Canada

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The Fishery

Total fishery landings of all marine fish off the west coast of Canada (Fig. 3) increased during the 1980s, reaching a maximum of 417,777 t in 1994, and declined through to the present, approaching landings common in the early 1980s (Fig. 4). The commercial fishery off Canada's west coast has been strongly influenced by the size and value of the wild Pacific salmon (*Oncorhynchus* spp.) fishery. Catches of all species of Pacific salmon reached historic high levels by the late 1980s (Fig. 5; Beamish and Noakes, 2004), followed by a precipitous decline to historic low levels from the late 1990s to the present.

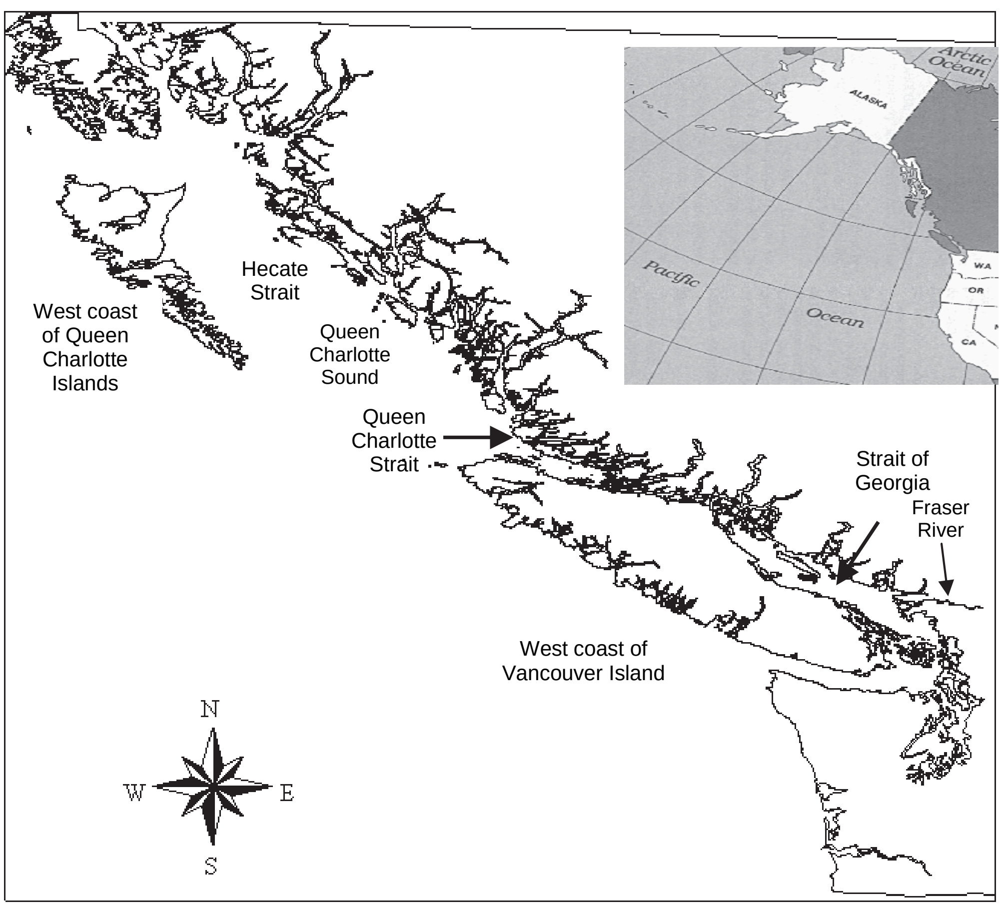


Fig. 3 Map of the west coast of Canada.

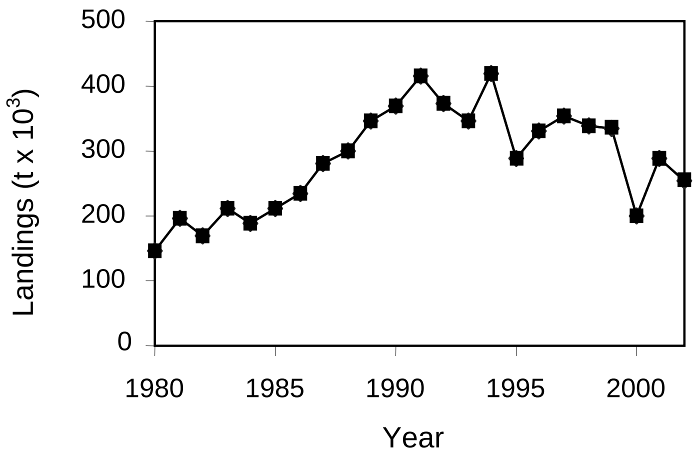


Fig. 4 Total landings of all marine fish off the west coast of Canada from 1980 to 2002. The FAO data base was used and catches of Pacific hake and Pacific sardine by Canadian fisheries were added.

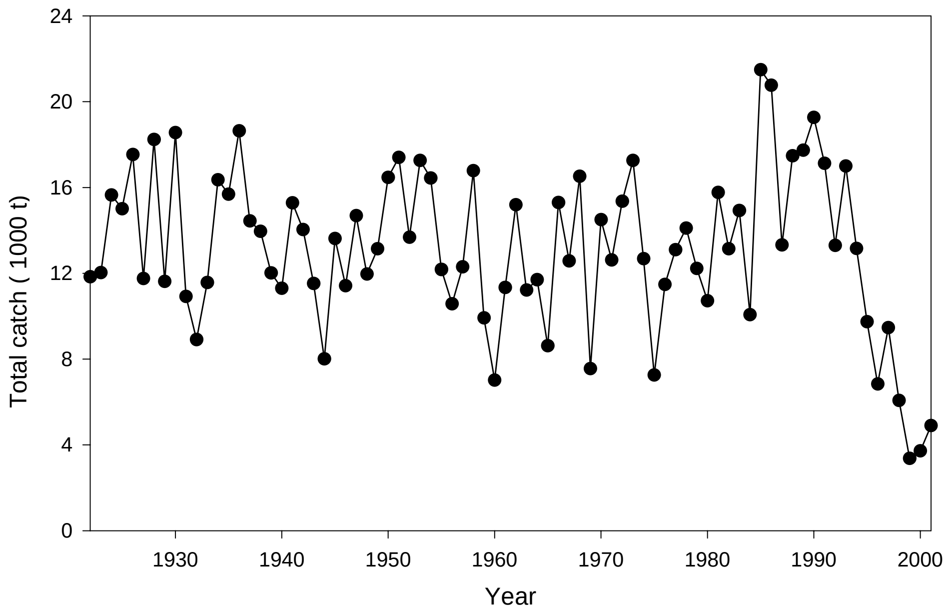


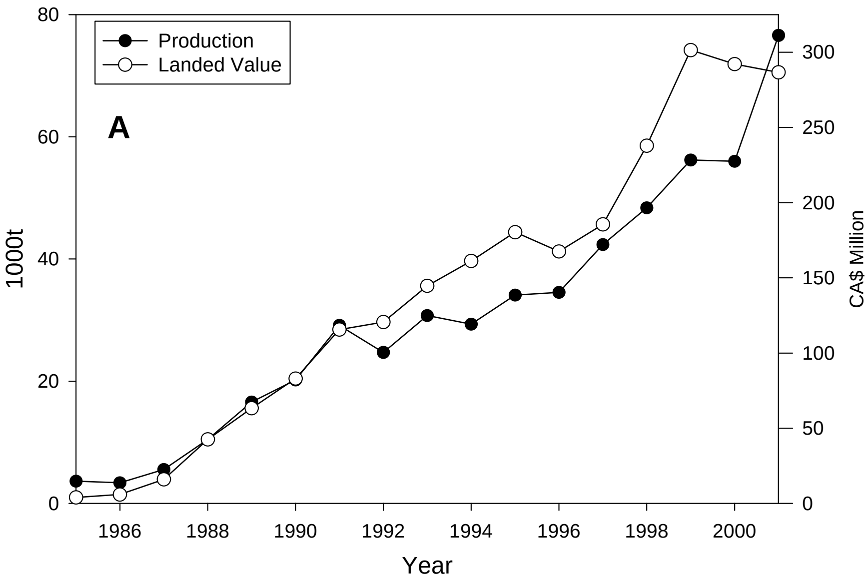
Fig. 5 Total annual Canadian catch of all species of Pacific salmon from 1922 to 2001.

The increase to the historic high levels and the rapid decline to historic low levels was a result of climate changes and management (Beamish *et al.*, 2000; Beamish and Noakes, 2004). The increases in the 1980s occurred because marine survival improved after the 1977 regime shift (Beamish and Bouillon, 1993) and management actions adapted to the improved ocean productivity by increasing escapements and protecting freshwater spawning habitat. However, another regime shift occurred in 1989 (Hare and Mantua, 2000; McFarlane *et al.*, 2000), which generally reduced the marine survival rate, and productivity of Pacific salmon that went to sea in the early 1990s (Beamish *et al.*, 2004a). It is possible that some overfishing occurred in the early 1990s, particularly for coho salmon (*O. kisutch*) and perhaps chinook salmon (*O. tshawytscha*), exacerbating the effects of the reduced marine productivity. As a result, the total returns of some stocks and some stock aggregates became so small that fisheries had to be reduced or shut down completely. Consequently, the total catches declined in part because of the reduced abundance, and in part because fisheries were closed or reduced. The decline in total catch in 2001 compared to the total Pacific salmon catch in 1985 was approximately 90,000 t, which was about 1.5 times greater than the average total catch of 60,000 t of all species of Pacific salmon in British Columbia from 1922 through to 2000.

The decline in Pacific salmon catch and the subsequent management decisions to close fisheries also appear to be related to economic conditions (Noakes *et al.*, 2002). There was a steady increase in the production of farmed salmon in British Columbia and in the world that paralleled the decline in the abundance of wild Pacific salmon in British Columbia. In British Columbia, the production of farmed salmon, which is primarily Atlantic salmon (*Salmo salar*), increased from 0.12 t in 1985 to 67.7 t in 2001 (Fig. 6A and B).

Another major change in ocean conditions occurred in 1998 (Fig. 7). This change was associated with improved marine survival of Pacific salmon in British Columbia (Beamish *et al.*, 2001; Beamish and Noakes, 2004; Beamish *et al.*, 2004a). The abundance of a number of species increased and in some cases, such as pink salmon (*O. gorbuscha*) produced in the Fraser River, the returns in 2001 and 2003 were at historic high levels (Beamish and Noakes, 2004). However, despite these increases in abundance, new considerations in management and reduced value of wild salmon continue to influence the size of catches.

The total landed value of all British Columbia fisheries, including farmed salmon, has been virtually constant at an average value of about CAD (Canadian) $600 million since 1993 (Fig. 8). The total catch of all species, including farmed salmon production, has declined slightly since the early 1990s (Fig. 9).



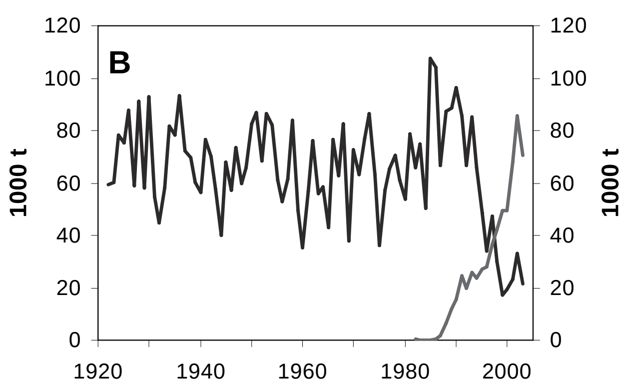


Fig. 6 (A) British Columbia aquaculture production and value from 1985 to 2001 (BCMAFF, 2002). (B) Total catch of wild Pacific salmon, as shown in Figure 5, (dark line) and the production of farmed salmon, beginning in the 1980s (grey line).

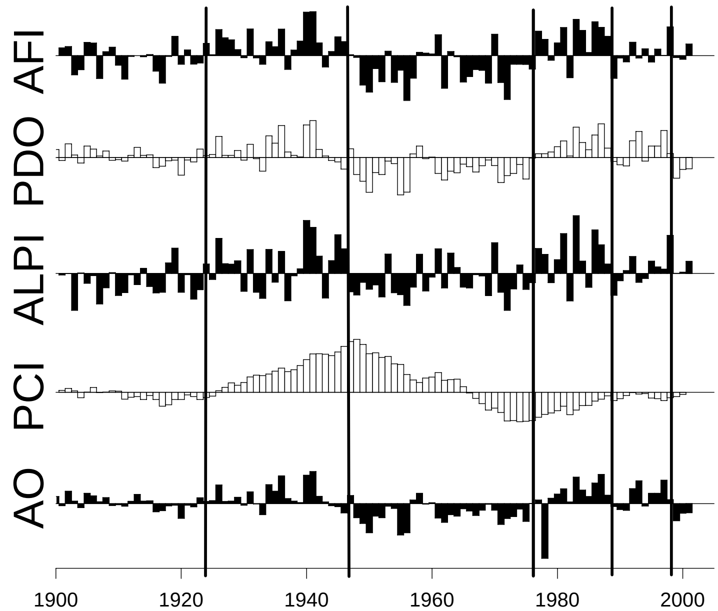


Fig. 7 Indices of climate change: the Atmospheric Forcing Index (AFI), Pacific Decadal Oscillation (PDO), Aleutian Low Pressure Index (ALPI), Pacific Circulation Index (PCI), and Arctic Oscillation (AO). Vertical lines denote timing of regime shifts.

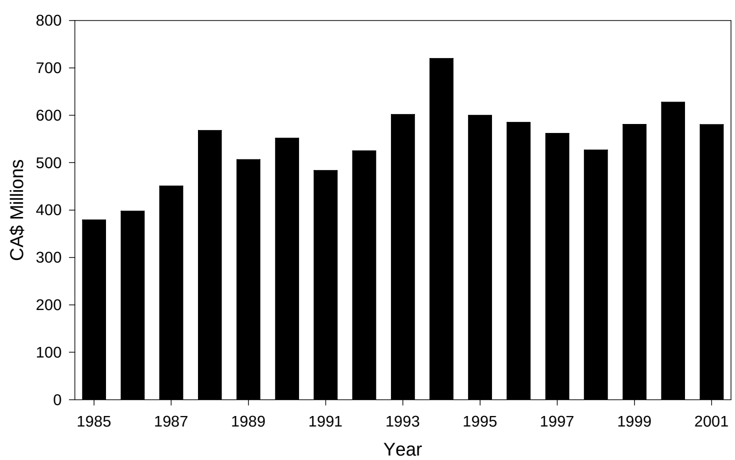


Fig. 8 Total value of fisheries landings in British Columbia (BCMAFF, 2002; Department of Fisheries and Oceans (DFO) commercial catch statistics Information Management Division, Pacific Region Data Unit).

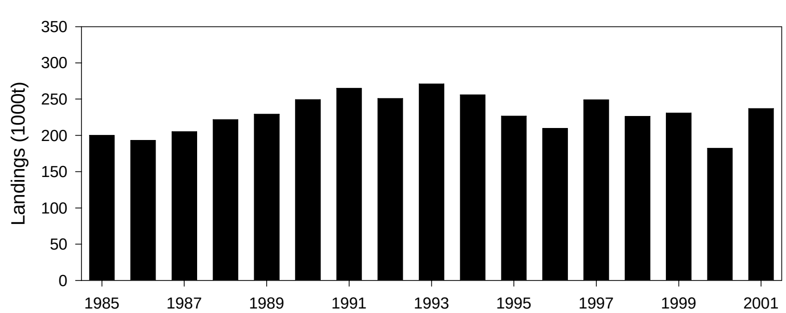


Fig. 9 Total commercial fishery landings plus aquaculture production in British Columbia from 1985 to 2001.

The total landed value of all fisheries, including farmed fish and shellfish, was CAD $580.4 million in 2001. The landed value of wild fish and shellfish was CAD $293.8 million. The landed values have actually increased since the 1980s, in part from the health and wealth associated with the fisheries for Pacific herring (*Clupea pallasii*), Pacific halibut (*Hippoglossus stenolepis*), sablefish (*Anoplopoma fimbria*), and Pacific hake (*Merluccius productus*). There is some discrepancy between the Food and Agriculture Organization (FAO) of the UN and Canada's Department of Fisheries and Oceans (DFO) statistics (Fig. 10A–F), but in general, there has not been extreme year-to-year variability. In fact, catches of Pacific halibut, sablefish and Pacific hake were relatively stable from the late 1980s to the late 1990s.

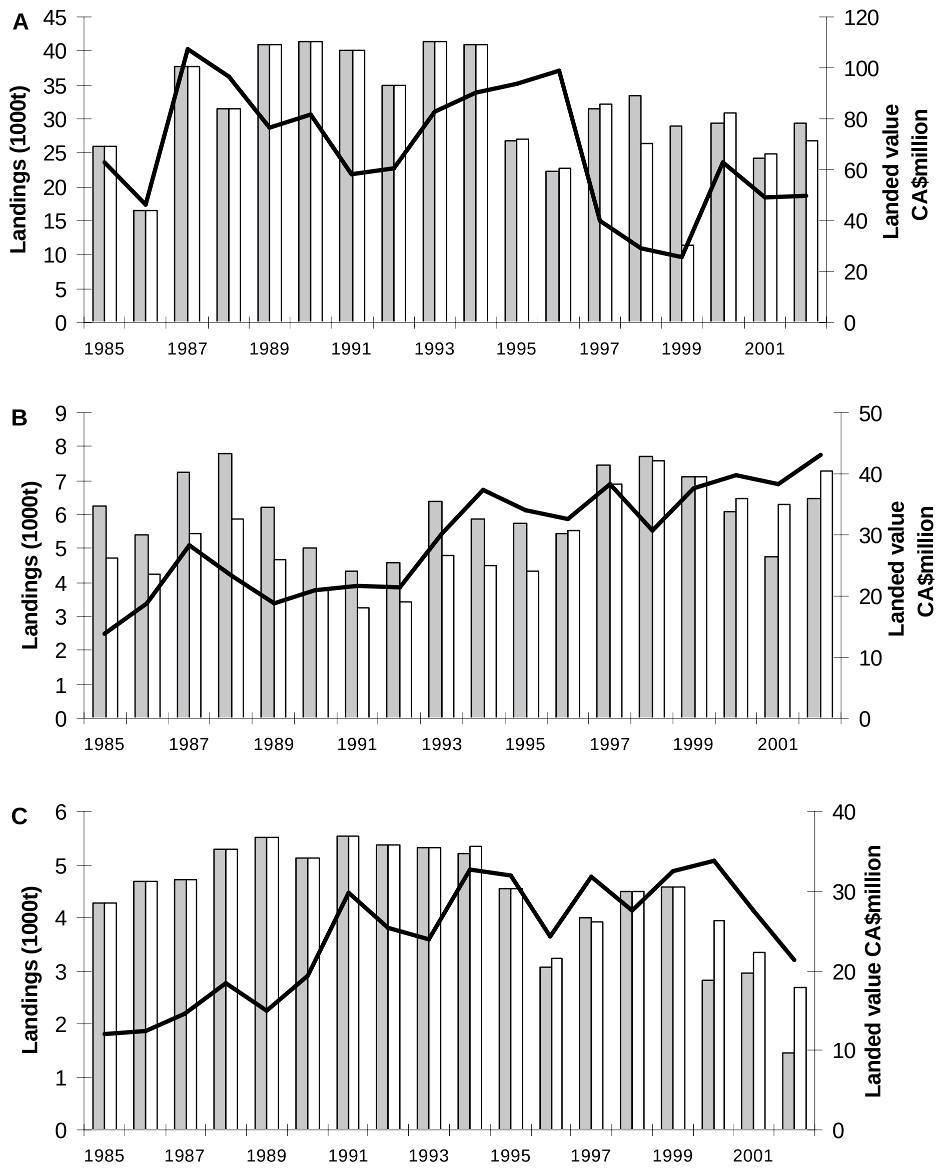
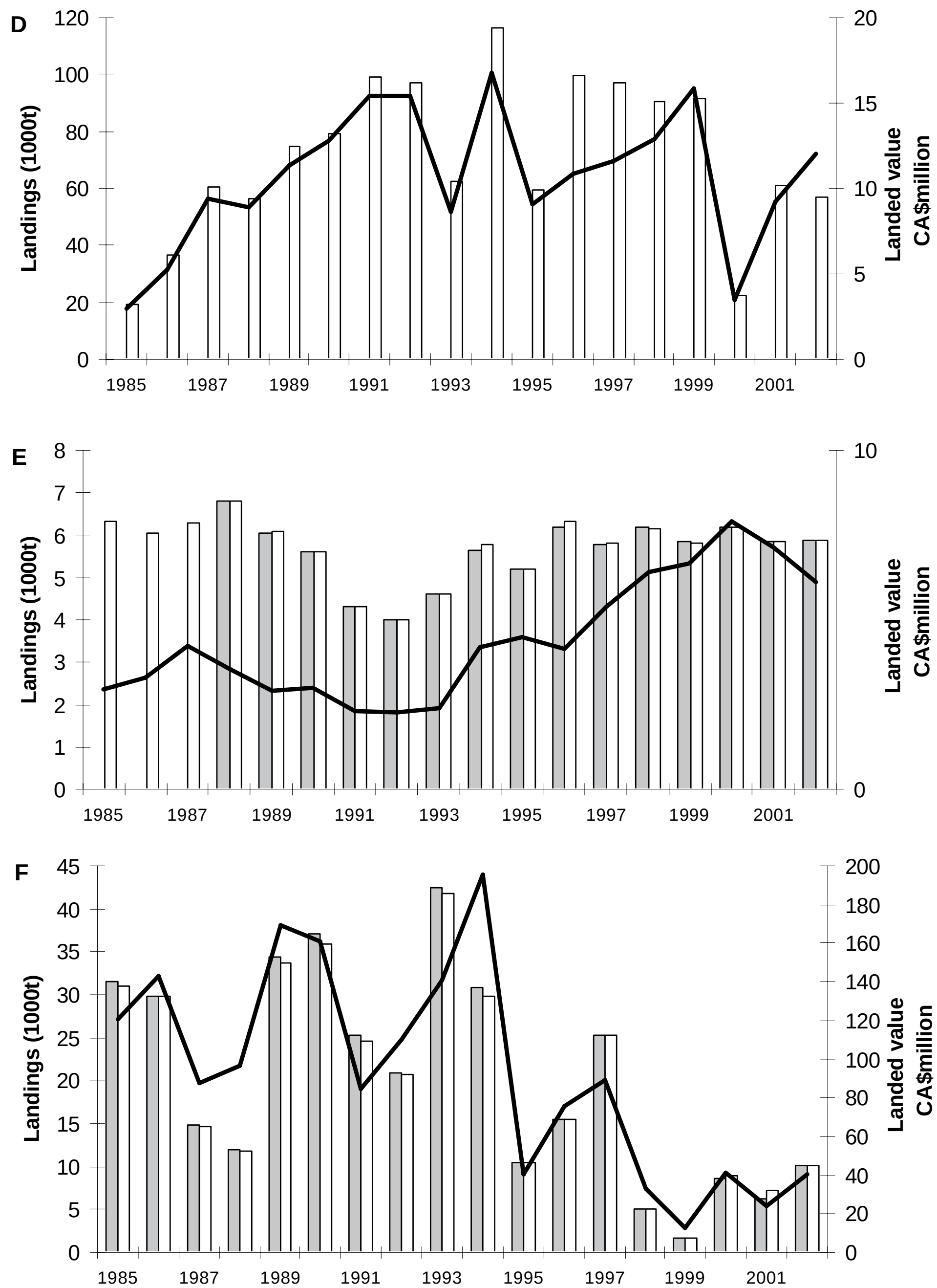


Fig. 10 FAO landings (grey bars), DFO landings (white bars) and landed value (solid line) of (A) Pacific herring, (B) Pacific halibut, (C) sablefish, (D) Pacific hake, (E) Pacific ocean perch, (F) sockeye salmon, (G) chum salmon, (H) pink salmon, and (I) Pacific cod in British Columbia fisheries.



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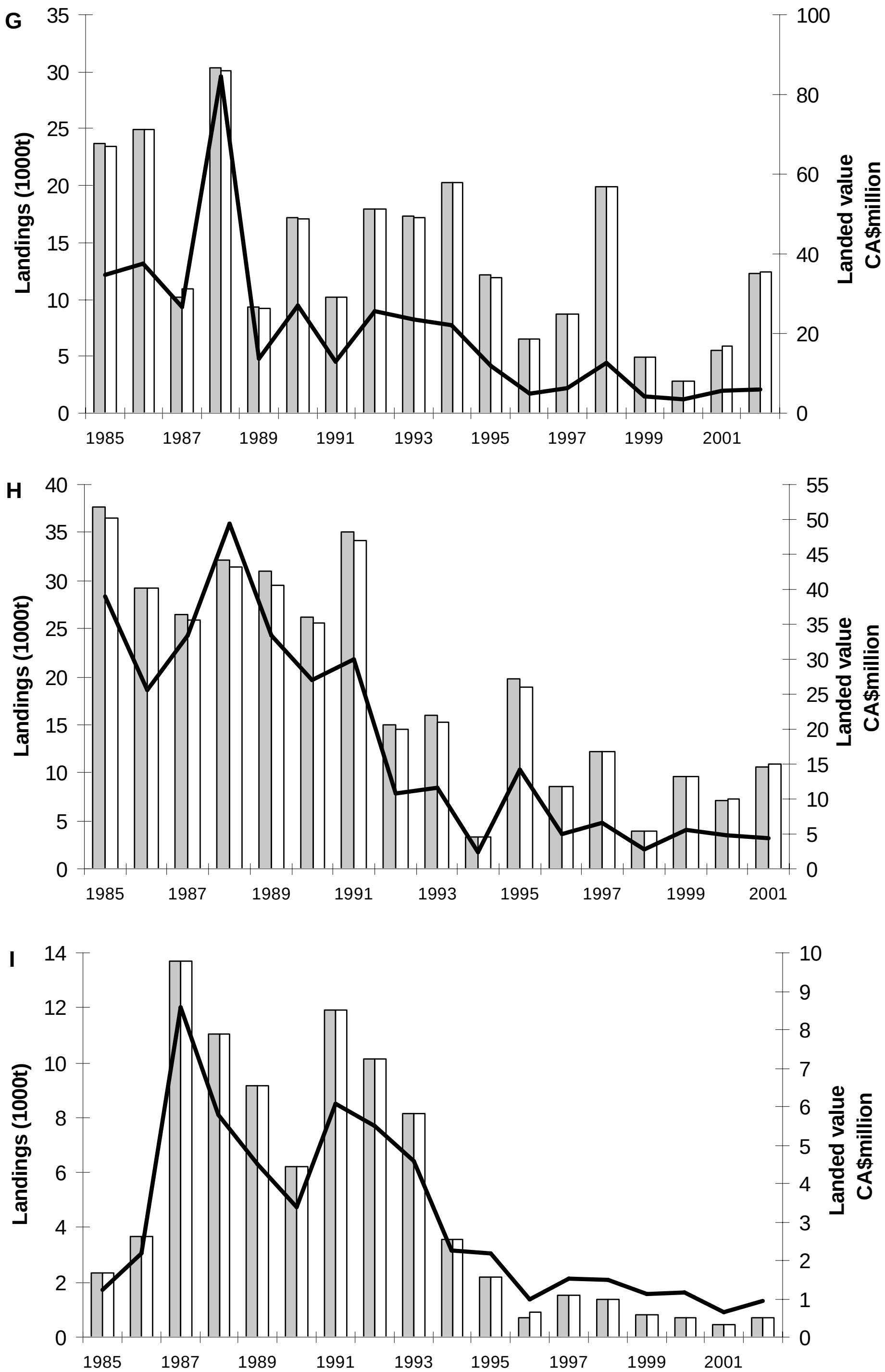

Fig. 10 Continued.

In this report, we focus on ten key species in the fishery off Canada's Pacific coast. These ten species accounted for approximately 43 to 73% of the weight of total landings from 1980 to 2000 (Table 3). Some of these species, such as Pacific halibut, Pacific herring, Pacific sardine (*Sardinops sagax*), and sockeye salmon (*O. nerka*) have been key species in the fishery since the late 1800s. Estimates of production are available for Pacific herring, Pacific halibut, Pacific hake, sablefish, and for pink and sockeye salmon from the Fraser River (Fig. 11). Catch is a good indicator of abundance for Pacific salmon up to the mid-1990s because exploitation rates were high (60–80%) and tended to be constant.

The longevity of a species may be an indication of the environmental impact on reproduction. McFarlane and Beamish (1986) hypothesized that the longevity of a species represents the longest period over evolutionary time that the species survived conditions unsuitable for successful reproduction in the preferred habitat. A species evolves to adapt to extreme climate-related variability in its preferred habitat. In the absence of fishing, the age structure of a population maximizes its ability to survive extremes in the mode of climate variability that most affects its ability to replenish itself.

Short-lived marine species, such as coho salmon and pink salmon, will be the immediate indicators of change and would be expected to have evolved the ability to survive wide fluctuations in their marine habitat at the population level. Pacific cod (*Gadus macrocephalus*) off British Columbia is at the southern limit of its distribution and may also provide an early indication of climate change impacts.

The longevities of fishes in the British Columbia fisheries increase from species that live 3 to 10 years, including Pacific salmon, to species that live 11 to 30 years, such as skate and some sole species through to species that live from 33 to 205 years, including walleye pollock and some rockfish species (Table 4). It would be expected that the strategies evolved to survive the various kinds of natural climate variability in the ocean habitat would differ among these types of fishes. This means that any assessment of climate impact on fish and fisheries must consider the impacts on the life history strategy of the particular species, as well as on its physiology. We propose that a working hypothesis for the impacts of global warming could be that the apparent impact may be related to longevity of a species. Thus, a short-lived species, such as pink salmon, would respond quickly to the impacts and the consequences would be detectable perhaps in a decade. Long-lived species could buffer the impact and it may take many decades to detect the response.

Table 3 Total catches (t) of the key fish species in the British Columbia fisheries (FAO, 2000).

Species	**1980**	**1985**	**1990**	**1995**	**2000**
Pacific herring	25,155	25,955	41,280	26,780	29,290
Pacific hake	12,311	14,429	72,866	70,418	22,400
Pacific ocean perch	–	9,043	5,598	5,207	6,177
Pacific halibut	4,396	6,255	5,031	5,745	6,095
Pacific cod	7,817	2,345	6,233	2,172	712
Pacific sardine	–	–	–	25	1,559
Sablefish	2,849	4,263	5,125	4,542	2,811
Sockeye salmon	7,727	31,568	37,134	10,533	8,665
Pink salmon	13,718	37,701	26,240	19,767	7,158
Chum salmon	16,809	23,646	17,181	12,115	2,783
Total	90,782	155,205	216,688	157,279	86,091
Total catch all species	147,108	212,896	370,608	289,782	199,442
% of all species catch	61.7	72.9	58.5	54.3	43.2

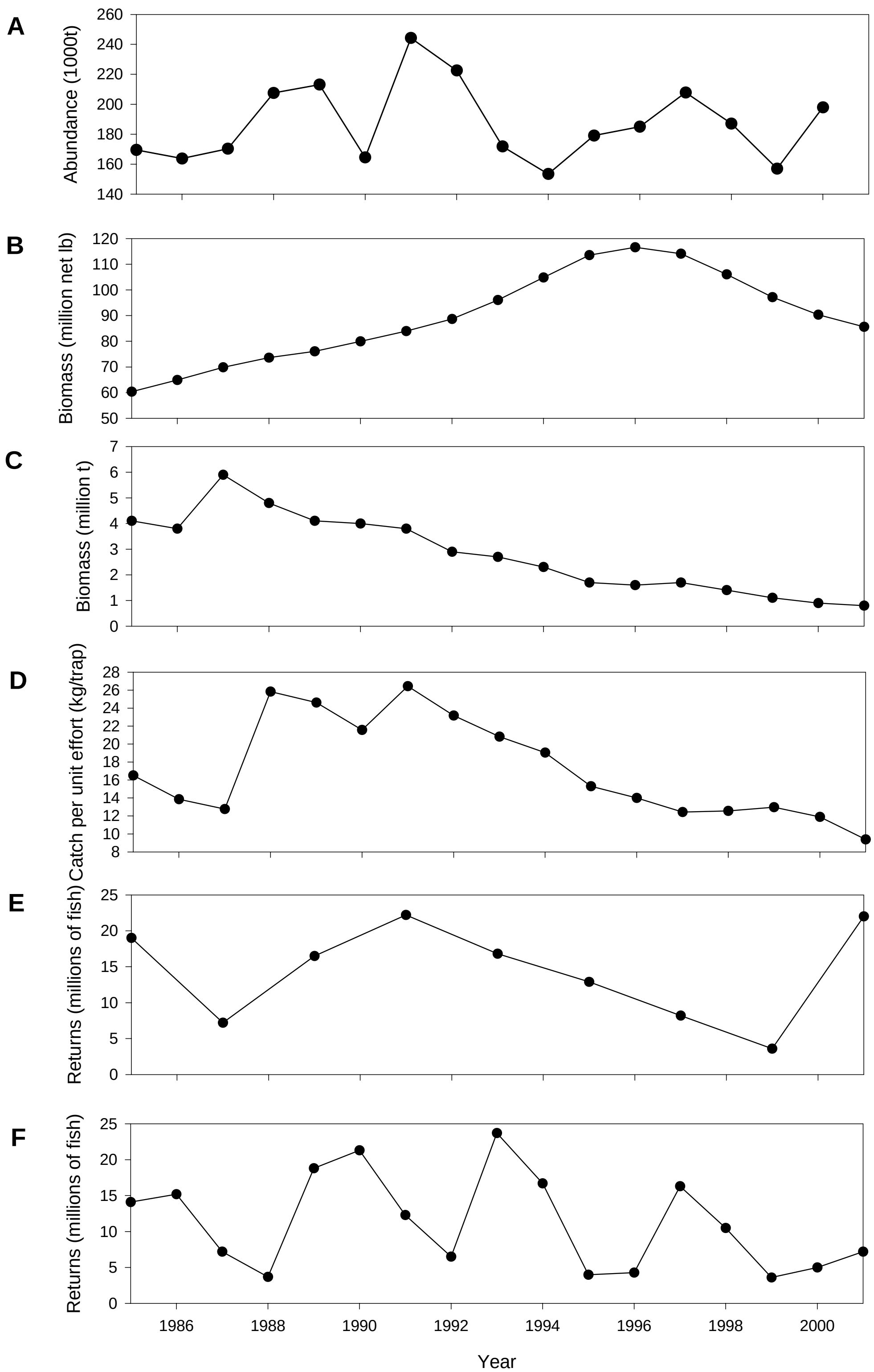

Fig. 11 Production indices of key British Columbia fish species. (A) Pacific herring pre-fishery abundance, (B) Pacific halibut legal sized fish abundance off the west coast of Canada, (C) Pacific hake age 3+ biomass off the west coast of Vancouver Island, (D) sablefish average catch per unit effort, (E) Fraser River pink salmon returns (odd years only), and (F) Fraser River sockeye salmon total production.

Table 4 Total catch and maximum age of finfish off the Canadian west coast (all gear) > 1 t landed in 2000 (King and McFarlane, 2003; Beamish *et al.*, 2006).

Species	Maximum age	Total weight (t)
Rougheye rockfish	205	848
Shortraker rockfish	120	234
Yelloweye rockfish	118	292
Sablefish	113	3947
Pacific ocean perch	100	6179
Yellowmouth rockfish	100	2050
Shortspine thornyhead	100	732
Spiny dogfish	100	244
Redbanded rockfish	93	556
Quillback rockfish	90	197
Rosethorn rockfish	87	17
Splitnose rockfish	86	92
Canary rockfish	84	662
Silvergray rockfish	81	1579
China rockfish	79	30
Tiger rockfish	69	7
Yellowtail rockfish	64	4124
Widow rockfish	60	1971
Vermilion rockfish	60	7
Sharpchin rockfish	58	401
Dover sole	57	3040
Redstripe rockfish	55	1193
Pacific halibut	55	6096
Greenstriped rockfish	54	35
Bocaccio	52	282
Longspine thornyhead	50	723
Copper rockfish	50	48
Black rockfish	50	25
Darkblotched rockfish	48	56
Harlequin rockfish	47	9
Petrale sole	35	405
Walleye pollock	33	1044
Big skate	30	1152
Longnose skate	30	208
Rex sole	27	393
Flathead sole	27	40
Arrowtooth flounder	25	4285
Rock sole	25	1229
Lingcod	25	1984
Pacific cod	25	708
Starry flounder	24	38
English sole	23	710
Pacific hake	23	22347
Slender sole	20	2
Wolf eel	~20	2
Kelp greenling	18	18

Table 4 Continued.

Species	Maximum age	Total weight (t)
Pacific herring	15	27725
Sandpaper skate	~15	4.2
Spotted ratfish	~15	13
Sardine	13	800
Butter sole	11	19
Albacore tuna	10	233
Sand sole	10	19
Curlfin sole	~10	18
Chinook salmon	8	510
Sockeye salmon	7	8670
Chum salmon	7	2780
Coho salmon	4	30
Pink salmon	3	7160

Climate and Ocean Impacts

There are five marine ecosystems off the west coast of British Columbia: (1) the Strait of Georgia, (2) west coast of Vancouver Island, (3) west coast of Queen Charlotte Islands, (4) Queen Charlotte Sound, and (5) Hecate Strait (Fig. 3). There is evidence that a north–south boundary exists and that the climate on either side oscillates as the climate regimes shift. Moore and McKendry (1996) showed that levels of snow pack and large river flows followed opposite trends in the northern and southern areas of the province. Prior to 1977, large river flows and snow pack in the southern part of British Columbia were above average, while flows and snow pack in the northern areas were below average (Moore and McKendry, 1996; Beamish *et al.*, 2000). This pattern reversed after the 1977 regime shift.

There is a minimum in the average sea level pressure off the west coast at about latitude 55°N (Beamish *et al.*, 2000) and it is possible that the oscillation in climate, observed on land, may also occur in ocean ecosystems at approximately 55°N latitude. Hare *et al.* (1999) reported a decadal-scale, north–south oscillation in the catch of coho and chinook salmon, although they did not identify the area where the oscillation was centred.

Beamish *et al.* (2000) looked at the latitudinal position of the lowest pressure from 1965 to the present and found a shift northward in the latitude of the lowest annual sea level pressure beginning in the mid-1970s. In addition to the northward shift of this area of low pressure, there was an increase in the variance of the average sea level pressure (mb) for 50°N between 125°W and 180°W (Beamish *et al.*, 2000). The trends were reversed after the 1977 regime shift. Thus, there is evidence that changing trends in climate may affect the same species differently on the west coast of Canada, depending on its latitudinal distribution.

Hollowed and Wooster (1992) reported shifts in winter sea surface temperatures (SSTs) for the coastal and offshore areas off the coast of British Columbia. Freeland *et al.* (1997) suggested that there is an overall warming trend in SSTs for the British Columbia coastal waters. When the SSTs for an area from 141°W to 123°W and 35°N to 60°N are broken into three regimes (pre-1977, 1977–1989, and post-1989) for winter and annual averages, a difference in warming is detectable. While there was an overall warming trend in winter, exhibited by warmer temperatures for the entire coast in 1989–1996, compared to 1965–1976, the increase in temperature was greater in the regime 1977–1988 than in 1989–1996. These differences in the amount of warming across regimes are not evident in annually averaged data. On an annual basis, there is a continuous increase in temperatures across regimes. Winter is an important period for reproduction of many British Columbia fishes; thus it is important to monitor climate–ocean systems during winter.

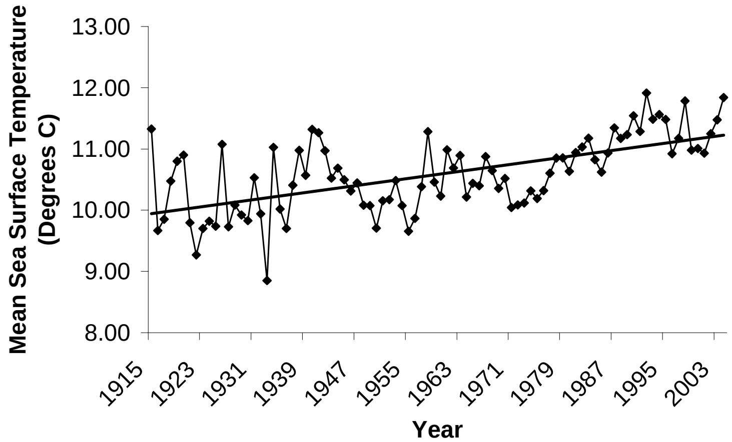

Fig. 12 Mean annual sea surface temperature measured at lighthouses around the Strait of Georgia from 1915 to 2004. A linear trend indicates an increase of 1.0°C over 90 years.

For inshore waters, like the Strait of Georgia, SSTs are measured at lighthouses or are available from temperature profiles. There is a long-term increasing trend in SSTs of 1.0°C from 1915 to 2004 (Fig. 12). Within the Strait of Georgia, SSTs from lighthouses were below average prior to 1977, were just above average from 1977 to about 1988, and in the 1990s continued to increase. SSTs measured just offshore from Nanoose Bay in the Strait of Georgia also exhibited a similar pattern. Bottom temperatures at this site have shown an overall warming, with the switch from below average to above average temperatures occurring in the late 1970s. It is important to note that the regional indicators of decadal-scale changes measure similar ocean–climate systems as do the basin-scale indicators. Changes in the large-scale climate and ocean indicators, therefore, would be expected to be reflected in the dynamics of the coastal oceanography off British Columbia. Beamish *et al.* (2000) reported that the winter (December through March) atmospheric patterns over British Columbia generally match those for the Pacific region. Prior to 1977, the winter frequencies of westerly and northwesterly circulations were above average. Since 1977, southwesterly circulation was above average until about 1991, when westerly or northwesterly circulation was again above average. The regime from 1977–1988 could be classified as a period of extreme low pressures and extreme variation. The post-1988 regime was characterized by a return to higher average annual pressures. There are studies that report north–south differences in Pacific salmon catch (Hare *et al.*, 1999) and ocean processes (Gargett, 1997). It is likely that these north–south differences are related to the changing pressure trends around 55°N.

Large rivers are important influences in the productivity of coastal areas in British Columbia. River flows into areas such as the Strait of Georgia have a significant impact on the estuarine circulation, and consequently on primary productivity. The largest rivers in British Columbia are also the important spawning areas for Pacific salmon. The Skeena, Nass and Fraser rivers originate from mountain snow packs and all produce large numbers of salmon. The maximum discharge from these rivers occurs about June, whereas smaller, more coastal rivers that receive most of their water from winter rains have their maximum discharge in the winter. Flow data are available for these smaller rivers, but the time series are too limited to allow for any kind of province-wide study. The average annual pattern of discharge from the Skeena, Nass and Fraser rivers shows distinct changes around 1977 (Beamish *et al.*, 2000). The northern rivers, the Skeena and Nass, both exhibited a decreasing trend in discharge from the late-1950s to 1976, and an increasing trend from 1977 to 1989. The increases in discharge post-1976 corresponded to the heavier than average snow pack observed in northern British Columbia by Moore and McKendry (1996). The Fraser River exhibited an increase in discharge from 1945 to 1976 and a decreasing trend from 1977 to 1989, which again corresponds to snow pack variation observed by Moore and McKendry (1996). Even with the opposite linear trends in the northern and southern rivers, in the regime prior to 1977, extreme high and low discharge years were virtually identical in all three rivers and fluctuations were more frequent and extreme. After 1977, the inter-annual fluctuations were less extreme and the extreme years in the south no longer matched those in the north.

Although there has not been a clear change in the total annual discharge for the Fraser River after the 1989 regime shift, there has been a clear change in the timing of the onset of the spring flows. The April discharges have dramatically increased since 1989 and were higher than all previous April flows. This indicates an earlier start of the spring freshet that eventually leads to the maximum discharge in June. As the Fraser River discharge is closely related to the oceanography of the Strait of Georgia via estuarine circulation (Thomson, 1981), it would be expected that changes in discharge would have impacts on the dynamics of this marine ecosystem.

Potential Impacts of Global Warming on the Climate and Ocean Environment of Key Species in the Fishery

In Canada, numerous senior government officials, business leaders, scientists and concerned citizens have characterized human-induced climate change as the greatest environmental and economic challenge of this century. In fisheries science, there now is solid evidence that climate change profoundly impacts the population dynamics of important species. No longer do scientists believe that abundance fluctuations are primarily a result of fishing effects. There is also compelling evidence that the climate in the past is an unreliable predictor of the future. This new understanding of the importance of including climate in fisheries management, along with the observation that the relationships of the past may not be guides for the future could be viewed as creating a crisis in fisheries management. Certainly, it is clear that we need to assess how the past dynamics of a species can be used to forecast future dynamics. If the past cannot be used as a guide to the future, there will be little choice but to reduce fishing in the face of uncertainty.

The Third Assessment Report of the Inter-governmental Panel on Climate Change (IPCC, 2001a) provided a series of scenarios which indicated the kind of changes that will occur to future climates. The extent of changes depends primarily on the level of emissions of CO_2. For example, if there are no changes in the current rate of increase of CO_2, then the global average surface air temperature is predicted to increase by 3°C by the 2080s compared to the present. The land areas will warm twice as fast as the oceans, with more warming occurring in the winter in high latitudes. If CO_2 emissions can be controlled and stabilized at two times the pre-industrial levels (*i.e.*, 550 ppm), or three times the pre-industrial levels (*i.e.*, 750 ppm), then the impacts will be different. A rise of 2°C about the present day, which is expected by the 2050s, would be delayed by 50 years if CO_2 emissions were stabilized at 750 ppm and by over 100 years if stabilization occurred at 550 ppm (IPCC, 2001b). If current CO_2 emissions were reduced by 60 to 70%, there would still be a 0.7°C increase in global average surface temperatures. This is approximately the magnitude of change observed over the last 150 years. Associated with this general warming in the past 150 years, there has been a gradual decrease in the number of cold days and an increase in the number of warm days. In northern latitudes, winters have been wetter and summers drier. The 1990s were particularly warm, with 1998 being the warmest year since instrumental records began in the mid-1800s.

A standard reference point used to provide a scale of possible change is 2°C by the 2050s if there is no change in the rate of CO_2 production (if CO_2 is stabilized at 550 ppm, the 2°C increase would occur about 2230). Sea level rise is mainly associated with the thermal expansion of water and water from melting glaciers and ice caps. This sea level rise is an inevitable consequence of global temperature increase. The projected rise between 1990 and 2100 is between 9 and 8.8 cm. The central value is 4.8 cm, which corresponds to an average rate of about two to four times the rate observed during the 20th century. An estimate of a 40 cm increase in sea levels by the 2080s would be delayed by about 25 to 40 years if CO_2 emissions were stabilized at 750 or 550 ppm, respectively. The variation in the range of sea level rise at the regional level could be substantial. It is likely that precipitation will increase in the northern mid-latitudes in the winter and in the northern high latitudes in the summer and winter. There is an expectation that the increases in precipitation will also result in increases in extreme precipitation events. Relative to the 1961 to 1990 average, the expected increases of 20 to 40% appear modest, but there is not good agreement among models.

The variables associated with global warming that affect fish production are temperature, precipitation, winds, currents, sea level, salinity, upwelling, ice coverage, and UV-B radiation. In the Third Assessment Report of the IPCC (IPCC, 2001a), there is better agreement among models about changes in temperature and sea level than about precipitation, winds, and storminess. Temperature is important, but winds and storminess may be the parameters that most affect ecosystems in the subarctic Pacific. The assessment of the impact of climate change on marine fishes in the third IPCC assessment report emphasized the impacts on the ecosystems that support the particular species of interest (IPCC, 2001a). The importance of temperature, salinity, nutrients, sea level, currents, and the amount of sea ice were noted, as all of these abiotic factors will be affected by climate change. However, there was much greater emphasis on the impacts of the carrying capacity of ocean habitats than in the past. The response of individual species to temperature change has been the focus for impacts because we know much more about temperature responses than the factors that affect carrying capacity. There are examples in the Third Assessment Report of how temperature increases will affect abundances and distributions, have an impact on spawning success, affect larval and juvenile survival, affect growth, and the rate of food production which, in turn, affects food availability for a species. However, scientists are increasingly recognizing that there are natural long-term fluctuations in fish production that occur over scales of 10 to 60 years. These natural cycles emphasize the importance of considering the ecosystem impacts of climate variations, as well as changes to individual species. The Third Assessment Report emphasizes that the assumptions that marine ecosystems are stable are no longer acceptable. In fact, some scientists are proposing that the success of future fish stock assessments and the success in sustaining world fisheries would depend to a large extent on the ability to predict the impacts of climate change on the dynamics of marine ecosystems. A complication in the understanding of climate impacts on ecosystems is the recent discovery that changes in ecosystem dynamics may occur quickly and persist in a new organization on a decadal scale.

Decadal-scale variability is now a generally accepted phenomenon within the fisheries science community (Beamish *et al.*, 1999; Hare and Mantua, 2000; Benson and Trites, 2002). Large-scale climate oscillations have been described for the Arctic (Thompson and Wallace, 1998), the Atlantic (Hurrell, 1995), and the Pacific (Beamish *et al.*, 2000; Hare and Mantua, 2000; McFarlane *et al.*, 2000). General trends in atmospheric circulation patterns that change quickly to new states have also been described for areas over Europe and over the subarctic Pacific (King *et al.*, 1998; Beamish *et al.*, 1999). The North Atlantic Oscillation has recently been shown to be related to a variety of marine ecosystem changes, and new regime-related explanations for old events are routinely being described. The large inter-decadal climate fluctuations that occurred in the North Pacific have not yet been reproduced effectively in climate models; however, they are a critical component of the variability. In the Pacific, decadal-scale variability results in abrupt changes in the dynamics of mid-ocean and coastal ecosystems (Deser *et al.*, 1996). Coupled global climate models or atmosphere–ocean general circulation models will have to be able to simulate the regime shifts before it will be possible to predict the changes to the dynamics of the fish populations in these ecosystems. One attempt to assess the decadal-scale changes by Mote *et al.* (1999) indicated that both the UK Hadley Centre and Canadian Climate Centre models predicted an increase in the intensity of the Aleutian Low pressure area in the winter in the subarctic Pacific. One model indicated a general trend towards stormier winters, while the other model indicated a greater variability followed by an increased trend to stormier winters. Increased storminess has been associated with increased production in the open ocean, but the impacts of a combination of warmer oceans and increased storminess remain to be determined.

Because decadal-scale variability can be large, and the causes are not known, it is possible that one of the most important impacts of global warming will be the change in the nature of decadal-scale variability. More frequent changes and more extreme changes will have profound impacts on ocean currents, followed by impacts on the dynamics of fish, fisheries, and fisheries management. Evidence for such impacts can be found in the effects observed in the 1990s for species such as coho (Beamish *et al.*, 2000). The magnitude and abruptness of such changes may become the major factor in the regulation and management of marine fisheries.

The impacts of decadal-scale changes in climate that may be superimposed on a gradual warming trend are difficult to forecast. We know that after the 1977 regime shift there was an abrupt increase in sea surface temperatures that was maintained. A good example of this change was observed in the Strait of Georgia (Beamish *et al.*, 2002; Fig. 13). There was an abrupt increase in sea surface temperatures in 1977, followed by another increase after the 1989 shift. In recent years, there has been a cooling following the 1998 regime shift. The cause of these climate shifts is not known. Changes in river discharge can be harmful to Pacific salmon that must migrate up the Fraser River in the summer during peak discharge (Morrison *et al.*, 2002). Morrison *et al.* estimated that greenhouse gas-induced climate change would cause a modest 5% increase in average flow over the years 2070 to 2099. However, they found that the peak flow would decrease by 18%, and on average would occur 24 days earlier. We suggest that regime shift impacts would exacerbate the impacts of changes in flows combined with temperature increases of 1.9°C (Morrison *et al.*, 2002). The additional energy required to migrate to spawning areas may stress Pacific salmon, making them susceptible to disease and other sources of mortality.

There is a north–south coastal oscillation in Pacific salmon production (Hare *et al.*, 1999). Chinook and coho salmon have higher marine survivals in the north during intense Aleutian Lows than in the south. Another mode of climate variability that has been reported to affect Pacific salmon and other west coast marine species is El Niño–Southern Oscillation (ENSO). State-of-the-art Global Climate Change Models are increasingly improving their ability to model ENSO changes in relation to greenhouse gas accumulations. Recent scenarios appear to be predicting more frequent El Niños or perhaps longer El Niño-like states (Timmerman *et al.*, 1999). It is critical that we understand how these modes of variability will change because we need to consider how the less variable changes in temperature or precipitation will impact on the biological processes that characterize the particular species.

Model predictions for coastal British Columbia indicate that for a doubling of CO_2, average surface temperature increases would range between 2° and 4°C. Precipitation increases would be greater in the south in the winter, perhaps a 30 to 40% increase, compared to a 10 to 20% increase in the north. In general, changes for British Columbia that can be inferred from recent model outputs for a doubling of the CO_2 scenario are that there would be an average temperature increase of about 2.9°C and a decrease (1.1 cm) in precipitation in the summer and an increase (3.4 cm) in the winter. There seems to be better agreement that the winters will be warmer and wetter, but there is less agreement about whether the summers will be wetter or drier (Mote *et al.*, 1999).

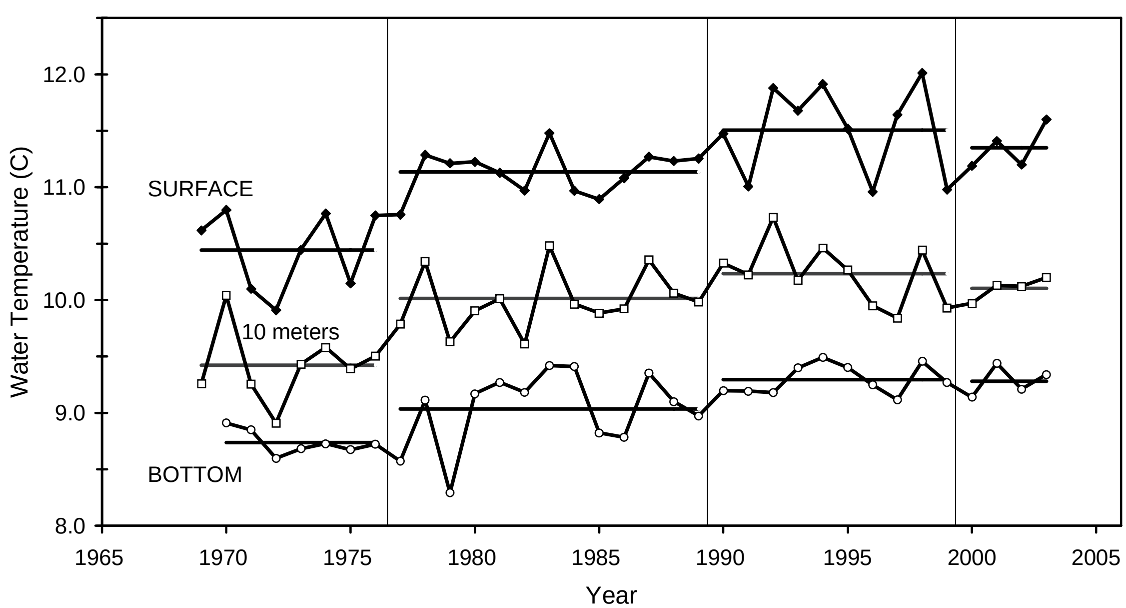

Fig. 13 Water temperatures at the surface, 10 m, and bottom in the Strait of Georgia from 1965 to 2001.

Beamish *et al.* (1997a) acknowledged that there is considerable uncertainty about the physical changes that will occur in the ocean habitat of key species in the marine fisheries of British Columbia. IPCC (1990) calculated that the warming would increase biological productivity in the coastal areas off the west coast of North America. Hsieh and Boer (1992) proposed that the opposite would happen. Beamish *et al.* (2002) suggested that the modelled scenarios of Mote *et al.* (1999) might mean that there would be a tendency for stormier winters and thus more conditions similar to those of the 1977 to 1989 regime. Welch *et al.* (1998) proposed that sea surface temperatures had an overriding influence on the distribution of sockeye salmon resulting in a more northerly distribution. Beamish *et al.* (1997b) reported that other factors in addition to temperature affect the relative abundance and distribution of fishes. There is a carrying capacity for the various species in aquatic systems that are a function of the biology of the species and its interrelationships with its environment and associated species. Specific factors that regulate the carrying capacity are poorly known for virtually all species, but we do know that there is some stability in the relationships among species, as large fluctuations in abundances are not common.

A summary of the potential global warming impacts is presented in Table 5. At the end of this report, we will discuss how these potential changes will affect the population dynamics of key species in the fishery that are described in the following section.

Key Species in the Fishery

Sablefish (*Anoplopoma fimbria*)

Biology

Sablefish are distributed from northern Mexico to the Gulf of Alaska and Aleutian Islands, along the edge of the continental shelf in the Bering Sea to the coasts of Siberia, Kamchatka and northern Japan. In Canada, most juvenile sablefish inhabit the shallow waters of Hecate Strait and the west coast of Vancouver Island, and move to slope waters off northern and southern British Columbia as they mature.

It is believed that there are two sablefish populations of the west coast of North America, separated at approximately 50°N into an Alaskan population and a west coast population. There is debate about the degree of movement between these two populations. Recent information using stable isotopes found in otoliths indicates that a third population may exist at the southern limit of the distribution. Adult sablefish are abundant in coastal British Columbia waters at depths greater than 200 m, and are most abundant between 600 and 800 m. Spawning occurs from January to March along the entire Pacific coast, at depths of about 300 to 500 m, with no appreciable

Table 5 Summary of potential changes and impacts of climate change by the year 2050.

Change	Impact
Increase in air and ocean temperatures of 1º to 2ºC	Freshwater temperature increases will affect Pacific salmon survival. Ocean temperature changes will affect growth, juvenile survival and distributions of some species, such as Pacific salmon, Pacific cod and Pacific hake.
Increased intensity of the Aleutian Low and more and longer periods of a positive Pacific Decadal Oscillation	Greater variability in primary production with a trend to improved abundance of long-lived species as a result of more frequent stronger year classes.
More frequent north–south oscillations in coastal productivity	In association with coastal warming, species off Vancouver Island will have reduced long-term production, while species in the north will have increasing trends in production.
Increased coastal precipitation and reduced coastal salinity	River flows will be reduced in the summer and will be higher in the winter. The lower flows and warmer temperatures will increase pre-spawning mortality of Pacific salmon.

latitudinal spawning migration. Larval fish hatch at about 300 to 400 m, and then descend to 1000 m by 18 days after spawning. Within a few days of their descent, larval sablefish begin to ascend and feed on copepod larvae. Recruitment appears to be determined at the larval stage. Juveniles are found in shallow (< 200 m) inshore waters and rear in nearshore and shelf habitats until age 2 to 5. As sablefish mature, they move back into the deeper water where spawning occurred.

Growth of young sablefish is rapid in the first few years, and then slows appreciably in this long-lived species. Length and age at 50% maturity are 58 cm, age 5 for females, and 53 cm, age 5 for males. Males tend to undergo a reduction in growth rate earlier than females. The majority of fish in the fishery are between the ages of 4 and 35, but the oldest sablefish aged to date is 113 years. In Canadian waters important prey items for sablefish include rockfish, Pacific herring and squid.

Fishery

The sablefish fishery is one of the few and oldest deep water fisheries of the world. The fishery was reported to be as large as about 6000 t in the 1910s. This early fishery provided a smoked or salted meat product as well as livers for vitamin A and D production. The fishery was encouraged as a way to adapt to a shortage of meat during the First World War (Ketchen and Forrester, 1954). Catches declined into the 1920s, possibly because of a reduced demand after the war. It was not until the late 1960s that catches of sablefish increased as a consequence of a Japanese fishery established outside of Canada's exclusive fishing zone. Following the extension of the exclusive fishing zone in 1977, the fishery was exclusively Canadian and accounted for annual catches ranging from 830 t in 1978 to 5,381 t in 1989. The average commercial landings from 1978 to 2002 were 4,071 t (Fig. 11). Sablefish landings fluctuated in the 1990s, with declines in recent years (Fig. 10C). The declines in catch are related to stock assessments that recognize a decline in biomass as indicated by the declining trend in catch per unit effort (Fig. 11D). Since 1973 the dominant fishing gear used by the fishery has been Korean conical traps (73% of the annual landings). In 1990, the fishery switched to an individual quota for each vessel in an attempt to stabilize the length of the fishing season, improve management, optimize the landed value, and reduce quota over-runs.

Climate and ocean effects

Sablefish exhibit decadal-scale patterns in the relative success of year classes (King *et al.*, 2000). By combining estimates of relative abundance of year classes determined from commercial catches and research surveys for adults and juveniles, McFarlane and Beamish (1992) and King *et al.* (2000) were able to reconstruct an index of year-class success. Year classes from 1960 to 1976 were generally poor with no indication of good year-class success. The 1977 year class was exceptionally large and year classes from 1978 to 1988 were generally average to better than average. Year classes following 1989 and 1990 were generally poor. McFarlane and Beamish (1986) proposed that sablefish live up to > 70 years because their ability to reproduce successfully each year was restricted by their biology and habitat. Their longevity represents the longest period of unsuccessful reproduction over evolutionary time. If this hypothesis is valid, sablefish recruitment is closely related to specific kinds of climate-related ocean conditions. One limiting factor would be the ability of the fragile eggs to remain suspended in mid-depths and for the larval sablefish to find copepod eggs and nauplii immediately after they begin exogenous feeding. It was observed that despite high fecundity, strong year classes resulted from both large and small spawning biomass (McFarlane and Beamish, 1986). It was also observed that the production of strong year classes was closely associated with copepod production at a site off the west coast of Vancouver Island (McFarlane and Beamish, 1992). The periods of above average year-class strength coincided with stronger Aleutian Lows, more frequent southwesterly winds, below average temperatures in the subarctic Pacific and warmer sea surface temperatures off the west coast of British Columbia (King *et al.*, 2000). In general, the pattern of year-class success matches the patterns of regimes and regime shifts. This is evidence that there are trends in sablefish production that are related to climate and ocean conditions on a decadal scale. The recent declines in biomass (Fig. 11D) reflect fishing removal and declining recruitment, which is related to the generally less productive regime in the 1990s.

Pacific herring (*Clupea pallasii*)

Biology

Pacific herring have traditionally been one of the major fisheries off Canada's west coast. They are pelagic, occurring both inshore and offshore from California to the Beaufort Sea. In British Columbia they enter the current fishery at age 2+ or in their third year of life. Few live past 7 or 8 years, although the maximum age is 15 years. They are sexually mature by age 2 to 5 years. In British Columbia, the fecundity of Pacific herring tends to increase with age and latitude, from about 19,000 eggs for a 2-year-old female, to a maximum of 38,000 eggs for an 8-year-old. The fish migrate into shallow waters in late fall to spawn, and return to deeper waters in late March and early April after spawning. After hatching, larval herring remain in the surface waters, and after a few months they form the large schools typical of adult behaviour. Pacific herring grow rapidly in their first 2 or 3 years until they reach sexual maturity, then growth rates decline.

Fishery

Pacific herring are easily fished when they migrate inshore to spawn in intertidal and subtidal areas. The British Columbia herring population consists of north coast stocks (Queen Charlotte Islands, Prince Rupert and Central Coast), and south coast stocks (Strait of Georgia and west coast of Vancouver Island). The fishery is managed separately for these five areas. The current fishery removes between 30,000 and 40,000 t of adults, but earlier fisheries harvested more than 200,000 t in some years (Hourston and Haegele, 1980). The Pacific herring fishery appears to have started in British Columbia about 1877 (Hourston and Haegele, 1980). After the collapse of the Pacific sardine in the late 1940s, Pacific herring became the major fishery off Canada's Pacific coast, and catches steadily increased to over 200,000 t in the early 1960s. Prior to 1970, Pacific herring were fished to produce fish meal and fish oil. Since 1970 virtually all Pacific herring are fished for roe, which is sold in Japan. The fishery was shut down for a brief period from 1967 to 1970 because of poor stock conditions, but in 1972 a fishery for roe began. Recent catch levels are a consequence of both good stock conditions and a high demand for roe (Fig. 11A). There has been some fluctuation in catch (Fig. 10A) that reflect interannual changes in biomass (Fig. 11A), but in general, herring populations are considered to be healthy. In some areas, in some years, the abundances are low, but in others, such as the Strait of Georgia, the abundances are at historic high levels. Recruitment levels have been estimated as part of annual stock assessments (Schweigert *et al.*, 1998), and these estimates can be used to identify relative year-class strength. The fishery closure from 1967 to 1971 is clear evidence of overfishing in the early 1960s (Hourston and Haegele, 1980).

Climate and ocean effects

Pacific herring have supported a major fishery off British Columbia since the early 1900s. Pacific herring stocks sustained almost 20 years of high catches from the 1940s through to the 1950s. However, there was a change in climate in the 1960s and herring recruitment declined suddenly. Unfortunately, the reduced recruitment was not detected and the population was severely overfished (Hourston and Haegele, 1980). After the fishery was closed in 1967, stocks recovered relatively quickly and fishing commenced in the 1970s. The lesson learned was that climate and ocean conditions can have profound impacts on the recruitment and abundance trends. Another lesson is that Pacific herring appear to be responsive to short-term, climate-related variability. The most important mode of variability for herring may not be the regime scale.

Ware (1991) studied the fluctuations in Pacific herring growth and abundance in southern British Columbia. He concluded that much of the variation in herring recruitment was associated with changes in Pacific hake abundance, zooplankton biomass, and the pattern of moderate and strong ENSO events. A negative correlation between size-at-age and sea surface temperature was believed to be related to fluctuations in plankton biomass that, in turn, were related to natural oscillations in the ocean and climate that occurred at periods of 5 to 16 years. Ware (1991) concluded that the abundance trends of Pacific herring (and other dominant migratory pelagic species) were strongly affected by oscillations in the climate–ocean environment. The timing of the changes in oscillations was observed to be more closely related to ENSO events than to the decadal- or regime-scale changes. However, there was similarity in the timing of the years of regime shifts and the years of change in trends of abundance described by Ware (1991).

In the Strait of Georgia, Beamish and McFarlane (1999) proposed that the key process that regulated herring abundance involved the timing of the vertical migrations and abundance of copepods. McFarlane *et al.* (2000) also reported that Pacific herring survival was higher in the 1990s due to reduced predation by Pacific hake. The availability of copepods to larval herring immediately after yolk sac resorption was proposed as the fundamental mechanism that alters the dynamics of the fish community in the Strait of Georgia. McFarlane *et al.* (2000) explained that the climate impact extended beyond changes in temperature and needed to be studied at the ecosystem level. Copepods are the component of the zooplankton community that links primary production to larval fish survival. Most fish in the North Pacific reproduce in the winter, immediately before juvenile copepods begin to develop from their diapause state in deeper waters to their juvenile stage in the surface waters. It is in the surface waters that the juvenile copepods complete their growth before returning to deep water in the late spring and summer (Miller *et al.*, 1984). Changes in the timing of copepod seasonal migration have been observed for the North Pacific (Mackas *et al.*, 1998; Mackas and Tsuda, 1999), and for the Strait of Georgia (Bornhold *et al.*, 1998), and typically coincide with decadal regime shifts.

Because Pacific herring are dependent on nearshore habitats for spawning, sea level rise and increased storminess would be expected to affect the dynamics of herring populations. Temperature, salinity and ocean circulation patterns are influential in the survival of Pacific herring eggs and larvae (Stocker and Noakes, 1988). On the west coast of Vancouver Island, recent increases in sea surface temperatures have been associated with poor recruitment, but in the Strait of Georgia there was an abrupt shift to warmer temperatures in 1976–1977 and herring abundance increased to levels believed to be close to historic high levels. Warmer surface temperatures off the west coast of Vancouver Island would be expected to be linked to increased Pacific hake abundance in the summer. Increased Pacific hake abundance will result in increased predation in herring and reduced abundances.

Pacific hake (*Merluccius productus*)

Biology

In Canadian waters, there are two distinct populations of Pacific hake: the Strait of Georgia population and the coastal population that occurs off the west coast of Vancouver Island and in Queen Charlotte Sound (Kabata and Whitaker, 1981; McFarlane and Beamish, 1985). The coastal stock ranges from southern California to Queen Charlotte Sound. Since the 1990s the percentage of the stock migrating to Canadian waters has increased, approaching 40% of the total coastal stock, and a range extension to southeast Alaska has been noted. Pacific hake have also been observed spawning off the west coast of Vancouver Island since 1994, although most hake spawn off California. Prior to this, the northernmost limit for hake spawning was thought to be Cape Mendocino, California.

Fish in the coastal population can reach a maximum age of 23 years; however, the majority of hake in Canadian waters are between the ages of 4 and 12. Pacific hake recruit to the Canadian fishery at 5 to 6 years and a fork length of approximately 45 cm. Hake show rapid, relatively constant growth to age 4, followed by little or no growth. Spawning generally occurs at depths up to several hundred meters off south-central California from January to March. In spring, adults migrate north and offshore to feed along the continental shelf and slope. In summer they form large midwater aggregations near the continental shelf break. Generally, it is the older age 5+, larger and predominantly female, hake that migrate in the Canadian zone. Over half of females reach maturity by age 3 and a length of approximately 40 cm. Hake have strong and weak year classes that are almost cyclic in the offshore stock, with strong year classes occurring every 3 to 4 years.

Fishery

Canadian landings of the coastal hake stock averaged 51,000 t annually over the period 1966 to 1989, and 85,000 t from 1990 to 1999. Since then (2000–2002), landings have declined to an average of 43,000 t annually as a result of declining availability in the Canadian zone. The decline in catch (Fig. 10D) resulted from a reduced quota that reflects a gradual decline in biomass (Fig. 11C).

Prior to 1977, the former Soviet Union caught the majority of Pacific hake in the Canadian zone, with Poland and Japan harvesting much smaller amounts. Since declaration of the 200-mile extended fishing zone in 1977, the Canadian fishery has been divided into shore-based, joint-venture, and foreign fisheries. In 1990, the foreign fishery was phased out. Since the demand of Canadian shore-based processors remains below the available yield, the joint-venture fishery continued through 2002. The majority of the shore-based landings of the coastal hake stock are processed into surimi, fillets, or mince by domestic processing plants.

Although significant aggregations of Pacific hake are found as far north as Queen Charlotte Sound, in most years the fishery has been concentrated below 49°N latitude off the south coast of Vancouver Island, where there are sufficient quantities of fish in proximity to processing plants.

The average size of Pacific hake in the Strait of Georgia is smaller than in the coastal population. The size in the fishery declined during the late 1970s and early 1980s from 44 to 43 cm, and decreased again in the 1990s to 36 cm. The average size of age 4 Pacific hake in the Strait of Georgia declined 7% in length and 16.3% in weight from 1979 to 1981 (to approximately 40 cm and 410 g), respectively. In the mid-1990s age 4 hake declined again, 13% in length and 51.2% in weight (to approximately 35 cm and 200 g, respectively). The second decline in size at age occurred at the same time as an increase in numbers of Pacific hake in the Strait of Georgia, as a consequence of strong year classes in the 1990s. There is a small fishery for Pacific hake in the Strait of Georgia, but the small size of the species reduces their commercial importance.

Climate and ocean effects

The coastal migratory stock of Pacific hake is characterized by strong year classes every 3 or 4 years (Dorn and Saunders, 1997). However, recent strong year classes (1990 and perhaps 1994) are not as large as those in the 1970s and 1980s (Dorn and Saunders, 1997). The 1989 climate-related ecosystem changes also had dramatic impacts on the migratory behaviour of the offshore stock. During the 1990s a larger percentage of the migrating stock from California entered the Canadian zone and migrated farther north than in the past into areas off the west coast of the Queen Charlotte Islands and into Hecate Strait (McFarlane *et al.*, 2000). This stock spawned off the west coast of Vancouver Island in 1994, rather than migrating to the traditional spawning grounds off California. The projected long-term increase in temperatures may result in more offshore hake moving into the Canadian zone, and in the spawning and rearing area off California moving north. However, upwelling and nutrient changes may reduce plankton productivity and thus year-class strength. The mechanisms that regulate the abundance of Pacific hake are not known. Therefore, it is difficult to know how abundances will change. If a greater percentage moves north in the summer, the abundance off Vancouver Island may increase over the next 50 years, assuming the stocks are not overfished.

Climate and ocean conditions are associated with year-class strength and migration, but the mechanisms that are linked to climate remain to be determined. There is a joint Canadian and United States process for managing the offshore Pacific hake stock, which could result in overfishing if adjustments are not made quickly during periods of poor recruitment.

In the Strait of Georgia, there has been an increase in Pacific hake abundance in recent years that may be related to an earlier abundance of plankton, resulting in a closer matching of plankton production and spawning activities. Conditions causing the improved survival appear not to be related to reduced Fraser River total flows, but to earlier spring flows and possibly to inflowing bottom water changes. Climate warming will likely result in earlier spring flows, indicating that Strait of Georgia hake will continue to experience high abundance.

Pacific halibut (*Hippoglossus stenolepis*)

Biology

Pacific halibut are a large, fast growing species that can live to a maximum age of 55 years. The maximum size is variable, but lengths to 267 cm and weights to 205 kg have been recorded. They are distributed from southern California to the Bering Sea and across to Japan. At present, the species is fished throughout its range in what may be considered a mature fishery. As a result, few halibut live longer than 30 years, with most being removed before they are 15 years old. The hook and line fishery is managed through the International Pacific Halibut Commission (IPHC) which has operated since 1923. The exploitable biomass is determined annually and quotas are set using a 20% exploitation rate.

Large females can produce up to 3 million eggs annually. Most spawning occurs in winter between December and February, off of the continental shelf at depths of 200–300 fathoms (about 365–550 m). Males mature around 7–8 years, females around 8–

12 years. Fertilized eggs hatch after 15 days. Larvae are free floating in their first few months and have eyes on both sides of their head. During this early stage, one eye migrates to the same (right) side as the other eye. Larval halibut are carried into shallower waters by currents, where they become bottom dwelling. Adults are found from near surface to 600 fathoms (1100 m). Preferred habitat is in sandy and rocky substrates, along reefs and in areas where fish and marine invertebrates are abundant.

Fishery

The Pacific halibut fishery is one of the oldest and perhaps the most successful fishery off Canada's Pacific coast. Canadian and U.S. fishermen started fishing the species commercially in 1888. Catches rose quickly to levels exceeding 30,000 t from 1914 to 1916. An international commission began to oversee the fishery in 1923 because the halibut that were fished in the Canadian and U.S. fisheries were recognized as one population and catches were declining. However, it was not until 1930 that catch was regulated by the commission. Today, the abundance is considered to be at the highest levels in history (Fig. 14A; Clark and Hare, 2002). A historic high abundance of a large, top predator is apparently inconsistent with world trends (Pauly *et al.*, 1998; Myers and Worm, 2003). The Canadian catch is a function of the available quota and effort up to 1977, as fishing was possible off the Pacific coast of the United States. After 1977 Canadian fishermen were restricted to fishing only in waters off Canada (Fig. 14C). The IPHC has reconstructed the exploitable biomass for the total population and for the exploitable biomass of halibut resident off the west coast of Canada, which is at historic high levels (Fig. 14B).

Climate and ocean effects

McCaughran (1997) reported that the productivity of the population declined from 1959 to 1972, consistent with a change in the marine survival after the 1947 regime shift. At this time very high catch rates were set at approximately 38,000 t. At the same time, foreign and domestic trawl fisheries caught and discarded large numbers of juvenile halibut that were incidental to their directed fisheries on other species. The combined effects resulted in historic low levels in 1973. McCaughran (1997) reported that the population would have declined naturally, and that the high fishing rate and large bycatch of juvenile halibut in the trawl fishery simply increased the rate of decline.

Pacific halibut are now known to exhibit a non-random response to environmental conditions in the ocean (McCaughran, 1997; Clark and Hare, 2002). The population will increase when the environment is favourable and the spawning biomass is adequate under the current approach to management. Clark and Hare (2002) showed that inter-annual and decadal-scale environmental variability is the major source of recruitment variability under the current management strategy. Recruitment beginning about age 8 years is related to the particular climate and ocean regime during the spawning year. According to their analysis, the period from about 1947 to 1976 was associated with reduced marine survival, while the period after 1977 was a period of above average marine survival. Another way of wording their conclusion would be to say that fishing does not affect recruitment under the current approach to management, which has a conservative exploitation rate and maintains an adequate spawning biomass. The evidence is convincing that climate changes at the regime scale have been a major influence on the dynamics of the Pacific halibut fishery. There also is evidence that halibut production is related to the lunar nodal cycle (Parker *et al.*, 1995).

Pacific ocean perch (*Sebastes alutus*)

Biology

Pacific ocean perch is the dominant rockfish in the groundfish fishery. However, the rockfish fishery has expanded to include up to 30 species (Table 6), and Pacific ocean perch is now about 30% of the total rockfish catch. Pacific ocean perch is a deep-water bottom species that lives up to 100 years. The age at 50% maturity is about 8 years and fish are thought to be fully recruited to the fishery at age 11 (Leaman, 1988). They are a schooling species that can readily be overfished.

Pacific ocean perch occur in the North Pacific from California to Russia. They are found at a range of depths down to 800 m, but are common between 200 to 400 m. Abundance appears to be associated with preferred temperatures at about 5.5° to 6.0°C. Juveniles may be distributed over a broader temperature range. Pacific ocean perch reproduce through internal fertilization. About September, females retain sperm that is obtained from males, for about 2 months prior to fertilization. After eggs are fertilized, the females move into deeper water (500 to 700 m) until larvae are released, in the late winter or early spring, apparently near the bottom. Young Pacific ocean perch rear in the pelagic areas for several years before moving to deeper water. There is a distinct relationship between size and depth, indicating that older and larger fish continue to move into deeper water. Age at 50% maturity may be between 7 and 9 years and about 25 to 35 cm in length, depending on location. Fish are recruited to the fishery between ages 10 to 15 years. There is clear evidence of strong variation in year classes, which is an indication that the ocean environment strongly affects recruitment.

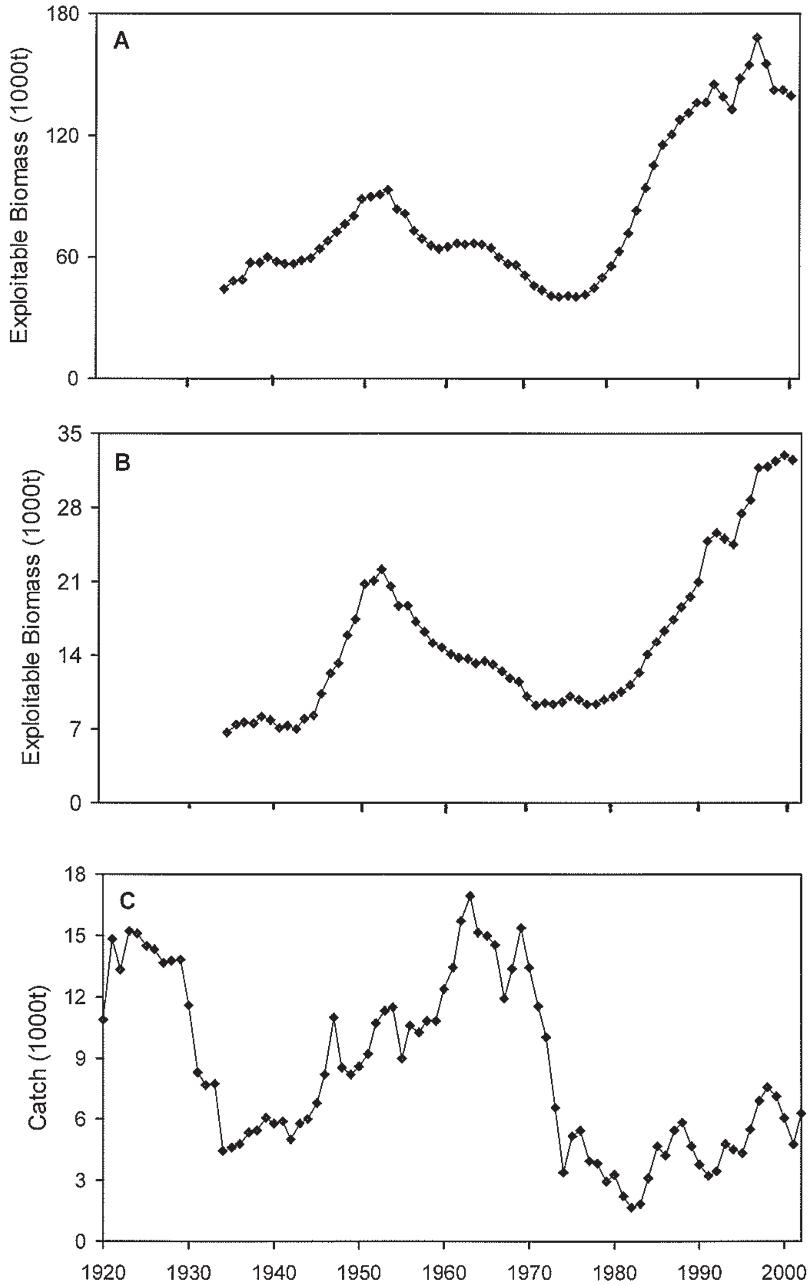

Fig. 14 (A) Exploitable biomass of the total west coast Pacific halibut population from 1935 to 2001; (B) exploitable biomass of Pacific halibut in Canadian waters from 1935 to 2001; (C) Canadian landings of Pacific halibut from 1920 to 2002.

Table 6 Average catch of rockfish by species in the Canadian west coast fishery from 1996 to 2000.

Species	Species name	Average catch (t)
Shortbelly rockfish	*Sebastes jordani*	0.02
Tiger rockfish	*S. nigrocinctus*	0.06
China rockfish	*S. nebulosus*	0.07
Aurora rockfish	*S. aurora*	0.57
Chilipepper rockfish	*S. goodei*	0.22
Dusky rockfish	*S. ciliatus*	0.23
Vermilion rockfish	*S. miniatus*	0.27
Copper rockfish	*S. caurinus*	3.47
Quillback rockfish	*S. maliger*	4.09
Harlequin rockfish	*S. variegatus*	4.25
Black rockfish	*S. melanops*	6.06
Yelloweye rockfish	*S. ruberrimus*	9.00
Rosethorn rockfish	*S. helvomaculatus*	12.16
Greenstriped rockfish	*S. elongatus*	25.16
Darkblotched rockfish	*S. crameri*	51.50
Splitnose rockfish	*S. diploproa*	63.16
Shortraker rockfish	*S. borealis*	65.41
Bocaccio rockfish	*S. paucispinis*	219.43
Redbanded rockfish	*S. babcocki*	247.13
Sharpchin rockfish	*S. zacentrus*	266.27
Rougheye rockfish	*S. aleutianus*	405.35
Shortspine thornyhead	*Sebastolobus alascanus*	579.78
Longspine thornyhead	*Sebastolobus altivelis*	604.61
Canary rockfish	*S. pinniger*	652.90
Redstripe rockfish	*S. proriger*	908.83
Silvergray rockfish	*S. brevispinis*	1173.99
Yellowmouth rockfish	*S. reedi*	1640.40
Widow rockfish	*S. entomelas*	1758.78
Yellowtail rockfish	*S. flavidus*	3988.31
Pacific ocean perch	*S. alutus*	5280.69

Fishery

The history of the Pacific ocean perch fishery prior to 1956 is difficult to document due to poor catch records, and because early rockfish catches were not commonly reported by species (Westrheim, 1987). Thus, it is probable that the early rockfish catches were dominated by Pacific ocean perch. In the late 1950s, Pacific ocean perch were identified in the catch which began to rise due to a dramatic increase in foreign fishing. Total catches increased rapidly from 3,000 t in 1956 to a maximum of 48,600 t in 1966 (Westrheim, 1987), the majority of which was caught by the Russian fleet. At this time, Pacific ocean perch represented over 50% of the total rockfish catches (Forrester *et al.*, 1978). By the time the 200-mile limit was implemented in 1977, the all-nation catches had declined to approximately 6,000 t annually. With the exception of a decrease in catch between 1991 and 1993 due to a change in fishing regulations (Richards, 1994), the Canadian fishery has maintained the catch close to the 6000 t level since the 1980s (Fig. 10E). Overall, the importance of Pacific ocean perch in rockfish catches decreased, beginning in the 1960s. As the fishery expanded into new areas, catches of other rockfish species increased, and catches of Pacific ocean perch decreased. In particular, yellowtail, yellowmouth, and widow rockfish have become increasingly important in recent years (Table 6). However, the proportion of Pacific ocean perch has been maintained at an average of 30% since 1996.

Climate and ocean effects

The effect of regimes on Pacific ocean perch productivity was considered for the first time in a 2001 stock assessment (Schnute *et al.*, 2001). A key finding in the assessment was that trends in Pacific ocean perch recruitment reflected climate regime shifts. Schnute *et al.* (2001) found that production was low prior to 1976, high during 1976–1988, and low again between 1989 and 1998. Currently, there are no strong incoming year classes and the fishery is supported by fish produced during the 1977–1988 regime. If there is a low level of productivity in the post-1998 regime, it is likely that the stock will not maintain itself at current fishing rates. However, the life history strategy of Pacific ocean perch lends itself to slow population growth and decline. Because of this, Schnute *et al.* (2001) stressed the importance of maintaining sufficient adult biomass so that the population can take advantage of future periods of improved recruitment. It is interesting to note that this is the strategy that McCaughran (1997) proposed as the reason for success of the Pacific halibut fishery, and it is a strategy that recognizes regimes of differing productivity.

Pacific sardine (*Sardinops sagax*)

Biology

Pacific sardines have only recently returned to waters off the west coast of Canada. However, Pacific sardines were the largest fishery in the 1930s and 1940s. Historically, sardines entered British Columbia waters in mid-June and returned to southern spawning grounds (California) in mid-October. Most spawning occurred from April to June in the southern California Bight. It was primarily the older, larger sardines that migrated north to feed off British Columbia waters.

Pacific sardines are distributed from northern Mexico to southeastern Alaska, although the main centres of concentration range from southern California–northern Baja California to the southern regions of British Columbia. There are two main spawning areas off southern California and Baja California.

Evidence of sardine spawning in Canadian waters is recent, based on reports of adults with ripe eggs in 1997, 1998, 1999 and 2004, and eggs and larvae taken off the west coast of Vancouver Island in 1992, 1993, 1997 and 2004. Age 0 juveniles (≈ 10 cm) were subsequently collected in March and April of 1998, 1999 and 2004, suggesting successful spawning and rearing in the area.

Sardines reach a size of 15 cm at age 1, 22 cm at age 2, after which growth slows to about 1 cm per year. Females grow faster and larger than males. The largest specimen was 39.4 cm long and weighed 486 g. The maximum recorded age was 13 years. Currently, in the Canadian fishery, few fish are older than 9 years, and most are 3 to 7 years old. Pacific sardines are batch spawners; large fish (21 cm) release 30,000 to 65,000 eggs per spawning. A single large female can spawn about three batches, releasing almost 200,000 eggs per spawning season. About 50% of females are mature at age 1, and 100% by age 2.

The diet of the sardine varies regionally, but as an omnivorous filter feeder, it includes copepods, diatoms, a variety of other zooplankton, and occasionally fish larvae.

Fishery

The fishery for Pacific sardines started in British Columbia in 1917 and quickly became the largest fishery on Canada's Pacific coast with catches averaging about 40,000 t (Fig. 15A and B). The Pacific sardines fished in Canadian waters were part of a population that was most abundant from southern California to southern British Columbia. The population off Canada's west coast consisted of older and larger fish that migrated north in early summer (Hart, 1943) and returned south in the fall. The sardines fished off Canada were believed by some to be part of a genetically distinct population that spawned at the northern limit of the spawning distribution in the south (Felin, 1954; Radovich, 1982). Others believed that it was one population in which the older fish migrated successively farther north as they aged (Schweigert, 1988).

The Canadian Pacific sardine fishery was concentrated from the late 1920s to the mid-1940s off the west coast of Vancouver Island, and extended

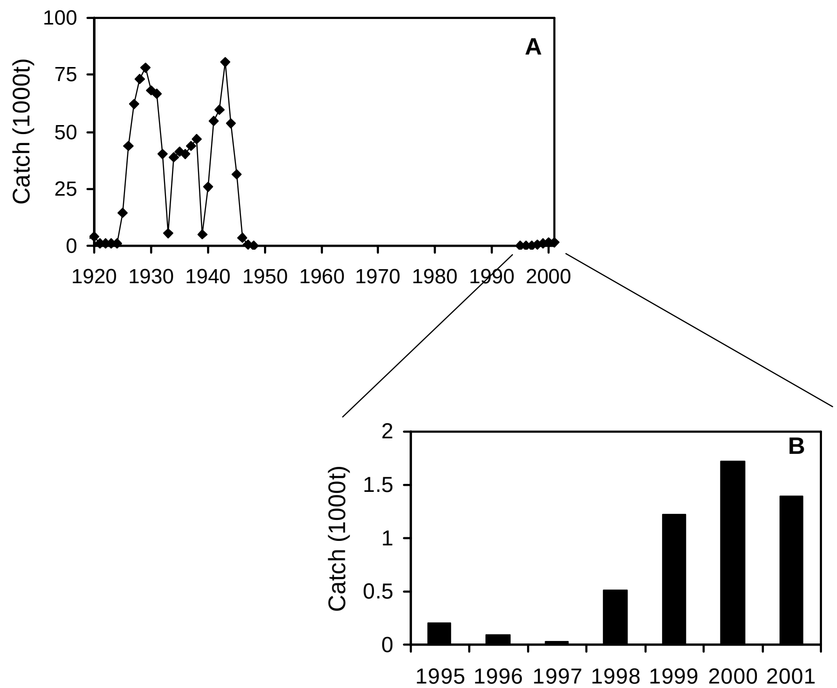

Fig. 15 (A) Catch of Pacific sardine in Canadian waters from 1920 to 2001; (B) combined research and fishery catches of Pacific sardine from 1995 to 2001 (updated from McFarlane and Beamish, 1999).

south to Washington State. Virtually all of the catch was reduced into fish meal and oil. The Canadian and U.S. fisheries in the 1930s and 1940s combined to become the largest fishery in both countries (Wolf, 1992). The Canadian fishery collapsed suddenly in 1947, followed rapidly by the collapse of the U.S. fisheries which collapsed by 1951 (MacCall, 1979). Initially the collapse was blamed on overfishing, but recently the collapse was regarded as another example of overfishing at a time of unfavourable environmental conditions (MacCall, 1979; Ware and Thomson, 1991). The mechanism responsible for the natural decline remains to be discovered, but a clue is the amazing synchrony in the abundance fluctuations among the sardine fisheries in the Pacific Ocean off Japan, Chile, and North America (Kawasaki, 1991). It is important to note that virtually no Pacific sardines were reported from waters off Canada after the collapse through to the early 1990s (Hargreaves *et al.*, 1994). The population of Pacific sardines to the south of Canadian waters started to increase in the late 1970s. Beginning about 1992, Pacific sardines appeared off the west coast of Canada (Hargreaves *et al.*, 1994; McFarlane and Beamish, 1999). The increase in abundance persisted through to the present and reflects a dramatic increase in the general population (McFarlane and Beamish, 1999; McFarlane *et al.*, 2000). In recent years, a small fishery for Pacific sardines occurred off the west coast of Vancouver Island (Fig. 15B). It is now generally accepted that the fluctuations in Pacific sardine abundance off Canada are related to climate and climate changes on a decadal scale. Fishing in Canada and the United States exacerbated the natural decline of this short-lived species (Radovich, 1982) but it was a change in climate that started the decrease in the late 1940s, and the increases in the late 1970s.

Climate and ocean effects

Kawasaki and Omori (1986) recognized synchrony in the trends of abundance of sardine populations off Japan, California and Chile. The collapse of sardine stocks off Canada and the United States in the late 1940s corresponded to the collapse off Japan. Beginning in the late 1970s, the stocks off Japan, California and Chile synchronously increased in abundance. Stocks declined off Chile and Japan in the late 1980s and early 1990s, but those off California have not done so yet. The results of Kawasaki and Omori's study (1986) indicate that large fluctuations in sardine populations are a consequence of large-scale changes in the climate and ocean factors affecting their carrying capacity.

In 1992, sardines reappeared in British Columbia waters and were captured in both commercial and research catches of Pacific hake (McFarlane and Beamish, 1999). Their abundance was determined to be large enough to initiate an experimental commercial fishery in 1995. Movement into the Canadian zone may be continuing because sardines are moving farther north each year. The large abundance of sardines in the Canadian zone was observed prior to the major increase in temperature of the surface waters as a result of the 1997 El Niño (occurring in August and September) and persisted off British Columbia through 1998. At the same time as large numbers of sardines appeared off British Columbia, the total abundance off California remained stable (450,000 t). Catches off California have been maintained although catch decreased in 1998. Sardines remained abundant and spawned off the west coast of Vancouver Island in 1998 even though El Niño conditions did not persist. The El Niño events in the 1950s through to the 1980s were not associated with changes in sardine movement and spawning biology. Thus, while movement of sardines into areas of British Columbia may be associated with recent El Niño events, it is likely related to other changes in the ecosystem. The changes in sardine distribution, abundance and spawning (and the similar changes in mackerel and hake) indicate that a shift in the dynamics of the ecosystem off British Columbia occurred in the early 1990s.

Pacific cod (*Gadus macrocephalus*)

Biology

Pacific cod are widely distributed in the coastal North Pacific from the Bering Sea south to Santa Monica, California, and west to the Japan/East Sea. Pacific cod grow rapidly in the first year, reaching 30 cm by age 1, and are sexually mature by 2 to 3 years old (Westrheim, 1987). Length at first maturity is approximately 40 cm, and length at 50% maturity is 55 cm. Pacific cod tend to disperse into deeper waters to feed, and congregate to spawn in shallower waters from February to March. They undergo a seasonal migration from shallow waters in the spring and summer to deeper waters in the fall and winter. Pacific cod in Canada are at the southern limit of their distribution and are therefore vulnerable to the expected climate and ocean changes. Four stocks of Pacific cod are defined for management in British Columbia: Strait of Georgia, west coast of Vancouver Island, Queen Charlotte Sound and Hecate Strait. In Hecate Strait, stock abundance remains at historic lows, recruitment of the last 9 year classes has been below historic levels, and the 1998 year class was the smallest ever. Abundance off the west coast of Vancouver Island also remains low. Pacific cod were common in the Strait of Georgia in the past. Presently, few fish remain, possibly because of the increase in water temperatures in recent years.

Fishery

Small Pacific cod fisheries take place in Queen Charlotte Sound and off the lower west coast of Vancouver Island. The major fishing occurs in Hecate Strait. Pacific cod spawning stock biomass and recruitment has been estimated for Hecate Strait using stock reconstruction based on ages estimated from lengths (Haist and Fournier, 1998), on which management actions were based. The species is a significant component of the multi-species groundfish fishery in Hecate Strait. Annual yields have varied between a high of 8,870 t in 1987 to a low of approximately 200 t in 2001. Landings since the mid-1990s have been very low (Fig. 10I). The trawl fishery has undergone a number of significant changes in recent years. Prior to 1992, the total catch of Pacific cod was unrestricted and the main management measures were area and season closures. Total allowable catches were introduced in the Hecate Strait area in 1992, in response to declining abundance. Trip limits were also introduced in the same year and these decreased steadily until 1995. For the 1996 season, trawl catches were limited to bycatch only because of stock concerns. Stock declines resulted from a decade of below average recruitment. The pattern of recruitment (age 2+) off the west coast of Vancouver Island from 1960 to 1988 was similar to that of Hecate Strait with the recent regime (1989–1997) characterized by 9 years of very poor recruitment.

Climate and ocean effects

High sea levels in Prince Rupert area are associated with high transport through Hecate Strait, resulting in poor recruitment for Pacific cod. Sea levels were high in the Prince Rupert area up until 2003, when they began to decline. The relationship between sea level and recruitment can be interpreted as an indication of the sensitivity of Pacific cod recruitment to ocean conditions. Bottom temperatures in the range of 6° to

7°C appear to be optimal for Pacific cod recruitment. Temperatures higher than 7°C will likely decrease recruitment. Laboratory studies on the effect of temperature on Pacific cod egg survival indicate that the optimal temperature is between 3.5° and 4°C with an acceptable range of 2.5° to 8.5°C (Alderdice and Forrester, 1971). Bottom temperatures in February that exceed 8.5°C would most probably reduce or eliminate recruitment. The southern limit of the commercial abundance of Pacific cod is northern Oregon and the southern limit of landings has been southern Oregon. Thus, there is little doubt that Pacific cod in British Columbia are at the southern limit of their distribution and are a sensitive indicator of temperature increases.

One method of monitoring the impacts of a changing climate is to identify a few species that are common to a large number of areas, and that respond quickly to a changing climate. Species should be commercially important so that continuous sampling is not a problem. There also should be a sound understanding of biology and some insights into the mechanisms that naturally regulate abundance. Pacific cod are a good indicator species in the Canadian zone.

Pacific salmon

We highlight the biology and fishery of pink, sockeye, and chum salmon. We assess the impact climate and ocean effects, along with global warming effects, in a combined discussion for all species, including coho and chinook in a section following the species summaries.

Pink salmon (*Oncorhynchus gorbuscha*)

Biology

Pink salmon are the most abundant of the Pacific salmon in British Columbia waters and in the all-nation catches of Pacific salmon. They have the shortest life span, approximately 2 years from hatching, and are the smallest salmon species. Pink salmon form distinct spawning brood-lines with some stocks spawning in years with even numbers (*i.e.*, 1996) and some with odd numbers (*i.e.*, 1997). The largest stocks of pink salmon occur in the Fraser River, where spawning occurs only in odd-numbered years. Farther north, spawning occurs in all years with a tendency for the even-year spawning stocks to predominate. Although pink salmon occur farther south than British Columbia, the centre of distribution is north of British Columbia. Fraser River stocks, therefore, are close to the southern limit of the range.

Females may produce 1,200 to 1,900 eggs depending on the stock and female body length. Spawning occurs from July through to early fall in riverbeds with coarse gravel. Pink salmon prefer to spawn in swift currents along the borders of streams or in riffle areas.

Fishery

Pink salmon are not highly esteemed in British Columbia, thus catches probably are not a good indicator of abundance. This is particularly true in recent years when there has been exceptional production in some stocks with virtually no commercial fishery. In Canada, total annual catches of pink salmon averaged 19,700 t, or approximately 14.7 million fish, from 1959 to 2000. Total catches of pink salmon increased after the 1977 regime shift, reaching a maximum in the early 1990s (Fig. 16). Since the early 1990s, there has been a dramatic reduction in catch.

A recent analysis of the coast-wide production of pink salmon indicated that over the past decade, the spawning abundances may have doubled or tripled compared to numbers in the 1960s and 1970s (B. Riddell, personal communication). Pink salmon produced in the Fraser River historically accounted for about 60% of the total British Columbia catch, although some of this 60% is caught by the United States. Their population dynamics and the response of the fishery is probably a good indicator of the dynamics of most pink salmon stocks. Virtually all stocks of pink salmon in the Fraser River spawn in odd-numbered years. The reason for the persistent dominance of these “odd-year stocks” and the general phenomenon of dominance among pink salmon stocks is unknown. In 2001 and 2003, there was a large return of pink salmon to the Fraser River. Management policy resulted in an exploitation rate on this return that was very low, resulting in a spawning escapement that was approximately two times the highest estimated escapement on record. These exceptional returns were produced from one of the lowest escapements on record in 1999. Clearly, there was a dramatic increase in the marine survival of pink salmon fry entering the Strait of Georgia in 2000.

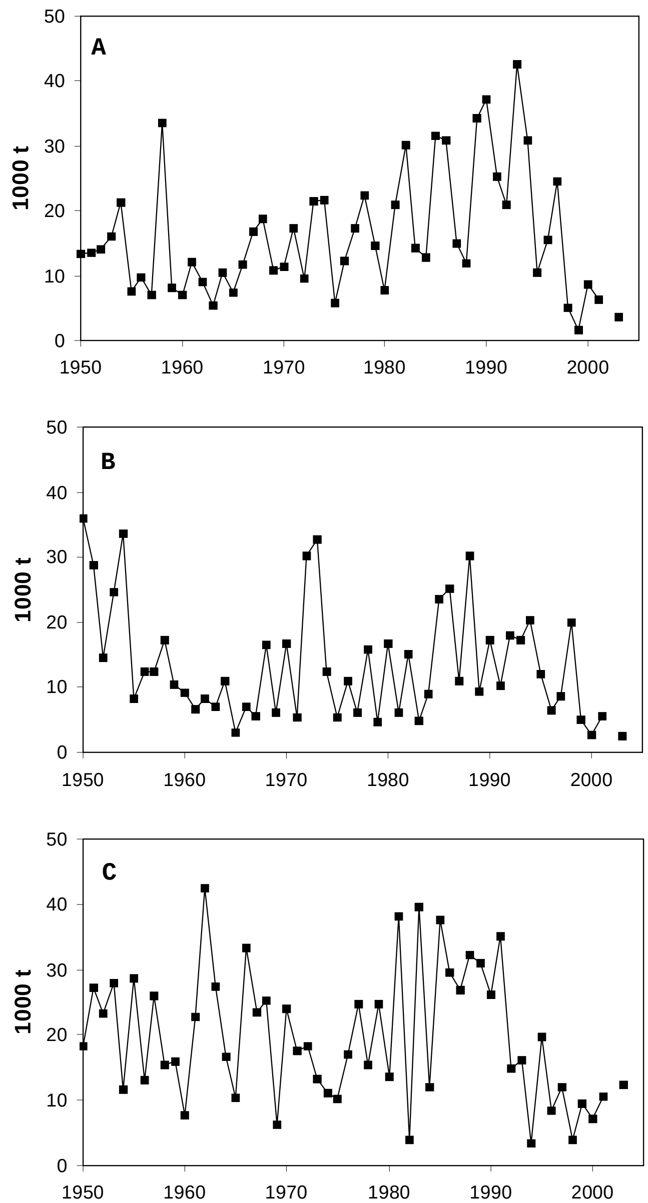

Fig. 16 Canadian catches of (A) sockeye salmon, (B) chum salmon, and (C) pink salmon.

Sockeye salmon (*Oncorhynchus nerka*)

Biology

Sockeye salmon are probably the fish that is of most interest to British Columbians. The Fraser River stocks have averaged about 80% of the British Columbia sockeye production and 25% of the catch of all salmon in British Columbia. These sockeye stocks can be considered to be at the southern edge of this species' range and are susceptible to changes in both the freshwater and marine environments. Most sockeye salmon return to the Fraser River in July and August and spawn in the fall. After hatching, alevins emerge in the spring and migrate into nearby lakes. After a year in the lake, most sockeye migrate in the spring to the ocean, where they grow and undertake extensive migrations before returning to spawn 2 years later. There are variations to this generalized life history (Foerster, 1968), but it is always a combination of a prolonged dependence on fresh water followed by a period of ocean residence of 2 to 3 years.

Fishery

Catches of sockeye follow a cyclic pattern. Sockeye production in the Fraser River follows a 4-year cycle (Foerster, 1968). For example, in 1997 there was the largest return of sockeye salmon in the 4-year cycle from 1994 to 1997, with fewer returns in 1998. For the first half of the 20th century catches were variable, but relatively stable. The total catch of sockeye salmon was low from about 1950 to 1975. The lowest catches occurred in 1965 and 1975. Catches increased dramatically, beginning in the late 1970s, with the record catch of 42,500 t in 1993 (Fig. 16), but declined quickly in the 1990s. The lowest catches on record of 1,710 t occurred in 1999. The declining trend in recent years is largely a result of reduced Fraser River sockeye production, since total production estimates for sockeye salmon from the Skeena and Nass Rivers from 1970 to 1996 (Wood *et al.*, 1997) illustrate that production increased in these northern rivers in the 1990s. The 1989 regime shift has been associated with some of the lowest catches in the history of the fishery and the change is seen primarily in the southern stocks. A study by Beamish *et al.* (2004b) showed that the stock and recruitment relationships for Fraser River stocks are closely related to climate regimes. The mechanism linking climate to marine survival may be growth in the first marine year (Beamish *et al.*, 2004b).

Chum salmon (*Oncorhynchus keta*)

Biology

Chum salmon may exist in about 800 rivers in British Columbia (Salo, 1991). There are distinct summer and fall spawning stocks, with runs in the north being earlier than in the south. In the south, spawning can occur from October to January. The general biology of chum salmon in British Columbia is similar to chum in other areas. In the spring, chums are some of the first salmon to enter the ocean, remaining in the nearshore areas until the end of May (Healey, 1980). They then move into more coastal waters and by mid-summer they leave the inshore areas and migrate offshore and into the Gulf of Alaska (Hartt and Dell, 1986). In recent years they have remained inshore in large numbers through to mid-September (Beamish and Folkes, 1998). Most chum salmon (about 60%) spend three winters in the ocean. The remaining fish spend 2 or 4 years at sea, with very few spending 5 years at sea. The average size at return is about 70 to 75 cm. Since the late 1970s, chum salmon have been produced in hatcheries. The total production reached a maximum in the early 1990s, and in recent years has declined. Chum eggs are hatched in hatcheries and the fry are fed in channels prior to release. In some cases the fed fry are placed in sea pens and reared in salt water prior to release.

Fishery

Chum salmon are generally the last species caught in the commercial fisheries. Most fisheries occur near river mouths, or what are called “terminal areas.” Fishing is with purse seines or gillnets. Smaller fisheries occur using troll gear. Chum salmon that retain their “silver colour” are frequently marketed for smoking. Those that are coloured externally are valued only for their roe. In recent years, catches increased in the late 1980s through to the early 1990s (Fig. 16). Catches were low in the mid- to late 1990s through to the present. Assessments of total production generally show that it has been stable for the past 30 years (Godbout *et al.*, 2004; Spilsted, 2004).

Impacts of Global Warming on all Pacific Salmon in the Fishery

Pacific salmon remain as the group of species that are of principal interest to British Columbians even though their commercial value has declined substantially. It is useful to assess the impact of climate changes on all species of Pacific salmon, rather than assessing the impact only on sockeye salmon, which remains one of the most important species in the commercial salmon fishery. The specific factors that regulate salmon abundance are not clearly identified, making it difficult to predict the impacts of altered ecosystems. Changes that could occur in fresh water as a consequence of climate change would have a major impact on Pacific salmon. These would impact on the migrations, spawning, hatching, and early rearing phases. Physical changes in temperature, precipitation, groundwater discharge, and increased ice-free periods for lakes could affect community structure and the survival, growth, and distribution of salmon species (Meisner *et al.*, 1987; Glantz, 1990; Magnuson *et al.*, 1990; Chatters *et al.*, 1991; Neitzel *et al.*, 1991; Northcote, 1992).

The Fraser River drainage in British Columbia is a major producer of Pacific salmon, accounting for 30 to 40% of all Pacific salmon produced in Canada. Because numerous stocks of the five species of salmon are at or near the southern limit of their range, the early impacts of climate change should be detectable in these stocks. Levy (1992) investigated these potential impacts by formulating eight hypotheses and considering the possible responses of salmon to climate change. His hypotheses can be summarized as follows: a warmer climate will increase water temperatures and decrease flows during spawning migrations, increasing pre-spawning mortality and reducing egg deposition. A warmer climate will increase water temperatures during egg incubation stages, causing premature fry emergence and increased fry-to-smolt mortality. At the same time, a warmer climate will increase the severity and frequency of winter floods, thereby reducing egg-to-fry survival rates. The productivity of lakes will be altered, but impacts on their suitability as nursery habitats for juvenile sockeye salmon is not known.

It is highly probable that there will be a direct relationship between increased river temperatures and pre-spawning mortalities for all salmon. In fact, in the late 1990s, abnormally high pre-spawning mortality occurred, and one of the explanations related the mortality to changes in climate. The impact of climatic warming on winter water temperatures is uncertain. Winter water temperatures are related to groundwater base flows, lake water runoff, precipitation levels, and perhaps changes in snowmelt patterns. It is probable, however, that both summer and winter temperatures will be higher. These changes are particularly relevant for coho and chinook salmon, which remain in fresh water during their first year after hatching. Warm summer water temperatures may be too high for optimal growth and may force the young salmon into suboptimal habitats. Poor growth in fresh water may contribute to increased mortality in the ocean. Coho salmon are vulnerable to warming because their embryonic development is sensitive to warm winter temperatures (Murray *et al.*, 1990).

Pacific salmon are particularly susceptible to temperature fluctuations because they have adapted to thermal regimes in both fresh and salt water. At the southern limits of salmon distribution, projected climatic changes would warm both marine and freshwater habitats, especially in the winter. High temperature has a profound effect on fishes because they cannot regulate their body temperature. Extreme temperatures may kill eggs, juveniles, or adult salmon; less extreme temperatures can affect growth, reproduction, and movement. Recommended temperatures for most Pacific salmon in fresh water range from about 7° to 16°C (Reiser and Bjornn, 1979), with extremes from 3° to 20°C. Upper lethal temperatures are 25° to 26°C. Southern rivers could approach these higher limits under projected climatic scenarios. In the marine phase of the life history of salmon, there are critical temperatures of 9° to 10°C that restrict feeding areas for salmon to areas cooler than these temperatures (Welch *et al.*, 1995). Ocean warming, particularly in the winter, could favour northern areas for the rearing of salmon.

Stream discharge patterns have a high degree of variation, and changes in the variability of timing and the expected increase in variation could reduce the accuracy of management and result in the need for reduced exploitation rates. Virtually all sockeye salmon spawn in rivers that flow into or out of lakes. After hatching, fry move into the lake where they must remain for a minimum of one year. Although there is uncertainty about how lakes will respond to a warmer climate, sockeye salmon in the Fraser River are at the extreme southern limit of their distributions and will be sensitive to changes in limnological conditions. Excessive warming may affect the ability of young sockeye to grow to the sizes necessary for survival in the ocean.

Warming of fresh water in the north may improve production. Much of the increases in total Pacific salmon abundance in the 1980s occurred in Alaska stocks, possibly indicating that warming in fresh water and coastal areas at this time was beneficial for salmon production. However, the function of northern aquatic systems has not been well documented, and large temperature increases could have unforeseen effects on Pacific salmon survival.

Beamish and Noakes (2004) examined the role of climate change on the past, present and future of Pacific salmon species off the west coast of Canada. They suggested that existing stock assessment models might be inadequate to predict the dynamics of a stock in a future of climate change. They provided one scenario that predicts an increase in the total production of Pacific salmon as climate changes. This contrasts with other interpretations, such as that of Welch *et al*. (1998), who used estimates of sea surface temperature increases to propose that the ocean habitat available to sockeye salmon would diminish and would move farther north. Both scenarios are possible and need to be evaluated as climate changes become more extreme. Beamish and Noakes (2004) also noted that Pacific salmon may move into the Canadian Arctic in increasing numbers.

Pacific salmon are well known for their homing ability from feeding areas in the open ocean to the exact areas of their birth in coastal freshwater rivers (Groot and Margolis, 1991). Less well known is their ability to stray. This straying rate can range up to 10% (Groot and Margolis, 1991), and it provides Pacific salmon with an ability to adapt to large-scale climate change such as past periods of glaciation. All five species of Pacific salmon have been reported in Canadian Arctic waters (Hunter, 1974; Craig and Haldorson, 1985; Babaluk *et al.*, 2000), with pink salmon being the most frequently observed and chinook salmon the least frequently seen. Babaluk *et al.* (2000) reported the first records of sockeye and pink salmon from Sachs Harbor on Banks Island in the Beaufort Sea. Although Pacific salmon had been observed in this area previously, the report of Babaluk *et al.* (2000) represented extensions of these earlier records. One report of a coho salmon caught on Great Bear Lake on 25 September, 1987 represented an extension of 1500 km east of an earlier report at Prudhoe Bay, Alaska (Craig and Haldorson, 1985). These reports are noteworthy because they highlight the rare occurrence of Pacific salmon in the Arctic; however, they also indicate that straying is occurring.

The Arctic is one area that may be exhibiting early impacts of global warming. Model predictions are that a doubling of CO_2 would reduce the extent of sea ice by 60% and the volume by 25 to 45% (Gordon and O'Farrell, 1997; IPCC 2007). There would also be greater freshwater runoff. During the period 1978–1996, there was a 2.9 to 3.5% per decade decrease in the extent of Arctic Sea ice (Cavalieri *et al.*, 1997; Serreze *et al.*, 2000; IPCC 2007). If such dramatic changes continue, conditions favorable to straying and perhaps feeding for Pacific salmon may improve.

In general, it is probable that the response of stocks north of 50° to 55°N will be different than stocks south of this area, based on a historical oscillation in productivity between northern and southern stocks (Hare *et al.*, 1999). We speculate that in the future the importance of this oscillation will diminish as the southern stocks struggle to adapt to a climate-related variability that currently exists south of the existing limits of Fraser River stocks. We expect that sockeye salmon and other Pacific salmon stocks in the Fraser River will be severely impacted, as they are virtually at their southern limits. It is important to remember that Pacific salmon are anadromous. The impacts will be in both fresh water and the ocean. In the ocean, we expect that the major sources of early marine mortality will become more variable and more extreme. Predation may increase as more pelagic predators, such as Pacific hake and mackerel, move north. Growth-based mortality (Beamish and Mahnken, 2001) may become more important and more variable. It may be possible to mitigate climate-related changes in fresh water; however, adjusting management to adapt to climate-related changes in the ocean would range between challenging and impossible. Nonetheless, if climate-related impacts could be identified quickly, it may be possible to use this information to convince Canadians and other countries that reductions in greenhouse gases are essential for the protection of Pacific salmon at their southern range.

Species, such as coho and chinook salmon, should be less impacted because these two species are not at their southern limits in British Columbia. However, these are the two species that are most affected by hatchery production (Sweeting *et al.*, 2003). It should be apparent that the fundamental scientific assumptions used in the management of Canada's Pacific salmon stocks must change. The ocean's capacity to produce salmon is now known to be an important consideration. This means that management must now consider the impacts of both fishing and climate–ocean changes on an aggregate of stocks of species in marine ecosystems. In hindsight, our expectations for the Pacific salmon resource on Canada's west coast in the 1990s were not even close to what occurred. Similarly, we know of no one who predicted that in 2001, the salmon returns to the Columbia River would be the largest on record and chinook salmon returns the largest since 1973 (Wakefield, 2001). Thus, we need to accept that our fisheries management science is not adequate to describe the factors that regulate Pacific salmon populations. The certainty of the future is that there will be continued change and that robust strategies need to be developed if we are to adapt successfully to both natural climate change and the modifications caused by human-produced greenhouse gases.

The short life span of pink salmon of 2 years between spawning, as well as their abundance and extensive distribution, makes pink salmon a desirable species for studies of environmental impacts such as greenhouse gas-induced climate change on the long-term population dynamics of all Pacific salmon. This increase in marine survival in 2000 coincided with a major shift in the trend of climate indicators. Thus, there is solid evidence that pink salmon respond to climate changes in a time frame that could be used to detect the impacts of greenhouse gas-induced climate change. Pink salmon are an excellent indicator species because they are distributed throughout the subarctic Pacific and there is a long history of careful management. The single year class and the short life span facilitate associations between climate change and estimates production. Additionally, the tendency for pink salmon to stray may also become an important indicator of factors affecting distributions.

We modified Levy's (1992) hypotheses that evaluated the linkages between climate and biological systems that could be used to plan for managing fragile northern freshwater and marine ecosystems in a warmer climate (Table 7). This table of possible impacts could be used to develop plans for the impacts of climate change on salmon fisheries throughout the range of Pacific salmon.

Impacts of Global Warming on the Key Non-salmon Species in the Fishery

A difficulty in forecasting climate change impacts on fisheries in British Columbia is the inability to obtain model outputs at a regional scale. It is also necessary to integrate modes of natural climate variability in the model scenarios for greenhouse gas-induced change. There is ample evidence that the recruitment of many species of west coast fishes is affected by these modes of natural variability. Therefore, it makes sense that they must be included in model formulation.

One way of assessing the impact of future climate change is to try to use past changes in the population dynamics of a species to identify future climate-related impacts. There are two major difficulties with this approach. One is that it is necessary to identify the impacts of fishing. To do this, assumptions are made about stock and recruitment relationships which assume that climate and ocean

Table 7 Potential impacts of global warming on Pacific salmon biology, life history and population dynamics in British Columbia.

Fresh water	Salt water
- Earlier timing of returning adults	- Earlier time and size of ocean entry
- Earlier time of entry into rivers	- Changes in predator composition
- Higher river temperatures	- Changes in ocean productivity will affect species differently
- River flow rates	- Changes in growth in the first marine year
- Reduced access to spawning areas	- Changes in juvenile migratory routes in response to temperature
- Earlier changes in the hatching times	- Increase in temperature
- Changes in the productivity of freshwater ecosystems, - Impact of species new to the ecosystem	- Decrease in salinity, - Changes in the Aleutian Low and Pacific Decadal Oscillation that are currently unknown
- More variability in growth	- Earlier timing of spring transition
- Increased percentage of hatchery salmon	- Changes in competitors for food, - Reduced marine growth
- Reduced ability to adapt to changes in habitat	- More variability in straying rates, - Loss of ability to adapt because of the loss of wild fish

effects are random. For example, the assumptions for the standard Ricker curve are that density-dependent effects occur in fresh water (Ricker, 1954) and that there is no trend in the climate-related impacts (Ricker, 1958). It is also virtually impossible to determine the objectives of fisheries management for the future.

A second difficulty is that past climate trends are probably not a guide to the trends expected in the future. Thus, if new climate states are to be expected, particularly more frequent extreme events, we should also expect new impacts. Nevertheless, it is useful to consider how past changes in population dynamics might have been affected by climate, not necessarily as a guide for future interpretations, but as evidence that we can no longer view fishing impacts as the only factor affecting abundance, and that we will need to be vigilant in our monitoring and evaluation of future changes in fish stocks. We estimate the impacts of climate change using our understanding of the biology of a species, our interpretation of the past impacts of fishing relative to the impacts of the ocean environment, and our belief that regimes and regime shifts are important and will become even more influential. We used average values of climate change taken from the Third Assessment Report of the IPCC and consider how these changes could influence the environment of the major species in the fishery (Table 5). A summary of the following impacts is included in Table 8.

Sablefish

Because adult sablefish appear to be able to adapt to natural short- and long-term shifts in ocean conditions, it is probable that global warming will not have impacts on adult sablefish in a time frame of 50 years that will threaten the long-term dynamics of the population. This does not mean that specific global warming impacts on the survival of eggs, larvae and juveniles will not occur; rather, that the adult fish may be able to survive such adverse conditions. Also, there will be time to detect changes in the population dynamics and to consider management options, but this does not mean that the population will be able to support current levels of exploitation, particularly at rates of around 15%.

An immediate concern is the impact of fishing on the population structure and the natural ability of sablefish to survive in unfavourable conditions. Fishing impacts over the past 30 years have reduced the percentage of older fish in the population. Presumably, the remaining fish still have the ability to live for extended periods; however, there may be some changes in their biology if the fishery is in some way exerting a selective force on the genetic composition of the population. If the impacts of global warming are negative and reproduction is less successful or fails, it may be important to ensure that a percentage of the existing population is allowed to live to the older ages that existed prior to commercial fishing. This may be best accomplished by establishing no fishing zones that are in the most favourable spawning areas. If periods of intense Aleutian Lows increase as a consequence of global warming, there is a possibility that recruitment periods may increase relative to the past 50 years.

Pacific herring

A key factor regulating abundance of Pacific herring appears to be predation (Ware and McFarlane, 1995; McFarlane *et al.*, 2001). A major predator is Pacific hake, which are at the northern limit of their distribution in British Columbia. It is possible that more hake will migrate farther north as the coastal areas warm. This will result in more predation on herring, providing offshore hake stocks are not overfished and reproduction off California and Oregon is not severely impacted by changes in ocean productivity.

The present management strategy for herring allows fishing only when abundances are above a minimum spawning biomass. This strategy should be adequate to adapt to the uncertainty of the impacts of greenhouse gas-induced changes. Recruitment levels have been estimated as part of annual stock assessments (Schweigert, 2001), and those estimates can be used to identify relative year-class strength. Since 1972, there are some consistent patterns in herring productivity, but the patterns are less clear than for other species. For herring in all five management areas, the regime shift years 1977 and 1989 were years of good recruitment, as was 1985, a year of very intense Aleutian Low pressures. Generally, the regime prior to 1977 had better recruitment than from 1977 to 1989. After 1989, recruitment in the Strait of Georgia has generally been above average, but recruitment continued to be poor in the other four areas until 1994. The poor recruitment during the 1977–1988 regime could be associated with the observed shifts to warmer SSTs; however, it can only be one indicator of the mechanism since Strait of Georgia stocks increased in the 1990s despite continued warming.

It is tempting to conclude that herring are quite adaptable and may increase in abundance in some areas and decrease in others, possibly maintaining the current catch levels. An important consideration is the commercial fishery removals. The current fishery appears to be conservative and well managed with specific "cut-off" levels below which no fishing is allowed. In addition, the demand for product is much less than in the 1950s and 1960s. Thus, it is likely that the pressure to overfish that occurred in the

Table 8 Summary of potential impacts of greenhouse gas-induced climate change on key species in the British Columbia fishery in the next 50 years.

Species	Potential impact
Sablefish	Stocks in the south may be reduced, but the northern stock may benefit from more strong year classes. A key factor will be the protection of the spawning stock from overfishing. If overfishing does not occur, the adult population should be able to survive prolonged periods of poor recruitment over the next 50 years.
Pacific herring	Stocks in the Strait of Georgia should remain at high levels, but offshore stocks would be reduced by increased predation.
Pacific hake	The Strait of Georgia stock should continue at high abundance. The offshore stock should also remain at higher abundance levels provided it is not overfished. If abundance increases, more fish will move farther north, perhaps off the Queen Charlotte Islands and into Queen Charlotte Sound.
Pacific halibut	The abundance within the population should remain at high levels as a consequence of a stormier North Pacific in the winter. The abundance off Canada may be reduced slightly as fewer juveniles migrate farther south.
Pacific ocean perch	The major impact will be increases in the frequency of strong year classes which will improve abundance.
Pacific sardine	In the Northeast Pacific, Pacific sardine abundances follow trends that are associated with the spawning and rearing environment off California and Mexico. The mechanisms remain unknown. If the Aleutian Low intensifies, it is possible that the trends in sardine production may continue, perhaps with increased production during favourable periods. Off British Columbia, Pacific sardine will increase in abundance and may establish resident populations in increasing productivity regimes, but the natural fluctuations will still occur. This means that one of the future regime shifts will result in conditions unfavourable for sardine reproduction and a natural collapse will occur. However, there may be residual stocks of sardine that reside longer, or all year, in the Canadian zone as more sardines move north into it in the summer.
Pacific cod	Pacific cod will gradually disappear from the Strait of Georgia and off the west coast of Vancouver Island as bottom temperatures warm.
Pacific salmon	Pacific salmon from the Fraser River stocks will suffer major impacts in fresh water and in the ocean. Sockeye, pink and chum from the Fraser River will be reduced in abundance as a consequence of reduced freshwater survival as juveniles and spawning adults. The production of wild coho and chinook will also be reduced, but the reduction will be less than for the other species. Pacific salmon stocks from the Skeena and Nass rivers and to the north will increase in abundance as a result of improved ocean productivity. Pacific salmon will begin to reproduce in Arctic rivers. Pink salmon will be excellent indicators of climate-related change. Basin-scale changes in growth, survival, and straying rates will all indicate when large-scale changes occur.

1960s will not be a factor. We propose that the herring population in the Strait of Georgia will continue to be high as long as Pacific hake remain abundant and have a small size at age (*i.e.*, no predation on herring). On the west coast of Vancouver Island, the abundance of herring will fluctuate, but will generally remain low as a consequence of Pacific hake predation that could extend much farther north and reduce abundances off the Queen Charlotte Islands. However, we emphasize that fluctuations will be common, as Pacific hake appear to be one of the key regulators of abundance. In the next 50 years, Pacific herring stocks will likely continue to fluctuate in abundance more or less in a manner similar to the dynamics observed during the past 25 years.

Pacific hake

There are two distinct and major populations of Pacific hake, one in the Strait of Georgia, and another off the west coast of Vancouver Island. There are also numerous small abundances of Pacific hake in the inlets along the British Columbia coast. The Strait of Georgia has been warming since the 1960s but the reasons for the warming have not been determined. Pacific hake in the Strait of Georgia have increased in abundance during this warming period and, at the same time, decreased their individual size. We expect that the Strait of Georgia will continue to warm. We also expect that the synchrony of improved primary production and intense Aleutian Lows or PDOs will continue, and even become more favourable for Pacific hake production. Thus, Pacific hake will continue to be the dominant species in the Strait of Georgia and their individual size will remain smaller.

Pacific hake off the west coast of Vancouver Island migrate into the Canadian zone from areas off California and Oregon. Impacts of global warming will affect the amount of production, the numbers that migrate into the Canadian zone, and the northern extent of their migration. As with Pacific sardine populations, an increase in the intensity of the Aleutian Lows and mid-ocean upwelling (as occurred in the 1980s) would result in an increase in the number and strength of above-average year classes, and subsequently mature biomass. Increased warming in coastal waters will result in a greater proportion of mature fish migrating north into Canadian zone. In addition, the extent of this migration will move farther north. For example, the increase in temperature during the 1990s resulted in approximately 40% of the mature stock entering the Canadian zone, compared to 25% during the 1980s. In some of the years (1992, 1993, 1997, 1998) commercial quantities of Pacific hake were common in northern British Columbia waters, and in at least two of the years (1997, 1998), were captured in the Gulf of Alaska.

Pacific halibut

Pacific halibut are currently distributed from California to the Bering Sea, thus they are able to tolerate a wide range of temperature as adults. The expected temperature increases in the next 50 years are well within this range. Pacific halibut that are recruited to the southern part of their range are juveniles that reared farther north. Unfortunately, the details of the recruitment of these juveniles into the area off British Columbia remains poorly understood.

Halibut stocks are currently at historic high abundances, in part because of the favourable ocean conditions from the late 1970s through to the late 1980s, and in part because of an error in the stock assessment that resulted in an underestimate of the total biomass. Because halibut are widely distributed as adults, it is probable that the effect of climate–ocean related changes is during the larval stage. Pacific halibut are now recognized to live to 55 years, although most fish in the fishery range in age from about 10 to 20 years. The existence of older fish in the population may indicate that over evolutionary time Pacific halibut experienced prolonged periods of poor recruitment. Therefore, future periods of poor recruitment should be expected. If, in the future, areas need to be closed to protect spawning stocks, there would need to be an agreement between Canada and the United States as both countries share the responsibility for conservation of this species. The fishery is managed by the IPHC which allows a percentage of the total biomass to be fished. As declines occur, the catch is reduced. At a minimum spawning biomass, no fishing would be allowed. The population is therefore protected from overfishing.

As for most species, the mechanisms that affect marine survival are unknown. Thus it is not possible to interpret specific environmental changes, even if such changes could be forecasted. In general, however, it is believed that strong onshore flows, resulting from strong northward flowing currents, are favourable for reproduction. A concern is that there could be a weakening of winds that could affect both the amount of onshore transport as well as the food required for the larval and young juveniles. If the impacts of global warming weaken onshore transport and reduce productivity, then halibut year-class survival may be poor, and there may be prolonged periods of poor recruitment.

In recent years, the percentage of the biomass in the southern portion of the range has decreased relative to the biomass in the mid-portion. The reasons for the change are unknown, but could be an indication that halibut recruiting to the southern areas no longer moves as far south.

The impact of climate change on halibut off British Columbia is most important at the larval and juvenile fish stage. As the year-class strength probably is determined at this stage and most larval and juvenile halibut are found in ecosystems north of Canada, it will be the conditions in the Gulf of Alaska, and perhaps the Bering Sea, that are most influential. The major factor affecting future production of the population appears to be the changes in the PDO or Aleutian Low. If there is a strengthening as predicted by Mote *et al.* (1999) and Salanthé (2006), it is possible that changes might improve productivity, at least in the short-term. However, fewer of these recruiting fish may migrate south into the Canadian zone. Production in recent years has been at historic high levels. Thus, any increases in the strength of the Aleutian Low would continue production at these high levels. If production of the population remained high on average, but southward migration was reduced, how would this affect the fishing quotas? If the adults at the southern limit of their distribution contribute much less to the total production than fish spawning farther north, should the exploitation rate be constant for all areas? It is probable that one consequence of greenhouse gas-induced climate change will be a requirement to re-negotiate existing fishing agreements with the United States.

Pacific ocean perch

Pacific ocean perch appear to respond to climate variability at the regime scale; however, given their late age at maturity, recruitment success or failure is not evident until long after year-class strength has been determined. It is noteworthy that the abundance of Pacific ocean perch (and other slope rockfish) abundance has increased steadily or remained stable since the late 1980s (Richards *et al.*, 1997), as a result of very strong year classes in 1976, 1980 and 1984, and average year classes in the early and mid-1980s. These strong year classes began recruiting to the fishery in the late 1980s. The high abundance of these stocks in the current regime is a reflection of the productivity in the 1977–1988 regime, a pattern similar to that described earlier for halibut. The inability to evaluate recruitment in time to make immediate changes to a fishery indicates that this species (and other rockfish with similar life histories) will likely be overfished if regime shifts occur more frequently. The most appropriate management adaptation may be to reduce exploitation rates, and to ensure that some habitat is restricted to fishing. More frequent and more extreme shifts in the Aleutian Low or PDO will introduce more variability in the recruitment of Pacific ocean perch, and there will be more periods like that of 1977–1989 and less of the conditions typical of the 1947–1976 period. With effective management, it is possible that there could be more frequent strong year classes.

Pacific sardine

We know from the studies of Kawasaki (1991) that fluctuations in the abundance of sardines are synchronous around the North and South Pacific Ocean. We also know that around Japan there have been major fluctuations in sardine abundance for centuries (Beamish *et al.*, 1999). Although the exact mechanism or mechanisms that cause these fluctuations are not clearly understood, it is clear that fishing effects are only marginally involved. Climate change and the associated changes in the ocean alter the conditions for successful reproduction in such a way that populations expand and contract rapidly on decadal scales. These expansions and contractions occur quickly, confirming that climate impacts have profound and rapid effects on the structure of large marine ecosystems.

The sardines that occur off British Columbia are produced to the south, off the coasts of California and Mexico. There is some spawning off British Columbia, but it is minor. We know that the period prior to 1947 was favourable for Pacific sardine production, and that the regime from 1948 to 1976 was not favourable. The sardine population increased off California from 1977 through to the early 1990s, indicating that periods of intense Aleutian Lows (positive PDO and stormy winters) resulted in improved sardine production. If greenhouse gas-induced climate change will increase the frequency of periods of intense Aleutian Lows and increased mid-ocean, winter upwelling (Mote *et al.*, 1999), then sardine population fluctuations should continue, possibly with more frequent favourable periods. Off British Columbia, sardines will still fluctuate in abundance, but warmer coastal waters may result in greater abundances, possibly with resident populations being established. However, periods of collapse will still occur.

Pacific cod

Projections of temperature changes are for surface waters and ocean temperatures to change slower than land temperatures. However, in the late 1990s, bottom temperatures in March in the Strait of Georgia were approximately 9.3°C. Thus, it is apparent that several degrees of warming will change the southern limit of Pacific cod distribution, and will, perhaps, move it as far north as southern Alaska. Pacific cod recruitment is therefore a sensitive indicator of ocean changes affecting groundfish. It is predicted that they will gradually disappear from the Strait of Georgia and off the west coast of Vancouver Island as bottom temperatures warm.

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