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The Role of Climate in the Past, Present, and Future of Pacific Salmon Fisheries off the West Coast of Canada

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Abstract.—Commercial Pacific salmon fisheries started in British Columbia in 1829. Catches increased until they reached a maximum of 93,210 metric tons (mt) in 1936 and then declined. Catches increased again in the late 1970s through to the late 1980s, reaching historic high levels of 107,500 mt in 1985. In the 1990s, catches declined rapidly to the lowest levels in the history of the fishery. The changes in catch reflect changes in abundance, which is now known to respond to trends in climate as well as to the impacts of fishing. This suggests that existing stock assessment models may be inadequate to predict the dynamics of the stock and the impacts of fishing in a future of climate change. Future models will need to avoid assumptions of time invariant parameters and may require separate freshwater and marine components. We use modeled sea level pressure changes in the subarctic Pacific to show that one interpretation of the impacts of global warming indicates that the abundance of Pacific salmon in the subarctic Pacific would be higher than the average abundances from 1950 to 2000. It also is important to note that the straying behavior of Pacific salmon may result in an increased abundance in the Arctic. However, the precision of the future scenarios produced by the current global climate change models for the mid-latitudes in the North Pacific is not sufficient to be certain about trends. The recent extreme fluctuations in Canadian Pacific salmon catches indicates that climate changes in general and climate change resulting from greenhouse gas emissions can profoundly affect Pacific salmon abundances. Future changes in trends in abundance will occur abruptly and the fluctuations may be large. We suggest that the immediate impact of global warming on Pacific salmon should be a realization that new management approaches need to be developed quickly.

Introduction

The second assessment report by the Intergovernmental Panel on Climate Change (IPCC) was published in 1995 (Houghton et al. 1995) and the third assessment report in June 2001 (IPCC 2001a, 2001b). In the 1995 report, principal impacts of greenhouse gas induced climate change were believed to be confounded by over capacity of fishing fleets, overfishing, and a deterioration of aquatic habitats. In the Pacific salmon fishery, on Canada's west coast, both over capacity of fishing fleets and overfishing have recently been controlled by vessel buy backs and reduced fishing mortalities (Department of Fisheries and Oceans 1998; Department of Fisheries and Oceans 2001). The deterioration of the freshwater habitat of Pacific salmon remains as a challenge to management, but there is a vigilance inside and outside of management agencies that is slowly reversing past trends. In managed fisheries, the 1995 IPCC report concluded that the impacts of global climate change would be potentially more important than the effects of fishing. The cautionary message was that there is uncertainty about the consequences of impacts, but certainty that there will be impacts. The very clear message in the second and third reports was that national fisheries would not be sustainable unless management agencies took global climate change seriously. For the manager, there will be the difficult task of determining a safe level of fishing while struggling to understand impacts of fishing, and the new concern of the impacts of natural climate variability and greenhouse gas induced changes.

Seasoned fisheries biologists are aware of the risks of attempting to forecast nature. Past abundance trends can be used to develop population dynamics models that to predict future population dynamics without clearly understanding the mechanisms. This typically requires a number of key assumptions to be made to facilitate the computations. Common assumptions are that sets of parameters related to physical processes and biological relationships will remain stable into the future or vary in a predictable fashion. Yet our scientific hindsight that tells us that ecosystems by their very nature are not fixed or constant. For Pacific salmon, add to this problem the new realization that climate has always had major impacts on their population dynamics (Finney et al. 2000) and it becomes clear what a difficult period in the history of salmon management we are entering.

In this paper, we show a sensitivity of Canadian Pacific salmon populations dynamics to climate. Our emphasis is on the marine phase of the life history of Pacific salmon for the aggregate of species and stocks. Species specific impacts in freshwater and in the ocean have also been considered by Henderson et al. (1992); Levy (1992); Beamish (1995); and Beamish et al. (1997a). These earlier publications addressed the potential impacts of global climate change using the known information about the biology and behavior of Pacific salmon. In this paper, we consider the new information relating to the extreme and sudden changes in abundances and climate indices that occurred during the 1990s. These regime shifts have profound implication for stock dynamics and fisheries management and we discuss various models for studying stock and recruitment. We examine the potential impacts of global climate change and implications for salmon stocks in the future. Finally, in the discussion we outline some strategies and factors that need to be considered when developing and implementing adaptations to deal with future climate change.

Pacific Salmon Catches

There are 6 species of Pacific salmon on Canada's west coast; sockeye *Oncorhynchus nerka*, pink *O. gorbuscha*, chum *O. keta*, chinook *O. tshawytscha*, coho *O. kisutch*, and steelhead *O. mykiss*. Steelhead has only recently been classified as a Pacific salmon. Catches of steelhead are small relative to the other species and are not included in our analysis. The first commercial landing in British Columbia occurred in 1829 (Lyons 1969). Complete catch data exist from 1922 to 2000, but data before 1950 are less accurate than after 1950. Without any smoothing, the catches appear to be relatively stable from the early 1920s to the late 1970s followed by an abrupt increase to the late 1980s and an equally abrupt decline through to the present (Figure 1A). When the catch trends were smoothed using a moving average of five, the trends in catch prior to the late 1970s show some fluctuations, but it is the change from the late 1970s to the present that have the most extreme fluctuations (Figure 1A). The catches in 1985 and 1986 were the highest in the history of the fishery, averaging 105,600 mt for these two years. By 1998, the catches dropped to the lowest in history of less than 25,000 mt. In 2000, the total catch of all species was approximately 7,500 mt.

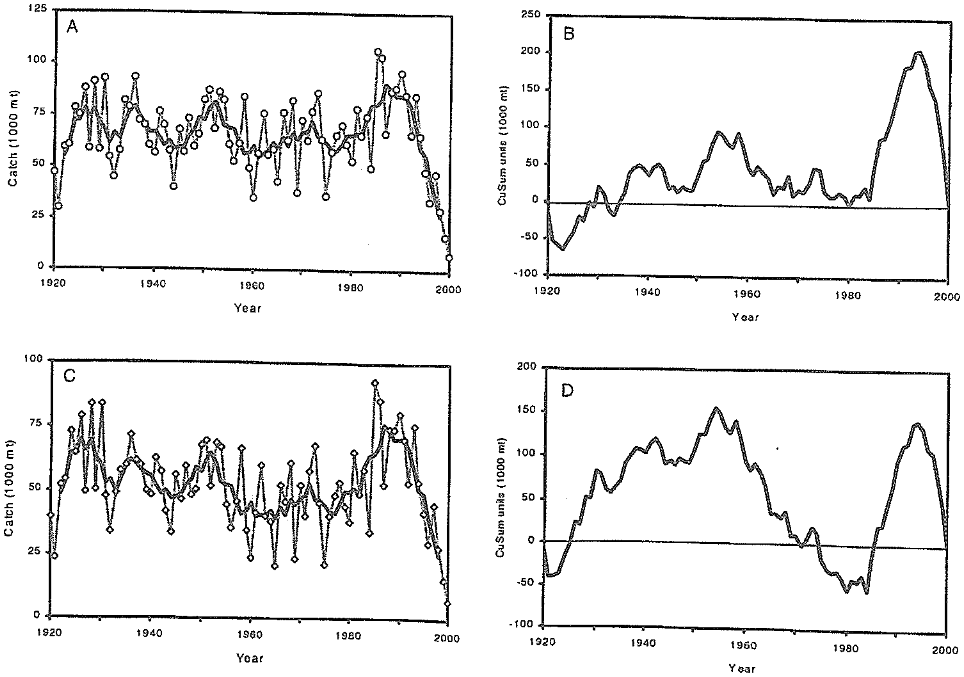

Figure 1. (A) The total catch of pink, chum, sockeye, coho, and chinook in Canada's west coast fishery. The solid line is the smoothed estimate using a moving average of five. (B) The CuSum of A; increasing trends represent periods of above average catch, decreasing trends represent periods of below average catch, and horizontal trends are approximately equal to the time series average. (C) The total catch of pink, chum, and sockeye, (approximately 90% of the catch in A). (D) the CuSum of C.

In this paper, we use a cumulative sum analysis (Murdoch 1979; Noakes and Campbell 1992) to highlight trends in time series. The cumulative sum analysis (CuSum) is sensitive to changes in trends because the differences from the mean become exaggerated over time, providing a useful graphical tool for the identification of change points in a data series. As with any tool, the CuSum can help direct attention to trends in the data, but care needs to be taken in its application and interpretation (Murdoch 1979). The CuSum chart is constructed by standardizing the time series by subtracting a constant (usually the series mean) and summing the deviations from the beginning of the series to the point of interest (Murdoch 1979). Changes in the length of the time series, the starting point or the constant used in standardization will change the shape of the CuSum chart, but will not generally affect the change points. A positive trend in the CuSum chart indicates above average catch while a negative trend indicates below average catches.

The trends in Canadian catch are more pronounced when only pink, chum, and sockeye are compared. (Figure 1C). There are 4 distinct trends that appear clearly in the CuSum charts (Figures 1B, D). Catches were generally above average from the early 1920s to the mid 1950s, followed by below average catches until the early 1980s. There was an abrupt increase beginning in the early or mid 1980s and an equally abrupt period of below average catches in the 1990s.

Why Catch Can Be Used to Estimate Trends in Abundance

For many commercially fished species, the catch is not an accurate measure of abundance unless there is an associated measure of the effort used to make the catch. However, for Pacific salmon, the fisheries are frequently managed to allow high harvest rates (Groot and Margolis 1991). Harvest rates vary by species and vary over the history of the fishery, but rates of 60% to 80% have been common (Groot and Margolis 1991). Harvest rates for a particular stock are difficult to estimate, as ocean fisheries will capture a mixture of stocks. Estimates of spawning biomass and subsequent production from these spawning fish are available for Fraser River sockeye salmon and Strait of Georgia coho salmon. The sockeye salmon data were collected as part of an international agreement by Canada and the United States to jointly manage sockeye salmon production in the Fraser River. Virtually all sockeye salmon in the Fraser River spawn in the fall, hatch over the winter, and enter the ocean one year later in the spring. Approximately 93% of these sockeye spend two years in the ocean before returning to spawn at a total age of four years (Roos 1991). Some of the stocks have distinct four-year cycles in abundance, which result in a natural four year cycle in the catch trends. Beamish et al. (1997b) estimated harvest rates for each brood year as the total catch/total return of age-four fish. In this study, we have updated the estimates from the 1991 brood year (the 1995 return) to the 1996 brood year (the 2000 return). The year of spawning, termed the brood year, is four years earlier than the return year for most sockeye from the Fraser River.

It is apparent that the harvest rates from 1960 to 1994 varied only slightly (Figure 2A). A linear regression from 1960 to 1994 brood year has a slope of 0.001. Beginning in the year 1995, there was a trend toward reduced catch and reduced harvest rates as a consequence of management decisions to reduce fishing mortality to protect some stocks that were in low abundance (Department of Fisheries and Oceans 2001). Except for the period after 1995, the stable harvest rates indicate that the resulting catch will be proportional to the natural abundances.

Coho harvest rates were determined using hatchery and wild coho that were tagged with coded-wire tags and recaptured in the sport and commercial fisheries. Estimates were made of the total number of a particular stock that were caught and this estimate was compared to the total return to a hatchery or the monitored wild stock to estimate the harvest rate. Coho are caught

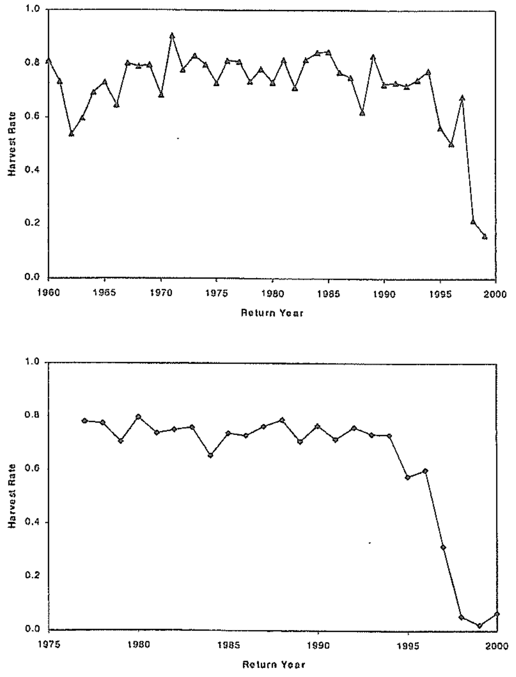

Figure 2. (A) Harvest rates (expressed as a percentage) of sockeye salmon produced in the Fraser River. (B) Harvest rates (expressed as a percentage) of coho salmon produced in 6 key stocks around the Strait of Georgia.

in their second ocean year before they return to spawn. The estimated harvest rate for coho ranges between 0.80 and 0.65 from 1977 to 1994 (Figure 2B). A linear regression for the data between 1977 and 1994 has a slope of -0.12, indicating that the average harvest rate is reasonably stable. Harvest rates decline after 1994, when management actions began to restrict fishing opportunities. After 1996, catches are no longer a comparable index of abundance, but the requirement to reduce harvest rates indicates that abundances were at extremely low levels. As seen from sockeye data, stability in harvest rates indicates that the trends in catch are indications of similar trends in abundance.

Canadian Catches of Pacific Salmon Compared to Total Pacific Catches

Total catches of Pacific salmon from all countries were obtained from the North Pacific Anadromous Fish Commission (NPAFC) and updated to 2000 (NPAFC 1997). The data we use is preliminary for 1998, 1999, and 2000. We show the catches of pink, chum, and sockeye as they represent about 90% of the total catch and because the estimates of coho and chinook catch earlier than 1950 are missing or are less reliable than after 1950. The average catch of pink, chum and sockeye from 1920 to 1999 was 519,000 mt. This compares to an average of 65,300 mt for catches of pink, chum and sockeye in the Canadian fishery. There is a distinct pattern in the total North Pacific catch, with large catches from the mid-1920s to the mid-1940s, followed by an abrupt decrease and rather constant catch from the mid-1940s to about 1977 (Figure 3A). The largest catches of 947,000 mt occurred in 1995 and catches have declined each year since 1995. The increasing trend in the Canadian catch after the mid-1970s (Figure 3B) is similar to the timing of the increase in the total Pacific catch, however, the total Pacific catch continued to increase until 1993–1994. The synchrony in the timing of the beginning of the increasing trend in the late 1970s has been interpreted to result from a common, large scale change in climate (Beamish and Bouillon 1993).

Trends in Canadian Catch in Relation to Large-Scale Changes in Climate

Canadian catches represent the aggregate catch of species that entered the ocean in different years. Virtually all pink salmon entered the ocean one year earlier than the catch year. Most sockeye from the Fraser River entered the ocean two years earlier than the catch year. Chum salmon, in general, entered the ocean four years earlier than the catch year (Groot and Margolis 1991). When catches were lagged to the year of entry and the data smoothed using a CuSum analysis, there are distinct, persistent trends (Figures 4A, B). Lagged catches are about average between 1925 and 1955 with no upward or downward trends in the CuSum chart during this period (Figure 4B). Lagged catches declined between 1955 and 1980 (downward trend in the CuSum chart) and then increased (upward trend in the CuSum chart) until about 1990 (Figure 4B). Lagged catches have decreased from the early 1990s to the present.

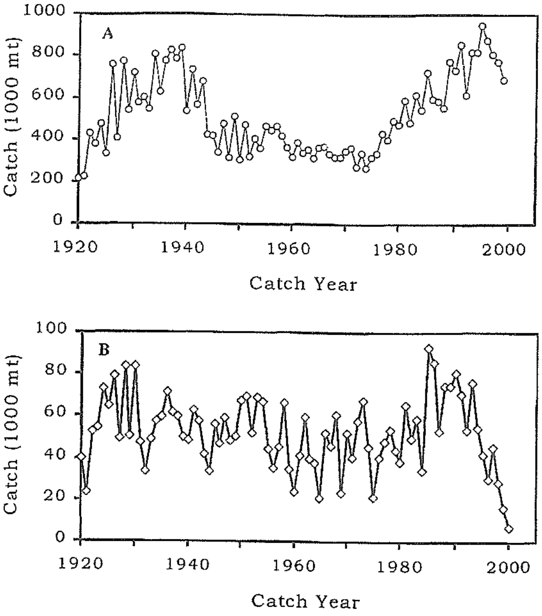

Figure 3. (A) The total catch of pink, chum, and sockeye from all fisheries in the North Pacific. (B) The Canadian catch of pink, chum, and sockeye for the same years as A.

Three indicators of large-scale climate change were used to examine links between salmon abundance and climate. The Pacific Decadal Oscillation (PDO) is an index of sea-surface temperature patterns in the central subarctic Pacific Ocean (Mantua et al. 1997). Trends in the PDO appear to change at similar times (perhaps slightly before) changes in trend for the lagged Canadian salmon catch (Figures 4A–D). Increasing trends in PDO appear to correspond to periods of increasing catch although the relationship may not be linear (Figures 4B, D). The Aleutian Low is the major weather system during the winter months in the north Pacific and affects our coastal climate, as well as upwelling in the subarctic Pacific (Deser et al. 1996). Beamish et al. (1997b, 1999a) have derived an Aleutian Low Pressure Index (ALPI) whose changes in trends appear to occur at similar times observed for the lagged Canadian salmon catch (Figures 4E, F). The Pacific Circulation Index (PCI) is an index of the pattern of the atmospheric circulation of the winter winds in the subarctic Pacific (King et al.

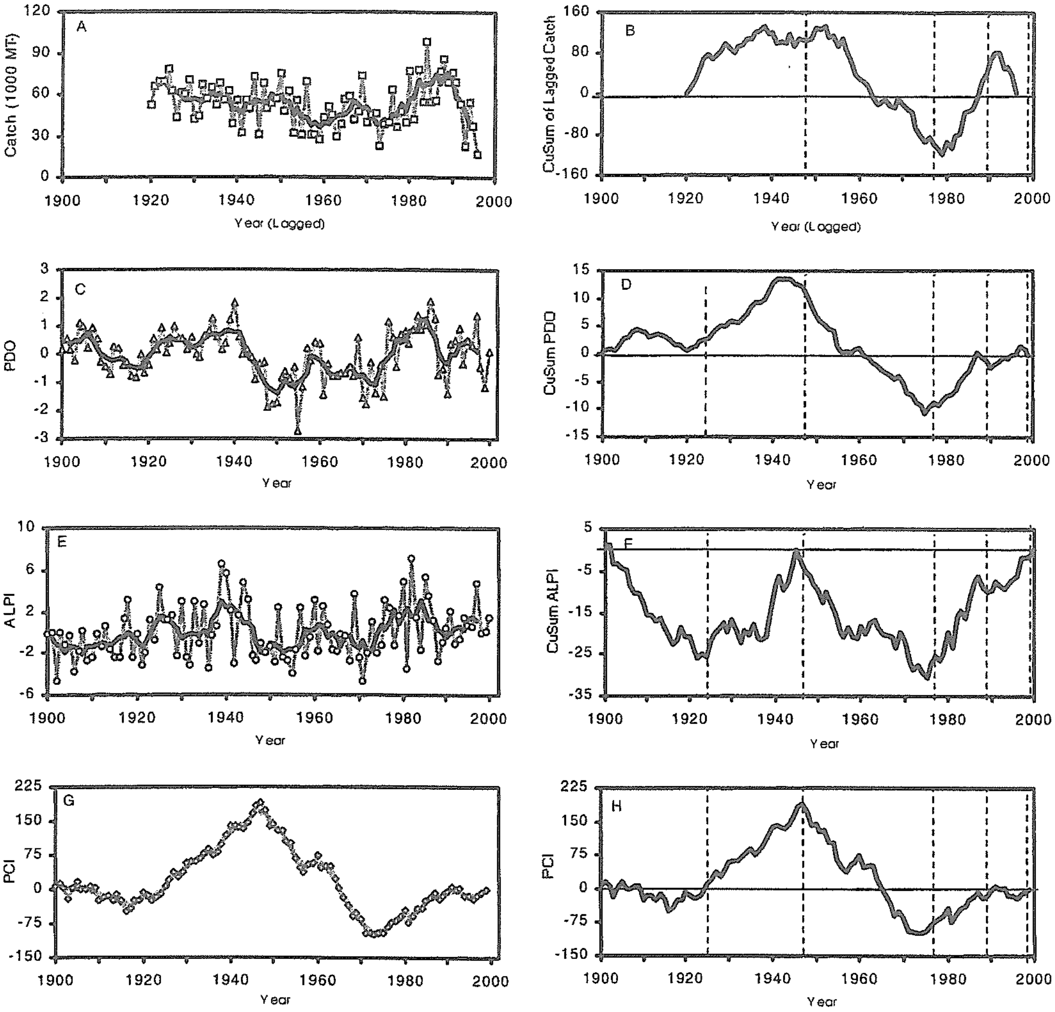

Figure 4. A comparison of the trends in Canadian Pacific salmon catch and trends in three indices of large-scale climate ocean changes. (A) is the catch of pink, chum, and sockeye, lagged back to the year in which most fish would enter the ocean. The solid line is the smoothed trend using a moving average of five. Figures C, E, G are the Pacific Decadal Oscillation, the Aleutian Low Pressure Index, and the Pacific Circulation Index (respectively). The *y*-axis are index units. The solid line is a moving average of 5. Figures B, D, F, H are the corresponding CuSum charts. The horizontal dashed lines indicate the regime shift years of 1925, 1947, 1977, 1989, and 1998.

1998). The PCI is a CuSum-based index, so the index and CuSum are the same (Figures 4G, H). As with the other indices, changes in trend for PCI occur at similar times and perhaps slightly before the lagged Canadian salmon catch (Figures 4B, H). Once again the relationships between catch and the various climate indices may not be linear.

The dashed, vertical lines in Figures 4B, D, F, H indicate the regime shift years of 1925, 1947, 1977, 1989, and 1998 (Beamish et al. 1999a, 2000). The trends in each of the three climate indices as well as the lagged Canadian salmon catch change at about the same time as indicated by changes in the slopes of the CuSum graphs (Figures 4B, D, F, H). The climate indices each represent in a unique fashion the state of the North Pacific Ocean and reflect changes in the general oceanographic conditions (such as coastal upwelling). The close, albeit not perfect, synchrony suggests a relationship between Pacific salmon production and large-scale climate patterns (Noakes et al. 1998). Changes in the climate indices appear to precede changes in salmon catch. One possible explanation would be inherent delays of complex biological systems to respond to relatively rapid environmental change (regime shifts).

The Regime Concept

Cycles are a common feature of biological and physical data series. Persistent states that change quickly to other persistent states have a number of terms, but here we refer to them as regimes (Isaacs 1975; Francis and Hare 1994; Beamish et al. 1999a). The frequency of regime changes and the duration of the persistent state is closely related to atmospheric conditions in sub-arctic region of the Northern Hemisphere and specifically the Pacific. Regimes are apparent in the pattern of the ALPI, PDO, and PCI (Figure 4). Regime shifts appear to have occurred about 1925, 1947, 1977, 1989, and 1998 (Hare and Mantua 2000; Beamish et al. 1999a, 2000). The periods in between these shifts are the regimes.

Other cyclic patterns exist that have different frequencies. The best known is the El Niño-Southern Oscillation (ENSO) cycle, which alternates between extreme values known as either an El Niño and a La Niña. Cycles of 65–70 years have been identified in a number of studies (Schlesinger and Ramankutty 1995; Minobe 1997; Ware and Thomson 2000). One of the more dramatic cycles of 300,000–500,000 years that has been discovered in the Vostok ice cores (Petit et al. 1999) exhibits large rapid increases in atmospheric carbon dioxide followed by gradual declines. It is the 10–30 year cycles that we identify as the periodicities that correspond to distinct organizations in marine ecosystems that are relevant to the population dynamics of Pacific salmon. Regimes, therefore, are defined in relation to physical variables such as surface temperatures, sea level pressures, and atmospheric circulation patterns that are known to affect the productivity of ecosystems.

The regime concept is important in fisheries management for several reasons. Regimes may change quickly. The 1998 regime shift may have occurred over several months as indicated by the decline of surface temperature in the tropical Pacific of 8°C over a 10 week period when the average annual change is approximately 3°C (McPhaden 1999). New regimes may also signal new changes in productivity that would normally be measured as marine survival for Pacific salmon. The analysis of any data series, therefore, must take into account the effects of regime shifts.

The responses to regime shifts observed in fish populations may not be uniform for all species or all ecosystems. For example, off Canada's West Coast, Pacific sardine *Sardinops sagax* stocks collapsed in 1947, but did not reappear until after the 1989 regime shift (McFarlane and Beamish 1999). There is evidence that Pacific salmon productivity was affected by the 1947, 1977, 1989, and 1998 shifts (Hare and Mantua 2000; McFarlane et al. 2000). The 1977 shift resulted in an increasing production of most stocks of Pacific salmon in Canada, in synchrony with Pacific salmon in the rest of the subarctic Pacific. The 1989 shift, however, reversed the trend in marine survivals in many Canadian stocks and those to the south of Canada's west coast (Beamish et al. 1999b) while only slowing the rate of increase in the stocks to the north and west. The 1998 change appears to be improving marine survival for Canadian stocks in the south and reducing survival for stocks to the north and west (Beamish et al. 2000). Thus, regime shifts represent reorganizations of ecosystems in which the dynamics are best viewed as new states, rather than cyclic changes from lower to higher and higher to lower marine productivity. There is concern that we are just finding out about the impacts of regimes in the natural regulation of fish populations. We suggest that an equally important concern is whether global warming will alter the frequency of regime shifts and the magnitude of the changes.

Stock and Recruitment with Relation to the Regime Concept

Various mathematical representations of the relationship between parent and progeny have been proposed for fisheries (Ricker 1954; Beverton and Holt 1957; Cushing 1973; Shepherd 1982; Noakes 1988). The most commonly employed representation is the Ricker model (Ricker 1954) that includes both density independent (a) and density dependent (b) components into a single model expressed as

$$R = \alpha \text{ S} \exp(-\beta S)$$

where R represents recruitment at a specific age (progeny) and S represents the spawning stock (parent). Ricker (1954) originally derived this relationship for Pacific salmon and the density dependent factor (b) was presumed to be related to conditions in freshwater such as limits to available spawning area. The density independent factor (a) represents the productivity of the population at low stock size and may also be related to environmental conditions including changes in habitat. A number of authors (Tang 1985; Noakes 1988; Stocker and Noakes 1988; Campbell et al. 1991; Chen and Irvine 2001) have explored incorporating environmental data (such as sea surface temperature) into stock and recruitment models with some success. Others have also incorporated factors to account for autocorrelations in the data as well as environmental variables (Noakes et al. 1987; Noakes 1988; Campbell et al. 1991; Downton and Miller 1998).

Regime shifts may lead to fundamental changes in production either in freshwater or the ocean or both. To date, attempts to explicitly account for regime shifts in recruitment models have been limited. A piecewise linear "broken stick" model (Figure 5) where the maximum recruitment level is limited is one alternative (Noakes 1988). Clark et al. (1999) used this model to examine changes in Pacific halibut *Hippoglossus stenolepis* recruitment resulting from the 1977 regime shift. Wada and Jacobson (1998) also examined fluctuations in Japanese sardine *Sardinops melanostictus* and potential links to regime shifts. It is also possible to adapt a Ricker curve by allowing one or both of the two parameters, a and b, to change as a result of regime shifts (Figure 6). One could also incorporate environmental data or an autocorrelated error term into the modified Ricker model or the piecewise linear model.

In the case of marine fish, a single recruitment function incorporating these various factors may be appropriate. For Pacific salmon, an alternative approach would be to have separate recruitment functions for the freshwater and marine stages of their life cycle where recruitment is the product or combination of these two functions such that

$$R = f(X) \times g(Y) \text{ or } R = g(f[X], Y)$$

where $f(X)$ is the freshwater stock–recruitment function, $g(Y)$ or $g(f[X], Y)$ is the marine stock-recruitment function, X represents the data and parameters (i.e., a, b, spawning stock index, environmental data, etc.) associated with f, and Y represents the data and parameters associated with g. In general, f and g could be either linear or nonlinear functions or nonparametric expressions combined with a variety of error terms. The two functions (f and g) could also incorporate regime components (such as the piecewise model in Figure 5) which may reflect changes in either the model parameters or functional relationships or both.

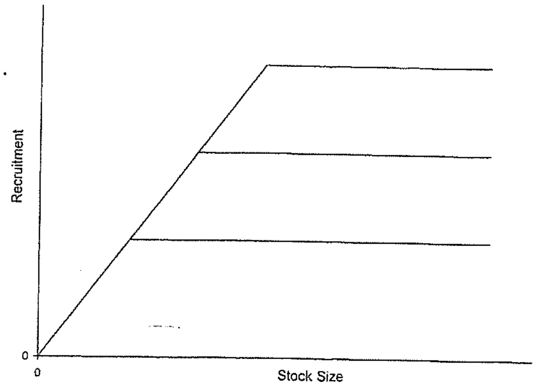

Figure 5. Piecewise linear "broken stick" stock-recruitment model such that recruitment, R, is given as R = minute (a S, R_{max}) where a is the slope of the productivity function from 0 to R_{max} and R_{max} is the maximum recruitment. The three horizontal lines represent production limits for three separate hypothetical regimes.

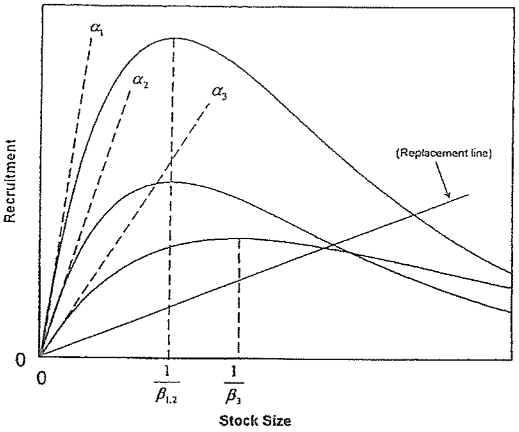

Figure 6. Ricker stock-recruitment curves for three hypothetical regimes where the model parameters a and b change according to the regime. The density dependent parameter, b, is assumed to remain constant for regimes 1 and 2.

Data limitations would, in general, preclude use of this approach (separate recruitment functic for freshwater and marine production) for all but a f salmon stocks. There are, however, instances wh data on freshwater production (i.e., survival from e to smolt) as well as catch and escapement informati exists potentially allowing the estimation of both f a g. For instance, hatchery production from an enhan ment program may be fixed at some target level su that f is a constant. There are also a number of ind streams where fences are used to enumerate juven salmon migrating to the ocean and adults returning spawn. In these cases, it may be possible to estima and g as two Ricker-type functions one for freshwa and one for the marine phase. It may also be possi to derive separate production models for hatchery a wild salmon coexisting in the same stream to test pothesis related to wild-hatchery interactions. Se rating freshwater and marine production as well as corporating components to model regime shifts is i portant in this case to ensure that inferences related interactions or regime shifts are fair and supported the observed data. Stock and recruitment time ser are also often of limited length and the duration tween regime shifts are short enough to warrant c sideration of these more complex models. While su models are likely to be computationally tractable, d limitations may affect their precision. Care needs be taken to develop models that are both functio and parsimonious.

While stock-recruitment models that incorpor freshwater, marine and regime components will be u ful to analyze and explain past events, it is difficult predict their utility in forecasting future recruitment given various global warming scenarios. It is plausible that a more robust approach that considers general patterns in recruitment may provide estimates of short-term trends (Noakes 1989; Mackinson et al. 1999; Chen and Irvine 2001). However, if there are structural changes in the ecosystem as a result of global warming then a more holistic approach to recruitment forecasting including multispecies models may be necessary. These approaches will provide new challenges both from a data and implementation aspect.

Impacts of Anthropogenic Interference on the Climate System

The third assessment report of the Intergovernmental Panel on Climate Change (IPCC 2001a, 2001b) was released in summary early in 2001 and in detail in June of 2001. The 1990s were shown to be the warmest decade in the past 1000 years. Much of the warming in the last 50 years resulted from increased greenhouse gas production. All of the internationally accepted emission scenarios for the future show increases in the average global temperature, increases in the average global precipitation and rising sea levels. Continued change is inevitable. The IPCC concluded that anticipatory adaptation has the potential to reduce many of the adverse impacts and enhance beneficial impacts. The costs of adaptation may be relatively small, especially if they are part of a more holistic approach to management, consistent with the developing emphasis on ecosystems.

An emphasis in the third assessment report is that the impacts of climate change can be abrupt (IPCC 2001b) and can affect the magnitude and frequency of regimes. The possibility that the impacts of greenhouse gas increases will be nonlinear poses a serious problem for the future management of Canada's Pacific salmon. Unfortunately, there is little agreement among the general climate and ocean models about the future impacts of greenhouse gas emissions in the mid-latitudes. This is particularly relevant in the subarctic Pacific where it has been shown that regime shifts are associated with an alternating pattern of coastal cooling and mid-ocean warming and coastal warming and mid-ocean cooling (Deser et al. 1996). The current inability of climate models to forecast these changes complicates the interpretation of global warming impacts on Canada's Pacific salmon stocks during their marine phase because small changes in marine survival of only a few percent can double or half the total returns. Pacific salmon will likely respond to the impacts of climate change very quickly in both their freshwater and marine habitats, as Pacific salmon are both short-lived and semelparous. It is the sudden decrease in productivity that presents the most obvious threat to stewardship. There also are concerns about the effectiveness of financial expenditures that may be directed at rebuilding stocks during periods when marine carrying capacity is not sufficient to produce abundances consistent with expectations.

Despite an inability to model the current impact of the increasing greenhouse gases on the subarctic Pacific, there is agreement that the general temperature related impacts could be 2–15 times larger than observed during the past 100 years. Even if greenhouse gas emissions were stabilized, the impacts of these emissions are projected to continue for hundreds of years. Once it is accepted that climate affects the dynamics of Pacific salmon populations off Canada's west coast in a nonrandom manner and it is accepted that greenhouse gas emissions are affecting climate, it is becomes clear that greenhouse gas emissions will affect Canadian Pacific salmon production in the future. A key to understanding future impacts is to understand how the climate indices such as the PDO or ALPI will change.

We used the results of the coupled ocean-atmosphere general circulation model runs used in the assessment of the impacts of climate variability and change in the Pacific Northwest of the United States (Mote 1999). Their 1998 model runs used the Canadian Climate Centre model (CCC) and the United Kingdom, Hadley Centre model (HC) because these are two key models used in the IPCC assessments (Houghton et al. 1995). The HC model gives a moderate projection of future changes (data courtesy of Anthony G. Barnston and Yuxiang He, NOAA, 5200 Auth Road, Camp Springs, Maryland 20746–4304) (Figure 7A). The CCC has the higher rates of globally averaged warming given the same greenhouse gas emissions scenario (Figure 7B). According to the model runs, the Aleutian Low (expressed as sea level pressure [SLP]) deepens (increasing trends in Figures 7A, B) and shifts southward (not apparent from Figure 7 but an output from the model) in response to the forcing of a simulated 1% per year increase in CO_2. The models have inherent assumptions that represent the interpretations and emphasis of the model builders, thus, the two models produce different results, but are consistent in the projection of trends.

Stronger Aleutian Lows or the warm phase PDO has been shown to be associated with increased ocean productivity of Pacific salmon in the 1980s (Beamish et al. 1999 a, b). Francis and Hare (1994) have shown that these conditions are linked with lower productivity for coho and chinook at the southern limit of their distribution off Oregon, Washington and southern British Columbia. Although the two global climate models models produce different results, they both indicate that there will be more periods of stronger Aleutian Lows and positive PDO's.

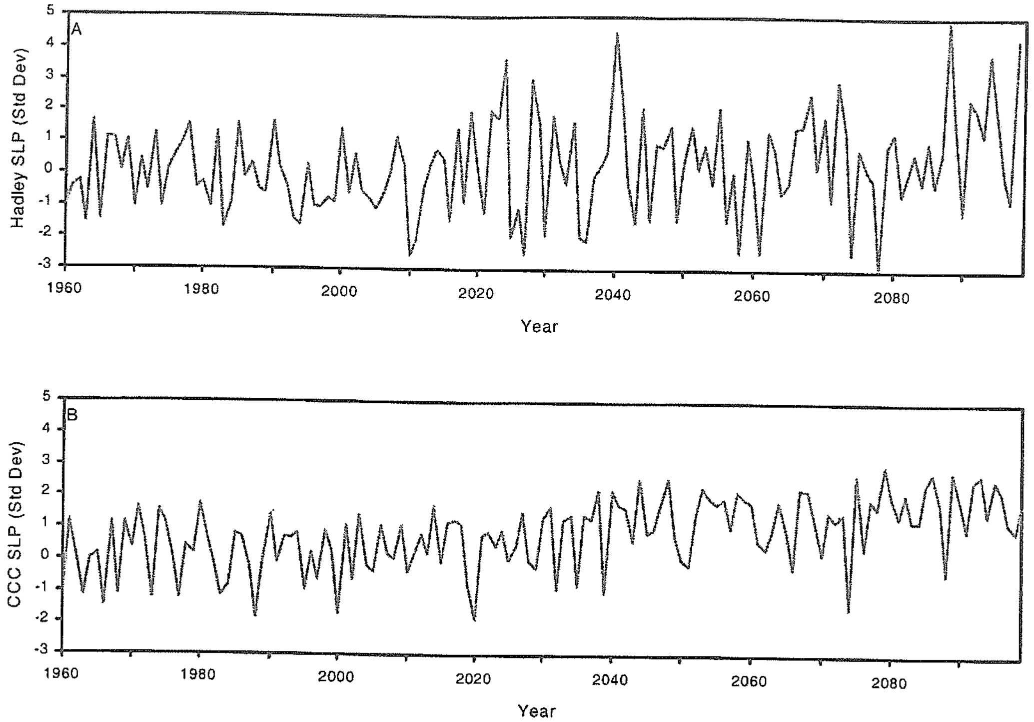

Figure 7. (A) The United Kingdom, meteorological office Hadley Centre, global climate change model of the impact of a 1% per year increase of CO_2 only on sea level pressure (SLP). (B) The Canadian Centre for Climate Modeling and Analysis model (CCC), using the same data as A. Both models were standardized to the 1961–1990 data. Data courtesy of Anthony G. Barnston and Yuxiang He (NOAA, 5200 Auth Road, Camp Springs, Maryland 20746–4304).

We standardized the Canadian Pacific salmon catch (pink, chum, sockeye), the total Pacific salmon catch, and the modeled Hadley and CCC time series (Figure 7) by subtracting the estimated mean and dividing by the estimated standard deviation for each series. Years in which the standardized catch exceeded 0.5 SD were classified as above average, below –0.5 SD were below average, and in between were average. The same classification scheme was used for the Hadley and CCC modeled time series (Figure 8). The data could be partitioned in other fashions, but this simplistic approach was used to assess general trends. Typically, large scale climate models such as the CCC and HC models provide only general representations of climate for discrete regions.

Although Canadian salmon catches dropped dramatically in the 1990s, all nation Pacific salmon catches have remained relatively high since the 1980s (Figures 8A, B). The HC model produces an alternating pattern of high and low production periods but the low productivity periods (< –.5 SD) become less frequent after about 2065 (Figure 8C). The CCC model predicts a more consistent pattern of higher productivity periods (< 0.5 SD) during most of the 21st century (Figure 8D). The relationship between salmon catch (Figures 8A, B)and the modeled results (Figures 8C, D) is not similar to the close relationship using actual data as shown in Figure 4. However, both models show a similar trend of more frequent extreme low pressure and, in some cases, more intense events. Both models consistently show that there will be a trend over the next 100 years to increased storminess in the subacrtic Pacific. Increased storms or positive PDO were associated with increased Pacific salmon production beginning in the late 1970s. If the general relationship between climate and salmon production holds true (Noakes et al. 1998), then the trend towards periods of higher productivity suggests that all nation Pacific salmon production could increase during the next 100 years. This is one plausible scenario, but of course is dependent on the reliability of the climate models.

An earlier study interpreted the CCC model output as providing evidence that temperature changes would greatly restrict the ocean habitat available to sockeye salmon (Welch et al. 1998). The model output was not specified, but typically early (and some current) climate

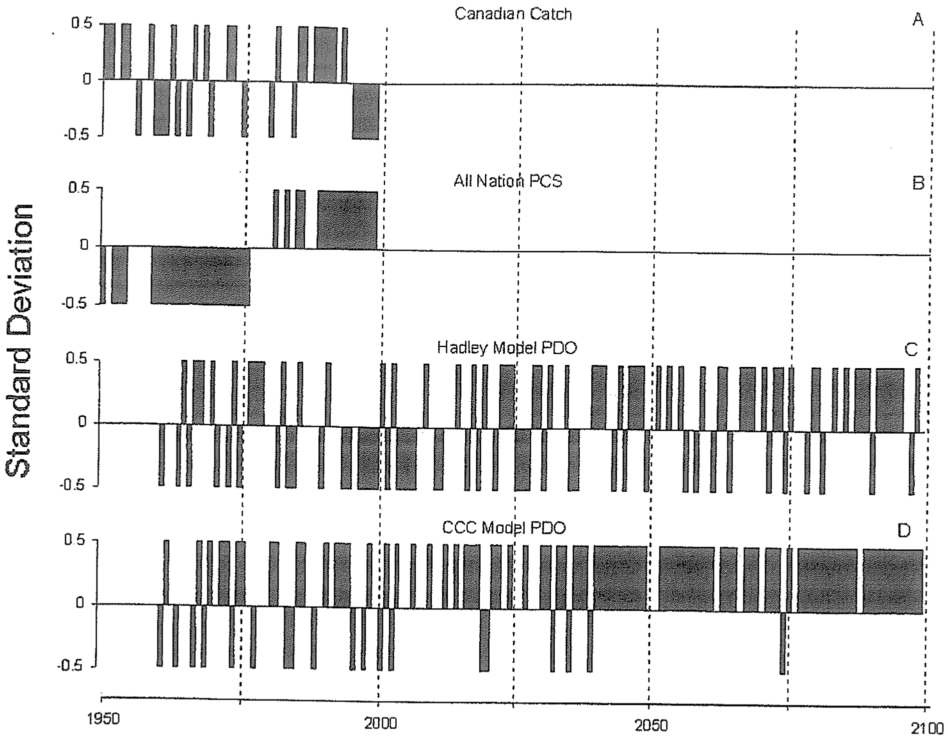

Figure 8. The model results from Figure 7 compared to trends in catch in Canada (A) and total Pacific catch (B) of pink, chum, sockeye, coho, and chinook. Catches are standardized by subtracting the mean of the time series and dividing by the standard deviation. Catches are partitioned into three groups; above average (> 0.5 SD), below average (< -0.5SD), and average. The Hadley (C) and CCC model (D) results were standardized and categorized the same way. Catches are shown from 1950 to 1998 while the climate model results are displayed from 1960 to 2100.

change models were insensitive to the decadal-scale variability characteristic of the oscillations in the PDO or ALPI. The study suggested that surface temperatures would limit the southern range of sockeye and that these limits would vary throughout the year and spatially throughout the ocean (Welch et al. 1998). The hypothesis that temperature exclusively regulates the distribution of salmon in the north Pacific requires further testing particularly given the mechanisms governing salmon production are not well understood. It is also generally accepted that specific temperature projections of models of the mid-latitude north Pacific represent scenarios rather than specific forecasts of temperature. Care should, therefore, be taken when using temperature output from only one model. In the third assessment report of the IPCC, it is acknowledged that models are still not capturing mid-latitude temperature changes in a consistent manner. Thus, it may be premature to be identifying future thermal structure. While the interpretation by Welch et al. (1998) has been criticized (Mote 1999), the Welch et al. (1998) study does present a plausible scenario that sockeye are sensitive to ocean temperature changes. Further investigation of their ideas is warranted as global climate models begin to capture the variability associated with the PDO and ALPI.

Discussion

There will be impacts of global warming on Canadian Pacific salmon production. The recent fluctuations from historic high levels of catch and abundance to historic low levels in just over a decade is clear evidence that the impacts can be severe, extreme, and immediate. Impacts will occur in freshwater and in the ocean. There will be opportunities to adapt to changes in freshwater habitat, but any adaptations must consider the nature of the change in the ocean. There is evidence that global warming impacts will be positive and negative depending on the location of an ecosystem. The possibility that the ocean-climate environment may become more like the period from the late-1970s to the late 1980s is an indication that productivity of the aggregate of Pacific salmon stocks in the ocean may tend to be at the higher end of historic productivity patterns towards the end of this century. However, this does not necessarily mean that the salmon stocks off Canada's west coast will respond synchronously with stocks farther north. The response of Pacific salmon is dependent on potential structural changes in the ecosystem resulting from climate changes.

Understanding the impact of global warming on Canadian Pacific salmon stocks is complicated by our poor understanding of the processes involved in the natural regulation of salmon and by our geography (Beamish et al. 2000). Ocean currents and the general pattern of sea level pressures result in a north-south oscillation in the climate in British Columbia (Moore and McKendry 1996). An oscillation in the productivity trends for Pacific salmon between northern and southern stocks has been described by Hare et al. (1999). The alternating pattern is similar to the phases of the PDO or ALPI. If the oscillation is real and persistent, there would be some area that may be the node in the oscillation, but this area remains to be determined. We do know that at about the level of latitude 55°, there is a long-term minimum in sea level pressure (Beamish et al. 2000). More information about this north-south oscillation in climate impacts needs to be determined before ecosystem impacts can be assessed reliably for Pacific salmon stocks off Canada's west coast. There also is a coastal-open ocean oscillation that affects British Columbia Pacific salmon (Deser et al. 1996). Both of these north-south and coastal-open ocean oscillations will be affected by a changing climate.

Although all species of Pacific salmon appear to be sensitive to climate change, pink salmon may provide an early indicator of global warming impacts. Pink salmon have the shortest life span of the species of Pacific salmon of approximately two years from hatching. They also are the smallest physically. The largest stocks of pink salmon in British Columbia occur in the Fraser River. There are stocks of pink salmon farther south of the Fraser River, but they are small compared to the abundance of pink salmon in the Fraser River. Thus, one anticipatory action would be to ensure that the dynamics of pink salmon from the Fraser River are adequately monitored.

Pacific salmon are well-known for their ability to home 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. It is this straying rate that can range up to 10% (Groot and Margolis 1991) that 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 from Canadian Arctic waters (Hunter 1974; Craig and Haldorson 1986; Babaluk et al. 2000) with pink salmon being the most frequently observed and chinook salmon the least frequently seen. Recently Babaluk et al. (2000) reported first records of sockeye and pink salmon from Sachs Harbor on Banks Island, in the Beaufort Sea. Although, Pacific salmon had been observed previously, the report of Babaluk et al. (2000) represented extensions of these earlier records. One report of a coho 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 1986). 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 25–45% (Gordon and O'Farrell 1997). There also would be greater freshwater runoff. Over the period 1978–1996, there has been a 2.9–3.5% per decade decrease in the extent of Arctic sea ice (Cavalieri et al. 1997; Serreze et al. 2000). If such dramatic changes were to continue, conditions favorable to straying and perhaps feeding for Pacific salmon may improve.

It is important to reflect on the reproductive strategy of Pacific salmon when considering the future impacts of climate change. The various species reproduce in freshwater where they produce large numbers of eggs and fry. Despite large mortalities in freshwater, large numbers of juveniles find there way to sea where marine mortality typically exceeds 90% (Groot and Margolis 1991). The anadromous behavior provides the various species with a marine habitat many magnitudes larger than the freshwater habitat and thus allows the population of adults to be many times more abundant than if they remained in freshwater. The work of Finney et al. (2000) shows that Pacific salmon have fluctuated naturally for the past 2000 years as they adapted to the natural changes in climate. Thus, we now know that climate and the ocean ecosystem have a major effect on the abundances of Pacific salmon.

There are literally thousands of stocks of each species. Within these stocks either individually or in aggregate, there is a variability that means that not all stocks will respond in exactly the same way to climate induced habitat change in the ocean. Presumably this is an adaptation to optimize species survival despite natural changes in freshwater and marine habitats that may be the result of large scale climate changes. However, human intervention into the life history strategy of Pacific salmon in attempts to adapt or to mitigate the effects of increased greenhouse gas build-up could have unexpected results if the consequences of any interventions are not clearly understood. Conceivably, our reaction to unexpected changes in salmon abundance could be as harmful as the change we are attempting to correct.

Our point is that we should be careful about manipulating one part of the life history of a species on the assumption that the dynamics of the remaining components of the life history will not also be impacted. This is particularly important because the impacts of climate change will be at the ecosystem level and not at the population level. We stress that adapting to climate change requires an improved awareness of the ecology of salmon and the impacts of their environment and associated species.

Models are only beginning to capture the large-scale variability associated with regime shifts. A major concern is the abruptness of changes. There is recent evidence of large-scale climate shifts that are astonishing. McPhaden (1999) reported that the end of the 1997–1998 El Niño in mid-May 1998 was characterized by a sudden and unexpected intensification of trade winds that caused such intense upwelling that the cold subsurface waters cooled the surface waters at one location (0°125°W) by 8° in 30 days, more than 10 times the average rate of cooling at that time of year.

It is important to consider where we are in our appreciation of the past, present, and future impacts of climate on Pacific salmon fisheries on Canada's west coast. In the past, climate, ocean, and associated species impacts on the dynamics of Pacific salmon stocks were believed to be far less important than the effects of fishing (Ricker 1954). In fact, climate was rarely mentioned as a relevant factor in the management of these stocks. It was recognized that the ocean affected the abundance of salmon, but it was believed that the impact of the ocean was less important than fishing because exploitation rates were high. The logic apparently was that if fishing removed 70% to 80% of the fish (Groot and Margolis 1991), then there was unused capacity within the ocean to produce more salmon. The bottleneck to achieving larger abundances was the number of juveniles produced in freshwater. This assumption was the logic behind the large hatchery program that was initiated on Canada's west coast in the early 1970s. According to these views, humans had the ability and scientific understanding to manage a fishery such that the number of juveniles could be optimized to rebuild abundances to levels that would be sustainable. Ricker (1973) published an analysis that showed that future maximum levels of abundances could not be as high as historic abundances. However, in less than a decade, catches (and abundances) were the highest in history. The explanation, which is now generally accepted, is that the capacity of the ocean to produce salmon fluctuates naturally (Beamish and Bouillon 1993; Finney et al. 2000).

It should be apparent that the fundamental scientific assumptions used in the management of Canada's Pacific salmon stocks have to 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. Our hindsight is that 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 that predicted that in 2001, the salmon returns to the Columbia River would be the largest on record and chinook 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.

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