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The History of Surprises Associated with Pacific Salmon Returns Signals that Critical Information is Missing from Our Understaning of their Population Dynamics

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Abstract.—Every year biologists around the rim of the subarctic Pacific eagerly wait to compare salmon abundances to expectations. After decades of surprises, it would seem logical to conclude that critical information is missing from the calculations of expected returns. Recent studies on the dynamics of coho salmon *Oncorhynchus kisutch* in the Strait of Georgia showed that growth in the early marine period strongly affects marine survival. In other studies, DNA stock identification methods are now being used to identify the feeding areas of various species and stocks of Pacific salmon throughout the subarctic Pacific. Thus, it is possible to relate regional ocean and climate conditions to marine survival. Complete life cycle studies that include information from freshwater, on ocean entry timing, early marine growth and ocean conditions in the locations that salmon populations feed or spend their winter are now technically possible. There is an international spirit of cooperation that, if properly funded, would support the focus of scientists to provide the missing information needed to produce reliable forecasts of adult Pacific salmon abundances.

Introduction

Years ago, Peter Larkin was asked if he would give an after-dinner speech at a conference the authors were organizing. He replied that he did not give talks anymore. The authors insisted that there would be a lot of young Turks in the audience who should hear what an old guy like him had to say about Pacific salmon. He agreed to give the talk and his opening line was that, as an old Turk he had some strong advice for the young guys in the audience.

This story needed to be told because the advice was to expect the unexpected and to think differently. Bill Ricker was another visionary who also advised to expect the unexpected. In the 1960s, Bill Ricker puzzled over the inability of management to restore or rebuild Pacific salmon abundances in British Columbia. In 1973, he published a paper, "Two mechanisms that make it impossible to maintain peak-period yields from stocks of Pacific salmon and other fishes" (Ricker 1973). In that paper he wrote, "a puzzling problem of Pacific salmon ecology is why the runs of major river systems, when brought under the best available management, rather consistently fail to produce levels close to what has generally been expected of them on the basis of their past history." Only 11 years later in 1985, the total Pacific salmon catch in British Columbia was the highest in history

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(Figure 1). The Canadian catch in 2008 was around 10,000 t, less than one sixth of the historic average and only 1% of the total Pacific salmon catch by all countries (Figure 2). No one would question the abilities and contributions of these two visionary scientists and a number of their colleagues. However, the unexpected effects of climate have changed our thinking about the population ecology of Pacific salmon and it is time for the young Turks to think differently.

Pacific Salmon Fisheries by All Countries

The fishery for Pacific salmon, by anyone's account, has to be considered to be remarkable. The authors think it is the world's most important fishery because of the commercial and cultural importance of the half dozen key species and because these species dominate the daytime biomass of fishes in the surface waters of the subarctic Pacific. They suspect that supporters of cod, herring, hake, sardines and anchovies might have other rankings of importance. However, in addition to the cultural and commercial importance, Pacific salmon are fairly well managed. Start with the record of the North Pacific Anadromous Fish Commission (NPAFC), remembering that it originated as the International North Pacific Fisheries Commission (INPFC) in 1952. NPAFC now has five member countries: Canada, Japan, Korea, Russia and the United States and all have agreed not to fish Pacific salmon on the high seas. Coordinated enforcement within the NPAFC has virtually eliminated the high seas fishing of Pacific salmon as any vessel trying to fish illegally most likely will get caught.

Look at the total Pacific salmon catch in the past 20 years (Figure 2). The highest total catch occurred in 2007, the second highest in 1995, and third highest in 2005. In fact, the catch of Pacific salmon has been at historic high levels for the past 15 years.

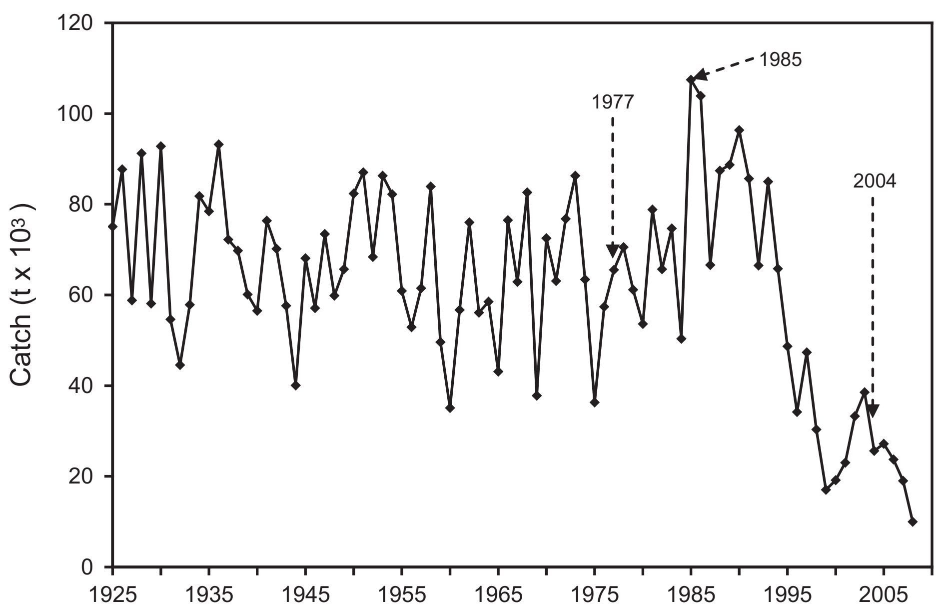

FIGURE 1. Total catch of Pacific salmon in British Columbia from 1925–2008 (data from the North Pacific Anadromous Fish Commission statistical yearbook 2002, see http://www.npafc.org/new/publications/Statistical%20Yearbook/index.htm).

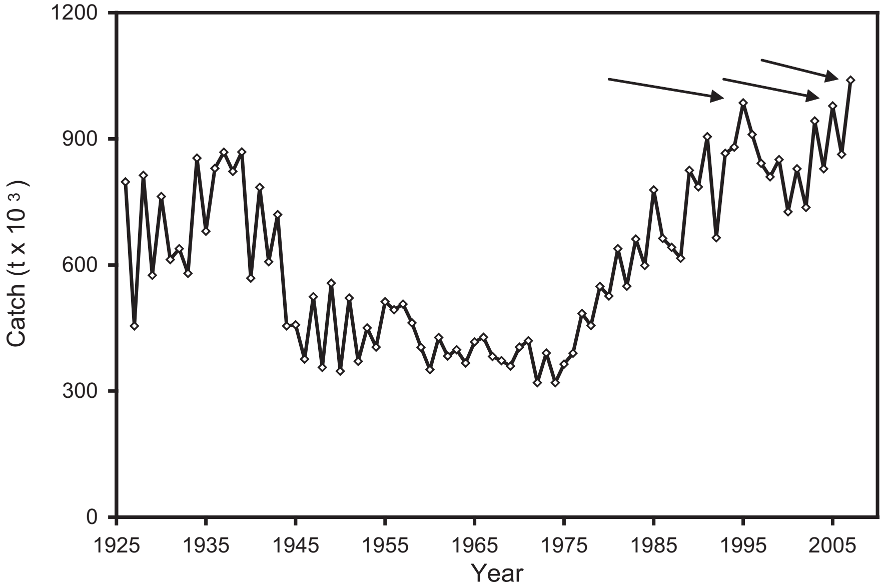

FIGURE 2. Total catch of Pacific salmon by all countries from 1925–2005, arrows indicate the largest catches (data from the North Pacific Anadromous Fish Commission statistical yearbook 2002, see http://www.npafc.org/new/publications/Statistical%20Yearbook/index.htm).

There is variability, as expected, but there is no disputing the trend. It is fair to conclude that Pacific salmon are well managed internationally and currently are at historic high levels of abundance. However, it is equally fair to conclude that we do not understand why the abundances are so large or what to expect over the next 50 years as global warming impacts the ecology of Pacific salmon life cycles in fresh water and in the ocean.

The general public are puzzled that scientists are unable to explain why Pacific salmon in general are doing so well and why it is so difficult to forecast returns. Biologists studying Pacific salmon, however, have learned to expect the unexpected. There are some who believe that it is not possible to forecast Pacific salmon returns reliably. The authors do not share this belief because scientists now have the technology and the international cooperation to understand how recruitment of Pacific salmon is regulated in the ocean. Accurate forecasting requires studies of the whole life cycle of salmon. If our modern salmon science dates from Dr. Ricker's paper on stock and recruitment in 1954, then it would appear that continuing to do the same things scientists did in the past 50 years probably will get us more or less where we are now in 2059.

Most scientists agree that the current high catches of Pacific salmon are a result of favorable ocean and climate conditions. Combining information on Pacific salmon production in freshwater or from hatcheries with an understanding of how ocean conditions regulate the marine survival will explain how recruitment is determined. The understanding of these processes will provide regional fisheries managers with new models that will more accurately link climate and physical processes to recruitment, abundance and distribution. There is a great need to act now because Pacific salmon are generally abundant and the next 50 years is a dangerous period for the management of Pacific salmon because of climate change.

The importance of carrying out "whole life cycle studies" of Pacific salmon can be shown from the history of managing coho salmon *Oncorhynchus kisutch* in the Strait of Georgia. The coho salmon story in the Strait of Georgia could start in the 1950s when reliable data became available, but 1977 is a good beginning as it was the official start of the Salmon Enhancement Program (Fisheries and Environment Canada 1978). Scientists studying Pacific salmon in the early 1970s believed that there was *a lot of headroom for the expansion of salmon populations before the rearing areas of the ocean became a limiting factor*. The Salmonid Enhancement Program was based on the assumption that there was unused rearing capacity in the ocean. All major species of Pacific salmon were enhanced in this program with the objective of doubling the annual catch of Canada's Pacific salmon, from about 25 million fish in the early 1970s to 50 million fish per year by 2003 (60,000 t to 120,000 t). It was believed that the biological potential to increase the production of coho salmon still remained in fresh water and salt water, but losses through environmental damage and overfishing had greatly reduced production. Artificial rearing of coho salmon in hatcheries would increase the egg to fry or egg to smolt survival, resulting in large increases in the number of juvenile coho salmon entering the ocean. Climate and ocean conditions were recognized to affect marine survival, but the effects were believed to be random. Although it was not explicitly written, the assumption was that average marine survival would not change greatly as the ocean had the capacity to produce greater abundances of coho salmon.

Coho salmon in the Strait of Georgia traditionally supported an important commercial and sport fishery (Figure 3). However, beginning about the late 1980s, there were declines in the escapements of wild coho salmon as well as declines in the marine survival of coho salmon produced in hatcheries (DFO 1990,1992; Irvine et al. 1992). These declines in abundance occurred despite the

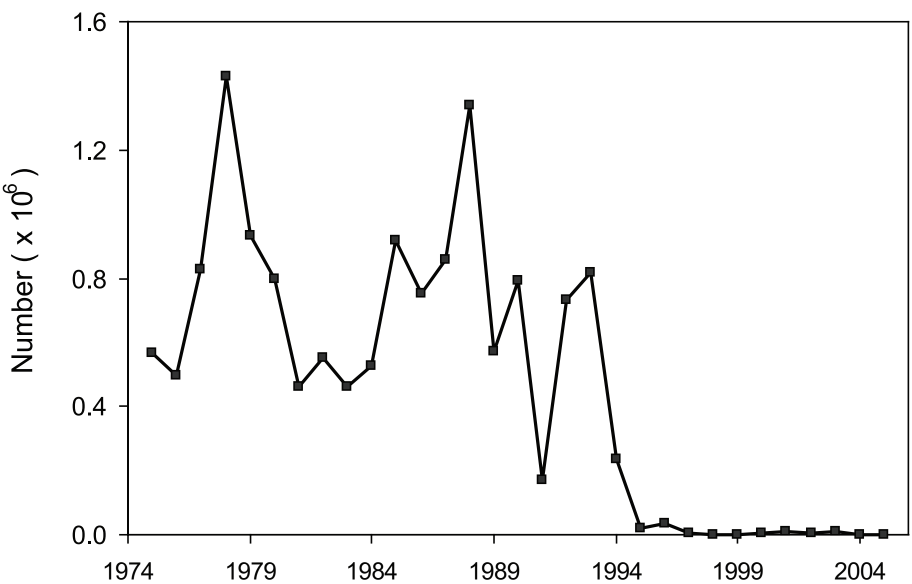

FIGURE 3. Catch of coho salmon in the commercial and sports fisheries in the Strait of Georgia from 1975–2005 (see http://www.pac.dfo-mpo.gc.ca/species/salmon/salmon_fisheries/catchstats_e.htm).

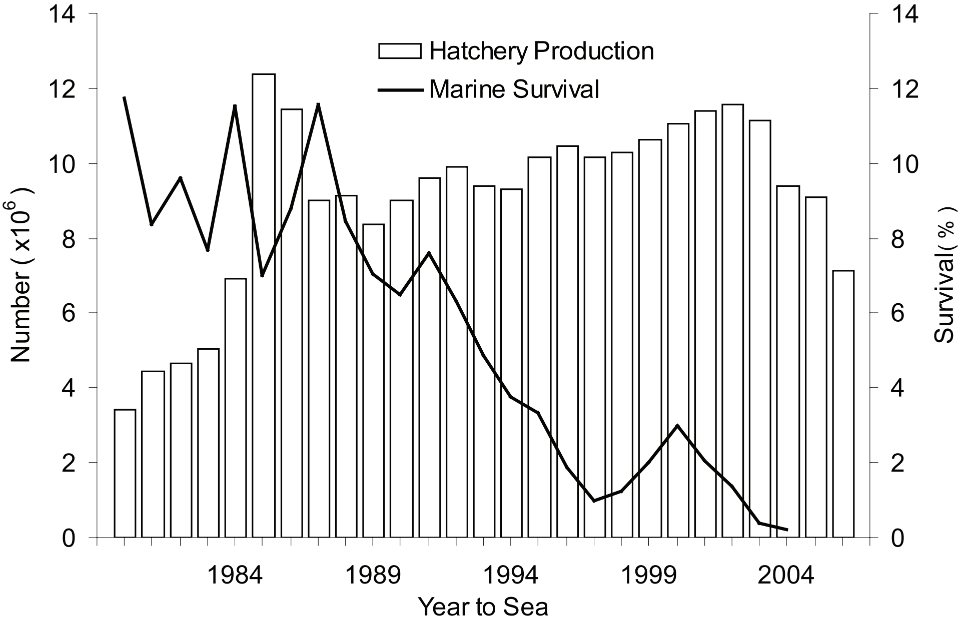

FIGURE 4. Hatchery production and marine survival of coho salmon in the Strait of Georgia from 1980–2006. Marine survival is shown as the year smolts enter the ocean. Brood year survival would be two years earlier, i.e., marine survival for 2004 is for coho salmon that spawned in 2002 and returned as adults in 2005 (Beamish et al. 2008).

attempts of hatcheries to rebuild and restore abundances (Figure 4). Overfishing and freshwater habitat loss were believed to be responsible for the decline in wild coho salmon as evidenced by the consensus reached in the final report of the Coho Steering Committee (DFO 1992) on how to restore abundances of coho salmon. This two-year study published in 1992 determined that the declines resulted primarily from overfishing and 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 salmon 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 salmon on wild stocks. The major recommendation of the Coho Steering Committee was to reduce the exploitation rate from about 75–80% to 65–70%. The benefits of a 10% reduction in fishing and an expanded vigilance in protecting freshwater habitat was calculated to produce 300,000–800,000 more coho salmon in six to twelve years. In fact, in six years (1998) the coho salmon fishery had virtually collapsed (Figure 3).

In 1997 the authors started a study of the marine phase of the life cycle of coho salmon in the Strait of Georgia (Beamish et al. 1999, 2000a; Sweeting et al. 2003). The abundances of juvenile coho salmon was determined each July, using the catches from a large trawl net and the volume of water fished (Beamish et al. 2000b). From 1998–2006, about 75% of all coho salmon released from hatcheries had their adipose fin removed. The number of these fin-clipped coho salmon in our catch were used to estimate the percentage of hatchery and wild coho in the Strait of Georgia (Figure 5A). We used this percentage and the known number of coho salmon smolts produced in hatcheries (Figure 4) to estimate the total number of wild and hatchery coho smolts that entered the Strait of Georgia (Figure 5B). We estimated the early marine survival up to about mid July by dividing the abundance estimates from the survey (Figure 5C) by the total number of smolts entering the strait (Figure 5B). This estimate of early marine survival (Figure 5D) was then compared with the final brood year marine survival (Figure 4). Brood year survival was determined using coded-wire tag recoveries from fisheries and from the coho salmon returning to the eight largest hatcheries (Beamish et al. 2008).

The variability in early marine survival up to July among years ranged from about 3% to 20%. It was observed that the average length of coho salmon in July was positively related to brood year marine survival (Figure 6). The lowest early marine survival occurred when the coho salmon in July were smaller. In years when the early marine survival was higher (1998–2001) there was still a substantial mortality that occurred later in the year, as evidenced by the corresponding brood year survival. The authors propose that this later-in-the-year mortality was related to the smaller fish not surviving the winter (Beamish et al. 2004). They also propose that the variability in marine survival is strongly related to very early marine growth. In years when coho salmon growth is very rapid, prior to the July surveys marine survival and abundance was higher. However, the brood year survival in recent years was substantially less than those observed in the late 1970s and early 1980s (Figure 4). Thus, it was concluded that the capacity for the Strait of Georgia to produce coho salmon is much reduced today compared to 30 years ago, probably because prey abundance is reduced by the time most coho salmon enter the Strait of Georgia. The authors are of the opinion that carrying capacity relates to the capacity for coho salmon to grow quickly once they enter the Strait of Georgia. The very high marine survival in the past would result from very good early marine growth. The large abundances in the past resulted from the high marine survival and not only the number of individuals that entered the ocean. The authors' study of the marine phase of the coho salmon life cycle shows that accurate forecasting of coho salmon returns requires more information than the number of spawning individuals or even the number of smolts entering the ocean.

Three examples are provided that show that technology and international cooperation exist to carry out the research to define how recruitment of Pacific salmon is regulated and to improve forecasting. Urawa (2004) and Urawa et al. (2005) used genetic stock identification to identify the seasonal migration of chum salmon *O. keta* of Japanese origin (Figure 7). The study showed that chum salmon of Japanese origin spend their second and third winter in the Gulf of Alaska. Urawa et al. (2005) speculated that chum salmon of Japanese origin carried out extensive migrations into the Gulf of Alaska in the winter because their preferred temperature range in the winter may be more widely available in the eastern North Pacific. Whatever the reason turns out to be, it is important to understand that winter conditions in the Gulf of Alaska affect the production of chum salmon produced in hatcheries in Japan. The study shows that migration models for all chum salmon stocks are possible because of the ability to identify the country of origin of chum salmon and the

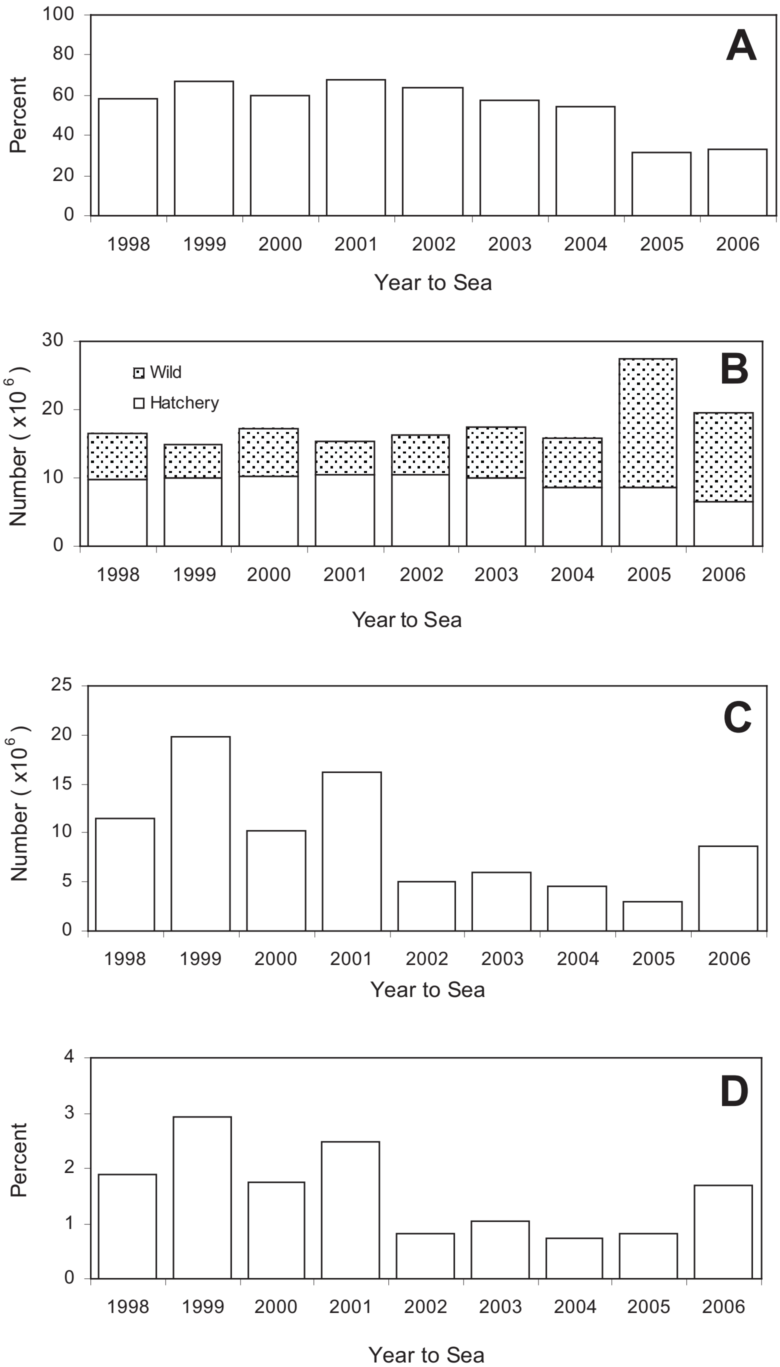

FIGURE 5. A) Percentage of hatchery fish in the coho salmon catches in the Strait of Georgia in July 1998–2006. B) Total numbers of wild and hatchery coho salmon smolts in the Strait of Georgia from 1998–2006, calculated using hatchery and wild percentages and hatchery production. C) July abundances of coho salmon for the Strait of Georgia from 1998–2006, excluding all U.S. fish. D) Early marine survival (ocean entry to mid-July) of coho salmon in the Strait of Georgia from 1998–2006 (Beamish et al. 2008).

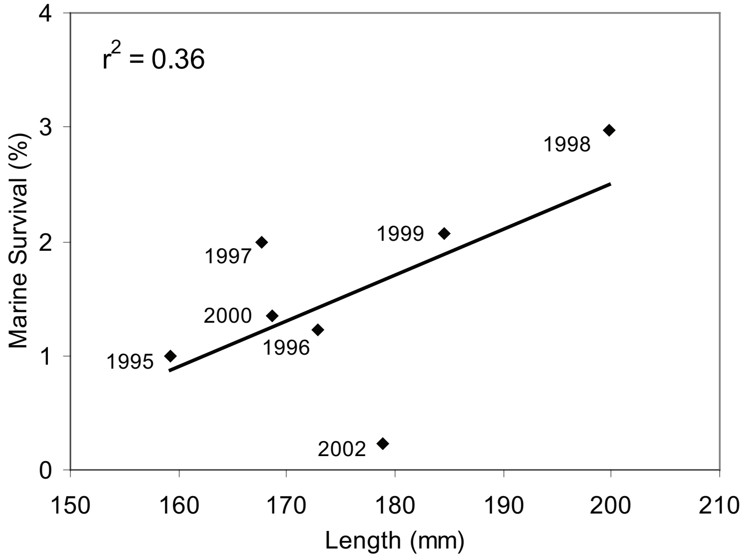

FIGURE 6. Average length of coho salmon in the July surveys compared to the marine survival for the brood year shown. The catch year is two years later than the brood year (Beamish et al. 2008).

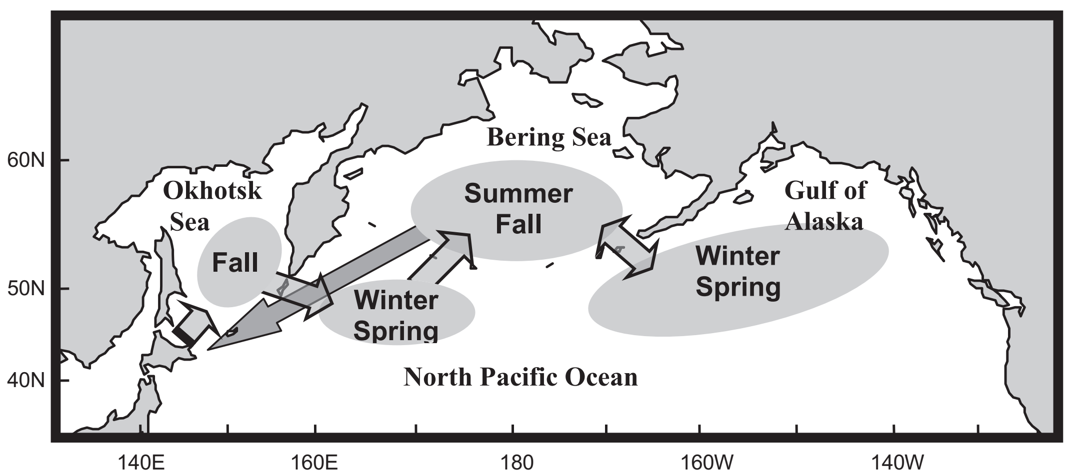

FIGURE 7. Model of seasonal migration routes of chum salmon produced in Japan (from Urawa 2004).

willingness of scientists to share samples. Surveys conducted in the major ocean feeding areas of chum salmon that monitor the abundance and condition can be associated with climate and ocean conditions to improve the accuracy of forecasting models of chum salmon returns.

Stock proportions and country of origin of immature sockeye salmon *O. nerka* sampled throughout the Bering Sea in 2002 and 2003 were identified in the Annual Report of the Bering-Aleutian Salmon International Survey (BASIS) 2004 (NPAFC, 2005) and in Habicht et al. (2005). Samples of immature sockeye salmon were collected throughout the Bering Sea in 2002 and 2003 through a cooperative research effort among Japan, Russia and the United States (Habicht et al. 2005; Helle et al. 2005). DNA analysis was used to show the location of immature sockeye salmon of Russian and United States origin. Studies such as these for immature sockeye salmon can be linked to climate and ocean data to determine how stocks that rear in different areas of the North Pacific are affected by regional variability in ocean habitat. This kind of study was also carried out by Kaga et al. (2006) for chum and pink salmon *O. gorbuscha*. They showed that the total lipid content of chum and pink salmon caught in the Gulf of Alaska in the winter of 2006 was significantly lower than in the western North Pacific. The low lipid content of pink salmon in the Gulf of Alaska may be related to the coast-wide poor marine survival that was observed in 2006. The three studies emphasize the importance of monitoring immature Pacific salmon in their ocean habitats and associating the growth and condition of these fish with regional climate and ocean conditions (see also Mantua 2009, this volume).

Fran Ulmer, former lieutenant governor of Alaska and U.S. representative to the North Pacific Anadromous Fish Commission (NPAFC), was mainly responsible for the Bering-Aleutian Salmon International Survey (BASIS) that started in 2001. BASIS was a concept that gave authority to work already in progress. BASIS created a team of researchers who worked as a family. Everyone was willing to help their colleagues and share data. As a result, millions of dollars of ship time and scientific information was shared annually among investigators in all Pacific salmon producing countries. Researchers were capable of determining where Pacific salmon were in the ocean, where they came from and their condition. Thus, BASIS and NPAFC helped to create an international team of researchers, determined to identify the processes that regulate Pacific salmon abundances in the ocean.

Conclusion

The authors propose that it is time to establish an international effort to carry out the research needed to improve forecasting. Philanthropic organizations and governments need to cooperate to provide adequate funds to support teams that will carry out this research. This may be difficult at first as it requires that organizations with different mandates cooperate to fund a common objective of conducting whole life cycle studies. This means that researchers looking at freshwater issues must work together with the researchers studying ocean impacts. Equally difficult is the need for commitments of five to ten years by the researchers and by managers and patrons of Pacific salmon research.

Scientists from all Pacific salmon producing countries have shown an ability to work in harmony to resolve the long-standing mysteries of Pacific salmon production. This cooperation and advances in genetic stock identification make it possible to understand the physical and biological processes that regulate recruitment. This understanding will complete our knowledge of the life history strategy of the various species of Pacific salmon and provide fisheries managers with new models that more accurately link climate and physical processes to recruitment, abundance and distribution. It is this understanding that will incrementally improve our ability to forecast until it becomes what Bill Ricker called the "Watson effect" (a reference to Sherlock Holmes). According to Watson effect, everything becomes simple once it is discovered. It is time to focus our funding on whole life cycle studies of Pacific salmon so that forecasting eventually becomes "elementary."

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