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Linkages Between A Composite Pacific Climate-Ocean Index and Fluctuations in British Columbia Salmon and Other Fish Populations

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Abstract

Several studies have described decadal-scale changes in North Pacific climate-ocean conditions. Generally, these studies focus on a single index. Using principal components analysis, we use a composite index based on three aspects of climate-ocean conditions: the Aleutian Low Pressure Index, the Pacific Atmospheric Circulation Index and the Pacific Decadal Oscillation Index. We link this composite index to decadal-scale changes in British Columbia salmon and other fish populations. Around 1989 there was a change from intense Aleutian Lows, above average south-westerly and westerly circulation patterns and warming of coastal sea surface temperatures to average Aleutian Lows, less frequent south-westerly and westerly circulation and slightly cooler coastal sea surface temperatures in winter. These climate-ocean changes were associated with changes in the abundance and ocean survival of salmon (*Oncorhynchus* sp.), distribution and spawning behaviour of hake (*Merluccius productus*) and sardines (*Sardinops sagax*) and in recruitment patterns of groundfish species.

Introduction

Forecasting has not been particularly successful in fisheries management. As a consequence, large fluctuations in catches occur without warning in major world fisheries, for example; salmon, walleye pollock (*Theragra chalcogramma*), sardines and Atlantic cod (*Gadus morhua*). These unexpected changes have obvious economic consequences as well as professional consequences. There is one view that understanding the mechanisms is unnecessary and fluctuations in abundance can be managed simply by adjusting harvest rates (Walters and Parma 1996). Even if this theory is correct the practical problem of reaching a consensus among managers and fishermen and restricting fisheries in time to sustain production may be insurmountable.

It is also becoming clear that single species management isn't working and the results are unacceptable to the public, who are becoming increasingly alarmed by the threats of overfishing to ecosystems. Moving from single species management to ecosystem management and improving forecasting techniques requires an improved understanding of the factors that regulate the abundance of fish populations naturally.

Recent studies have shown that large scale climate changes can be associated with both large scale and regional fluctuations in fish abundance. In the north Pacific, a number of indices of climate trends have been proposed (Minobe 1997, Mantua et al. 1997, Beamish et al. 1999, King et al. (in press)). The Aleutian Low pressure system has been introduced by researchers such as Beamish and Bouillon (1993) and Trenberth and Hurrell (1995). The Pacific Interdecadal Index, is a widely used index strongly influenced by sea surface temperatures in a large area of the central North Pacific (Mantua et al. 1997). A new index which incorporates the atmospheric circulation patterns for the North Pacific ocean is useful because it characterizes the flow of the westerlies which determines storm track directions and oceanic circulation in the North Pacific (King et al. 1998).

In this report we examine these three indices and show that they are responding to a common forcing mechanism. We compare the combined index that we name the Atmospheric Forcing Index (AFI) with commercially important fish off British Columbia. We propose that this composite index may be a method of identifying when changes in the productivity of north Pacific fishes may be expected.

Composite Index:

The Aleutian Low Pressure Index (ALPI) (Fig. 1a) was obtained from the Pacific Biological Station website (http://www.pac.dfo-mpo.gc.ca/sci/sa-mfpd) and is the most recent compilation of the index reported in Beamish et al. (1997). When the Aleutian Low is intense and associated winds are strong, there is enhanced upwelling of nutrients and a general increase in productivity in the surface waters of the subarctic Pacific. A weakening of the Aleutian Low is a lessening of mid-ocean upwelling, which is typified by a warming trend in the central north Pacific, and a cooling of coastal waters. The negatively north-westerly anomalies which are the basis of the Pacific Circulation Index (PCI) (Fig. 1b was also obtained from the Pacific Biological Station database http://www.pac.dfo-mpo.gc.ca/sci/sa-mfpd) and Doc. # 318 from NPAFC (King et al. 1998). Methodologies associated with the calculation of the PCI have been submitted for publication (King et al. (in press)) and original data was obtained from the Arctic and Antarctic Research Institute, St. Petersburg, Russia. The PCI is a new atmospheric circulation index similar to the Atmospheric Circulation Index produced for the Atlantic (Girs, 1971). It is based on a simplified interpretation of daily atmospheric circulation patterns over the Pacific. In general, it identifies the dominant annual wind patterns which can also be categorized as a measure of waviness of the westerlies. The Pacific Interdecadal Index (PDO) (Fig. 1c was obtained from a database maintained by S. Hare http://www.iphc.washington.edu/staff/hare/html/decadal/post1977/pdo1.html). The Pacific Decadal Oscillation has been considered a distinct climate phenomenon. Its influence has been described by Mantua et al. (1997) as affecting physical and biological processes ranging from river flows to salmon abundance.

The 3 indices were combined using principal component analysis based on their correlation matrix. The first principal component (Fig. 2) scores positive for an intense Aleutian Low, above frequency of south-westerly and westerly atmospheric circulation and a general cooling in the central north Pacific and warming in the coastal areas. The composite index scores negative for a weak Aleutian Low, a decrease in south-westerly and westerly circulation, and a warming trend in the central north Pacific and cooling along the coast.

The composite index, as the first principal component of the combined 3 indices expresses 68% of the total variation which according to the brocken-stick model (Frontier 1976) is considered significant ($p<0.05$). Therefore, it can be used as a common measure of atmospheric forcing. The composite index was influenced about equally by each of the 3 indices (ALPIλ = 0.81, PCIλ = -0.87, PDOλ = 0.81) indicating that each index may be an expression of a common and as yet undetermined mechanism.

The composite index changes trends in the early 1920s, late 1940s, the mid-1970s and the late 1980s. It is possible that a new trend started about 1998. These times of change are consistent with regime shift years of 1927, 1947, 1977 proposed by Minobe (1997), Mantua et al. (1997) and Beamish et al. (1999). A change in 1989 was proposed by Beamish et al. (1999) but was not recognized by Mantua et al. (1997). It is important to note that the changes in the composite index are at a different frequency than the oscillations associated with ENSO events. It is the frequency associated with this atmospheric forcing index that we believe most influences the processes that regulate the abundance of key commercial species naturally, off Canada's west coast (Beamish et al. in press).

Key species:

Beamish and Bouillon (1993) reported that total Canadian salmon production, as indicated by catch, declined to low levels from the mid-1950s to the mid-1970s. After the 1977 regime shift salmon catches increased to historic high levels by the late 1980s. However, by the mid-1990s catches were at historic low levels, in part because of restricted fishing opportunities. However, these restrictive harvest policies were directly related to low abundances. It is not until 1994 that the declining trend is clear (Fig. 3), however the brood year strength for fish caught in 1994 would be determined from 1990-1993, depending on the species. Therefore the decline in salmon production is both consistent with the regime change in 1989 and unprecedented in the historical catch records. Clearly a change occurred in the mechanisms that regulated the abundance of salmon. For sockeye salmon (*Oncorhynchus nerka*) from the Fraser River, it was possible to examine productivity changes in relation to harvest rates (Beamish et al. 1997). Despite an almost constant harvest rate, there was an increase in the stock specific productivity after the 1997 regime shift indicating the marine survival had improved. Possibly the most dramatic shift in trends in abundance has been for southern coho (*Oncorhynchus kisutch*) (Fig. 4). Beamish et al. (1999b) showed that marine survivals of coho from the Strait of Georgia, Puget Sound and off the coast of Washington and Oregon declined synchronously beginning in the early 1990s. The resulting returns were sufficiently low that severe fishing restrictions were implemented in virtually all of these areas. In addition to the declines in marine survival there was a change in the behaviour of coho from the Strait of Georgia which was associated with a change in the beginning (timing) of the spring freshet in the Fraser River, increased sea level heights, and a change in the direction of winter winds. In a recent study, Bradford and Irvine (in press) studied 40 coho populations from the Thompson River watershed to determine if the large scale climate impacts that occurred in the ocean also occurred in fresh water. He did not find that climate had a large scale and synchronous fresh water impact on coho production. This means that the large scale climate impacts on the population dynamics of coho occur primarily in the ocean. Additional evidence that large scale climate impacts occur in the ocean is seen in the declining return of hatchery fish even though the numbers of hatchery fish entering the ocean have either increased or remained constant (Beamish et al. 1997). The decline in salmon reflects a general decline in total British Columbia fisheries which is reflected in both the total catches and perhaps more dramatically in the landed value (Fig. 5).

The species presented in Table 1, represent over 90% of the current landings of groundfish off Canada's west coast. For the period 1977 to 1988 the percentage of average of above average year classes ranged between 50 and 78% (with one exception – Pacific hake from the Strait of Georgia). After 1988 (1989-present), only 25-35% of the year classes were average or above average. Clearly the synchronous response in year class success across this diverse group of species is a reflection of large scale climate/ocean processes. For example, sablefish, which is currently the most valuable of groundfish species shows clear decadal-scale trends in year class strength from 1960 to 1998 (Fig. 6) (King et al. 1999). In addition to the catch trends of most species there have been distributional changes that have significantly altered relative species compositions in ecosystems off the west coast of Canada. Pacific sardines were captured off British Columbia in 1992, after a complete absence of 45 years (McFarlane and Beamish, 1999). Abundance continued to increase and in 1995 an experimental fishery was initiated. Their initial disappearance from British Columbia waters corresponded to the 1947 regime shift. The abundance was estimated to be 60,000t (McFarlane and Beamish, 1999) in 1997, exceeding the estimated abundances of Pacific herring. By the mid-1990s sardines were found in the surface waters along the entire west coast. In addition, in 1997 and 1998 sardines remained off Canada's west coast year round and successfully spawned in Canadian waters for the first time (McFarlane and Beamish, 1999).

Pacific hake (*Merluccius productus*) are a large migratory population which historically spawned off Baja, California during the winter and migrated north to summer feeding grounds. Approximately 25 to 30% of the mature biomass moved into Canadian waters. Since the early 1990s a much larger percentage of the stock (approximately 40%; > 400,000t) was present in the Canadian zone. Additionally, these fish moved farther north and remained off the west coast of Canada year round. Since 1994 these hake have spawned off the west coast of Vancouver Island.

Pacific herring are one of the most important fisheries off the west coast. Herring are managed as 5 distinct fisheries/stocks. The abundance trends and recruitment patterns are different in each of these areas. However, synchronous strong year classes were identified in all 5 stocks in 1977, 1985 and 1989. In general, the Strait of Georgia stocks support the most important fishery. The stock has increased dramatically in the 1990s as a result of a number of strong year classes. Off the west coast of Vancouver Island the stock has declined during the same time period. Northern stocks show the same differing dynamics.

Discussion

There has been a synchronous change in the productivity and in the landings of British Columbia fisheries since 1989. These changes are consistent with the switching of the composite index of atmospheric forcing from positive to negative values. The mechanisms involved remain to be determined and probably differ among species. For example, the poor returns of salmon may reflect increased predation in the early juvenile stage. However the large-scale response as observed for coho would indicate that it is unlikely that a suite of predation were able to synchronously feed more heavily on coho. Beamish and Mahnken (1998) proposed that a second growth based mortality occurred in the fall and winter that was related to growth during the summer months which in turn would be affected by the availability of prey. According to their hypothesis, climate could be the common factor that would affect the abundance and availability of coho prey throughout their distribution. An important consideration when attempting to explain the mechanism for British Columbia salmon and other species is the different climate patterns north and south of Queen Charlotte Sound. Ware and McFarlane (1989) recognized the oceanographic response and identified the ecosystems north and south of this boundary as two different domains. Moore and McKendry (1996) also identified precipitation responses. They noted that there was a tendency before 1977 for precipitation to be lighter in the north and heavier in the south. After 1977 the situation was reversed. The differing north/south response in also noticed in the decadal scale trends in flow patterns of large rivers (Mantua et al. 1998, Beamish et al. in press).

Identifying the impacts is complicated because of the poor understanding of the early life history of the various fishes and the national factors that affect year class (brood year) strength. We point out that different responses may occur if the species relationship within ecosystems respond differently. The changes in the ecosystems are apparent because groundfish are also impacted and the distributions and spawning behaviour of hake and sardines changed. This indicates a common factor forcing these changes. Though the common factor remains to be determined the Atmospheric Forcing Index appears to be a suitable indicator of regional changes in productivity of commercial species.

The change in the late 1970's in the composite index also influenced salmon and groundfish productivity as has been reported previously by Beamish and Bouillon (1993, 1995). Earlier changes are difficult to study because many fisheries were not developed and data was generally scarce.

It is possible another change occurred around 1998. If this changes real it would not imply that there will be a reversal in the dynamics of ecosystems to pre 1989 relationships.

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List of Figures

Table 1 Numbers of strong, average and below average year classes for selected groundfish species during 1977-1988 and 1989 to present.

	1977-1988			1989-Present		
Species	Strong	Average	Below Avg.	Strong	Average	Below Avg.
Sablefish	5	3	4	2	1	6
Pacific hake (Offshore)	4	2	6	1	1	6
Pacific Hake (Strait of Georgia)	1	6	4	5	2	2
Rock Sole	4	4	4	0	2	6
English Sole	2	5	5	0	2	6
Dover Sole[a]	4	4	4	0	2	6
Yellowtail Rockfish[b]	3	6	3			
Pacific Ocean Perch[b]	3	4	5			

a. based on relative year class abundance of US stocks (J. Fargo, Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, British Columbia, V9R 5K6, pers. comm.)

b. estimates are not available since year classes have not yet recruited to the fishery

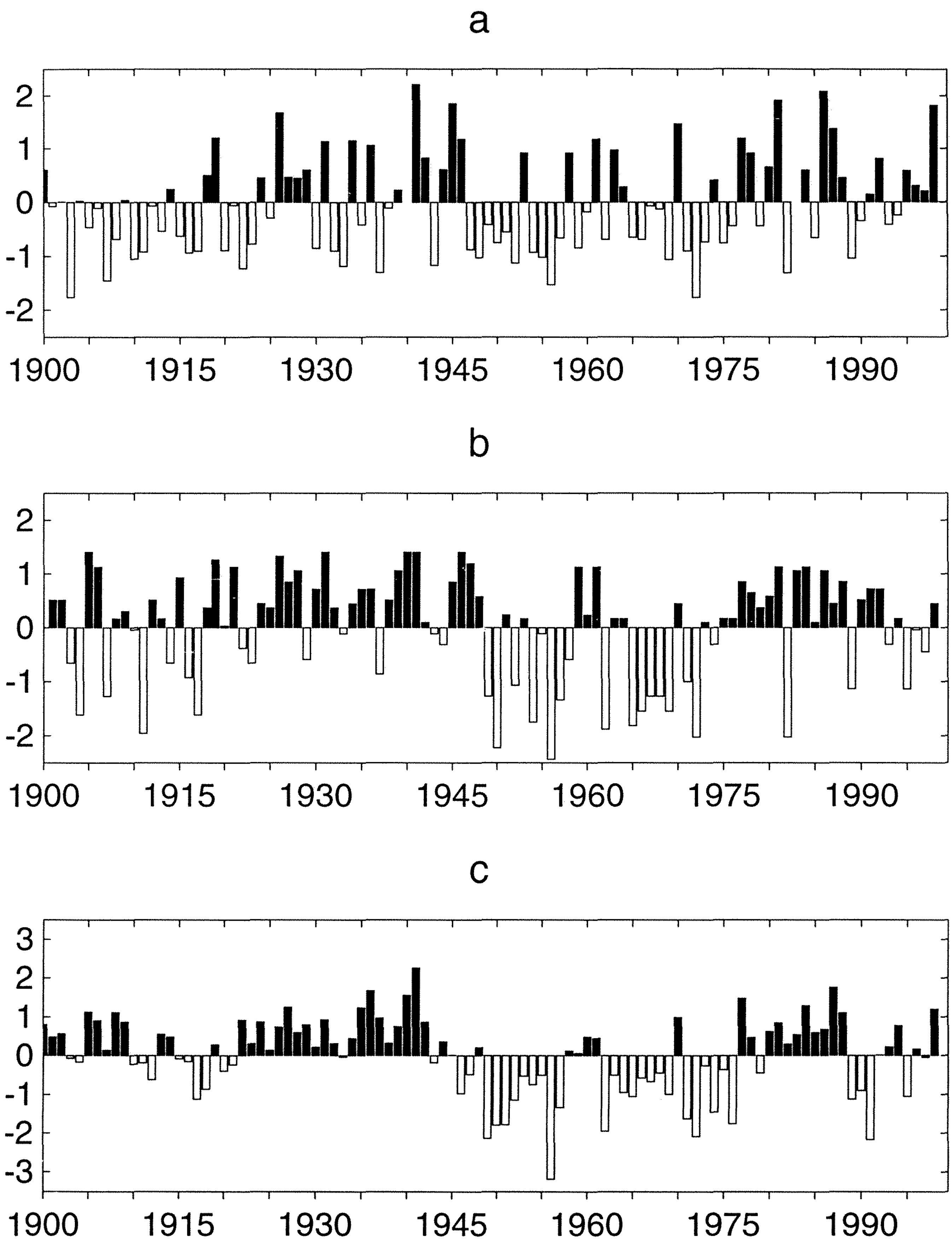

a
2
1
0
-1
-2
1900
1915
1930
1945
1960
1975
1990
b
2
1
0
-1
-2
1900
1915
1930
1945
1960
1975
1990
c
3
2
1
0
-1
-2
-3
1900
1915
1930
1945
1960
1975
1990

Fig. 1

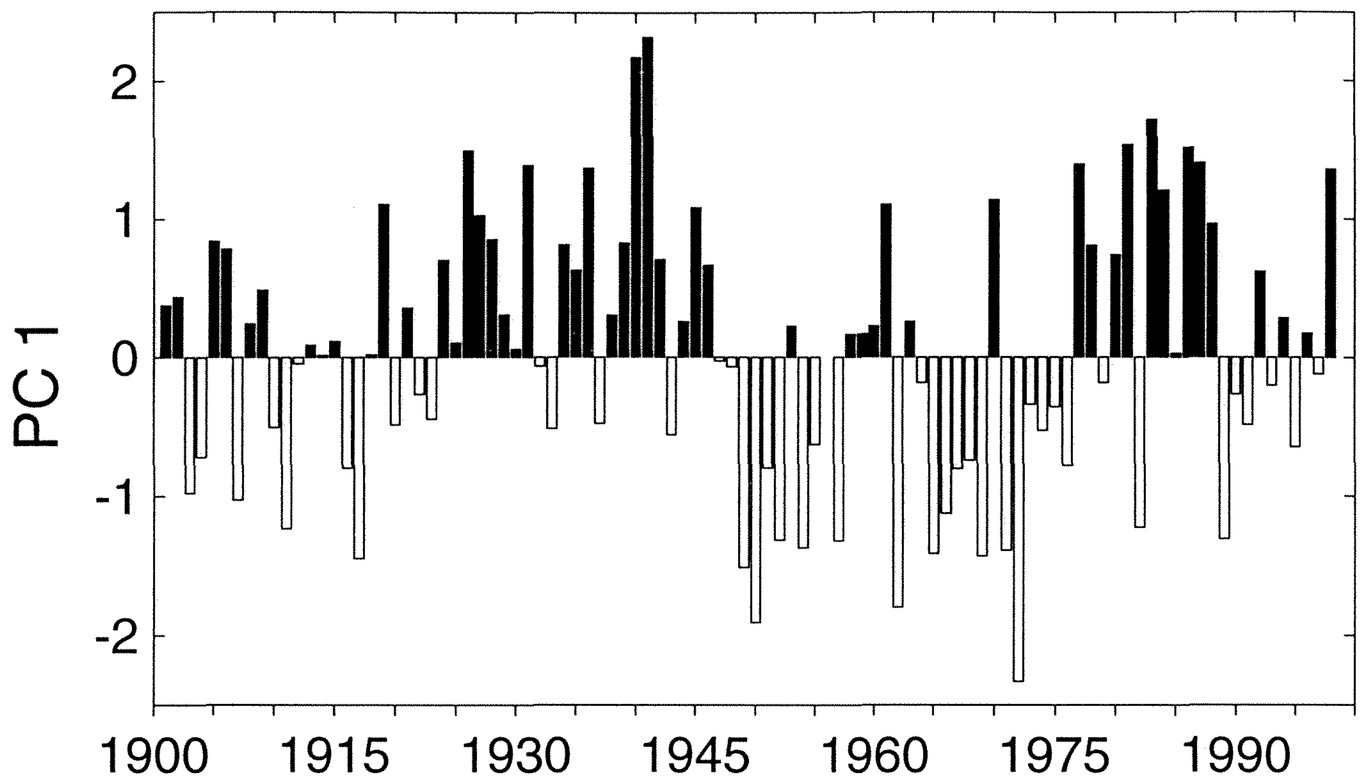
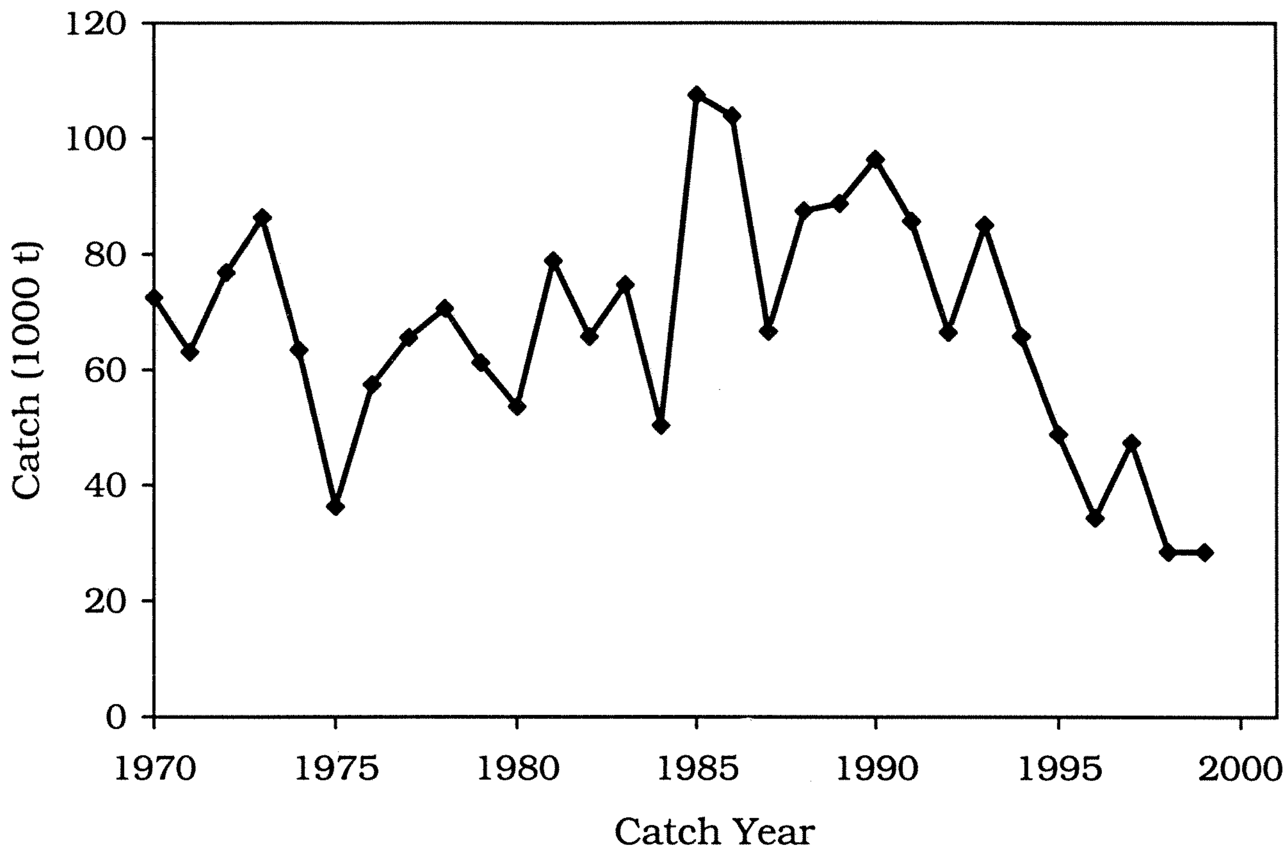


Fig. 2



120
100
80
60
40
20
0
Catch (1000 t)
1970
1975
1980
1985
1990
1995
2000
Catch Year

Fig. 3

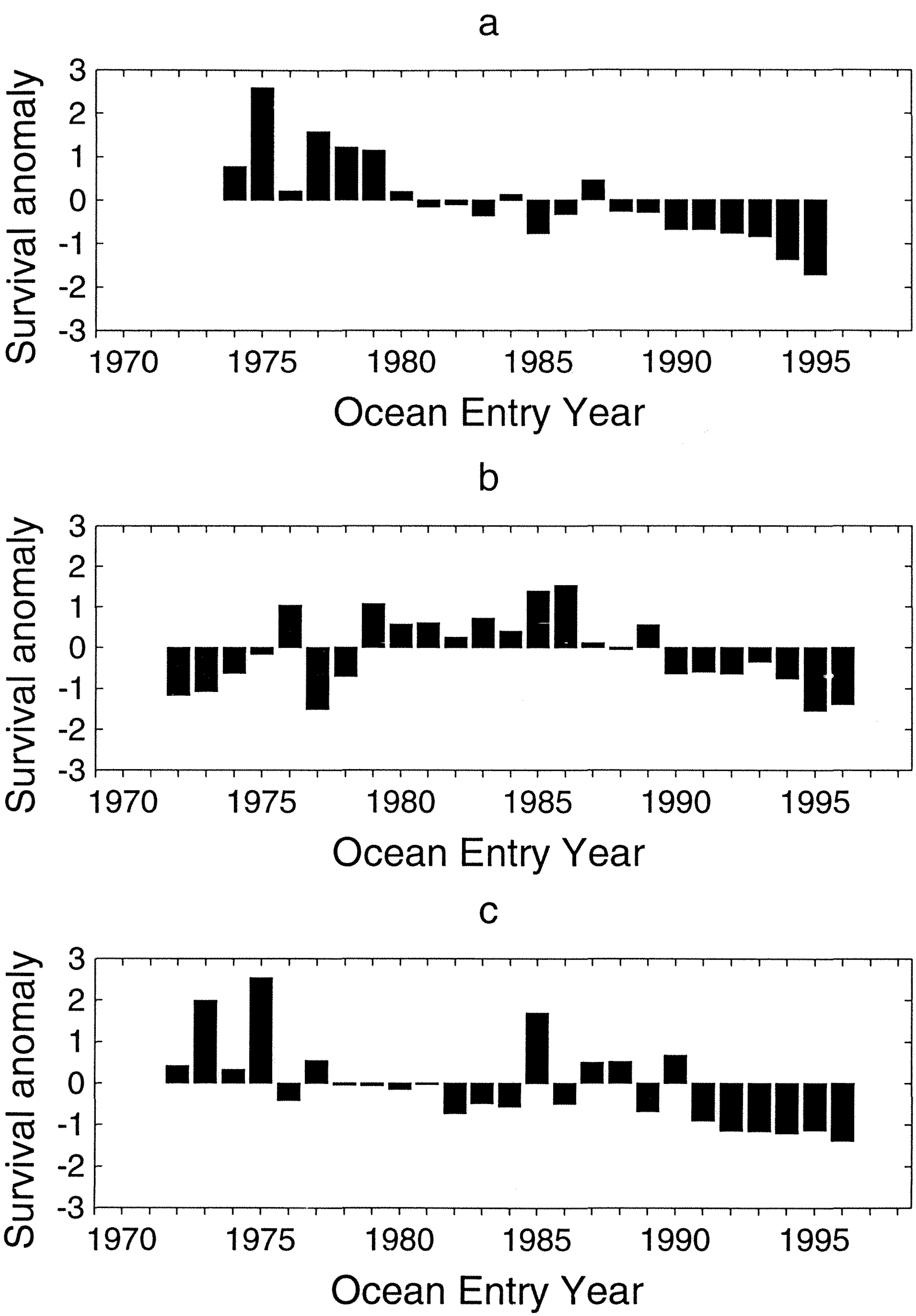
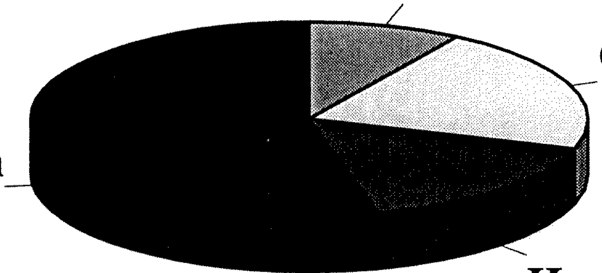

a
b
c
Survival anomaly
3
2
1
0
-1
-2
-3
1970
1975
1980
1985
1990
1995
Ocean Entry Year

Fig. 4

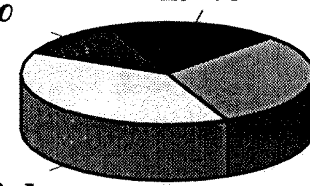
BRITISH COLUMBIA LANDED VALUES
Wild Production

1988
$769.8 million (1998 $)



Salmon	$410.4 million (1998 $)
Herring	$126.9 million (1998 $)
Groundfish	$164.1 million (1998 $)
Shellfish	$ 68.5 million (1998 $)

1998
$295.0 million (1998 $)



Salmon	$55.0 million (1998 $)
Herring	$35.0 million (1998 $)
Groundfish	$115.0 million (1998 $)
Shellfish	$ 90.0 million (1998 $)

Note: 1998 data are estimated

Fig. 5

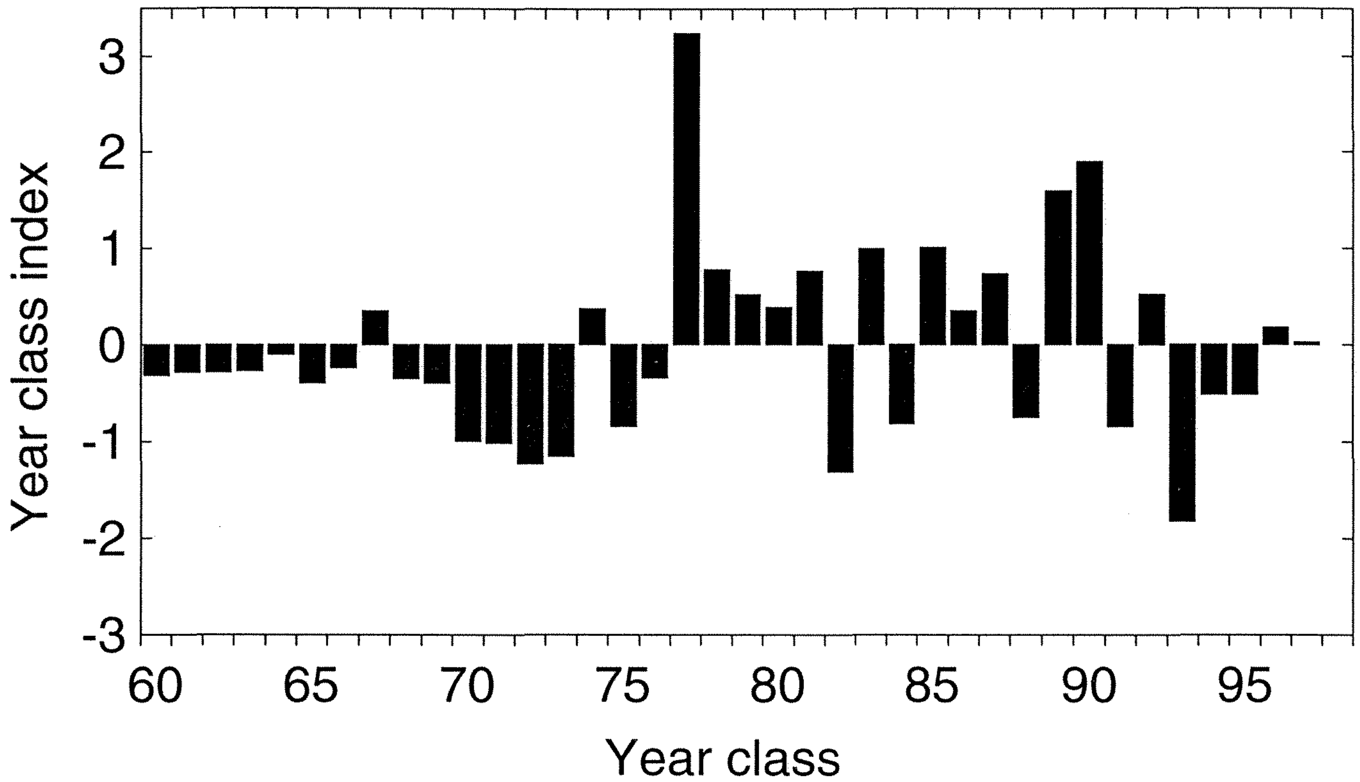


Fig. 6