

Pacific salmon: climate-linked long-term stock fluctuations

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Dr. Leonid Klyashtorin is Leading Scientist at the Russian Federal Research Institute of Fisheries and Oceanography (VNIRO, Moscow, Russia). For 15 years he studied primary productivity of the Southern Pacific (1958-1964) and marine and freshwater fish respiration and fish swimming energetics (1965-1980). Since 1980, Dr. Klyashtorin has been working on problems of salmon ranching and wild salmon stock fluctuations in the Pacific and Atlantic Oceans. His recent research interests include the impact of global (long-term) climate changes on the populations of the main commercial marine pelagic species and inter-relation between ocean carrying capacity limitations and the dynamics of wild salmon populations.

INTRODUCTION

The impact of large-scale climate change on the salmon productivity of the North Pacific is an important scientific and economical problem. Commercial catching may not always be a good indicator of abundance, but for larger aggregations of stocks we suppose that catches represent the abundance trends of the total aggregate (Beamish and Bouillon, 1993).

Reliable information on the trends of commercial catch is necessary to estimate the carrying capacity of the North Pacific for salmon. The commercial catches have been collected for more than 70 years, but the statistics of salmon catches in the 20-40s needs to be substantially corrected. (Klyashtorin and Smirnov, 1992, 1995; Chigirinsky, 1994). The dependence of the long-term fluctuations of Pacific salmon abundance on climate changes was demonstrated recently by a number of papers (Beamish and Bouillon, 1993, Klyashtorin, and Smirnov, 1995). Nevertheless, reliable predictive climatic indices for salmon dynamics still have not been determined. The main purposes of this paper are the following.

- To refine the long-term dynamics of total salmon catch and evaluate the carrying capacity of the Pacific for salmon stocks
- To determine if the climatic characteristics are correlated with salmon stock dynamics
- To outline new approaches to the forecast of the long term dynamics of Pacific salmon stocks

SOURCES AND APPROACHES

Basic data on catch statistics were obtained from the following sources: FAO Yearbook Fishery Statistics (1957-1996); Pacific Salmon Catch 1900-1986 (1989), Kazarnovsky (1987), Chigirinsky (1994), Current Fishery Statistics (1991), and Hilborn and Vinton (1993).

Time series on Global and Hemispheric anomalies of surface temperature (dT) were taken from Halpert et al, 1994. The Aleutian Low Pressure Index (ALPI) expressed as the area (millions square kilometers) bordered by 100.5 kPa isobar is recognized to be an important factor affecting the climate in the North Pacific. The time series on ALPI are published in

the paper by Beamish and Bouillon, 1993.

The Atmospheric Circulation Index (ACI or the so-called Vangengeim-Girs' Index) is the generalized data on the atmospheric activities in the Atlantic-European region for the period of more than 100 years (Girs, 1971). According to Vangengeim-Girs' approach, all visible variations of atmospheric circulation can be combined into three basic types by the direction of the air transfer: Meridional (C); Western (W), and Eastern (E).

The dominant forms of atmospheric circulation were estimated using the data from daily charts of atmospheric pressure in the North Atlantic-Eurasian region. The recurrence of each circulation form (W, E, or C) taken place during the year was expressed as "days". Annual total sum of "days" with different circulation forms is equal to 365. It was shown that the recurrence of the "days" with a dominant form of the atmospheric circulation is more conveniently expressed as "anomalies" (relative to the long-term average). Even more convenient is to use the consequent summation of the anomalies and to use the so-called "integral curve" of atmospheric circulation. Annual sums of the anomaly recurrences of all circulation forms are equal to zero:

$$SC + SW + SE = 0$$

For the last 100 years, long-term periods have been observed when some forms of atmospheric circulation dominated over the other. These periods were named "Circulation Epochs". The so-called epochs of Meridional (C) and Combined (W+E) are specified:

$$S(W + E) = -SC$$

The epoch of meridional circulation (C) dominated for the periods of 1890-1920 and 1950-1980. The epoch of the combined circulation (W+E) dominated for 1920-1950 and 1980-1990. Current (W+E) epoch is not completed yet, and will likely finish during the first decade of the next century. In this paper, the index (W+E) used as a basic characteristic of global atmospheric circulation is labeled by the abbreviation ACI (Atmospheric Circulation Index). The generalized time series on the atmospheric circulation forms for 1891-1995 (according to Vangengeim-Girs) were kindly placed at our disposal by the Federal Arctic and Antarctic Institute in St. Petersburg, Russia.

Time series on the Earth Rotation Velocity Index (ERVI) were calculated from the data of International Time Bureau (Sidorenkov and Svirenko, 1991; Klyashtorin and Sidorenkov, 1996).

RESULTS AND DISCUSSION

Reliable statistic on Pacific salmon catches started in 1920. The statistical reports do not completely cover the Asian catch dynamics for the first part of the century. For example, for 1920-40s, up to 380 Japanese fishing concessions operated in the coastal regions of Kamchatka, Sakhalin, and South Far East of Russia (Primorie). Japanese drifter catch in the 50-mile coastal zone was also highly developed. It was shown that the average Japanese catch (primarily of chum and pink salmon) in the Soviet Far East in 1920-1943 was about 200 thousand tons, and in some years it reached 370 thousand tons (Kazarnovsky, 1987; Chigirinsky, 1994).

Refined data on the Pacific salmon catches for 1929-1994*) are presented in *Figure 1a*. A specific "Saw-like" shape of the curve displays interannual fluctuations of the pink salmon abundance. The contribution of the latter to the total salmon catch in the North Pacific is 35-40%. The 5-year average (*Figure 1b*) gives a visual indication of the long-term periodicity in the salmon catches. The catches increased in the 1920-1940s. From 1936 to 1942, the average catch was more than 900 thousand tons (and about 1000 thousand tons in 1937 and 1941). In 1944, the salmon catch decreased sharply, due to the destruction of the Japanese fishery caused by the Second World War. In 1948, the catch dropped to 1 thousand tons (!), and the average catch for 1946-1953 was as low as 8 thousand tons. We tried to restore the catch trend taking into account the collapse of Japanese salmon fishery in this period. *Figure 1b* illustrates the probable total catch dynamics (dashed line). In the 1950-60s (the period of salmon stocks depression), the total salmon catches dropped to 400 thousand tons.

Beginning in the 1970s, the salmon catch started to rise again. It increased most sharply in the 1980s, but slowed down in the 1990s. In 1991, 1993, and 1994, the total catch was somewhat higher than 900 thousand tons, and in 1996 (according to preliminary data) it will likely exceed 1000 thousand tons for the first time since the 1930s.

The rough long-term dynamics of the total salmon catch in the North Pacific for the 20th century is the following: the period of growth in the 20-40s, depression in the 50-60s, and recent rise in the 80-90s.

*) *Data on catches used in the paper are available from PICES Secretariat based on personal request.*

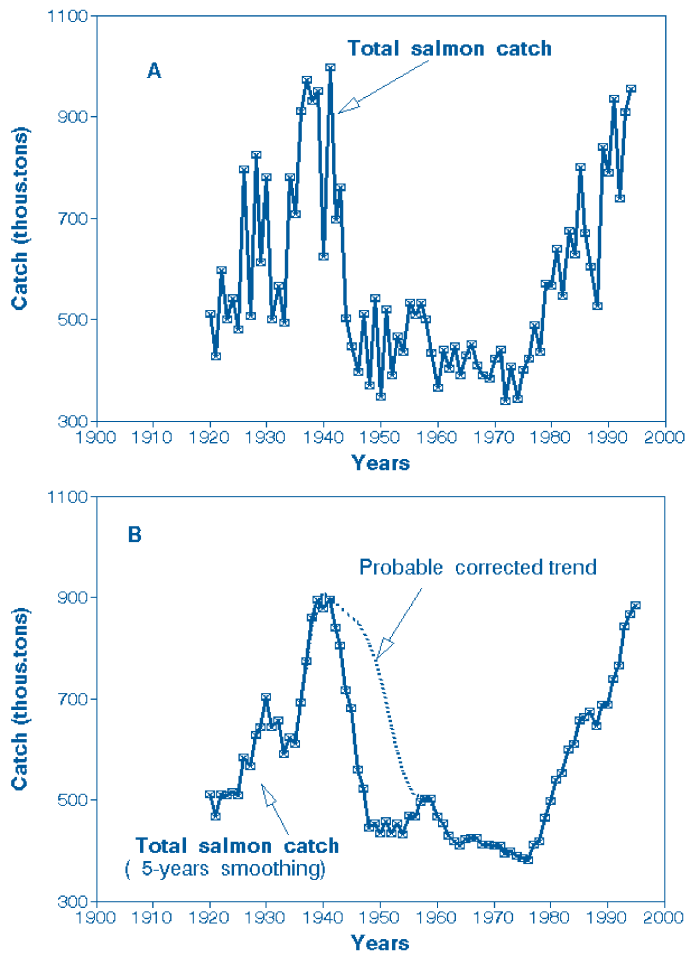


Fig. 1 Total Pacific salmon catch according statistics data (A) and smoothed catch trend with corrections for suspension of Japanese salmon fishery in 1942-52 (B).

Dynamics of Asian and American Salmon Catches

The dynamics of salmon catch from each continent is generally similar but there are individual specifics (Figure 2). In the late 30s, the Asian salmon catch was 550 thousand tons and exceeded the American salmon catch by almost 200 thousand tons. During the depression in the 50-60s, the American and Asian salmon catches have dropped to an equal level of about 200 thousand tons. The catch of “American” and “Asian” salmon started to rise simultaneously in the middle of the 70s.

American salmon catch increased rapidly, and to the 90s it exceeded the level of the 30s by 150 thousand tons on average. The Asian salmon stock increased slower than the American stocks, and in the 90s the Asian catch was 160 thousand tons lower than the corresponding figure in the 30s. This difference is due to the special reproduction characteristics of American and Asian salmons for the last 60 years.

Dynamics of Rached Salmon Catches

In the 30s, artificial reproduction of Pacific salmon was of no particular importance. Period of “salmon stock depression” in the 50-60s has stimulated the development of salmon ranching. In Japan, the catches of rached chum have increased by almost 200 thousand tons since the early 60s, and have stayed stable at this level for the recent decade (Shirahata, 1985; NPAFC, 1994, 1996). In Canada, the program development of salmon ranching started in the early 70s. Annual catches of rached chum, pink, and red salmon are now approximately 12 thousand tons (Hilborn and Winton, 1993). In the USA, the catches of rached salmon (primarily pink and chum salmon in Alaska) reached 30-35 thousand tons in the late 80s, and fluctuated around this level in recent years (Meacham and Clarck, 1994; NPAFC, 1994, 1996; FRED, 1989, 1990, 1992). The production of rached salmon in Russia is approximately 15-20 thousand tons, primarily pink salmon.

The total catch of the rached Pacific salmon is now around 240-280 thousand tons, which is more than a quarter of the total salmon catch in the North Pacific region. The proportion of rached salmons in the Asian catch is about 50% (45-50%), and the corresponding figure for American salmon is about 10% (8-12%).

The geographic distribution of salmon reproduction has significantly changed since the 30s. In the 30s, the chum salmon reproduced in Japan provided no more than 3% of the regional catch. In the last decade, up to 85-90% of Asian chum was reproduced in the hatcheries of Hokkaido and Honshu. The catches of rached chum exceed historical total catches of Japan-originated salmon by a factor of 5-7.

Dynamics of Wild Salmon Catch

The total catch of wild Pacific salmon in the 90s decreased by approximately 250 thousand tons compared to the 30s. This “deficit” is not uniformly distributed throughout the Asian and American continents, first noticed by Jackson and Royce (1986). The catch of Asian-originated wild salmons in the 90s decreased by approximately 350 thousand tons compared to the 30s. Correspondingly, the catch of American-originated wild salmons increased

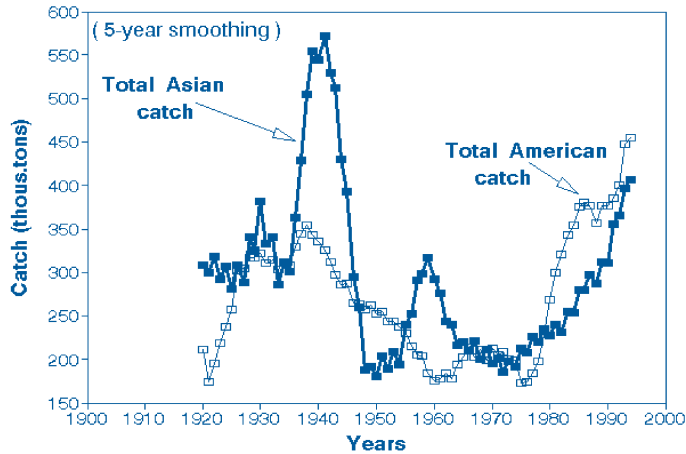


Fig. 2 Asian and American salmon catch 1920-1994.

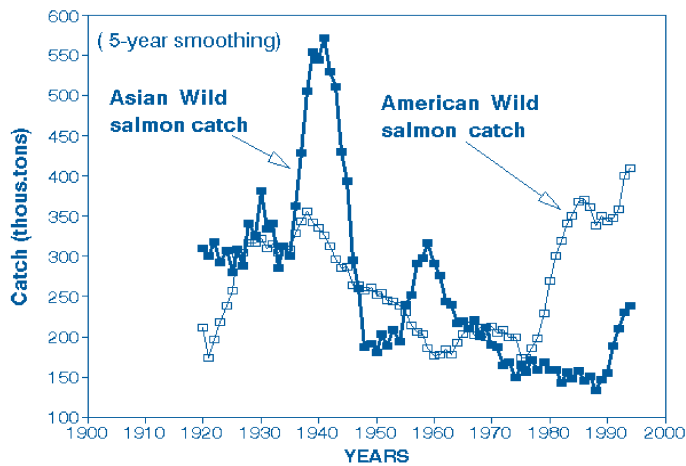


Fig. 3 Asian and American wild salmon catch 1920-1994.

100-110 thousand tons (Figure 3). The increase in the production of wild American salmons observed in the 70-90s has resulted from a significant rise in the reproduction of natural stocks of red and pink salmons in Alaska.

In the late 30s, annual catch of pink and chum salmon in the coastal regions of Northern and Southern Kuril Islands was 90 and 60 thousand tons, respectively. In the 80-90s salmon catch in this region did not exceed 40 thousand tons, i.e. was reduced by about 100 thousand tons compared to the 30s. In the late 30s - early 40s, average salmon catch in the Russian South Far East (Primorie) was about 10 thousand tons, and now it does not exceed 1 thousand tons. The main reason of this tenfold decrease is the degradation of spawning area in local rivers caused by mining and industrial wastes, removal of the coastal forests, and poaching. The salmon catches in the Amur river dropped since the 30s by 25-30 thousand tons for the same reasons.

The number of fishing industry installations in the West Kamchatka has decreased tenfold since the 30s. In the period of rapid elevation of salmon populations in the 70-80s, commercial salmon stocks of the West Kamchatka were underutilized, which resulted in the spawning area being overcrowded by highly-abundant generation of pink salmon, followed by a decrease in the salmon abundance according to the well-known mechanism (Ricker, 1954).

Estimates suggest that underutilization of commercial pink salmon stock in the years of highly productive generations reaches 100-150 thousand tons (Personal communication of professor V.P. Shuntov, Pacific Institute of Fisheries and Oceanography, TINRO, Vladivostok, Russia). Thus, since the 1930s, wild salmon catches in the North Pacific have decreased by about 250 thousand tons, and the ranched salmon catches correspondingly increased by 250-280 thousand tons. Therefore, it can be suggested that “disappeared” wild salmons were “substituted” in the oceanic feeding area by ranched salmons, and total catch in the North Pacific in the 90s returned to the historical maximum (about 1000 thousand tons) of the 30s.

Estimation of the North Pacific Carrying Capacity for Salmon

Carrying capacity of the North Pacific for the salmon can be roughly estimated from the assumption that the salmon fishery catches about 70% of the spawning population. Total annual production of salmons in the North Pacific feeding area can be assessed as about 1400 thousand tons. It can be conceived that the population of wild salmon now is at the level of the 30s, however with the same amount of ranched juveniles. Then, the total population of young salmons (wild and ranched) in the feeding area would be significantly greater than the present. In this case, an overpopulation of the feeding area is quite possible, accompanied by intense competition for food resources and retardation of fish growth.

Decrease in mean individual weight of salmons from high-abundant generations is a well-known

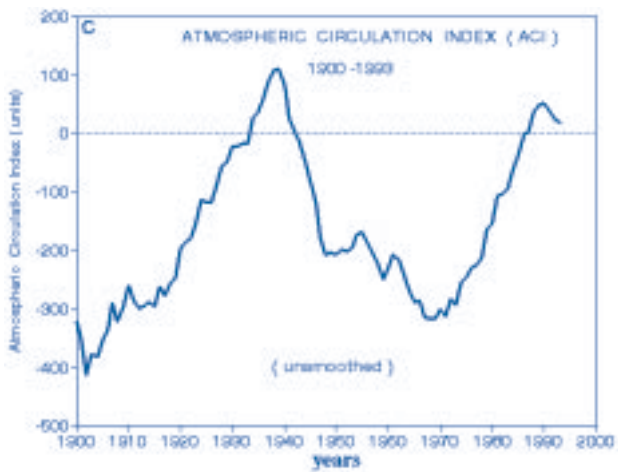
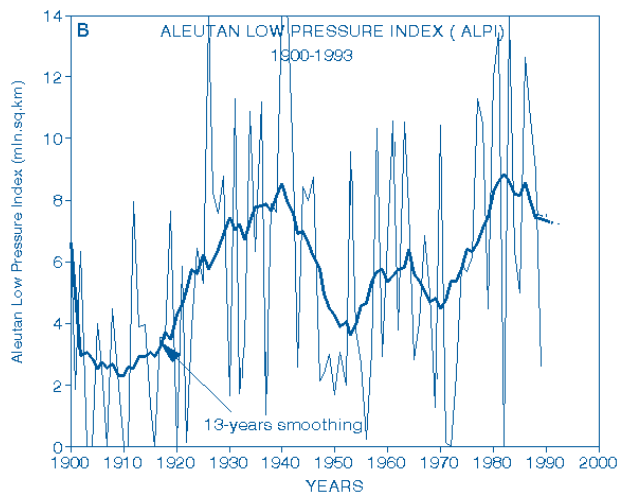
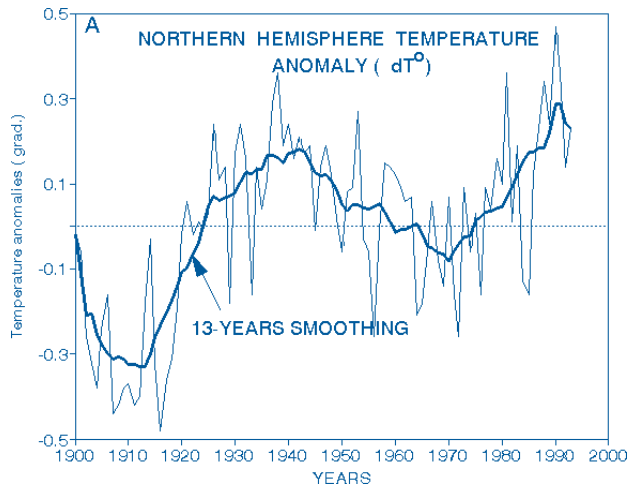


Fig.4 Trends of the Northern Hemisphere air surface Temperature Anomalies (A), Aleutian Low Pressure Index (B) and Atmospheric Circulation Index (C) 1900-1993.

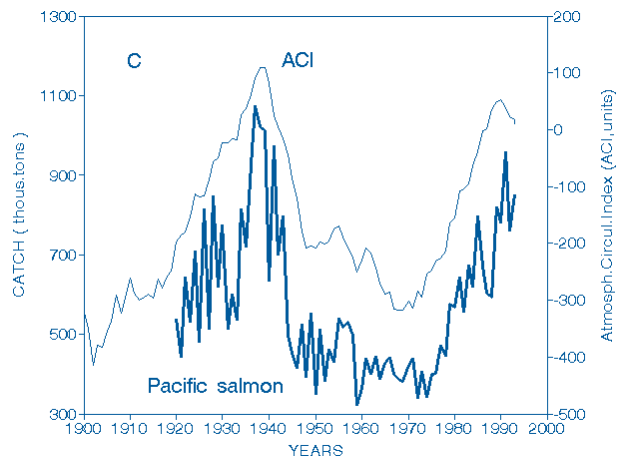
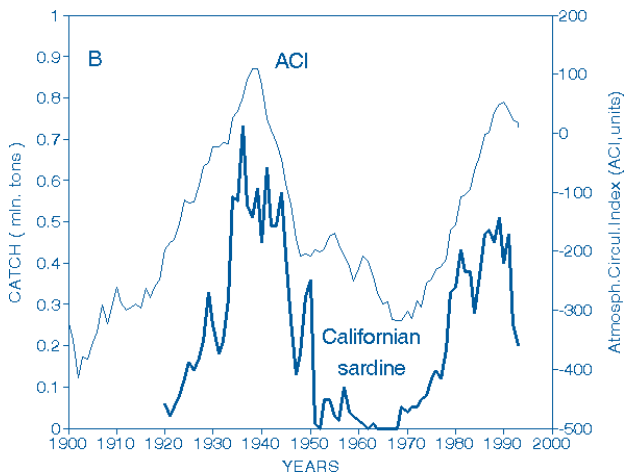
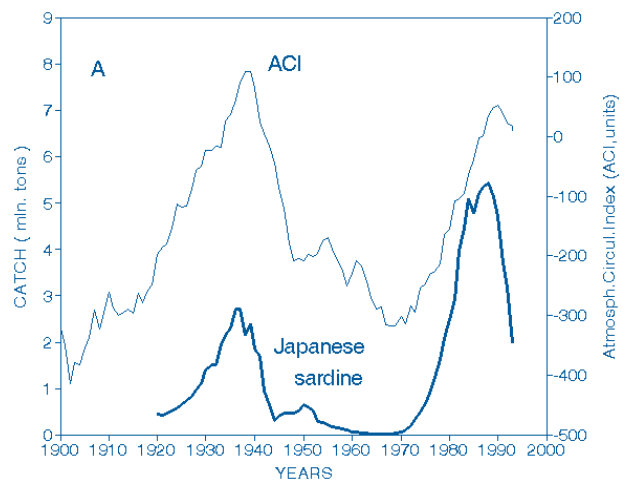


Fig.5 Salmon and sardine commercial catch in the Northern Pacific and Atmospheric Circulation Index (ACI) trend 1900-1993. A - Japanese sardine; B - Californian sardine; C - Pacific salmon (All series are unsmoothed).

phenomenon (Pravdin, 1940, Anonymous, 1992; Heard, 1993; Bigler et al., 1995). This is particularly well defined for pink salmon: the differences between the mean weight of the individuals from low- and high-abundant generations can be as large as 30-40% (Ishida, 1966). Despite the decrease in the individual weight, the total catch increases manifold in the years of a highly-abundant generation return. This is evidence of the existence of a high biomass of food resources in the salmon feeding area, and on the other hand, it is a sign of the individual competition for food resources.

It appears that the annual release of more than 2 billion chum juveniles from Japanese hatcheries should increase the density of young salmon in the feeding area, aggravate food competition, and decrease commercial returns. However, the amount of adult chum returning to the Japanese coast is roughly proportional to the amount of juveniles that has been released to the ocean (Kaeriyama, 1989). A decrease in the mean individual size was registered in the case of more than 1 billion juveniles released. The release of each extra 250 thousand chum juveniles (after 1 billion) diminishes the mean weight of individual adults by 3-4%. Therefore, the potential decrease in the total ranched chum salmon production in response to the release of 2 billion juveniles should be about 10% (i.e. about 20 thousand tons of total commercial chum catch from 200 thousand tons expected). Even maximal (or close to maximal) increase in the juveniles abundance in the feeding area does not bring about lowering of the salmon survival, but somewhat retards salmon growth in the ocean. It may be suggested that total salmon production from the Pacific can be increased by 10-20% above the present level.

It must be emphasized that the carrying capacity of the oceanic feeding area for Pacific salmon undergo significant long-term fluctuations. Based on the catch statistics and above-mentioned suggestions, the level of carrying capacity of North Pacific for salmon can be approximately evaluated as 1400-1700 thousand tons in the period of maximal oceanic production to 600-800 thousand tons in the minimum. These variations correspond to the long-term fluctuations of feeding conditions in the ocean. The evidence was found in a large-scale doubling of summer zooplankton biomass in the Pacific between the 50-60s and 80s and

estimated salmon biomass was nearly twice as high during the 1980s as it was in the late 1950s (Brodeur and Ware 1992, 1995).

Salmons do not represent the most abundant pelagic species feeding in the North Pacific. The commercial catches of Japanese sardine and Californian sardine together exceed 6000 thousand tons, and the corresponding figure for Alaska pollock is more than 7000 thousand tons. Long-term fluctuations of salmon commercial catches coincide with the fluctuations of sardines and other pelagic species in the Pacific (Klyashtorin and Smirnov 1995, Klyashtorin and Sidorenkov 1996). The large-scale synchronous fluctuations of pelagic species abundance are believed to be caused by climate fluctuations of global or hemispheric scale (Shuntov and Vasilkov, 1982; Lluch-Belda, Crawford et al., 1989; Kawasaki, 1993).

Looking for Reliable Climatic Index

Time series of dT and ALPI (*Figure 4*) demonstrate high variability, and statistically reliable trends of their dynamics can only be obtained by using 13-year averages. Contrarily, the curve of ACI is low-variable, and do not need to be smoothed. The curves of ACI, the smoothed curves of ALPI and dT exhibit similar long-term dynamics: maximum in the 30s, minimum in the 50-60s, and the recent maximum in the 90s. The smoothed curves of dT and ALPI correspond basically to the dynamics of sardine and salmon catches, but the quantitative correlation is not very high. Long-term fluctuations of sardine (Japanese and Californian) and salmon catches coincide in phase (Klyashtorin, Smirnov, 1995), and ACI dynamics also corresponds to the dynamics of these species (*Figure 5*).

The total commercial catch in the beginning of the century differs significantly from the present one because of technology progress, modernization of the fishing fleet, and development of oceanic fishing. For example in the 1930s, the catch of Japanese sardine was 2700 thousand tons, and in 1989 the catch was 5200 thousand tons, which was caused by the fast development of commercial fishing in the second half of the century (Kawasaki, 1992a). Therefore, the relationship between climate changes and catch dynamics should be expressed as relative units or considered separately for each period.

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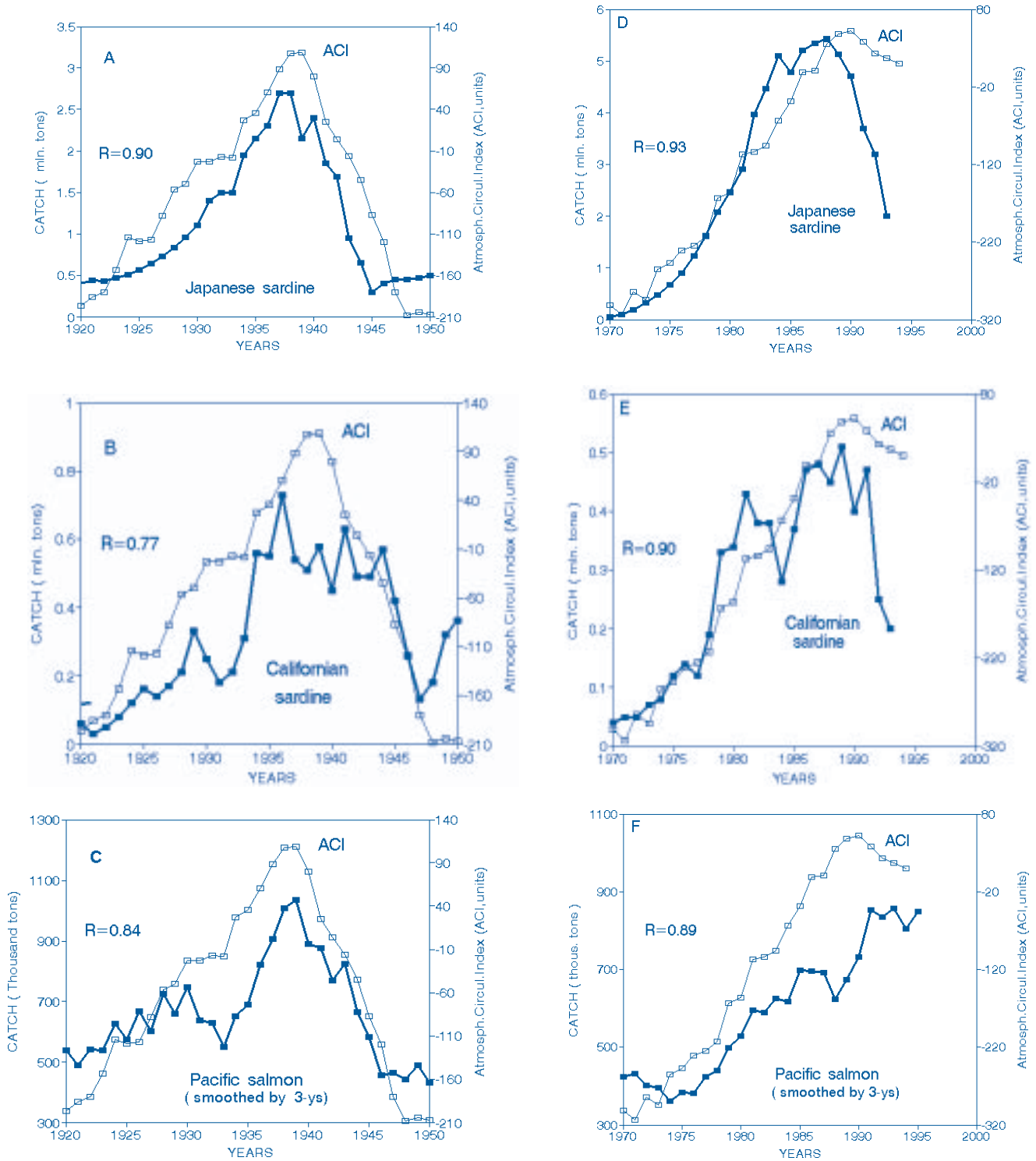


Fig. 6 Relationship between salmon and sardine catch and Atmospheric Circulation Index (ACI) trend in the Northern Pacific for the periods of 1920-1950 (A, B, C) and 1970-1993 (D, E, F).
 A-Japanese sardine. B-Californian sardine. C-Pacific salmon.
 D-Japanese sardine. E-Californian sardine. F-Pacific salmon.

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The correspondence between ACI and sardine (salmon) catches for 1920-1950 and 1970-1994 is illustrated in *Figure 6*. The correlation coefficients between ACI and of Japanese sardine catch are 0.90-0.95. The corresponding figures for Californian sardine and Pacific salmon catches are 0.77-0.92 and 0.71-0.84, respectively. The curve of Pacific salmon catch has characteristic “saw-like” shape caused by the alternation of low and high-abundance (even and odd) generations of pink salmon. 3-year smoothing of this curve results in significantly higher correlation between ACI and salmon catches (0.84-0.89). A tight correlation is also found between ACI dynamics and catch fluctuations of most abundant Pacific species: Alaska pollock, Anchovy, Chilean jack mackerel and some others (Klyashtorin and Sidorenkov, 1996).

The Atmospheric Circulation Index (ACI) is calculated from the data obtained in the Atlantic-European region, but ACI trend corresponds to the long-term climate changes at a global scale (Girs, 1971). ACI fluctuations are synchronous with the fluctuations of the global and hemispheric temperature anomaly (dT), and corresponds to the dynamics of ALPI that is an important climate-governing index of the North Pacific.

ACI dynamics also correlates tightly (correlation coefficient equals 0.8) with the Earth Rotation Velocity Index (ERVI) that is a global geophysical parameter, digitally opposite to the Length of Day Index (Sidorenkov, 1980) (*Figure 7*).

The following hypothesis can be suggested to explain the above-considered phenomena. Some proportion of water evaporated from the ocean surface is carried to the polar regions and deposited in the ice sheets of Greenland and the Antarctic. Ice flows to the oceans do not vary much in time, and the increase in the ice mass is close to the dynamics of atmospheric precipitation and snow deposition. The latter is determined by dominant wind directions, and depends on the general direction of the air transportation during different climatic epochs (long-term changes in ACI). The water mass transfer from the ocean to the polar regions causes changes to the inertial moments and Earth rotation velocity (Sidorenkov, 1980). Changes in ERVI correspond to the fluctuations of some characteristics of global water exchange (Klige, 1985). Independently on a real mechanism of the above-considered phenomenon, tight correlation between ACI and ERVI makes it possible to accept the latter as a reliable global index of large-scale climate changes (Sidorenkov and Svirenko, 1991).

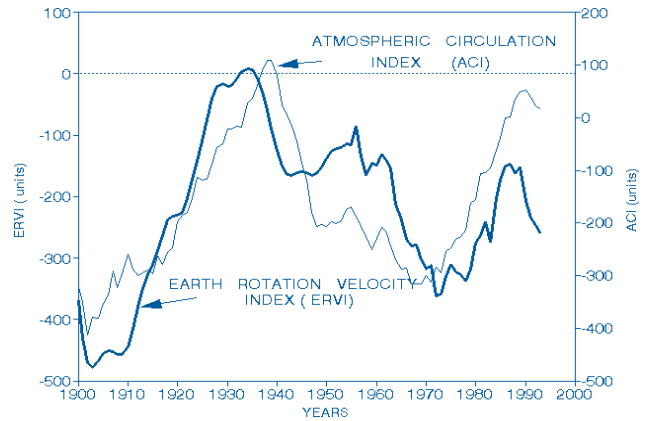


Fig. 7 Trends of Atmospheric Circulation (ACI) and Earth Rotation Velocity (ERVI).

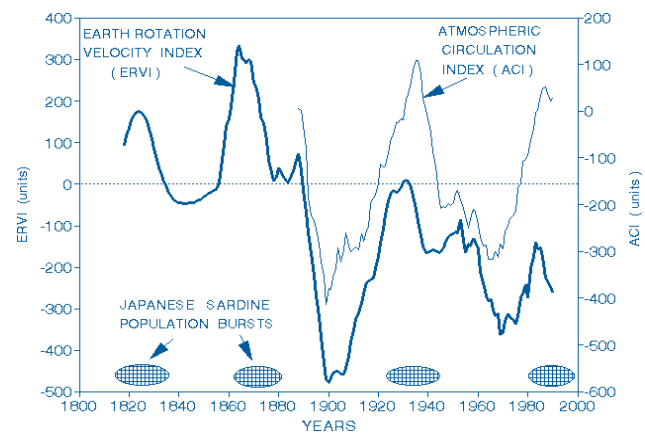


Fig. 8 Trends of Atmospheric Circulation Index (ACI), Earth Rotation Velocity Index (ERVI) and Japanese sardine stock bursts for the period of 1800-1993.

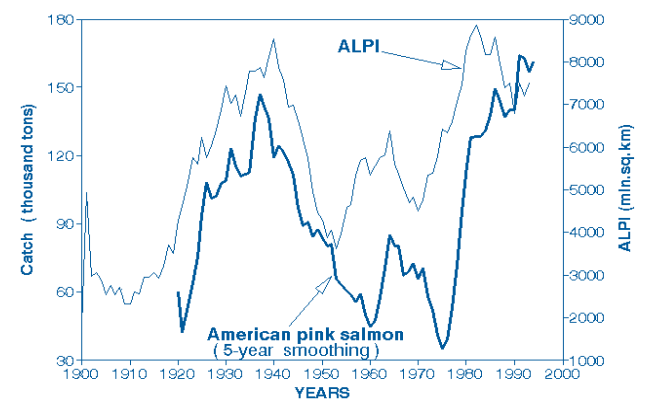


Fig. 9 A comparison between trends of ALPI and American pink salmon catch.

Periodicity in the Fish Production Fluctuations

Regular fishing statistics exist only for 70 years, however, the periods of high abundance of Japanese sardine have been registered in the Japanese chronicles since the 16th century (Kawasaki, 1992a,b, 1994).

Seven bursts of sardines have been registered over the past 400 years, (Kawasaki 1992a,1994) with average periodicity of about 60 years (from 50 to 70). Reliable time series on ERVI is 180 years old, and time series of ACI is about 100 years old. A good correspondence in ACI and ERVI dynamics (maximums), and outbursts of Japanese sardine are illustrated in *Figure 8*. The dynamics of Californian sardine and anchovy abundance was reconstructed recently by the method of detailed analysis of bottom deposition columns (Baumgartner, et al., 1992). The sardine outbursts have repeated regularly for almost 2000 years, with approximately 60-year periods. The bursts of anchovy took place with similar periodicity, but roughly opposite in phase to the sardine fluctuations.

Pacific salmon stocks also exhibit approximately 60-year periodicity, with maxima in the 1870s, 1930s, and

1990s (Beamish and Bouillon, 1993; Klyashtorin and Smirnov, 1992, 1995). Despite relatively high variability, the important climate-forming factor of the Northern Pacific - ALPI, agrees with the catch dynamics of American pink salmon (*Figure 9*).

CONCLUSIONS

Long-term fluctuations of pelagic fish production in the Pacific region in this century probably can be conceived as a result of two climate-related “waves”. The first wave, with the maximum in the late 30s, was observed in the 20-50s. The second one started in the 70s and apparently reached its maximum in the late 80s-early 90s (*Figure 10*).

The development of the first climate-related wave of the 20-50s was manifested by synchronous change in the trends of basic climatic indices (dT, ALPI, ACI, ERVI) and stock dynamics of basic commercial species (salmons and sardines). After reaching a maximum in the late 30s, the catch trends and climatic indices decreased, and followed through the 40s to the “depressive” phase of the 50s (*Figure 10a*). The trends of climatic indices and catch dynamics follow in the

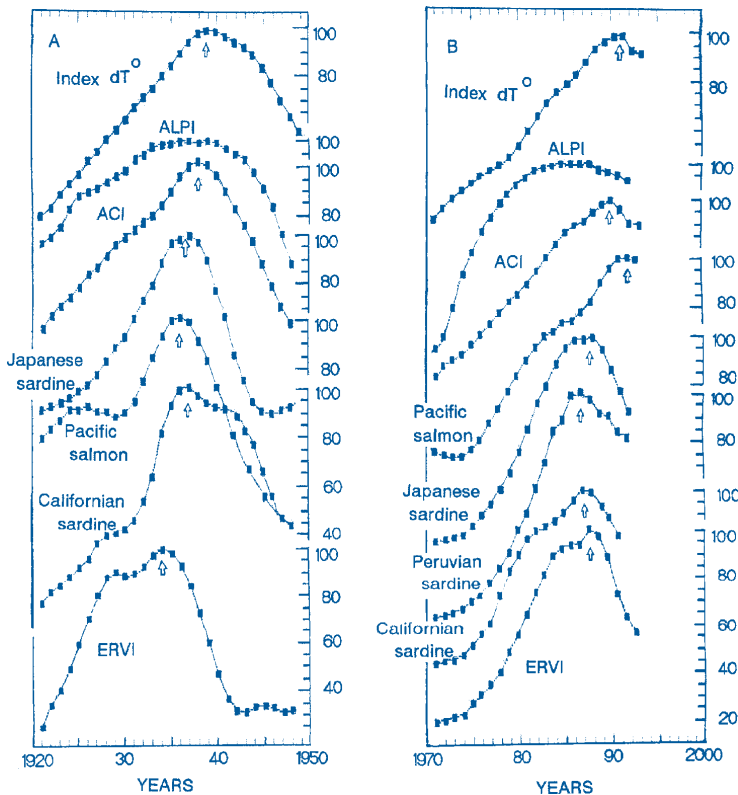


Fig. 10 The scheme of the general trend of climatic indices and commercial catches in the Pacific for the periods of 1920-1950 (A) and 1970-1993 (B). All curves are presented in per-unit form relative to a specific maximum taken as 100 percent and marked by arrows. All catches are smoothed by 5-years averaging.

dT - Annual air surface temperature anomalies (13-year smoothing); *ALPI* - Aleutian Low Pressure Index (13-year smoothing); *ACI* - Atmospheric Circulation Index (5-year smoothing); *ERVVI* - Earth Rotation Velocity Index (5-year smoothing).

same manner during the development of the second wave of the 70-90s (*Figure 10b*). They reached their extreme points almost simultaneously (in the late 80s-early 90s), and now apparently come to their final phase analogous to the one of the 40s. The second climate-produced wave will likely be in a final phase in the beginning of the next century.

The dynamics of total salmon catches in the Pacific region is similar to that of main commercial pelagic species, and correlates with the above-considered global and hemispheric climatic indices. Based on the latter, one can conclude that the phase of fast catch increase (observed in the 80s) is already finished. In the near future, the catch trend will pass its extreme point, and gradual decline of the salmon abundance (and catches) will start in the beginning of the next century like it was in the 40s. It may also be assumed that by analogy with the period in the 40s, in the late 90s the trend of temperature anomaly (dT) will begin a gradual decline in line with ACI, ERVI, ALPI, and pelagic commercial catch. This contradicts the conventional belief in “global warming”, but corresponds to the latest data on the dynamics of global and hemispheric temperature anomaly (Halpert et al., 1995). It is reasonable to expect that in the beginning of the next century, the oncoming new climatic phase will affect not only the oceanic but terrestrial ecosystems of all the Pacific region as well.

The large-scale changes in the Pacific fish production illustrate the response of oceanic system to long-term climatic changes. “In many instances biological organisms are integrators of environmental variables and may be more sensitive to low frequency climate events than physical time series” (Polvina et al., 1994). High correlation between ACI, ERVI, and catch trends allow us to consider these indices as predictors of long-term changes in salmon and other pelagic species abundance in the Pacific. Together with the concept of the approximately 60-year climate-production cycle, the application of these indices makes it possible to predict the dynamics of Pacific pelagic commercial species for 5-10 years ahead.

The existing forecasts of all scales may also be corrected in advance, as soon as new data on ACI and ERVI come to our disposal. Unlike many other meteorological indices, ERVI can be measured with high precision by astronomical methods, and the data on its actual dynamics can be obtained anytime. As soon as the mechanism of its high correlation with global water exchange processes is found, ERVI can be used as a basic indicator of global climate trends (Klyashtorin, 1996; Klyashtorin and Sidorenkov,

1996). The mechanism of the effect of climate changes on the fish production is not clear yet. The main reason is apparently the changes in total productivity of oceanic system in response to the long-term change in atmospheric circulation, heat transfer and oceanic surface turbulence (Bakun, 1990; Hsien and Boer, 1992; Brodeur and Ware, 1992, 1995).

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