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TECHNICAL REPORT

Workshop on Climate Change and Salmon Production

Technical Editor: Katherine Myers

VANCOUVER, CANADA, 1998

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Foreword

The Workshop on Climate Change and Salmon Production was held in Vancouver, Canada, 26-27 March 1998. The Workshop was organized and sponsored by the North Pacific Anadromous Fish Commission (NPAFC). Each Party to the Commission designated one scientist to the Workshop Steering Committee. The Chairman for the NPAFC Committee on Scientific Research and Statistics chaired the Steering Committee. Each member of the Steering Committee chaired one half-day session of the Workshop. All necessary arrangements were made by the NPAFC Secretariat in cooperation with the Steering Committee and the Canadian Party to the Commission.

Over 70 scientists, industry representatives and fisheries officials attended the Workshop. There were 20 presentations of scientific papers followed by the discussion sessions. Extended abstracts are included in this Technical Report, which also contains opening address by the Chairman of the Steering Committee and short review of the Workshop by the Coordinator. The material presented in this Technical Report has not been peer reviewed and does not necessarily reflect the views of either the NPAFC or the Parties. The material has been edited by the technical editor for clarity and publication purposes only. Items in this Report should not be cited except as personal communication and with the author's permission.

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Opening Remarks

Distinguished Ladies and Gentlemen:

I am happy to welcome you to this workshop in beautiful British Columbia, in the magnificent city of Vancouver. My gratitude goes to the government of Canada for the opportunity to meet here. On behalf of all the participants, I thank the Canadian Party for its warm hospitality and excellent organization of the workshop.

I thank members of the Steering Committee for their work. Also, I commend their sprit of mutual understanding and their desire to move closer to one another. My thanks - to the Secretariat of the North Pacific Anadromous Fish Commission, for the accuracy and responsibility in their work. I realize they may have had some difficult time, but one can only guess that. As for all of those present, we saw only the smiles of Secretariat members, and their readiness to be of assistance.

I express my deep appreciation to the Commission for its financial support, which provided an opportunity for scientists from member countries to attend this workshop. I also would like to thank Dr. Irina Shestakova, Executive Director of the Commission for all her efforts, which allowed to develop some reserve funds and turn the idea of a workshop into a reality.

Ladies and gentlemen, we were brought here because of the need to discuss a problem of paramount importance: the effect of climate on fish stocks. It may be fruitful to understand that the actual pattern of fisheries is to a great extent determined by large-scale restructuring in oceanographic conditions, entailing changes in the community of dominant species.

We have witnessed the eras of Japanese sardine, herring, and walleye pollock. These are examples that we have at hand. Each restructuring in the community of commercial fish species is a fraught with many-sided consequences. Every restructuring in communities brings about modifications in the pattern of fisheries, the outfit of vessels, and the system of catch processing. New products begin to be manufactured. The need arises to convince people to purchase these products. In other words, changes in the composition of commercial fish species communities have far-reaching socio-economic consequences. This causes lots of problems to various people, from heads of states to common fishermen. That is why it is quite important to study the effects of climatic change on fish communities.

Ultimately, as the final result of such studies, it is important to learn to forecast changes in the communities of commercial species.

This is an assembly of highly qualified experts from various countries. Most of them have contributed many years of their lives to the subject of this workshop.

I hope this workshop will be fruitful. The current situation regarding salmon stocks is becoming quite acute. Suffice it to mention that Canadian fisheries have just suffered an extremely low level of salmon catches. All of the reasons mentioned above explain the interest in our work by our governments, which imposes a special responsibility on ourselves. The holding this workshop within the framework of the North Pacific Anadromous Fish Commission indicates recognition of the reputation of this organization.
Again, may I welcome all the participants, and I declare the Workshop open.

Oleg Gritsenko
Chairman of the NPAFC Committee
on Scientific Research and Statistics,
Chairman of the Workshop Steering Committee

The Regime Concept and Recent Changes in Pacific Salmon Abundance

R. Beamish, D. Noakes, G. McFarlane and **J. King**
Department of Fisheries and Oceans, Pacific Biological Station
3190 Hammond Bay Road, Nanaimo, B.C., Canada V9R 5K6

In 1991, we reported a relationship between long-term trends in total Pacific salmon catches and the intensity of the Aleutian Low (Beamish and Bouillon 1991). A more complete version of the study was published two years later (Beamish and Bouillon 1993). Since then there have been a number of papers that have shown convincing relationships between decadal-scale climate trends and long-term trends in Pacific salmon production (i.e., Beamish 1995, Hare and Francis 1995, Mantua et al. 1997). However, others have reported that changes in salmon abundance could be explained entirely by fishing effects (Farley and Murphy 1997). The issue is not which explanation is correct, as both fishing and the environment can be important, but how fishing and long-term trends in the climate/ocean environment interact to regulate recruitment (Steele 1996).

An important component of this problem is the existence of trends in climate. If trends in climate are real, then the dynamics of aquatic ecosystems that are affected by climate will respond to these trends (Gargett 1997). We propose that there is evidence that indicates that trends in climate are real. We consider these trends or regimes to be a multi-year period of linked recruitment patterns in fish populations or a stable mean in a physical data series. A regime shift is characterized by synchronous and abrupt changes in the means of physical and biological data series.

We examined six well-known indices of Northern Hemisphere climate, the Aleutian Low Pressure Index (ALPI), the Southern Oscillation Index (SOI), the North Atlantic Oscillation Index (NAOI), the Atmospheric Circulation Index (ACI), the Length of Day (LOD), and the Northern Hemisphere Surface Temperatures (NHST). We standardized all indices (zero mean and unit variance). Intervention analysis on the standardized time series detected significant shifts in 1976-1977, which is a well-documented shift in several Pacific climate, environmental, and biological time series (Ebbesmeyer et al. 1991). The longer time series illustrated shifts in the late 1940s and mid-1920s that are consistent with dates reported by Mantua et al. (1997) and Minobe (1997). The time series can also be expressed as a cumulative sum (or CuSum), which is a form of integration that provides a visual method of studying trends (Fig. 1). We used the four pressure indices (SOI, ACI, ALPI, NAOI) to create a composite regime index (RI). This index can be shown to correspond closely to total salmon catches. The RI is also similar to the CuSum form of the Pacific Decadal Oscillation (PDO; Mantua et al. 1997). The inescapable conclusion is that climate indices in the Northern Hemisphere are closely linked and that there are synchronous shifts in the patterns (Fig. 1). We also propose that there is a common and as yet unknown factor that causes the shifts.

The ALPI remains as a reliable index of North Pacific climate trends. The changes in the CuSum of ALPI are consistent with the changes of RI and PDO. We use the ALPI as it has been associated with physical changes in the subarctic Pacific ecosystem (Gargett 1997), and, therefore, can be associated with physical and biological oceanographic processes, including salmon survival.

The ALPI changed in 1989-1990, when the Aleutian Low weakened. The trend to weak lows has now persisted for 10 years and is approaching the length of the 1977 to 1988 period of intense lows. Thus, we believe that there was a regime shift in 1989-1990, although the change was not to a pre-1977 state. In this respect, we propose that regime shifts are not cycles or oscillations but changes in states that can be multi-dimensional. Off Canada's west coast, in the Strait of Georgia, for example, the 1989-1990 change was from warm sea surface temperatures (SST) to even warmer SST, and was associated with more zonal winds in the winter, earlier spring freshettes, higher sea levels, and lower winter surface salinites.

If the associations between the intensity of the Aleutian Low and food production in the 1980s apply in the 1990s, it would be expected that a weakening of the Aleutian Low would be associated with a reduction in food production for salmon. The increasing temperatures would compound the impact on growth by increasing metabolic demands. If the hypothesis of Beamish and Mahnken (1998) that carrying capacity is determined by a late fall/winter mortality that is associated with growth rate during the summer is valid, the reduced food and
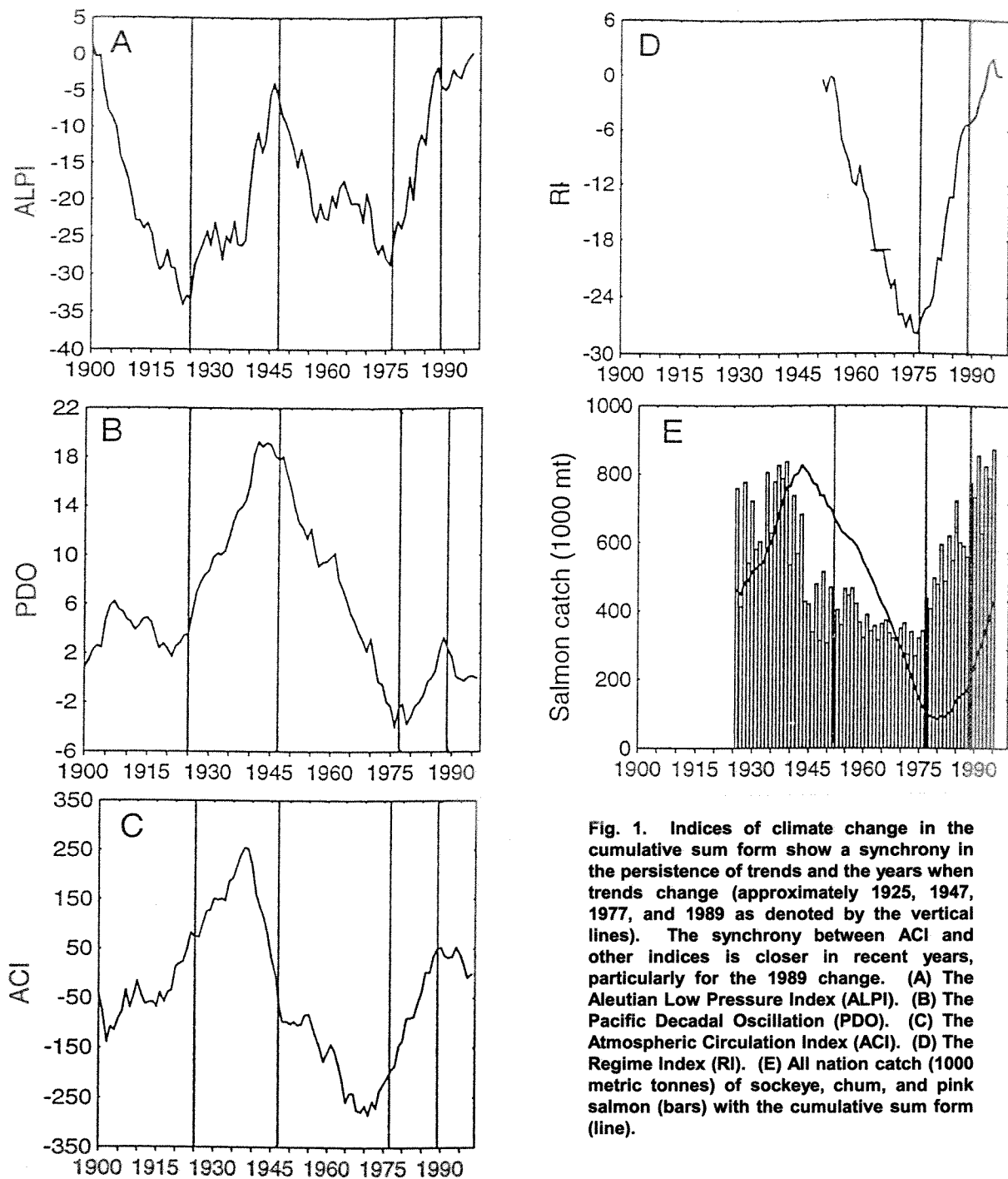
Fig. 1. Indices of climate change in the cumulative sum form show a synchrony in the persistence of trends and the years when trends change (approximately 1925, 1947, 1977, and 1989 as denoted by the vertical lines). The synchrony between ACI and other indices is closer in recent years, particularly for the 1989 change. (A) The Aleutian Low Pressure Index (ALPI). (B) The Pacific Decadal Oscillation (PDO). (C) The Atmospheric Circulation Index (ACI). (D) The Regime Index (RI). (E) All nation catch (1000 metric tonnes) of sockeye, chum, and pink salmon (bars) with the cumulative sum form (line).

increasing temperatures could increase marine mortalities in the first ocean winter. A dramatic example of the impact of the 1989 change can be seen in the synchronous decline in the marine survival of North American southern coho stocks. The return to weak Aleutian Lows in the 1990s and an even lower marine survival of coho at the southern limits of their distribution off North America, is an indication that changes in climate trends may not necessarily cause oscillations in salmon production such as proposed between northern and southern areas for chinook and coho stocks, but shifts in production among a number of possible levels.

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What Happened to Pacific Salmon in the North Pacific Ocean During the Years of an El Niño Event?

Yukimasa Ishida, Tomonori Azumaya, Soto-o Ito,
Yasuhiro Ueno, and **Kiyoshi Wakabayashi**
National Research Institute of Far Seas Fisheries
5-7-1 Orido, Shimizu, Shizuoka 424-0902, Japan

Key Words: Pacific salmon, relative abundance, survival index, El Niño

In the spring of 1997, a strong El Niño event occurred and extremely high sea surface temperatures (SSTs) were observed in the Gulf of Alaska and Bering Sea during the salmon surveys in summer in the North Pacific Ocean. In this study, (1) SST and relative abundance of Pacific salmon in 1997 were compared between the El Niño and normal years on the basis of data collected by salmon research vessels in offshore waters from 1991 to 1997, and (2) an index of survival rate of pink salmon calculated from coastal catch data in Japan, Russia, Alaska, and Canada was examined for the period 1980-1997, which had four El Niño events and one La Niña event.

Four Japanese salmon research vessels conducted gillnet and longline fishing operations in the western and central North Pacific (WNP and CNP), Bering Sea (BS), and Gulf of Alaska (GA) during the period June to August from 1991 to 1997. Four major survey areas were defined as follows: the western North Pacific (38-50°N, 154-177°E), the central North Pacific (35-48°N, 179°E-179 °W), the Bering Sea (55-59°E, 175°E-175°W), and the Gulf of Alaska (50-57°N, 144-146°W).

SSTs in the western and central North Pacific in 1997 were 1.17°C and 1.22°C significantly colder, and Bering Sea and Gulf of Alaska SSTs were 1.01°C and 1.81°C significantly warmer than the previous six-year means. Higher SSTs in the Bering Sea and Gulf of Alaska in 1997 may be due to the strong El Niño event occurring in the spring of 1997. However, different SSTs were observed in the 1991 and 1992 El Niño years. SSTs were high in the western and central North Pacific in 1991, and SSTs were low in the Bering Sea in 1992 (Fig. 1). The magnitude of the El Niño event was different between 1991-92 and 1997-98. El Niño events are a phenomena in equatorial waters. These factors may cause the differences in SSTs between 1991-92 and 1997-98.

The relative abundance (catch per unit effort, CPUE) of salmon was compared between normal years from 1993 to 1996 and the 1997 El Niño year. Sockeye salmon CPUE increased in the Bering Sea and Gulf of Alaska, but decreased in the western and central North Pacific in 1997 (Fig. 2). Chum salmon CPUE decreased in the Gulf of Alaska, but increased in the western and central North Pacific in 1997. In the Bering Sea, chum salmon CPUE in odd years is usually lower than that in even years. In 1997, chum salmon CPUE was higher than the previous odd-year means from 1993 to 1995 (Fig. 3). In 1997, pink salmon CPUE increased in the western and central North Pacific and substantially increased in the Bering Sea, but decreased in the Gulf of Alaska compared to the previous odd-year mean (Fig. 4).

Fig. 1. Mean sea surface temperatures (SST) in four major survey areas from 1991 to 1997.

For year-t class of pink salmon, four life stages, spawning (fall and winter in year t), juvenile (spring and summer in year t+1), wintering (fall and winter in year t+1), and adult period (spring and summer in year t+2), were classified as El Niño, La Niña, or normal year. However, there was no clear relation between changes in survival rates and El Niño events. However, a weak but positive correlation was observed in the index of survival rates between Russian and Alaskan pink salmon (Table 1). This suggests that Russian and Alaskan pink salmon may be affected by the same factors such as SSTs. It is necessary to examine the relations between the survival index of pink salmon and SSTs by time and space in the North Pacific Ocean. A detailed analysis will be presented elsewhere.

Fig. 2. Sockeye salmon catch per unit effort (CPUE) in four major survey areas from 1991 to 1997.
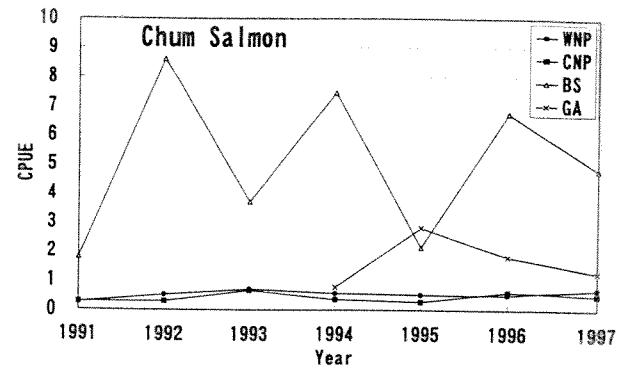
Fig. 3. Chum salmon catch per unit effort (CPUE) in four major survey areas from 1991 to 1997.
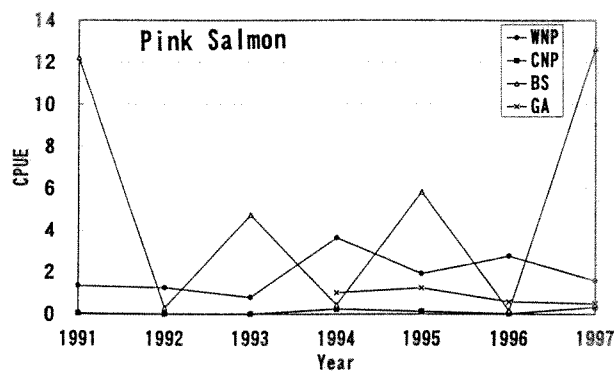
Fig. 4. Pink salmon catch per unit effort (CPUE) in four major survey areas from 1991 to 1997.

Table 1. Correlation in the survival index between stocks of pink salmon.

	Japan	Russia	Alaska	Canada
Japan		-0.147	0.229	0.060
Russia			0.302	-0.087
Alaska				0.035
Canada				

Cyclic Climate Changes and Pacific Salmon Stock Fluctuations:
A Possibility for Long-Term Forecasting

Leonid B. Klyashtorin
Russian Federal Institute of Fisheries and Oceanography, VNIRO,
Moscow 107140, Russia

Maximums of Pacific salmon production took place in the 1870s, 1930s, and 1990s with roughly 60-year periodicity. Total harvest of Pacific salmon amounted to 1 million tons (mln. t) in the 1930s, declined to 0.4 mln t. in the 1950-60s and increased again to about 1 mln. t. in the 1990s (Fig.1). The carrying capacity of the North Pacific for salmon is not constant and exhibits long-term climate-governed fluctuations (from 1.4-1.7 to 0.4-0.6 mln. t). The populations of Pacific salmon of Asian and American origin undergo long-term simultaneous oscillations. This is believed to be caused by large-scale climate changes (Fig. 2). The dynamics of the Surface Air Temperature Anomalies (dT) and Aleutan Low Pressure Index (ALPI) over the Northern Hemisphere are weakly correlated with the dynamics of the main commercial stocks because of high interannual variation. In contrast, the Atmospheric Circulation Index (ACI), characterizing regular periods (the so-called "epochs") of dominant meridional or latitudinal direction of atmospheric transport, is substantially less variable. The ACI dynamics have been observed over the N. Hemisphere for more than 100 years (since 1891). The ACI dynamics are in phase with the general trend of dT and are highly correlated (r = 0.75-0.90) with Pacific salmon stock dynamics and long-term fluctuations of Japanese sardine, Californian sardine, Alaskan pollock, and some other species (Fig. 3). Recent data on the cyclic alternation of meridional and latitudinal ACI epochs suggest that ACI can be used as a predictive index, and allows one to forecast the long-term dynamics of Pacific Salmon stocks for 5-15 years. This is also confirmed by the close correlation between ACI and an important global geophysical characteristic: the Earth Rotation Velocity Index (ERVI). ERVI has been measured continuously by astronomic methods for more than 200 years and can be used as an additional predictive index. The changes that have occurred to the Pacific salmon population during the last century can be pictured as two sequential climate-governed "waves" with the maximums in the late 1930s and in the late 1990s (Fig. 4).

Fig. 1. Total Pacific salmon catch 1920-1995.
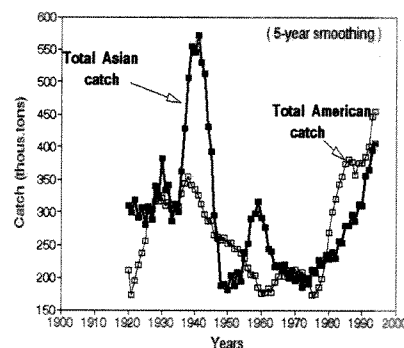
Fig. 2. Asian and American salmon catch 1920-1995.
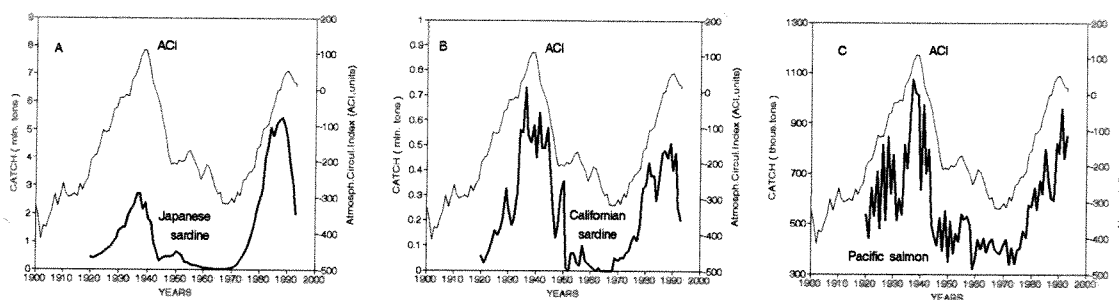
Fig. 3. Salmon and sardine catch and Atmospheric Circulation Index (ACI) dynamics for 1900-1994.
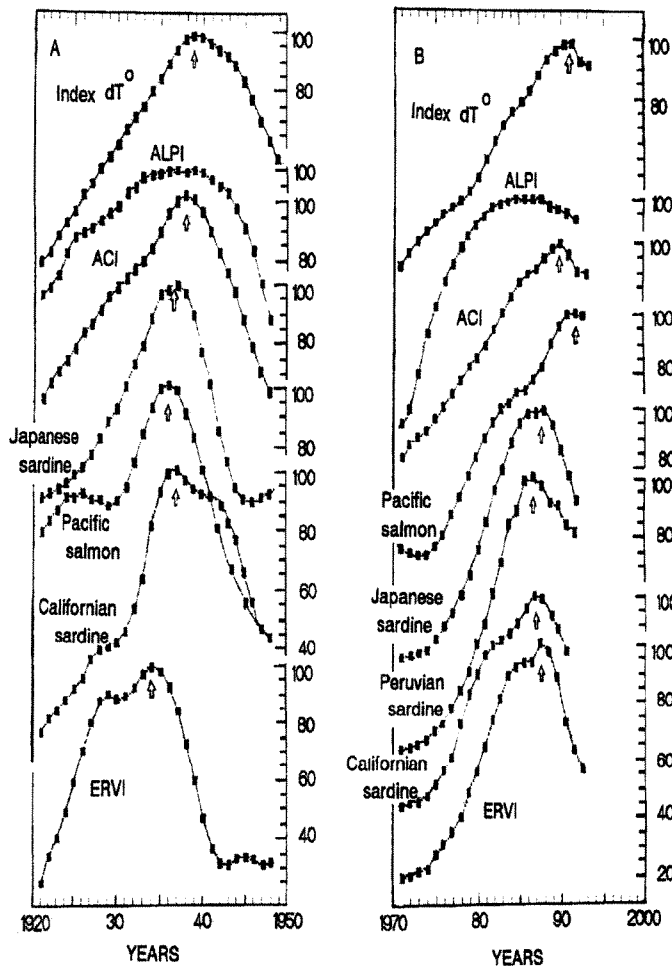
Fig. 4. The scheme of general trends of climatic indices and commercial catches in the Pacific for the periods of 1920-1950 (A) and 1970-1994 (B). All curves are presented in per-unit form relative to a specific maximum taken as 100 percent (marked by the arrows). All catches are smoothed by 5-year averaging.

dT - Annual air surface temperature anomaly (13-year smoothing); ALPI - Aleutan Low Pressure Index (13-year smoothing); ACI - Atmospheric Circulation Index (5-year smoothing); ERVI - Earth Rotation Velocity Index (5-year smoothing).

The recent "wave" is not completed and is now reaching its final phase, similar to the one in the 1940-50s. Nowadays, total Pacific salmon harvest is at its peak, but all of the above-discussed indices suggest that the Pacific salmon population will decline gradually in the near future (according to the trends in predictive indices and main pelagic stock dynamics in the N. Pacific). There is good reason to believe that future changes in climate and salmon stocks will follow the same dynamics that took place in the past climatic phase in the 1940-50s (Fig. 5 and 6).
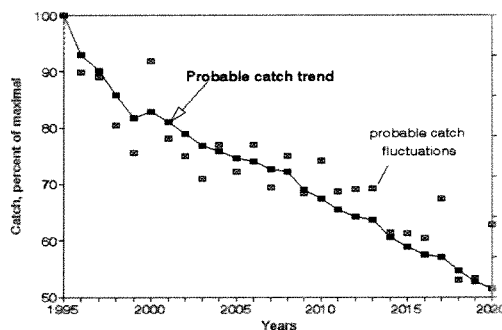
Fig. 5. Probable dynamics of American salmon catch 1995-2020 (in percent of maximum).
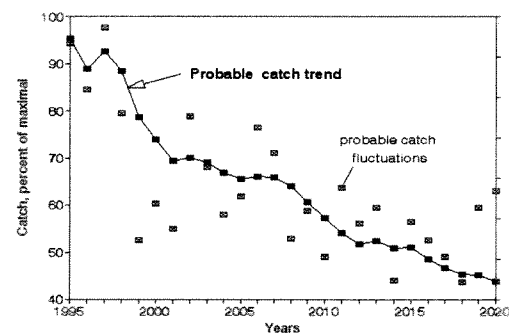
Fig. 6. Probable dynamics of sockeye salmon catch 1995-2020 (in percent of maximum).

Influence of the 1990 Ocean Climate Shift on British Columbia Steelhead (*O. mykiss*) and Coho (*O. kisutch*) Populations

D.W. Welch[1], B.R. Ward[2], B.D. Smith[3], and J.P. Eveson[1]

[1] Pacific Biological Station, Dept. of Fisheries & Oceans Nanaimo, B.C., Canada V9R 5K6

[2] British Columbia Ministry of Environment, Lands & Parks, Fisheries Research & Development Section 2204 Main Mall, University of British Columbia, Vancouver, B.C., Canada V6T 1Z4

[3] Environment Canada, Pacific Wildlife Research Centre 5421 Robertson Road, Delta, B.C., Canada V4K 3N2

British Columbia steelhead trout (*Oncorhynchus mykiss*) populations showed coherent patterns of adult recruitment until the 1990s, when recruitment patterns diverged between northern and southern British Columbia rivers. From 1963 until 1990 the pattern of temporal change in adult steelhead recruitment was similar for rivers in all regions of British Columbia (Fig. 1).

A major increase in steelhead recruitment occurred in all regions of the province following the 1977 regime shift. Subsequently, an out of phase response occurred after 1990, indicating that the effect of the 1990 regime shift had both temporal and geographical structure. Steelhead entering the ocean from rivers located in northern regions of the province had increasing recruitment after 1990, while steelhead entering southern B.C. coastal regions have had sharply decreasing recruitment (Fig. 2).

Fig. 1. Changes in normalized angler catch rates for wild adult steelhead caught in freshwater, 1967-96. The normalized abundance indices are grouped into four regions of the coast, with rivers with major steelhead populations shown separately, and rivers with minor populations aggregated. Following 1977 (vertical line) adult steelhead recruitment to all areas of the B.C. coast increased sharply. A period of high recruitment in the early 1980s is evident in all regions, as well as a smaller increase in the late 1960s. Steelhead recruitment increased again after 1990 for all rivers in northern B.C., while south and central coast populations show sharp declines; outer coast stocks show an intermediate response. Marine survival for the Keogh R. population is superimposed on each graph and shows the same pattern of increase in the early 1980s. The decline after 1990 is mirrored in the steelhead returns to essentially all rivers on either side of the Strait of Georgia and the central coast. The pattern of returns for North Coast stocks is quite different.

Fig. 2. Summary graph of the changes in B.C. steelhead by region. The pattern of change in Keogh River marine survival is superimposed, and matches the average recruitment response for all rivers in the south coast region.

In both the Keogh River steelhead population (located in southern B.C.; Fig. 3) and coho salmon (*O. kisutch*) in Oregon (Fig. 4), the evidence clearly indicates that the overall recruitment response since 1977 was primarily shaped by changes in marine (not freshwater) survival. These changes appear to occur both suddenly and show considerable persistence. A possible reason for the change is that ocean productivity declined in southern B.C. after 1990, reducing the marine growth of juvenile salmon.

Keogh R Steelhead Study

Oregon Coho & B.C. (Keogh) Steelhead

Fig. 3. Changes in marine survival of Keogh River (northern Vancouver Island) steelhead trout relative to year of ocean entry. From 1977-89 marine survival average 15.5% and deviations from this average were closely correlated with size of smolts at ocean entry; predicted deviations from mean survival prior to 1990 were positively correlated with size at ocean entry. Marine survival in 1990 and later years dropped to only one-fourth of its former average, and was no longer related to size at ocean entry. A broad scale pattern of change in marine survival is also evident, with survival increasing to a maximum in the early 1980s and then declining; however, the sudden decline in 1990 is the dominant feature of the time series.

Fig. 4. Comparison of the changes in marine survival for Oregon coho salmon (bars) and Keogh River steelhead (line). The horizontal lines show the average marine survival for Oregon coho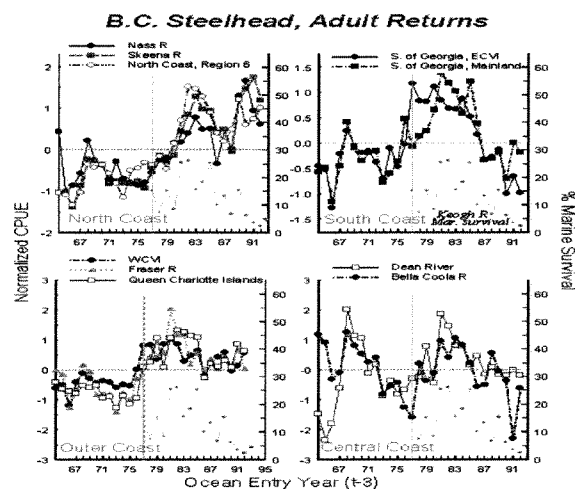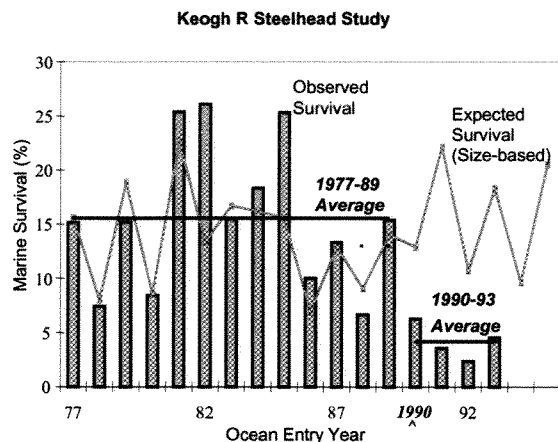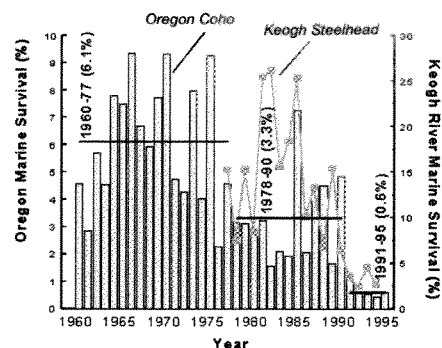 salmon for the three regime periods 1960-77, 1978-1990, and 1991-95. Note that the year defining the last period is one year later than the time of the sharp decline in Keogh River steelhead.

Atmospheric winds show large scale patterns of geographic and temporal coherence. We examined the patterns of coherence in the upwelling favourable winds along the west coast of North America at 15 standard locations (Fig. 5) calculated by the NOAA Pacific Fisheries Environmental Group (*http://www. pfeg.noaa.gov/products/upwell.html*). The Bakun upwelling indices are based on estimates of offshore Ekman transport driven by geostrophic wind stress, and averaged to monthly values. They are expressed in units of cubic meters of upwelling per second per 100 meters of coastline. Monthly values of the Bakun winds were analyzed for the period January 1946 to March 1997. We

Standard Positions of Upwelling Index Calculations

Fig. 5. Location of the standard positions for the Bakun wind indices used in the analysis.

conducted a hierarchical cluster analysis on the correlation matrix to examine the groups into which the months or regions clustered, in order to reduce the dimensionality of the dataset.

We first averaged the data over all 15 regions in order to obtain a single set of 12 monthly values for the upwelling indices in each year, and then performed a cluster analysis on the monthly time series to identify seasons of similarly varying winds for the whole coast. We then aggregated the monthly indices indicated by these clusters into three seasonal indices: winter (October-February), spring (March-June), and summer (July-September). We then separately compared the geographic clusters for each of the three seasons that resulted in order to identify regions of geographic coherence in the pattern of upwelling-favourable winds.

The clearest spatial clustering is for summer (Fig. 6), the period of strongest upwelling and also the season when juvenile salmon enter the ocean from the rivers. The results from the cluster analysis indicate that the summer winds fall into a series of internally coherent geographic regions. Stations in the northern Gulf of Alaska positively co-vary (A-E) and clearly cluster separately from Stations F-O lying to the south.

Fig. 6. Hierarchical cluster analysis of the pattern of geographic covariation in the Bakun winds.

Fig. 7. Pattern of temporal change in the Bakun winds for the 6 northern-most stations along the west coast of North America. The times of the 1977 and 1990 regime shifts are indicated, and show only weak evidence for a change in upwelling favourable winds at this time.

Stations E and F are located near the northern and southern ends of Vancouver Island, respectively, and are near the coastal region that showed the sudden change in ocean survival after 1990. They fit into different clusters, indicating that the patterns of coherence in the Bakun winds are different between these regions. There is some indication for an intensification in upwelling favourable summer winds for Station F after 1977, but not for the regions to the north where most of the improvement in salmon survival actually occurred (Fig. 7). Following 1990 there is a weakening in the Bakun index for Station F and a somewhat reduced pattern of coherence of the pattern of change in the winds between Station F to the south and the wind patterns in Stations A-E farther to the north.

If the geographic pattern of wind flows changed after 1990 so that the coastal region indexed by Stations E or F now more strongly followed the wind pattern for regions to the south where steelhead survival decreased after 1977, this could explain the sudden change in the geographic pattern of survivals in southern British Columbia (Fig. 7). However, there is little convincing evidence for this change in the winds. Thus although there was a marked intensification of the Aleutian Low following 1977, the Bakun index shows little evidence of an influence on the degree of coastal upwelling.

Although the reasons for the sudden decline in ocean survival of coho salmon and steelhead are unclear, there is very good evidence that sudden climatic changes in the ocean have had a major impact on their productivity. A major effort is needed to try and establish why large regions of the ocean suddenly change and cause improved or decreased ocean survival at particular times.

Inter-Annual Dynamics of Pink Salmon Abundance in the Sea of Okhotsk Populations in the 1990s

V.I. Radchenko
Pacific Scientific Research Fisheries Center (TINRO-Center),
Vladivostok, 690600, Russia

❧ ⬥❈❈⬥❈❈❈❧ ❧

In the 1990s, large-scale changes (now called "regime shifts") took place in the pelagic ecosystems of the far-eastern seas. At this time, some relations between global physical factors and salmon stocks have been analyzed and considered. This led to general conclusions that salmon production must also change in the near future. Since salmon abundance was relatively high in the late 1980s, a forthcoming decrease has been predicted (Beamish and Bouillon 1993; Chigirinsky 1993). However, in the 1990s, pink salmon catches were as high in the Russian Far East as in Alaska. This fact attracts special attention to the issue of inter-annual dynamics of Asian pink salmon abundance.

To better understand my paper, I define some of the terms used below. Young pink entering the sea are called "outmigrants." Pink salmon in their first fall and winter are called "juveniles." I also define "immature" pink salmon as those fish that occur in the Pacific before the start of their anadromous (adult) migrations. "Maturing" fish are those in their last summer of ocean migrations, "mature" salmon are those approaching the coast and coastal fisheries, and "spawners" are adult fish on the spawning grounds.

In the 1990s, data were collected from the Sea of Okhotsk populations on all basic stages of pink salmon life history. In 22 research vessel cruises, data to estimate juvenile and maturing pink salmon abundance were collected. Surveys were conducted by pelagic trawl (108/528 m). The horizontal diameter of the trawl mouth was about 50-55 m, and the vertical opening was 45-50 m. The highest tow speed (4.5-5.0 knots) was maintained. Wire length, which reflects distance from the trawl to vessel, was 350-400 m. The upper trawl panel was kept on the sea surface.

Salmon biomass and numbers were calculated by the square method (Shuntov et al. 1988). The formula for this method is as follows: $B(orN) = \dfrac{Sq}{sk}$; where B - fish biomass, N – numbers, S - investigated area, q - average catch on survey area, s - the area swept during a 1-hour haul, k - factor of trawl catchability. The factor k takes into account the body size, form, and motility of fish, and their propensity to schooling. On the basis of long-term experience, the factor k value for salmon is 0.3. The data on spawners and outmigrants numbers were provided by Drs. A. Kaev (Sakhalin NIRO) and S. Sinyakov (Kamchatka NIRO). Harvest data are based on fisheries statistics.

In 1992-1993, some disturbances were observed in the stock dynamics of all regional groupings of pink salmon. On the eastern Sakhalin coast, there was an unexpectedly low pink salmon catch in 1993. In the Kuriles region, the catch level became almost stable in 1994-1997, after the catch decrease in 1993. However, there was a slight predominance of the even-year race. Among secondary pink salmon stocks, the northern Okhotsk Sea coast population estimates of mature pink salmon and harvest in 1992 and 1993 increased sharply. There was a noticeable increase in the western Kamchatka pink salmon stocks in 1994 and 1996. Estimates of mature fish increased to 130-140 million fish. The enhanced Hokkaido pink salmon population acquired a two-year cyclisity in that time, despite the almost equal numbers of smolts that were released annually (Table 1). The total estimate of mature Okhotsk Sea pink salmon in even years increased sharply in 1994 (215 million fish), and the even-year runs were higher than odd-year runs.

The predominance of the even-year race of pink salmon since 1994 was evident from the early 1990s, as can be seen in the higher estimates for outmigrants of these generations (Table 1). After 1992, this predominance was set at a level of 1 to 2.4 billion fish.

Another unexpected circumstance was the sharp increase in the estimated numbers of pink juveniles in the offshore waters of the Okhotsk Sea and North Pacific Ocean since 1993, which were approximately three times higher than 1991-1992 estimates. Before 1993, natural mortality of pink outmigrants before late fall appeared rather high (92.8-94.1%). After 1993, survival rates were stable for two even years (30.5-30.7%) and for two

Table 1. Total estimate of pink salmon abundance (millions of fish) of the Okhotsk Sea populations at various life history stages in 1990s.

| Year | Spawners | Outmigrants, Russian coast: | Release by Japan | Total Outmigrants | Pelagic estimates | | Mature to Russian coast | Mature to Japan coast | Total Mature | Russian Catch, (tons ×10³) |
					Juveniles fall	Maturing summer				
1990	42.1	3364	130	3494	450	n/a	78.1	5.5	83.6	50.4
1991	51.2	4119	136	4255	250	277.0	154.6	12.4	167.0	129.3
1992	25.7	3764	132	3896	279	103.7	70.9	15.6	86.5	67.8
1993	57.0	4938	138	5076	882	107.0	91.4	17.1	108.5	48.8
1994	109.8	2488	140	2628	807	271.0	195.4	19.6	215.0	103.6
1995	34.7	4855	140	4995	834	230.0	96.4	9.6	106.0	89.5
1996	81.6	3157	118	3275	1000	210.0	148.0	19.1	167.1	88.0
1997	38.9	4115	138	4253	n/a	n/a	165.8	6.1	171.9	102.3

odd years (16.7-17.4%). According, pink survival in ocean gradually declined during the 1990s. Estimates of maturing pink salmon varied from those of juveniles by 61.6% in 1991 to 25.2% in 1996. Catch and escapement varied from the previous fall pelagic estimates by 38.9% in 1993 to 13.7-14.1% (with the lowest value in 1995).

Two pairs of time-series estimates of pink numbers display high correlation with one another (R > 0.7), the results of fall and summer surveys and also the results of summer surveys and estimates of total mature pink salmon. The high correlation between fall and summer surveys demonstrates the gradual increase in natural mortality rate during the ocean phase. These results suggest that this increase is determined by some large-scale factor or process developing from year to year, which may be related to changes in the North Pacific pelagic ecosystems. It can be noted that numbers of spawners are not correlated with any other time series. Furthermore, the correlation coefficients gradually decrease from outmigrant numbers to estimates of mature pink salmon.

Growth rate of pink salmon was described by a logarithmic relationship between pink salmon body weight and dates of year for eight months after sea entrance (Fig. 1A). In summer, growth rate is noticeably higher than in fall and winter. Therefore, in Fig. 1B a shorter period for inter-annual comparisons of juvenile pink salmon growth is used. In this case, growth in weight can be approximated by linear regression: y = 2.3177x + 164.09. The mean pink salmon body weight for January 1 was calculated as follows: y = 2.3177*15 + 164.09 = 198.9 g (15 is number of 5-day periods in the time interval).

The calculations indicate that the weight of pink juveniles in even years changed from 164.7 to 186.2 g by January 1 (after 1992). This emphasizes the close relation between mean body weight and outmigrant numbers. The smallest juveniles occurred after the most abundant downstream migration in 1993 (4.94 billion fish). The biggest juveniles – 226.9 g, or at 28 g above average, were caught after the lowest number of outmigrants in 1994. Maturing pink salmon were also largest in 1995; mean weight in coastal catches was 1.45 kg for the Okhotsk Sea coast stocks. On the whole, pink salmon generations spawned in 1994-1997 demonstrated a good correlation between initial body weight of juveniles and final body weight of mature fish. In contrast, in 1991-1992 the body weight of spawners was more likely related to numbers of maturing and mature pink
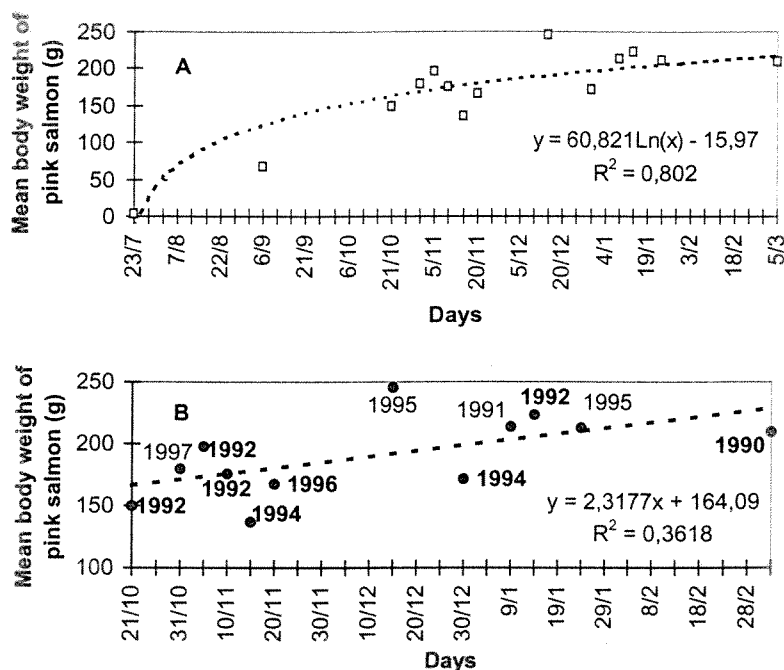
Fig. 1. Mean body weight (g) of pink salmon juveniles during oceanward migration through the southern Okhotsk Sea in the 1990s. (A) Approximated from late June; (B) Approximated from late October to early March.

salmon. According to coastal fishery statistics, mean body weight was 1.25 kg in 1991, which was a high-yield year and 1.50 kg in 1992, a low-yield year, despite the almost equal body weight of juveniles in both years.

Significant fluctuations in pink salmon numbers and body weight in the 1990s suggest that processes of large-scale changes are not finished in Okhotsk Sea pink salmon populations. There is some evidence that the environmental conditions for pink salmon feeding routes in the ocean may be less favorable in the 1990s than in 1980s (Beamish and Bouillon 1993). Secondly, salmon juveniles have become the ordinary prey for common predatory species of fish and mammals because of their high abundance.

Change in the mean weight of pink salmon is mainly related to their population density during the ocean phase. Asian pink salmon are usually larger in years of low numbers of mature fish than in adjacent years

(Shuntov 1994). However, in the 1990s no relation was found between body weight of juveniles and their survival in ocean. From the time of sea entrance to late fall, survival was higher for smaller and more abundant outmigrants in 1993 and 1995.

For analysis of environmental change and its influence on salmon stocks, it is important to determine what large-scale changes in climate and hydrological regimes of the Okhotsk Sea and North Pacific Ocean took place in 1991-1993. At that time, the most significant changes were observed in salmon abundance dynamics, survival, and body weight.

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Changes in Abundance of Far East Pink Salmon (*Oncorhynchus gorbusha*) Stocks in the Context of Climatic Variability in the North Pacific Region

A.S. Krovnin
Russian Federal Research Institute of Fishery and Oceanography (VNIRO)
17 V.Krasnoselskaya, Moscow 107140, Russia

Spatial and temporal features of climatic variations in the North Pacific region over the last 40 years were analyzed. Data on mean winter (January-April) sea surface temperatures (SST) in the North Pacific (20-55°N), mean winter (December-February) sea level pressure in the North Pacific area (20-70°N, 100°E-90°W), and geopotential heights on the 700-hPa surface in the Northern hemisphere were used. Data on SST and sea level pressure are available from the Russian Hydrometeorological Center (Moscow), and those on geopotential heights are available from the U.S. National Center for Atmospheric Research. To characterize the changes in the Far East pink salmon production data on catches for West and East Kamchatka, and the South Kuril Islands areas were used. Five large-scale subdomains with coherent SST anomaly fluctuations were defined, using a Ward's hierarchical clustering method. They are the eastern part (Region 1), the central part (Region 2), the northwestern part including the most of the Sea of Okhotsk and waters east off Kamchatka (Region 3), the southwestern part (Region 4), and the southern part (Region 5) of the North Pacific Ocean. Results of correlation analysis show that the spatial structure of SST anomaly variations in the North Pacific is characterized by two almost independent patterns: changes in the SST anomalies in the eastern and central North Pacific, as well as in its northwestern and southwestern parts, are out-of-phase. These two patterns are significantly correlated with well-known atmospheric teleconnection patterns: the Pacific/North American and Western Pacific patterns, respectively). In each subdomain defined, there are clear decadal variations in SST anomalies. The most prominent shifts from one climatic regime to another occurred in early 1960s, 1976-1977, and around 1987, when the clear tendency toward warming appeared in all regions. It is very possible that another shift occurred in the mid-1990s, but available data do not allow us to confirm this with certainty. The changes in SST anomaly patterns strongly correspond to changes in the character of atmospheric circulation that occurred during shifts from one climatic regime to another. For example, weakening of Aleutian Low since 1988-1989 was accompanied by the apparent surface warming in the central North Pacific and cooling in the Gulf of Alaska and the area of Aleutian Islands.

Beginning in 1996, the signs of cooling during the winter period appeared in the southern part of Region 2, where the drop in SST anomalies exceeded 0.6°C compared with the period of 1989-1995. Possibly this indicates the start of the next decadal change in the North Pacific climate system. Partly, this is confirmed by the 1997 El Niño event, because all previous shifts occurred during the period of or just after the warm events in the tropical Pacific. All four Far East pink salmon stocks also exhibit clear decadal variations both in odd and even years. Catches of eastern and western Kamchatka pink salmon declined until about 1977. After this time, their constant increase is observed. For South Kurils and Southeast Sakhalin the situation is somewhat different. There, the constant increase in catches started in the early 1970s. The comparison of variations in SST anomalies in Regions 1, 2, and 3, and in East and West Kamchatka pink salmon catches shows their strong relationship. The best relationship was found for Region 1, which includes the area of Aleutian Islands, where these stocks spend the winter (Fig.1a,b). A weaker relationship was obtained for Region 3, where fish stay during their early marine period of life. This indicates that favorable winter conditions are more important for survival and subsequent formation of the level of East and West Kamchatka pink salmon stocks than environmental conditions during their early marine period of life. For Southeast Sakhalin and South Kuril Islands pink salmon stocks, the strongest relationship was obtained for Region 3 (Fig.1c), and a weaker relationship was obtained for Region 1. This may confirm the hypothesis that for these two stocks favorable environmental conditions during their early marine period of life, when fish start to feed, are more important than those in the area where they spend their first winter, as compared to East and West Kamchatka pink salmon. Fish migrating to the wintering area located near the Aleutian Islands are stronger and larger in size. Thus, they may survive more unfavorable winter conditions. Further research on this problem with oceanic circulation, primary production, food base, and other data is needed.
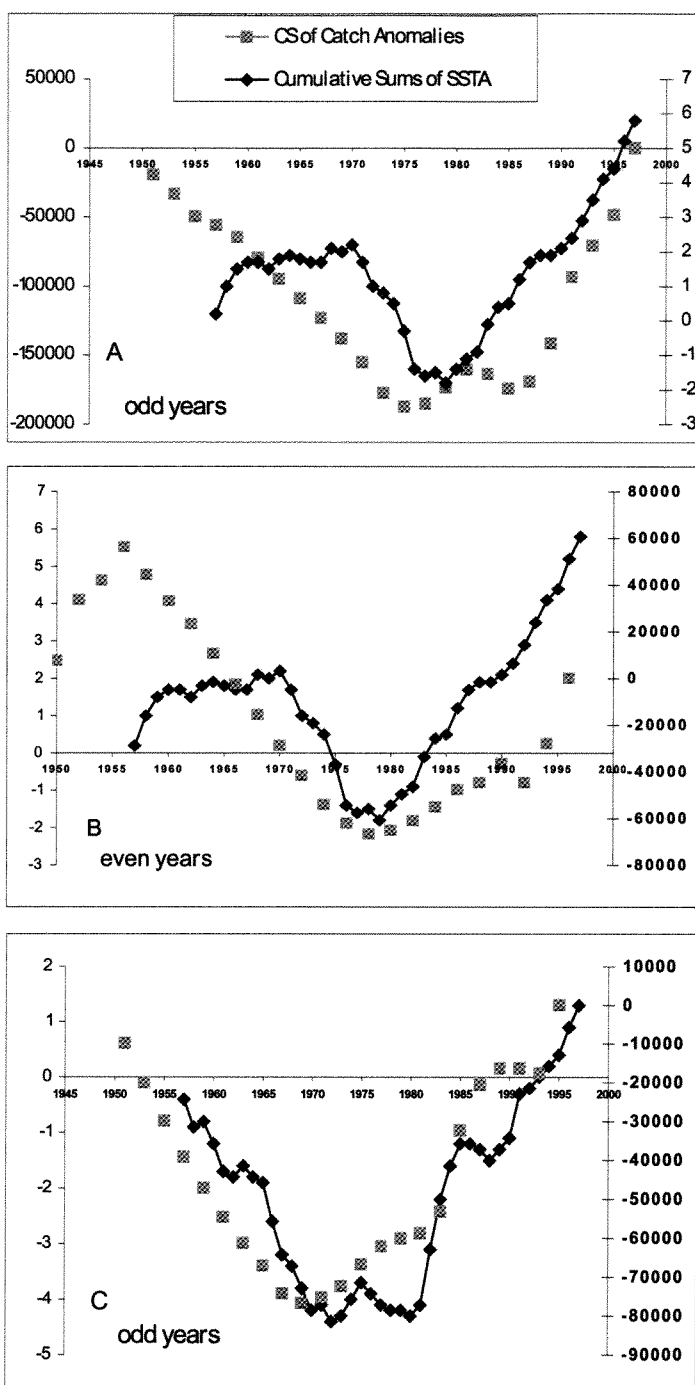
Fig. 1 Cumulative sums of sea surface temperature anomalies (SSTA) and pink salmon catches in eastern Kamchatka (A), western Kamchatka (B), and south Kurile Islands (C) areas. SSTA are in Region 1 (eastern North Pacific) for A and B and Region 3 (northwestern North Pacific) for C.

Long-Term and Spatial Correlations Between Survival Rates of Pink Salmon *(Oncorhynchus gorbuscha)* and Sea Surface Temperatures in the North Pacific Ocean

Tomonori Azumaya, Yukimasa Ishida,
Yasuhiro Ueno, and **Kiyoshi Wakabayashi**
National Research Institute of Far Seas Fisheries
5-7-1 Orido, Shimizu, Shizuoka 424-0902, Japan

Key Words: SST(sea surface temperature), pink salmon, survival index

Pink salmon*(Oncorhynchus gorbuscha)* are the most abundant salmon species in the North Pacific Ocean (Fig. 1). Year-to-year changes in abundance of pink salmon showed a similar trend in both odd- (solid line) and even-year (broken line) classes. Abundance began to increase in 1976, although it remained at low levels in the early 1960s to mid 1970s. Pink salmon abundance is controlled by spawner abundance and environmental factors. However, little is known about what, when, and where environmental factors affect pink salmon in the North Pacific Ocean.
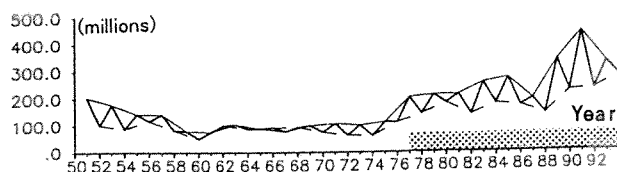

Fig. 1. Interannual change in abundance of pink salmon (*Oncorhynchus gorbuscha*) in North Paific Ocean. Solid line shows odd-year class and broken line shows even-year class.

Figure 2 shows the time series of the survival rate of pink salmon in the North Pacific. Changes in the survival rate were different between Russian (bold line) and Alaskan (thin line) pink salmon. Figures 3(a) and (b) show the spatial correlations between survival rates of Russian and Alaskan pink salmon and sea surface temperature in August in North Pacific Ocean. Relatively high positive correlation coefficients were found between survival rates of Russian pink salmon and the SST in the Sea of Okhotsk and the waters off the East Kamchatka in August. On the other hand, the survival rates of pink salmon from Alaska were related to SSTs in the waters along the west coast of North America in August. These seasons correspond to the period when mortality rate is the highest in the ocean life of pink salmon. This suggests that the survival rates of pink salmon are affected by SST changes at a local level.

As an index of survival rate of year-t class, the ratio of catch in year t+2 to year t was calculated for Russian and Alaskan pink salmon. This index of survival rate includes both freshwater and ocean mortality, including fishing mortality. Correlations between survival rates of pink salmon and sea surface temperature (SSTs) were investigated by monthly and $2° \times 2°$ area using data from 1977 to 1993. Pink salmon run sizes in Russia and Alaska, estimated by Rogers (1995), and the monthly mean gridded SST data set (GLBSST) in the North Pacific, provided by the Japan Meteorological Agency, were used in this study.
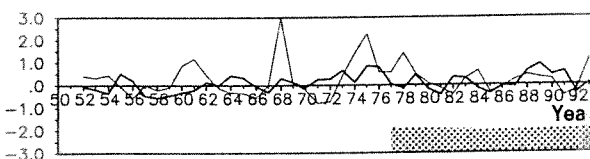
Fig. 2. Time series of the survival rate of Russian (bold line) and Alaskan (thin line) pink salmon.
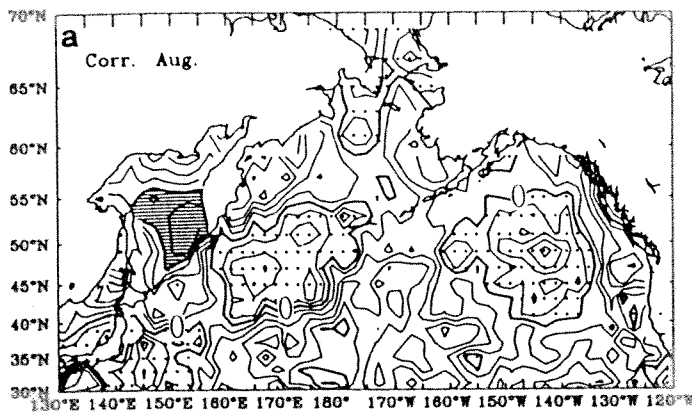
Fig. 3(a). Spatial distribution of correlation coefficients between the survival rate of Russian pink salmon and sea surface temperature in August. Hatch indicates the area of correlation coefficients more than 0.5. Dots indicate the area of negative correlation coefficients.
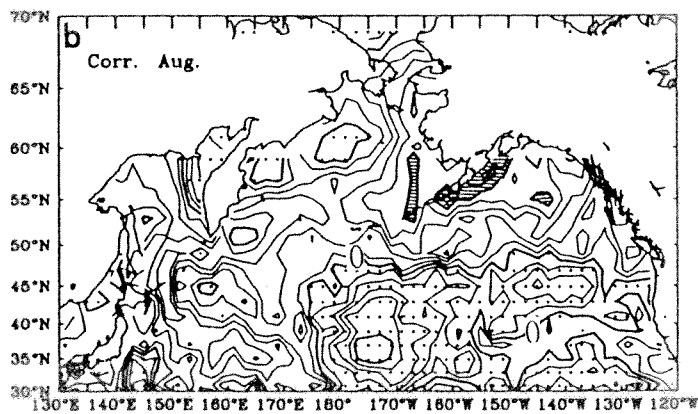
Fig. 3(b). Spatial distribution of correlation coefficients between the survival rate of Alaskan pink salmon and sea surface temperature in August. Hatch indicates the area of correlation coefficients more than 0.5. Dots indicate the area of negative correlation coefficients.

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The Importance of Early Marine Growth to Interannual Variability in Production of Southeastern Alaska Pink Salmon

James M. Murphy, Herbert W. Jaenicke, and **Edward V. Farley, Jr.**
Auke Bay Laboratory, Alaska Fisheries Science Center
National Marine Fisheries Service, 11305 Glacier Hwy., Juneau, Alaska 99801

Key Words: pink salmon, southeastern Alaska, growth, mortality

A number of recent studies have provided increasing evidence that changes in climate play a significant role in determining production dynamics of salmon in the North Pacific (Beamish and Boullion 1993; Francis and Hare 1994; Pearcy 1996). However, our understanding of linkages between climate change and Pacific salmon production is still poor (Pearcy 1997). We present data that show a strong correlation between early ocean growth and production (commercial catch) of southeastern Alaska pink salmon (*Oncorhynchus gorbuscha*), and suggest that the relation may provide evidence of size-selective mortality in pink salmon during the early marine life-history stage.

Scales were collected from the late run adult pink salmon returning to the Auke Creek weir in the northern region of southeastern Alaska from 1979 to 1996, and scale circuli (C) distances were used as a proxy of somatic growth. Approximately 50 scales were selected each year, and a Calcomp Digitizing Tablet was used to count and measure distances between circuli along an axis 20 degrees from the anterolateral line. Commercial catches were used as an estimate of southeastern Alaska pink salmon production (data provided by Alaska Department of Fish and Game). Escapement data were not included in the estimate of production because escapement levels are estimated from peak counts of index streams and actual escapements are unknown.

We found differences in scale growth between years of high production (1979-1982, 1984, 1987, 1988) and low production (1983, 1985, 1986, 1989-1996) of southeastern Alaska pink salmon (Fig. 1). The largest difference in growth occurred at the earliest circuli intervals, and the difference in growth persisted through C8. Little difference in scale growth from C8 to C15 was observed between years of high and low production levels.

Fig. 1. Southeastern Alaska pink salmon scale growth during high production (commercial catch > 30 million) and low production (commercial catch < 30 million).

These circuli coincide with the approximate location of a supplementary check in pink salmon scales (Bilton and Ricker 1965). Growth from C15 to C19 was also higher during years of higher production.

Year-to-year changes in early marine scale growth (C1-C6) were highly correlated (p<0.001) with production (commercial catch) of pink salmon in southeastern Alaska (Fig. 2). This association remained significant even after differencing both time series to remove trends, and when early marine scale growth was included in a spawner-recruit model. However,
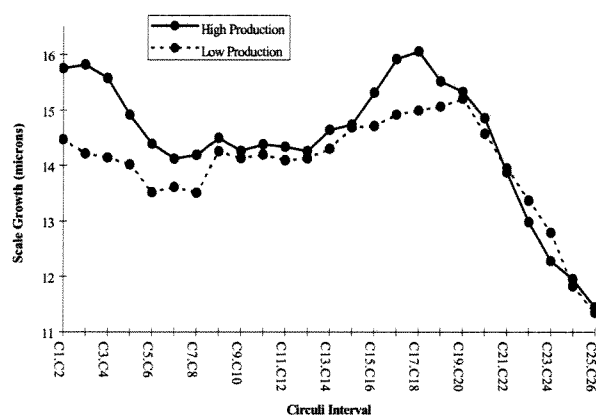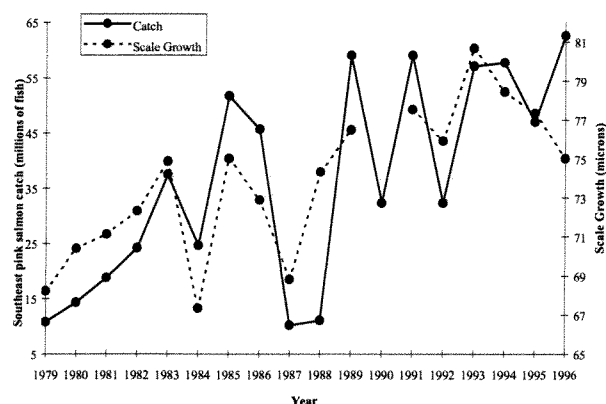

Fig. 2. Southeastern Alaska pink salmon scale growth and commercial catch for 1979 to 1996. Scale data were not collected during 1990.

scale growth during their later coastal ocean residency (C15-C19) was not significantly correlated with production. These findings are consistent with Healey (1982), who found production of chum salmon (*O. keta*) to be significantly related to scale growth from C2 to C4. Our results indicate that growth may be an important linkage between climate change and pink salmon production in southeastern Alaska through size-selective mortality where predation risk is higher for slower growing individuals.

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Primorye Pink Salmon Growth at High and Low Abundance

O. S. Temnykh

Pacific Research Fisheries Centre (TINRO-centre),
4, Shevchenko Alley, Vladivostok 690600, Russia

Key words: pink salmon, dynamics, growth, scale

Pink salmon from the northern Primorye coast stock are characterized by having the largest size of all Asian stocks and by certain peculiarities in their size structure:

- Odd-year pink salmon from high-abundance generations are generally larger than even-year fish. Over the whole period of observations (1940-1996) the average length of odd-year pink salmon was 50.6 cm and even-year pink salmon were 47.8 cm.

- There is a negative correlation between the average size and stock abundance in most pink salmon populations (Bigler et al. 1996), except for the pink salmon from Primorye. Correlation coefficients between pink size and catches in Primorye were insignificant r = 0.17 (P>0.05).

A scale structure analysis showed that beginning from 1970s there were essential changes in the growth rate of pink salmon. The number of circuli within the first annual zone has increased and the number of circuli within the second year of life zone has decreased in fish caught during 1971-1990. The analysis of scale radii showed similar results (Fig. 1). The size of the first annual zone increased primarily due to an increase in the winter zone, which is indicative of a prolonged period of growth retardation in winter. The second-year sea growth was more highly correlated with fork length than the first year of growth. Correlation coefficients between the number of circuli in the second-year zone and fish size equaled 0.56 (P<0.05) and 0.42 (P<0.05) for even- and odd-year pink salmon, respectively. Consequently, average pink salmon size reduction observed in the 1970-1990s was due to the reduction of growth rate mainly during second summer periods at sea.

Similar decreases in the average body size were observed for all three stocks of pink salmon (Amur, western Sakhalin, Primorye), which forage together in the Japan Sea (Fig. 2). I speculate that starting from the beginning of 1970s feeding conditions in the Japan Sea were less favorable for pink salmon, which resulted in peculiarities of growth of pink salmon from all three regional stocks.

Fig. 1. Interannual variability of Primorye pink salmon scale growth.
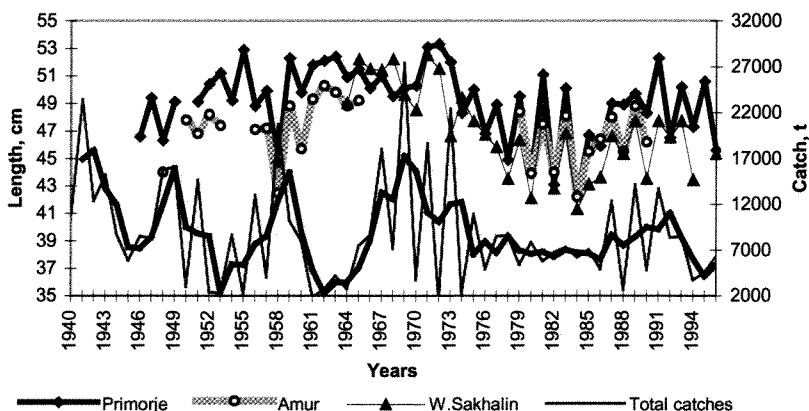
Fig. 2. Dynamics of total catches of Japan Sea pink salmon and average fish size for the main stocks.

Some peculiarities in the dynamics of Japan Sea pink salmon stock abundance were observed starting from the 1970s. Regular cyclic changes in abundance dynamics were characteristic for the Japan Sea pink salmon stocks. There were 10-11 year cycles associated with 11-year solar cycles, and long-term (40-60 year) fluctuations of abundance determined by changes in forms of atmospheric circulation (Birman 1985, Gavrilov and Pushkareva 1996). There was a rise in solar activity in 1979. At this time there also was a change in atmospheric circulation from the meridional into the
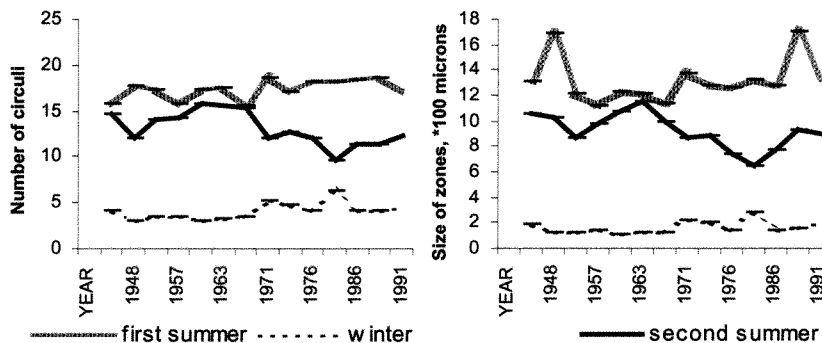
zonal circulation form, although it was not accompanied by an increase in pink salmon abundance in the Japan Sea (Fig. 2).

There was a rapid rise in abundance of the Japanese sardine in the early 1970s. This may have caused stress in the food relationships of fish in the Japan Sea (Kun 1990, Belayev and Zhigalin 1996). It may be possible that during increased sardine abundance in the 1970-1980s there was increased pressure on the planktonic communities, which led to changes in their structure. This could have served as one of the reasons for increase of feeding competition between different pink salmon stocks. In this regard, the role of the Amur pink salmon with respect to the other Japan Sea stocks is of particular interest. There is a significant decrease in average size of pink salmon in Primorye, coupled with an increase in the percentage of Amur stock in the total pink salmon catch in the Japan Sea (Fig. 3). The correlation between Primorye pink salmon body size and the catches of Amur pink salmon (r = - 0.55) was stronger than that between Primorye pink salmon size and its stock abundance. During 1970-1980s the Amur pink salmon stock dominated in the Japan Sea in odd and even years. It was then that the size of pink salmon from the Japan Sea stocks decreased. This period was characterized by the strongest negative correlation between Primorye pink salmon length and catches in the Amur river (r =-0.92, P=0.00).
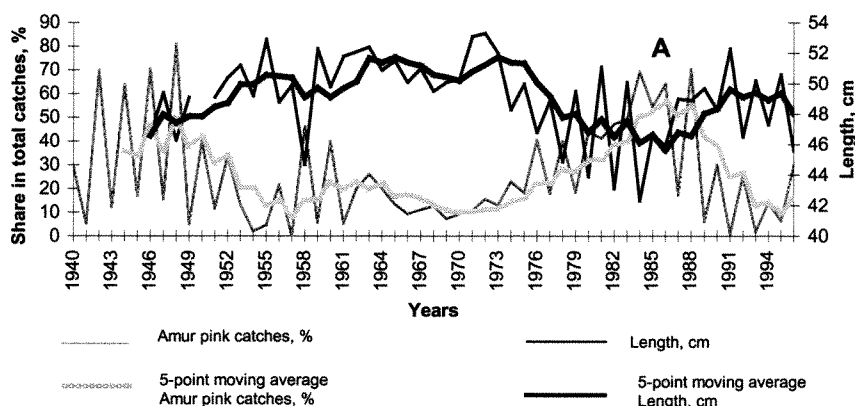
Fig. 3. Share of Amur pink salmon stock in total catches and average Primorye pink salmon length.

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Ocean Distribution, Feeding Ecology, and Return of Pacific Salmon in the 1997 El Niño Event Year

Masahide Kaeriyama[1], Shigehiko Urawa[2], Masa-aki Fukuwaka[2], Katherine W. Myers[3],
Nancy D. Davis[3], Shogo Takagi[4], Hiroshi Ueda[4], Kazuya Nagasawa[5] and Yukimasa Ishida[5]

[1]Hokkaido Tokai University, Sapporo 005-8601, Japan

[2]National Salmon Resources Center, 2-2 Nakanoshima, Sapporo 062-0922, Japan

[3]Fisheries Research Institute, University of Washington, Seattle, Washington 98195, U.S.A.

[4]Faculty of Fisheries, Hokkaido University, Hakodate, Hokkaido 041-0821 , Japan

[5]National Research Institute of Far Seas Fisheries, Shimizu, Shizuoka, 424-8633, Japan
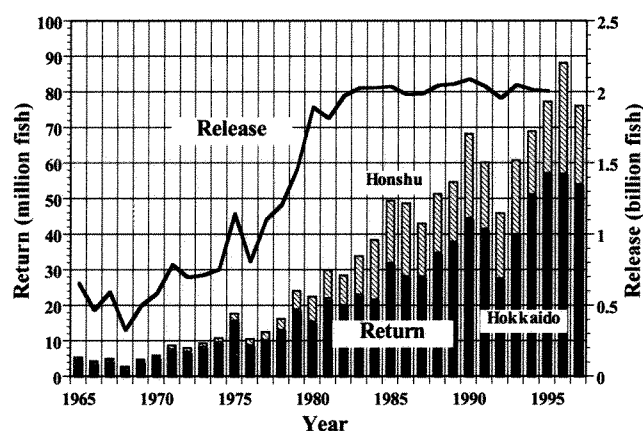
We investigated the effect of oceanic environment related to the 1997 El Niño event on the offshore distribution, migration, and feeding ecology of Pacific salmon in the North Pacific Ocean and the Bering Sea, and return pattern of Japanese chum salmon in 1997.

Numbers of adult chum salmon returning to Japan in 1997 were 54 million fish in Hokkaido and 22 million fish in Honshu, and totaled about 76 million fish (Fig. 1). This run size was about 85% of the 1996 record level (88 million fish). Their run pattern showed extreme fluctuation by area and run timing. In Hokkaido, the early run, which returned by October, was 10.4 times greater in abundance and 6.1 times higher in return rate (survival rate from release to return) than the late runs, which returned after November in 1997. The 1997 abundance and return rate of early runs was greatly increased in the Okhotsk and Nemuro regions compared to the previous five-year means. However, abundance and return rate of Japan Sea populations and some of the late runs was decreased. In Honshu, returns were higher in the Pacific area and lower in the Japan Sea area than the previous five-year means. A similar fluctuation of salmon run pattern was observed in the Pacific Rim nations in 1997 (NPAFC 1997). For instance, although the run size of Fraser River sockeye salmon was of the magnitude predicted, the Bristol Bay sockeye catch and total run were the lowest since 1978. Japanese pink salmon run size was also at an extremely low level, however, Russian pink catch was at or near record level.

Fig. 1. Changes in numbers of adult returns and juvenile releases of chum salmon in Japan during 1965-1997.

A significant positive relationship between the return rates of age-3 adults (R_3) and age-4 adults (R_4) was observed in the Hokkaido Japan Sea chum salmon populations during the 1989-1992 brood years: $R_4=5.891R_3$ ($r^2=0.969$, P<0.025) (Fig. 2). The return rate of age-4 adults in 1997 was actually 0.97%, although it was estimated as 2.65% from the above formula and the return rate (0.45%) of age-3 adult in 1996. This result suggests that age-4 adults of the 1993 brood-year cohort might have had a lower return rate in 1997 because of some influence during the offshore migration period from autumn of 1996 to summer of 1997, despite the fact that their return rate at age 3 was high.

Fork length data of age-4 female adults returning to 11 rivers (Ishikari, Abashiri, Kushiro, Nishibetsu, Shari, Shibetsu, Shiriuchi, Shizunai, Teshio Tokachi, and Yurappu rivers) in Hokkaido from 1953 to 1997 were used to quantify change in body size at maturity of chum salmon. The fork lengths showed a decreasing trend from the late 1970s to the early 1990s, minimized in 1994 (average 626 mm). However, it has recently increased again, and averaged 649 mm in 1997 (Fig. 3). A significant negative relationship between the population size of the
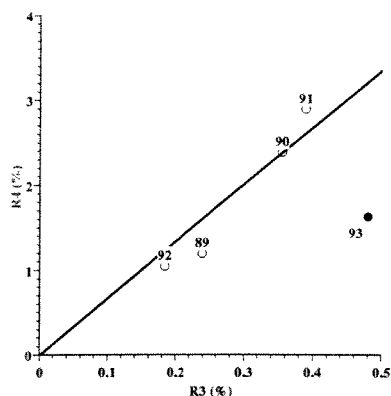
Fig. 2 Relationship between the return rates of age-3 adults (R₃) and age-4 adults (R₄) in the Hokkaido Japan Sea chum salmon populations during the 1989-1993 brood years.
$R_4 = 5.891 \ R_3 \ (r^2 = 0.969, P < 0.025)$

Fig. 3. Changes in annual means of fork length in age-4 female adults returning to 11 rivers in Hokkaido from 1953 to 1997.

Hokkaido chum salmon population and annual mean fork length of age-4 adult chum salmon returning to 11 rivers was observed in Hokkaido ($r^2 = 0.7494$, $P < 0.001$).

A significant negative relationship between run season (month) and fork length was observed for the Tokachi and Shibetsu river populations in 1997. The younger adults (age 3) showed a more significant trend than the older adults (age > 4). This result supports the hypothesis of "precedent migration of larger individuals which have higher growth rate" (Kaeriyama 1996). That is, early-run populations with a high growth rate were generally greater in population size and higher in return rate than late-run populations with a low growth rate in 1997.

Oceanographic data acquired on board the research vessel *Oshoro maru* indicated that the average sea surface temperature (SST) in the central Gulf of Alaska was 2.5°C warmer in 1997 than in 1996. The warmer summer surface temperature in the Alaska gyre in 1997 may be related to the El Niño event through an atmospheric connection (Freeland 1998).

Catch per unit of effort (CPUE: number of fish per tan of research-mesh gillnets) of Pacific salmon was distinctly greater in the Bering Sea than in the Gulf of Alaska, central, or western North Pacific Ocean in the 1990s. In the Gulf of Alaska, total CPUE of Pacific salmon recently showed decreasing trends (Ishida et al.

1997). CPUEs of chum, pink, and coho salmon in 1997 were lower than those in normal years. In the Bering Sea, on the other hand, total CPUE of sockeye, chum, and pink salmon was about two times higher in 1997 than in other years, although the total CPUE was usually almost constant. Especially, CPUEs of pink and chum salmon in 1997 were significantly higher in the Bering Sea and lower in the Gulf of Alaska than previous three-odd-year means (t-test: P<0.001, Fig. 4).

In the Gulf of Alaska, squid, especially *Berryteuthis anonychus*, dominated in stomach contents of Pacific salmon, except for chum salmon, which mainly fed on gelatinous zooplankton from 1994 to 1996 (Myers et al. 1997). In 1997, however, the dominant prey shifted from squid to zooplankton (euphasiids and copepods) in pink and sockeye salmon, and to fish in steelhead trout. The level of food niche overlap, which was calculated by the simplified Morishita index, among Pacific salmon was much lower in 1997 than in 1994-1996.
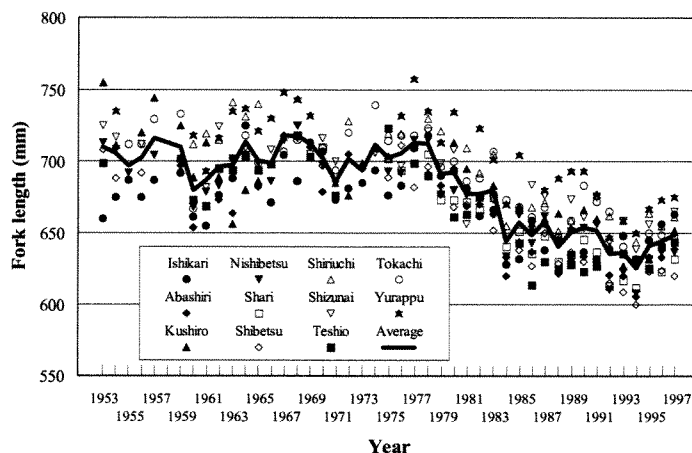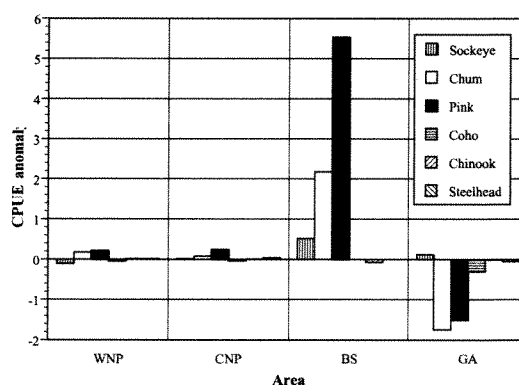

Fig. 4. CPUE anomalies of Pacific salmon in western (WNP) and central (CNP) North Pacific Ocean, the Bering Sea (BS), and the Gulf of Alaska (GA) in 1997.

These data indicate that Pacific salmon, which annually distribute in the Gulf of Alaska during spring-summer seasons, migrated from the Gulf of Alaska, where SST and food resources changed, to the Bering Sea and increased the CPUE in the Bering Sea in 1997.

These results suggest that salmon distribution was concentrated in the Bering Sea, leading to more intra- and inter-specific competition among Pacific salmon populations in 1997. Furthermore, the 1997 run pattern of Japanese chum salmon, as well as other Pacific salmon populations in the North Pacific Ocean, may have been influenced by increased competition, and showed extreme fluctuations by area and run timing.

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How Related are Environmental Sources of Variation for British Columbia and Alaska Sockeye Salmon?

**Randall M. Peterman, Brian J. Pyper, Michael F. Lapointe[1],
Milo D. Adkison[2]**
School of Resource and Environmental Management
Simon Fraser University, Burnaby, B.C., CANADA V5A 1S6

and

Carl J. Walters
Fisheries Centre, University of British Columbia, Vancouver, B.C. V6T 1Z4

Pacific salmon populations (*Oncorhynchus* spp.) show considerable variation over time in survival rates, growth rates, and age at maturity. To better manage these stocks, it is necessary to understand the spatial extent and temporal patterns of environmentally-driven variability in these components of recruitment. We used a multi-stock comparison to identify these spatial and temporal characteristics of variability. The data we used span four decades (late 1940s to mid-1990s) for 29 sockeye salmon (*O. nerka*) stocks from a wide geographical area across British Columbia and Alaska: 16 Fraser River stocks (southern B.C.), the Skeena and Nass River stocks (central B.C.), the Copper River and Cook Inlet stocks (central Alaska), and 9 Bristol Bay stocks (western Alaska). The distributions of stocks from these various regions overlap for much of their marine life.

Specifically, we examined patterns of covariation among these stocks using annual indices of (i) survival rate (residuals from the best-fit stock-recruitment curve), (ii) growth rate (body size at a given adult age), and (iii) mean age at maturity. For each of these components of recruitment, correlation coefficients were calculated for pairwise comparisons among stocks. In addition, we computed correlations among the marine and freshwater survival-rate indices of 6 stocks for which smolt abundance data were available -- the Chilko (Fraser R.), Skeena River, and 4 Bristol Bay stocks. For indices of body size and mean-age, we used principal components analysis (PCA) to further identify the common components of variability among stocks.

For indices of survival rate, we found strong positive covariation among survival-rate indices of the 9 Bristol Bay stocks (all 36 correlations were positive; average $r = 0.45$). There was weaker but predominantly positive covariation among the 16 Fraser River sockeye stocks (94 of the 120 correlations were positive; average $r = 0.15$). However, there was no evidence of positive covariation between Fraser River and Bristol Bay stocks (average $r = -0.05$) or with stocks of other regions in B.C. and Alaska. These results suggest that within each region (i.e., Fraser River or Bristol Bay), the interannual variability of survival rates of sockeye stocks is influenced by common environmental processes, but that these processes are distinct for each of these two regions. Furthermore, analyses of freshwater and marine survival-rate indices indicated that the observed covariation in survival rates of Bristol Bay stocks was due to a combination of freshwater and, to a greater extent, marine processes, whereas marine processes may be most important for Fraser River stocks.

Patterns of covariation among survival rates of Fraser River and Bristol Bay stocks have also been examined by fitting different types of models that include environmental effects to stock-recruit data (details given in Adkison et al. 1996). For the 9 Bristol Bay stocks, the best-fit model was a one-time shift in parameters of the Ricker stock-recruitment curve, coinciding with the rapid change in the mid-1970s in intensity of the Aleutian low-pressure weather systems and associated wind-driven processes (Hare and Francis 1995). On average, the Ricker 'a' parameter (an index of productivity) of these stocks increased 3-fold between the early and late 1970s, whereas the Ricker 'b' parameter did not change appreciably or consistently among stocks. This dramatic increase in productivity is consistent with Brodeur and Ware's (1992) finding that zooplankton abundance increased

between those two periods in the Gulf of Alaska. In contrast, the 12 Fraser River sockeye stocks examined in this analysis did not show a consistent change in either 'a' or 'b' parameters over this same period. This result is consistent with our findings that environmental processes causing covariation among survival rates of Fraser River sockeye salmon differ from those processes affecting Bristol Bay sockeye salmon, and suggests that only the latter were strongly influenced by the mid-1970s climate shift.

In contrast, for the index of growth rate, we found widespread positive covariation across all ages and stocks from B.C. and Alaska (2,345 of the 2,556 correlations were positive; average $r = 0.37$), indicating that both regional and ocean-basin scale processes were important determinants of adult body size. The dominant principal component for body size, which accounted for 58% of the total variation, had a significant decreasing time trend ($P<0.001$) over the period 1971 to 1994.

Indices of age at maturity also showed both regional and ocean-basin scale covariation, although the covariation was weaker (397 of the 496 correlations were positive; average $r = 0.17$). In contrast to the body-size data, the dominant principal component (accounting for 35% of the total variation) for mean age had a significant increasing time trend ($P<0.001$) from 1971 to 1990. These patterns of covariation and time trends in mean age and body size of B.C. and Alaska sockeye salmon may be related to physical oceanographic variables (Cox and Hinch 1997) and ocean abundance of salmon (Bigler et al. 1995). Further details will be published elsewhere.

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The Collapse of the Rivers Inlet Sockeye Fishery:
The Case Against a Freshwater Cause

S.M. McKinnell, C.C. Wood, D.T. Rutherford, K.D. Hyatt, and D.W.Welch

Pacific Biological Station, 3190 Hammond Bay Road
Nanaimo, B.C., Canada V9R 5K6

Owikeno Lake is a large, oligotrophic, glacially turbid coastal lake that drains into Rivers Inlet via the Wannock River. Throughout much of the 20th century, Owikeno Lake vied with the Skeena River to produce the second largest catch of sockeye in British Columbia (Fig. 1). Several years of low escapements during the late 1950s and early 1960s and widely fluctuating catches beginning in the late 1960s led to five years of severe fishery restrictions (1979-1984). These years of higher escapements did not result in higher catches. Logging in the Owikeno watershed began during the 1960s and this became one of the popular hypotheses for the decline of the stock. If Owikeno Lake had become less productive after the 1960s because of habitat damage or other factors, the data should indicate that fewer fry were produced for a given number of spawners.

Fig. 1. Rivers Inlet sockeye catch.

Very few sockeye juveniles spend a second year rearing in Owikeno Lake so samples of fry collected during the summer are almost exclusively the product of a single cohort. Trawl survey estimates of juvenile abundance in Owikeno Lake have been collected intermittently since 1960. The most intensive surveys occurred from 1960 to 1968. These data indicate that there is density-dependent growth in juvenile sockeye in Owikeno Lake (R^2=81%; Fig. 2). When sockeye fry were abundant in the lake during the summer (July-August), their body size as pre-smolts was smaller. Samples collected for the 1994 and 1995 brood years indicate that this relationship still holds (Fig. 2). The good relationship between pre-smolt weight and juvenile abundance allowed us to use pre-smolt weights as a proxy for fry abundance. In years when neither trawl surveys nor pre-smolt weights were available, we used freshwater scale growth measured from returning adults to infer juvenile abundance. Our measure of freshwater scale growth was the principal component of the correlation between age 1.2 and age 1.3 freshwater growth from adult sockeye of the same brood year (Fig. 3).
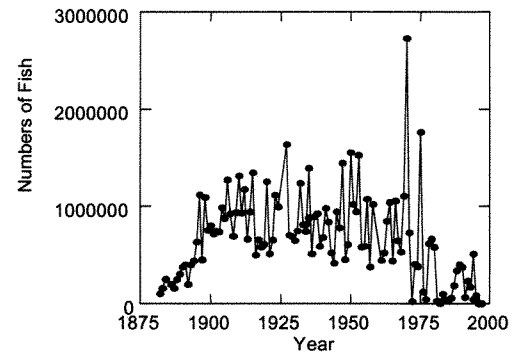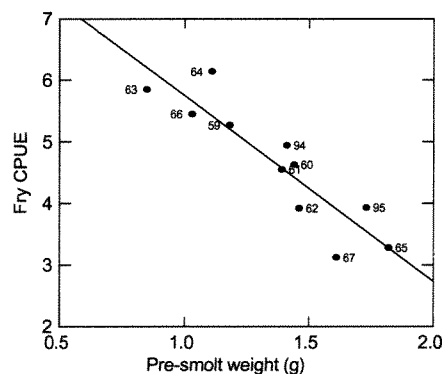

Fig. 3. Sockeye fry catch per unit effort (CPUE) index (log scale) in summer versus mean annual pre-smolt weight (g) by brood year.
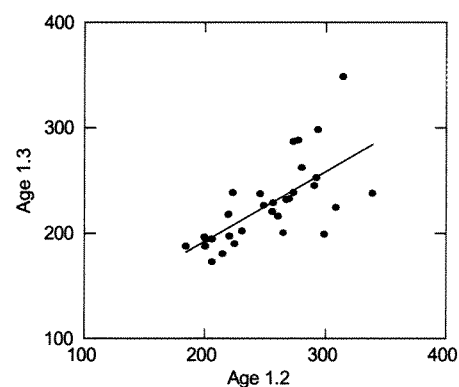

Fig. 2. Freshwater scale growth (microns) taken from returning adults, by brood year.

A 46-year index of juvenile sockeye abundance in Owikeno Lake was reconstructed by combining archival data from trawl surveys, pre-smolt sizes, and freshwater scale growth (Fig. 4). These data suggest that fry abundance was generally lower during the 1950s than during subsequent decades. There is no evidence of a long-term decline in fry abundance. Years of low fry abundance include 1954-1957, 1965, 1967, 1989, 1992, and 1996. These years generally coincide with years of lower than average escapements; 1992 was the notable exception (Fig. 5). Our index of escapement does not include unreliable estimates of spawner abundance in turbid rivers or streams. Spawner abundance declined to very low levels from 1994 to 1996. Total closures of the Rivers Inlet sockeye fishery occurred in 1996 and 1997. A low escapement in 1994 resulted in an above average fry recruitment index.
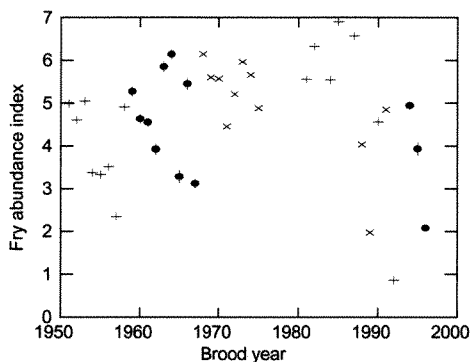
Fig. 4. Estimated abundance (± 1 standard error (s.e.) for trawl data) of juvenile sockeye in Owikeno Lake. The source of the estimates are indicated by the plot symbols (•) trawl, (x) pre-smolt weight, (+) freshwater scale growth.

Fig. 5. Escapement (numbers) to clear (non-glacial) streams. Arithmetic (above) and geometric (below) means are indicated by the dashed lines.

Clear stream escapements exceeding about 175,000 spawners have not resulted in low fry recruitment (Fig. 6). Fry recruitment from clear stream escapements below 175,000 has been variable, but was typically adequate even from lower escapements. Note that the brood years 1963 and 1968 that produced two years of phenomenal catches were not the peak years of fry abundance. This suggests that good marine survival coupled with good fry recruitment can produce very good catches, but this combination has not been observed since the early 1970s.

Although the total escapement estimates are suspect, if one assumes that the total escapement estimates are correlated with the true escapement, a marine survival index can be computed as the log(total returns/fry CPUE) by brood year. The marine survival index has decreased over the last 50 years (Fig. 7). As has been demonstrated for other sockeye populations and other salmon species, marine survival is correlated with smolt size (Fig. 8).

Fig. 6. Sockeye fry abundance versus clear stream escapement index by brood year.
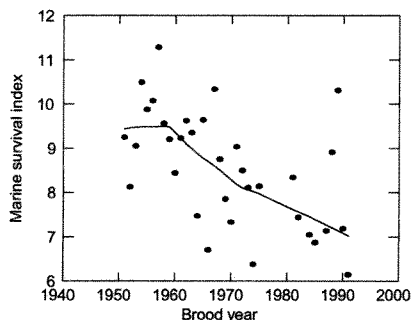
Fig. 7. Marine survival index for Rivers Inlet sockeye.

Fig. 8. Marine survival of Owikeno Lake sockeye versus mean pre-smolt weight. Brood years are indicated.

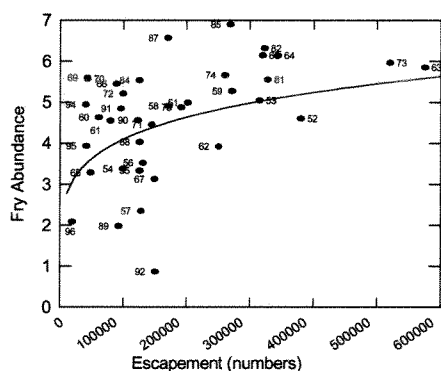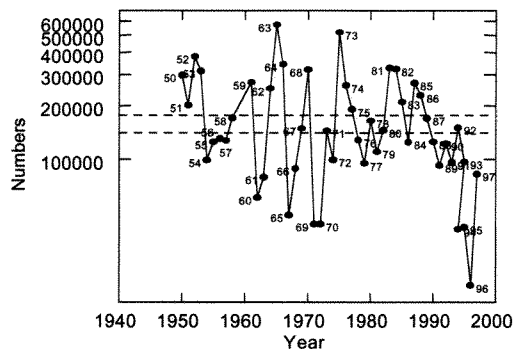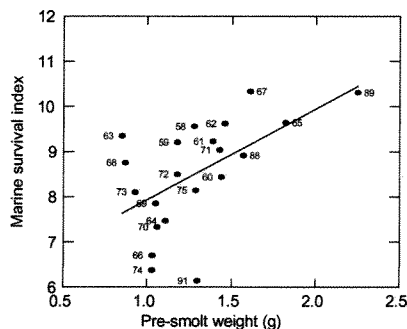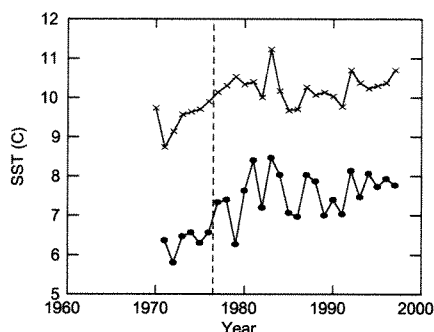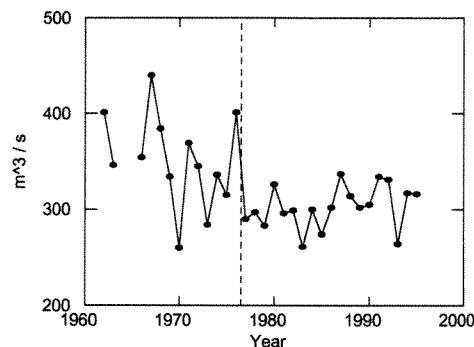There is a clear signal of the 1976/77 climate change in the Wannock River discharge data and in the adjacent Queen Charlotte Sound sea surface temperatures (SSTs). Discharge from the Wannock River was significantly lower after 1976 than before (Fig. 9). Both winter and spring SSTs were significantly warmer after 1976 than before (ANOVA: $P<0.001$, Fig. 10). There is no evidence of physical, chemical, or biological changes within Owikeno Lake. Recent secchi depth and zooplankton biomass measurements are within the levels of variation seen from 1960-1968.

Fig. 9.   Wannock River annual mean discharge. The vertical line indicates the 1976/77 climate change.

Fig. 10. Winter (below) and spring (above) sea surface temperatures sea surface temperatures (SSTs) at Egg Island, Queen Charlotte Sound.

Owikeno Lake sockeye smolts have the smallest mean size of any on the B.C. coast, and as such, they may have unique physiological or environmental constraints on marine survival. Reduced freshwater discharge in Rivers Inlet may have changed some aspect of the marine environment in the inlet that is critical to the survival of sockeye smolts. Very small smolts may have difficulty during the transition to salt water. Reduced estuarine circulation may result in less primary and secondary biological production in the inlet. Reducing the freshwater lens may reduce feeding opportunities. Migration timing may be affected if currents are reduced. The warmer ocean they now encounter may be bringing new predators to the region, or placing additional physiological or behaviour demands on the fish.

The returns in 1998 will result from age 1.3 fish produced from the 1993 brood year and age 1.2 fish produced from the 1994 brood year. There were no summer trawl surveys in Owikeno Lake during 1994 (1993 brood) and no juvenile weights were measured. Freshwater scale growth measured on returning age 1.2 adults in 1997 suggests that fry abundance for the 1993 brood year was low. Low fry densities tend to produce adults that mature as age 1.2 rather than age 1.3 adults. The apparent low fry abundance and its probable effect on age at maturity suggests that most of the production from the 1993 brood year has already returned. Although the 1994 escapement index was one of the lowest, the juvenile abundance that resulted from this spawning was very good. This suggests that most of the 1994 brood year will return in 1999 as age 1.3. Despite higher fry abundance, there is no evidence in coastal ocean climate data to suggest that marine survival will improve returns in the next few years.

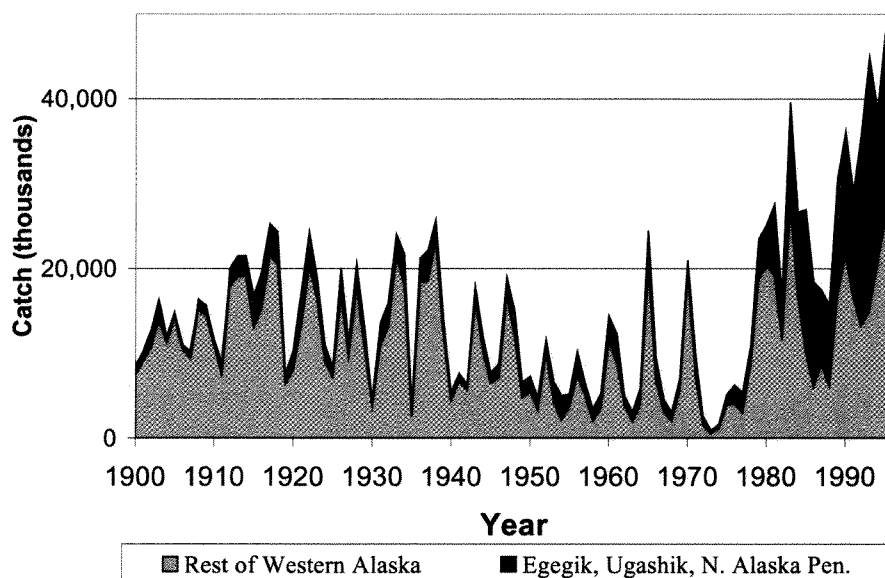# Historical Trends in Rate of Fishing and Productivity of Bristol Bay and Chignik Sockeye Salmon

Douglas M. Eggers
Alaska Department of Fish and Game
P.O. Box 25526, Juneau, Alaska 99802-5526 USA

Historical salmon catch data have been related to long-term environmental data in support of the hypothesis that large-scale salmon production is driven by decadal-scale climatic processes (Hare and Francis 1995; Beamish and Brouillon 1993). However, the historical Alaskan salmon catches have been affected by political and economic factors independent of climatic influences (Cooley 1961). The large increase in western Alaska sockeye catch in the late 1970s has been often cited as evidence for the late 1970 regime shift in the North Pacific Ocean (Hare and Francis 1995). However, a large component of this increased catch, since the late 1970s, came from fisheries in the Egegik, Ugashik, and North Alaska Peninsula fishing districts (Fig. 1). The fishing effort in these fishing districts was very low prior to 1950, and recent increases in western Alaska sockeye catches cannot be attributed soley to a North Pacific regime shift.

Fig. 1. Western Alaska sockeye salmon catch, 1900 - 1997 partitioned into Egegik, Ugashik, North Alaska Peninsula Districts, and other fishing districts of western Alaska (Nushagak, Naknek-Kvichak, Togiak, and Kuskokwim Districts).

Complete assessment of catch and escapement by age is available since the 1956 run year for Bristol Bay river systems and since the 1922 run year for Chignik early- and late-runs of sockeye salmon. These data sets were extended to the 1904 run year for Bristol Bay fishing districts (Nushagak, Naknek-Kvichak, Egegik, and Ugashik) and to the 1895 run year for the Chignik pooled early- (Black Lake) and late-runs (Chignik Lake). The early period catches and fishing effort (powerboat driftnet equivalent vessel days for Bristol Bay fishing districts, and trap days for the Chignik fishing district) were used to estimate total runs during the periods prior to routine escapement enumeration. The total run by age was estimated based on average district age composition from the recent periods. Complete returns (return by age from parent escapement) for the 1904-1991 Bristol Bay brood years and 1895-1991 Chignik brood years were constructed from the extended base of total run by age.

Ricker-type escapement return relationships were fit to the data and time-series of anomalies in production were constructed. The trends in productivity anomalies are believed to be the best indicator of long-term climate changes because trends in catches reflect changes in pattern of fishing. There was a high degree of autocorrelation in production anomaly, with alternating multi-year episodes of low and high production observed for all stocks. In general, there were similar patterns of production anomaly among the stocks of sockeye salmon examined (Fig. 2). The production anomalies during period from the turn of the century to early-1930 brood

years was generally positive, during the period from the mid-1940 to the late-1960 brood years generally negative, and during the period from the late-1970 to early-1990 brood years generally positive.
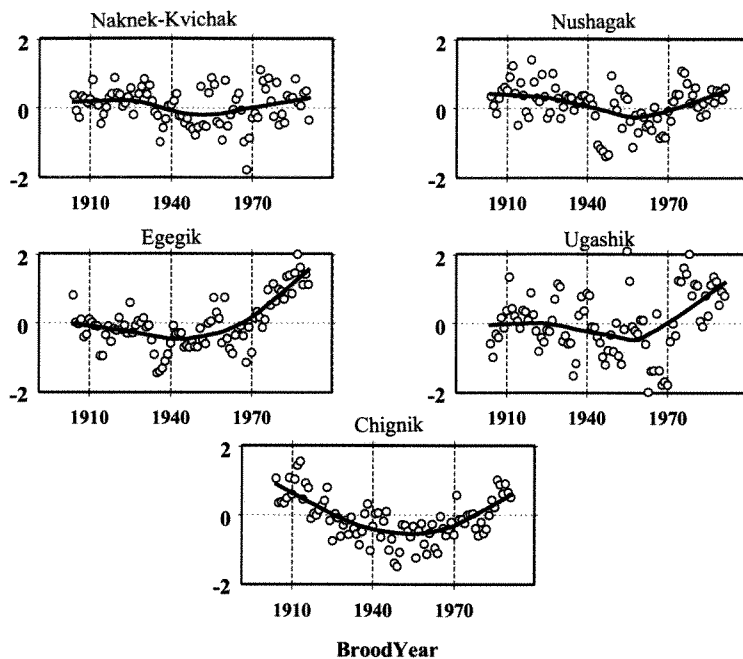
Fig. 2. Trends in sockeye production anomaly (solid line is loess fit and points are in ln (observed return/predicted return)) from fitted Ricker-type spawner recruit relationship, 1904-1991 brood years for Naknek-Kvichak District, Nushagak District, Egegik District, Ugashik District, and Chignik District.

There were differences in pattern of abundance and exploitation rate among the stocks. The runs to the Nushagak and Chignik districts were low in early 1950s and have increased steadily since. The runs to Ugashik were very low in the early to mid 1970s. The runs to Egegik were lowest in the early 1970s. The off-cycle runs to Naknek-Kvichak district were very low from the late 1950s to the early 1970s, however there is no trend in the cycle-year runs since the fishery was initiated. The Nushagak District, Ugashik District, off-cycle Naknek-Kvichak District, and Chignik District had periods of very low catch and escapement levels. In general, stocks that were fished heavily during episodes of low production were depleted. The periods of time that depletion of stocks occurred was not consistent among stocks and suggests that the interaction of fishing and climate-induced variation in productivity determines abundance of salmon.

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Hydrography and Zooplankton Off the Central Oregon Coast During the 1997-1998 El Niño Event

William T. Peterson[1], Michael Schiewe[2], Ed Casillas[2]
Bob Emmett[3] and Kym Jacobson[3]
[1]NOAA, NMFS, Northwest Fisheries Science Center (NWFSC),
Hatfield Marine Science Center, 2030 S. Marine Science Drive, Newport, OR 97365
[2]NOAA, NWFSC, Northwest Fisheries Science Center (NWFSC),
2725 Montlake Blvd. E., Seattle, WA 98112
[3]NOAA, NMFS, Northwest Fisheries Science Center (NWFSC),
Hatfield Marine Science Center, 2030 S. Marine Science Drive, Newport, OR 97365

Monitoring of hydrography and zooplankton at stations 2, 5, 9, 18 and 28 km off Newport, Oregon was initiated in May of 1996. The purpose of this effort was to compare present ocean conditions to conditions observed in the 1970s at these same stations. Sampling is conducted at fortnightly intervals. In this paper, we describe conditions that prevailed during the summer of 1997.

Ocean conditions in 1997 in the Oregon upwelling zone began in a "normal" fashion: upwelling was initiated with an early spring transition (late March); this was followed by a boom in zooplankton production during April -- copepod densities were the highest that have ever been observed for that time of the year. Biological production began to slow during the first week of May due to a weakening in upwelling, and surface waters began to warm. Zooplankton numbers declined at the same time, and continued to do so throughout the summer. A brief but strong upwelling event occurred from 12 July through 19 August with little biological response; after that, upwelling ceased altogether (Fig. 1). As a result of weak upwelling in early summer, sea surface temperatures on the shelf warmed from 12° to 17°C (May until mid July), cooled to 10°C during the upwelling event, but warmed in late August to a record temperature of 18.5°C (Fig. 2). This is warmer by 1 degree than any observation made during the 1983 El Niño event. Secchi depths were deep during both the early and late summer warm event, averaging 10 m during June and July and exceeding 15 m during the late-summer warming event (Fig. 3). Usual secchi depths are on the order of 3-5 m during the summer upwelling season.

Given that upwelling was weak during the summer of 1997 and that the copepod species captured in shelf waters were a mixture of shelf species and species with offshore affinities (Table 1), we suggest that the warming in 1997 was due solely to onshore advection of warm offshore waters. The scientific question is: "Were the atmospheric pressure patterns that lead to coastal upwelling off Oregon affected by the redistribution of atmospheric pressure systems along the equator as a result of the El Niño event?" We know that extremely anomalous sea surface temperatures were observed in the Gulf of Alaska and the Bering Sea during the summer of 1997. Was warming in the North Pacific due to anomalous meteorological events that were in turn linked to equatorial events through an atmospheric teleconnection?

Sampling completed on 5 March 1998 showed that zooplankton species with southern affinities dominated the shelf waters. However, sampling on 18 March 98 revealed that the zooplankton was dominated by the usual neritic coastal cool water species (Table 1) suggesting that the El Niño has abated and that an early spring transition may occur this year.
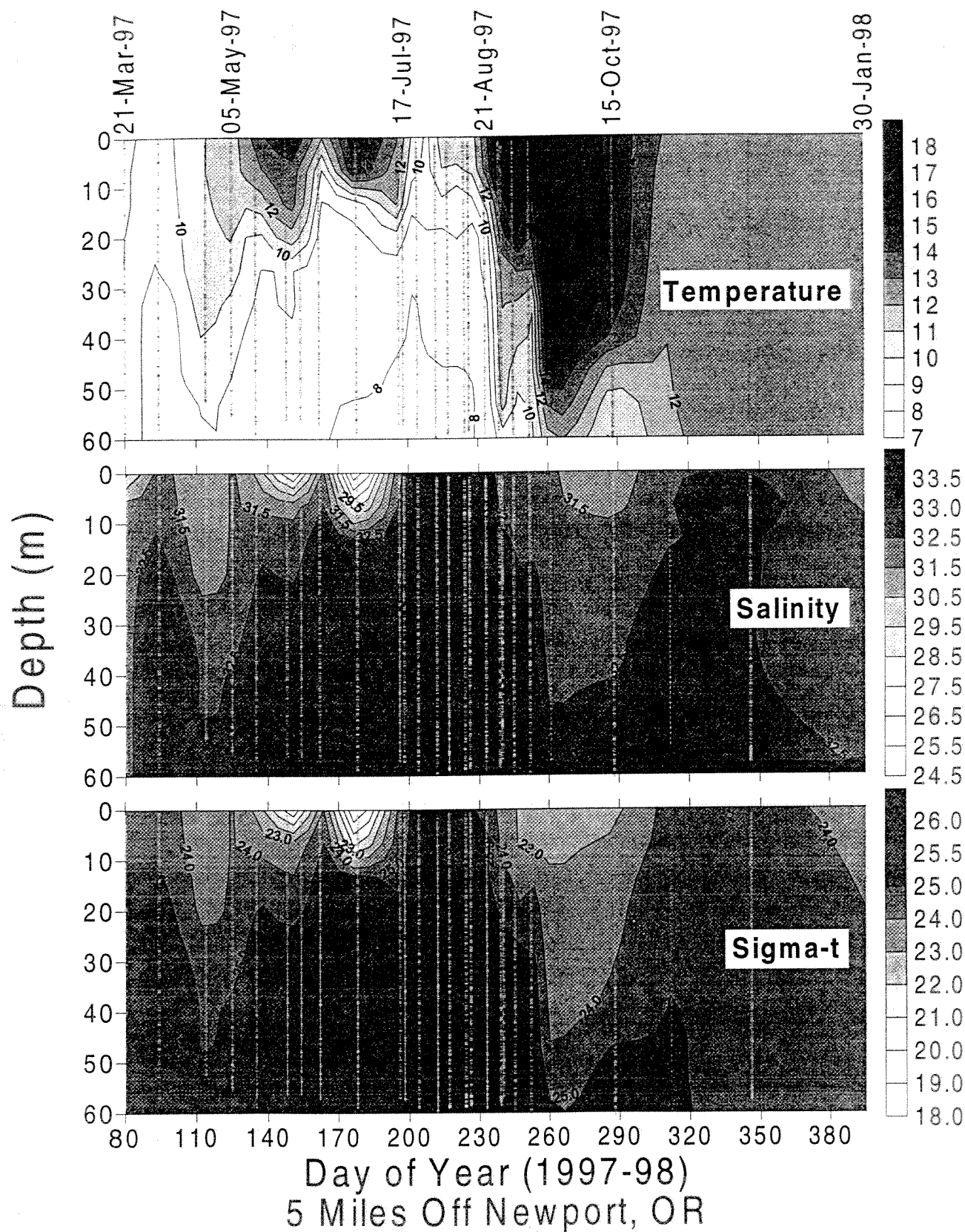
Fig. 1. Time-depth plot of temperature, salinity, and density measured with a Seabird SBE-19 CTD at the five mile station (9 km from shore; water depth 60 m) off Newport Oregon from 21 March 1997 until 30 January 1998. Note that the upwelling season extended for only five weeks during the summer of 1997 (as indicated by the presence of cool salty water in the upper layers of the water column).
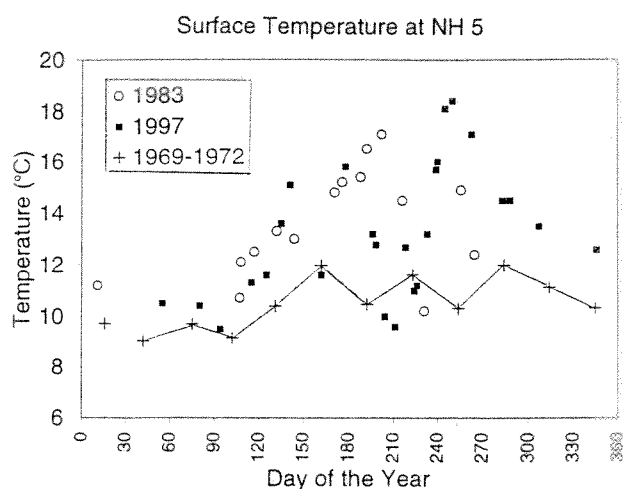
Fig. 2. Surface temperatures at the station NH 5 (9 km shore) during 1997 compared to the El Niño of 1983 and to monthly averaged surface temperatures measured in 1969-1972 at the same stations.
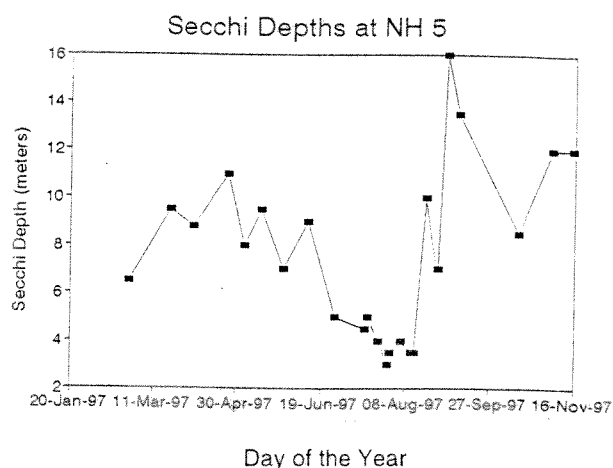
Fig. 3. Secchi depths at NH 5 measured in 1997.

Table 1. Density of zooplankton species collected at a station 9 km off Newport, OR (water depth 60 m) with a 1/2 m diameter, 202 micrometer mesh plankton net hauled vertically from 58 m to the surface, during the summer of 1997. The "warm event" began on 20 August and reached a maximum in late September.

	Date (June through September) in 1997									
	6/27	7/15	7/23	7/30	8/6	8/14	8/21	8/28	9/2	9/9
COOL WATER SPECIES										
Calanus marshallae	17	49	125	31	46	553	559	61	5	0
Pseudocalanus mimus	461	1470	1719	678	207	796	987	173	184	22
Paracalanus parvus	159	219	1218	130	84	103	102	555	495	710
Centropages abdominalis	168	1138	72	157	103	73	17	17	0	0
Acartia longiremis	0	0	54	104	65	225	204	113	25	4
Oithona similis	537	601	1737	574	245	474	493	113	709	372
Metridia pacifica	0	0	0	31	8	24	0	0	0	0
WARM WATER SPECIES										
Calanus pacificus	0	4	0	0	0	0	0	17	36	32
Calanus tenuicornis	0	0	0	10	4	0	0	9	5	2
Eucalanus californicus	0	0	0	0	4	0	0	52	15	0
Ctenocalanus vanus	0	0	0	0	0	0	17	9	15	10
Clausocalanus spp.	0	0	0	0	0	0	34	9	10	8
Acartia danae	0	0	0	0	0	0	0	0	15	6
Corycaeus anglicus	0	0	0	0	0	0	0	26	76	64
Dolioletta gegenbaurii	0	0	0	0	0	0	0	130	71	22
Oikopleura sp.	352	422	734	182	103	182	1684	312	684	26

Long-Term Changes in Climate, Zooplankton Biomass in the Western North Pacific, and Abundance and Size of East Sakhalin Pink Salmon

Kazuya Nagasawa

National Research Institute of Far Seas Fisheries, Fisheries Agency of Japan,
5-7-1 Orido, Shimizu, Shizuoka 424-8633, Japan

East Sakhalin pink salmon (*Oncorhynchus gorbuscha*) are one of the biggest stocks in Asia. This species is distributed as juveniles in the Okhotsk Sea from summer to autumn and occurs as immature fish in the western North Pacific Ocean in winter and spring. Based on data collected from the late 1950s to the early 1990s, this paper examines what factors contributed to changes in abundance of the stock and also analyzes annual changes in body weight related to stock abundance.

During the period from the mid-1970s to the late-1980s, the Aleutian Low Pressure Index (ALPI) was high (Beamish et al. 1997), but sea surface temperature (SST) and macrozooplankton biomass in the Oyashio region remained low (Odate 1984). As both copepod abundance and ALPI showed similar year-to-year fluctuations in the Gulf of Alaska (Beamish and Bouillon 1993), the observed relationship of ALPI to macrozooplankton biomass in the Oyashio region was opposite to that in the Gulf of Alaska.

The annual catch of pink salmon along the east coast of Sakhalin gradually increased from the 1960s to 1997. However, it declined from 1978 to 1984 despite the decreasing catch by the Japanese high-seas salmon fishery. The annual catch increased again in 1985 and remained at a high level in the late 1980s and 1990s. The catch trend was similar to long-term changes in macrozooplankton biomass in the Oyashio region, suggesting that the east Sakhalin pink salmon production is affected by macrozooplankton production in this region.

In the intense Aleutian Low pressure period from the mid-1970s to the late 1980s, SST was high in the Gulf of Alaska while it was low in the Oyashio region. This may have been caused by differences in wintertime wind direction and stress: the northwest cold wind from Siberia and the southwest warm wind from the subtropical area predominated in these regions, respectively (cf. Yasuda and Hanawa 1997).

From the late 1950s to the late 1980s, there was a clear negative relationship between the body weight and abundance of pink salmon from east Sakhalin. Recently, however, the body weight of pink salmon from this region increased even in the years of high stock levels. Thus, the past body weight and abundance relationship of pink salmon has not been applied to the current year classes, and it is likely that the carrying capacity of the western North Pacific Ocean for east Sakhalin pink salmon has improved.

Because the impact of the Aleutian Low Pressure differs between regions in North America and Asia, research on climate change and ocean production is needed on both regional and whole North-Pacific scales.

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Forage Base and Feeding of Pacific Salmon in the Sea

V.I. Karpenko, L.V. Piskunova, and **M.V. Koval**
Kamchatka Research Institute of Fisheries & Oceanography (KamchatNIRO)
18, Naberezhnaya Str., Petropavlovsk-Kamchatskiy, 683602, Russia

This paper is devoted to the analysis of feeding of three Pacific salmon species—pink, chum, and sockeye salmon—during their marine life, i.e., from first entering the sea until finishing their anadromous (adult) migration. Data collected by the staff of the Marine Salmon Investigations Laboratory for more than 40 years were used. The general area of the research comprised the southwestern part of the Bering Sea and adjacent waters of the North Pacific Ocean to the south from the Commander Islands. For additional information, some data concerning the area offshore of western Kamchatka in the Sea of Okhotsk and the waters adjacent to the Northern Kuril Islands were also presented. The majority of the data have already been published in Russia and, partially, abroad.

Only a small part of all of the collected data is presented in this report because our general goal was to analyze the dynamics of food composition of salmon during the course of their marine life. The contents of salmon stomachs are a much more reliable indicator of the abundance of general forage organisms, usually large zooplankton species, than the standard plankton catches. Observation of changes in food composition allowed us to make conclusions about structural changes occurring in plankton and nekton communities that resulted from the effects of climatic and oceanographic factors. Observed annual or decadal changes in the forage base and feeding of salmon are discussed by species and zones of distribution. Stomach fullness (%oo) = food weight (g)/fish weight (g) x 10,000. Food composition (%) = individual prey species weight (g)/food weight (g) x 100. Food similarity (%) was calculated by summing the minimum food composition for those prey common to the groups being compared. Food variability or differences (%) = 100% — food similarity.

Pink Salmon

Littoral zone: The main of food of pink salmon for all years consisted of insects, larvae and imago, which varied from 47% to 92% of the total food weight. Only in June throughout the 1970s, the dominant prey was Harpacticoida (53.1%), and in July throughout the 1990s small copepods, *Eurytemora herdmani* (40.2%) and *Paracalanus parvus* (21.8%) were dominant.

Food composition in this zone in June and July from the 1970s until the 1990s differed by 94.7% and 21.8%, respectively. Maximum similarity on food composition (58.6%) was noted in June through the 1980s-1990s.

15-mile zone: The main pink salmon food in 1960s-1970s consisted of small copepods, *Pseudocalanus elongatus* and *Eu. herdmani*, and consisted of larvae and juvenile fish in the 1980s-1990s. In the 1990s, the rate of the fish component in the food of pink salmon amounted to 82%. The stomach fullness of fish usually was over 150%oo, and when salmon were feeding on crustaceans it was lower than when salmon were feeding on juvenile fish. The spectrum of pink salmon food in the 1980s and 1990s compared to that in the 1970s was changed by 95.6% and 49%, respectively.

Open waters of Karaginsky Bay: The main pink salmon food in the 1960s was Pteropoda (83.3%), and the in the 1970s-1980s it was larvae (40.5%) and juvenile (78.4%) fish, respectively. The stomach fullness of fish was lowest in this zone, rarely more than 100%oo. In the 1980s the composition of food was changed by 95.9%, compared to that in the 1960s.

Bering Sea: In the open waters of Bering Sea pink salmon preferably consumed euphausiids, juvenile fish, and hyperiids. In the 1960s-1970s the dominant prey were euphausiids (60%), in the 1980s the dominant prey

was juvenile fish (35%), and in the 1990s hyperiids were dominant (32.6%). The spectrum of food of pink salmon in the 1970s, compared to that in the 1960s, was changed by 37.5%, in the 1980s by 57.9%, and in the 1990s by 69.4%.

Bering Sea (anadromous migrations): In 1965, pink salmon mostly fed on hyperiids and juvenile sculpins, and moderately on euphausiids. In 1992, the main of food was fishes (29.6%), squids (23.0%), and euphausiids (20.0%), and hyperiids were only 10.6% of the food weight. The food spectrum of pink salmon in 1996 comprised euphausiids (mostly *Thyssanoessa longipes*; 67.4%), myctophids (12.3%), and copepods (*Calanus cristatus*; 9.8%); the stomach fullness was 146.2%oo.

Chum Salmon

Littoral zone: Chum salmon in this zone almost solely consumed insects (larvae and imago). Only in June was another food component observed; in the 1970s—gammarids (38.6%), and in 1980s and 1990s—fish (29.0% and 22.1%, respectively). The stomach fullness usually was over 200%oo. The food spectrum was wide. In June in the 1980s and 1990s, the food spectrum was different than in June in the 1970s (76.1% and 69%, respectively); the food spectrum in July (54.5% and 53.3%) was comparable to the 1970s.

15-mile zone: In the 1970s chum salmon fed on larval and imago insects (51.9%) and gammarids (16.6%). In the 1980s and 1990s chum salmon mostly consumed juvenile fish (28.5% and 57.3%, respectively), and sometimes *Parathemisto japonica* and Appendicularia. Usually the stomach fullness was more than 150%oo. In the 1980s food composition differed from the food composition in the 1970s by 89.5%, and in the 1990s it differed by 78.6%.

Open waters of Karaginsky Bay: In the 1960s, chum salmon consumed *P. japonica* (53.9%) and Polychaeta (30.9%), and in the 1970s—sandlance (49.2%) and Appendicularia (29.9%). The stomach fullness in this zone was the lowest, less than 50%oo. The spectrum of food in the 1970s differed from that in the 1960s by 96.9%.

Bering Sea: In the 1960s, the main chum salmon food was euphausiids (61.8%), and in the 1980s food mainly consisted of approximately equal parts of Pteropoda (29.3%), Appendicularia (26.4%), and euphausiids (24.6%). In the 1990s chum salmon fed on hyperiids (31.7%) and euphausiids (26.9%). Average stomach fullness was high, and ranged from 130 to 215%oo, the highest fullness being noted in the 1990s.

Bering Sea (anadromous migrations): In 1965, chum salmon fed preferably on Pteropoda and hyperiids, episodically consuming copepods (*Eucalanus bungii*). In 1992, chum salmon fed on pteropods (62.9%), euphausiids (15.7%), and hyperiids (11.6%). Pteropoda was the main of food of chum salmon in 1996 (43.0%), and they also consumed myctophids (35.2%) and euphausiids (the rate decreased to 7.1%). Average stomach fullness in 1996 was 69.5%oo.

Sockeye Salmon

Littoral zone: The main food of sockeye salmon consisted of insects and juvenile fish. Juvenile fish dominated in the food composition in June and July in the 1970s (60% and 64%) and in June in the 1980s (64.7%); insects were the dominant prey in July in the 1980s (55.5%) and 1990s (63.3%). The food spectrum included significant rates of gammarids, shrimps and Cumacea. The stomach fullness varied extensively (60 -365%oo). The year-to-year spectrum of sockeye salmon food in June differed completely (100%). In July in the 1980s, the food spectrum differed by 75.1% in comparison to that in the 1970s, and by 82.8% in July in the 1990s.

15-mile zone: In the 1970s, sockeye salmon fed solely on imago and larval insects (95.9%), in the 1980s and 1990s sockeye salmon consumed juvenile fish (41.2% and 100%, respectively). The stomach fullness was high over 200%oo. The spectrum of food in the 1980s differed from that of the 1970s by 91.2%, and from the spectrum in the 1990s by 100%.

Open waters of Karaginsky Bay: In the 1960s, sockeye salmon fed solely on fish; average stomach fullness of fish amounted to 11%oo. In the 1970s, sockeye salmon consumed euphausiids (76.3%), and in the 1980s they

fed on zoea of Decapoda (60.6%) and euphausiids (36.4%). The stomach fullness was less than 100‰oo. The spectrum of food in the 1970s compared to that in the 1960s changed by 94.1%. The spectrum observed in the 1980s compared to that in the 1960s was completely different (100%).

Bering Sea: In the 1960s, sockeye salmon fed mostly on juvenile fish (40.7%) and hyperiids (40.0%), and in the 1980s on *P. japonica* (69.9%) and Pteropoda (17.7%). Average stomach fullness was low (27.6‰oo in the 1960s and 72.4‰oo in the 1970s). The food spectrum in the 1980s differed from that in the 1960s by 55.1%.

Bering Sea (anadromous migrations): The main food of sockeye salmon in 1965 consisted of hyperiids and juvenile squids, and the percentages of Pteropoda and copepods (*Eu. bungii*) were low. Hyperiids (42.8%) also formed the basis of sockeye salmon food in 1992. The rates of juvenile shrimps, squids, and Decapoda were 16.8%, 16.6% and 11.1%, respectively. In 1993, the main food of sockeye salmon consisted of euphausiids (*Thyssanoessa longipes*; 40%) and hyperiids (21%), and the percentages of Pteropoda and juvenile squids were relatively low (14.9% and 10.9%, respectively). In 1996, the primary foods were juvenile squids (32.2%) and Pteropoda (21.4%), and sockeye also consumed myctophids (12.4%) and *Thyssanoessa raschii* (9.8%). The average stomach fullness in sockeye salmon in 1996 was only 32.4‰oo.

The above discussion concerned changes in the food composition and stomach fullness of pink, chum, and sockeye salmon within a large, isolate basin, the Bering Sea. The most stable food composition is found in the estuaries and littoral zone, which is related to the high rate of freshwater and brackish water animals in these habitats. As salmon migrate seaward, the variability in the food spectrum and the role of some pelagic animals increases. The highest variability in food composition and volume of zooplankton was found in the most abundant species, pink salmon. In sockeye and chum salmon variability in these characteristics was lower.

Regional changes in climate and ocean conditions, noted by many scientists, have significant effects on the changes in food composition. Moreover, the influence of the abundance of consumers, in particular of pink salmon, is significant. This influence has been revealed by the comparison of food composition in the years of low (1960s-1970s) and high (1980s-1990s) abundance, though the difference between the 1960s and 1970s or 1980s and 1990s is not as clear. Apparently, the abundance of pink salmon had an influence on the level of food supply of other salmon species, and may determine their biological parameters (size, weight, age maturity, and etc.) and production potential.

Similar analysis of the feeding ecology of salmon within different areas, e.g., the Sea of Okhotsk, offshore of the Kuril Islands, and the Pacific waters adjacent to Kamchatka, is expected to be carried out. Studies of the influence of food composition on biological parameters and salmon production is expected to be continued for other areas of salmon reproduction and marine rearing in the North Pacific.

Abiotic and Biotic Factors Influencing Food Habits
of Pacific Salmon in the Gulf of Alaska

Kerim Aydin
High Seas Salmon Project, Fisheries Research Institute,
P.O. Box 357980, University of Washington
Seattle WA 98195 USA

A major difficulty in assessing feeding competition, and thus quantifying density-dependent growth and the carrying capacity of Pacific Salmon in the North Pacific Ocean, arises from the large amount of variability in high-seas foraging conditions, both within and between years. Differences in prey populations, prey patchiness, seawater temperature, and other oceanographic conditions all conspire to mask the relationship between salmon density and food. In addition, "salmon density" as measured by catch per unit effort (CPUE) does not represent uniform competition, as salmon may differ in their food preferences depending on species, size, age, or maturity condition.

In this study, I analyzed the food habits of salmon collected on the research vessel *Oshoro maru* along a 145°W transect line, between 50° and 56°N, in July 1994-97. In addition, I examined data collected over the oceanic seamounts at 143-147°W, 55-57°N, in the 1980s and 1990s. Using generalized additive models (GAM), generalized linear models (GLM), and graphical analysis of stomach contents data, I show the contribution of some biotic and abiotic factors to feeding variability in pink, chum, sockeye, and coho salmon. The results of these analyses reveal some of the interplay between sea surface temperature, oceanographic conditions, salmon size and maturity, catch rates, and interannual changes in salmon prey.

Along the 145°W transect line in the 1990s, CPUE data indicate that pink and coho salmon show low interannual variability in July distribution, increasing in density from south to north. Sockeye and chum salmon also increase in density from south to north, but show a southerly peak of distribution in 1994 and 1996 at local temperature minima. This peak may be due to salmon clustering around temperature minima, increased catchability at minima, or salmon aggregation at the oceanographic transition between the Subarctic Current and the Ridge Domain. The southerly limit of salmon distribution does not correspond with a precise temperature minimum.

Feeding along the transect line is divided into two zones, the southerly zone being a region of high squid consumption for pink, coho, and sockeye salmon, and the northerly zone having high crustacean zooplankton consumption for pink and sockeye salmon. Chum salmon primarily consume gelatinous zooplankton in both zones. The divide between these two zones varies by species and year; for example, in 1996 coho consume squid along the entire transect line.

Examination of interannual variability over the seamount area reveals similar stomach content indices (SCI=(prey weight* 10^6)/(salmon body weight)) values for all species in the 1990s, regardless of prey species consumed. The one exception is in 1996, in which coho salmon have an extremely high SCI due to the extension of squid into northern regions (Fig. 1). In addition, pink salmon have a significant odd/even cycle in SCI due to euphasiids, with high euphasiid catches in odd years. This differs from the southern region, where pink salmon have significantly higher squid consumption in even years. SCI increases with temperature for all species, although the highest temperature ranges are found only in 1997.
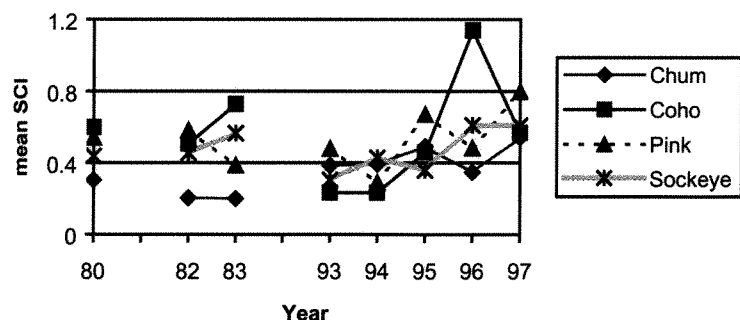

Fig. 1. Mean SCI (prey weight*10^6/body weight) of four salmon species in the seamount area (143-147°W, 55-57°N).

Examining SCI variation by individual body weight of salmon reveals differences between salmon species. Chum salmon show a constant volume of food as body weight increases, possibly due to constraints of feeding on gelatinous zooplankton. Coho salmon eat an increasing percentage of body weight per day, perhaps due to an increasing ability to catch squid. Sockeye salmon food consumption differs by age and body weight, with younger, smaller (1-ocean) age class of fish having twice the SCI of older fish. Finally, pink salmon eat a constant percentage of body weight per day for all sampled size ranges, although they show an ontogenetic prey shift from small zooplankton to squid as their body weight increases (Fig. 2). Bioenergetic models indicate that the body weight decreases in pink salmon in recent years may have shifted the adult pink salmon prey base substantially away from squid towards zooplankton.

Measures of density dependence, by comparing CPUE of salmon to salmon stomach contents, reveals a weak inverse relationship between CPUE and SCI of squid and euphasiids in all salmon species. This trend is dominated by the 1995 data, a time of extremely high CPUE and low stomach contents weight.

Finally, the ratio of individual diet diversity to group diet diversity varies interannually in a statistically similar manner between salmon species, regardless of differences in total diversity or prey items consumed, and independent of SCI or density dependence. This indicates that a factor other than prey type or availability may act on salmon feeding behavior, possibly arising from prey patchiness forced by interannual differences in pelagic mixing.
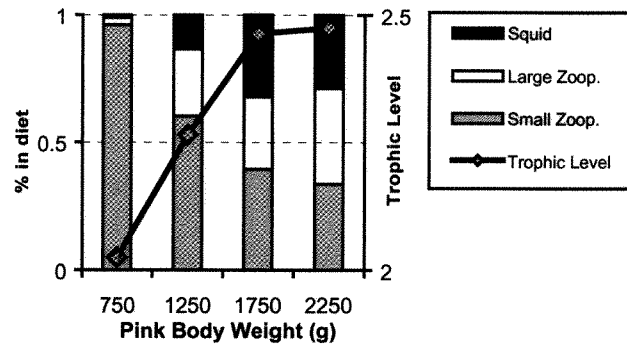
Fig. 2. Change in July high seas diet and trophic level of maturing Gulf of Alaska pink salmon with changing body size. Shift in mean body weight of some stocks between 1970s and 1990s is between 1750g and 1250g size categories above.

The State of the N.E. Pacific Ocean January-June 1997

Howard Freeland
Institute of Ocean Sciences
Sidney, B.C. V8L 4B2, Canada

Figure 1a, b, and c shows the monthly mean sea-surface temperature (SST) anomalies in the eastern North Pacific from January 1997 through February 1998. The period was dominated overwhelmingly by the surprising events developing in the equatorial Pacific. The development of the 1997/98 El Niño was a surprise by itself, but the development so very early in the year was nothing short of astonishing.
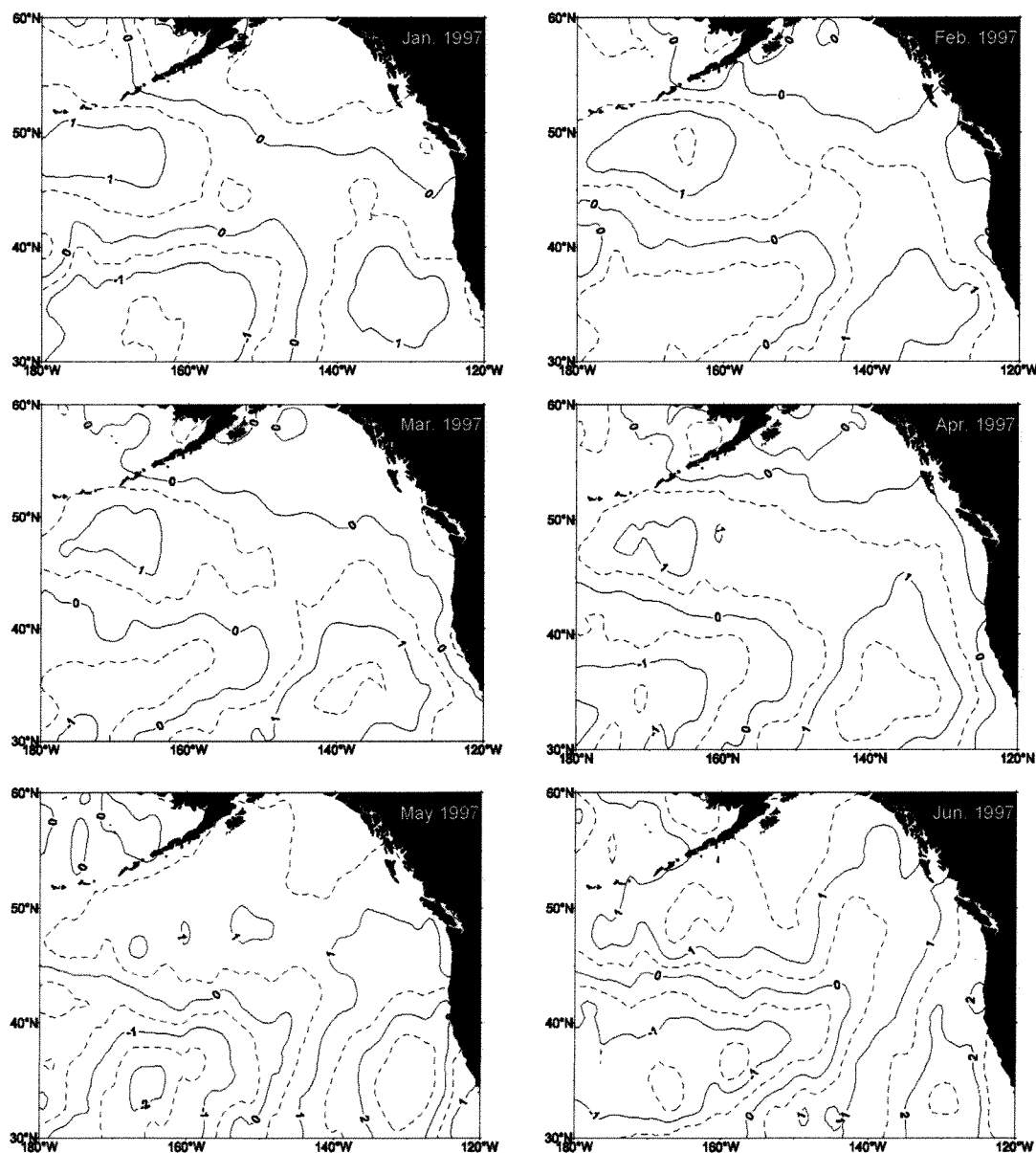

Fig. 1a.   Monthly mean sea-surface temperature anomalies for the eastern North Pacific Ocean, from January through June 1997, inclusive. The solid contours are at intervals of 1°C, and dashed contours at intervals of 0.5°C.

Fig. 1b. Monthly mean sea-surface temperature anomalies for the eastern North Pacific Ocean, from July through December 1997, inclusive. The solid contours are at intervals of 1°C, and dashed contours at intervals of $^1/_2$°C.

Fig. 1c. Monthly mean sea-surface temperature anomalies for the eastern North Pacific Ocean, from January through February 1998, inclusive. The solid contours are at intervals of 1°C, and dashed contours at intervals of 0.5°C.
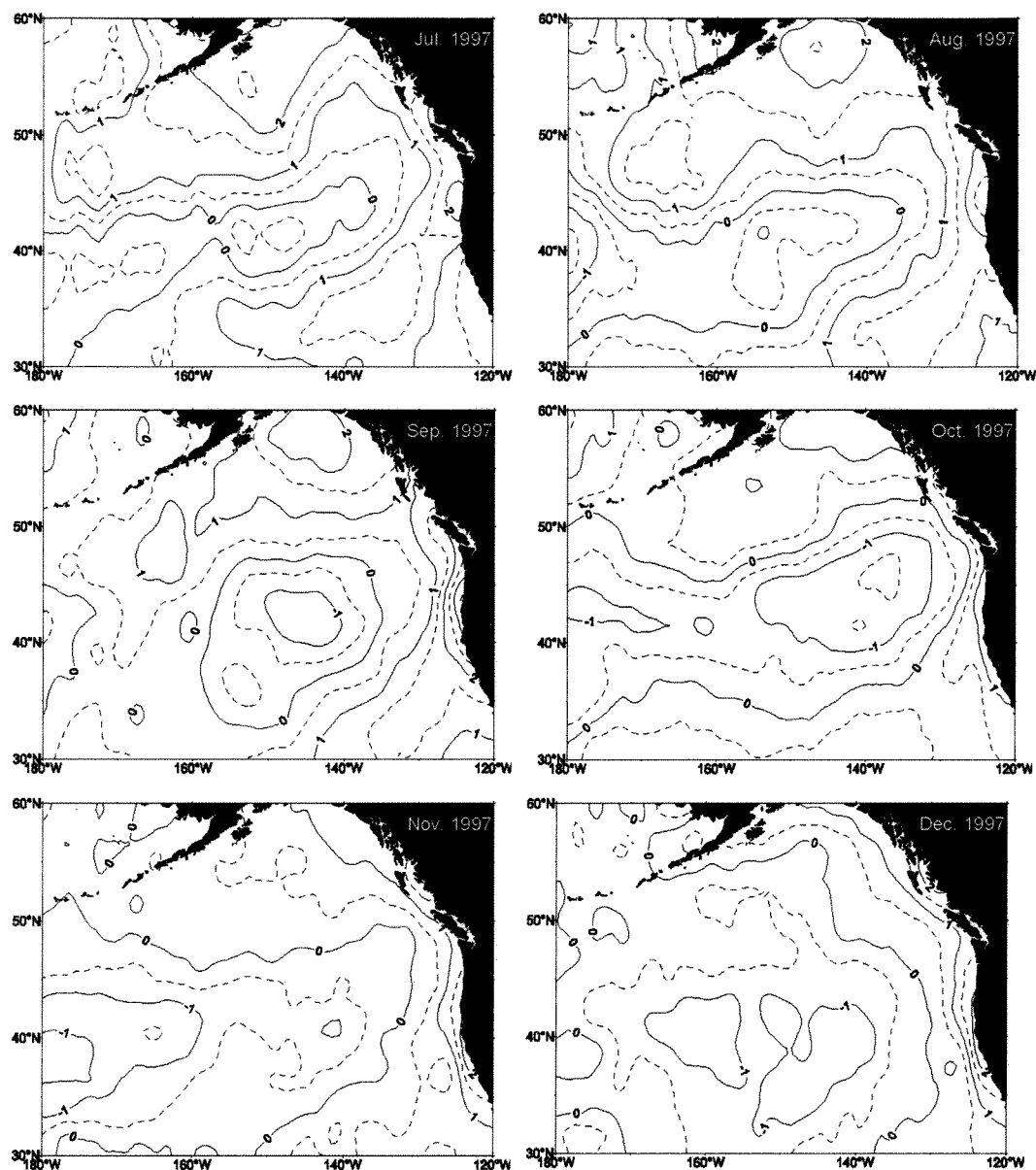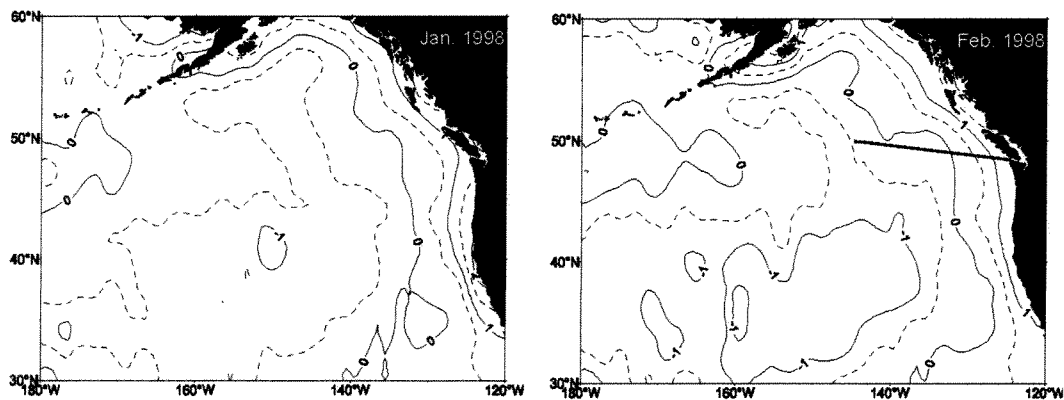
The SST anomalies show that conditions were close to normal at the beginning of 1997 (Fig. 1a, b, and c). In the Gulf of Alaska, SSTs were even marginally below normal in January through April. In March, the first indications of an incipient El Niño became apparent to anyone who was watching sea-level changes on the equator. The event developed with great rapidity. By May 1997 extreme warm anomalies appeared off California, while SSTs remained near normal in the Gulf of Alaska (Fig. 1a). By June the anomalies penetrated through the entire northeastern Pacific, and were heading towards the dateline along the Aleutian Islands. The pattern of anomalies displayed in June 1997, positive SST anomalies around the coast of North America, and negative anomalies in the central Pacific, is the classic pattern of response of the northeastern Pacific to El Niño forcing. This pattern is observed in response to all El Niño events.

The most intense anomalies shown here occurred in September 1997 (Fig. 1b). In support of that, at the B.C. lighthouses (where sea surface temperatures have been observed daily for 65 years) the highest monthly mean surface temperatures ever recorded were observed at the west coast stations in September. Though anomalies off western Canada remain high, the tongue of high SST that previously extended along the Aleutians past the dateline shows evidence, in early 1998, of retreating to Kodiak Island.

Figure 2 shows a plot of the subsurface temperature anomaly field observed during the outbound trip along Line-P during February 1998. Line-P extends from the mouth of the Juan de Fuca Strait (southern Vancouver Island) to Ocean Station Papa at 50°N and 145°W, and is indicated by a bold line on the February 1998 panel on Fig. 1c. The section is in general agreement with the sea surface temperature chart for February indicating near-normal conditions along most of Line-P. Also in agreement with the surface maps, the largest anomalies are close to the coast of Vancouver Island. However, the surface chart is striking in that it shows the largest anomalies subsurface between depths of 100 m and 200 m. In this respect the anomaly pattern is very similar to the anomalies observed along Line-P in March 1983.

Fig. 2. Temperature anomalies observed during the February 1998 Line-P cruise.

The sea-level response demonstrates the magnitude of the impact of the 1997/98 El Niño on the coast of British Columbia. Sea level is standing, as of early March 1998, about 35 cm above normal. This anomaly is larger than the anomaly that occurred in 1983, and indeed has set new record anomalies around the coast of British Columbia.

Finally, no discussion of the state of the Pacific Ocean would be complete without some speculation about what the future holds. Figure 3 shows a plot of the southern oscillation index (SOI) observed daily by the Queensland Department of Natural Resources and the Department of Primary Industries in Australia. By mid December 1997, the southern oscillation index had returned close to normal. However, through January there was a slow trend towards increasingly negative values culminating at the end of January and beginning of February in a large "westerly wind burst." This burst of El Niño-like activity on the equator was also clearly visible in the wind field observed on the equator by the Tropical Atmosphere-Ocean array. Since then, the index has fluctuated but remained persistently negative.

Fig. 3. Daily values of the southern oscillation index from January 1st 1998 to present.

Thus it is too early to claim that the 1997/98 El Niño is over, even on the equator. At higher latitudes, SSTs remain high over large regions of the North Pacific. Further, the positive anomalies are distributed well down in the water column. The excess heat cannot be removed from the ocean in short order, thus the 1998 fishing seasons in the N.E. Pacific will be influenced by the 1997/98 El Niño.
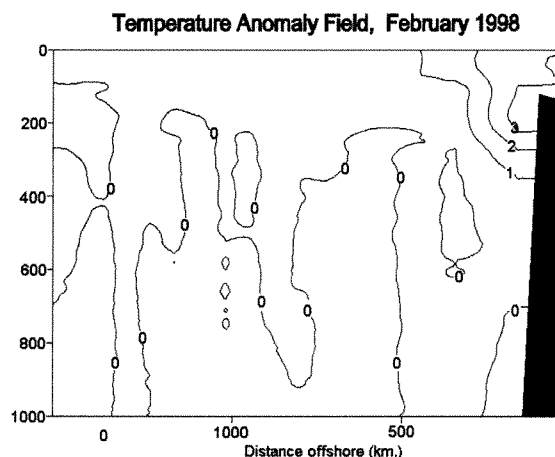
Ecosystem Anomalies in the Eastern Bering Sea During 1997

J.D. Schumacher[1], P.J. Stabeno[2], N.A. Bond[3], and J.M. Napp[4]

[1]Two Crow Environmental Consultants, PO Box 215, Silver City, NM 88062
[2] Pacific Marine Environmental Laboratory/NOAA, Bldg. #3,
7600 Sand Point Way NE, Seattle, WA 98115
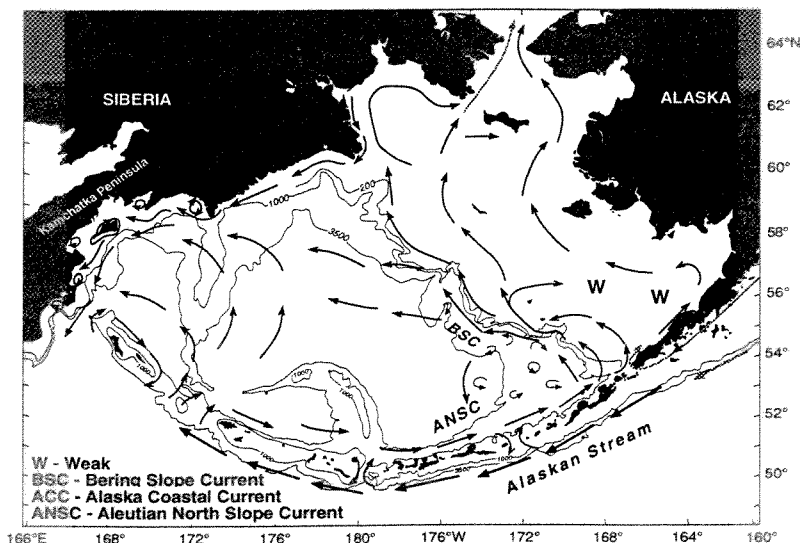[3]PMEL/JISAO, 7600 Sand Point Way NE, Seattle, WA 98115
[4]Alaska Fisheries Science Center/NOAA, Bldg. #4,
7600 Sand Point Way NE, Seattle, WA 98115

During summer 1997 much of the eastern shelf of the Bering Sea experienced an anomalous bloom of coccolithophorids, which was first observed as aquamarine waters from ships during July (Fig. 1; Vance et al., in press; Stabeno 1998). The bloom was also clearly visible from space, as shown by some of the first images from the multispectral Sea-viewing Wide-Field-of-view Sensor (SeaWiFS) scanner in September. Between August and September, reports of moribund and dead short-tailed shearwaters came from biologists and the public on both sides of the Alaska Peninsula including Bristol Bay. The sockeye salmon run in Bristol Bay was far below expectation: an estimated 5–12 million animals failed to appear in the fishery, which was declared a "commercial failure" (Fisheries 1998). At the same time, significant numbers of large baleen whales were observed foraging within the milky waters (Tynan 1998). Chlorophyll-a concentrations during the bloom were low in agreement with such blooms in other regions of the world (e.g., North Sea, Gulf or Maine; Fig. 2). The tiny phytoplankton cells contain little chlorophyll-a or particulate organic carbon, but they make a large impact on water color. Concomitant with these changes in the biological environment, anomalous conditions were evident in many of the features of the physical environment.

Much of the eastern Pacific Ocean exhibited warm sea surface temperature (SST) anomalies during 1997. The SST anomaly extended northward from the equator, where El Niño conditions existed.

Fig. 1. A schematic of upper ocean circulation in the Bering Sea. Bering Canyons is located at about 54°N, 166°W, and the chlorophyll-a time series was collected at 56.9°N, 164°W (Site 2; after Stabento et al., in press; Schumacher and Stabeno, in press.)

Fig. 2. Time series of concentration of chlorophyll-a at Site 2. Note the spring bloom in early April and the gradual increase during summer. The blooms in september followed storms. (These data are preliminary.)
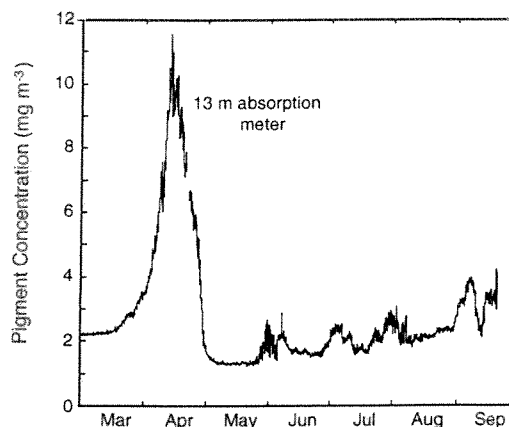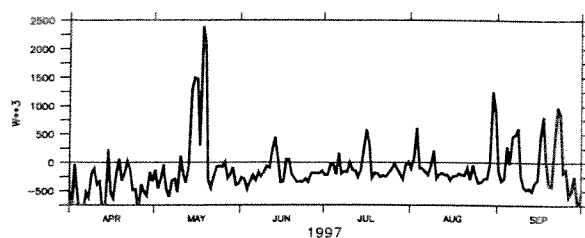
Fig. 3. Time series of the anomaly of the daily wind speed cubed using observations from St. Paul Island. Note the event in mid-May. The mean was defined as the daily average wind speed cubed from 1950-1996.

The signal in the Bering Sea, however, resulted from regional wind mixing and heat exchange with atmosphere, rather than propagation of an oceanic anomaly from the equator. As occurred in recent years (Stabeno et al. in press), an early spring diatom bloom (about 12 mg/m^3) was associated with sea ice (Napp et al. 1998). By the end of April, chlorophyll concentrations had decreased to pre-bloom values. During April, winds were unusually weak, and these conditions generally persisted through August. The anomaly in wind speed cubed (a proxy for mixing), follows the same general pattern as the winds (Fig. 3). A striking mixing event, however, did occur in mid-May. The impact of this storm was to mix the upper 45-50 m, thereby making nutrients from the lower layer available in the upper water column. This reduce d the reservoir of nutrients typically found throughout the summer in the lower layer (Napp et al. 1998). While ice extent wa s rather typical, melt-back was rapid, and, together with the weakness of the vertical salinity structure, this suggests a minimal flux of low salinity water. As a result, the pycnocline was shallow but weak throughout the summer, permitting further depletion of nutrients. This likely occurred through both a vertical flux of nutrients across the pycnocline to the surface and net photosynthesis or both below the mixed layer throughout the summer. An examination of heat content revealed that it was similar to that in the previous year. The heat, however, was concentrated in a shallow mixed layer. The extreme SST anomalies appear to be due primarily to the lack of winds, rather than to increased solar radiation resulting from reduced cloud cover. This warm upper layer extended over portions of the coast al domain into waters as shallow as 35 m. In general, the coastal domain waters are mixed. One consequence was that the transition between coastal and middle shelf water was poorly defined and 10s of kilometers wider than previously reported (Schumacher and Stabeno, in press). The changes in structure likely affected the usual biophysical d ynamics that result in primary and secondary production throughout summer.

While biophysical processes likely account for much of the nutrient depletion on the shelf, a change in the flux from source waters may have exacerbated this situation. Observation s of temperature and salinity versus depth were collected along a slope/shelf transect. In spring 1997, transport in bo th the Aleutian north Slope Current (ANSC) and the Bering Slope Current was unusually large, $>6 \times 10^6$ m^3 s^{-1}, whereas transport is typically $<4 \times 10^6$ m^3 s^{-1}. Moored current records from the ANSC revealed strong consistent flow, supporting the inference of strong flow and showing that the flow was steady this year. How the e nhanced strength of these currents affects shelf/slope exchange is not known. The flux of oceanic water through Bering Canyon also is a source of nutrients for the shelf (Schumacher and Stabeno, in press). During 1997, satellite tracked drifters revealed that little or no onshelf flow occurred.

Whether a part of an interdecadal cycle or of global warming, the arctic climate is warming. A group of scientists convened in 1995 to hypothesize physical change in the Bering Sea under a globa l warming scenario (U.S. GLOBEC 1996). Among the changes they forecast were that wind mixing energy, the supply of nutrients, and ice extent and thickness would decrease, and sea surface temperature would increase. These expected changes are consistent with those observed during 1997 in the eastern Bering Sea. The associated changes in biota, however, at present defy forecasting because knowledge of biophysical process, system time lags, and life histories of many of the important species is lacking.

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Ocean Variations Along the Eastern Gulf of Alaska Due to ENSO

Steven D. Meyers[1], Arne Melsom[2], and James J. O'Brien[1]
[1]Center for Ocean-Atmospheric Prediction Studies, The Florida State University,
Tallahassee, FL USA
[2]Norwegian Meteorological Institute, Oslo, Norway

Interannual variability in the coastal upwelling and upper ocean circulation in the eastern Gulf of Alaska (GOA) is linked to the El Niño/Southern Oscillation (ENSO) phenomenon in the tropical Pacific Ocean, largely via coastal Kelvin waves. Results from a high-resolution six layer, isopycnal, wind-forced Pacific basin model provided by the Naval Research Laboratory, Stennis, MS (NRL) are examined within the GOA. ENSO warm events are found to produce downwelling equatorial Kelvin waves that propagate into the GOA as coastally trapped waves. These waves suppress upwelling along the western coast of North America. Sufficiently large waves destabilize the Alaska Current, creating multiple strong anticyclonic eddies along the coast that slowly propagate into the GOA, where they survive for more than one year. The typical diameter of the anticyclonic eddies is <=200 km. These eddies are strongly baroclinic, with a typical value for the velocity difference between layers 1 and 2 of 15 cm/s. Cold El Viejo (La Niña) events generally suppress eddy formation in the GOA by stabilizing the coastal circulation. Observed sea level variations are similar to model results.

The numerical model used in this study is the NRL Pacific basin multi-layer model (Wallcraft 1991), which is based on the semi-implicit, free surface model of Hurlburt and Thompson (1980). The model is formulated using an Arakawa C-grid. The daily 1981-1995 surface windstress product from the European Center for Medium Range Forecasting, with the monthly climatology replaced by the Hellerman-Rosenstein climatology, drives the ocean circulation. Recent results from this class of models and additional model description is given by Hurlburt et al. (1996).

The 1/12-degree ETOPO5 bottom topography data set is used in order to include effects of realistic bathymetry. The topography data set was first interpolated to the model grid and then smoothed with a 9-point smoother. This is to reduce the energy generation at small scales, which are poorly resolved by the model. In the model integration, the amplitude of the topography above the maximum depth of 6500 m was multiplied by 0.78 to confine it to the lowest layer. The model includes realistic coastline geometry, determined by the 200-m depth contour of the ETOPO5 topography, which is the minimum depth in the model and represents the shelf break. The model domain extends from 20°S to 70°N latitude and has a horizontal resolution of 0.0625-degree in latitude and about 0.083-degree in longitude.

Model results indicate anticyclonic eddy formation along the eastern GOA nearly every winter of the 1981-1995 run. The eddies drift westward. The non-ENSO year eddy amplitude is about a +15 cm deviation of the sea surface height (SSH). The nominal diameter of these eddies is 60 km, and their lifetime is 1 to 1.5 years. Following the 1982/83 El Niño, eddy amplitudes reached roughly a +45 cm deviation with diameters of nearly 200 km (Fig. 1). These eddies are also long-lived, lasting over 1.5 years. These are large compared to the net SSH change across the model GOA of 80 cm, and much greater than the change across the Alaska Current. Therefore the large eddies represent a disruption of the Alaska Current by ENSO.

No anticyclonic eddies were found following the 1988/89 cold event, but cyclonic patches with amplitudes around -20 cm were found in the model. This suggests an asymmetry between the warm and cold ENSO events. The downwelling waves of the warm event strengthen the Alaska Current, steepening the isopycnals until instability occurs. The upwelling cold events flatten the isopycnals and stabilize the system. Sufficiently strong along-shore wind events associated with ENSO can have a similar effect (Ramp et al. 1997).

A match-filter technique is employed to detect eddies from TOPEX/Poseidon (satellite instrument) altimetery along a single track in the eastern GOA during late 1992 through 1996 (Meyers and Basu 1998). Anticyclonic and cyclonic eddies have similar spatial distributions, with most occuring between 50°N and the northern limits of the GOA. Anticyclonic eddies have a broad distribution of amplitudes (5-20 cm) compared to cyclonic features, which are almost normally distributed over 5-13 cm. The average amplitude of anticyclonic eddies increases following the 1994/95 El Niño and decreases following the 1995/1996 El Viejo. A similar result was found by Matthews et al. (1992).
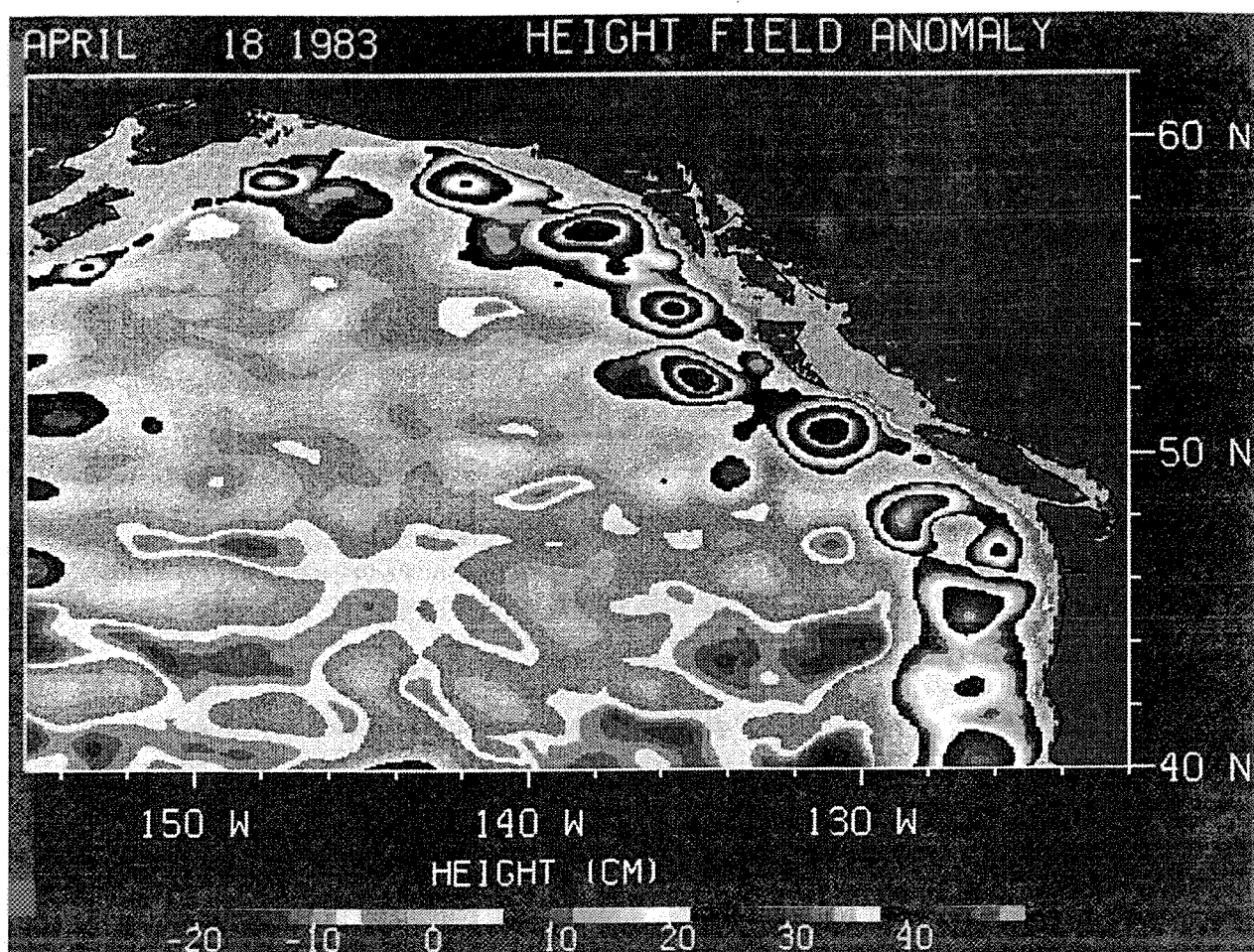
Fig. 1. Sea surface height anomaly (minus the 1981-1995 mean) following the 1982/83 El Niño. Eddies for due to the destabilization of the Alaska Current by a coastal Kelvin wave.

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III. Workshop Review

A growing body of scientific evidence supports hypotheses about the direct and indirect effects of environmental change on fish production. These effects are often a consequence of complex changes in marine and freshwater ecosystems. The causal mechanisms linking the various physical and biological processes are neither completely defined nor understood, but there is general consensus that these links exist.

Recognizing the importance of these issues, the North Pacific Anadromous Fish Commission (NPAFC) hosted a 2-day workshop to examine evidence from around the Pacific rim on the effects of climate change on the production of Pacific salmon. Discussions focused on the oceanographic conditions and trends in the North Pacific (particularly in 1997), changes in primary productivity both in terms of biomass and species composition, trends in regional and global indices of climate change, and the effects of biological and oceanographic factors on the production of various Asian and North American salmon stocks. While it was clear that El Niño resulted in anomalous conditions in 1997, there was also a recognition that longer term decadal-scale trends in climate were also affecting salmon production.

Salmon catches in the North Pacific have undergone significant fluctuations in the past 70 years, and have been at or near historic high levels (about 900,000 t) in the last few years. Some of this observed increase can be attributed to the significant salmon enhancement activities around the Pacific rim, but evidence presented at this workshop suggests strong connections between climate change and subsequent increases in marine productivity and survival. For example, a strong correspondence between salmon catch and the Atmospheric Climate Index (ACI) in the northern hemisphere indicates that salmon production increased naturally because of a shift to a more productive regime in the late 1970s. A number of speakers at the workshop noted similar patterns (synchronous shifts) in other indices of climate change, supporting the concept of decadal-scale shifts between low- and high-productivity regimes. Evidence presented at the workshop suggests there may have been a shift to a new productivity level (regime) in the late 1980s or early 1990s, but this shift was not a return to the pre-1977 levels. If confirmed, then this shift would at least partially account for the observed changes in salmon catches in the 1990s, particularly for North American stocks.

The effects of the 1997 El Niño continue to influence oceanographic conditions particularly along the North American coast, and are expected to persist for some time. There is still no clear pattern developing for 1998, and no bold predictions either for or against renewed El Niño conditions were ventured at the workshop. There was some recognition by participants that La Niña or the colder climate (reverse) equivalent of El Niño also had dramatic influences on our climate, ocean conditions, and fish stocks. However, the La Niña phenomenon has received considerably less attention than El Niño, and this should change. Although both types of extreme events are likely to cause transient changes in coastal ecosystems, there was no strong evidence to link either El Niño or La Niña events to longer-term shifts in productivity. These events may signal or perhaps even trigger longer-term shifts in productivity, but these isolated and random events do not account for the observed persistent trends in salmon productivity.

There was a recognition that environmental conditions need to be explicitly accounted for in our assessment and management of fish stocks. This concept is not new and indeed has been alluded to in the process of explaining away large discrepancies encountered with traditional fisheries models. What is new is the relative importance given to the environment and ecosystem changes. The effects of climate change on fish production are now being given nearly equal consideration to the competing hypothesis that fish production is governed solely by an intrinsic stock-recruitment relationship and fishing. In reality, all of these factors are important, and ways must be found to incorporate all of the relevant information when assessing and managing fish populations. Such fundamental changes in approach will require time and, above all, education both within and outside the scientific community. The NPAFC Workshop on Climate Change and Salmon Production and efforts in other related programs will help speed the process. However, much work remains to be done. There is a need to continue both regional and global studies on climate change and fisheries, and international collaboration is essential to resolve this important issue.

Donald Noakes
Coordinator of the Workshop Steering Committee