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Evidence of a new regime starting in 1996 and the relation to Pacific salmon catches

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Abstract

Changes in climate trends in the Pacific have been reported about 1890, 1925, 1947, 1977, and 1989. Indices of northern Hemisphere climate, changed in approximately 1996, possibly indicating a new shift in climate/ocean ecosystems. If we are in a new regime, it may be characterised by greater variability in association with a general warming trend. There has been a decrease in the length of day, indicating speeding up of the Earth's rotation. In the winter of 1998, there was an intense Aleutian Low. The Southern Oscillation Index has oscillated between a La Niña in 1995/96, an El Niño in 1997 and a La Niña in 1998. The dominant wind direction in the Pacific changed from the Z-type, or westerly type, to the M1-type, or the northwesterly type. In the Atlantic, there was a dramatic drop in the North Atlantic Oscillation Index in 1996. In British Columbia, Fraser River flows have fluctuated from the second highest this century in 1977 to the lowest in 1998. All this is occurring while sea surface temperatures off North America are continuing to warm. Declines in total Pacific salmon catch started about 1996 and continued through 1997 and 1998. Declines off Canada have been most dramatic since 1995 and when lagged to account for life history timings, the decline is associated with a 1989/90 regime shift. In Canada, coho stocks have experienced increases in marine mortality that have been associated with shifts in climate, resulting in management measures that in combination with naturally low abundances of wild coho may result in the 1998 total salmon catches being the lowest in this century. In 1998 there was an intense Aleutian low. If the intense lows persist, the productivity of Pacific salmon stocks in the subarctic Pacific may improve,

but it is important to understand the nature of the new regime, if it is real, before forecasting the impact on Pacific salmon abundance trends.

Introduction

In the past there was a tendency to believe that the historic, unfished abundances of salmon were much larger than present. The lower abundances in recent times were considered to result from fishing effects. According to these views, higher abundances were possible if more young salmon could be added to the ocean. Abundance, therefore, was affected most strongly by factors that affected the number of juveniles produced in fresh water. It is generally accepted now that both fresh water and the ocean environments are important in the regulation of Pacific salmon abundance. This indicates that there is a rather urgent need to reconsider the role of the ocean and fresh water in the life history of Pacific salmon because the marine phase can no longer be viewed as under-utilised habitat.

In this report, we continue our examination of the influences of climate and the ocean environment on the abundance trends of Pacific salmon. We are emphasising the impacts of long-term changes that are associated with regimes and shifts in regimes. Multi-year periods of linked recruitment patterns and are associated with stable means in a climate or ocean environment data series are becoming a new issue in salmon management (Mantua et al. 1997, Beamish et al. 1998a). Understanding the influences of both environmental impacts and associated species impacts in the ocean is also an important part of the rapidly developing requirement to move from single species management to ecosystem management.

Three important objectives of salmon management are (1) to protect and preserve stocks, (2) optimise returns to fisheries, and (3) forecast abundance trends. All of these objectives require an improved appreciation of relationships between changes in trends in the climate and the ocean environment. The coherence (Figure 1) among the atmospheric pressure and atmospheric circulation indices (Aleutian Low Pressure Index and Pacific Circulation Index) in the subarctic Pacific and the predominantly sea surface temperature index of the Pacific Decadal Oscillation (Mantua et al. 1997) is a clear indication that climate trends are linked to ocean processes. If atmospheric processes and the ocean processes are linked in a regime context, then marine ecosystems should also be linked. There is evidence of such a linkage with plankton production (Brodeur and Ware 1992, Sugimoto and Tadokoro, 1997). Thus, there is a sound biological basis to expect that shifting climate trends will affect the feeding and survival of fishes. Identifying the change in productivity of fishes may be difficult because the biological change may be more gradual and because of the confounding effects of fishing.

The last regime change probably occurred around 1989 (Beamish et al. 1998a, Watanabe and Nitta 1997. Earlier changes occurred about 1890, 1925, 1947, and 1977 (Mantua et al. 1997, Minobe 1997). It is possible that another change occurred about 1996. We present the recent climate and ocean indices in this report, in order to alert readers that a recent change may have occurred. Some authors consider the changing regimes to be cyclic (Hare et al. 1998, Gargett 1997, Mantua et al. 1997), but we suggest that changes result in shifts that can be characterised by a number of states. For some parameters there may only appear to be three choices, i.e.: smaller, larger, or unchanged. However, rates of change and the extent of change could add considerably more dimensions. An important consideration is that the climate indices have global or Northern Hemisphere associations. Thus the impacts should be on a large number of regional ecosystems. These synoptic effects do not have to cause similar changes in all ecosystems, even among similar species. Another consideration is the impact of global warming. If regime shifts have occurred for centuries (Baumgartner et al. 1992, Beamish et al. 1998a), the impact of global warming may be affecting both the frequency and the amplitude of the shifts.

Evidence for a regime change about 1996

An index of decadal scale changes on a planetary scale is the index of earth rotation or the length of day (Stephenson and Morrison 1995, Beamish et al. 1998a). As the earth rotation speeds up, the length of day (LOD) decreases and vice versa. The actual measurement is in milliseconds and is standardised to the LOD on January 1,1958. The index offers the potential to measure energy transfers over decadal scales among the solid earth, the atmosphere, and the oceans. Remembering that energy is not created or lost on our planet, we can accept that energy must come from somewhere, for example, to increase the winter winds in the Pacific and it must go somewhere in the summer as winds are reduced in strength. Seasonal changes in LOD can actually be measured and compared to the decadal scale changes in Figure 2. For example, the almost 2 millisecond change from 1976 to 1986 is equivalent to almost 6 times the seasonal and energy change (Stephenson and Morrison, 1995), and the change from 1912 to 1929 would be about 12 times. The impact of the strong 1983

El Niño slowed the rotation of the earth by 0.5 milliseconds (Dickey et al. 1994). Thus, the LOD is a sensitive measure of atmospheric processes that eventually may be detected as decadal-scale shifts in the trends of energy flows. In recent years, there was a shortening of the LOD from about 1972 to 1988 and a lengthening from about 1989 to 1995. In 1996, the trend appears to have changed again. The 1997 value would be strongly influenced by the strong El Niño and the projected value (IERS, 1998) indicates that the trend that started in 1996 may continue (Figure 2).

The Aleutian Low Pressure Index (ALPI) is an index of the intensity of the low pressure system in the subarctic Pacific (Beamish et al. 1997). The atmospheric circulation index (ACI) and the Pacific circulation index (PCI) are indices of atmospheric processes in the Atlantic and Pacific respectively. The derivation of the ACI is described in Beamish et al. (1998a) and PCI in King et al. (1998). As ACI (Figure 3A) and PCI (Figure 3B) are in the cumulative summation (CuSum) form (Murdoch 1979), we also express the ALPI in the CuSum form (Figure 3C). All three indices show a distinct change about 1989 or 1990. In general, the Aleutian Low became persistently less intense and the atmospheric processes in the North Atlantic (ACI) were characterised by an above average frequency of zonal (westerly) winds (Beamish et al. 1998b) while those in the North Pacific (PCI) were characterised by continued above average frequency of zonal circulation and an increase in the frequency of meridional (northwesterly) circulation (King et al. 1998). There is a change in ALPI in 1998 and possibly in ACI in 1995. There was a drop in the PCI in 1996 reflecting a decrease in zonal winds and an increase in meridional (northwesterly) winds but this trend does not appear to continue in 1997 (King et al. 1998).

The Southern Oscillation Index (SOI) is considered to be an indicator of El Niño and La Niña events. These events represent extreme pressure fluctuations in the tropical Pacific and their impacts extend throughout the planet (Trenberth 1997). There is a decadal-scale pattern in the SOI that corresponds to the timing of regime shifts in the other indices. The pattern of fluctuations characteristic of the 1950s and 1960s (equal El Niño and La Niña events), changed from 1977 to 1988 (strong El Niño and no La Niña events) and changed again from 1990 to 1995 (very strong and persistent El Niño events only, Figure 4). In 1996 there was a moderate La Niña and in 1997 a strong El Niño. Another La Niña event is occurring in 1998. If the change in SOI in 1996 is a new trend, it may represent a pattern characteristic of the 1950s and 1960s, but with stronger events (i.e. greater amplitude in SOI).

Because our climate indices are associated with global processes, we consider that the atmospheric processes in the Atlantic may be informative of impacts in the Pacific. The North Atlantic Oscillation Index (NAOI) is the difference between the normalised winter (December through March) sea level pressures at Lisbon, Portugal, and Stykkisholamr, Iceland (vanLoon and Rogers 1978). The fluctuations form a teleconnection with other areas and the Icelandic Low fluctuations are related to changes in the Aleutian Low in the Pacific (Walker and Bliss 1932, Wallace and Gutzler 1981). The change in the NAOI occurred about 1980 when anomalies were almost all positive and change in the pattern of fluctuations after 1989 (Figure 5). However, the largest change since 1976 occurred in 1996 when the index became negative as a result of a weakening of westerly winds and a weakening of the Icelandic Low.

In summary, there was a change in the pattern of the global climate indices (ACI, ALPI, LOD, SOI, and NAOI) within the period 1995 to 1998. The change is apparent in 1996 in the LOD, NAOI, and in the SOI as a La Niña event after persistent El Niño conditions. ACI changes about the same time (1995), but the ALPI change is not clear until 1998 and there is no evidence of a distinct change in PCI though it does drop in 1996. It is not possible to be certain that these changes represent shifts in a regime, as we cannot forecast if a new stable state will persist. It is, however, important to recognise that the previous regime beginning about 1989 may have ended and the dynamics of ecosystems may change again. The association of these changes with Pacific salmon and other fish production highlights the importance of studying the potential impacts now.

Assuming a possible regime shift in 1996, we compared the mean annual (January through December) sea surface temperatures (SST) off the west coast of North America (127°W to 141°W and 35°N to 57°N) for the period of 1989-1995 to the years 1996 and 1997. We used the Comprehensive Ocean-Atmosphere Data Set (COADS) database (Woodruff et al. 1987 and website) from 1989-1992 and the Integrated Global Ocean Services System (IGOSS) database (Reynolds and Smith 1994 and website) from 1989-1998. We grouped all data into monthly means of 2° x 2° blocks centered over each odd degree. When we compared the mean winter SST for 1989-1995 to those of 1996, the waters along the North American coast were on average 0.4°C warmer in 1996 while those towards the central North Pacific were 0.2°C cooler. The coastal SST were 0.4°C cooler in 1997 than in 1996 and the central waters were 0.2°C warmer. In 1998, the coastal waters were 0.9°C warmer than 1997 while the central waters were 1.1°C cooler. There was a definite switch in coastal SST in the winter of 1996. In addition the warmer coastal waters in 1998 are a reflection of the intense Aleutian Low.

Regional responses on the West Coast of Canada to these large-scale events are characterised by trends in the flow of the Fraser River. Several studies have demonstrated Fraser River flow linkages with large-scale shift in precipitation patterns (Moore and McKendry 1996), with decadal scale changes in other large West Coast rivers (Mantua et al. 1997), or with regime shifts in the Pacific (Mantua et al. 1997, Beamish et al 1997). There was a change in flow pattern at the time of the 1989 regime shift. From 1989 to the present, discharge in April has been larger than earlier years (Figure 6) even though the annual trend continued to be below average flows (Figure 7). In 1997, the annual pattern changed but April flows remained above average. In 1998, it appears that the flows may be one of the lowest on record including a return to average April flows. It is possible therefore, that the pattern of flow has changed after 1996 and that the change is toward more extreme fluctuations in annual flow and average April flows.

Pacific salmon catches

We report catches of pink, chum, and sockeye salmon (Figure 9) from all Pacific salmon producing countries to represent total salmon catch (Beamish and Bouillon 1993, Hare and Francis, 1995, Mantua et al. 1997). Catch data from 1926-1995 were obtained from International North Pacific Fishery Commission publications and data for 1996 were obtained from NPAFC. Catches of coho and chinook are not included because it is difficult to obtain accurate data earlier than 1950 and they amount to approximately 10% of the total all-nation catch and will not have an major impact on total catch trends. Total catch began to increase in 1977, to the largest catch in history in 1995 (Figure 8). Catch began decreasing in 1996. Estimates of total catch in 1997 remain preliminary and 1998 were based on early reports from Canada and the United States. If the 1998 total catch is less than 1997, then the decline is probably a real trend that started in 1996. If the all nation catch is broken down into Asian and North American catches and compared (Figure 9), declines are evident in both series but starting one year later in the Asian catch.

A 1990 shift in productivity should have cascading effects on salmon abundance, but the timing of those effects will vary according to life history strategies. For example, since pink return to freshwater one year after ocean entry, ocean productivity effects on their abundance could be evident in the catch data as early as 1991. Similarly, most sockeye return one to four years later and chum return after two to five years later. As an example, we used the pink, sockeye, and chum catch data for Canada (1920-1997) but lagged each series by 1, 4 and 5 years respectively to correspond to their approximate ocean entry year. We selected the maximum time for sockeye and chum (4 and 5 years) in order to accommodate all lag effects. We recognise that this does not account for stock specific differences in their age at return to freshwater from the ocean, but in a general manner it facilitates a comparison with climate indices for North American stocks. The total catch data for all three species is expressed as a CuSum similar to our climate and ocean regime indices and there is a distinct shift in catch trend corresponding to 1990, or the 1989 regime shift (Figure 10). This implies that shifts in salmon catch data associated with a possible regime shift in 1996 will not be evident until sometime after the year 2000.

A major issue for the management of the Canadian salmon fishery in 1998 was the requirement to protect wild coho. Marine survivals of coho have declined throughout the 1980s and 1990s. In the south, in the Strait of Georgia, Puget Sound and off Washington and Oregon, marine survivals have declined from an average of 14.6 % in the late 1970s to 1.6 % in the recent years (Figure 11). In some areas of the north the marine survival of returning adults in 1997 was close to zero (DFO, 1998). In the south, there was a large scale synchronous change to lower marine survivals that was associated with the change in climate that occurred in 1989 (Beamish et al. 1998b). The change in climate regimes in 1989 was associated with a change in behaviour that resulted in the collapse of the coho fishery in the Strait of Georgia in 1991, 1995, 1996, 1997, and 1998 (Beamish et al. 1998b). Another concern was the increasing percentage of hatchery coho (77%) in the Strait of Georgia (Beamish et al. 1998c) and throughout the southern distribution. A study by DFO (1998) concluded that the abundance of spawning wild coho continued to decline throughout British Columbia in recent years. In particular, stocks of wild coho in the Thompson River, (which flows into the Fraser River) and in the Skeena River, (in northern British Columbia), were in extremely low abundance. Generally low returns of spawning fish were also reported in the Taku River which flows from British Columbia into Northeast Alaska and is the major produces of coho north of the Skeena River. Declines in spawning escapement are a consequence of poor marine survival and high exploitation rates. Prior to 1996, exploitation rates were 70% to 80%. The continued declines in spawning escapement in 1995/1996 resulted in management actions that reduced exploitation rates to approximately 60% in 1996, 25-35% in 1997 and a total fishing closure in 1998. Escapements of coho were at extremely low levels in 1997 requiring that in 1998 restrictions be placed on fisheries for any salmon stocks which might have an adverse impact on coho stocks that were at critically low abundances (DFO, 1998). In addition, fisheries for coho were closed in virtually all areas. As a consequence of these fishing restrictions and an abundance that was generally low and possibly declining for all species, there is little doubt that Canadian salmon catches will be low.

Discussion

Indices of climate and ocean trends changed in recent years, possibly in 1996. Not all indices changed at the same time, but the changes in some of the indices were distinct relative to past trends. It is too soon to be certain that there has been a shift from the regime that we propose started about 1989. However, if the recent trends persist, a new regime may be characterised in the Pacific by more extreme variations, more winds from the northwest and warmer surface waters. The impact on Pacific salmon stocks is difficult to forecast because there is still great uncertainty about the impact of climate ocean changes on the mechanisms that regulate Pacific salmon abundance. We propose that the trend of declining salmon catches beginning in 1996 may be a response to the earlier change about 1989 and may not be a response to the 1996 shifts. Beginning about 1989, the Aleutian Low became less intense and changes occurred in a number of other indices (Beamish et al. 1998a). The Aleutian Low persisted in that average state until 1998. This 7-year period of average intensities followed the 13-year period of intense lows that started in 1977. If the period of intense lows was the reason that salmon productivity increased, we should expect that the shift in 1989 to average lows would also affect salmon productivity. The continued high catches and productivity through to 1995 would be expected if declines in productivity started after the 1989, although the impact on chum would have occurred a few years later. Maximum total catches of pink salmon occurred in 1991 and sockeye in 1993 illustrating that their responses to a shift in Aleutian Low was lagged according to their life history. Thus there was a change in the productivity of the combined pink and sockeye stocks after 1990, consistent with the trend of weakening Aleutian Lows. The regime that started in 1990 was characterised by average Aleutian Lows and average northwesterly circulation. There was a reversal of trends in the Canadian catch and a reduction in the rate of increase of total catches, but the reversal of trends did not occur until 1996. There are different associations among atmospheric circulation patterns and salmon catches in different regimes suggesting that regime shifts are not oscillations from one state to another but that several different states and relationships between variables are possible. There are well-documented links between atmospheric circulation, ocean circulation and marine productivity therefore, we suggest that Pacific-wide synoptic climatology offers the link between changes in the atmosphere and change in the ocean conditions and marine productivity. The recent low catches, therefore could be a combined effect of the impact of the 1989 change and possibly an initial response to a new change to conditions beginning in 1996. The intense Aleutian Low observed in 1998 may indicate a future period of improved productivity particularly if additional intense lows continue to occur. Recognising the varying life histories of

Pacific salmon species, their responses to the 1998 intense Aleutian Low will be lagged accordingly.

Figure Captions

Figure 1. A) The Pacific Decadal Oscillation (PDO) from Mantua et al. (1997) and B) in the cumulative summation form (CuSum) of PDO provides a visual representation of the trends within the time series. C) The winter (December through March) Pacific Circulation Index from King et al. (1998). D) The CuSum form of the Aleutian Low Pressure Index (ALPI) from Beamish et al. 1998. The regime shifts of 1925, 1947, 1977, and 1989 are shown by the vertical lines and illustrate the similarity in the timing of regime changes among these indices.

Figure 2. The trend in the average annual change in the length of day (in milliseconds, ms) from 1900 until 1997. The open circle is the IERS (1998) forecasted value.

Figure 3. A) The index of atmospheric circulation (ACI). B) The Pacific circulation index (PCI). The CuSum form of the ALPI from Figure 1 is shown in C for comparison. The vertical lines show the regime shifts of 1925, 1947, 1977, and 1989.

Figure 4. The monthly Southern Oscillation Index (SOI) smoothed by a 5 month running mean. Values below –1 are considered to be El Niño events and values above +1 are La Niña events.

Figure 5. The North Atlantic Oscillation Index (NAOI) from 1951 until 1997 shown as standardised anomalies.

Figure 6. The total discharge in from the Fraser River in April from 1912 to 1998 expressed as m^3/sec. The mean value is shown as a solid line and $\pm$ one standard deviations are denoted by dotted lines. The increasing flows after 1990 are unique to the time series.

Figure 7. The annual discharge (1912-1997) from the Fraser River (m^3/sec) from April 1 to March 31 with April 1 as the year indicated. The mean value is shown as a solid line and ± one standard deviations are denoted by dotted lines.

Figure 8. The total Pacific salmon catch of pink, chum, and sockeye from 1926 to 1998. The 1997 value is preliminary and the 1998 value is an estimate.

Figure 9. The total Pacific salmon catch of pink, chum, and sockeye from 1926 to 1998 for Asian (solid line) and North American (dotted lines) catches.

Figure 10. The cumulative summation of total Canadian catch of sockeye, pink and chum salmon (1920-1997) after each series was lagged to ocean entry year. The regime shifts of 1925, 1947, 1977, and 1989 are shown by the vertical lines.

Figure 11. The marine survival (percent) of juvenile coho in A) the Strait of Georgia, B) Puget Sound and C) off Washington and Oregon.

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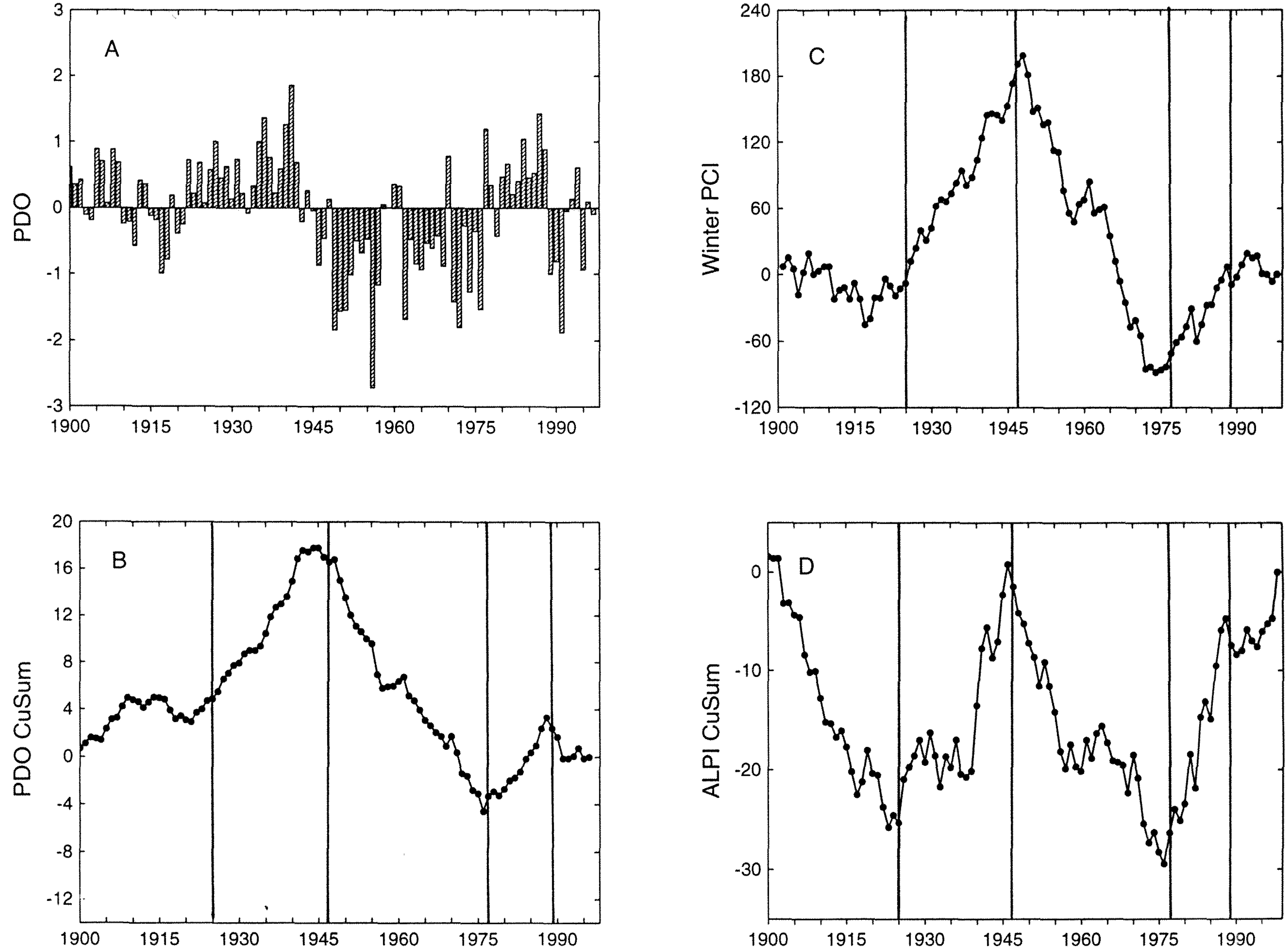
Fig 1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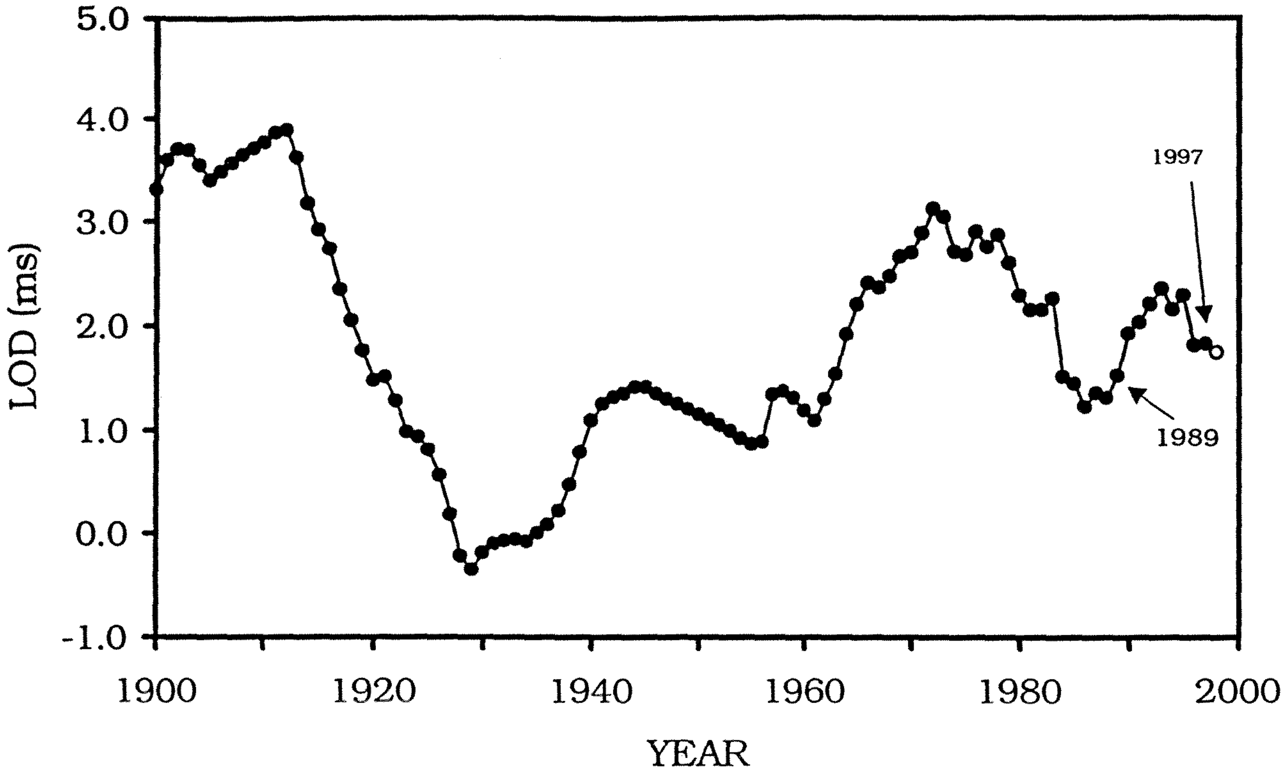
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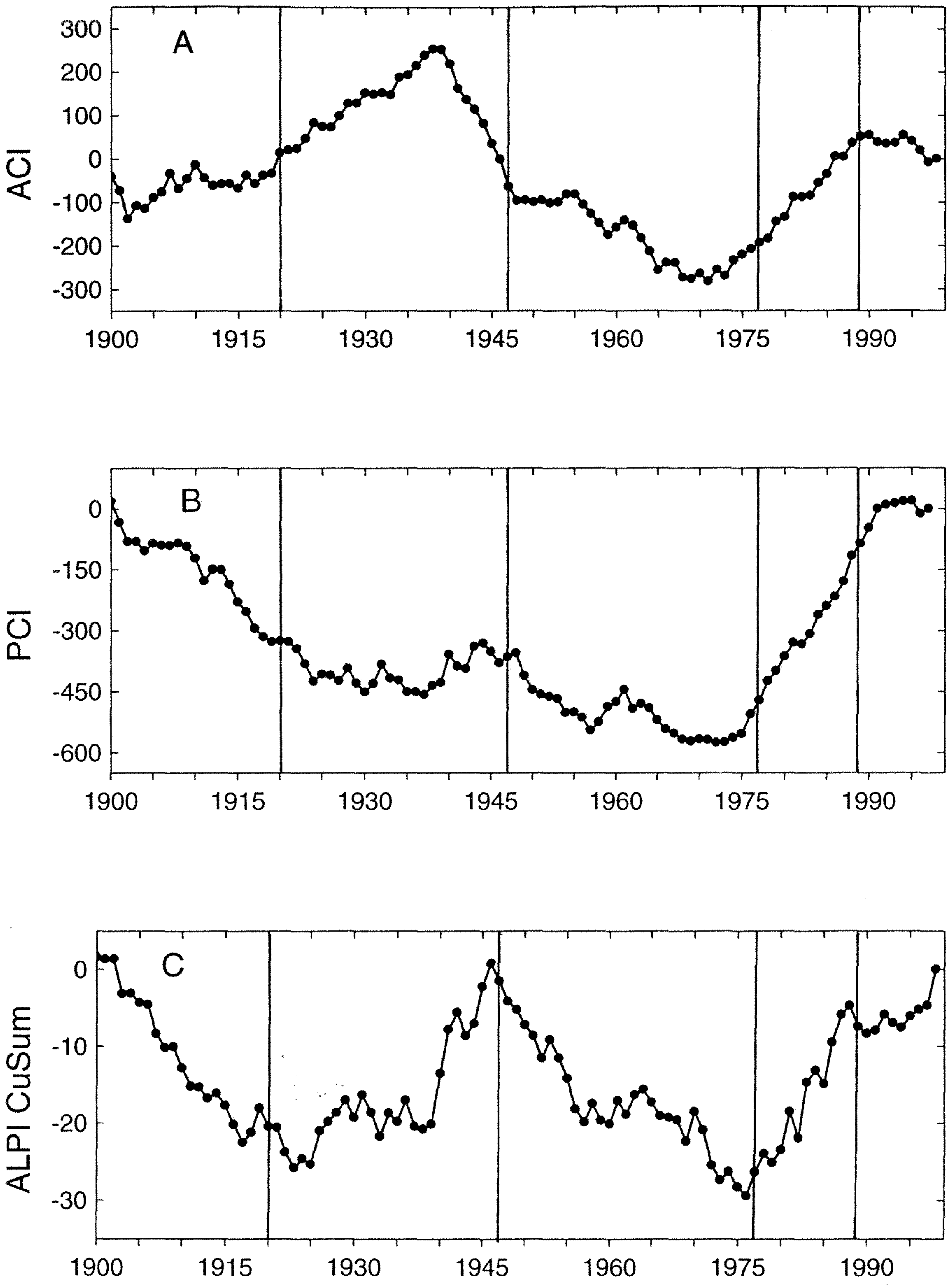
321 Fig. 2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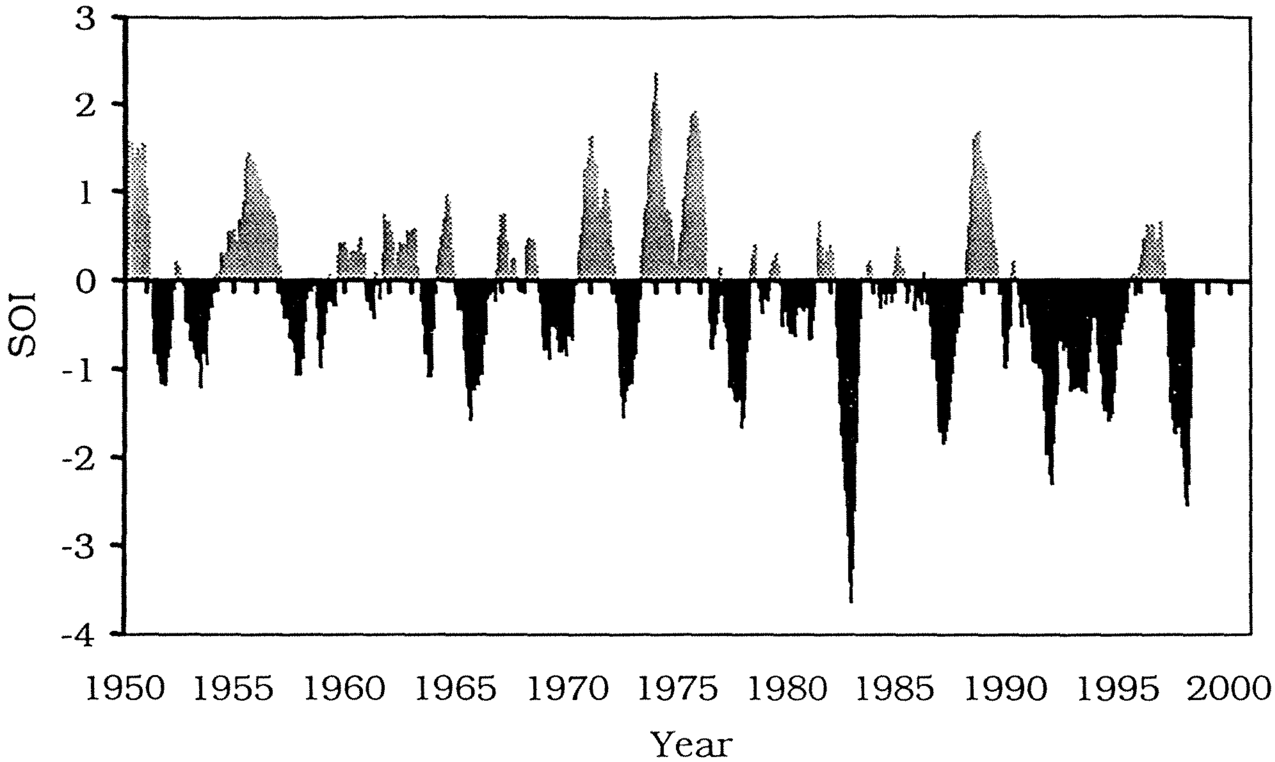
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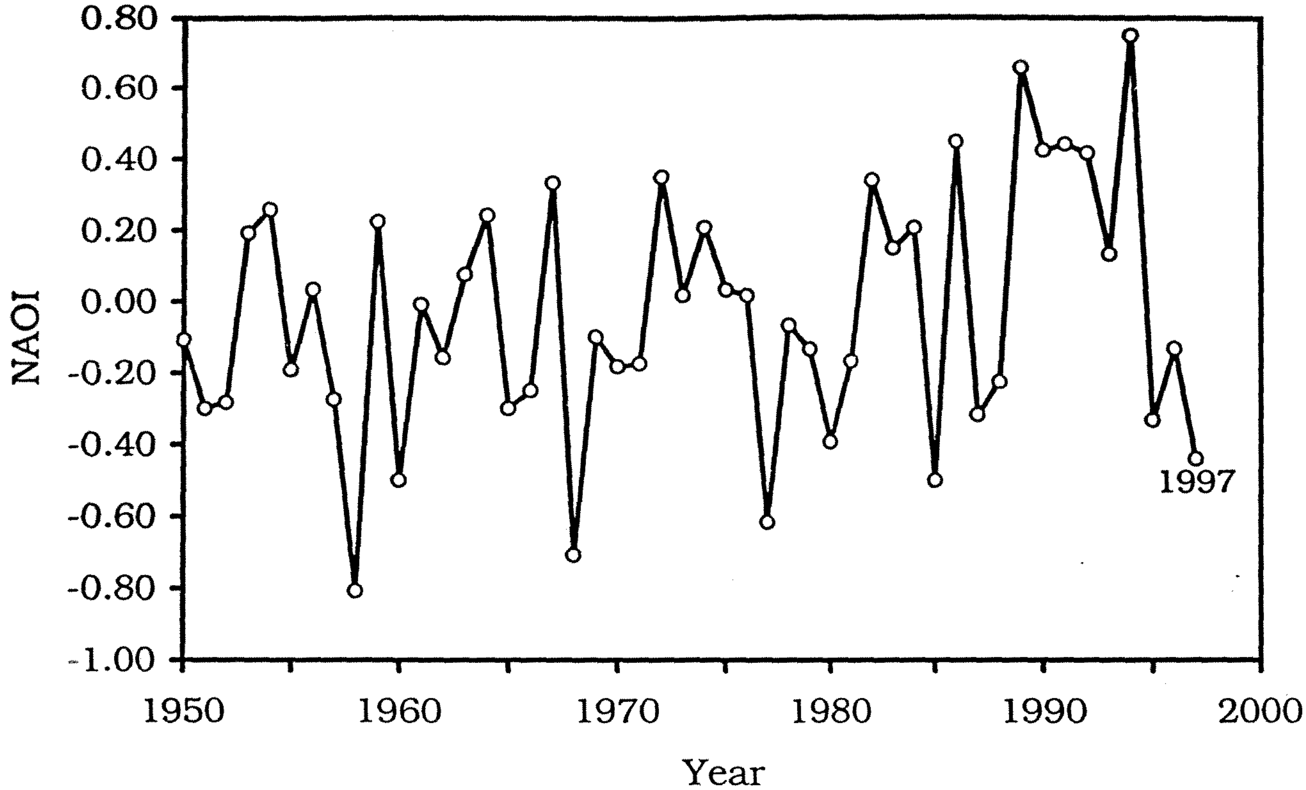
Fig 4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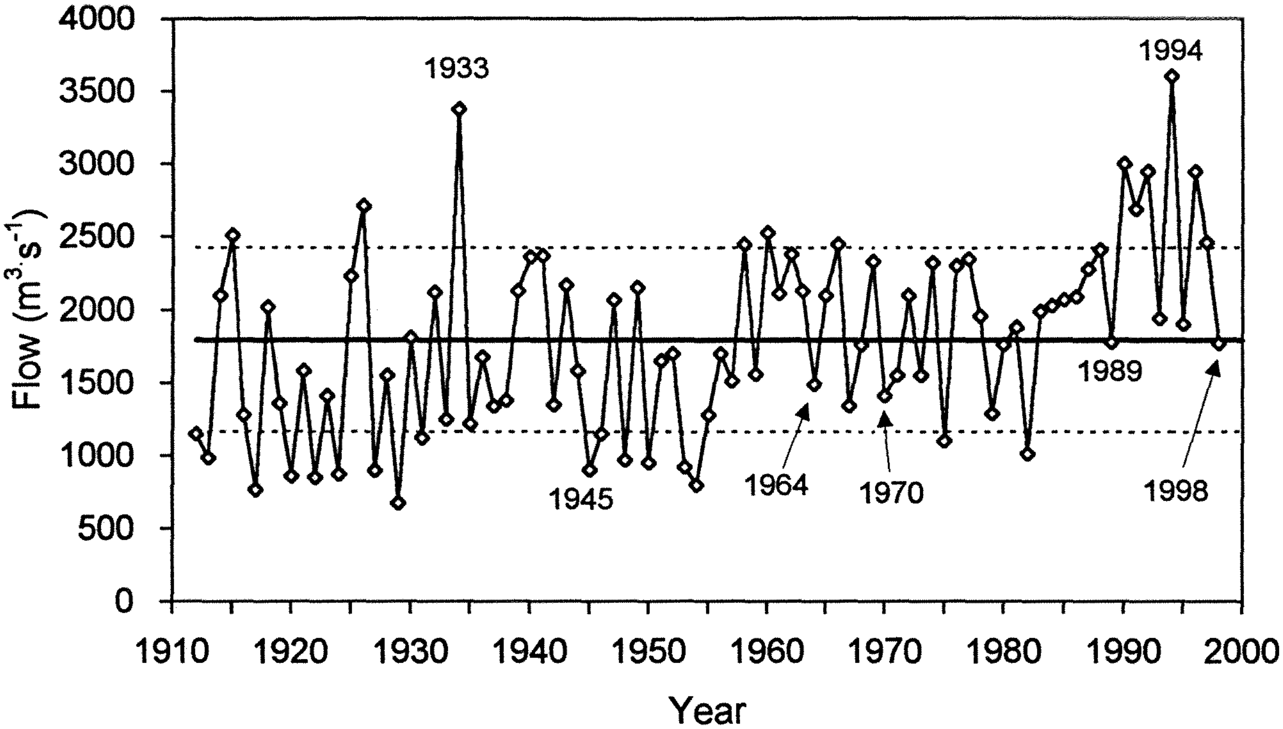
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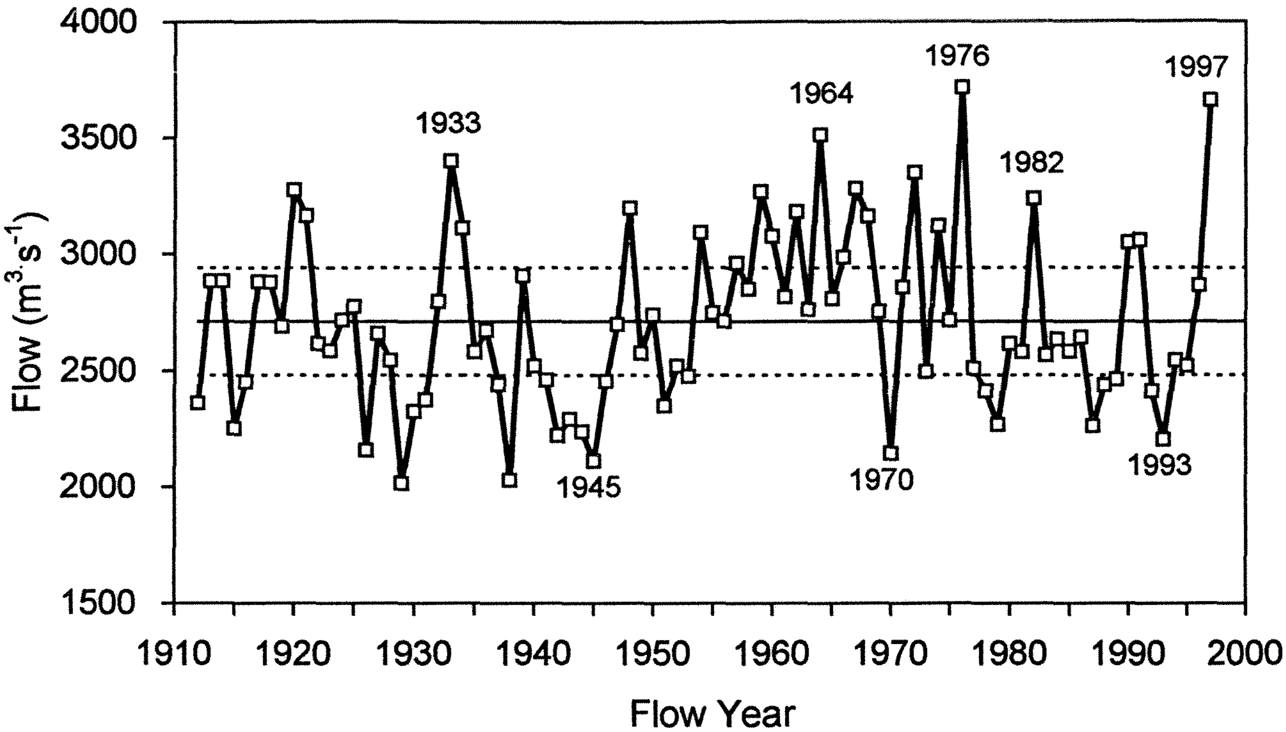
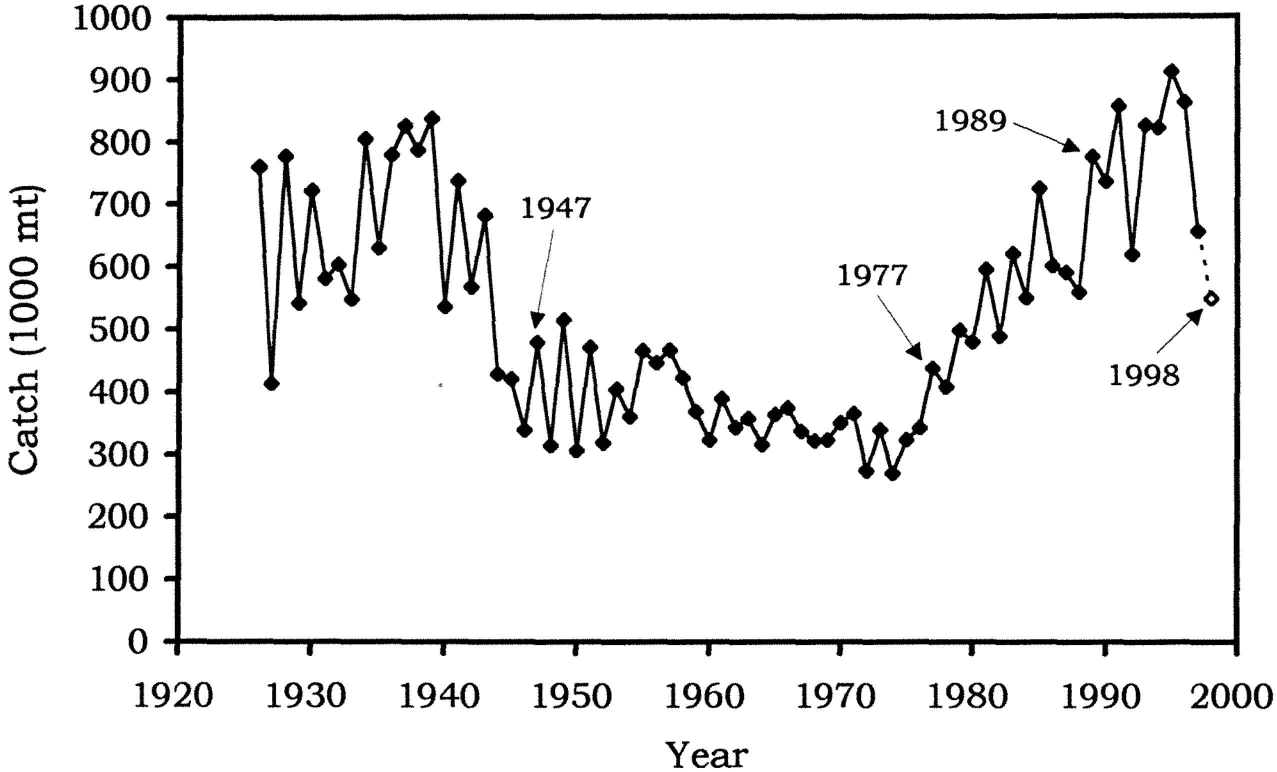
Year

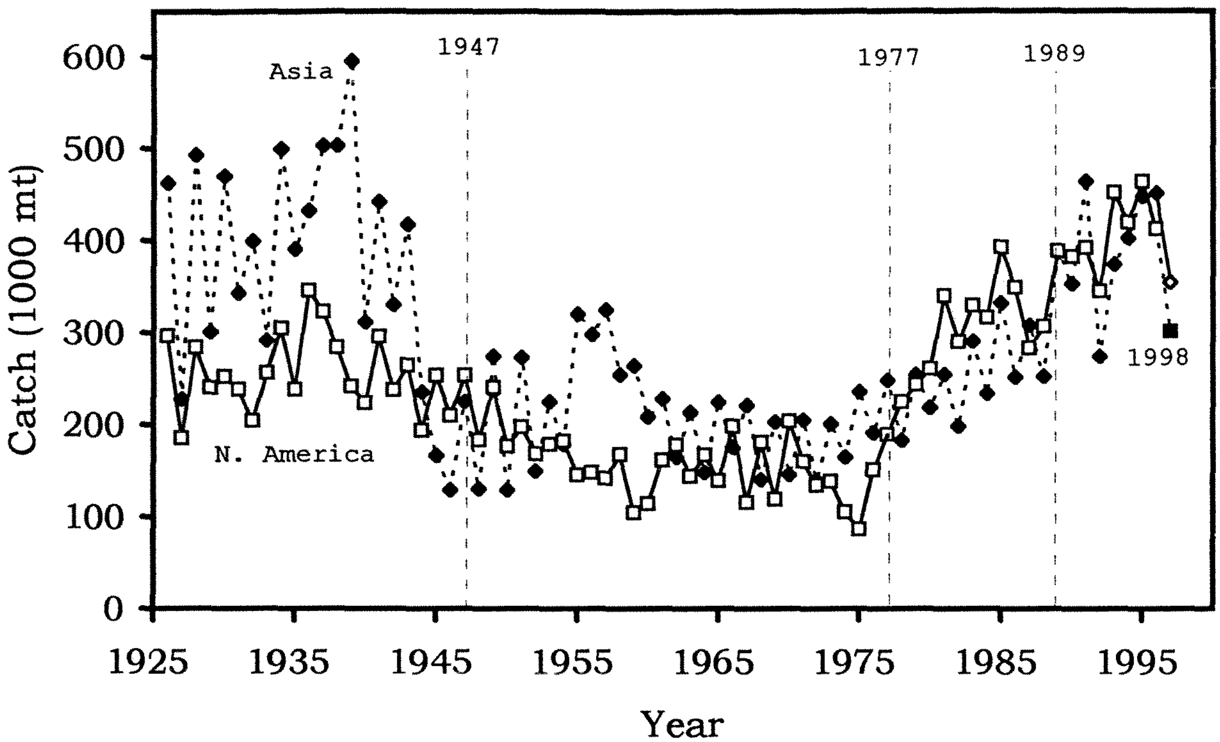
Doc 321 Fig 6


4000
3500
3000
2500
2000
1500
Flow ($m^3 \cdot s^{-1}$)
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Flow Year
1933
1945
1964
1970
1976
1982
1993
1997



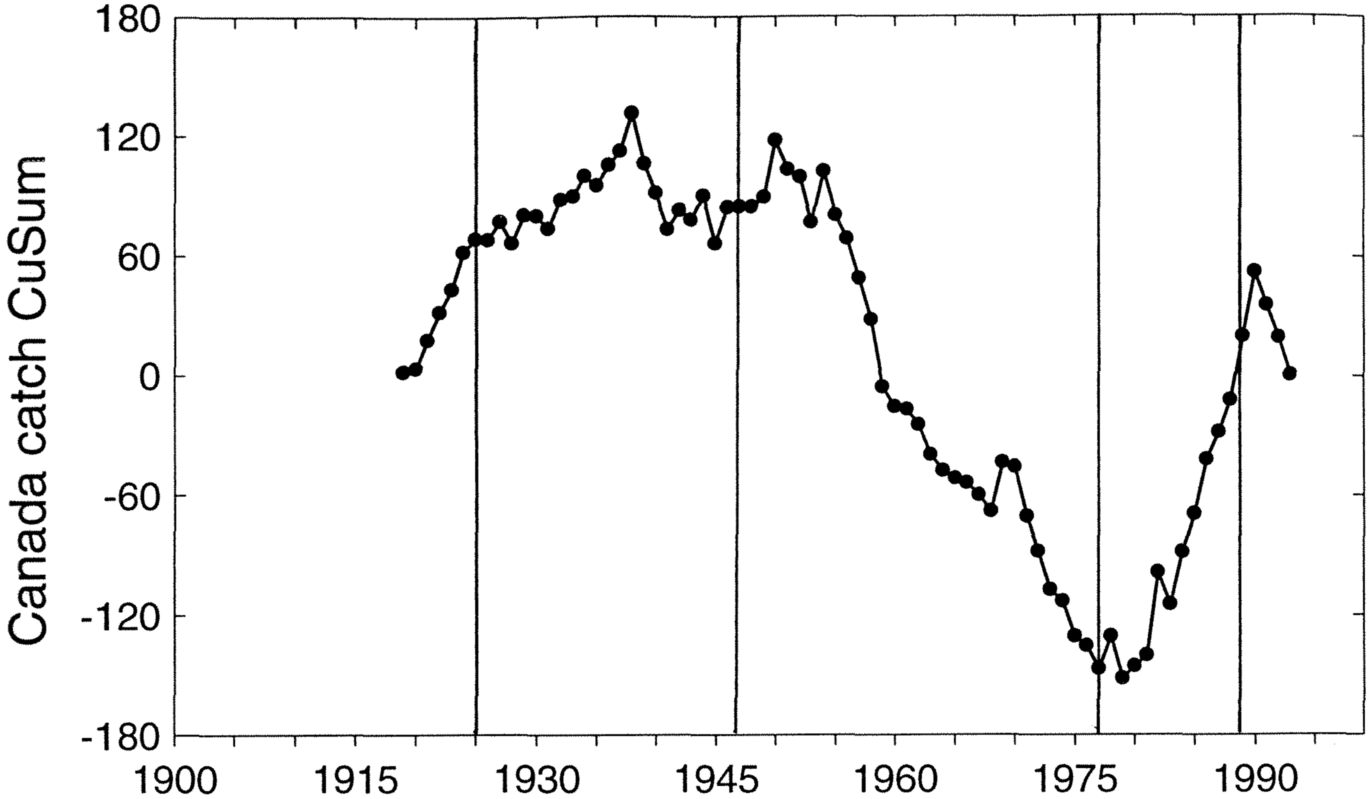
1000
900
800
700
600
500
400
300
200
100
0
Catch (1000 mt)
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year
1947
1977
1989
1998

Doc 22! Fig 9

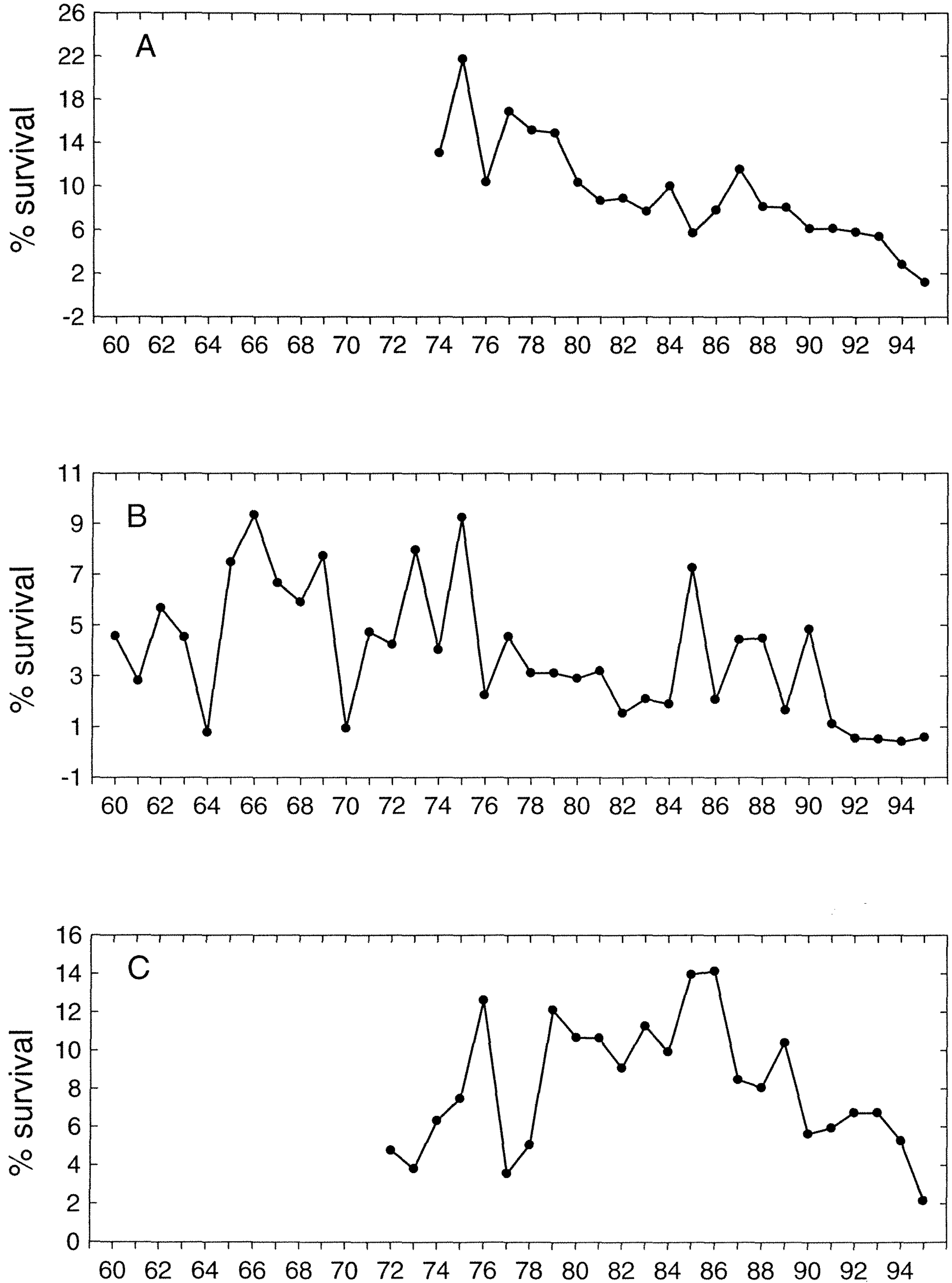


Catch (1000 mt)
0
100
200
300
400
500
600
Asia
N. America
1947
1977
1989
1998
1925
1935
1945
1955
1965
1975
1985
1995
Year

Doc 321 Fig 9



Doc 331 Fig 16



A
% survival
26
22
18
14
10
6
2
-2
60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94
B
% survival
11
9
7
5
3
1
-1
60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94
C
% survival
16
14
12
10
8
6
4
2
0
60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94

Doc 321 Fig 1