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We Are on the Right Path, But It is Uphill Both Ways

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Abstract.—It was not too long ago that our best available science advised that Pacific salmon abundance could be rebuilt to historic levels by adding more fish to the ocean. In Canada it was proposed that an enhancement program would not only benefit Pacific salmon, but it would also be repaid when the increased abundances were fished and taxed. The belief that there was unused carrying capacity in the ocean that could be filled with hatchery-reared fish persisted into the 1990s as indicated by plans to rebuild coho salmon, *Oncorhynchus kisutch*, stocks. It was in the 1990s that most researchers accepted that Pacific salmon production was related to trends in ocean carrying capacity. It was also accepted that regimes were real, resulting in persistent states in carrying capacity that shifted quickly to new states on a decadal scale. It was unsettling that climate trends could be directly related to Pacific salmon production because fisheries management science at the time did not include climate as a major factor that caused trends in production. The recognition that climate was a major factor regulating salmon productivity was also alarming since most scientists believed that humans were rapidly changing the climate. An additional concern was that hatchery-reared Pacific salmon were now common throughout the distribution of Pacific salmon and it was uncertain how the ability of Pacific salmon to adapt to climate variability had been compromised by the intermixing of hatchery and wild fish. The days of blaming everything on overfishing are gone. Providing the best available scientific advice now requires maneuvering through the uncharted waters of climate change with a science that has lost some of its steerage. The solution may be something we have known for years. Fisheries management science must improve forecasts. Model forecasting on a large scale may improve greatly as we discover the planetary forces that shift climate regimes and alter the trends in ocean carrying capacity for Pacific salmon. Model forecasting on a regional scale will also improve as the linkages between climate and marine survival are discovered. Fisheries scientists need to form teams that include biologists, oceanographers, climatologists, and perhaps physicists. Science organizations that find ways to establish, recognize, and reward these teams will probably provide the best management advice.

Introduction

World fisheries developed after the Second World War as a way of feeding people, employing people, and developing national economies. At that time there was little understanding of how much fish was available around the world and an even poorer understanding of how to manage so that fisheries would be sustainable. Governments were developing their fisheries on one hand, but recognized that they had responsibilities to be stewards of aquatic resources on other hand. Banks and businesses became involved, recognizing that they also needed better infor-

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mation about the size and sustainability of the resource in order to make wise investments. Bill Ricker was one of the first fisheries scientists to develop a method of determining how much fish could be caught from a population without removing so many fish that recruitment was substantially reduced or failed (Ricker 1954). It is noteworthy that 50 years ago Ricker was concerned that the existence of climate trends would have important consequences on the productivity of Pacific salmon. Ricker found no evidence of climate or ocean trends at that time and assumed that a random model could be used to assess climate impacts on recruitment (Ricker 1958).

In this chapter we look at how the initial assumptions about climate impacts on Pacific salmon populations affected management. Hindsight shows us that strategic management could not be successful. We now find ourselves in a situation where we need to re-think how we model the mechanisms that drive our assessment models, recognizing that at the same time humans are changing climate through our emissions of greenhouse gases. An advantage is that we are now on the right road as we accept that the effects of climate and oceans on recruitment must be modeled along with the effects of fishing. We also now know that the climate-related impacts on production occur in trends or cycles. The nature and modes of variability of the cycles or fluctuations vary. Very long-term changes (glacial scale and longer) are only of passing interest in fisheries management. It is relatively shorter trends that are most relevant. One of the first cycles to be recognized was the Russell cycle that identified a 60-year fluctuation in plankton and fish abundance in the English Channel that was related to warming and cooling (Russell et al. 1971). Minobe (1999) also identified cycles of this length in the climate and ocean in the northern North Pacific Ocean. There are the approximately 30-year fluctuations in Pacific sardine populations (Kawasaki and Omori 1986; Beamish et al. 1999). Oscillations are observed in the scale depositions off the Pacific coast of North America (Souter and Isaacs 1974) or in the stable isotope concentrations in the sediments of lakes that produce sockeye salmon *Oncorhynchus nerka* (Finney et al. 2002). There are also the shorter term, three to five-year variations related to El Nino/Southern Oscillation (ENSO), but it is the decadal-scale changes (Mantua et al. 1997) that we suggest are the scales of variability most relevant to the major stocks of Pacific salmon throughout their range as well as the day-to-day lives of these stocks.

Natural trends in physical variability that are linked to biological variability indicate a linkage between fisheries management and physics. Einstein[1] wrote that God does not play dice with the universe. If there is order in the climate and ocean processes that affect the dynamics of fish populations, then the discovery of this order may simplify fisheries management and improve forecasting models. We suggest that trends in the seasonal length of day (LOD) may be an index of this order on a basin scale as well as a method of identifying regime shifts. We propose that discovery of the linkage between physics (astronomy) and Pacific salmon production will make forecast models more reliable on a basin scale and therefore make management more credible. More reliable forecasts can be defined as getting production trends right, identifying changes in trends earlier, and improving the understanding of the complex interactions of the mechanisms that regulate production. We agree with Mantua and Francis (2004) that future management needs to move away from expecting that accurate forecasts of production at the stock level are possible, particularly as the expected impacts from a changing global climate begin to occur. However, better management is not just getting the numbers right. Better manage-

[1]Albert Einstein in a letter to Max Born, 1926 wrote, "at any rate, I am convinced that He [God] does not play dice."

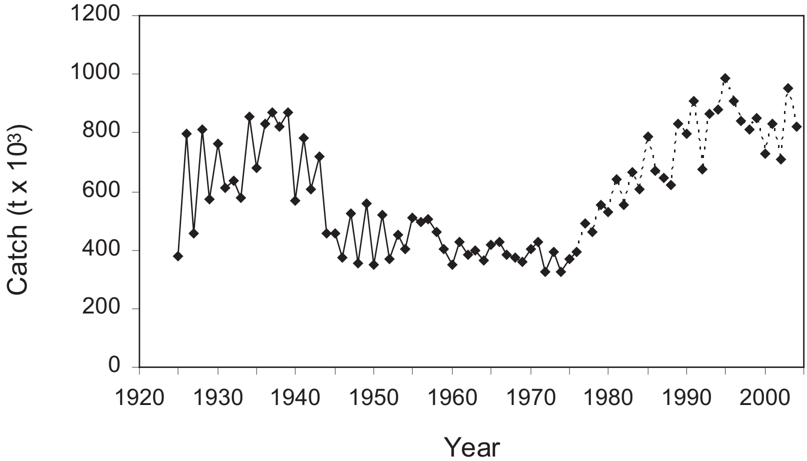

FIGURE 1. Total commercial catch (t) of Pacific salmon by all countries from 1925 to 2004. The dotted line shows the increase in catch from 1977 as a consequence of the increase in the ocean production of salmon after the 1977 regime shift.

ment is also a social issue that strengthens the relationship among scientists, managers and clients. It is the better understanding of the linkages between the life history strategies of the species we fish and the processes that shape those strategies that contributes to better decision making and to better relationships with the public. Mantua and Francis (2004) argue that it would be wise to move away from trying to produce more accurate forecasts of Pacific salmon production. We agree that the desired accuracy of the past may not be possible, but we suggest that it is possible to use regional indices of climate and their impacts to improve management, even at regional scales.

Uphill Getting There

In the early 1970s the total catch of all species of Pacific salmon by all countries had been declining very slightly for about 20 years (Figure 1). Salmon biologists around the rim of the North Pacific did not then have accurate total catches; however, national catch records showed similar trends. In Canada there was no indication of increases in catch despite the new approaches to management resulting from the now historic paper of Ricker (1954) that showed how fishing could be regulated to rebuild stocks and optimize recruitment. This inability to rebuild stocks to anticipated higher abundances prompted Ricker to publish another famous paper in 1973 that identified two mechanisms that made it impossible to maintain peak-period yields from stocks of Pacific salmon. Ricker (1973) considered that a puzzling problem of Pacific salmon ecology was that major runs of Pacific salmon rather consistently failed to produce levels close to what was generally expected of them based on their past history. It is important to recognize that the prevailing view among fisheries scientists was that ocean and climate impacts on recruitment were not responsible for the persistent declines in abundance. Furthermore, it was believed that carrying capacity for Pacific salmon in the ocean was not being fully utilized because of the mechanisms proposed by Ricker (1973) and because of damage to the freshwater rearing areas. This interpretation led to the establishment of the Salmon Enhancement Program in 1977 (Fisheries and Environment Canada 1978). The argument that convinced government officials to support the program was that the ocean capacity to produce Pacific salmon was underutilized because of a shortage of juvenile salmon. It was explained that the technology existed to rear Pacific salmon artificially in hatcheries or in specially designed channels and officials were reassured that no new science was needed. Artificial rearing would increase the egg-to-fry or egg-to-smolt survival, resulting in dramatically improved production of juvenile Pacific salmon in freshwater. When the resulting juveniles entered the ocean they would be able to survive and grow as a consequence of the underutilized ocean carrying capacity. Because the impact of ocean and climate was proposed to be random, it was possible to use average estimates of marine survival to calculate how many fish of what species needed to be reared to achieve a level of production that could begin to "repay" the costs of the program through taxes on the expected returns to the fishery (Figure 2). One estimate of the total additional production was 27.1 million fish after 25 years (Figure 2) and a total catch of about 50 million fish. It is now 25 years later and the total catch estimates for Canada in 2004 were 7.7 million fish, or about 15% of the forecasted production. The reduced catch in recent years is a result of management reducing fishing opportunities as well as reduced abundance, but it is clear that there are not 50 million salmon returning to Canadian rivers. The point we are making is that there was a natural trend in abundance that is related to ocean carrying capacity and is independent of the enhancement activities. This natural trend was evident in record high catches in the mid 1980s (Figure 3), only eight years after the Salmon Enhancement Program was started. These record catches resulted from a change in the climate and ocean habitat of Pacific salmon that produced a natural increase in marine survival after the 1977 regime shift (Beamish and Bouillon 1993).

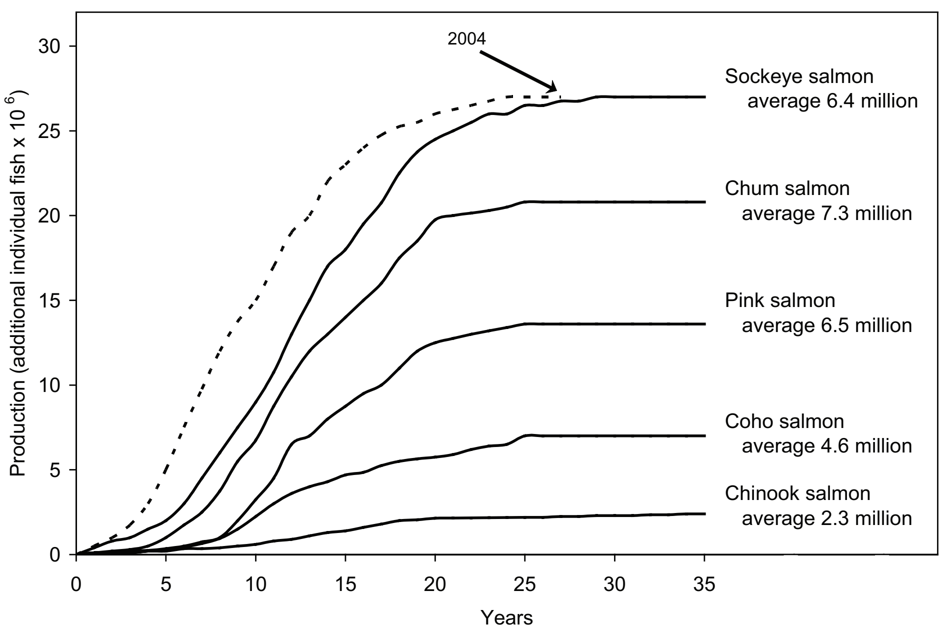

Figure 2. The proposed cumulative production of Pacific salmon in British Colombia over a 35-year period that would result from a hatchery and enhancement program started in 1977. The dashed line represents the proposed total production of all species.

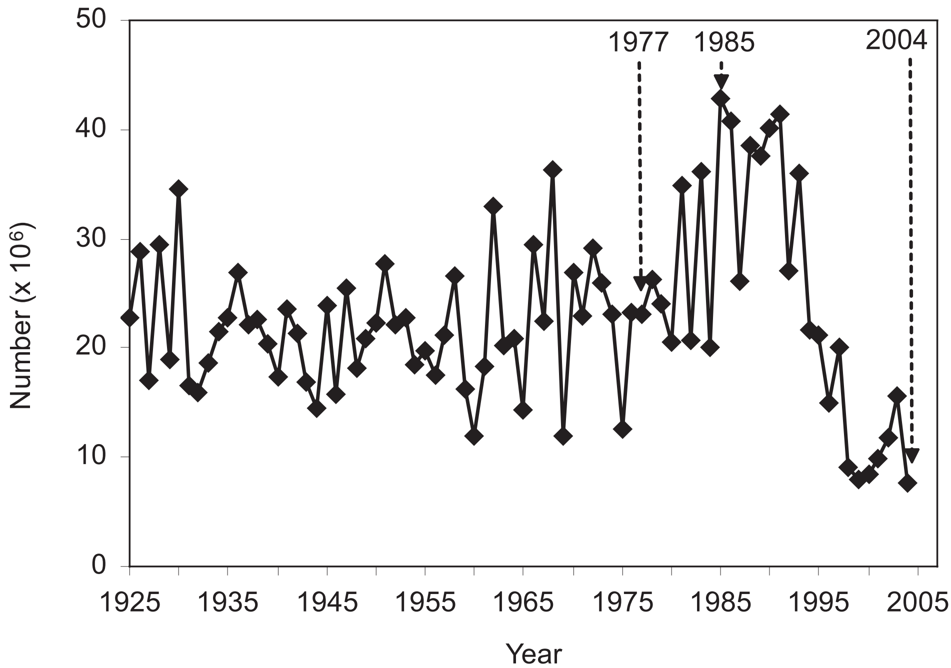

FIGURE 3. Total commercial catch of Pacific salmon in British Columbia from 1924 to 2004. Following the 1977 regime shift, there was an increase in catch with the highest catch occurring in 1985. Then catches declined and the 2004 catch of Pacific salmon is the lowest on record.

The belief that climate and ocean carrying capacity were not the principal factors regulating Pacific salmon production persisted through to the early 1990s as evidenced by the consensus reached in the final report of the Coho Steering Committee (Fisheries and Oceans Canada 1992) on how to restore coho salmon abundance. Disturbing decreases in coho survival occurred in a number of areas in the late 1980s and early 1990s. The resulting declines in abundance occurred despite the attempts of hatcheries to rebuild and restore abundances. A two-year study published in 1992 (Fisheries and Oceans Canada 1992) determined that the declines resulted primarily from overfishing and freshwater habitat loss, although it was acknowledged that in the longer term, "studies of the carrying capacity of estuarine and marine survival and growth in the Strait of Georgia should be conducted to evaluate whether the marine carrying capacity is being taxed." Participants in the study concluded that, because the catch of enhanced coho (not wild coho) salmon had risen rapidly as a result of the hatchery program, it was tempting to simply produce more coho salmon in hatcheries and solve the problem. The authors of the coho report wrote that, "it can be argued that coho stocks could be rebuilt simply by expanding this enhancement effort several fold." The authors also cautioned that this approach would be expensive and there was accumulating evidence of detrimental effects of hatchery-reared coho on wild stocks. The major recommendation of the Coho Steering Committee was to reduce the exploitation rate from 75 to 80% down to 65–70%. The benefits of a 10% reduction in fishing and an expanded vigilance in protecting freshwater habitat was identified as 300,000–800,000 more coho salmon being available to fisheries in six to

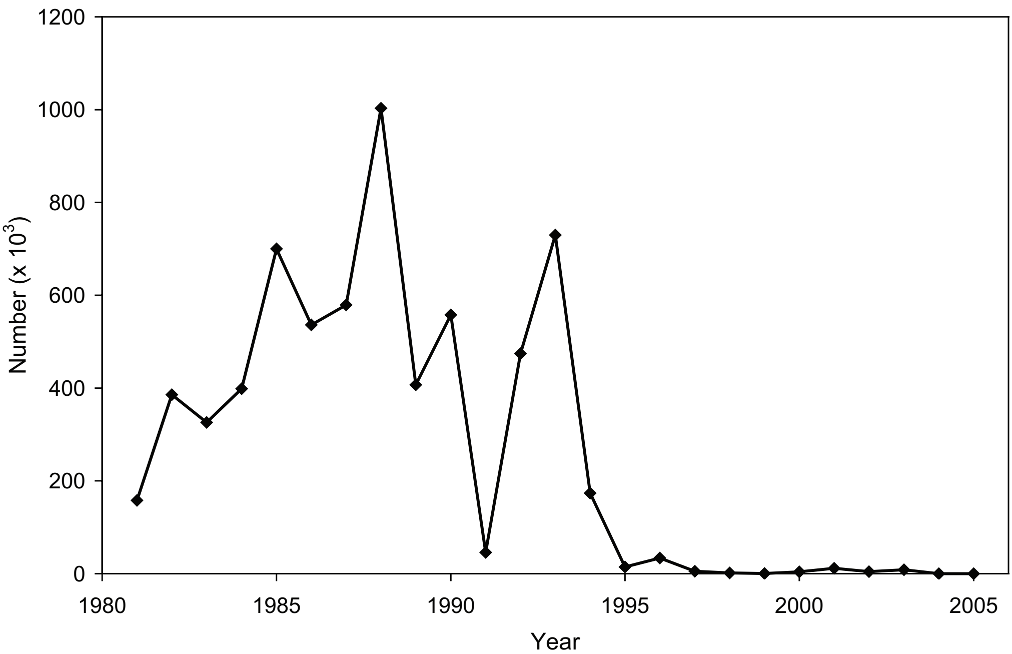

FIGURE 4. The recreational catch of coho salmon in the Strait of Georgia from 1980 to 2005 (Source: DFO Pacific Regional Data Unit 2005).

twelve years. In fact, in six years there were about 600,000 fewer coho salmon in the catch (Figure 4). The reduced catch was a result of reduced abundance and a managed reduction in catch. Fisheries for coho salmon collapsed a few years later.

The inability to manipulate stocks to desired or calculated levels generally was not the result of poor management or poor science. Pacific Region government and university scientists were highly regarded within the world fisheries community. There were excellent managers in the Pacific Region and support for management was strong, as indicated by the large Salmon Enhancement Program which from 1977 to 2004 spent about 700 million Canadian dollars. The problem was that a basic assumption in management and in the science was not valid. Nonrandom climate and ocean impacts profoundly affected Pacific salmon marine survival and production trends (Beamish et al. 2004). Science had not yet recognized that the capacity to produce salmon in the ocean occurred in trends, which sometimes changed quickly. Despite well-intended efforts, we were on the wrong road and we could not get to our destination from the direction we were headed.

Uphill Coming Back

Regimes and regime shifts refer to decadal-scale climate and ocean patterns and sudden shifts in these patterns. A regime shift is an abrupt, climate-driven change in the productivity of a marine ecosystem. The magnitude of the changes is believed to be a function of the amount of energy exchanged between the atmosphere and the solid earth (Beamish et al. 1999). The impact on Pacific salmon depends on the magnitude of the shift, the life history strategy of the particular species, and the regional response of a marine ecosystem to the shift. A number of papers have been written describing and discussing the impacts on fish populations of persistent trends in physical and biological parameters that shift quickly to new states (Beamish and Bouillon 1993; Francis and Hare 1994; Mantua et al. 1997; Beamish et al. 1999; Hare and Mantua 2000; McFarlane et al. 2000; Zhang et al. 2000; Benson and Trites 2002; Clark and Hare 2002; Yasunaka and Hanawa 2002). A good summary of current thinking was recently produced by a team of international scientists. Working under the umbrella of PICES, they concluded that regimes were real and that, "based on North Pacific climate and ocean indices, there were regime shifts in 1989 and 1998" (King 2005). The report concluded that "marine resource management agencies need to develop policies with explicit decision rules and the subsequent actions to be taken as soon as there are indications that a regime shift has occurred. These decision rules need to be included in long-range policies and plans." It is the regime scale of climate variability that strongly affects the productivity of Pacific salmon throughout their range (Beamish and Bouillon 1993; Hare and Francis 1995). Other species of fish are affected but also may respond to modes of climate variability.

The importance of regimes and regime shifts in the production of Pacific salmon was recently demonstrated for pink and sockeye salmon in the Fraser River (Beamish et al. 2004). Production data for these species in the Fraser River are some of the best in the world as the stocks are managed by the Pacific Salmon Commission in cooperation with representatives from Canada and the United States (Pacific Salmon Treaty 1999). The stock and recruitment relationship for both species of salmon significantly improved when the relationships were separated into regimes (Beamish et al. 2004). For sockeye salmon, the residuals from a standard Ricker curve for stock size and subsequent recruitment from 1959 to 1998 were not random indicating that environmental factors affecting production were not random (Figure 5). Of critical importance was the observation that the slopes of the stock and recruitment relationships were significantly different between regimes (Figure 5). Thus, the trends in productivity may change quickly at the time of a regime shift. If the change is to a much lower productivity as occurred after the 1989 shift, it may be necessary to reduce exploitation rates or stocks could be quickly overfished. In such a case, the mechanism affecting a severe reduction in abundance is fishing, but the cause of the overfishing would include the natural reduction in production.

The recognition that climate-related impacts on production are important means that we are now on the right road for salmon management but incorporating this understanding into their stewardship is not easy. Fisheries scientists have to accumulate an understanding of the processes that link climate to ocean survival of salmon, as was done for freshwater production. We have to do this at the same time that the climate is changing due to elevated greenhouse gas emissions. Furthermore, it is uncertain how past relationships with climate will relate to future relationships. Thus, it is a dangerous time for Pacific salmon management and a very steep road for fisheries management science.

After receiving the PICES report on regimes (King 2005), Michael Sissenwine, the former Director of Scientific Programs and Chief Science Advisor for the U.S. Oceans and Fisheries Programs responded that, "managers want to know if future regime shifts can be predicted, or if not, are there early warning signs, and how will they recognize the next shift whenever it occurs? These are difficult and important scientific questions. They are the epitome of relevance." (Sissenwine 2004). Thus, for Pacific salmon management, we need to be able to forecast when regime shifts will occur or at least be aware that a shift has occurred.

The recognition that regimes and regime shifts are real is important because it links

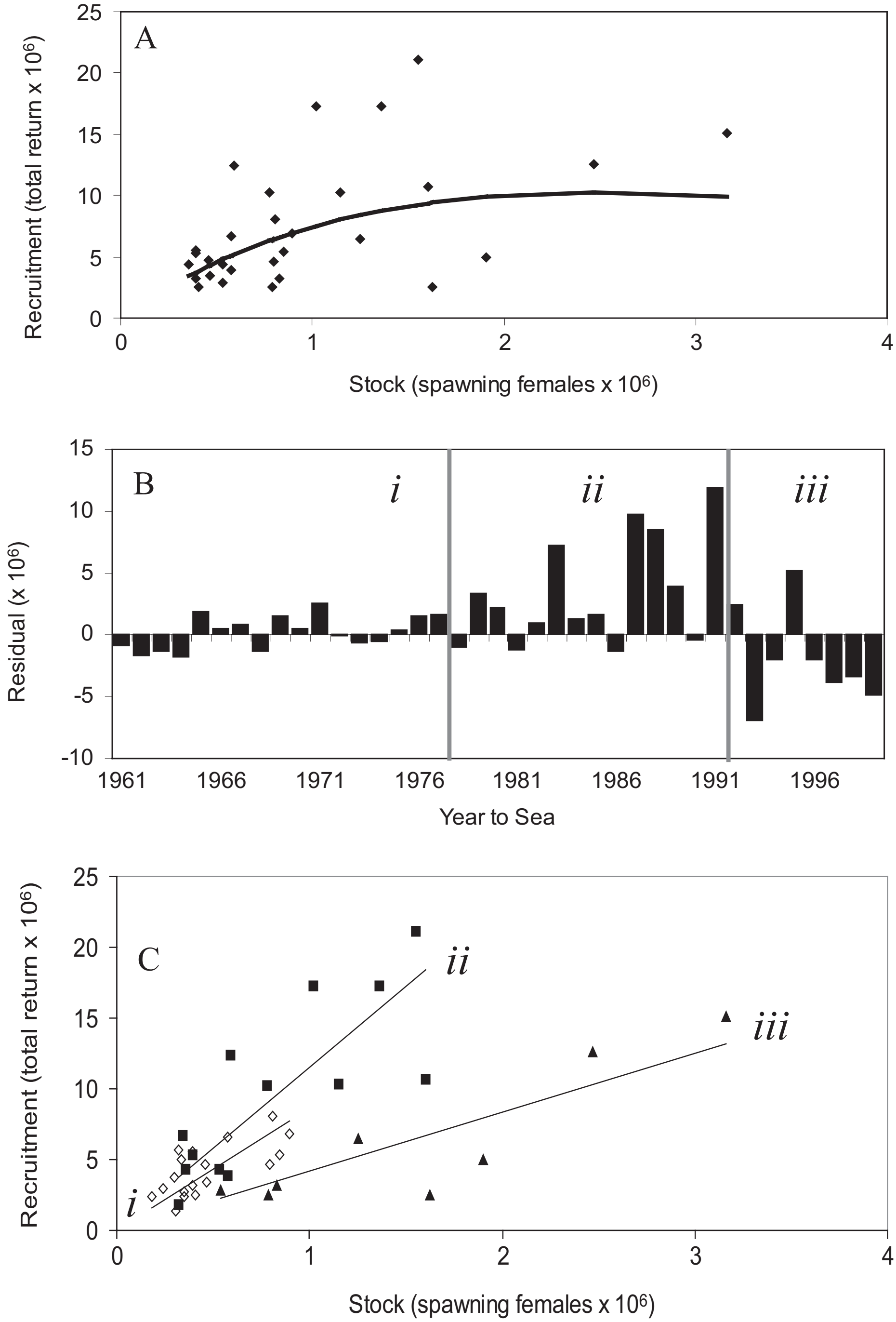

FIGURE 5. Stock (spawning females) and recruitment (total return) relationship for sockeye salmon *Oncorhynchus nerka* from the Fraser River from 1961 to 2000 year to sea. (A) Ricker curve fit to the entire time series of data. (B) Residuals from the Ricker curve. The pattern of all residuals are divided into *i*,*ii* and *iii* to represent the three regime periods as described in Beamish et al. (2004). (C) The stock and recruitment data with straight lines fit to data from each regime period. Lines *i*, *ii* and *iii* correspond to regime periods from panel B.

biology and physics. We suggest that it may be possible to detect when regimes shift and perhaps even determine the magnitude and direction of the change by monitoring planetary energy transfers. Changes in the strength of the Aleutian Low (Beamish and Bouillon 1993; Mantua et al. 1997) indicate that energy transfers are involved. Thus, planetary processes control regimes. We believe that models that incorporate the mechanisms regulating regimes will provide advance warning of regime shifts and perhaps eventually be able to identify the general structure of the newly organized ecosystems. Management improves, as Sissenwine (2004) wrote, because of the advance knowledge of a change in ocean carrying capacity for a given species.

Length of Day (LOD)

A first step in linking astronomy to biology may be the identification of an index of regime shifts that is associated with planetary energy transfers. The length of day (LOD) is an index of the earth's rotational velocity (Munk and MacDonald 1960; Lambeck 1980; Hide and Dickey 1991; http://hpiers.obspm.fr/iers/eop/eopc03). The LOD is the difference between the astronomically measured duration of the time it takes the earth to complete one rotation and the standard 24-d duration which was established as exactly 86,400 s on January 1, 1958. Changes in the LOD are expressed as the difference in milliseconds between the measured day relative to the standard day. There are seasonal and decadal-scale trends in the LOD (Hide and Dickey 1991; Figure 6). All trends in the LOD are a result of energy transfers among the four shells of the planet: atmosphere, hydrosphere, solid earth (crust and mantle) and core (Figure 6A). The four shells of the planet do not rotate at the same speed, but the total energy involved is constant (Lambeck 1980). If the total angular momentum of the atmosphere-solid earth is constant, then changes in the strength of the zonal winds as occurs in the Northern Hemisphere winter result in an equal but opposite change in the angular momentum of the solid earth. This change is indexed by the LOD. Seasonal changes including changes of a few days to a few years in the LOD are closely linked with changes in the upper atmospheric winds (Hide et al. 1980; Rosen and Salstein 1985, 1991; Dickey et al. 1993; Rosen 1993; Pais and Hulot 2000). Thus the LOD can be used as an index of atmospheric processes. The index is of large scale change. Regional changes that are known to be important to Pacific salmon dynamics (Hare et al. 1999) would involve additional regional indices such as surface temperatures at the time of the spring plankton blooms. Decadal-scale changes representing annual trends are believed to occur as a consequence of energy transfers between the core and the solid earth (Hide and Dickey 1991). Decadal-scale changes in LOD (Figure 6B) are generally considered to reflect energy changes between the core and mantle (Hide et al. 1980; Lambeck 1980). Beamish et al. (1999) used the decadal-scale LOD to report that periods of decreasing and increasing LOD could be related to periods of strong and weak sardine (*Sardinops* spp.) production, possibly indicating an LOD relationship with the structure of large marine ecosystems. However, it is the pattern of the seasonal LOD that we suggest may be an index of regimes and regime shifts (Figure 6C). It is the upper atmospheric winds and not ocean forcing that causes seasonal changes in the LOD (Gross et al. 2004). The strength of the Aleutian Low, or the energy associated with the Aleutian Low, is represented by the Aleutian Low Pressure Index (Beamish et al. 1997a), the North Pacific Index (Trenberth and Hurrell 1995) and the Pacific Interdecadal Oscillation (PDO; Mantua et al. 1997). In the subarctic Pacific,

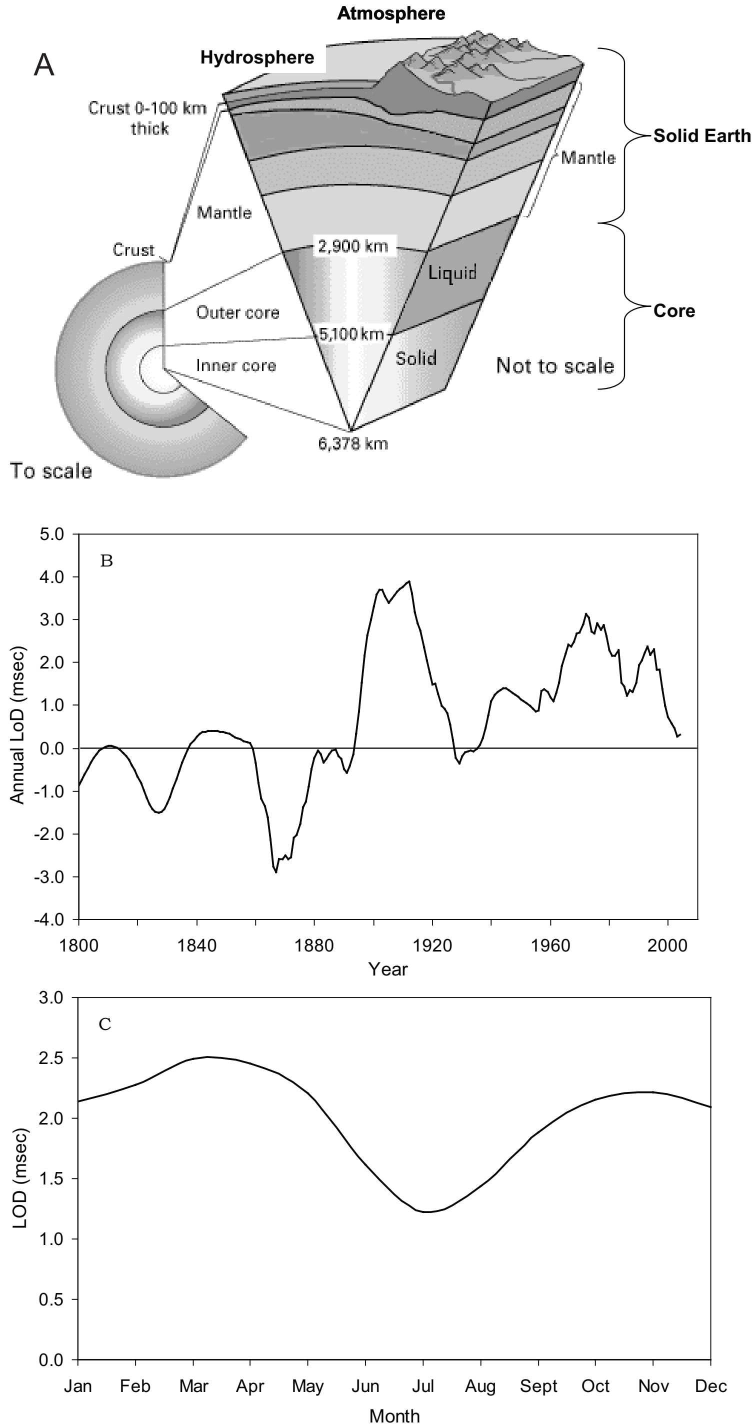

FIGURE 6. (A) Cutaway earth, showing 4 layers: atmosphere, hydrosphere, solid earth and core. (B) Annual trends in Length of Day (LOD) anomaly on a decadal scale from 1800 to 2004. (C) An example of the seasonal trend in LOD anomaly showing an increase in rotation rate in summer months in the northern hemisphere (Source: Hide and Dickey 1991).

it is the strength of the Aleutian Low that affects winter storminess which in turn affects Pacific salmon production (Beamish and Bouillon 1993; Francis and Hare 1994; Hare and Francis 1995). The seasonal LOD slows down in the northern hemisphere in the winter and speeds up in the summer, as a consequence of the stronger zonal winds, stormier climate in winter and the mountain torques resulting from larger land mass in the northern hemisphere (Figure 6C). There are regime-like trends in the seasonal LOD. Daily estimates of LOD since 1993 are available on the IERS website (http://hpiers.obspm.fr/iers/eop/eopc03). The 1998 regime shift was characterized in the seasonal LOD as a change in pattern about May 1998 to a new pattern of faster rotation (Figure 7A). The 1989 regime shift is not as distinct in the seasonal LOD record but it is also possible to show that the 1989 shift was represented by a slowing down in October/November to a general pattern of longer LOD (Figure 7B). The linkage between the slowing down of the solid earth, or a longer LOD, and trends in Pacific salmon production is through the winds. The patterns of atmospheric circulation also change on decadal scales (Beamish et al. 1999; King et al. 2006; Klayshtorin 1998) with an index of the dominant directions related to large scale Pacific salmon production. Recent regime shifts occurred in 1977, 1989 and 1998, or at 12- and 9- year intervals. This may indicate that the next shift would occur after about ten years or about 2009, perhaps in the fall. This speculation is based only on the length of recent regimes. If the next regime shift is associated with a change to a new pattern in seasonal LOD, as observed in 1998 (Figure 7A), then it would support the hypothesis that shifts in the trends of the seasonal LOD are related to regime shifts.

Time will tell if the seasonal LOD is a useful index of the exact timing of regime shifts. Regardless, because planetary energy transfers are involved in regime shifts, it may be more promising to search for indices of regime shifts in the physics of the process rather than the oceanography or biology of the result.

Climate Change

Climate change is another uphill challenge for fisheries science. Most scientists are confident that global warming will affect the production of Pacific salmon. Climate change is a serious issue for fisheries management science because past climate impacts may not be representative of future climate impacts, particularly if the impacts are nonlinear. We also do not know how global warming will alter the atmospheric circulation in the subarctic Pacific. One scenario proposes that warming in the North Pacific would decrease the temperature difference between the tropical Pacific and the subarctic Pacific resulting in decreased winter storm intensity and a northward shift in the average line of wind stress curl which separates the subarctic and subtropical Pacific. If this occurred, there would be weaker Aleutian Lows, less mid-ocean upwelling, increased stratification and a warmer, shallower mixed layer, typical of the negative-phased PDO (Mantua et al. 1997). According to this scenario, past relationships between salmon production and PDO (Hare and Mantua 2000) would indicate that total salmon production would be reduced. Another scenario is virtually the opposite. Using the models of Mote et al. (1999), Beamish and Noakes (2002) proposed that more intense Aleutian Lows in a global warming scenario could increase the productivity of Pacific salmon for more northern stocks. This becomes even more critical when one considers that the average changes induced by global warming scenarios are projected to be significantly greater in the high latitude regions.

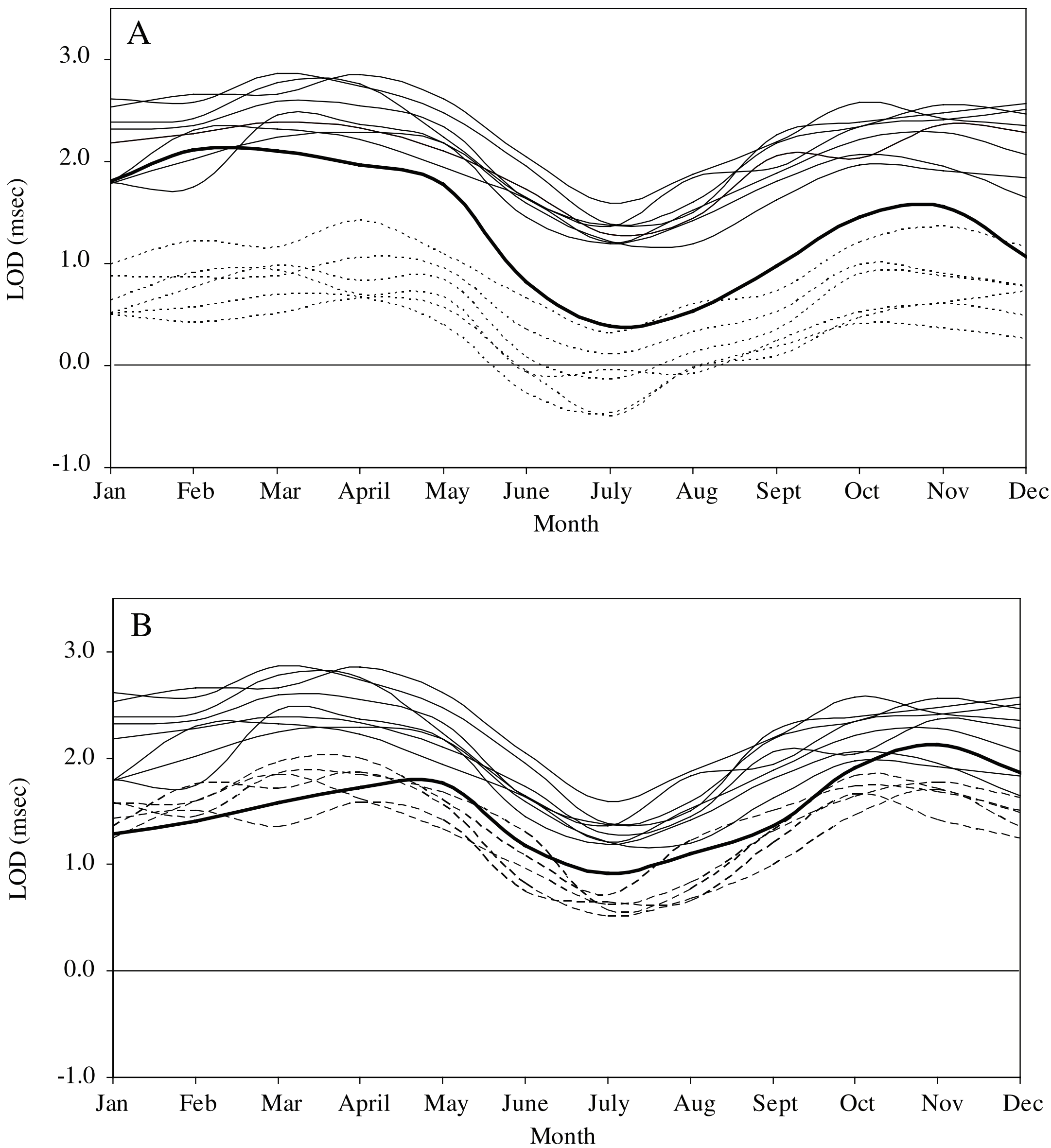

FIGURE 7. Seasonal patterns in the LOD. As described in the text, the LOD is an anomaly from the standard 24-day rotation, relative to the agreed-to point established on January 1, 1958. (A) The heavy solid line is the pattern observed in 1998 showing a shift to a new pattern in May. The thin solid lines represent the LOD values for 1990 to 1997. The short dashed lines represent the values for 1999 to 2004. (B) The heavy solid line is the pattern observed in 1989 showing a shift to a new pattern in October–November. The long dashed lines represent the LOD values for 1983 to 1988. The thin solid lines are the LOD values for 1990 to 1997.

It is very likely that carbon dioxide levels in the atmosphere will continue to increase (Figure 8) and the increase may accelerate in the future. China apparently has plans to quadruple its economy in the next 30 years (Elliott et al. 2002). This will require additional energy equivalent to about 50% of what is currently used annually in the United States. Much of this new energy will come from burning coal, with the obvious consequences, and possibly other greenhouse gases. An equally disturbing possibility is the thawing of the permafrost in northern latitudes. Peat lands in the subarctic region are relatively stable in part because of the underlying permafrost. Peat lands contain huge quantities of carbon that could be released if the permafrost disappears (Environment Canada 2004). These are only two examples of major, potential, new sources of carbon dioxide that, in addition to the current increasing trend, indicate that it is most probable the atmospheric levels of carbon dioxide will continue to increase.

The Problem of Hatchery and Wild Pacific Salmon

A significant percentage of Pacific salmon in the ocean now originate from hatcheries. One major problem is that it is not known if the large abundances of hatchery salmon have compromised the ability of wild salmon to adapt to the potential effects of climate change. Beamish et al. (1999) estimated that from 1974 to 1992 the percentage of hatchery-produced chum salmon *O. keta* in the total Pacific catch went from 39% to 84%; and that of hatchery-produced pink salmon *O. gorbuscha* went from 10% to 23%. In some coastal areas off the west coast of North America, the percentage of coho *O. kisutch* and chinook salmon *O. tshawytscha* from hatcheries exceeds 70% (Sweeting et al. 2003; Northwest Fisheries Science Center 2003; Brannon et al. 2004). Although the debate about damage to wild salmon by hatchery salmon continues (Hilborn and Eggers 2001; Wertheimer et al.

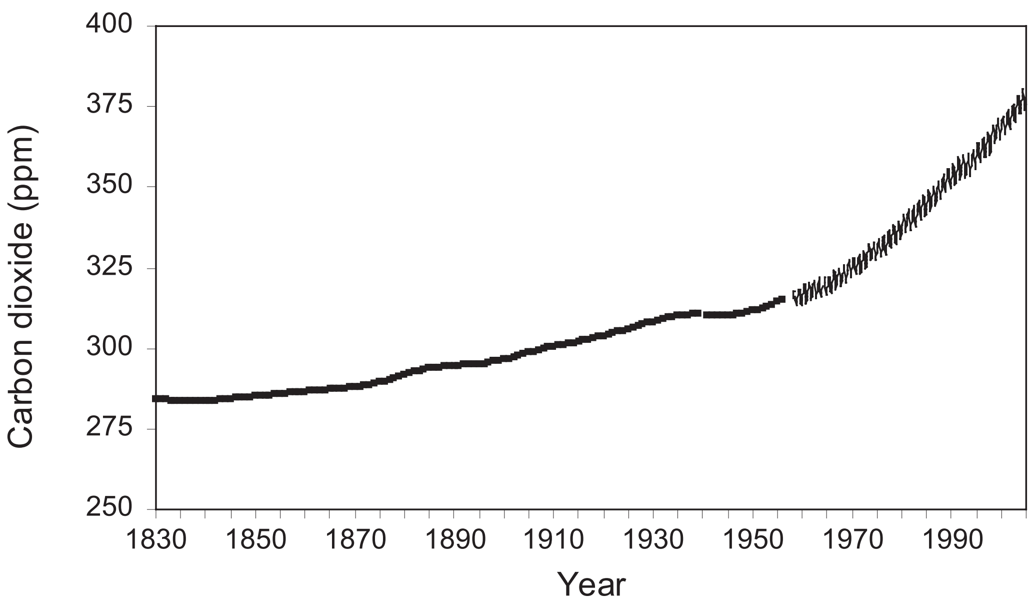

FIGURE 8. Increase in atmospheric carbon dioxide levels from 1832 to 2004. Data from 1832 to 1958 are historical CO_2 data measured from Law Dome, East Antarctica ice cores and has been smoothed using 20-year running averages (Source: Etheridge et al. 1998). Monthly data from 1958 to 2004 are from Mauna Loa (Source: Keeling 2004).

2001a, 2001b) there is evidence of replacement (Lichatowich 1999; Hilborn and Eggers 2000) and concern about the genetic effects when hatchery and wild fish breed (Utter 2004; Goodman 2005).

We define a wild salmon as a fish from a spawning population that has not experienced reproduction with hatchery fish more frequently than the natural straying rate. According to this definition, stray hatchery fish that spawn naturally may be affecting wild salmon. The impacts on wild stocks may not be evident, or critical, in periods of higher ocean carrying capacity for Pacific salmon. However, if wild stocks are being replaced, what will happen when there is the inevitable shift to reduced ocean carrying capacity for salmon? Pacific salmon have evolved to survive periods of unfavorable habitat conditions in fresh water and in the ocean, and to expand in favorable habitat conditions. It is a fundamental precept of ecology that above some minimum population size, abundance is not regulated by the number of eggs or young, but by the available habitat. For Pacific salmon, the critical habitat is both in fresh water and the ocean. For example, we know that on the Pacific coast of Canada, there have been important changes in climate since the glacial period about 14,000 years ago that would affect the reproduction of Pacific salmon in fresh water. There was a transition from a glacial to an interglacial climate between 12,500 and 9,000 years BP (Walker and Pellatt 2003). Summer temperatures were about 3°C warmer between 9,000 and 7,000 years BP. Summer temperatures declined from 7,000–3,000 years BP with more precipitation and a stronger Aleutian Low. Pacific salmon adapted to these changes by evolving stocks with different life histories. Thus, Pacific salmon of all species have produced thousands of stocks throughout their range that differ slightly in their biology and life history strategy giving the species resiliency in a naturally changing environment (Hilborn et al. 2003). The rapid climate change we have observed in the past century may overwhelm this biological/evolutionary adaptability. Biologists are also concerned that a replacement of wild salmon by hatchery salmon or a loss of genetic diversity through interbreeding with hatchery fish could affect the evolved ability of a species to survive future periods of unfavourable habitats in fresh water and in the ocean. The concern is legitimate as there has been little research to assess the long-term consequences of the massive hatchery programs. It should be recognized that in the extreme, a management approach could be to disregard wild fish and use the ocean as a pasture for hatchery fish, as has occurred in Japan and as we now do for many land animals. In such a scenario, there would have to be continued selection for fish that produced the best returns in the changing ocean habitats. Beamish et al. (1997b) wrote, "The massive production of artificially reared Pacific salmon and the potential for large-scale changes in climate—ocean environment constitute a basin scale experiment with the Pacific salmon ecosystem." The hatchery program may be a legacy of the earlier belief that the ocean was limitless in its capacity to produce salmon as long as the fishing rates were high. However, the program is very successful in some areas such as Japan where about 2 billion chum fry are released each year (North Pacific Anadromous Fish Commission 2004) and there are virtually no wild chum stocks. Thus, all Pacific salmon in the ocean of a particular species may not be affected by climate and climate change in the same way.

Conclusion

Pacific salmon have not behaved as expected based on early stock and recruitment theory. The major reason for the difficulty in understanding the factors regulating production was a poor understanding of the importance of climate impacts. We now know that climate is important and that it is the regime scale of variability that appears to most affect

Pacific salmon production throughout their range. This new understanding of physical and biological processes that regulate recruitment can provide fisheries managers with new information that can be modeled to link climate and physical processes to recruitment, abundance and distribution. However, much work remains in fisheries management science before the new models are reliable.

Scientists need to determine how climate affects the productivity of a species including the populations and stocks of the species. Understanding the mechanisms ensures that climate changes can be directly linked to production. Because climate impacts occur in trends or regimes, it is important to work out the physics of regimes and regime shifts. The discovery of the mechanism that shifts regimes will improve the ability of models to identify when trends in salmon abundance may change. Including climate in regional forecast models will also improve management (Weitkamp and Neely 2002). The massive hatchery programs that have developed in the last 50 years have produced fish that possibly are not as resilient to climate changes as wild fish. Long-term research needs to determine if this concern is real and, if it is real, hatchery fish and wild fish will need to be distinguished in models that assess interventions into their population dynamics.

The recognition that climate and climate change must be considered in the management of salmon stocks adds complexity to the structure of a science organization charged with supplying the best information to managers and stakeholders. Both freshwater and ocean habitats of Pacific salmon must be a component of any future modeling exercise. Biologists, oceanographers, climatologists, and physicists need to work together. The best models probably will come from teams of scientists. The best science organizations that find ways to establish, recognize and reward these teams will become recognized for the consistently high quality of their advice.

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