PACIFIC FISHERIES RESOURCE CONSERVATION COUNCIL

Conseil pour la conservation des ressources halieutiques du pacifique

CLIMATE EFFECTS ON PACIFIC SALMON IN THE OCEAN

Creating a Canadian Focus

APRIL 2008

PREPARED FOR

Pacific Fisheries Resource Conservation Council

Suite 290, 858 Beatty Street, Vancouver, BC V6B 1C1

PREPARED BY

Dave B. Preikshot, Ph.D.

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CREATING A CANADIAN FOCUS

Prepared for Pacific Fisheries Resource
Conservation Council by
Dave B. Preikshot, Ph.D.
3012 Westview Street
Duncan, BC V9L 2C5
d.preikshot@fisheries.ubc.ca

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Dave B. Preikshot, Ph.D.

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For further information about this document and about the Pacific Fisheries Resource Conservation Council (PFRCC), contact:
Pacific Fisheries Resource Conservation Council
290–858 Beatty Street
Vancouver, BC V6B 1C1
CANADA
Telephone 604 775 5621
Fax 604 775 5622
www.fish.bc.ca
info@fish.bc.ca

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LIST OF ABBREVIATIONS

ABL:	Auke Bay Laboratory (NMFS)
ACI:	Atmospheric Circulation Index
ADF&G-DCF:	Alaska Department of Fish and Game Division of Commercial Fisheries (State Government)
AFSC:	Alaska Fisheries Science Center (NMFS)
ALPI:	Aleutian Low Pressure Index
ARIMA:	AutoRegressive Integrated Moving Average
BASIS:	Bering-Aleutian Salmon International Survey (NPAFC)
BASS:	Basin Studies Task Team (PICES)
BC:	British Columbia
BCCF:	British Columbia Conservation Foundation
CCCC:	Climate Change and Carrying Capacity Program (PICES)
C-CIARN:	Canadian Climate Impacts and Adaptation Research Network (Federal Government)
CDEP:	Climate Diagnostics and Experimental Prediction program (NOAA)
CFAME:	Climate Forcing and Marine Ecosystem Response Task Team (PICES)
CIG:	Climate Impacts Group (University of Washington)
CSES:	Center for Science in the Earth System (University of Washington)
DFO:	Department of Fisheries and Oceans (Canada, Federal Government)
DWW:	Days of Westerly Winds
EEZ:	Exclusive Economic Zone
EMAG:	Ecosystem Monitoring and Analysis Group (NMFS AFSC)
ENSO:	El Niño Southern Oscillation
ERVI:	Earth Rotational Velocity Index
ESU:	Evolutionarily Significant Units
EwE:	Ecopath with Ecosim
GAM:	General Additive Model
GGBSRP:	Greater Georgia Basin Steelhead Recovery Plan (BCCF)
GLOBEC:	GLOBal Ocean ECosystem Dynamics (International Council for Science Scientific Committee on Oceanic Research and the United Nations Educational, Scientific and Cultural Organisation)
HU GSFS:	Hokkaido University Graduate School of Fisheries Sciences
ICES:	International Council for the Exploration of the Sea

INPFC:	International North Pacific Fisheries Commission
IPCC:	Intergovernmental Panel on Climate Change (United Nations)
IPHC:	International Pacific Halibut Commission
IPSFC:	International Pacific Salmon Fisheries Commission
KamchatNIRO:	Kamchatka Fisheries and Oceanography Research Institute (Russia)
LOD:	Length Of Day
MALBEC:	Model for Assessing Links Between Ecosystems (UW SoF)
MODEL:	Conceptual/Theoretical and Modeling Studies Task Team (PICES)
NEMURO:	North Pacific Ecosystem Model for Understanding Regional Oceanography
NMFS:	National Marine Fisheries Service (NOAA)
NOAA:	National Oceanographic and Atmospheric Administration (US Federal Government)
NPAFC:	North Pacific Anadromous Fish Commission
NRC:	Natural Resources Canada (Federal Government)
NWFSC:	Northwest Fisheries Science Centre (NMFS)
OCCP:	Ocean Carrying Capacity Program (NMFS)
OCH:	Oscillating Control Hypothesis
OPI:	Oregon Production Index
PBS:	Pacific Biological Station (DFO)
PDO:	Pacific Decadal Oscillation
PFRCC:	Pacific Fisheries Resource Conservation Council
PICES:	North Pacific Marine Science Organisation
PNU:	Pukyong National University
POST:	Pacific Ocean Shelf Tracking Project
PSARC:	Pacific Scientific Advice Review Committee (DFO)
PSC:	Pacific Salmon Commission
PSEF:	Pacific Salmon Endowment Fund
PSF:	Pacific Salmon Foundation
PSMFC:	Pacific States Marine Fisheries Commission
PWS:	Prince William Sound (Alaska)
REEM:	Resource Ecology & Ecosystem Modeling Program (NMFS AFSC)
REFM:	Resource Ecology and Fisheries Management Division (NMFS AFSC)

RISA:	Regional Integrated Science and Assessment program (NOAA)
SakhNIRO:	Sakhalin Fisheries and Oceanography Research Institute
SFU REM:	Simon Fraser University School of Resource and Environmental Management
SLH:	Sea Level Height
SotS:	State of the Salmon Project (Wild Salmon Center, Oregon)
SSH:	Sea Surface Height
SSS:	Sea Surface Salinity
SST:	Sea Surface Temperature
TINRO:	Pacific Scientific Research Institute of Fisheries and Oceanography (Russia)
UAF SFOS:	University of Alaska, Fairbanks, School of Fisheries and Ocean Sciences
UBC FC:	University of British Columbia Fisheries Centre
US:	United States of America
UW SoF:	University of Washington School of Fisheries

EXECUTIVE SUMMARY

The North Pacific Ocean is a vast ecosystem that changes not only with seasonal cycles, but also over decades and centuries. Ecosystem changes at this oceanic scale affect Canadian salmon populations, which spend most of their lives in the marine environment. Given that the effects of global warming, successful stewardship of Canadian Pacific Salmon will depend on better understanding how changes in climate affect the North Pacific environment.

Creating a Canadian research group to deepen our understanding of how climate affects salmon in the North Pacific would best foster this kind of successful stewardship.

This report will show that the scientific foundation for such a research group solidly exists in Canada. The results would not only be a better understanding and management of our own salmon populations but the establishment of Canada as a beacon guiding others in the stewardship of salmon around the Pacific.

The decadal- and centuries-long cycles and changes of the ocean have profound effects on species in the North Pacific ecosystem. Population cycles of many fish species have been shown to wax and wane with long-term climate variation. Such long-term and large-scale changes have also been noted for Canadian Pacific salmon stocks. However, research upon, and management of, Pacific salmon in Canada has tended to focus on short-term changes (annual or high/low stock cycles) as manifested over relatively small geographic areas (watersheds and rivers).

With a change in our understanding, recent research has made it possible to identify quantitative indicators of ocean ecosystem status for fisheries management. Given that the earth will become significantly warmer in the coming decades and centuries, it will be crucial to understand how global changes in climate may influence changes in North Pacific ecosystems and thus salmon populations.

The first part of this report reviews literature on Pacific salmon. The following themes have emerged; carrying capacity: bottom-up control; fisheries and predation: top-down control; the influence of salmon hatcheries; the effects of competition and density-dependence; the existence of a critical phase in the ocean; different salmon production regimes in space and time; and changes in salmon growth and energetics.

The second part of this report examines the lead Research institutions and universities with significant salmon climate projects.

This report shows that research conducted over the last 15 years has opened up a new understanding of how nature regulates the production of salmon in the oceans. The implication of this knowledge is that salmon populations can now be understood in the context of an ecosystem framework. This ecosystem-level understanding requires that research and management be conducted with more integrative and long-term approaches.

Given the type of research that has been done regarding the effects of climate variation and change on oceanic salmon populations, and the nature of the organisations conducting such work, guidelines are provided for the construction of a Canadian-based research institute designed to provide timely and useful advice to relevant federal and provincial ministries, user groups, and the public at large. By hosting such an institute, Canadian research would provide the context within which other nations frame the debate over and conclusions upon managing salmon stocks in the North Pacific.

This institute would attract world-class researchers on climate change and marine fish issues to work in Canada. More importantly, it would encourage such researchers trained in Canada, to stay here. By building the capacity to understand how climate changes the populations of our salmon stocks Canada could easily become the world leader in this new research field. By leading, rather than following, Canadians could establish the talking points around which other researchers, organisations, and countries frame the future debates and decisions on how to manage salmon in the changing Pacific Ocean environment.

INTRODUCTION TO LITERATURE REVIEW

This review describes investigations into the reasons why climate-driven changes in the ocean environment may be particularly important in understanding salmon population changes. In particular, this first section provides a framework to help understand the questions researchers have addressed. That is: Why are certain questions asked while others ignored? What research is being done, and what answers have arisen from this work?

This literature review is not an exhaustive examination of all research in the area of the effects of climate change and variation on oceanic salmon populations. Rather, it has been assembled to provide a look at the work that has been done by the leading researchers upon this issue, specifically research presented in peer-reviewed publications relevant to a Canadian context.

The idea that environmental effects such as climate may play a role in the regulation of fish populations in the ocean has been examined since, at least, the so-called 'Thompson-Burkenroad debate' of the 1940s and 1950s (Hilborn and Walters 1992). The sides of this debate pivoted on the question of whether apparent decreases in North Pacific halibut stocks during the 1920s were due to overfishing (Thompson) or environmentally-driven changes in the survival of juveniles (Burkenroad). Both hypotheses could be shown to explain the decline but the arguments of Thompson were more compelling to the researchers of the day, and personnel of the International Pacific Halibut Commission (IPHC), and the overfishing hypothesis became the preferred explanation (Hilborn and Walters 1992). By the mid 1970s, however, better understanding of linkages between environmentally-driven oceanographic mechanisms and life-history parameters of fishes like halibut, *e.g.*, recruitment, growth, and survival compelled a second look at this debate. By 1975 the IPHC was willing to say the environmental effects were likely playing a role in the dynamics of halibut populations (Skud 1975). By the close of the 20th Century IPHC researchers were linking changes in growth and recruitment of halibut in different North Pacific Ocean ecosystems to climate-driven regime shifts (Clark *et al*. 1999).

Many people familiar with fisheries science recognise the publication of *Climate Change and Northern Fish Populations* (Beamish 1995) as the first widespread discussion of the prevalence and importance of this linkage by the fisheries research community. Several of the papers from that publication are reviewed here and many of the ideas from these works are still relevant. As a result of these new ideas, investigations into how climate change affects ocean ecosystems, and salmon populations therein, became far more common and accepted by the research community after the mid 1990s.

The number of papers presented in this review is just over 100. The national identification of research on climate and North Pacific salmon in the ocean reflects the makeup of nations that exploit this valuable resource: United States, Canada, Russia, Japan, China and Korea. Most research appears to originate in the first four countries in this list. The majority of the research presented here is North American in origin, likely as a result of English being the primary language of this review. Many of the prominent researchers from Japan, Russia, and Korea, however, are represented, largely in papers and work done under the auspices of two organisations, the North Pacific Anadromous Fish Commission (NPAFC) and the North Pacific Marine Science Organisation (PICES). In general, the contributions of Japanese and Russian researchers complement, or amplify, those from researchers in North America. As will be seen in the section on research institutions, Canadian organisations and scientists have been well represented in this area of investigation, if not always with dedicated and/or long-term funding.

As time progresses and the numbers of researchers dedicated to this topic continue to expand, reviews should be revisited, revised, and expanded. Nevertheless, the research reviewed here contains the major themes currently being investigated in the area of climate change and salmon populations.

The literature review is intended to show how climate change influences salmon during their oceanic life. In parallel work, research has also been conducted on climate change and the fresh-water portion of salmon life histories. Indeed, research on the fresh-water aspects of salmon life histories had been the focus in the past because it was held that production in freshwater was what limited salmon production. It was also easier to conduct research and formulate policy based on the freshwater associations of salmon, because this was the geographic space in which humans can most easily interact with salmon. By the early 1980s, it had become apparent that the ocean phase of life history was at least as, if not more, important to the eventual production of salmon (Pearcy 1984). Much of the research reviewed below is, therefore, a reaction to the previous emphasis upon fresh-water influences on salmon populations. Around the time researchers began to take note of salmon production in the ocean, the issue of climate change and variation also came to the fore. In a case of scale mismatch the perception of larger-scale, long-term processes, like climate variation, is not likely in the context of work done at smaller area scales, like spawning beds and watersheds. By expanding the research scale, *i.e.*, oceanic versus river basins, it became possible to perceive how large-scale processes, like climate change and variation, might influence salmon populations.

In assembling these research papers, seven themes emerged:

1. Carrying capacity: bottom-up control,
2. Fisheries and predation: top-down control,
3. The influence of salmon hatcheries,
4. The effects of competition and density-dependence,
5. The existence of a critical phase in the ocean,
6. Different salmon production regimes, in different ocean areas, and
7. Changes in salmon growth and energetics.

These themes have overlaps and are not exclusive of each other. A brief description of each is provided below, with a discussion of how ideas pertaining to that theme have evolved with pertinent concepts from papers in this review. Following the discussion of major themes are thumbnail descriptions of all the papers in this research review.

This common framework of perception among researchers and across national boundaries suggests that, given the seven research themes summarized above and described below, an international consensus is growing as to what the impact of climate variation has been on salmon populations in the past. The consensus of salmon-climate research conclusions suggests agreement on what the future may hold and how to develop regional and international research and management to meet the challenge of risk to wild salmon populations in a changing ocean environment.

RESEARCH THEMES

CARRYING CAPACITY: BOTTOM-UP CONTROL

This theme represents the backbone of the body of research on the effects of climate change on salmon populations. In the most basic form, this line of reasoning holds that changes in climate patterns force changes in the oceanic production of phytoplankton and zooplankton. This bottom-up control increases or decreases the amount of energy available to higher levels in the trophic web. Some ideas in this vein were described as early as McLain (1984) and Anonymous (1984), but this mechanism was truly examined for the first time in detail by contributions in Beamish (1995). The connexion of physical processes such as winds, pressure systems, ocean currents, sea surface temperature (SST) and sea surface salinity (SSS) to production changes of salmon populations has been explored by several authors. Large-scale temporal and spatial changes in SST across the North Pacific have been shown to be associated with changes in the production of salmon populations across that area (Mantua and Francis 2004 and Mantua *et al*. 1997). At regional scales, associations have been seen between sockeye, pink and chum salmon production and SST at the time of ocean entry, *i.e.*, a smaller spatial and temporal scale (Mueter *et al*. 2005 and Mueter *et al*. 2002). In other regional studies, upwelling has been shown to affect the production of coho (Logerwell *et al.* 2003) and chinook (Scheuerell and Williams 2005). The consensus of most researchers looking at climate and salmon production is that the North Pacific underwent a regime shift in 1976–1977, in which the production of salmon in the Northeast Pacific (and the Gulf of Alaska/Bering Sea in particular) increased significantly (Beamish, Benson *et al*. 2004, Hare and Mantua 2000, Francis and Hare 1994 and Hare and Francis 1995). There also appear to be production regime shifts occurring at smaller, regional spatial scales at a greater frequency (Beamish, Schnute, *et al.* 2004). Some effort has also been given to determine how different Earth-scale and even astronomical processes may be the prime mover behind regime shifts (Schumacher 1999 and Klyashtorin 1997). Preikshot (2007) shows how a consideration of the area and temporal scale of populations and ecosystems being modelled necessarily reflects the scale of climate signal, which correlates to simulated changes in salmon populations.

FISHERIES AND PREDATION: TOP-DOWN CONTROL

It may seem counterintuitive that fishing and predation may play a role in research on climate-driven changes in salmon populations. Several researchers, however, have noted that the existence of a bottom-up driver to the energy available does not de facto preclude mitigation by top-down mechanisms as well. Field *et al*. (2006) show that, for a dynamic simulation model of the California Current, the addition of top-down drivers complementary to bottom-up drivers provided better fits of simulated salmon biomasses to estimated historic trends. A similar result was seen in dynamic simulation models of the Georgia Strait, British Columbia Shelf, and Northeast Pacific Ocean (Preikshot 2007). Hunt *et al*. (2002) suggesting that in the Bering Sea climate-driven changes in sea ice coverage may change the system such that it switches from bottom-up to top-down control.

THE INFLUENCE OF SALMON HATCHERIES

Salmon hatcheries have been introduced in many places because it was thought that limitation in salmon production was due to factors occurring during the freshwater phase of their life-history (Pearcy 1992). It was also suggested that hatchery-raised fish could help alleviate fishing pressure upon wild fish of the same species. Declining catches of coho and chinook in the California Current and southern BC area, during the 1990s, however, created some questions about the efficacy of hatcheries. Early examples of concern over the effects of hatcheries can be seen in Mathews (1984) and Nickelson and Lichatowich (1984), who suggested that hatchery output might have to be moderated in consideration of ocean production characteristics. By the late 1990s, Coronado and Hilborn (1998) and Beamish *et al*. (1997) clearly stated that the ocean had a limited capacity to produce salmon and that hatchery production must be conducted in recognition of this. Evidence has emerged that hatchery produced salmon may simply have replaced production of wild stocks of chum (Kaeriyama 2003), coho (Pearcy 1992) and pink salmon (Morita *et al*. 2006 and Hilborn and Eggers 2000). In cases where numbers appear to have not been affected it has been shown that density-dependence effects driven by hatchery fish may have decreased the average body size of salmon of that species (Helle and Hoffman 1998). It was also suggested that hatchery-raised salmon of one species may have a negative impact on other salmon species (Ruggerone and Goetz 2004 and Ruggerone and Neilson 2004). An alternative analysis of hatcheries has come from Shuntov and Temnykh (2004) who reason that because salmon form a small portion of the zooplanktivorous portion of the ocean food web it is unlikely that they have ever exceeded carrying capacity.

THE EFFECTS OF COMPETITION AND DENSITY-DEPENDENCE

As might be inferred from the discussion in the preceding paragraph, issues around hatchery-raised salmon are an important component of this theme, as with competition effects described in Ruggerone and Goetz (2004) and Ruggerone and Neilson (2004). In a more general sense, the idea has been put forward that during regimes in which production is lowered it might be naturally expected that competition for limited salmon food resources should be more intense. In the case of coho in the Georgia Strait it has been suggested this competition may be strong enough to limit juvenile growth and lead to higher mortality (Beamish and Mahnken 2001). In a case of decreased competition, Hunt *et al*. (2002) show how increased recruitment of piscivores, which ate many salmon competitors for zooplankton, allowed salmon biomass to expand in the Bering Sea. Helle and Hoffman (1998) observed that size-at-maturity declined in some chum stocks after the 1977 Northeast Pacific regime shift, and Bigler *et al*. (1996) found the same phenomena in sockeye, despite increased numbers.

THE EXISTENCE OF A CRITICAL PHASE IN THE OCEAN

Many researchers have come to think that for some salmon there is a critical phase, soon after ocean entry, during which juvenile salmon mortality is high enough that small changes to it can have significant consequences on numbers of returning adults. An early example is seen in Anonymous (1984) in which a consensus opinion arose from a workshop of salmon researchers that investigating the dynamics of a juvenile oceanic critical phase would be of much use. The mechanism behind the critical phase is climate-driven changes to factors like predator distribution, food availability, and growth (Beamish, Mahnken and Neville 2004 and Beamish and Mahnken 2001). Changes in such factors could significantly alter marine survival of juvenile salmon. It also has been suggested that changes to sea surface temperature (SST) may of itself alter food availability to improve or hinder juvenile survival (Trudel *et al*. 2002). The existence of a critical phase early in the life history appears to play a role in the production of salmon across many regions (Mueter *et al*. 2005).

DIFFERENT SALMON PRODUCTION REGIMES IN SPACE AND TIME

One fascinating observation, arising from the effect of the manifestation of physical climate effects at different area and time scales, is that climate effects are neither equal nor pervasive. The impact of climate driven changes to salmon production depends on whether one is observing changes to a single stock, a groups of stocks, a metapopulation, or all salmon in the North Pacific. While there is agreement that, when integrated over the whole North Pacific, total salmon production increased after the 1977 regime shift, it was also noted that in many regions of the North Pacific some species and stock groups experienced declines in production. For coho salmon, northern (Alaska Gyre) stocks increased while 'southern' (California Current) stocks declined (McFarlane *et al*. 2000 and Coronado and Hilborn 1998). A similar pattern was noted in northern versus southern stocks of sockeye, pink and chum salmon (Pyper *et al*. 2005 and Mueter *et al*. 2002). The existence of inverse production regimes in the Alaska Gyre and California Current was described as a linkage between changes in zooplankton production and salmon production by Hare and Francis (1995) and then Francis and Hare (1997). Gargett (1997) suggested an oceanographic mechanism that would drive these changes by relatively larger or smaller portions of the West Wind Drift being deflected north to the Alaska Gyre or south to the California Current in different production regimes.

CHANGES IN SALMON GROWTH AND ENERGETICS

It has long been recognised that salmon have a preferred thermal habitat for growth and migration. In general, temperatures higher than about 12ºC tend to be less desirable for salmon particularly sockeye. The impact of historic climate variation upon these limits may have been the periodic waxing and waning of total available ocean habitat. Welch *et al*. (1998) suggest, however, that if the North Pacific warms, in accordance with climate change predictions, total habitat for salmon may shrink precipitously. The consequence for sockeye from BC would be less habitat in which to grow and longer ocean migration times. Temperature also affects how salmon grow. Smaller size-at-maturity in sockeye was observed when they experienced warmer Northeast Pacific ocean conditions from 1950 to 1993 (Cox and Hinch 1997). Hinch *et al*. (1995) showed in a bioenergetics model of sockeye salmon that growth would be severely restricted in a warmer North Pacific Ocean. This impact could be severe enough to render impossible the upstream migration of some adult sockeye. Trudel *et al*. (2002) found for coho, however, that while there may be a temperature effect on growth, it was indirect. coho growth in different temperature regimes appeared to be limited by the prey quality available in warmer ocean waters more so than the energetic cost of being in the warm water itself.

PAPERS REVIEWED

Adkison, M.D. and B.P. Finney. 2003. The long-term outlook for salmon returns to Alaska. Alaska Fish. Res. Bull. 10: 83–94.

The authors foresee no potential for dramatic declines in Alaskan salmon stocks barring significant freshwater habitat alteration from global warming. The authors maintain that because most future climate change scenarios predict changes of a few degrees, alteration of Alaskan salmon ocean habitat outside the bounds of past variability is unlikely. However, because it has been shown that ocean circulation can change drastically with climate change such as that predicted, new currents and circulation could harm Alaskan salmon stocks significantly. Thus, as long as temperature change is the only effect of climate variation in the future, then Alaskan salmon stocks will continue to be productive.

Anderson, J.J. 2000. Decadal climate cycles and declining Columbia River salmon. Pp. 467–484. In E. Knudsen (ed.) Proceedings of the Sustainable Fisheries Conference, Victoria, B.C. American Fisheries Society Special Publication No 2x. Bethesda, MD.

This paper shows how climate and anthropogenic factors may have combined to effect a 'ratcheting down' of chinook populations on the Columbia River. The authors contend that past research tended to ignore the contribution of climate-driven changes in chinook populations. Poor ocean production, resulting from climate-driven bottom-up processes may make any effort to mitigate anthropogenic factors moot. Therefore, the authors argue that the overlap of anthropogenic and climate effects should be considered to avoid falsely assessing the success or failure of a particular salmon policy.

Anonymous. 1984. Oceanic working group. Pp. 87–99 in W.G. Pearcy (ed.) The influence of ocean conditions on the production of salmonids in the North Pacific. Oregon State University Sea Grant Program, Corvallis.

This paper summarises the recommendations of the workshop attendees as to how best to maximise benefits from future research on why salmon ocean survival changes. The consensus was that interannual changes in the factors affecting early marine survival of salmonids appeared to be more important than those affecting later phases of salmonid ocean life history stages. Thus, when combined with the expense of marine research programs, the group's opinion was cautious about recommending greatly enhanced work in the ocean. They do say further work in three areas would be helpful: more examination of the relationships between physical and biological time series; more sampling work on time varying changes in the ocean environment (though note by that time sampling at ocean station Papa had be shut down—a fact that was tangentially criticised by the working group); and lastly, separating causes of estuarine, coastal and oceanic mortality. In retrospect the first and third recommendations appear to have been done. The second recommendation involves expensive research and has never been effectively pursued, *e.g.*, to answer questions of specific salmon habitats, feeding habits, and interactions with predators and competitors.

Aydin, K.Y., G.A. McFarlane, J.R. King, B.A. Megrey, and K. W. Meyers. 2005. Linking oceanic food webs in coastal production and growth rates of Pacific salmon (*Oncorhynchus* spp.), using models on three scales. Deep Sea Res. II 52: 757–780.

Though this paper does not deal explicitly with salmon and climate change, the elucidation of seasonal food web processes that influence salmon production in the North Pacific could be useful to future research. In particular, the manner in which primary production is communicated to the upper parts of the ocean food web occupied by salmon affects both salmon prey abundance and type. Such changes in prey abundance and type are significant, given the ontogenetic shifts in salmon species growing in the ocean. It can thus be expected that climate driven changes in prey abundance and type will have consequences at least as dramatic as those observed for the seasonal processes modelled in this research.

Aydin, K.Y., G.A. McFarlane, J.R. King, and B.A. Megrey. 2003. PICES-GLOBEC international program on climate change and carrying capacity. The BASS/MODEL report on trophic models of the subarctic Pacific basin ecosystem. PICES Sci. Rep. 25: 97 p.

This report describes research that incorporated two modelling approaches, Ecopath with Ecosim (EwE) and North Pacific Ecosystem Model for Understanding Regional Oceanography (NEMURO) designed to study changes in the Northeast and Northwest Pacific oceanic gyres. As such, the modelling work was meant to characterise general ecosystem processes and was not intended to specifically explain changes in salmon response to climate. Nevertheless, climate scenarios were explored. When the EwE model was set to back-calculate changes in primary production likely to result in bottom up forcing of observed changes in salmon populations, a regime shift is suggested by increased primary production after 1976.

Babaluk, J.A., J.D. Reist, J.D. Johnson, and L. Johnson. 2000. First records of sockeye (*Oncorhynchus nerka*) and pink salmon (*O. gorbuscha*) from Banks Island and other records of Pacific Salmon in Northwest Territories, Canada. Arctic 53: 161–164.

Case studies are presented of the first recorded instances of sockeye, pink, chum, and coho being found in various parts of the Canadian Arctic. The authors suggest that in the past cold temperatures may have prevented salmon from colonising much of the Arctic. However, with climate warming this paucity of Pacific salmon may cease to be the case. It is cautioned that any expansion of Pacific salmon into the Arctic could have an effect upon local populations of salmonids like Arctic charr (*Salvelinus alpinus*) and Dolly Varden charr (*Salvelinus malma*).

Bakun, A. and K. Broad (Editors). 2002. Climate and fisheries: Interacting paradigms, scales, and policy approaches. Palisades, New York: International Research Institute for Climate Prediction, Columbia University, NY: 67 p.

Although this book provides brief discussions on salmon in particular, it does provide a general examination of the conceptual framework that will be needed to make the scientific advice regarding climate and fisheries useful for management decision-making. It is noted, for instance that in the case of declining production of Northeast Pacific coho and chinook after 1980 fisheries mortality remained high. This contradiction was because of a belief that production was stochastic and not an auto-correlative regime-like process. This implies that most salmon fisheries management needs to be conducted with the frame of reference of being in a high or low production regime and setting appropriate harvest goals to the regime. This is similar to argument voiced by Beamish *et al.* (2004), Francis and Mantua (2003), Miller (2000) and Hare *et al.* (1999)

Beamish, R.J. (Editor). 1995. Climate change and northern fish populations. Can. Spec. Publ. Fish. Aquat. Sci. 121: 768 p.

This compilation was an early examination of cases relating climate change to fish ecosystems. This effort represents the beginnings of serious and coordinated investigations of climate variation and its impact upon fish populations and aquatic ecosystems in a way that management could use for formulating plans and research agendas. It included many papers with the following articles relevant to salmon:

Chatters, J.C., V.L. Butler, M.J. Scott, D.M. Anderson, and D.A. Neitzel. A paleoscience approach to estimating the effects of climatic warming on salmonid fisheries of the Columbia River Basin. Pp. 489–496.

Cooney, R.T., T.M. Willette, S. Sharr, D. Sharp, and J. Olsen. The effect of climate on North Pacific pink salmon (*Oncorhynchus gorbuscha*) production: Examining some details of a natural experiment. Pp. 475–482.

Hare, S.R. and R.C. Francis. 1994. Climate change and salmon production in the Northeast Pacific Ocean. Pp. 357–372.

Helle, J.H. and M.S. Hoffman. Size decline and older age at maturity of two chum salmon (*Oncorhynchus keta*) stocks in western North America, 1972–92. Pp. 245–260.

Henderson, M.A., R.E. Diewert, J.G. Stockner, and D.A. Levy. Effect of water temperature on emigration timing and size of Fraser River pink salmon (*Oncorhynchus gorbuscha*) fry: Implications for marine survival. Pp. 655–664.

Hinch, S.G., M.C. Healey, R.E. Diewert, and M.A. Henderson. Climate change and ocean energetics of Fraser River sockeye (*Oncorhynchus nerka*). Pp. 439–445.

Ishida, Y., D.W. Welch, and M. Ogura. Potential influence of North Pacific sea surface temperatures on increased production of chum salmon (*Oncorhynchus keta*) from Japan. Pp. 271–275.

Ricker, W.E. Trends in the average size of Pacific salmon in Canadian catches. Pp. 593–602.

The Hare and Francis paper is reviewed separately; it provided a theoretical basis for much of the climate and salmon ecosystem research up to the present.

Beamish, R.J., McFarlane, G.A., and King, J.R. 2005. Migratory patterns of pelagic fishes and possible linkages between open ocean and coastal ecosystems off the Pacific coast of North America. Deep-Sea Res. II 52: 739–755.

Despite the fact that this work does not specifically address climate and salmon dynamics directly, it does provide an important frame of reference to address such dynamics. In particular, it is noted that salmon, among many fishes, may move across ecosystem boundaries. Such knowledge is crucial for correctly identifying which climate driven ocean habitat mechanisms may act on salmon because during different parts of their life history they can be in quite different ocean habitats. The transfer of energy and nutrients across ecosystem boundaries is also an important consequence of this migratory behaviour. The inference for climate change research is potential changes in the magnitude and timing of these movements resulting in new regimes of oceanic salmon production.

Beamish, R.J., A.J. Benson, R.M. Sweeting, and C.M. Neville. 2004. Regimes and the history of the major fisheries off Canada's west coast. Prog. Oceanogr. 60: 355–385.

The authors show that most of the species of fish subject to exploitation off the West Coast of Canada have experienced climate-derived effects. For salmon, in particular, shifts in catch trends appear to have occurred in the mid 1950s, late 1970s and early 1990s. In the authors' estimation, catch trends appear to be responding more to climate-associated regime shifts than to directed management activities.

Beamish, R.J. and D.R. Bouillon. 1993. Pacific salmon production trends in relation to climate. Can. J. Fish. Aquat. Sci. 50: 1002–1016.

Similar trends in catches of sockeye, pink and chum were observed, when summed over all nations. Similarity in national trends also existed, but was weaker. This research illustrates the importance of accounting for spatial scale in detecting long-term salmon population changes associated with climate variation.

Beamish, R.J., C. Mahnken, and C.M. Neville. 2004. Evidence that reduced early marine growth is associated with lower marine survival of coho salmon. Trans. Am. Fish. Soc. 133: 26–33.

Research is presented showing that coho salmon surviving the first winter year tend to have wider growth circuli in their otoliths, implying that they were larger than their cohorts that did not survive the winter. This follows up the 2001 Beamish *et al*. paper about critical size and period. In this latter work it is proposed that larger size helps the fish get through the lean months of winter.

Beamish, R.J. and C. Mahnken. 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. Prog. Oceanogr. 49: 423–437.

Research is presented suggesting that there are two important sources of mortality soon after ocean entry by juvenile salmon: mortality immediately upon entry via predation; and mortality upon those juveniles that fail to reach a critical size by the end of their first year in the ocean. Growth-related mortality near the end of the first ocean year thus contributes to year-class strength, and climate could be driving such a mechanism by creating times of lower productivity, hence driving up competition for food.

Beamish, R.J., C. Mahnken, and C.M. Neville. 1997. Hatchery and wild production of Pacific salmon in relation to large-scale, natural shifts in the productivity of the marine environment. ICES J. Mar. Sci. 54: 1200–1215.

The argument is presented that if the north Pacific is shifting to a lower salmon production regime (1989 shift) then hatchery production of salmon may have a deleterious effect upon wild stocks. Hatchery planning needs to be done in the context of an ocean that does not always produce the same biomass of salmon.

Beamish, R.J., G.A. McFarlane, and R.E. Thomson. 1999. Recent declines in the recreational catch of coho salmon (*Oncorhynchus kisutch*) in the Strait of Georgia are related to climate. Can. J. Fish. Aquat. Sci. 56: 506–515.

Over the period described, coho catches in the Strait of Georgia declined dramatically. This trend was associated with changes in oceanographic characteristics of the Strait of Georgia like Sea Surface Height (SSH) and number of days of westerly winds (DWW). Although SSH and DWW are regional, smaller-scale, oceanographic characteristics, they change as a response to larger scale climate processes. This paper shows how large-scale climate processes can affect the dynamics of populations in smaller geographic areas. The researchers expressed caution over the difficulty of linking large to small-scale mechanisms and then linking the small-scale climate process to different movements and production characteristics of coho salmon.

Beamish, R.J., D.J. Noakes, G.A. McFarlane, L. Klyashtorin, V.V. Ivanov, and V. Kurashov. 1999. The regime concept and natural trends in the production of Pacific salmon. Can. J. Fish. Aquat. Sci. 56: 516–526.

Although climate regimes persist for decades, the actual shifts can be quite sudden. When a shift does happen, the mechanisms underlying production of salmon may also change, altering the assumptions that need to be considered in managing fish resources. The synchrony of many of the physical and biological indices measuring regime shifts suggests that there is a single underlying cause. Length of Day (LOD) is posited as such a 'prime mover' because it is influenced by core-mantle interactions and changes in the hydrosphere and atmosphere. Decadal LOD variation is shown to have been associated with changes in many fish populations and climate indices.

Beamish, R.J., D.J. Noakes, G.A. McFarlane, W. Pinnix, R. Sweeting, and J. King. 2000. Trends in coho marine survival in relation to the regime concept. Fish. Oceanogr. 9: 114–119.

Coho populations in BC, Washington and Oregon appear to have declined after the 1989 regime shift. Low coho marine survival may persist until there is a change in production and oceanographic regimes in the Northeast Pacific. The fact that the same coho production change occurred at the same time, in all three regions of the southern portion of coho range, suggests that oceanographic regimes play a crucial role in coho population dynamics.

Beamish, R.J., J.T. Schnute, A.J. Cass, C.M. Neville, and R.M. Sweeting. 2004. The Influence of climate on the stock and recruitment of pink and sockeye salmon from the Fraser River British Columbia, Canada. Trans. Am. Fish. Soc. 133:1396–1412.

This work shows how spawner recruitment relationships for sockeye and pink salmon improved when the data was separated by regime changes. In qualitative terms, the post-1977 regime-shift was productive for both Fraser sockeye and pink until 1988 when a new regime made the ocean less productive for Fraser River pink and sockeye. The authors contend that the existence of regimes needs to be included in management plans to ensure that catch, escapement and abundances are related to the limits imposed by the extant regime. The authors propose that for Fraser salmon production regimes shifts appear to be occurring at a decadal scale (1977, 1988 and 1998) and hypothesise the next in or around 2008. Therefore, at the very least, fisheries oceanographers should begin looking for evidence of a regime shift in 2008. They caution, however, that mechanisms underlying regime shift still need further elucidation.

Beamish, R.J., R.M Sweeting, and C.M. Neville. 2004. Improvement of juvenile Pacific salmon production in a regional ecosystem after the 1998 climatic regime shift. Trans. Am. Fish. Soc. 133: 1163–1175.

In the Strait of Georgia after 2000, juvenile coho and chinook fed more frequently and had more food in their stomachs. Evidence is also presented about greater salmon production in the Strait of Georgia after 2000. The authors suggest that this was a lagged response to pervasive changes in regional, basin and planetary-scale climate indices in 1998. It should be noted that 2002 data did suggest lower productivity which the authors ascribe to natural variation in the new regime. The authors suggest that LOD is a useful predictor for regime shifts due to its association with the changes noted in this paper and their previous work on regime shifts, *e.g.*, Beamish *et al*. (1999). This result is similar to the result presented in Peterson and Schwing (2003).

Bigler, B.S., D.W. Welch, and J.H. Helle. 1996. A review of size trends among North Pacific salmon (*Oncorhynchus* spp.). Can. J. Fish. Aquat. Sci. 53: 455–465.

45 of 47 sampled salmon populations showed decreasing body size between 1975 and 1993. This work suggests that although salmon numbers generally went up after the 1977 regime shift, there may be a limit to the ability of the ocean to make total biomass of salmon as reflected in decreasing body mass per individual.

Bradford, M.J. and J.R. Irvine. 2000. Land use, fishing, climatic change, and the decline of Thompson River, British Columbia, coho salmon. Can. J. Fish. Aquat. Sci. 57: 13–16.

The authors show that climate induced declines in ocean coho production, combined with overfishing and anthropogenic freshwater habitat degradation, have produced the decline in coho abundance seen in Thompson River coho. The authors point out there is no direct evidence to support the theory that climate derived change in freshwater habitat may have contributed to coho declines, though it seems likely.

Brodeur, R.D., J.P. Fisher, D.J. Teel, R.L. Emmett, E. Casillas, and T.W. Miller. 2004. Juvenile salmonid distribution, growth, condition, origin, and environmental and species associations in the North California Current. Fish. Bull. 102: 25–46.

This paper does not deal with climate effects directly but has relevance because it describes the effects of changes in ocean habitat on juvenile chinook and coho. By inference, such information could be useful in predicting effects of climate-driven habitat change on chinook and coho.

Chatters, J. C., D.A. Neitzel, M.J. Scott, and S.A. Shankle. 1991. Potential impacts of global climate change on Pacific Northwest spring chinook salmon: an exploratory case study. Northwest Environ. J. 7: 71–92.

Modelling work was done by this team to investigate in-river effects of warming on chinook salmon. The paper was not available for review and this entry is based merely upon an abstract. It is included as an example of early direct exploration of how warmer habitats might affect salmon populations.

Chelton, D.B. 1984. Commentary: short-term climatic variability in the Northeast Pacific Ocean. Pp. 87–99 in W.G. Pearcy (ed.) The influence of ocean conditions on the production of salmonids in the North Pacific. Oregon State University Sea Grant Program, Corvallis.

This paper discusses some of the statistical problems involved with analysing correlations between long-term data sets such as those used in studies of climate-driven changes in salmon production. In general, assigning significance to a correlation between environmental and biological time series is not straightforward because of correlation within the individual time series that reduces the actual degrees of freedom in the overall analysis. The author provides a quick method of correcting degrees of freedom for such effects to produce more powerful analyses. The author analyses data sets of sea level height (SLH) at various stations off the West Coast to not synchronous changes from the 1940s to 1980s. The time scale of change being analysed is annual and decadal changes are only discussed tangentially. The author points out that synchronous rise and fall of SLH reflects synchronous changes in both the Alaska and California Currents. These changes, however, are such that when one of the two current systems strengthens or weakens, relative to its long-term average, the other changes in the opposite direction. The mechanistic explanation for this is held to be the position of the bifurcation of the West Wind Drift in the Northeast Pacific and the relative amount of water being transported north or south. The author proposes that when SLH drops along the west coast, relatively more water is moved to the North, stronger currents to the north increase onshore transport and yield SLH increases, while to the south weaker current decrease offshore transport and yield SLH increases. While the author points out that little data exists to quantitatively examine this mechanism it could explain why Bristol Bay and Fraser River sockeye stocks appear to be out of phase in productivity changes. This is very similar to ideas expressed by Gargett (1997) that show how such a mechanism can explain the inverse production regimes of the Alaska and California Currents.

Cooney, R.T., J.R. Allen, M.A. Bishop, D.L. Eslinger, T. Kline, B.L. Norcross, C.P. McRoy, J. Milton, J. Olsen, V. Patrick, A.J. Paul, D. Salmon, D. Scheel, G.L. Thomas, S.L. Vaughan, and T.M. Willette. 2001. Ecosystem controls of juvenile pink salmon (*Oncorhynchus gorbuscha*) and Pacific herring (*Clupea pallasi*) populations in Prince William Sound, Alaska. Prog. Oceanogr. 10 (Suppl. 1): 1–13.

This study attempts to link climate-derived bottom-up driven changes in phytoplankton and zooplankton production to changes in juvenile pink mortality. Although the researchers specifically address seasonal variation, climate variation is discussed obliquely. The paper is vague in stating how production characteristics might vary under different regimes.

Coronado, C. and R. Hilborn. 1998. Spatial and temporal factors affecting survival in coho salmon (*Oncorhynchus kisutch*) in the Pacific Northwest. Can. J. Fish. Aquat. Sci. 55: 2067–2077.

Results from coded wire tag data is used to analyse survival rates of hatchery and wild coho from a variety of areas in the Northeast Pacific. The authors conclude that the mid to late-1980s witnessed increased coho ocean survival in northern areas (Alaska current) and decreases in the south (California Current). This fits with the inverse production regimes idea, and the authors also note the oceanographic and production features (*i.e.*, upwelling versus downwelling currents) that characterise the habitats of southern versus northern regions in the study. The authors determine that survival rates for hatchery, wild and net-pen-raised coho were not significantly different. Given this similarity, it is concluded that changing ocean conditions are crucial to survival and that, given the observed declines in survival at the time of writing, drastic cuts in harvest might be necessary. The authors also advise more reliance on natural production to ensure the genetic diversity and persistence of southern stocks.

Cox, S.P. and S.G. Hinch. 1997. Changes in size at maturity of Fraser River sockeye salmon (*Oncorhynchus nerka*) (1952–1993) and associations with temperature. Can. J. Fish. Aquat. Sci. 54: 1159–1165.

This research shows that size-at-maturity declined from 1950 to 1992 for all females, and 80% of all males, in the Fraser River stocks studied. Size-at-maturity also tended to be smaller during relatively warmer years, regardless of whether closer to 1950 or 1992. This conclusion was among the first to suggest a physiologic result of global warming upon salmon, with the implication that smaller salmon would have a more difficult time surviving upstream passage. Such a situation would be exacerbated given that, if the upriver migration were in warmer waters, a further energetic demand would be placed upon the smaller sockeye containing less energy to complete migration in the first place.

Crossin, G.T., S.G. Hinch, A.P. Farrell, D.A. Higgs, and M.C. Healey. 2004. Somatic energy of sockeye salmon *Oncorhynchus nerka* at the onset of upriver migration: a comparison among ocean climate regimes. Fish. Oceanogr. 29: 22–33.

Return-migrating adult Chilko and early Stuart sockeye were seen to have greater somatic energy in years with higher ocean productivity. More specifically, somatic energy was higher in years with relatively lower SST and relatively higher values of the North Pacific Index. Some between-stock differences were observed, and this may be due to particular ocean habitats of various stocks. For instance, it is suggested that, based upon migration timing evidence, Chilko salmon may mature near the centre of the Alaskan Gyre. The gyre may be an area more resistant to lower productivity during a regime shift than more coastal areas, potentially used by other stocks. Low energy levels at the start of river migration can contribute to higher en route mortality. This would be even more likely where river conditions are poor for migration, *e.g.*, high flow, high temperature. This amplifies the results presented in Cox and Hinch (1997).

Drake, D.C., R.J. Naiman, and J.M. Helfield. 2002. Reconstructing salmon abundance in rivers: an initial dendrochronological evaluation. Ecology 83: 2971–2977.

This research shows that salmon escapement can be correlated to tree ring growth. Tree rings might therefore be useful in estimating historic salmon escapements.

Eggers, D.M., J. Irvine, M. Fukuwaka, and V.I. Karpenko. 2004. Catch trends and status of North Pacific salmon. PICES Spec. Publ. 1: 227–261.

The authors provide a graphical and numeric inventory of national and regional changes in catches (numbers and weight) of sockeye, pink, chum, coho, and chinook from 1925 to 2003. Though not written with a view to explaining climate effects, this paper does provide a consensus framework of changes in salmon production across the North Pacific over a time frame useful to other researcher examining climate effects.

Emmett, R.L. and M.H. Schiewe (Editors). 1997. Estuarine and ocean survival of Northeastern Pacific salmon. NOAA Tech. Mem. NMFS-NWFSC-29: 313 p.

This work is a collection of papers from workshop presentations. The workshop illustrated how processes occurring on various scales could be unified in understanding the effects of climate upon salmon during various life history stages. In particular, the effects upon young salmon were brought to the fore in many of the presentations, *i.e.*, work illustrating the effects described as the ‘critical period hypothesis’.

Field, J.C., R.C. Francis, and K. Aydin. 2006. Top-down modeling and bottom-up dynamics: Linking a fisheries-based ecosystem model with climate hypotheses in the Northern California Current. Prog. Oceanogr. 68: 238–270.

In this research a dynamic food-web model simulating historic changes in the California current was run with an aggregated salmon group made up of chinook and coho. The model simulated climate variation with two mechanisms; bottom-up forcing of phytoplankton production and top-down mediation of vulnerability of prey species to key predator species. The best fit (of simulated biomasses to historic stock assessments) was with a top-down Pacific Decadal Oscillation (PDO) signal and no bottom-up climate signal. However, there was a better visual fit, specifically for the salmon data, when the model was run with a top-down PDO vulnerability signal combined with a bottom-up Oregon Production index (OPI) signal. For more on the OPI see Logerwell *et al.* (2003).

Finney, B.P., I. Gregory-Eaves, J. Sweetman, M.S.V. Douglas, and J.P. Smol. 2000. Impacts of climatic change and fishing on Pacific salmon abundance over the past 300 Years. Science 290: 795–799.

This group compared salmon abundance indicated by ocean-derived nitrogen in sockeye rearing lakes to sea surface temperature (SST) derived from tree rings. The relationship between salmon abundance and SST appears often to be non-linear and subject to variation. The relationship was seen to be linear from 1700 to 1850, then decoupled from 1850 to 1920. Recent management to maintain constant escapement also appeared to have caused any relationship to falter in recent years. Lack of a simple relationship between SST and salmon abundance suggests complex manifestations of climate-driven bottom-up changes.

Francis, R.C. and N.J. Mantua. 2003. Climatic influences on salmon populations in the Northeast Pacific. Pp. 37–76 in A.D. MacCall and T.C. Wainwright (eds.) Assessing extinction risk for west coast salmon. NOAA Tech. Mem. NMFS-NWFSC-56.

The researchers show how large, basin-scale climate indices appear to have a linear relationship with salmon populations measured at large scales, whereas the relationships are more complex at the regional scale, see, *e.g.*, Finney *et al.* (2000). For the purposes of protecting genetically important populations, or evolutionarily significant units (ESUs), definitions occur at a fairly small (regional or smaller) scale. Therefore, it is the more complex non-linear effects of climate change that will be of concern to managers who want to incorporate climate into planning to protect salmon species diversity. However, the authors conclude that climate effects alone are likely not enough to threaten a species because it consists of several ESUs. Because climate effects occur over decadal scales and are often apparent in hindsight, it remains desirable to employ different management strategies when the regime is recognised as having changed.

Francis, R.C. and S.R. Hare. 1994. Decadal scale regime shifts in the large marine ecosystems of the North-east Pacific: a case for historical science. Fish. Oceanogr. 3: 279–291.

In this research, climate variation is suggested to influence salmon early in their life history, upon entry to the ocean environment. These climate effects were observed at decadal scales but not interannual scales. This was an important paper linking climate to salmon population change due to changes in both estuarine and ocean survival of Northeastern Pacific salmon.

Francis, R.C. and S.R. Hare. 1997. Regime scale climate forcing of salmon populations in the Northeast Pacific—some new thoughts and findings. Pp. 113–128. In Emmett, R.L. and M.H. Schiewe (eds.) Estuarine and ocean survival of Northeastern Pacific salmon. NOAA Tech. Mem. NMFS-NWFSC-29.

This paper shows how production of both plankton and salmon vary on decadal scales and production regimes of the California current and Alaska Gyre appear to be inversely correlated. This work elaborated work presented in Hare and Francis (1994) and showed the mechanisms likely linking climate change to salmon population change.

Gargett, A.A. 1997. The optimal stability `window': A mechanism underlying decadal fluctuations in North Pacific salmon stocks? Fish. Oceanogr. 6: 109–117.

The author proposes water column stability as the mechanism linking climate to salmon production. Water column stability is also used to explain inverse production regimes of salmon in Northern BC and Alaska versus salmon from southern BC through California, as suggested by Francis and Hare (1994). During positive phases of the Pacific decadal oscillation (PDO), the Alaskan low is deeper and further west while the California high is more westward. This results in greater stability of water in the Gulf of Alaska, where nutrients are in excess. This allows phytoplankton production to be relatively higher. Southerly winds off the southern US west coast mean less upwelling and, hence, less phytoplankton production. In a negative PDO phase, the opposite situation exists with unstable waters in the Gulf of Alaska and relatively lower production, whereas the California current area experiences more northerly winds, promoting upwelling and phytoplankton production. This mechanism builds upon ideas discussed in Chelton (1984).

Gedalof, Z. and D.J. Smith. 2001. Interdecadal climate variability and regime-scale shifts in Pacific North America. Geophys. Res. Lett. 28: 1515–1518.

This paper does not include any discussion of how climate change may relate to fish. Long-term (centuries) historic records of tree ring growth are used to show that pervasive regime shifts, like that of 1976/1977, have occurred regularly during the 400 years up to the year 2000. Regime shifts detected in the analysis were; 1662, 1680, 1696, 1712, 1734, 1758, 1798, 1816, 1840, 1923, 1946, and 1977.

Hare, S.R. and R.C. Francis. 1995. Climate change and salmon production in the Northeast Pacific ocean. PP. 357–372. In R. J. BEAMISH (ED.) Climate change and northern fish populations. Can. Spec. Publ. Fish. Aquat. Sci. 121.

The researchers employ time series of salmon production, indicated by landings, to examine likelihood of regime shifts with univariate autoregressive integrated moving average (ARIMA) models. The ARIMA models suggest that regime shifts occurred in the late 1940s and late 1970s. This work was an early and compelling project linking changes in salmon production to climate-driven bottom-up forcing.

Hare, S.R. and N.J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Prog. Oceanogr. 47: 103–145.

In this paper, evidence was provided to strengthen the case for a 1977 regime shift and to show indications of a similar phenomenon in 1989. However, the signals for the two shifts differed in quality. The 1989 changes were not as pervasive (though more obvious in biological indices) and did not return the system to pre-1977 conditions. It is also shown how the relatively large North Pacific and Bering Sea ecosystems appear to filter climate variability and that biological responses to climate variation seem to be non-linear. Therefore, it is concluded that monitoring of biological indices appears to be a better method to detect regime shifts sooner.

Hare, S.R., N.J. Mantua, and R.C. Francis. 1999. Inverse production regimes: Alaska and West Coast Pacific Salmon. Fisheries 24: 6–14.

This research illustrates how production of salmon off the West Coast of North America varies inversely with that of salmon in the Alaskan Gyre. This seems to be a bottom-up function of local-scale environmental changes associated with the large-scale PDO. This implies that the presently less productive West Coast US salmon ecosystem needs to be more conservatively managed and that the recovery of associated stocks may need to wait for the next reversal of the PDO. Given these considerations, management actions need to be considered in the long-term to avoid falsely assessing, as failure, policies that do not have immediate positive results in periods of low productivity.

Helle, J. H. and M.S. Hoffman. 1998. Changes in size and age at maturity of two North American stocks of chum salmon (*Oncorhynchus keta*) before and after a major regime shift in the North Pacific Ocean. N. Pac. Anadr. Fish Comm. Bull. 1: 81–89.

The authors examine size-at-maturity changes in two stocks of chum salmon (one from Alaska, the other from Washington) and note a drop in both after 1980, which they associate with the 1976/1977 regime shift. The authors note similar declines have been observed for Japanese stocks of chum. The authors suggest a density-dependent population factor drove this phenomenon because of the large chum hatchery program of Japan, combined with the observation of increased numbers of chum being offset by decreased body size-at-age of those fish. There is a suggestion that because of the sensitivity of chum salmon to changes in oceanic carrying capacity (as evidenced by rapidly changing size-at-maturity), they may be useful as harbingers of regime shifts.

Hilborn, R. and D. Eggers. 2000. A Review of the hatchery programs for pink salmon in Prince William Sound and Kodiak Island, Alaska. Trans. Am. Fish. Soc. 129: 333–350.

This research shows that production of wild Prince William Sound (PWS) pink salmon decreased after the introduction of PWS hatchery pinks. Ostensibly, the hatchery pinks were meant to increase total production and harvest, while mitigating mortality upon wild pinks. However, wild PWS pink production declined after the mid 1970s, whereas other adjacent pink stock complexes experienced production increases. The authors state that hatchery production is likely to replace wild production when and where the stocks overlap in habitat and harvest. In the event of a regime shift to lower production, such an interaction could be devastating to wild stocks.

Hinch, S.G., M.C. Healey, R.E. Diewert, K.A. Thomson, M.A. Henderson, R. Hourston, and F. Juanes. 1995. Climate change on marine growth and survival of Fraser River sockeye salmon. Can. J. Fish. Aquat. Sci. 52: 2651–2659.

The authors constructed a bioenergetics model of sockeye salmon to simulate growth at sea. They conclude that, given estimates of green-house type warming increasing SST in the North Pacific by as much as 3.5°C, size-at-maturity for sockeye salmon could be reduced by as much as 14%. Because of this, it may be more difficult for the smaller fish, with necessarily smaller body energy reserves, to complete up-river spawning migrations. Further, given the results of Hodgson *et al.* (2006) that timing of migration is relatively fixed for each stock and Welch *et al.* (1998) that sockeye ocean habitat is shrinking and moving farther north, sockeye may face a ‘double whammy’ of having to migrate greater distances in the ocean to even get to natal rivers, potentially exposing them to greater predation risk.

Hodgson, S., T.P. Quinn, R. Hilborn, R.C. Francis, and D.E. Rogers. 2006. Marine and freshwater climatic factors affecting interannual variation in the timing of return migration to freshwater sockeye salmon (*Oncorhynchus nerka*). Fish. Oceanogr. 15: 1–24.

The authors found that, following spring-summer periods with relatively warm SSTs, sockeye populations tended to return to southwestern Alaska early, whereas Fraser River populations returned late and other populations showed no consistent pattern. In support of this, the authors further determined that temperature changes affect the position of salmon in the ocean and that the time at which return migration is initiated remains unchanged by the location of a fish. When taken into consideration with the conclusions of Welch *et al*. (1998) that sockeye habitat may be shrinking in the North Pacific, the ability of the salmon to adapt to a warmer ocean may be even less than previously expected.

Hollowed, A.B., S.R. Hare, and W.S. Wooster. 2002. Pacific Basin climate variability and patterns of Northeast Pacific marine fish production. Prog. Oceanogr. 49: 257–282.

This paper illustrates that salmon stocks appear to be responding to climate forcing on a decadal PDO time scale. This linkage is evidenced by an autocorrelation indicating that the stocks are responding to a low-frequency climate signal. It was also found that interannual El Niño Southern Oscillation (ENSO) type variation did not appear to be as important to salmon as it is to gadids. The opposite effect of the PDO upon Alaskan versus contiguous US salmon stocks is concluded to be due to the different effect of PDO regime change on zooplankton production in the two regions.

Holt, C.A. and R.M. Peterman. 2004. Long-term trends in age-specific recruitment of sockeye salmon (*Oncorhynchus nerka*) in a changing environment. Can. J. Fish. Aquat. Sci. 61: 2455–2470.

The authors show that when assigning time-varying parameters to a model predicting sockeye abundance one year into the future, changes in the parameters tended to be positively correlated among stocks from different regions. The authors conclude that this is due to large-scale bottom-up effects driving changes in life history characteristics like age-at-maturity.

Hunt, G.L. Jr., P. Stabeno, G. Walters, E. Sinclair, R.D. Brodeur, J.M. Napp, and N.A. Bond. 2002. Climate change and control of the Southeastern Bering Sea pelagic ecosystem. Deep Sea Res. II 49: 5821–5853.

The authors propose an oscillating control hypothesis (OCH) to describe climate-derived changes in the Bering Sea pelagic ecosystem from top-down to bottom-up control phases. Cold regimes imply late ice retreat and limited zooplankton prey, causing bottom-up limitation for consumers. During warm regimes, early ice retreat promotes increased zooplankton production and a plentiful bottom-up supply for consumers. As the warm phase continues, however, increasing good recruitment years means more adult piscivores that then have a top down effect upon grazing fishes. The implication for salmon in this process is that in late warm-phase periods, when adult predators are imposing high mortalities upon planktivorous fish, the salmon prosper because they have less competition for food and are not as heavily predated upon by the large piscivorous fish.

Jones, S.A., B. Fischhoff, and D. Lach. 1999. Evaluating the science-policy interface for climate change research. Climatic Change 43: 581–599.

The authors determined that climate change research appears to be incompatible with decision-making processes used by managers despite the fact that managers appear to be willing to use such information. For decision-makers, climate effects appear to be lost within natural variation. Therefore, more research is needed to quantify linkages between climate change and salmon habitat.

Kaeriyama, M. 2003. Evaluation of carrying capacity of Pacific salmon in the North Pacific Ocean for ecosystem-based sustainable conservation management. N. Pac. Anadr. Fish Comm. Tech. Rep. 5: 6–7.

The author shows waxing and waning of carrying capacity similar to regime shifts noted for other salmonids in the North Pacific. Based on this work, the author warns that wild chum have simply been replaced by hatchery chum and that hatcheries are not fulfilling their supposed conservation role of meeting the demands of expanded fisheries.

Kaeriyama, M., M. Nakamura, R. Edpalina, J.R. Bower, H. Yamaguchi, R.V. Walker, and K.W. Myers. 2004. Change in feeding ecology and trophic dynamics of Pacific salmon (*Oncorhynchus* spp.) in the central Gulf of Alaska in relation to climate events. Fish. Oceanogr. 13: 197–207.

Results in this study show that gonatid squid were the main prey item for all species of salmon except chum, which focused upon gelatinous zooplankton. During the 1997 El Niño and the 1998 La Niña events, squid contribution to all species diet compositions decreased, except for coho. Chum switched to a wider variety of zooplankton. The researchers conclude that salmon adapt to climate-induced changes of their oceanic food resources by switching prey and even looking for prey items at very different trophic levels.

King, J.R. (Editor) 2005. Report of the study group on the fisheries and ecosystem responses to recent regime shifts. PICES Sci. Rep. 28: 162 p.

This paper summarises work done by PICES to address the question of what the implications of the 1998 regime shift were for the production of fishes in the North Pacific. This report provides a detailed and cogent explanation of known mechanism that lead to production changes within regions of the North Pacific, as well as across the entire basin. As such, this report is far too extensive to summarise here, but it is a recommended starting point for anyone who wishes to have a good understanding of the most up-to-date knowledge of how climate and regimes affect the fishes, including salmon, of the North Pacific.

Klyashtorin, L. 1997. Pacific salmon: climate-linked long-term stock fluctuations. PICES Press. 5(2): 2–7, 30–34.

The author compares data from several fish populations measured over large area scales to show how they appear to be changing in-phase with several climate indices. Indices of climate change employed ranged from the North Pacific scale (*e.g.*, the Aleutian low- pressure index /ALPI) to the global scale, *e.g.*, Earth rotational velocity index (ERVI). The atmospheric circulation index (ACI) is suggested to be particularly useful in characterising regime changes because, even when unsmoothed, ACI trends mirror those of many North Pacific pelagic fish species. There is a strong correlation between the ACI and ERVI. The ERVI is argued to be the best indicator of global climate trends and also as the source of long-term fluctuations of salmon and many of the other major commercially fished species. The author hypothesises that the ERVI could be linked to the ACI by transport of water from oceans to the poles, affecting the inertia moment of the globe.

Klyashtorin, L.B. 1998. Cyclic climate changes and Pacific salmon stock fluctuations: a possibility for long-term forecasting. N. Pac. Anadr. Fish Comm. Tech. Rep. 1: 6–7.

The material presented in this paper is a refinement of the Klyashtorin (1997) paper and asserts that the ACI is the best climate change signal to use in predicting changes in salmon productivity. The author predicts that total American (*i.e.*, primarily Alaskan) salmon catches, and sockeye in particular, will decline between 2000 and 2030 as the ACI enters a descending phase.

Klyashtorin, L.B. and F.N. Rukhlov. 1998. Long-term climate change and pink salmon stock fluctuations. N. Pac. Anadr. Fish Comm. Bull. 1: 464–479.

This paper is another argument in favour of the ACI as the best indicator of regime change for fishes of the North Pacific Ocean. In this case, comparisons are made between historic changes the ACI and pink salmon production in various regions of the North Pacific. In the authors' opinion, the value of the ACI as an indicator of regime shifts lies in the fact that its long term oscillations, approximately 30 year cycles, are generally free of annual and seasonal noise. Thus even when unsmoothed, it correlates rather closely with long-term changes in North Pacific fish and salmon stocks. The authors also note tight correlations between even and odd-year stocks of pink salmon. The authors suggest that the ACI can thus be used, in conjunction with present-year pink salmon abundance, to forecast one-year-ahead pink salmon abundance.

Koslow, J.A., A.J. Hobday, and G.W. Boehlert. 2002. Climate variability and marine survival of coho salmon (*Oncorhynchus kisutch*) in the Oregon production area. Fish. Oceanogr. 11: 65–77.

The authors show a principal-components analysis of coho production and climate indicators. Several physical indicators (upwelling, mixed layer depth, wind mixing, stratification, SST or transport of the California Current) appear to play some role in helping define the production characteristics faced by coho. The authors conclude that oceanographic variability controls coho marine survival, and that this is most crucial during the first year after ocean entry and just prior to adult return migration.

Kruse, G.H. 1998. Salmon run failures in 1997–1998: A link to anomalous ocean conditions? Alaska Fish. Res. Bull. 5: 55–63.

Certain runs of sockeye, chum and chinook in Alaska during 1997–1998 were noted to be unusually low. The author discusses evidence that these low returns may be caused by bottom-up climate-driven effects upon salmon at various stages of life history. Potential mechanisms investigated here included food available to juveniles, changes to migration pathways, density dependence and food available to adult populations. The author calls for at-sea investigations of the biological consequences of climate change in the North Pacific, especially with reference to the changing populations of coccolithophores and warm water species and the effect these would have on the food web.

Lehodey, P., J. Alheit, M. Barange, T. Baumgartner, G. Beaugrand, K. Drinkwater, J.-M. Fromentin, S.R. Hare, G. Ottersen, R.I. Perry, C. Roy, C.D. van der Lingen, and F. Werner. 2006. Climate variability, fish, and fisheries. J. Clim. 19: 5009–5030.

This paper reviews much of the recent significant research on climate change and fisheries using salmon in the North Pacific as an example. With respect to salmon and climate the authors take particular note of the inverse production phase after the 1977 regime shift in which northern BC and Alaskan stocks were more productive, while southern BC and California current stocks were less productive. The authors note, however, that California current stocks after 1999 appear to have experienced improved productivity. They also point out that, although there were more salmon in the Gulf of Alaska after the 1977 regime shift, there was also evidence that populations had grown to such an extent that competition was having a negative effect upon body size, similar to phenomena described by Ruggerone and Nielson (2004), Helle and Hoffman (1998) and Bigler *et al.* (1996).

Levin, P.S. 2003. Regional differences in responses of chinook salmon populations to large-scale climatic patterns. J. Biogeogr. 30: 711–717.

Before 1977 when PDO was relatively low, productivity of Snake River chinook tended be negatively correlated with PDO values. Conversely, middle Columbia chinook productivity was weakly positively correlated and upper Columbia chinook productivity was moderately positively correlated to PDO values. After the 1977 regime shift, all three stocks of chinook tended to be positively correlated to values of the PDO. This study shows that stocks in the same river can have different responses to climate effects even though the ocean habitat they inhabit is similar. The author suggests that this observation could be due to in-stream migration effects or some unknown effect when the juveniles enter the ocean at slightly different times. The author concludes that the mechanism is as yet unknown, and the ocean processes need to be investigated by field studies.

Levitus, S., J. Antonov, and T. Boyer. 2005. Warming of the world ocean, 1955–2003. Geophys. Res. Lett. 32, L02604. doi: 10.1029/2004GL021592.

This paper provides a convincing argument that the world ocean is warming. The authors contend that the most likely cause is anthropogenic increases in greenhouse gases. It is interesting to note that, while the world ocean did heat up over the whole period, that increase was not monotonic. Indeed, most of the 1980s witnessed a downward trend. This general increase in temperature could lead to regime-like changes, though it would be more pervasive than the decadal or interannual Pacific Ocean and regional production regime shifts which have been the focus of this review.

Levy, D.A. 1992. Potential impacts of global warming on salmon production in the Fraser River watershed. Can. Tech. Rep. Fish. Aquat. Sci. 1889: 96 p.

This early analysis of the effects of climate change upon salmon looks at how changes in flow characteristics of the Fraser River affect migrating salmon. The suggestion is that a warmer river would be a stressor upon return-migrating adult sockeye. This research is the first attempt to infer the effect of likely changes in the Fraser River upon salmon.

Logerwell, E.A., N. Mantua, P.W. Lawson, R.C. Francis, and V.N. Agostini. 2003. Tracking environmental processes in the coastal zone for understanding and predicting Oregon coho (*Oncorhynchus kisutch*) marine survival. Fish. Oceanogr: 12: 554–568.

The authors of this study have developed a model capable of explaining most of the variation (r2 = 0.75) in the OPI. They employ a general additive model (GAM) consisted of 4 components: (1) winter climate prior to smolt migration from freshwater to ocean, (2) spring transition from winter downwelling to spring/summer upwelling, (3) the spring upwelling season and (4) winter ocean conditions near the end of the first year-at-sea of maturing coho. Such modelling may provide a way to predict coho survival and a way to understand the mechanisms that influence coho survival. This model also shows how oceanic processes can explain not only decadal changes in populations but also year-to-year changes in salmon population characteristics (in this case annual coho production). This goes beyond the conclusions of Francis and Hare (1997) who found only decadal sources of climate forcing in salmon populations.

Mantua, N.J. and S.R. Hare. 2002. The Pacific Decadal Oscillation. J. Oceanogr. 58: 35–44.

This contribution is a review of PDO knowledge, though the mechanisms underlying PDO changes remained unclear as of report writing. Klyashtorin shows that changes to the ACI (which is very similar to the PDO) may be related to the ERVI. Evidence shows two complete PDO cycles, with cool PDO regimes prevailing from 1890–1924 and 1947–1976, and warm PDO regimes from 1925–1946 and from 1977 to the mid-1990's. Evidence from coral growth and tree rings further that suggests PDO-like variation may go back as far as to the 1600s. The inverse production regimes of salmon in Alaska versus those of the US West coast are also mentioned.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Am. Meteorol. Soc. 78: 1069–1079.

The Pacific Decadal Oscillation (PDO) is described in detail and compared to climate and biological indicators of regime shifts in the North Pacific Ocean. The PDO, which measures SST anomalies in the North Pacific, suggests coherent and recurring regimes of ocean-atmosphere dynamics. These regimes are demonstrated to have coherent and persistent links between large-scale physical and biological processes. The perspective provided by this work (the existence of decades-long periods of relatively high or low salmon production with identifiable phases) suggested boundaries within which realistic management goals may be framed.

Mantua, N.J. and R.C. Francis. 2004: Natural climate insurance for Pacific northwest salmon and salmon fisheries: finding our way through the entangled bank. Pp. 127–140 in E.E. Knudsen and D. MacDonald (eds.). Sustainable Management of North American Fisheries. American Fisheries Society Symposium 43.

This work examines issues that arise from the problem that climate effects upon salmon are important but often unpredictable. In order to mitigate this unpredictability, the authors recommend: de-emphasizing the role of pre-season run-size predictions; emphasizing pre-season and in-season monitoring of both salmon and their habitat; and developing strategies to increase the resilience of short and long-term planning decisions. Developing what the authors characterise as 'climate insurance' consists of maintaining healthy estuarine and spawning habitats as well as adequate escapement levels. Such actions should mitigate negative effects of climate upon salmon productivity. The authors deem it unlikely that engineering-type solutions and prediction models will provide the certainty, given present-day technology, to obviate the use of climate insurance policies.

Mathews, S.B. 1984. Variability of survival of Pacific salmonids: A review. Pp. 161–183 in W.G. Pearcy (ed.) The influence of ocean conditions on the production of salmonids in the North Pacific. Oregon State University Sea Grant Program, Corvallis.

The author examines various North American salmon stocks to find oceanographic links to changes in ocean survival. The only group for which a linkage was found was Oregon and Columbia River coho whose marine survival appeared to be influenced by coastal upwelling from the early 1960 to early 1980s. The author states that the mechanism causing this could be bottom-up or top-down but does not identify which is more likely. He does, however, point out that either mechanism implies different management strategies. If there is bottom-up control, he suggests altering hatchery coho releases to match the production regime. If there is top-down control, decisions regarding hatchery releases would require knowledge of whether predation is density independent or inversely density-dependent. This is representative of early suggestions that hatcheries do not make more salmon simply because they exist, but rather they may be limited in their ability to mitigate mortality upon wild fish by production mechanisms that occur in the ocean.

McFarlane, G.A., J.R. King, and R.J. Beamish. 2000. Have there been recent changes in climate? Ask the fish. Prog. Oceanogr. 47: 147–169.

The authors derived a composite climate index using a principal components analysis of the Aleutian Low Pressure Index (ALPI), the Pacific Atmospheric Circulation Index (ACI) and the Pacific Interdecadal Oscillation Index. The derived index was compared to changes in many Northeast Pacific fish species, including salmon. Before 1989, the ALPI was very low resulting in above-average westerly and south-westerly circulation and warmer coastal conditions in the Northeast Pacific. After 1989, the ALPI tended to be at values closer to long term mean resulting in less frequent westerly and south-westerly circulation and relatively cooler coastal ocean conditions. BC salmon catches declined to historic lows after the 1989 shift. In particular, coho marine survival plummeted and that, after 1989, the ocean ecosystem in BC had a lower productivity for salmon. The Pacific Ocean north of Queen Charlotte Sound does appear to have responded differently from the rest of the BC coastal system, which concurs what would be predicted from the inverse production regime ideas in Hare *et al*. (1999) and Hollowed *et al*. (2002).

McGowan, J.A., D.R. Cayan, and L.M. Dorman. 1998. Climate-ocean variability and ecosystem response in the northeast Pacific. Science. 281: 210–217.

This work reviews how changes in climate indices compare to changes in indices of abundance of marine organisms. The focus is on the California current, though some comparisons are made to the Gulf of Alaska. Frequency of so-called warm events has been increasing in the California current area since the 1970s. It reiterates that production trends in the California current and Gulf of Alaska are out of phase and that, even in the same ecosystem, not all organisms respond in phase to regime shifts. For instance, Pacific cod, Steller Sea lions, king crab, kittiwakes and murres in the Gulf of Alaska declined even though salmon, walleye pollock, and arrowtooth flounder increased.

McLain, D.R. 1984. Coastal ocean warming in the northeast Pacific, 1976–83. Pp. 61–86 in W.G. Pearcy (ed.) The influence of ocean conditions on the production of salmonids in the North Pacific. Oregon State University Sea Grant Program, Corvallis.

The author notes that SST during the period after 1976 tended to be warmer than that preceding it. The paper takes more notice of annual phenomena, though, describing how declines in upwelling, associated with diminished wind fields and El Niño events, may lead to diminished biological productivity in the California current area. In the Gulf of Alaska area, however, the author points out that warmer years may result in increased biological productivity. These ideas are a qualitative description of what later is called inverse production regimes (Hare *et al*. 1999). Post 1977, the author hypothesized increased Bristol Bay sockeye production being due to warmer winters, allowing better stream flow and flushing for eggs and improved biological productivity in ocean and freshwater habitats, *i.e.*, bottom-up forcing.

Miller, A.J., D.R. Cayan, T.P. Barnett, N.E. Graham, and J.M. Oberhuber. 1994. The 1976–77 climate shift of the Pacific Ocean. Oceanogr. 7: 21–26.

This paper is a description of how a nine-layer model of the Pacific Ocean was able to hind-cast the 1976–1977 regime shift when forced by monthly anomalies of surface wind stress and heat flux. The authors conclude that changes in the mid latitude atmosphere (particularly the anomalous conditions of the winter of 1976) drove the regime shift. They feel that further study is warranted as to whether Ekman transport or geostrophic circulation contributed to establishing the regime shift.

Miller, K.A. 2000. Pacific salmon fisheries: climate, information and adaptation in a conflict-ridden context. Climatic Change 45: 37–61.

This essay explores how climate effects on salmon populations made dividing up the catch more difficult when northern and southern stocks responded differently to the last regime shift. Climate change and variation means that situations can arise in which long-term trends in abundance have nothing to do with past or present management actions. Even worse, management actions that were effective in the past may no longer be tenable to one or both parties in the previous catch agreement. Such situations become more problematic in the management of trans-boundary stocks. In particular, the problem of assigning ownership of fish is noted. For instance: Is it where they were born or where they grew up? In the disputes over salmon allocation in the late 1990s, Canada said the former and Alaska the latter. From the Canadian perspective, Fraser River salmon spawn in Canada. For the Alaskans, Fraser River salmon feed most of their adult life off the Alaska coast.

Miller, K.A. and G.R. Munro. 2004. Climate and cooperation: A new perspective on the management of shared fish stocks. Mar. Res. Econ. 19: 367–393.

This essay describes how unpredictable effects of climate change have led to the conflict between Canada and the US over Pacific salmon management. The author says that fishery agreements must have built-in flexibility to be resilient to unpredictable climate effects. Examples are the use of side-payments and pre-agreements on what to do in the face of sustained changes in productivity or migration patterns. Common scientific understanding also needs to be fostered to maintain a unified frame of reference. The authors suggest game theory as an application that may help to explore co-operative management in the face of uncertain climate effects.

Morita, K., S.H. Morita, and M. Fukuwaka. 2006. Population dynamics of Japanese pink salmon (*Oncorhynchus gorbuscha*): are recent increases explained by hatchery programs or climatic variations? Can. J. Fish. Aquat. Sci. 63: 55–62.

The authors conclude that increased pink salmon catches after 1990 were more likely to be caused by climate-forced ecosystem changes than by hatchery augmentation of the population. The reason is that synchronous increases in non-hatchery augmented populations of pink salmon were observed across the North Pacific after 1990. This conclusion mirrors the results of Hilborn and Eggers (2000) and Beamish *et al.* (1997) regarding the influence of hatcheries on salmon production in the ocean. The authors conclude that the effectiveness of pink hatchery programs should be questioned. They contend that the goal of protecting the genetic diversity of wild fish could be compromised by the presence of hatchery fish in a mixed stock fishery that has some small stocks within it. The authors' advice to managers is to use alternative strategies like spawning-bed enhancement, removal of dams and improving fish passage as more effective tools to conserve salmon stocks. Ironically, these are freshwater enhancements that may not have any more effect than hatcheries if the limit on salmon production is caused by ocean mortality or carrying capacity issues.

Morita, S.H., K. Morita, and H. Sakano. 2001. Growth of chum salmon (*Oncorhynchus keta*) correlated with sea-surface salinity in the North Pacific. ICES J. Mar. Sci. 58: 1335–1339.

This study shows that decrease in size-at-maturity of chum salmon from 1975–2000 is linked to decreases in SSS. Decreasing SSS could result from climate-change driven increases in rainfall or melting polar ice. The authors propose that in a lower salinity ocean production may be lowered, though they do not state why that would be. They also posit that there may be an as-yet-unknown indirect mechanism. They therefore recommend further research.

Mueter, F.J., R.M. Peterman, and B.J. Pyper. 2002. Opposite effects of ocean temperature on survival rates of 120 stocks of Pacific salmon (*Oncorhynchus* spp.) in northern and southern areas. Can. J. Fish. Aquat. Sci. 59: 456–463

In this research, warm coastal temperature anomalies were associated with higher survival rates for Alaskan stocks of pink, sockeye and chum, but had the opposite effect for stocks in BC and Washington. Sea surface temperature measured at a regional scale proved to be a better predictor of salmon survival rates than large-scale indices like the PDO. The inference is that survival rates are thus tied to processes occurring at the regional scale, suggesting a manner in which potential effects of climate change at regional scales may be more accurately predicted.

Mueter, F.J., B.J. Pyper, and R.M. Peterman. 2005. Relationships between coastal ocean conditions and survival rates of Northeast Pacific Salmon at multiple lags. Trans. Am. Fish. Soc. 134: 105–119.

Research is presented showing that survival rates of sockeye, pink and chum were all related to SST around the time of juvenile migration to the sea. No relation was found to upwelling conditions. The correlations of SST to pink and sockeye survival rates from BC and Washington have opposite signs from those for pink and sockeye from Alaska, as seen in many other papers. Consistency is also held with the hypothesis that there is a critical time early upon ocean entry related to ocean survival for salmon.

Mueter, F.J., D.M. Ware, and R.M. Peterman. 2002. Spatial correlation patterns in coastal environmental variables and survival rates of Pacific salmon in the Northeast Pacific Ocean. Fish. Oceanogr. 11: 205–218.

Survival rates of juvenile pink, sockeye and chum in the Northeast Pacific were compared among stocks and to SST, SSS and upwelling. Stock survival rates were seen to be similar within distances of 500 to 1000 km. Of the environmental variables, summer SST was seen to most closely correlate to changes in survival. Thus, the regional scale is most important, in the view of these researchers when considering climate effects on salmon.

Myers, K.W., R.V. Walker, H.R. Carlson, and J.H. Helle. 2000. Synthesis and review of US research on the physical and biological factors affecting ocean production of salmon. N. Pac. Anadr. Fish Comm. Bull. 2: 1–9.

This paper reviews work by US scientists and concludes that while climate change and fishing are the two main causes of salmon production change, the mechanisms effecting those changes remain unclear. In order to elucidate the mechanisms, the authors recommend three complementary courses of action: international baselines for salmon stock identification; ship-borne oceanic research on salmon growth, distribution and migration timings; and creation and distribution of internationally relevant databases on salmon production.

Mysak, L.A. 1986. El Niño, interannual variability and fisheries in the Northeast Pacific Ocean. Can. J. Fish. Aquat. Sci. 43: 464–497.

The author shows how climate variability on an annual scale changes salmon ocean life-history characteristics like migration routes of Fraser River sockeye, early return times for Bristol Bay sockeye, and changes of weight-at-maturity for return-migrating Fraser sockeye several years after an el Niño event.

Nagasawa, K. 2000. Long-term changes in the climate and ocean environment in the Okhotsk Sea and western North Pacific and abundance and body weight of East Sakhalin pink salmon (*Oncorhynchus gorbuscha*). N. Pa. Anadr. Fish Comm. Bull. 2: 203–211.

The author shows that after an interdecadal weakening of the Aleutian low pressure system, after 1989, production of Northwest Pacific pink salmon increased. No relationship was seen with zooplankton in the data analysed, but in a high mortality groups this might not be relevant. If zooplankton production dramatically increased after 1989, the biomass might have remained the same or even declined and still provided ample forage to fish predators.

Nickelson, T.E. and J.A. Lichatowich. 1984. The influence of the marine environment on the interannual variation in coho salmon abundance: An overview. Pp. 24–36 in W.G. Pearcy (ed.) The influence of ocean conditions on the production of salmonids in the North Pacific. Oregon State University Sea Grant Program, Corvallis.

The authors attribute declines in marine production of coho after 1976–1977 to weakening of offshore upwelling in the Oregon area. They obliquely critique the continued increasing production of hatchery coho as futile in the face of a less productive ocean. This line of reasoning is picked up in a more forceful manner by other researchers, *e.g.*, Ruggerone and Goetz (2004), Hilborn and Eggers (2000), and Beamish *et al.* (1997).

Noakes, D.J., R.J. Beamish, and M.L. Kent. 2000. On the decline of Pacific salmon and speculative links to salmon farming in British Columbia. Aquaculture 183: 363–386.

In this examination of a topical salmon management issue, salmon hatcheries, overfishing, spawning habitat destruction and climate change are all argued to be more likely threats to wild salmon stock abundance than salmon farming.

Pearcy, W.G. 1992. Ocean ecology of North Pacific salmonids. Washington Sea Grant Program, University of Washington Press, Seattle and London: 179 p.

This publication reviews the extant knowledge of salmon ecology and thus is not specifically an examination of climate effects. There are, nonetheless, sections devoted to how climate processes might influence salmon populations. Chapter 4, for example, reiterates the conclusion of Mathews (1984) that because only one group of coho stocks were observed to be highly correlated with an environmental variable, such research would not be profitable in helping to formulate stock-specific management policies. Thus, more field work designed to examine specific processes in the marine environment that may affect survival is recommended. The flaw in this reasoning appears to be the failure to recognise the very large interdecadal-scale of climate change effects. Such long-term processes would, by definition, be undetectable over small area scales. As Holling (1992) points out, there is a positive relation between spatial and temporal scales.

Chapter 5 has a discussion of how coho hatcheries in the California current area were established with the belief that limitation of coho production was due to effects in freshwater. However, it became apparent from declining production in the face of expanding hatchery smolt releases in the 1970s and 1980s that hatcheries might actually be hurting wild coho production. Related to this is a description of mechanisms thought to be relevant to coho production; ocean conditions (that is: bottom-up forcing driven by upwelling), density-dependent mortality (potentially when large hatchery smolt releases coincide with low upwelling), and increased at-sea mortality (which could be caused either by a bottom-up driven decrease in growth during poor production years resulting in smaller salmon more vulnerable to predation, or a top-down driven decrease in survival directly sponsored by some process making the juvenile salmon more accessible to predators).

Chapter 6 has a discussion of how changes in the Aleutian Low pressure system appear to be related to changes in salmon production in the Gulf of Alaska. After 1976, it was noted that intensification of the Aleutian low resulted in generally warmer conditions in the Gulf of Alaska, which was coincident with greater production, in particular of pink and sockeye. It is interesting to note that in this chapter there is no difficulty in recognising the relationship between long-term and large-area scales. Perhaps this is because when stocks decline they are triaged one-at-a-time, whereas when stocks increase it is easier to lump them together without worry. There is also some discussion of evidence for density-dependence in this chapter, and what the effect of hatcheries (in the United States, Canada, Russia, and Japan) might be. The author determines that there is no conclusive evidence for density-dependence and says that more research needs to be done regarding the critical time and space scales of salmon in the ocean. The elucidation of these critical time and space scales appears to be well underway given work done by Ruggerone and Goetz (2004) and Beamish and Mahnken (2001).

Peterman, R.M., B.J. Pyper, and J.A. Grout. 2000. Comparison of parameter estimation methods for detecting climate-induced changes in productivity of Pacific salmon (*Oncorhynchus* spp.). Can. J. Fish. Aquat. Sci. 57: 181–191.

The authors examine the efficacy of different algorithms to identify climate driven changes in salmon stocks in the parameters of a Ricker model. This investigation is crucial in that it provides a framework within which management decisions could be made to avoid sub-optimal harvest policies by quickly identifying new stock recruitment parameters resulting from regime shifts and climate change.

Peterson, W.T. and F.B. Schwing. 2003. A new climate regime in Northeast Pacific ecosystems. Geophys. Res. Lett. 30(17), 1896, doi:10.1029/2003GL017528.

Evidence is presented in this paper that the California current may have moved 'back' to a state more productive for salmon following the 1997–1998 El Niño. In support of this argument it is noted that survival for coho went up as did catches of chinook. This study represents an examination of preliminary trends in which changes in the California Current (more upwelling and lower SST) appear to have fostered a switch to a more productive zooplankton regime. Whether or not this will prove to be longer lasting is left unknown, though the authors say it could be indicative of a regime shift.

Preikshot, D.B. 2007. The Influence of geographic scale, climate and trophic dynamics upon North Pacific oceanic ecosystem models. (PhD thesis). University of British Columbia, Resource Management and Environmental Studies and the Fisheries Centre, Vancouver: 208 p.

In this research, ecosystem models were used to examine the combined effects of bottom-up (*i.e.*, climate-driven mechanisms) and top-down (*i.e.*, fisheries and predation) mechanisms upon salmon and other fish species in different North Pacific ecosystems. It was found that while fisheries and predation explained much of the variation in historic salmon population changes, the addition of climate change mechanisms to simulations invariably improved the ability of the models to hind-cast population changes. Climate driven changes were modelled as variations in primary production. It was seen that the predicted changes in primary production for each model were influenced by the area scale of the model. Therefore, large area ecosystems showed high correlations with climate indices measured over large areas, such as PDO, and small area ecosystem models showed high correlations with climate indices measured over small areas, such as sea surface salinity. These differences in production reproduce the inverse production regimes observed by Hare *et al*. (1999). The observations of increases in salmon populations in the Gulf of Alaska after 1977, and declines in southern BC after 1989, are similar to conclusions from ecosystem models of the Northeast Pacific Gyre (Aydin *et al*. 2003) and Northern California Current (Field *et al*. 2006.).

Pyper, B.J., F.J. Mueter, and R.M. Peterman. 2005. Across-species comparisons of spatial scales of environmental effects on survival rates of Northeast Pacific salmon. Trans. Am. Fish. Soc. 134: 86–104.

This paper is a continuation of the research described by Mueter *et al*. (2002) on the relevant scales at which salmon population characteristics appear to vary. The conclusion of the authors, after examining spawner-to-recruit survival of 116 Northeast Pacific stocks of sockeye, pink, and chum salmon between 1948 and 1996, was similar to that of Mueter *et al*. (2002). More specifically in this paper, the regional (100s of km) and even local (10s of km) scale relations are deemed to be more important in characterising changes to salmon populations than basin-scale (1000s of km) processes.

Quinn, T.P. and D.J. Adams. 1996. Environmental changes affecting the migratory timing of American shad and sockeye salmon. Ecology 77: 1151–1162.

The authors find that the timing of up-river migration is delayed by increasing river temperature, but lagged by a few years. They suggest that the early life history of the salmon may have much to do with the lag. They point out that return migration occurs much later in life in sockeye because the conditions facing the juveniles may not mirror those facing the adults, resulting in a lag of the effects upon the adults.

Rand, P.S., S.G. Hinch, J. Morrison, M.G.G. Foreman, M.J. MacNutt, J.S. Macdonald, M.C. Healey, A.P. Farrell, and D.A. Higgs. 2006. Effects of river discharge, temperature, and future climates on energetics and mortality of adult migrating Fraser River sockeye salmon. Trans. Am. Fish. Soc. 135: 655–667.

The authors show that Fraser River flow (high, warm or both) during recent years put unusually high energy demands on early returning Stuart sockeye. In their work, an energetics model, coupled with Fraser River flow predictions to the year 2100, suggests that while the river temperatures will increase, the decreased flow will tend to compensate energetically. However, the authors caution that this would not negate the effects of extremely hot temperatures and that the general compensatory effect of low flow may not be applicable to other salmon stocks. Simulations done with declines in average size of return-migrating adult sockeye salmon, as was demonstrated by Cox and Hinch (1997), suggest it will be more difficult for smaller adult sockeye to cope with the flow conditions predicted for the Fraser River over the next 100 years.

Rogers, D.E. 1984. Trends in abundance of Northeastern Pacific stocks of salmon. Pp. 100–122 in W.G. Pearcy (ed.) The influence of ocean conditions on the production of salmonids in the North Pacific. Oregon State University Sea Grant Program, Corvallis.

The author shows that the pattern changes in winter temperatures measured in Bristol Bay and Kodiak are similar to the pattern of change observed for sockeye catches in Western Alaska and pink catches in Central Alaska. He also points out that, while there was an increase in salmon catches across the Northeast Pacific after the winter of 1976–1977, the increase in Alaskan catches was greater in magnitude than in other areas. This is an early qualitative identification of what years later would be identified as inverse production regimes as described by Hare *et al*. (1999). There is a caveat that, because of the complex and variable life history of salmon, tying changes in salmon production to a single variable like temperature could be problematic. Though this seems to be answered rather effectively by later work, *e.g.*, Mantua and Hare (2002) and Mantua *et al*. (1997) that related temperature change across the North Pacific to changes in salmon production at that scale. The author speculates that the likely mechanism of mortality is from changes in habitat making them more available to predators.

Ruggerone, G.T. and F.A. Goetz.2004. Survival of Puget Sound chinook salmon (*Oncorhynchus tshawytscha*) in response to climate-induced competition with pink salmon (*O. gorbuscha*). Can. J. Fish. Aquat. Sci. 61: 1756–1770.

The authors present research on the issues arising from the fact that return migrating pink salmon are more abundant in even years than odd years in Puget Sound. Juvenile chinook salmon mortality appears to have responded to this even/odd year dichotomy differently in different regimes. From 1972 to 1983, juvenile chinook survival was higher due to greater prey availability and larger numbers of pink juveniles providing a buffer against predation. From 1984–1997, juvenile chinook salmon survival was lower due to competition with pink salmon juveniles in the face of lower ocean productivity. Juvenile chinook salmon released into the ocean in even years after 1984 also had lower growth in their first ocean year. The 1984 regime shift is held to be coincident with 1982/83 El Nino. The paper concurs with the critical size and period ideas of Beamish and Mahnken (2001). Most wild chinook entering Puget Sound tend to be smaller than hatchery raised chinook juveniles, so wild salmon survival could be affected by competition from hatchery raised juveniles. Competition is more important when ocean productivity limits prey availability, such as in 1984–1997. Note that these Puget Sound derived production regime shifts do not precisely coincide with Strait of Georgia salmon production regime shifts in Beamish *et al*. 2004 (1977, 1988 and 1998). The detection of these 'regimes' at smaller scales is thus reflecting more local processes. For chinook and coho, which tend to stay closer to their natal stream when in the ocean (compared to sockeye, pink and chum), such smaller-scale indices may be more appropriate.

Ruggerone, G.T. and J.L. Nielsen. 2004. Evidence for competitive dominance of pink salmon (*Oncorhynchus gorbuscha*) over other salmonids in the North Pacific Ocean. Rev. Fish Biol. Fisheries 14: 371–390.

Research is presented describing how competition from pink salmon was seen to occur both before and after 1977 regime shift with Bristol Bay and Russian sockeye salmon. Competition between pink salmon and chum salmon in the North Pacific and Puget Sound was also observed before and after the 1977 regime shift. However, with chinook salmon, the 1982/83 El Nino precipitated a change noted in Ruggerone and Goetz (2004) from no competition to competition with pink salmon. This competition from pink salmon, existing across climate regimes, suggests that while the 1977 regime shift was favourable to all salmon species, by increasing survival at some critical phase of life history, later life-history stages may have seen competition from the larger numbers of surviving adult pinks. Such competition was evidenced by growth limitation on many species: a result that amplifies implications arising from the critical size hypothesis discussed in the Beamish *et al*. (2004) papers. Such competition implies potential harmful competition from hatchery pinks with not only wild pinks, see, *e.g.*, Hilborn and Eggers (2000) but also other salmon species.

Scheuerell, M.D. and J.G. Williams. 2005. Forecasting climate-induced changes in the survival of Snake River spring/summer chinook salmon (*Oncorhynchus tshawytscha*). Fish. Oceanogr. 14: 448–457.

The authors use a Bayesian model to predict, with high correlation (R2 = 0.71), one-year-ahead changes in smolt-to-adult survival of Snake River chinook, based on indices of coastal upwelling. Stronger upwelling in April and September was associated with higher smolt-to-adult survival, through bottom-up amplification of zooplankton production. In the fall, however, weaker upwelling promotes zooplankton retention at a time when primary production is limited. Thus, ideal annual conditions are strong upwelling in spring and summer and weak upwelling in the fall. This work shows that smaller-scale climate variation indices (in this case upwelling) may be more useful when attempting to characterise the effects of climate upon particular stocks rather than metapopulations, *e.g.*, as also shown in Ruggerone and Goetz (2004) and Mueter *et al*. (2002).

Schumacher, J.D. 1999. Regime shift theory: a review of changing environmental conditions in the Bering Sea and eastern North Pacific Ocean. Proceedings of the Fifth North Pacific Rim Fisheries Conference, 1–3 December, Anchorage AK. 19p.

The author describes four potential mechanisms to cause regime changes in the North Pacific Ocean: changes in solar activity; lunar-nodal cycle of the moon; atmospheric interaction between high-latitude atmospheric pressure patterns, and air-sea interactions between North Pacific circulation and the Aleutian Low.

Seo, H., S. Kim, K. Seong, and S. Kang. 2006. Variability in scale growth rates of chum salmon (*Oncorhynchus keta*) in relation to climate changes in the late 1980s. Prog. Oceanogr. 68: 205–216.

These researchers found that growth rates for juvenile chum from the east coast of Korea were higher in the 1990s than the 1980s. The factor contributing to this may have been the higher zooplankton abundance off Korea in the 1990s. In the sea of Okhotsk where the chum spend their first summer, growth did not change from the 1980s to 1990s. In the Bering Sea occupied by the chum from 2 to 4 years-old, the growth rates were higher in the 1980s than in the 1990s. This Bering Sea change was also associated to changes in zooplankton biomass.

Shuntov, V.P. and O.S. Temnykh. 2004. The North Pacific Ocean carrying capacity—is it really too low for highly abundant salmon stories? Myths and reality. N. Pac. Anadr. Fish Comm. Tech. Rep. 6: 3–7.

The authors argue that salmon carrying capacity has been underestimated. They point out that salmon make up a small portion of the total zooplanktivorous biomass and, therefore, the addition of hatchery-raised salmon should not affect the total amount of available zooplankton prey. They show that in the Sea of Okhotsk it was estimated that salmon consume between 0.7 and 1.5% of all zooplankton while all nekton, when summed, consume only 10% of available zooplankton. This goes against prevailing thoughts in Canada and the US on the subject of hatcheries.

Stephenson, S.A. 2006. A review of the occurrence of Pacific salmon (*Oncorhynchus* spp.) in the Canadian Western Arctic. Arctic. 59: 37–46.

This paper is a compilation of known records of all five Pacific salmon species though the vast majority were for chum salmon, which occur naturally in the Mackenzie River. As for the other four species, records are for single individuals or several infrequent strays. No evidence exists of spawning populations for any east of Point Hope, Alaska (at the North end of the Bering Strait). The authors contend these results show that, as yet, climate variation has not led to the establishment of Pacific salmon stocks in the Western Canadian Arctic (other than the chum salmon already there). The authors also caution that the sparse human population combined with infrequent sampling could also have an effect on what the data appear to be showing. As an extension of this logic, increased sightings could represent the increased effort to find the salmon in recent years and the response to climate change investigations in the Arctic.

Tolimieri, N. and P. Levin. 2004. Differences in responses of chinook salmon to climate shifts: implications for conservation. Env. Biol. Fishes 70: 155–167

This research show how different stocks, or ESUs of chinook salmon from Washington, Oregon, Idaho, and California responded differently to large-scale regime shifts in 1977 and 1989. The differing responses of stocks illustrate the value of different ESUs within a species. While there was an overall decline across all stocks, some did not decline at all after the 1977 regime shift and some may have increased. This suggests that the differing productivity responses are a de-facto insurance against climate uncertainty.

Trudel, M., S. Tucker, J.E. Zamon, J.F.T. Morris, D.A. Higgs, and D.W. Welch. 2002. Bioenergetic response of coho salmon to climate change. N. Pac. Anadr. Fish Comm. Tech. Rep. 4: 59–61.

This paper only uses three years of data but does examine how changes in SST may influence coho growth. The authors find that the physiologic growth within observed SST changes, in itself, explained far less of the change in coho growth than growth resulting from eating the different zooplankton prey that would be found in different temperature regimes. This relates to the critical size and period hypothesis described in Beamish and Mahnken (2001).

Wainwright, T.C. and R.G. Kope. 1999. Methods of extinction risk assessment developed for US West Coast salmon. ICES J. Mar. Sci. 56: 444–448.

The authors show a multivariate assessment tool to describe risk of extinction of chinook salmon stocks. Climate effects were included as one of the factors considered as relevant to assess extinction risk for some salmon stocks, though overall it was limited in importance. This is similar to what Francis and Mantua (2003) argued: that climate variation itself would not be a likely mechanism of extinction.

Welch, D.W., Y. Ishida, and K. Nagasawa. 1998. Thermal limits and ocean migrations of sockeye salmon (*Oncorhynchus nerka*): long-term consequences of global warming. Can. J. Fish. Aquat. Sci. 55: 937–948.

The authors determine that by 2050 the effects of greenhouse gas warming would effectively remove sockeye salmon habitat from the North Pacific, and that the Bering Sea would likely become the better thermal habitat. Significantly, sockeye are shown to respond to very small variations in temperature, thus the restriction of them to more northern ocean habitats will decrease the total available habitat for all North Pacific sockeye stocks. BC stocks would face increased distances to migrate to and from these limited ocean habitats. The authors note that, despite our increasing awareness of the effects of changing ocean habitat and climate upon salmonids, most research is still done on fresh water phases of salmon life-history. There is a call for ocean research as well. Because of the preponderance of freshwater research, the authors feel that decreased production may be incorrectly assigned to freshwater habitat loss rather than marine habitat loss.

Yatsua, A. and M. Kaeriyama. 2005. Linkages between coastal and open-ocean habitats and dynamics of Japanese stocks of chum salmon and Japanese sardine. Deep-sea Res. II 52: 727–737.

The authors demonstrate high correlations between the Aleutian low pressure index and carrying capacity for North Pacific sockeye pink and chum. However, they also found that for individual populations of chum, local environmental conditions (SST and anthropogenic factors (hatcheries, overfishing) were more important than population changes. This reinforces the determination of climate scale effects as observed in Scheuerell and Williams (2005), Ruggerone and Goetz (2004) and Mueter *et al.* (2002).

Zabel, R.W., M.D. Scheuerell, M.M. McClure, and J.G. Williams. 2006. The Interplay between climate variability and density dependence in the population viability of chinook salmon. Cons. Biol. 20: 190–200.

Strong evidence was found for density-dependent recruitment and also linkages between third year survival and ocean conditions. When density dependence effects were combined with simulated poor ocean conditions, which the authors call the worst-case scenario, the risk of quasi-extinction of the stocks was greatly increased. Other portions of life history were not observed to have much effect on population viability. Given that much effort is devoted to increasing in-river migration success (and that authors found it had little bearing upon population viability) it is suggested this not be seen as the best allocation of management resources. The likely effects of climate change make the future ocean conditions for chinook more likely to mimic the modelled worst-case scenario. Even more troubling, poor ocean conditions combined with density dependence effects could lead to rapid stock crashes in the future. The authors propose increasing fresh water carrying capacity to mitigate the combined effects of density dependent recruitment with likely poor future ocean survival in the third year. The authors also note that the responses of individual stocks in a river basin (in this case the Snake) may vary from the basin scale results shown here. Such differences of stock response to regime change were demonstrated for Columbia River chinook by Tolimieri and Levin (2004).

INTRODUCTION TO PART 2

The first part of this report was a review of literature regarding the effect of climate change and variation on oceanic salmonid populations, with special attention to research relevant to a Canadian context. In that review, a heavily annotated bibliography was presented to guide the reader through the new and emerging science devoted to climate effects on oceanic salmon. Based on this literature survey, the reader is invited to consider research themes that fall into seven categories: 1) bottom-up control, 2) fisheries / predation, top-down control, 3) salmon hatchery effects, 4) competition and density-dependence, 5) the existence of a critical ocean phase, 6) different production regimes in space and time, and 7) changes in growth and energetics. All the literature described contained one or some combination of those seven themes. Indeed, a full understanding of these seven issues will be needed to form research and management responses to the challenge posed by climate change to salmon ocean habitats.

Naturally, the authors of the work described in the review did not produce their results in institutional vacuums. We know that some level of response has already been developed to the issue of climate and salmon in the ocean. Because this research is relatively young, however, the institutional response is still in the 'gearing up' phase. This second review, thus, is a look at what that institutional response has been both in Canada and around the Pacific Rim. In this report the reader will see reviews of research organisations that have made significant contributions to studying the effect of climate change on oceanic salmon. The first section describes five of the leading research institutions that have had direct experience in generating targeted research on the question of climate and salmon in the ocean. The second section examines marine science organisations that have played a less direct role in researching the issue but have made important contributions. The last section describes how academic institutions have played a role in this research.

Throughout this review, as the organisations and the research they conduct are described, try to keep in mind the seven themes that framed the literature review on salmon-climate research. Some organisations have hundreds of employees and others fewer than a dozen. When evaluating these research organisations, it may become apparent that some, most, or all of the themes that frame Canada's needs for research on climate and salmon in the ocean have already been undertaken elsewhere. It may also be that none, or no combination of the institutions reviewed satisfy the requirements of research specific to Canada. Regardless, the way in which research teams were assembled, the number of researchers needed, and the nature of the institution hosting the researchers is valuable information for guiding the creation of a program in Canada to understand the mechanisms linking changes in climate to changes in salmon in the Pacific.

LEAD RESEARCH INSTITUTIONS

CANADIAN CLIMATE IMPACTS AND ADAPTATION RESEARCH NETWORK

HISTORY AND GOALS

The Canadian Climate Impacts and Adaptation Research Network (C-CIARN) was established in 2001 to promote research on the effects of climate change and ways to adapt to such changes. In furtherance of this goal it also sought to bring researchers together. The C-CIARN program was cancelled in June 2007, as it was deemed to have successfully achieved its mandate. As part of this work regional and sector groups were established and C-CIARN Fisheries was one of these. C-CIARN Fisheries was based in the Pacific Biological Station (PBS) in Nanaimo, BC. As in the case of its larger parent organisation, C-CIARN Fisheries was mandated to encourage research into climate change and fisheries by creating a network of researchers and stakeholders. As part of its operating principles, C-CIARN Fisheries was to have an independent voice and encourage transparency in dealing with issues relating to its mandate. Information on the history of C-CIARN and C-CIARN Fisheries was taken from their respective internet archive pages: www.c-ciarn.ca and www.fishclimate.ca.

RESEARCH

Due to its mandate, C-CIARN Fisheries did not engage in research itself, but provided a forum within which research could occur. Also, most of the work sponsored by C-CIARN Fisheries was not specific to issues regarding salmon. Salmon were implicitly covered by much of the research sponsored by C-Cairn Fisheries and some projects were specifically dedicated to salmon issues. For example, Dr. John Dower at the University of Victoria did a two year study on the effect of recent climate change on the early marine growth rates of juvenile salmon in the Strait of Georgia, though this work began, or was at least funded even before the creation of C-CIARN Fisheries; see the Natural Resources Canada (NRC) news archive at www.nrcan-rncan.gc.ca/media/archives/. Also note that this research overlaps work done by Dr. Richard Beamish and colleagues at the PBS, *e.g.*, Beamish *et al*. (2004) and Beamish and Mahnken (2001), an organisation further detailed in its own section. One major achievement of C-CIARN Fisheries was organising conferences and workshops in which researchers studying the effects of climate change and variation were able to compare results. In particular, the *Climate and Fisheries: Impacts, Uncertainties and Responses of Ecosystems and Communities Conference* in Victoria during October 2005 was a productive forum sponsored by C-CIARN Fisheries. More than a third of the presentations were directly related to salmon and climate issues and many more included salmon as an implicit component (Anon. 2005).

TEAM

C-CIARN Fisheries was headed by Dr. Karen Hunter and Dr. Kim Hyatt at the PBS. The advisory committee was made up of 21 researchers, managers and policy experts, from across Canada.

RELEVANCE TO PRESENT AND FUTURE CANADIAN NEEDS

C-CIARN Fisheries represented a first step in coordinating research on fisheries and climate issues. It provides a useful framework for what an effective salmon research and management network might look like. Because C-CIARN Fisheries is no longer active some momentum may have been lost for future attempts to create research bridges. However, C-CIARN Fisheries was not specific to salmon, so it may yet be possible to encourage Canadian salmon researchers, as a targeted group, to pool knowledge on the effects of climate change in a new forum. There would have to be added incentives, however, for such a new forum to succeed: the generation of novel and useful research. A new climate and salmon specific forum could generate interest and participation by specifically funding research, not merely facilitating the exchange of ideas from other institutions. The work of C-CIARN Fisheries, thus provides us with a model upon which a fruitful salmon and climate research network might be constructed. Further to this, C-CIARN Fisheries had a mandate that spanned fresh water, estuarine and oceanic environments. If a research group addressing salmon climate interactions is to be novel and relevant it must be focused upon understanding processes that occur in the oceanic phase of salmon life history. As is apparent from the groups listed in this report there are presently many groups dedicated to understanding mechanisms, climate driven or otherwise, that affect salmon in fresh water and estuarine environments. The mere creation of a salmon climate research group that covers all aspects of salmon life history will thus implicitly duplicate structures already in existence. Most of the questions that remain in understanding changes in salmon populations are those related to the marine phase of their life history.

CLIMATE IMPACTS GROUP

HISTORY AND GOALS

The Climate Impacts Group (CIG) began in 1995 as one of three groups in the Center for Science in the Earth System (CSES) at the University of Washington (UW). The CIG is funded and managed, as part of CSES, through two National Oceanographic and Atmospheric Administration (NOAA) programs; the Regional Integrated Science and Assessment (RISA) program and the Climate Diagnostics and Experimental Prediction (CDEP) program. The goal of the CIG is to conduct research into climate effects specifically on the Pacific Northwest region of the US and to promote the use of this information in regional decision-making. The research conducted by the CIG can be divided into three categories: natural sciences, social sciences, and outreach to stakeholders. Natural sciences research of the CIG is, in turn, comprised of five sectors: regional climate, hydrology and water resources, forest ecosystems, aquatic ecosystems, and coastal environments. It is the aquatic ecosystem sector of the CIG that is responsible for research into climate and salmon issues as they pertain to the ocean environment.

RESEARCH

The aquatic ecosystem sector of the CIG follows four primary research themes: 1) the relative utility of salmon restoration strategies given habitat and climate changes due to both natural and anthropogenic forcing, 2) how climate variation affects the survivability of Pacific Northwest salmon throughout their lifecycle, 3) explaining the role of climate in the Washington-Oregon coastal marine ecosystem, and 4) to increase the effectiveness of resource management decisions and the resilience of crucial ecosystems. Two of these research goals are directly related to salmon and the other two have salmon as a large implicit component.

TEAM

The key researchers in the CIG aquatic research sector are Dr. Bob Francis and Dr. Nathan Mantua though many others have made contributions. Given the numerous papers the two key researchers have listed in the companion Part 1 literature review to this report, six as primary author and six as co-author(s), the relevance of this group to the study of climate effects upon salmon in the ocean can not be disputed. From 1997 to the time of the preparation of this report researchers from the CIG aquatic ecosystem sector have published 49 articles in peer reviewed literature, of which 14 explicitly deal with salmon, with most of the others including salmon as an important component.

RELEVANCE TO PRESENT AND FUTURE CANADIAN NEEDS

The CIG aquatic research sector has provided not only relevant research on the effect of climate change on salmon in the ocean, but also ways for management and the public to use this research. For example, a reliable model has been developed to use environmental and climate indicators to make in-season forecasts of Oregon coastal coho salmon survival (Logerwell *et al.* 2003), and key large-scale indicators of Northeast Pacific climate regime shifts, relevant to salmon, have been developed (Hare and Mantua 2000 and Mantua *et al*. 1997). The two key researchers have also explored ways to develop salmon management strategies that are more robust to the effects of climate change (Mantua and Francis 2004). Other relevant activities of the CIG aquatic research sector are regularly hosting meetings and workshops, providing a platform for the delivery of graduate level courses at the University of Washington, and making presentations to the public, media, and members of executive and legislative branches of the government. The integration of the CIG aquatic research sector across academic, social and managerial fora has given it a significant degree of relevance. This legitimacy across different user group frameworks is useful in delivering messages. Research is all too often regarded as motivated by environmentalists, industry, government, or some combination of the three. The creation of a climate change and salmon research group on the University of Washington campus appears to insulate the research products from the perception of interference by one or more interest group. Incidentally, this is similar to the Pacific Fisheries Resource Conservation Council (PFRCC), discussed below in the ‘Other Salmon and Marine Science Organisations’ section with its stated goal of providing independent advice to Federal and Provincial governments, First Nations, and the Public.

As suggested in the section on C-CIARN Fisheries and the PFRCC there is fertile ground in Canada and British Columbia for the frank discussion of salmon management in the face of climate change. The CIG aquatic research sector provides the model of a useful research motor that, if added to the pre-existing machinery of Canadian organisational groups, like C-CIARN and the PFRCC, could be tasked specifically to create a Canadian research base on the effects of climate change on salmon on our Pacific coast.

DFO PACIFIC REGION, PACIFIC BIOLOGICAL STATION, FISHERIES CLIMATOLOGY

HISTORY AND GOALS

The Pacific Biological Station (PBS) was established in 1908 and continues to be the focus of fisheries research on the West Coast of Canada. The original facility was a lab building with a wharf, which was replaced by an expanded research facility in 1950. PBS expanded a second time, in 1970, with the addition of more office and laboratory space and again, in 1984, with the addition of more laboratory space. Within the various projects conducted by staff at the PBS two subsections, salmon and groundfishes, have made contributions to the study of climate change and its effect on the ocean environment. Salmon investigations have been ongoing since 1926. Research on groundfishes at PBS has been ongoing since 1942. A Fisheries Climatology Group exists within the groundfish section of PBS.

RESEARCH

While there is no dedicated funding to study the effects of climate change on salmon and other fishes in the ocean, the PBS fisheries climatology group has directed significant effort towards investigating when the ocean enters different periods of productivity. Given the ability to define and even predict such regimes, information on relative production could then be used to improve stock assessments. The years after 2000 also have been characterised an over-arching effort among researchers at PBS to describe how climate drives changes in the way the ocean-ecosystem functions. Summations of such work can be seen in documents like the Ocean Status Reports, which have been prepared annually, since 2000, by members of the Pacific Scientific Advice Review Committee (PSARC). The 2006 Ocean Status Report (DFO 2007) includes extensive analyses on how climate has affected stocks of chum, sockeye, coho, and chinook with likely future stock effects given predicted ocean conditions.

TEAM

The Fisheries Climatology Group has three researchers from the groundfish section and three researchers from outside. Dr. R. Beamish, in particular, has authored much of the published literature, from Canada, on the effects of climate change upon salmon in the ocean. However, members of this group have other areas of research responsibility.

RELEVANCE TO PRESENT AND FUTURE CANADIAN NEEDS

PBS has been a key institution for the development of Canadian research into climate effects on salmon in the ocean. Unfortunately, no formal program with dedicated 'hard' funding exists to study climate effects. The effect of climate is instead studied as part of other projects. Therefore the attention devoted to climate issues is subject to the explicit needs of each project. Regardless, the PBS tradition of research excellence and the number of projects conducted there have combined to make it the largest repository of local knowledge of salmon biology. However, the early 21st Century witnessed a decline in funding available to DFO science, relative to the late 1980s and early 1990s (Peterson *et al.* 2005). This tighter money situation presents a challenge to researchers in PBS who may want to pursue more research in the arena of climate and salmon in the ocean. Because current responsibilities are already great, and because some limited research on climate effects on salmon in the ocean is part of extant projects, it may be difficult for regional mangers to fund an ocean climate-salmon project.

NORTH PACIFIC ANADROMOUS FISH COMMISSION

HISTORY AND GOALS

The North Pacific Anadromous Fish Commission (NPAFC) is the successor organisation to the International North Pacific Fisheries Commission (INPFC). The INPFC existed from 1952 to 1992 and was dedicated to the coordination of international studies upon both anadromous and non-anadromous fishes in the North Pacific. Whereas the INPFC consisted of only Canada, the US, and Japan, the NPAFC also includes Korea and Russia. The NPAFC was set up to focus on salmonids, in particular seven species: chum, pink, sockeye, chinook, coho, steelhead, and cherry. The goal of the convention is to promote the conservation of stocks of the aforementioned species through prohibitions on directed fisheries and limitation of salmonid by-catch in other fisheries. These conservation measures are used within a 'convention area' which is defined as Pacific Oceanic waters north of 33ºN and outside of member states' territorial waters.

RESEARCH

The Science sub-committee of the NPAFC acts as a planning body to facilitate co-operation by member states and to set priorities for these joint research programs. In order to achieve this goal the Science sub-committee formulates multi-year science plans, the most recent for the period from 2006 to 2010. The 2006–2010 plan identified two questions to guide NPAFC work towards an ecosystem-based approach to salmon conservation. First, what are the present trends of salmonid production and how are these trends related to population structure and diversity? Second, what are the effects that climate change will have on salmonids and species that are associated with salmonids in North Pacific ecosystems? The NPAFC science plan explicitly identifies climate change as a factor in salmonid production change. Further, because climate change, and variation, may likely be greater than in the past it is crucial to better understand how climate forcing has affected oceanic salmonid production in the past and how this may change in the future. Such work entails a massive coordination of researchers from the signatory countries. However, the NPAFC is candid in admitting that it had been difficult to obtain funding in the first years of the 21st Century.

TEAM

The various working groups and committees of the NPAFC are made up of dozens of researchers from member nations. More specifically, the Science sub-committee consists of one representative from each member state, chaired by Dr. R. Beamish, *n.b.*, the proponent of much of the research on climate effects on salmon in the North Pacific at PBS.

RELEVANCE TO PRESENT AND FUTURE CANADIAN NEEDS

Canadian researchers contribute greatly to the work coordinated by the NPAFC. As of 2007, the NPAFC carried out several research programs in addition to the work of the Science Sub-Committee; the Working Group on Stock Assessment, the Working Group on Salmon Marking, the *ad hoc* Working Group on Stock Identification, and the Bering-Aleutian Salmon International Survey (BASIS) Working Group. While none of these research streams is explicitly dedicated to the effects of climate change on salmon in the ocean environment, significant contributions have arisen from their work, see *e.g.*, contributions in Myers (1998) and Beamish *et al*. (2006). Further, the research carried out by the NPAFC is unlikely to target questions specific to the needs of Canadian scientists and decision makers. The NPAFC does provide a useful framework within which Canadians might formulate questions worthy of study for our own purposes, given what others have found locally and what collaborative work has found regionally.

NORTH PACIFIC MARINE SCIENCE ORGANIZATION—CLIMATE CHANGE AND CARRYING CAPACITY PROGRAM

HISTORY AND GOALS

The North Pacific Marine Science Organisation (PICES) was established in 1992. The purpose of PICES is to advance knowledge about North Pacific Ocean (North of 30ºN) and marginal seas by promoting and coordinating international marine research. Specifically, PICES is tasked to do this through investigating climate change, global weather, marine resources in the context of their ecosystems, and human effects like fishing and pollution. In 2007 the membership of PICES was Canada, the People's Republic of China, Japan, the Republic of Korea, the Russian Federation, and the United States of America. In the role of coordinating research, PICES not only links partners among its member countries but also with external international marine research organisations like the International Council for the Exploration of the Sea (ICES) and Global Ocean Ecosystem Dynamics (GLOBEC).

In promoting research PICES is organised into various groupings depending on the nature of the research topic. Research topics are divided into the following categories: scientific committees, working groups, sections, study groups, scientific programs, task teams and advisory panels. PICES has deemed that Climate Change is a significant issue of concern to all members and with effects that span all ecosystems in the North Pacific. Therefore, climate change is handled as a scientific program, the PICES Climate Change and Carrying Capacity Program (PICES CCCC). A scientific program is defined by PICES as an issue requiring the devotion of significant resources for a period as long as ten years.

As a scientific program, the idea of a PICES CCCC program was first agreed upon in 1993 and the first meeting was held in 1994 (PICES 1996). This illustrates that, from its start, PICES recognised the significance of relating climate changes to the changes that occur in Pacific marine ecosystems and its fish populations. Another outcome of the long-term dedication of PICES to the CCCC was relating the long-term time scale of the program (ten or more years) to the long-term time scale of the phenomenon under study (decadal changes in climate regimes). Although PICES does not regulate fisheries, the CCCC was seen as having relevance to all member countries as they carried out their own management programs.

RESEARCH

The major focus of the PICES CCCC has been the participation of its members in two task teams, the Conceptual/Theoretical and Modeling Studies Task Team (MODEL) and the Climate Forcing and Marine Ecosystem Response Task Team (CFAME). The MODEL task team has worked extensively with the Basin Studies Task Team (BASS), which is now disbanded, in the production of regional and basin scale ecosystem models of the North Pacific (Kishi 2004 and McFarlane *et al.* 2001). This ecosystem modelling work includes dynamic simulation efforts at upper-trophic level based models, *e.g.*, Ecosim (Aydin *et al.* 2003), lower-trophic level based models, *e.g.*, NEMURO (Werner *et al.* 2007). This research has allowed the community of fisheries researchers in the North Pacific to form a better understanding of how climate has forced changes in the structure of ecosystems and changes in populations of managed species like salmonids. Indeed salmon have often been included in modelling work produced by MODEL, though determining how climate variation changes populations of salmon, *per se*, in the ocean is not an explicit goal of either the CCCC or MODEL.

TEAM

As of November, 2007, the PICES CCCC had 21 members, with representatives from all PICES member states. The PICES CCCC is chaired by Dr. Michio Kishi of the Graduate School of Fisheries Science at Hokkaido University and Dr. Harold Batchelder from the College of Oceanic and Atmospheric Sciences at Oregon State University. As with several of the other organisations discussed previously Dr. R. Beamish from PBS in Nanaimo is a member of the committee and has been since its inception.

RELEVANCE TO PRESENT AND FUTURE CANADIAN NEEDS

The intention of the CCCC is to predict future configurations of North Pacific ecosystems, given suspected climate trends. While it is true that salmon are an important species to the management agencies of all PICES members, the research and modelling work done by the CCCC must reflect the *whole* ecosystem. Remember; salmon are a small proportion of the total fish biomass in the North Pacific, even in the various pelagic habitats. For modellers this suggests that top-down or bottom-up changes to ecosystem structure are more likely to be driven by other species. Therefore, salmon in such work would *reflect* other changes. Further, PICES work will treat Canadian habitats as but one component of the whole basin. It should be borne in mind that Canadian waters are much smaller in area than those belonging to most other PICES members: about 11 % of US waters, 5 % of Russia, and 17 % of Japan, see table 1 in Hunt *et al*. (2000). Further, Canadian waters represent 0.6 % of all waters PICES considers germane to its research and, therefore, important to the CCCC. It must be concluded that topics of specific application to Canada's salmon may not play a huge role in many of the collaborative products arising from research targeting the North Pacific Basin. Climate influences on ocean salmon populations will likely be a portion of the CCCC that receives much attention, but it does not drive that research.

OTHER SALMON AND MARINE SCIENCE ORGANISATIONS / RESEARCH CONTRIBUTORS

ALASKA DEPARTMENT OF FISH AND GAME—DIVISION OF COMMERCIAL FISHERIES

The goal of the Alaska Department of Fish and Game Division of Commercial Fisheries (ADF&G-DCF) is to ensure an optimal harvest of Alaska's fishery resources while maintaining sustainability. This charge stems from the Alaska state constitution, which charges the legislative and executive branches of the state with responsibility to ensure the "…maximum benefit of its people…and…management of renewable resources on a sustained yield basis…" (ADF&G 2007). In order to achieve this goal the ADF&G-DCF is tasked to provide research services including: stock assessment of salmon and other fished species, harvest management of fished species, genetics research, pathology, ageing and tagging research, aquaculture regulation, database management and dissemination of research conclusions. Climate change issues appear to be fairly low on the priority list of the ADF&G-DCF. The relative lack of interest by ADF&G in climate change may reflect the generally positive effects that recent climate variation has had on Alaskan fish stocks in general (Benson and Trites 2002) and salmon in particular (Lehody *et al*. 2006 and Hare *et al*. 1999).

ALASKA FISHERIES SCIENCE CENTER OCEAN CARRYING CAPACITY PROGRAM

The Alaska Fisheries Science Center Ocean Carrying Capacity Program (AFSC OCCP) is located at the Auke Bay Laboratory (ABL) in Juneau Alaska—an installation of the National Marine Fisheries Service (NMFS). The research of the AFSC OCCP is directed towards integrating oceanography with assessments of fish stocks and habitats in the Gulf of Alaska and Bering Sea. In this research salmon investigations are particularly important and strong institutional linkages exist with the NPAFC and GLOBEC and, therefore, with PICES. Significant research on climate effects on salmon in the ocean environment occurs within the Ecosystem Monitoring and Analysis Group (EMAG). EMAG research has linked changes in climate and oceanography to changes in time series of salmon, growth, production, age, size and survival (Helle *et al*. 2007 and Helle and Hoffman 1998).

ALASKA FISHERIES SCIENCE CENTER RESOURCE ECOLOGY AND FISHERIES MANAGEMENT DIVISION

The NMFS also operates the Alaska Fisheries Science Center Resource Ecology and Fisheries Management (AFSC REFM) Division. Within REFM is the Resource Ecology & Ecosystem Modeling (REEM) Program. Work has been done at REEM to model historic and future changes in the Northeast Pacific and Eastern Bering Sea ecosystems. A significant portion of this research has been collaborative with colleagues in PICES as part of the CCCC program. Although groundfish and crab stocks are the primary focus of research at REFM and REEM, the ecosystem framework used by these researchers means that observations on changes in oceanic salmon populations are often emergent (Field *et al*. 2006 and Gaichas 2006).

BRITISH COLUMBIA CONSERVATION FOUNDATION—GREATER GEORGIA BASIN STEELHEAD RECOVERY PLAN

The British Columbia Conservation Foundation (BCCF) is a charitable organisation established in 1969 that seeks to maintain and foster wildlife populations though sponsorship of field research projects. Among the current BCCF projects is the Greater Georgia Basin Steelhead Recovery Plan (GGBSRP), which is operated in conjunction with the British Columbia Ministry of Water, Land and Air Protection using funding from the Habitat Conservation Trust Fund (Baird 2005). Because of the nature of Canada's constitutional history the purview of the Provincial government's control over fish resources is constrained to fresh water. Thus, it is not surprising that the majority of research and projects sponsored by the GGBSRP are found in fresh water, *e.g.*, habitat restoration, and stock assessments based on in-river techniques like snorkel and angling surveys. The guiding philosophy for the GGBSRP (Lill 2002) does note that a full understanding of changes to marine survival, driven by climate variation, are of great consequence to changes in steelhead stocks. However, it is noted that the purpose of the GGBSRP should be to improve freshwater habitat and, therefore, production to the point that lower marine survival, whether climate induced or not, can be mitigated.

NORTHWEST FISHERIES SCIENCE CENTRE FISH ECOLOGY DIVISION

The Northwest Fisheries Science Centre (NWFSC) in Seattle has a Fish Ecology Division which conducts extensive research on issues related to salmon: adult and juvenile migration, early entry to the ocean, climate-driven changes in ocean productivity, and factors regulating predators and prey of salmon. As an example of the scope of the work conducted at the NWFSC, its researchers published about three dozen peer-reviewed articles in scientific journals in 2006. The Fish Ecology Division has a climate change and ocean productivity program which is tasked with identifying mechanisms governing lower trophic level production in the Northern California Current.

PACIFIC FISHERIES RESOURCE CONSERVATION COUNCIL

The Pacific Fisheries Resource Conservation Council (PFRCC) was established in 1998 to provide advice to Federal and Provincial ministers responsible for managing British Columbia's fisheries as well as the general public (PFRCC 1999a). Initially, the PFRCC was seen as a way to help foster cooperation between Federal and Provincial governments in efforts to conserve and rebuild salmon stocks in BC. Although the PFRCC is focused on salmon, it frames its advice within the context of the marine and fresh water ecosystems in which salmon populations are found. Despite being funded by government, the advice provided by the PFRCC is independent of government control. Because of this independence the PFRCC provides a conduit for the free flow of information on salmon issues to both the ministers responsible as well as the public. The PFRCC is tasked to provide a strategic review of actions being taken by government to further the goal of salmon conservation. In this strategic role it also reviews the research that has been done, in the past, and should be done, in the future, to understand freshwater and marine phases of salmon life histories.

Research conducted at the request of the PFRCC appears in the form of reports that are published under four themes relevant to salmon conservation: stocks, habitat, fisheries, and aquaculture. Further, every year is witness to a summary of activities by the PFRCC, including key portions of reports from that year, in the form of an annual report. Because of the strategic, long-term, perspective the PFRCC fosters to study salmon and salmon ecosystems, many of these reports include assessments on climate change. One of the early salmon stock reports (PFRCC 1999b) details the proceedings of a workshop at which university and government researchers met with and representatives from First Nations groups, Federal and Provincial governments, non-governmental organisations, and the press. This workshop allowed people from different backgrounds to discuss climate change effects on salmon and salmon-ecosystems in both the ocean and fresh water. Other reports (PFRCC Nelitz *et al*. 2007a and 2007b) have dealt with the effects of climate change on salmon in fresh water ecosystems.

The Managing Director of the PFRCC is Gordon Ennis. The PFRCC consists of a chair, and deputy chair, supported by both regular and *ex-officio* members who represent an array of First Nations, user groups, government organisations, academic institutions and non-governmental organisations. In general, the reports produced at the behest of the PFRCC are prepared by independent researchers, not permanent PFRCC staff.

The attention to the fresh water phase of salmon life history in much of the historic research of the PFRCC is not surprising. Government and academic research on salmon had also been dominated by fresh water salmon habitat, given that human interaction was easiest there. It was also thought that life-history phases like spawning, egg to larval survival, and downstream migration were the most important in determining the strength of salmon populations. However, an increasing body of research and literature now suggests the importance of the ocean phase of salmon life history in determining the size of salmon populations. This is illustrated by the appearance of the climate change and oceanic salmon population publications, detailed in Part 1 of this report (the Literature Review), in the late 1980s and early 1990s. As research on climate driving changes to ocean ecosystems and hence salmon populations has grown, so too has the interest of the PFRCC to incorporate this knowledge in its work. It should not be said that the PFRCC has operated outside this research either. From the outset of its work it was noted that

For at least the first half of this century, DFO laboured under the assumption that the number of salmon returning from the sea was limited only by the number of salmon that spawned in its parent generation, and that fishing effort was the only demonstrable restraint on abundance…By mid-century, scientists had begun to accept that things weren't so simple, and that other factors—such as competition between salmon for food—also had to be taken into account….By the 1990s, nobody was suggesting that the ocean was endlessly bountiful. And nobody was suggesting that it did not matter what happened to salmon in the sea. Experience had shown that, beyond influencing the numbers of returning salmon, ocean conditions affected the physical status of returning fish…(PFRCC 1999a)

The evolving recognition by the PFRCC, and others, of the role that changes in the marine environment play in changing salmon populations means that the effects of climate on ocean production must be better understood. In the Canadian fisheries science/ fisheries management context there is a general acceptance by most stakeholders that the PFRCC is a model of the effective marshalling of resources to cope with complex questions, difficult research and hard choices. A similar approach could therefore be used to frame questions about the effects that climate change has on salmon in the ocean environment in the past, present, and future.

PACIFIC SALMON COMMISSION

The Pacific Salmon Commission (PSC) was established to implement the Pacific Salmon Treaty of 1985. The PSC is the successor organisation to the International Pacific Salmon Fisheries Commission (IPSFC), which was established in 1937. The PSC is responsible for salmon stocks originating in either country which are subject to interception by fisheries of the other country. The two goals of the PSC are described as: conservation of salmon to ensure optimal production and division of harvests that ensure the benefit of both countries. Although it does not explicitly target research on the effects of climate change on salmon in the ocean, stock assessments and other work done by the PSC include such considerations.

PACIFIC SALMON FOUNDATION

The Pacific Salmon Foundation (PSF) was established in 1987, but became much larger and more active after the establishment of the Pacific Salmon Endowment Fund (PSEF) in 1998. The PSF and PSEF now act in partnership. The goal of the PSF is to conserve and enhance salmon stocks for the benefit of future and present generations. This goal was pursued in the past through the creation of community-based salmon habitat restoration. More recent work has included developing recovery plans for targeted stocks and watersheds. The PSF has occasionally partnered with researchers conducting research on the effects of climate variation on salmon in the marine environment, *e.g.*, the Pacific Ocean Shelf Tracking (POST) Project (Welch *et al.* 2005). None the less, the focus of the PSF remains on increasing salmon populations via enhancement of fresh water production.

PACIFIC STATES MARINE FISHERIES COMMISSION—ANADROMOUS FISH PROJECTS

The variety of marine fish species, fishing gear types, and political jurisdictions (interstate and international) of the US Pacific Coast has given rise to a number of commissions and councils to manage fisheries and coordinate research. The Pacific States Marine Fisheries Commission (PSMFC) is an interstate entity with projects dedicated to anadromous fishes, the Columbia River, habitat research, invasive species, and marine research. Other such US organisations, on the Pacific coast, include: the Lower Columbia River Estuary Partnership, the Pacific Fishery Management Council, Pacific Marine Conservation Council, the Pacific Salmon Commission, the North Pacific Anadromous Fish Commission, the North Pacific Fishery Management Council, the Northwest Indian Fisheries Commission, and the Northwest Power and Conservation Council. As an interstate organisation, the goal of the PSMFC is to conserve and manage fisheries resources of the US Pacific States by providing state governments with an organisation that coordinates research and monitors fisheries. In dealing with salmonids, the PSMFC is pursuing about three dozen anadromous fish projects. Most of these projects focus on fresh water portions of salmon life-histories, reflecting the jurisdictional scope of state governments in the US.

RUSSIAN FISHERIES AND OCEANOGRAPHY RESEARCH INSTITUTES

Three major research institutes on the Russian Pacific Coast engage in research that contributes significantly to understanding the relationships between climate, oceanic ecosystems and salmon populations: the Pacific Scientific Research Institute of Fisheries and Oceanography (TINRO), the Kamchatka Fisheries and Oceanography Research Institute (KamchatNIRO) and the Sakhalin Fisheries and Oceanography Research Institute (SakhNIRO). TINRO has been conducting research since the 1930s and its research is focused on studying oceanographic processes that regulate marine resources like fish. Staff at TINRO collaborate in international fisheries projects, like NPAFC BASIS and PICES and have made significant contributions to understanding how climate variation influences salmon in the ocean. SakhNIRO and KamchatNIRO have existed under various guises since the 1930s. SakhNIRO has several divisions, three of which (the laboratories of salmon, biological oceanography, and commercial fisheries) conduct research related to climate change and salmon in the ocean. KamchatNIRO has the goal of understanding the processes governing changes in anadromous and marine fisheries resources around the Kamchatka peninsula.

STATE OF THE SALMON

The State of the Salmon (SotS) project was launched in 2003 as a program of the Wild Salmon Center in Portland Oregon. The SotS project was started with seed funding from the Gordon and Betty Moore Foundation, which remember also provides funding for the salmon Model for Assessing Links Between Ecosystems (MALBEC) program of the University of Washington School of Fisheries. The SotS project seeks to promote salmon conservation across the North Pacific by finding ways to relate information on salmon across national, disciplinary, and stakeholder barriers. The SotS project aims to assimilate this extant wide body of information and devise tools to make this interdisciplinary information accessible and informative to stakeholders, managers and researchers. As part of this data assimilation and dissemination, the SotS project includes research on the effects of climate on salmon in the Ocean, *e.g.*, it is an active participant in the salmon MALBEC project (see Universities section below).

UNIVERSITIES WITH SIGNIFICANT SALMON CLIMATE PROJECTS

Several Universities across the North Pacific have projects and scientists dedicated to marine fisheries research. Examples include the University of British Columbia Fisheries Centre (UBC FC), the University of Washington School of Fisheries (UW SoF), the Simon Fraser University School of Resource and Environmental Management (SFU REM), the University of Alaska (Fairbanks) School of Fisheries and Ocean Sciences (UAF SFOS), the Hokkaido University Graduate School of Fisheries Sciences (HU GSFS) and Faculty of Fisheries, and the Pukyong National University (PNU) Departments of Marine Biology and Marine Products Management. Significant contributions to the study of climate effects upon the marine environment and salmon populations in ocean ecosystems have been made by personnel of all these institutions. As well, many of the researchers and staff are key players in previously described organisations which play a more specific role in determining the mechanisms linking climate change to changes in salmon populations of the Pacific.

Teams of professors and graduate students may also devote much of their personal research to specific questions on salmon and ocean climate change effects, *e.g.*, UBC FC—Preikshot (2007), UW SoF—Mantua and Hare (2002), Coronado and Hilborn (1998), and Myers (1998), SFU REM—Peterman *et al*. (2000), UAF SFOS—Quinn and Adams (1996), HU GSFS—Morita *et al*. (2006), and PNU—Seo *et al*. (2006). Collaborative research between research groups has also been important in developing understanding of links between climate and salmon in the ocean. One example is the Model for Assessing Links Between Ecosystems (MALBEC) project (Mantua *et al*. 2007). MALBEC is used to investigate how changes in freshwater and ocean habitats may have influenced salmon populations in the past and may influence them in the future across the North Pacific. The model can be used to investigate how climate-driven bottom-up changes in production may affect salmon populations. This work complements other academic research of ocean ecosystem models which have salmon as a component: Kamezawa *et al*. (2007), Field *et al*. (2006), and Guénette and Christensen (2005).

DISCUSSION

The number of organisations devoting at some research effort to the question of how changes in climate may affect salmon in the ocean is quite large. This suggests that little doubt exists among research and management groups around the Pacific Rim as to the importance of this issue. However, it does not appear that any of the research organisations described here, is dedicated to researching the issue completely from a Canadian perspective. A complete examination would require that all of the seven research issues, described in the literature review, were systematically addressed in one research 'house'. A good start in Canada was made by the efforts of C-CIARN Fisheries and by researchers at PBS. Unfortunately, C-CIARN Fisheries has been disbanded and PBS does not have dedicated programme or funding for climate and fisheries research (and climate and salmon, in particular) as a stand-alone effort. It would appear from the many articles in the literature review, however, that the need to understand how salmon populations are behaving in the ocean is more important than ever. It is now accepted that historic climate variation has changed ocean conditions in the past and that salmon populations have changed in response. Therefore, given that climate change is expected to bring larger variation in the future we can expect that the ocean ecosystem, and salmon population responses, will be even larger than historic norms. There is at present sophisticated knowledge as to how the changes in freshwater habitat influence salmon and how to enhance freshwater production. This freshwater work is only half of the equation, however, as salmon are also marine creatures. Clearly the need to understand these climate-driven marine dynamics is more urgent now than ever.

Organisations like the NPAFC and PICES are making significant progress in researching the effects of climate change on salmon in the ocean, but their work is not directed towards specific Canadian interests. Such transnational and multilateral organisations can not be expected to take care of particular interests of member states. They provide a platform where member states can share and synthesise knowledge. Canadian researchers have been valuable participants in such international work despite limited resources with which to work. Therefore, the establishment of a Canadian-based research group, devoted to investigating climate-driven changes in marine salmon habitats, would improve not only our own knowledge, but also our contribution to our international partnerships like PICES and the NPAFC.

When examining extant research programs, with a frame of reference based on the seven themes arising from the literature review, widely different degrees of coverage exist. PICES and NPAFC deal with all seven research issues, though they do appear to devote disproportionate resources to different subsets of those themes. For example, NPAFC has more experience with changes in growth and energetics (Nagasawa 2000 and Helle and Hoffman 1998), and carrying capacity (Shuntov and Temnykh 2004 and Kaeriyama 2003). PICES has chosen to devote more if its resources to investigating different production regimes and aspects of top-down and bottom-up control (Aydin *et al*. 2003). Scientists at PBS have provided extensive contributions on the question of a critical ocean phase (Beamish *et al*. 2004 and Beamish and Mahnken 2001), in addition to work on different production regimes (Beamish and Bouillon 1993) and growth (Trudel *et al*. 2002).

The CIG appears to be providing a comprehensive and integrated research program, but it is responsive to its US funders. Therefore, any researcher results pertinent to Canada's needs would be purely incidental. This pattern is true of most of the other 'Salmon and Marine Science' organisations; they are responsive to a specific government or user group that does not necessarily share the interests of the people and government of Canada.

The PFRCC and C-CIARN have provided fora for the discussion of many of these themes in a Canadian context, though C-CIARN has since been silenced and the PFRCC has its own mandate which is more broad than climate issues *per se*. Although many of the issues surrounding this research are being addressed in Canada, this work has not been systematic or had dedicated funding. Many interesting results have been produced by the research organisations described above, but none has yet to assemble this research into a comprehensive package that would be of use to managers and the public in Canada.

Several of the groups described here are relatively small but provide a good model for the financial and staffing resources needed to undertake a directed research topic. The State of the Salmon project operates on a staff budget of about $600,000 a year (Wild Salmon Centre 2006) to remunerate a research group of 8 researchers, of masters or doctoral level qualification. The Pacific Salmon Commission spends approximately $2,000,000 to employ 26 staff members (Pacific Salmon Commission 2006), which is also a mixture of doctoral and masters level researchers. It was envisioned by Lill (2002) that in order to properly address issues related to the preservation of steelhead salmon in the Georgia Basin funding would have to range between $2 million to $4 million annually. However, keep in mind that the GGBSRP is a field work intensive program, not a lab-based project. Given the literature reviewed in part one of this study, most of the work by researchers in a Canadian climate change ocean salmon project would be lab-based, with only some field work. A comparison is apt with the GGBSRP, given that the scope of the work it has undertaken would be similar to the scope of work for a Canadian salmon climate project

From these estimates we can infer that a trained and experienced PhD-level researcher would expect to earn $80,000 to $120,000 per year. An integrated study on the effects of climate on salmon in the ocean could realistically be expected to require at least one senior and one junior scientist for each of the seven research areas described as components of the extant literature. With a director and support staff such an organisation would require about $2 million dollars of funding to support the salaries of employees.

Preference should be given to housing such a research group within an existing research organisation to promote information sharing. A housing partnership with a government agency like DFO could take advantage of the institutional memory that exists in PBS. If operating in a government facility, however, the research team would require independence similar to the arm’s length relationship between DFO and the PFRCC. On the other hand a housing partnership with a university may promote a perception of independence while taking advantage of opportunities within an academic environment. A University relationship might produce a research group similar in staffing and appearance to the CIG at the University of Washington.

In establishing a Canadian research organisation dedicated to studying climate effects on salmon in the ocean, it must be borne in mind that financial and political dedication needs to match the time scale as well as the area scale of the topic at hand. Much of the foregoing discussion has dealt with dedicating Canadian research to oceanic areas in our Exclusive Economic Zone (EEZ) or even international waters. Both PICES and the NPAFC represent solid international efforts to address fisheries research over such large spatial areas. However, climate change and variation are phenomena that, by definition, need to be understood, not only in the context of large areas, but also long time scales—decades and centuries. Despite the recognition, by the PICES CCCC that the effect of climate on fisheries needs to be monitored on a long-term basis, its funding is approved annually by member countries. This financial model makes it difficult to devise strategic planning for the long-term research that needs to be done in relating the effects of climate to changes in salmonids at sea. Moreover, engaging a dedicated cadre of professional researchers will be difficult without the guarantee of long-term governmental commitments, via institutionalisation, and the requisite political will.

Long-term research and management will necessarily require long-term monitoring of the effects of climate change on salmon of Canadian origin in the North Pacific. Oceanic salmon monitoring is already done by various groups at DFO's PBS. The marriage of existing monitoring to a dedicated climate ocean salmon research program would help in the tactical deployment of future monitoring. Therefore, an emergent benefit of understanding links between climate changes and oceanic salmon populations is giving management and science a strategic long-term and large-scale framework within which realistic and beneficial tactical planning can be conducted.

With respect to the research themes outlined in the literature review, and the context of those themes on the BC coast, a Canadian Ocean Salmon Research Program should develop research questions in seven categories:

1. How have oceanographic conditions off the BC coast changed? When and how are they likely to change in the future? How have such changes affected primary and secondary production and what are likely future changes? How do the large marine habitats of BC differ with respect to salmon production, *e.g.*, the Strait of Georgia, the upwelling zone off Vancouver Island, and the downwelling zone off the central and northern coast? How has production changed within these regions and how are they likely to differ in the future? Will energy available to salmon production be different in the future than it has been in the past and will that differ by species? Can bottom-up forcing be regulated in any of these habitats and are there ecosystem management strategies, *i.e.*, of salmon prey that could be used to achieve this?

2. How have Canada's west coast salmon fisheries responded to climate variation in the past? What fishing management strategies might be used to mitigate suspected climate effects on salmon populations? What ecosystem management strategies might be used to regulate predation on salmon? Are there potential new predators on salmon in the future, given suspected changes in BC's marine habitats?

3. Should hatchery production in BC respond to climate-driven changes in marine production? Which species are more likely to benefit from BC hatcheries? Do the interactions between hatchery salmon and wild salmon differ between ocean regimes?

4. How will changes to marine habitats affect the growth environment for salmon species? Is there significant competition between salmon species now and is it likely to increase or decrease in the future? What is the role of hatchery salmon (overlaps theme 3) in competition and density dependence in marine habitats?

5. If there is a critical ocean phase, where does it occur? Have these habitats changed in ways similar to, or divergent from, larger marine habitats (overlaps theme 4) of the west coast of Canada? Can climate-driven mechanisms be studied to help manage juvenile salmon in those places? Are climate changes likely to influence the timing and duration of critical ocean phases?

6. When do ocean habitats off the west coast of Canada enter high or low salmon production regimes? Is this timing coincidental with regime shifts of other ecosystems of similar scale in adjacent US waters? How do salmon production regime shifts in Canadian marine habitats respond to large scale regime shifts across the North Pacific Basin? Are salmon production regime shifts in the future going to be similar in frequency and magnitude to those of the past?

7. How will climate-driven changes in ocean condition affect the growth of different salmon species and critical stocks of those species? Given that some salmon species mature far offshore; chum, sockeye and pink, while other mature on continental shelf waters or nearshore marine waters; coho and chinook, are growth changes similar or different?

By developing a research plan, incorporating these questions, a comprehensive Canadian response can be formed to mitigate the effects of climate change on salmon in the ocean. Answers to these questions will also give Canada an enhanced ability to discuss management issues with other countries that pertain to salmon stocks in international and transboundary areas. Therefore, researchers in such a program must be encouraged to participate in the work of groups like NPAFC and PICES. Ideally this program would also host workshops and conferences to highlight both important issues and Canadian achievements in research on climate effects on marine salmon. Canadian researchers and managers would be empowered when collaborating with colleagues by having a unified perceptual framework that would have institutional and academic rigour.

Regardless of where such a group is housed, it would attract world class researchers on climate change and marine fish issues to work in Canada. More importantly, it would encourage such researchers trained in Canada, to stay here. The astute reader will note that a disproportionately large contributions have been made by Canadians in the field of climate-ocean-salmon studies. Canadian scientists like Dr. R. Beamish at PBS were instrumental in establishing the significance of climate effects on salmon populations at sea. There is, therefore, fertile ground in BC to nurture a Canadian-oriented study of how climate change and variation affects salmon in the Pacific. By building the capacity to understand how climate changes the populations of our salmon stocks Canada could easily become the world leader in this new research field. By leading, rather than following, Canadians could establish the talking points around which other researchers, organisations, and countries frame the future debates and decisions on how to manage salmon in the changing Pacific Ocean environment.

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Pacific Fisheries Resource Conservation Council
Suite 290, 858 Beatty Street, Vancouver, BC V6B 1C1
www.fish.bc.ca