hexagonal convection cells. Rayleigh explained this in 1916 in terms of a bouyancy driven instability. In bouyancy driven convection the expected pattern would be a stripe pattern of convection rolls, rather than the cellular pattern observed by Benard. The convection observed by Benard is now understood to be driven by temperature dependent surface tension forces rather than by bouyancy. Nevertheless, the stripe or roll state formed in bouyancy driven convection is today referred to as Rayleigh-Benard Convection.

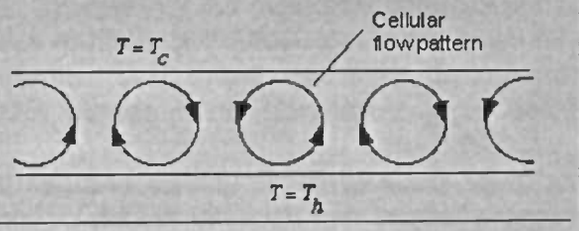

Figure 14: Rayleigh-Benard convection.

2.2.3 Shear instabilities at the mixing layer base

In the presence of a stable vertical density gradient, such as that at the base of the mixed layer, instabilities can be produced in the (otherwise laminar) flow by velocity shear, i.e. vertical gradients in the horizontal velocity. Such instabilities exist as wavelike "billows" in the thermocline (Woods, 1968).

The shear-induced billows generate turbulence, which then enhances the mixing process in the vicinity of the base of the mixed layer, and allows the "mixing down" of fluid to occur much more efficiently than would happen if the mixing was purely convective.

Storm-induced oscillations create shear at the base of the mixed layer and produce the observed rapid storm-induced deepening of the oceanic mixed layer (Hasse & Dobson, 1986).

2.2.4 Free convection driven by surface heat loss or salinisation

Heat loss from the surface during the night drives convective motions that move cells progressively farther from the surface, to depths on the order of 100m. During the day, heating of the surface by the sun damps out the convective motions, and cells near the surface remain trapped there by formation of a shallow diurnal thermocline, until convection resumes shortly after sunset.

This illustrates that small-scale physical processes that shape the nutrient and light environment are strong functions of near-surface stratification. Strong vertical stratification severely inhibits the vertical motions associated with turbulence, and thus the associated vertical turbulent fluxes. In contrast, where water columns are weakly stratified vertical excursions and fluxes may be large (Gargett, 1997).

2.2.5 Double diffusion

The salts that are dissolved in the oceans have profound effects on a large scale because evaporation-precipitation patterns have an opposite buoyancy effect to thermal forcing. On a microscale, salts have profound effects due to the fact that the molecular diffusion of heat is 70 times faster than that of salt. This difference in molecular diffusivities is the basis for a variety of phenomena known as double-diffusion, and these can lead to important differences between heat and salt-fluxes, with consequences for much larger scales (Ruddick, 1997).

Conventional turbulent mixing, for which heat, salt and density diffusivities are equal and positive, reduces contrasts in density. In contrast, double diffusion can increase density contrasts, and this is the key to understanding many of its oceanic consequences:

1) the possibility of mixing without an external source of kinetic energy (named double-diffusive convection),
2) formation of regular series of layers,
3) the strange effects on vertical motion and stretching that modulate thermohaline circulation, and
4) even lateral mixing over thousands of kilometres via thermohaline intrusions.

(Ruddick, 1997)

(1) Double-diffusive convection" is a form of "self-driven" turbulence that is formed by the phenomena salt fingers and diffusive convection (Turner, 1973).

Salt fingers occur spontaneously when warm, salty water overlies cooler, fresher water (see figure 15). This increased surface of the interface between the warm, salty water and cooler, fresher water offers an opportunity for enhanced heat exchange by molecular diffusion, which cools of the warm, salty surface water. Since the molecular salt diffusivity is 70 times smaller, the warm, salty water becomes denser, and therefore falls downward. The cooler fresher water becomes less dense, and rises. The net effect is a growing field of nearly vertical fingers in which vertical advection of salt by the fingers is the most important feature. The vertical motion is enabled by the lateral diffusion of heat between the fingers, but requires the density difference of the salt field to drive it (Ruddick, 1997).

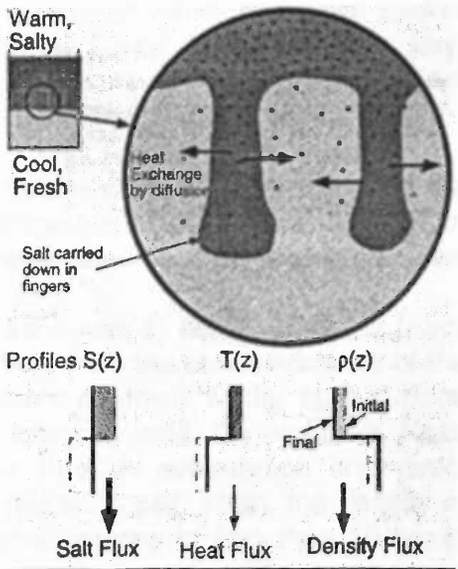

Figure 15: The mechanism of salt fingers (after: Ruddick, 1997).

When warmer saltier water underlies cool, fresh water as often occurs in subpolar waters, diffusive convection can occur, which is a different form of instability. When a small fluid parcel is perturbed downward into warmer water, it will gain heat from its surroundings and become lighter. This will make it rise in the density gradient to cooler levels, where it loses the heat, becomes heavier and falls again. The fluid parcel transfers the heat upwards, while the small molecular diffusion of salt keeps the salt flux from becoming large. The net result is upward heat and salt fluxes (positive eddy diffusivities) and a downward density flux, with a negative eddy diffusivity for density. The result of this growing oscillation can be a breakdown of smooth stratification into layers (as described in section 2) (Ruddick, 1997).

Because the double-diffusive convection is a form of "self-driven" turbulence that extracts the potential energy of the salt field (in the case of salt fingers) or the temperature field (in the case of diffusive convection), the double-diffusive fluxes might be large, especially because the formation of layers can enlarge them.

(2) After a convection layer forms and becomes warmer than the region above, molecular diffusion of heat in the region above the layer creates a gradient region with diffusive sense stratification (warm salty water underlying cooler fresher water). As the thermal boundary layer grows, the gradient region eventually becomes unstable, either to the overstable oscillations or to Rayleigh-Benard convection. The region than breaks down and forms a new convection layer, and molecular heat diffusion above this layer starts the process anew. The resulting series of layers separated by sharp interfaces is called a diffusive thermocline staircase, often found in subpolar regions of the ocean. The heat and salt fluxes across the interfaces are thought to be via molecular diffusion, whereas the fluxes are carried through the layers by convection (see figure 16). The downward salt flux by salt fingers can form layers in a similar fashion, by fluxing density into a stable stratification, and reducing the density gradient to the point of convection. The main consequence of layer formation is to increase the fluxes over the molecular value, and since thicker layers mean larger steps, then thicker layers mean larger fluxes. In a qualitative way, double-diffusion matters most where layers occur, because that is where it is dominant enough to make layers, and because the fluxes are larger with the layers (Ruddick, 1997).

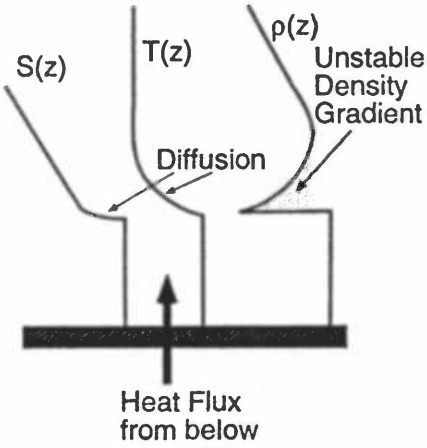

Figure 16: Formation of layers in a salt gradient by heating from below (after: Ruddick, 1997)

(3) One of the important large-scale consequences of double-diffusion is its effect on the strength of thermohaline circulation, which is driven by properties of the relative densities of the major water masses in the deep ocean, that are differentiated by their temperature and salinity (Ruddick, 1997).
Except near the poles, the upper mixed layer of the oceans with its relatively stable lower boundary (permanent thermocline) isolates the deep waters from the direct influence of the driving forces of solar radiation and winds. In polar waters relatively warm, salty surface water from lower latitudes encounters the sea ice and intensely cold, dry arctic air. Next, the warm, saline water loses heat rapidly to the air through evaporation and direct conduction, and large volumes of sea ice are formed, releasing salt. Then, the density of the surface waters will increase and sink, usually in small regions of less than 10 km in diameter. Lateral mixing with surrounding water which is relatively cold and fresh, produces large amounts of water with closely defined temperature and salinity characteristics, which than spreads out from the polar regions along the bottom of the worlds' oceans (Dobson & Hasse, 1986).

The balance between upwelling of cold deep water, and the mixing downward of warmed surface waters allows a steady state to be achieved for a surface thermocline boundary layer (see figure 17a). But thermohaline circulation can be shut down due to a negative (upgradient) density diffusivity, that is expected to hold for salt-fingers. It is dense water that upwells from the deep, and the downward density flux only tries to make this more dense, so a balance can't easily be achieved (see figure 17b) (Ruddick, 1997).

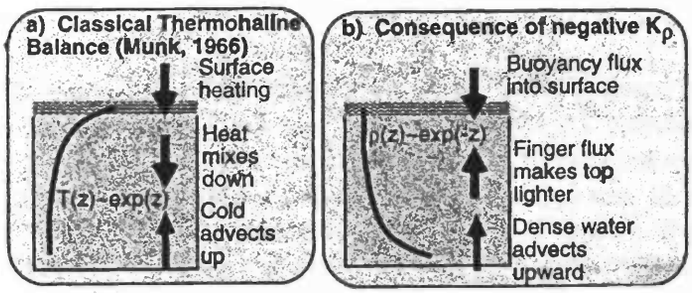

Figure 17: Effect of negative density diffusivity on the classical thermohaline balance (after: Ruddick, 1997).

(4) A very intriguing effect of double-diffusive vertical fluxes is the growth of thermohaline intrusions. These are quasi-horizontal layering motions that advect water laterally across a frontal boundary and cause lateral mixing. The layers are driven by the density changes that double-diffusive fluxes create.
Intrusions are extremely common and often are found to be the single most significant mixing agent, causing an anomaly to be lost on a time scale of a year. Furthermore, intrusions were found by their slope and density anomaly to be driven by double-diffusive vertical fluxes. Most spectacular intrusions have been found to be coherent over scales of hundreds to thousands of kilometres (Richards & Pollard, 1991; Ruddick, 1997).

In short, the unique and nonintuitive feature of double-diffusion is a downward density flux, which constitutes a negative eddy diffusivity for density. This provides the potential energy that drives the mixing and is an important part of the mechanism that creates layers. Layer formation can enhance double-diffusive fluxes, although interactions with shear, internal waves, and turbulence may change the fluxes considerably. The upgradient density flux has consequences for the larger scale. Thermohaline circulation can be shut down because the classical vertical upwelling-diffusion balance is severely upset having a negative density diffusivity. On an intermediate scale, lateral temperature-salinity gradients combine with vertical double-diffusion to form thermohaline intrusive layers, in which lateral mixing over scales up to thousands of kilometres is driven by the density changes induced by double-diffusion (Ruddick, 1997).

2.3 Light climate in a turbulent regime

Turbulent processes modulate the light environment of phytoplankton by moving them in the strong vertical gradient of near-surface light. The importance of light to primary productivity is shown by the classic P versus I curves (Parsons *et al.*, 1977). These curves show that the primary productivity P increases strongly as light intensity I increases, to a maximum that depends on the individual species. However, in the real ocean the photosynthetic response is more complicated, because the productivity P depends besides on intensity also on the time a certain intensity level is maintained.

The classic result is obtained when labcultures are grown at intensity I for a short period of time, on the order of 10 minutes. These short time scales are in the real ocean reasonable for variations associated with the largest turbulent eddies that advect phytoplankton in the near-surface mixing layer (Gargett, 1997).

However, when measured over longer exposures, these cultures exhibit photo-inhibition, where productivity falls further as the light level gets higher (Marra, 1978). These longer time scales are also relevant to light variation in the real ocean. Figure 18 shows the time-depth trajectory of a neutrally buoyant float, which is comparable with a single phytoplankton cell, superimposed on one daily plot, showing deep mixing during the night and shallow mixing during the day. The particles actually move up and down through the mixing layer with a 1- to 4-h period in one data set from the Northeast Pacific, with deep mixing at night and shallow mixing during the day. These dynamics are important in the growth and export of phytoplankton in and from surface waters (McNeil & Farmer, 1995; Gardner, 1997).

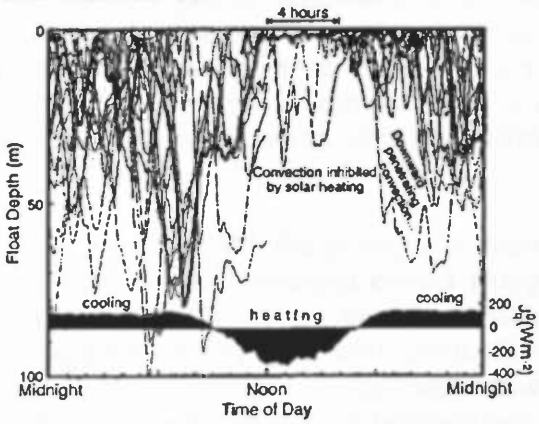

Figure 18: Time trajectory of a neutrally buoyant floatover several daily cycles superimposed on one daily plot showing deep mixing during the night and shallow mixing during the day (after: McNeil and Farmer, 1995).

2.4 Mixed-layer pump

The rates of biological processes rely on the availability of nutrients and light. The dynamics of the surface mixed layer of the ocean play a crucial role in controlling both the upward mixing of nutrients and the period of time plankton spend at different light levels. The mixed layer depth varies not only seasonally, but also on daily time-scales with solar heating, nocturnal convective cooling, wind mixing and subducting watermasses. The mixed layer depth generally decreases during the day and increases at night, depending on the net effect of environmental factors. Particles produced in a thin surface layer during the day are mixed downward as the mixed layer depth thickens at a rate faster than the settling velocity of individual phytoplankton. Particles that remain below the mixed layer depth at night can settle in a zone of greatly diminished mixing, and rapidly settling particles can escape reincorporation into the mixed layer the following night. This daily variation in the depth of mixing creates a "mixed-layer pump" that is an important mechanism of exchange between surface waters and the deep ocean (Gardner, 1997).

The mixed-layer pump moves particles downward faster than they can settle by gravity. The same process can mix nutrient-rich deep water upward and fuel primary production the following day, and it can "pump" any component up or down that has a gradient across the diurnal depth excursion of the mixed layer. Such mixing is much more rapid than diffusion (Gardner, 1997).

3 Food chain

3.1 Primary production

Primary production in the upper layers of the ocean is sensitive to fluctuations in temperature, supply rate of nutrients to the euphotic zone, variations in light intensity, and ocean circulation (Eppley & Holm-Hansen, 1986). Ocean production helps control the partitioning of carbon between the large ocean reservoir and relatively small atmospheric reservoir. Any global change in the climate system (e.g. changes associated with global warming, increases in atmospheric CO_2 and other greenhouse gases, and alteration of the general circulation of the atmosphere and the oceans) should affect global ocean production and the flux of biogenous particles to the seafloor (Eppley & Holm-Hansen, 1986; Ramanathan, 1988). Interannual and interdecadal changes in climate offer an opportunity to assess the regional expression of such an effect for areas with a detailed productivity record (Venrick *et al.*, 1987).

Coastal upwelling is the upward transport of water along the coast with the previous surface water being displaced offshore by cold, dense water from depth. Upwelling events along the Southern California Coast are characterised by a sudden decrease in sea surface temperature, a shoaling of the nutricline, and a increase in phytoplankton production (Eppley & Holm-Hansen, 1986). In contrast, periods of downwelling and northward flow (associated with an intensified Aleutian Low), show an increase in sea surface temperature, deepening of the nutricline, raised sea water level, and decreased primary production (Eppley & Holm-Hansen, 1986; Tont, 1976).

El Niño conditions are represented by anomalously warm sea surface temperature in the eastern Pacific, negative swings of the Southern oscillation, high sea level along the coast and reduced upwelling. Lange *et al.*, (1990) showed that El Niños are almost always associated with a decrease in total diatom flux (see figure 19), except in the early 50's.

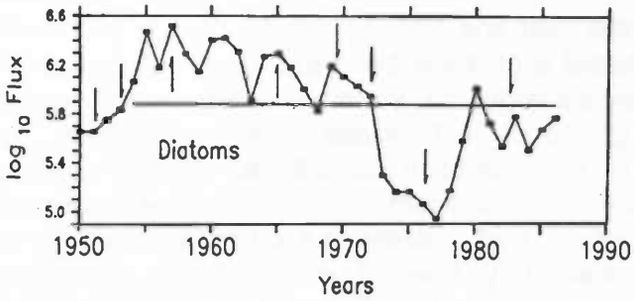

Figure 19: Diatom log transformed estimated fluxes in Santa Barbara Basin, from 1950-1986. Horizontal line indicates average flux for 1954-1986. Arrows indicate the onset of the El Niño events (after: Lange et al. 1990)

Total diatom flux values since 1973 are significantly lower than from 1954 to 1972 off the California coast. Time series (1953 to 1986) of sea surface temperature and sea level pressure show a warming tendency towards the coast, and an intensification of the Aleutian Low over the latest 14 years, providing for a weakening of the California Current and a reduction of coastal upwelling. These long-term environmental changes have affected diatom production in the coastal ecosystem off California (Lange *et al.*, 1990).

A simple conceptual summary of the interaction between physics, represented by water column stability, and biology, represented by primary production, can be illustrated as shown in figure 20. The primary production will be low in conditions of both a low and a high stability of the water column. When the upper ocean stability is weak, the vertical fluxes provide plenty of nutrients, but the production will be low because the large vertical excursions result in low average light. During conditions of very high stability of the water column, the primary production is also low due to the failure of sufficient nutrient supply.
At the intermediate stability, within the range of an "optimal stability window", both the light and nutrients will be adequate for a large primary production (Gargett, 1997b).

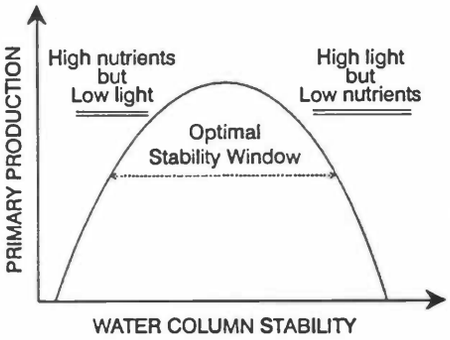

Figure 20: Schematic of an optimal "window" in water column stability (after: Gargett, 1997b).

But of course marine biology does not only consist of phytoplankton and one can move up the food chain through zooplankton to marine fish stocks such as salmon populations.

3.2 Zooplankton

Zooplankton plays an important role in the biological cycling of carbon and other elements in the ocean. Macro-zooplankton forms a significant part of the food web, may compete with larval fish for food, and is the main diet of some birds and many schooling, commercially fish species (Roemmich & McGowan, 1995).
In the California Current, the water temperature has increased between 1951 and 1993 with about 1,5 °C. Roemmich & McGowan (1995) suggest that the observed warming is linked to the zooplankton decline. As the sea surface is heated, the temperature difference across the thermocline increases. For a given along-shore wind stress, the (upwelling) displacement of the thermocline is inversely proportional to stratification. In other words, an increase in stratification results in reduced displacement of the thermocline. With less upward displacement, shallower layers bearing fewer nutrients are exposed to light, leading to less new production and ultimately to decreases in zooplankton. Depending of relative magnitudes, this effect of heating could offset or even reverse the effect of an increase in wind stress.

There is a close relationship between the average intensity of the Aleutian Low and the average production of copepods. There was a significant relationship between the intensity of the Aleutian Low and copepod production in the central North Pacific Ocean (see figure 21) (Beamish & Bouillon, 1993). The average annual production of copepods increased 1.5 times from 1976-1980 compared with the average from 1965 to 1975.
This link between the Aleutian Low Pressure System and zooplankton can be explained by a change in mixed layer depth (Polovina *et al.*, 1995). During 1977-1988, when increases in zooplankton were observed in the Gulf of Alaska, the analyses found an intensification of the Aleutian Low led to a shallower mixed layer depth

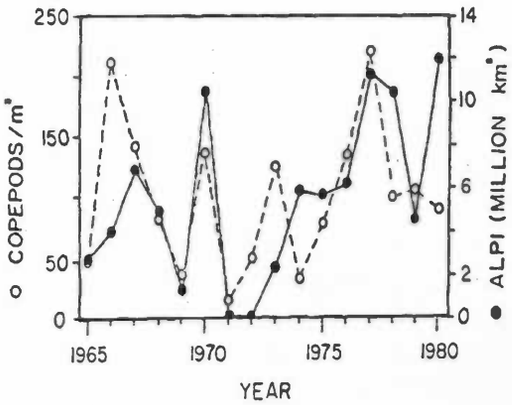

Figure 21: Relationship between copepod abundance (broken line, open circles) and the Aleutian Low Pressure Index (solid line, solid circles) (after: Beamish & Bouillon, 1993).

in the Gulf of Alaska resulting in increased plankton production. The observed changes in mixed layer depth and simulations of the plankton model by Polovina *et al.* (1995) are consistent with these observed biological changes. The shallower mixed layer depth of up to 50% during winter and spring 1977-88 are shown, based on the model simulation, to result in a 50% increase in primary and secondary production for up to 8 months. Hence, in the subarctic gyre, light appears limiting to production, and shallower mixed layer depths result in high production.
The 1977-1988 climate event in the central and North Pacific substantially altered the mixed layer depth, and the ocean ecosystem responded to this change. The results are consistent with the idea that the subarctic is light-limited while the subtropic is nutrient-limited. In between is a region balanced between the two limitations (Polovina *et al.*, 1995).

Because copepods are a principle food for many marine species, including salmon and prey of salmon, and because copepods are the dominant species in the zooplankton, the increases in salmon production during 1977-1988 are believed to be closely related with the increases in zooplankton production in the marine environment. Hence, there is a clear link between the intensification of the Aleutian Low and salmon production (Beamish & Bouillon, 1993).

3.3 Salmon

There are seven species of Pacific salmon, five occurring on both the North American and Asian continents (pink salmon (*Onchorhynchus gorbuscha*), chum salmon (*O. keta*), sockeye salmon (*O. nerka*), coho salmon (*O. kisutch*), and chinook salmon (*O. tshawytscha*)) and two (masu salmon (*O.masou*) and amago (*O. rhodurus*)) only in Asia (Groot *et al.*, 1991).

3.3.1 The life cycle of the Pacific Salmon

Pacific salmon are a unique group of fish possessing unusually complex life histories. The life cycle of the Pacific salmon begins in autumn when the adult female deposits fertilised eggs in gravel beds in rivers or lakes. The young salmon emerge from the gravel the following spring and will either migrate immediately to salt water or spend one or more years in a river or lake before migrating. Migrations in the ocean are extensive during the feeding and growing phase, covering thousands of kilometres. After one or more years the maturing adults find their way back to their home river, returning to their ancestral breeding grounds to spawn. They die after spawning, and the eggs in the gravel signify the beginning of a new cycle (Groot *et al.*, 1991).

The unique anadromous life cycle of Pacific salmon, which begins and ends in fresh water streams and involves an extensive period of feeding in the ocean pasture, makes them vulnerable to a variety of environmental changes and to overfishing in both the marine and fresh water environments. A growing body of evidence suggests that many populations of Pacific salmon are strongly influenced by marine climate variability (Beamish & Bouillon, 1993; Hare & Francis, 1995; Mantua *et al.*, 1997).

3.3.2 Salmon production

Pink, chum, sockeye, coho, and chinook salmon contribute to major commercial fisheries in the North Pacific Ocean and adjacent seas. Approximately 90% of the commercial catch taken each year by Canada, Japan, the United States and Russia is composed of pink, chum and sockeye salmon (see table 1) (Beamish & Bouillon, 1993).

Table 1: Average catch (100t) of Pacific salmon (a = 1926-1989; b= 1952-1989) (after Beamish and Bouillon, 1993).

	USA	*Japan*	*Russia*	*Canada*	***Total***
Pink	77.2	68.2	71.1	20.8	**273.3**
Chum	32.1	69.1	43.0	18.2	**162.4**
Sockeye	57.3	17.6	8.0	14.0	**96.9**
Coho	16.5	5.4	4.0	10.7	**36.6**
Chinook	14.1	0.9	1.5	6.3	**23.1**
Total	**197.5**	**161.2**	**127.6**	**70.0**	**556.3**

The catch of Pacific Salmon as shown in table 1 fluctuated throughout this century, with high catches occurring in the late 1930s and 1980s. Changes in the abundance of Pacific salmon are generally considered to be related to changes in the abundance of spawners, often referred to as escapement (fish that escape the fisheries). As a consequence, management strategies for salmon commonly attempt to maximise sustainable production by achieving optimal spawning escapements. Because a large percentage of salmon returning to spawn are caught in the fishery, the abundance of spawners is generally smaller than catch (Beamish & Bouillon, 1993).

Catch is an acceptable index of abundance because a large percentage of salmon stocks is caught in the coastal fisheries (exploitation rates typically range from 65 to 85 %). Catch may not always be a good indicator of abundance, but for larger aggregates of stocks, catch trends represent the abundance trends of the total aggregate (Beamish & Bouillon, 1993).

Combined all-nation catches of pink, chum and sockeye salmon (see figure 22) averaged 673100 t from the mid-1920s to the early 1940s, with maximum catches occurring in the late 1930s with a historic high catch of 837400 t in 1939. A period of low catch occurred from the mid-1940s until the mid-1970s, except for a small increase around the mid-1950s (average from 1944 to 1975 was 374100 t). The lowest salmon catch of 275600 t occurred in 1974. Up to 1989, production increased (Beamish & Bouillon, 1993).

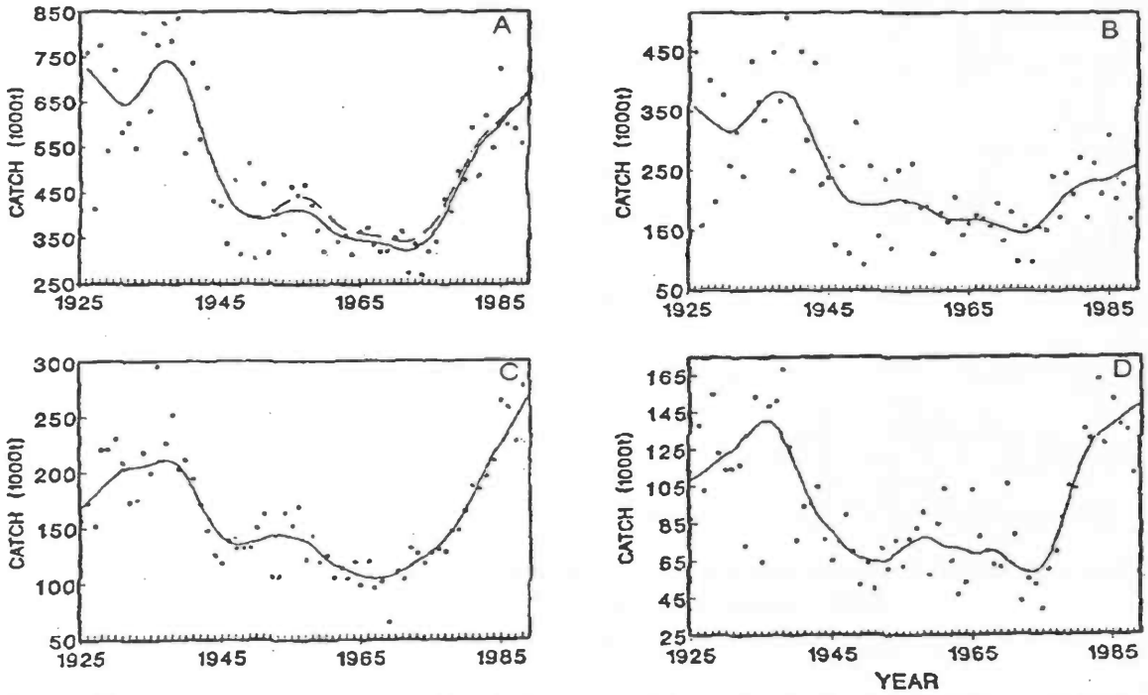

Figure 22: Trends in catches of combined all-nation catches of pink, chum and sockeye salmon (A) and all-nation catches of pink (B), chum (C) and sockeye (D) salmon (after: Beamish & Bouillon. 1993).

The patterns of the all-nation catch for each of the three species were also similar. All trends identify high catches from 1925 to the mid- to late 1930s, a decline to the mid-1970s, and then an increase to the end of the data series in 1989. The trends for chum and sockeye salmon indicate that catches in the mid- to late 1980s were equal to or exceed historic catches in the time series, whereas the trends for pink salmon indicated that the catch in the 1980s had not reached previous levels (Beamish & Bouillon, 1993).

The trends in total catches for individual species for each country (see figure 23) were similar to the general trend in catches observed for combined all-nation and combined

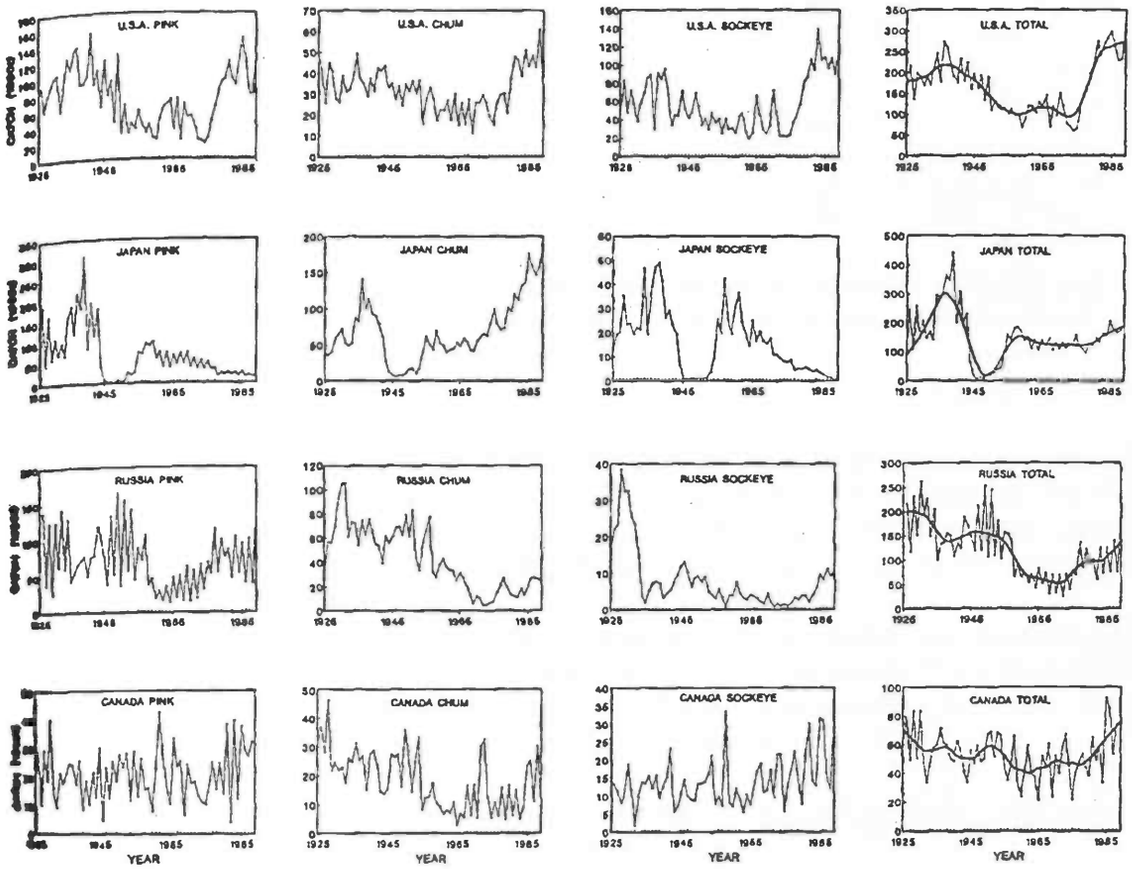

Figure 23: Catches of pink, chum and sockeye salmon and the total catch of the three species for United States, Japan, Russia and Canada (after: Beamish & Bouillon, 1993).

individual species catches, but were not as distinct (Beamish & Bouillon, 1993).

Salmon catch trends for the United States (mainly Alaska) for pink, chum and sockeye, and total all-species catch were virtually identical to the trends for all-nation, all species catches as shown in figure 22.

Total Japanese catches were high until the early 1940s but were significantly reduced during World War 2 and for several years afterward. Catches recovered by the mid-1950s and they remained relatively stable until the mid-1980s.

Russian salmon catches appear to have declined slightly during World War 2 but returned to previous levels until the mid-1950s. Average catches from 1925 to 1933 and from 1941 to 1955 were about equal. Total catches did not increase in the late 1970s and early 1980s, but increased in the late 1980s.

Canadian catches were the lowest of the four countries and catch trends were more variable. Total catches were high from 1925 to the early 1940s, were slightly lower up to the early 1950s, increased briefly to the mid 1950s, and remained relatively stable until the early 1980s (Beamish & Bouillon, 1993).

The catches in Asia and North America started to decline at the same time, but the decline was more rapid in Asia (see figure 24). Only the Asian catches showed the small increase in catch in the 1950s. The increase in catch in the late 1970s was much more abrupt in North America than in Asia (Beamish & Bouillon, 1993).

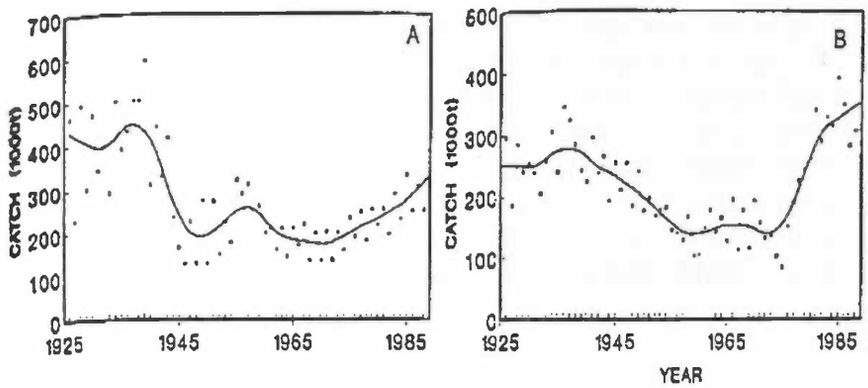

Figure 24: Trends in catches of the combined Asian (A) and North American (B) catches of pink, chum and sockeye salmon (after: Beamish & Bouillon, 1993).

Pacific salmon production has a rich history of confounding expectations. For much of the past two decades, salmon fishers in Alaska have prospered while those in the Pacific Northwest have suffered. Yet, in the 1960s and early 1970s, their fortunes were essentially reversed. Could this pattern of alternating fishery production extremes be connected to climate changes in the pacific basin?

Signatures of a recurring pattern of interdecadal climate variability are widespread and detectable in a variety of pacific basin climate and ecological systems. This climate pattern, the Pacific (inter-) decadal oscillation, is a pan-Pacific phenomenon that also includes interdecadal climate variability in the tropical Pacific (Mantua *et al.*, 1997).

A remarkable characteristic of Alaskan salmon abundance over the past half-century has been the large fluctuations at interdecadal time scales that resemble those of the Pacific (inter-) oscillation (see figure 25) (Hare & Francis, 1995; Hare, 1996).

It is believed that sockeye and pink salmon abundances are most significantly impacted by marine climate variability early in the ocean phases of their life cycles (Hare, 1996). Therefore, the key biophysical interactions are likely taking place in the nearshore marine and estuarine environments where juvenile salmon are generally found.

Recent work suggests that the marine ecological response to the Pacific (inter-) decadal oscillation-related environmental changes starts with phytoplankton and zooplankton at the base of the food chain and works it way up to top-level predators like salmon (Venrick *et al.*, 1987; Hare & Francis, 1995; Roemmich & McGowan, 1995; Hare, 1996). This "bottom-up" enhancement of overall productivity appears to be closely related to upper-ocean changes that are characteristic of the positive polarity of the Pacific (inter-) decadal oscillation. For example, some phytoplankton-zooplankton population dynamics models are sensitive to specified upper ocean mixed-layer depths and temperatures (Mantua *et al.*, 1997).

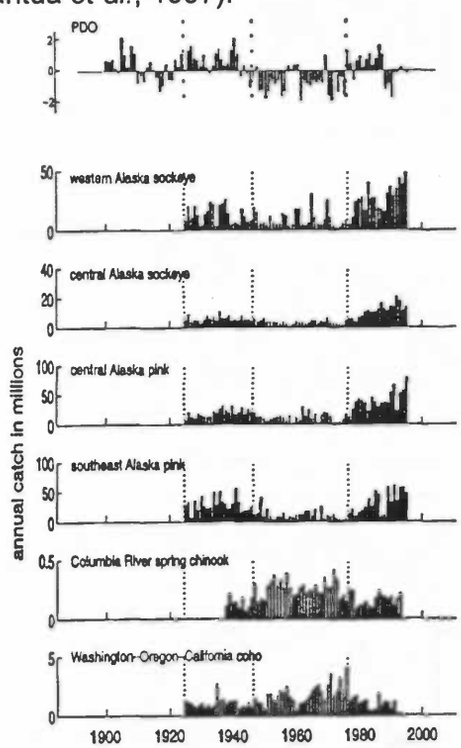

Figure 25: Selected Pacific salmon catch records with Pacific (inter) Decadal Oscillation signatures (after: Mantua et al., 1997).

As mentioned before, similar catch trends exist for the combined all-nation catches of pink, chum and sockeye salmon and the combined all-nation catches for each species. The changes in these trends occurred at almost the same time throughout the northern North Pacific Ocean. The strong similarity of the pattern of pink, chum and sockeye salmon catches indicates that common events affect the production of salmon in the North Pacific Ocean. These common events influence catch over a vast area despite high fishing effort, different fleet dynamics, different gear, and different management policies. The Aleutian Low is a large-scale climate system that affects vast areas of the northern North Pacific Ocean (Beamish & Bouillon, 1993).

3.3.3 Aleutian Low

The Aleutian Low Pressure System is the dominant meteorological feature in the winter and spring North Pacific atmosphere and has strong links to North Pacific oceanography. Changes in production of fisheries have been linked to the strength of this system (Polovina *et al.*, 1994; Beamish & Bouillon, 1993). Obvious pathways for these effects are changes in cloud cover, upper water temperature and, especially, mixed layer depth, influencing the production of plankton and therefore the whole oceanic food web (Polovina *et al.*, 1995).

Off the Pacific coast of Asia, it is known that north-south shifts in the Aleutian Low affect winter sea surface temperatures in the western North Pacific Ocean off the coast of Japan and the strength of the East Asian Winter Monsoon over Japan. A northern shift in the Aleutian Low produces warmer winters and weaker East Asian Winter Monsoons, while a southern shift in the Aleutian Low produces colder winter sea surface temperatures and stronger East Asian Winter Monsoons. This confirms that the strength and position of the Aleutian Low also affect ocean conditions along the Asian coast (Hanawa *et al.*, 1989).
This relationship between the Aleutian Low and large-scale effects on sea surface temperatures in the western North Pacific Ocean shown by Hanawa *et al.* (1989), suggests that the intensification of the Aleutian Low could effect the productivity of vast areas of the North Pacific Ocean.

The marine distribution of Pacific salmon differs among species (see figure 26) with overlapping distributions of Asian and North American stocks in the North Pacific Ocean. The climate in this region from late in the year to early in the next year is dominated by the Aleutian Low pressure system.
Hence, climate-ocean events in the central northern North Pacific Ocean can effect both Asian and North American salmon stocks and can also influence coastal regions. The overlapping distribution of salmon and the potential wide-range effects of climate and oceanographic conditions suggest that the changes in production of salmon originating from the four major salmon-producing countries might be affected by common events in the marine environment (Beamish & Bouillon, 1993).

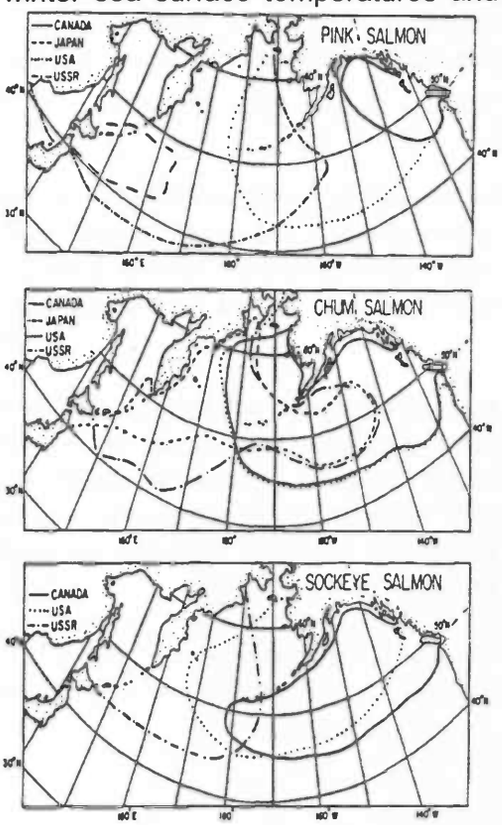

Figure 26: Known limits of ocean distribution of pink, chum and sockeye salmon, 1956-1989 (after: Beamish & Bouillon, 1993)

The pattern of the Aleutian Low Pressure Index corresponded closely to the trend in combined all-nation salmon catches (see figure 27). The declines in catches from the late 1930s to the late 1940s correspond to a sharp decline in the Aleutian Low Pressure Index. Similarly, the increase in catches beginning in the mid-1970s followed an increase in the index. There was a small fluctuation in the salmon production index in the early 1950s when the Aleutian Low Pressure Index changed, but catch trends declined again in the late 1950s. The correlation between the annual Aleutian Low Pressure Index and the annual North Pacific Ocean Salmon Production was not significant (Beamish & Bouillon, 1993).

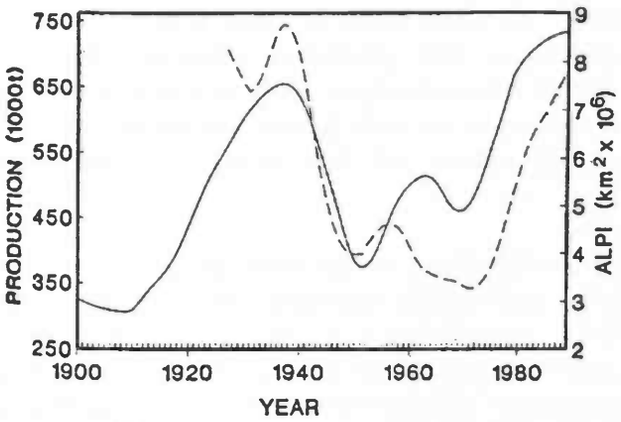

Figure 27: Comparison of the combined all-nation catch of pink, chum and sockeye salmon (broken line) and the smoothed Aleutian Low Pressure Index (solid line) (after: Beamish & Bouillon, 1993).

Climate variation can influence survival over a number of years, making it difficult to identify correlations between salmon survival and environmental variation. The low correlation between the annual Aleutian Low Pressure Index and annual salmon production, indicate that the annual relationship between all-nation salmon production and the Aleutian Low Pressure Index is highly variable either because climate-induced productivity changes occur over a number of years or there is much interannual variation not explained by the general climate index or both (Beamish & Bouillon, 1993).

3.3.4 Climate

The ocean consists of nearly 1.4 billion cubic kilometres of salty water, about 97 percent of the free water on Earth. In comparison, the atmosphere holds only about 0.001 percent. This volume of water exerts a powerful influence on Earth's climate by transporting heat, water, and other climate-relevant properties around the globe and by exchanging these properties with the atmosphere (Beamish & Bouillon, 1993).

Climate changes in the North Pacific Ocean can affect the strength of the California Current from the north and from the south as a result of El Niño events. Because fluctuations in the strength and nutrient content of the California Current affect zooplankton volume off the coast of California more than does coastal upwelling, a strong California Current that occurs when the Aleutian Low is intense could produce increases in plankton and these increases can persist for 1 to 3 years. The El Niño event of 1976-1977 could influence the productivity of fish stocks through changes in upwelling along the coast of California and by affecting the major winter climate system in the North Pacific. A major change in climate can, therefore, affect productivity of waters from California to the Bering Sea (Beamish, 1993).

It is clear that the climate change that began in 1976 was a major event all along the West Coast of North America that was associated with increases in primary and secondary production on a large scale. Associated with these changes were major changes in fish abundance. The period 1976-1978 and 1977 in particular, was a time of exceptional productivity for fishes found off the pacific coast of Canada and the United States (Beamish, 1993).

The upper ocean heat storage (or the volume of surface layer water above the thermocline) is closely related to the magnitude of primary production. The depth of the surface layer regulates productivity because ocean water below the thermocline is approximately 1000 times richer in nutrients than water above the thermocline. Climate-induced changes in heat storage affect the depth of the surface layer and are the principal mechanisms regulating primary and secondary productivity (Barber & Chavez, 1983; Venrick *et al.*, 1987). Heat loss from the surface waters and increased wind stress will increase vertical mixing, bringing nutrients into the euphotic zone. Reid (1962) proposed that horizontal divergence in the upper layer in the centre of the Alaskan gyre brings nutrients into the mixed layer, and Thomson (1981) showed that the horizontal divergence transports this water towards the edge of the gyre. Thus, large productivity changes may result from changes in the depth of the euphotic zone. Beamish and Bouillon (1993) showed that there was a close association between an index of the Aleutian Low pressure system and the all-nation production of Pacific salmon. The smoothed trend of the index they developed changes shape in 1976, indicating a change towards more intense (low pressure) lows in the winter and spring. The intensification of the Aleutian Low beginning in 1976 would increase wind stress and upwelling offshore during the winter of 1976-1977, resulting in increased nutrient supply to the surface that could be transported as nutrients, food, or both into rearing areas for young fishes (Beamish, 1993).

If climate over the North Pacific Ocean affects survival of Pacific salmon and results in long-term trends in production, there should be evidence of density-dependent growth, the increase in mean age and decrease in mean body weight. Such a carrying-capacity effect would likely be related to food availability o a large geographic scale. Ishida *et al.* (1993), have identified density-dependent growth in North Pacific salmon stocks during the period of increasing abundance.

Climate events over the tropical South Pacific Ocean are associated with sea surface temperatures in the North Pacific Ocean and the Bering Sea. Therefore, sea surface temperatures as well as sea surface pressures are linked between the South and North Pacific through the atmospheric circulation and the intensification of the Aleutian Low. This shows that salmon production trends may be associated with climate variables other than the Aleutian Low Pressure Index and with climate events in areas other than the North Pacific Ocean (Beamish & Bouillon, 1993).

3.3.5 Temperature

Temperature can affect fish production directly and indirectly, and because temperature is often used as an index of climate change, the salmon production trends are compared with sea surface temperature trends in the northern North Pacific Ocean.

As shown in figure 28, the Northern Hemisphere surface air temperature anomalies produced a trend that was similar to the Aleutian Low Pressure Index. (Beamish & Bouillon, 1993).

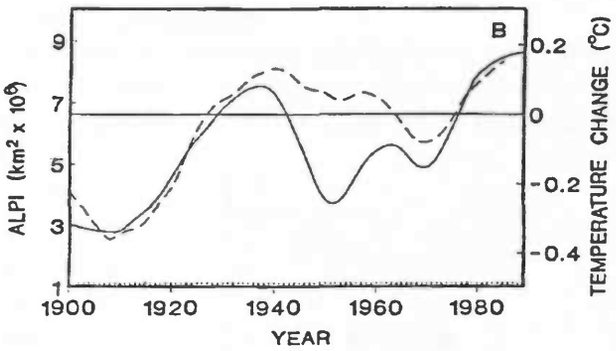

Figure 28: Northern Hemisphere mean surface temperatures (broken line), compared with the Aleutian Low Pressure Index (solid line) (after: Beamish & Bouillon, 1993)

The Strait of Georgia is the most important marine area off the West Coast of Canada and one of the most important salmon-producing areas in the North Pacific Ocean. The physical oceanography is mainly affected by runoff and nutrient-rich inflowing deep water of oceanic origin. The annual cycle of temperature change reflects the change in the volume of cool oceanic water that enters the Strait of Georgia to replace surface water transported out as a consequence of Fraser River discharge. The annual temperature cycle of bottom water was relatively uniform until 1976 (see figure 29), but from 1976 until 1980 the cycle was disrupted. After 1980, a new cycle was established; average annual bottom water temperatures were warmer and there was less annual fluctuation. The timing of the change in this annual pattern of bottom water temperature coincides with other changes in climate and oceanography, including the record discharge from the Fraser River (Beamish 1993).

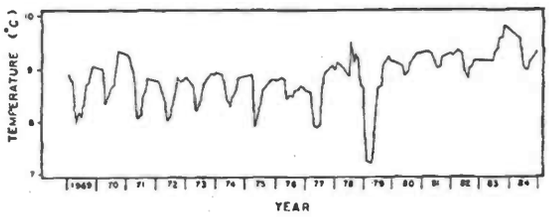

Figure 29: Bottom water temperatures in the Strait of Georgia (after: Beamish, 1993).

3.3.6 Fresh water environment

Due to the anadromous lifecycle of salmon, the increases in salmon abundance might also have resulted from improvements in productivity in the freshwater environment. But the increases in salmon survival in the late 1970s occurred at the same time as other commercially important marine fishes (e.g. pollock, herring, cod, rockfish, mackerel and anchovy) had exceptionally high survival. Therefore, the reason for this increase is believed to be the large increases in food for these fishes that occurred in the late 1970s, and not an improvement of fresh water quality (Beamish, 1993).

3.3.7 Hatchery

Artificial rearing or enhancement activities may have contributed to the increases in production starting in the mid-1970s.

Hatchery production by Japan, Russia, Alaska and Canada may have assisted in the rate of increase of abundance by providing large numbers of smolts at a time of improved marine survival (Beamish & Bouillon, 1993).

3.3.8 Link between atmopheric condition and salmon production

The answers to the questions of what mechanisms are involved between the large step between the state of the atmosphere and the well being of the salmon stock and why the northern and southern stocks vary out of phase, might be drawn by returning to the level of primary production and the idea of competing effects of water column stability on nutrient and light supplies as summarised in the "optimal stability window" in figure 30. Considering the general characteristics of subpolar and subtropical gyres, it can be assumed that phytoplankton stocks in these northern (N, subpolar) and southern (S, subtropical) gyres exist respectively at the low stability and high stability ends of the "optimal stability window". The subpolar phytoplankton populations are limited mainly by light, the subtropical stocks by nutrients (Gargett, 1997b).

If the water column stability increases everywhere in the Northern Pacific, the light level becomes higher and therefore the N populations become into a more favourable condition. The southern stocks move out of the optimal stability window into less favourable conditions, as higher stratification lowers the nutrient supply (see figure xb).

The opposite happens when water column stability decreases everywhere: the southern phytoplankton stocks will flourish, while the northern populations will struggle.

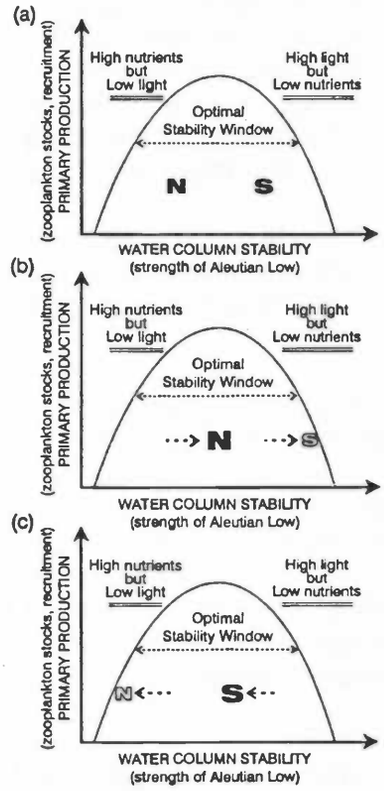

Figure 30: Optimal stability window; summary of competing effects of water column stability on nutrient and light supplies (after: Gargett, 1997).

These major oceanic effects can be directly translated into a mechanism for out-of-phase variation in northern and southern fish stocks, such as salmon, linked to the strength of the wintertime Aleutian Low. This can be assumed because it is possible to make linear connection up a simple food chain (so that more phytoplankton means more zooplankton, means more fish) and the strength of the winter/spring Aleutian Low is directly related to coastal ocean stability over the eastern North Pacific.

The atmospheric control of coastal water column stability, hence primary production, is a possible mechanism connecting salmon stocks and the strength of the Aleutian Low. Because this atmospheric forcing acts to produce in-phase variation in stability along the eastern boundary, northern and southern stocks may vary out of phase because of the existence of an "optimal stability window" (Gargett, 1997).

4 Discussion

The North Pacific Ocean has long been associated with large-scale anomalies on climatic scales in related atmospheric and oceanic patterns. Interannual variation in mixed layer depth is cited as the mechanism that enables atmospheric variation to produce biological variation in oceanic ecosystems (Venrick *et al.*, 1987; Mann, 1993; Polovina, 1995). A deep layer might increase phytoplankton production, by supplying more deep nutrients; or it might decrease it, by mixing cells into darker water. However, most studies use wind or atmospheric pressure as proxies for mixed layer depth and develop a qualitative rather than a quantitative link between interannual variation in mixed layer depth and biological production (Polovina, 1995).
Gargett (1997) has hypothesised that the most productive ecosystems occur where there is optimum stability in the water column; sufficient to maintain phytoplankton in the sunlit surface layer of the ocean but not so strong as to suppress the transport of nutrients into the euphotic zone.

Like the interannual fluctuation and trends of phytoplankton biomass and primary production (Venrick *et al.*, 1987) zooplankton is also subjected to interannual or interdecadal fluctuations, probably due to the same reasons as for phytoplankton.
For the period 1965-1981, a significant correlation has been observed between copepod abundance during the period March-May in the Gulf of Alaska and the intensity of the Aleutian Low pressure system (Beamish & Bouillon, 1993; Beamish, 1993).
This link between the Aleutian Low Pressure Index and copepods is thought to be the reason for the coherence between the Aleutian Low Pressure and salmon production since salmon feed both directly on copepods and on fish which feed on copepods (Beamish & Bouillon, 1993).

Beamish & Bouillon (1993) have argued that trends in North Pacific salmon production follow changes in the Aleutian Low Pressure Index from 1925-1989. Above average North Pacific salmon catches occurred during 1925-1945 and 1977-1989, when the Aleutian Low Pressure System was more intense than average, while below average salmon catches occurred during 1946-1976 when the Aleutian Low was weaker than average.
The changes in Northeast Pacific fish populations, including salmon stocks, have been related to the regime shift of 1976-1977 and to a reverse shift in the late 1940s (Beamish, 1993; Hare & Francis, 1995).
The dramatic increase in catch that occurred in the late 1970s suggested that the marine environment is closely linked to the increases in salmon production (Beamish & Bouillon, 1993).

At the higher trophic levels of marine ecosystems, like fish stocks such as salmon populations, there are besides physics many other factors that can influence the biology, such as predation, commercial and recreational fisheries and habitat destruction. For example, overfishing during the high-production period from 1925 to 1940 may have reduced production and resulted in the observed long period of low catches from 1945 to 1975 (Beamish & Bouillon, 1993).
However, the most convincing argument that observed trends in fish abundance are not only the result of management actions in response to overfishing is the consistent similarity among trends. It is unlikely that overfishing periods would be similar among the four main countries surrounding the North Pacific Ocean (United States of America, Canada, Japan and Russia) for all three species (pink, chum and sockeye salmon) and that at about the same time, each management agency in each country would initiate programs of rebuilding that resulted in an almost simultaneous improvement in abundance (Beamish & Bouillon, 1993).
Besides this, evidence is accumulating that also climate variability on decadal time scales is an additional and strong influence on the size of these marine fish stocks (Beamish, 1995).

The natural question arises: is salmon stock affected directly by changes in ocean conditions related to climate variability or are the effects propagated mainly through the marine food web, i.e. by affecting the food supply of the target fish species?
The answer is undoubtedly that both direct and indirect effects are important. For example, it has been documented that oceanic thermal fronts clearly limit the southern extent of some salmon species – apparently a behavioural response (Welch, 1998). On the other hand, as mentioned above, there is evidence of a correlation between zooplankton and fish population abundance, suggesting propagation of variability through the planktonic food web.

After all this it can be concluded that the trends in salmon production in the North Pacific Ocean from 1925 to 1989 were not primarily a result of fishing effort, management actions, or artificial rearing, but rather that the trends in abundance were strongly linked to the environment. The Aleutian Low pressure system is most probably associated with the changes in salmon abundance. This is suggested by the robustness of the general trend in the species pink, chum and sockeye salmon for all countries over such a vast geographical area, the continuous rather than precipitous change in abundance, and the close association of the trends in the Aleutian Low. The mechanism involved could result from increased upwelling in the ocean under the centre of the Aleutian Low (Reid, 1962; Thompson, 1981) resulting in increased productivity (Venrick *et al.*, 1987). The resulting horizontal divergence (Reid, 1962) would transport plankton and nutrients along the edge of the coast of North America.

What will the future bring?

The most recent climate shift in the Northeast Pacific Ocean, characterised by a switch from cold and wet conditions to warm and dry conditions in the Pacific Northwest of the United States, occurred in 1977. Previous studies have demonstrated that past climate shifts have had major impacts on regional marine resources (e.g. Hare & Francis, 1995; Mantua, 1997; Beamish Bouillon, 1993), among others, found this especially for the Pacific salmon.

Studies of oscillations in ocean surface water drift and tree-ring records by Ingraham *et al.* (1998) suggest that a new climate shift is imminent in the Northeast Pacific Ocean and may have a major impact on marine resources, particularly pacific salmon. The predicted climate shift, driven by large-scale changes in the Earth's atmospheric wave pattern, is expected to become evident in the in the next few years. The climate shift is expected to favour increased salmon runs in the Columbia River and decreased runs in Alaska.

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