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## Salmon Run Failures in 1997–1998: A Link to Anomalous Ocean Conditions?

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**ABSTRACT:** In July 1998 Alaska's Governor Tony Knowles submitted a request for federal disaster relief owing to severe economic and social hardships in some western Alaska communities affected by unusually poor salmon runs, especially Bristol Bay sockeye salmon *Oncorhynchus nerka* and Yukon River chinook *O. tshawytscha* and summer chum *O. keta* salmon. Other anomalies were also noted in these runs: late run timing, smaller-than-average fish, altered migration pathways, and anecdotal reports of higher occurrences of parasites and increased signs of predation. Were these poor returns attributable to unusual marine environmental conditions in 1997/98? Decadal changes in salmon productivity have been related to indices of the strength of the Aleutian Low in winter, which may affect feeding success during early marine life. Analysis of return-per-spawner data is needed to determine whether this climate-salmon relationship continues to hold. Additionally, significant changes in ocean conditions occurred in the North Pacific and Bering Sea in 1997/98 that may have had profound effects on the marine ecosystem. Not only was there a very strong equatorial El Niño, but light winds, low nutrients, and high solar radiation led to the first-recorded bloom of coccolithophores in the Bering Sea in summer 1997 and a bloom occurred again in spring 1998. At-sea research is urgently needed on the biotic implications of these conditions, from effects on primary and secondary producers to effects on invertebrates, fish, birds, and marine mammals through the pelagic and benthic food webs.

### INTRODUCTION

On July 31, 1998, State of Alaska Governor Tony Knowles submitted, through the Federal Emergency Management Agency, a request to President Bill Clinton to declare a major disaster for Alaska as a result of very low salmon returns to some western Alaska river systems. Similar low returns occurred in western Alaska in 1997. Many residents of this region earn their living by commercial fishing, and in most communities there are few alternative employment opportunities. Moreover, subsistence fishing is an important cultural activity, and salmon compose a large portion of annual food consumption. Low salmon harvests coupled to depressed prices have created substantial economic and social hardships in the affected communities.

Were these low salmon returns in 1997 and 1998 due to anomalous ocean conditions? This paper examines that question, and more specifically (1) the status of salmon returns to western Alaskan river systems in 1997 and 1998, (2) contemporary thinking about the effects of climate on salmon productivity, (3) evidence that salmon were under stress in the marine en-

vironment in 1997 and 1998, (4) normal patterns of variability in the North Pacific and Bering Sea, and (5) anomalous conditions that existed in the marine ecosystem in 1997 and 1998 and possible consequences to growth and survival of salmon and other marine biota.

### SALMON LIFE HISTORY

In his excellent review of sockeye salmon *Oncorhynchus nerka* life history, Burgner (1991) pointed out that, after 1–3 years residence in fresh water, smolts migrate through Bristol Bay and slowly travel southwestward along the north side of the Alaska Peninsula. As juveniles, some migrate to the western Bering Sea and others migrate south through the Aleutian passes into the North Pacific. At sea, young sockeye salmon feed on copepods, amphipods, barnacle larvae, ostracods, euphausiids, and larval and juvenile fishes. Older sockeye salmon primarily feed on euphausiids, amphipods, copepods, and juvenile fish and squid. Bristol Bay sockeye salmon mature in the second or third year at sea depending on their natal stream

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and interannual variation. Upon maturity, they migrate up to 2,200 km to return to their natal streams in Bristol Bay.

In contrast to sockeye salmon, most chum salmon *O. keta* begin their migration to the sea soon after their emergence (Salo 1991). Juveniles leaving the Yukon River are quickly dispersed at sea by the large river plume, but little is known of their early marine life history. During their first year at sea, the distribution of chum salmon is similar to juvenile sockeye salmon. There is a slow southwestward movement along the north side of the Alaska Peninsula. As juveniles, chum salmon are distributed throughout the Bering Sea and Gulf of Alaska, where they reside until maturity. Typically, Yukon River chum salmon mature after 3 or 4 years at sea, living to age 4 or 5. At sea, chum salmon often feed on euphausiids, copepods, pteropods, and fish and squid larvae. Maturing chum salmon from the Gulf of Alaska migrate through the Aleutian passes, northeast along the Alaska Peninsula, and then north to the Yukon River.

Upon emergence, chinook salmon *O. tshawytscha* fry take up residence in the stream for 1–2 years (Healey 1991). The distribution of Yukon River chinook salmon during early marine life is poorly known. Young chinook salmon tend to be found near the coast. Older, larger chinook salmon from western Alaska rivers are found throughout the Bering Sea and into the central and western Gulf of Alaska. At sea, young chinook salmon eat euphausiids, copepods, amphipods, crab larvae, cladocerans, barnacle larvae, and young fish. Fish make up the bulk of the diet of matur-

ing chinook salmon. Adults returning to the Yukon River are primarily 5 and 6 years old.

## POOR SALMON RETURNS TO WESTERN ALASKA

Salmon runs to some western Alaska river systems were very poor in 1997 and 1998. A summer fishery on the Yukon River targets chinook and chum salmon. Preseason catch outlooks were for 88,000–108,000 chinook salmon and 500,000–800,000 chum salmon in 1998 (ADF&G 1998b). Actual chinook salmon catches were only 43,500, less than half the lower end of the preseason outlook (Figure 1). This harvest is the lowest on record since Alaska statehood (1959), was only 41% of the annual average catch of 105,000 chinook salmon since 1961. The chum salmon catch of 28,800 fish is similar to the disastrously low 1993 catch and was only 4% of the average catch since 1974 (Figure 2). Additionally, chum salmon runs to the Kuskokwim River were weak in 1997, and it is too early to fully assess the Yukon River fall-run chum and coho salmon returns for 1998. The Norton Sound coho salmon run was also weak in 1997, and the chum salmon run was below historical levels in both years.

The Bristol Bay fishery for sockeye salmon has been the largest sockeye salmon fishery in the world. However, very weak runs occurred in 1997 and 1998 compared to previous 10-year (30.0 million) and 20-year (25.1 million fish) average catches (Figure 3). In 1997, the Alaska Department of Fish and Game

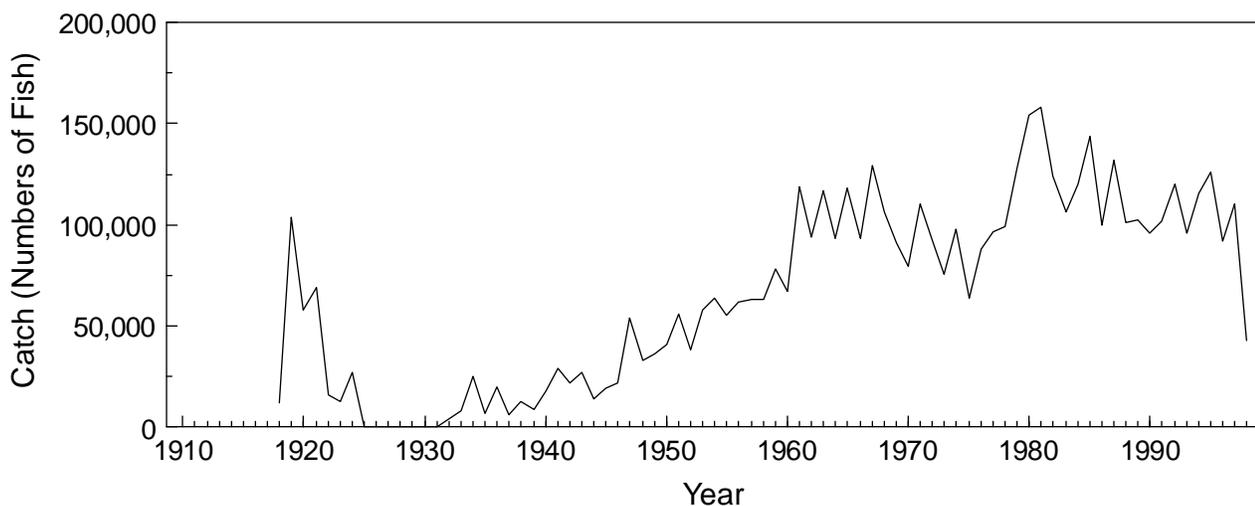


Figure 1. Commercial catches of chinook salmon on the Yukon River during 1918–1998 (Herman Savikko, ADF&G, Juneau). Data for 1998 are preliminary.

(ADF&G) forecasted an inshore run of 33.6 million fish and a catch of 24.8 million (ADF&G 1998a), but the actual inshore run size was only 18.8 million fish and the catch was 12.1 million. Forecast error, measured as the percent deviation between actual and forecasted runs, was -74.6%, the second largest departure on record (since 1961). Actual catch in 1997 was 49% of forecasted catch. In 1998, sockeye salmon returns were even weaker. ADF&G forecasted an inshore run of 30.2 million with a catch of 20.6 million fish. Actual run size was 17.6 million fish (-71.6% forecast error) and catch was 9.7 million (47% of the forecasted catch). The harvest in 1998 was 27% below 1983–1997 average catch and was 66% of the average catch in this century (Figure 3).

Weak salmon runs to western Alaska could be due to a combination of anthropogenic and natural factors in freshwater and marine environments. Conventional wisdom leads us to believe that salmon returns are driven by a density-dependent stock-recruitment relationship (Ricker 1954). Where adequate data are available, escapement goals are set in an attempt to maximize the long-term average catch from the stock (Hilborn 1985). In cases where data are limiting, escapement goals are set at levels that maintain historical yield based on past performance (Bergstrom et al. 1997). For the Yukon River drainage, spawner counts of chinook and summer chum salmon generally met or exceeded escapement goals in parental years for most Alaskan spawning areas (see Appendix E.4 and E.6 in Bergstrom et al. 1997). However, lack of sonar, counting towers, and weir enumeration projects on some rivers prior to 1994 prevent a complete assessment of

summer-run chum escapement histories. Extant aerial surveys are often limited and only provide estimates of peak counts rather than total escapement. For Bristol Bay sockeye salmon, escapement goals were met in all major river systems in parental years corresponding to the 1997 and 1998 returns (see Appendix Table 1 in ADF&G 1998a). Given adequate parental escapement levels, it appears highly unlikely that fishery management is responsible for poor returns to these systems in 1997 and 1998.

Freshwater conditions have been implicated in salmon productivity through density-dependent predation mortality (Ricker 1954), changes in zooplankton biomass (Kyle 1994), stream temperature (Henderson et al. 1995), stream flow (Nickelson and Lichatowich 1984), and other factors. The lack of relationship between hatchery releases and adult returns stimulated early investigations into the role of the marine environment on salmon survival (McGie 1984). Potentially important marine factors affecting survival include coastal upwelling (Nickelson and Lichatowich 1984), ocean temperatures (Ishida et al. 1995), predation (Rogers 1984), density-dependent factors related to at-sea salmon abundance (Peterman 1978), and prey availability (Cooney 1984).

Freshwater and marine factors can affect returns differentially. For instance, poor returns of a single age group to a particular river system or to river systems within a geographic region may implicate factors operating in freshwater or early marine stages. Poor returns across multiple age groups and widely separated river systems may be more indicative of poor conditions affecting fish sharing a common marine en-

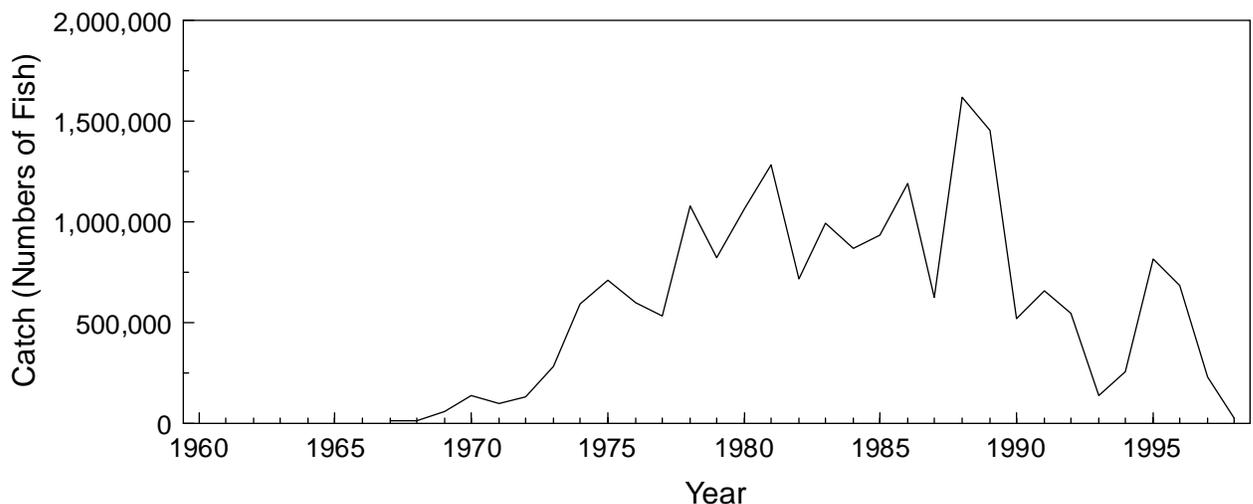


Figure 2. Commercial catches of summer chum salmon on the Yukon River during 1967–1998 (ADF&G 1998b). Catches include estimated number of fish harvested for sale of roe. Data for 1998 are preliminary.

vironment. In the case of chinook salmon to the Yukon River, there was a failure of all returning age groups. All Bristol Bay sockeye salmon age groups were 3-4 million below the 1997 forecast. In 1998 a striking failure also occurred in fish spending 2 winters at sea (age .2); data have not yet been completely analyzed regarding possible declines in other age groups. Although a complete analysis is needed, the present patterns suggest that marine environmental factors probably contributed to reduced salmon survival. If so, this would be consistent with Peterman et al. (1998) who concluded that survival rates of Bristol Bay sockeye salmon returns were affected by freshwater, but most importantly, marine processes.

### TYPICAL VARIABILITY OF THE GULF OF ALASKA AND BERING SEA

The Gulf of Alaska and Bering Sea are continually changing. On seasonal time scales, the Aleutian Low Pressure System intensifies and moves east into the Gulf of Alaska in winter (Favorite et al. 1976). It serves as a magnet for storms that cause deep ocean mixing, thereby bringing up nutrients from depth into the upper layers. As spring approaches, storms become less frequent and increased solar radiation warms the upper layer. High nutrient concentrations, a stratified upper layer, and increased sunlight create ideal conditions for the spring phytoplankton bloom (Hobson 1980). In the Bering Sea, production is related to inner, middle, and shelf-break fronts separating 4 do-

mains (McRoy et al. 1986). Also, melting of the sea ice edge in early spring causes a phytoplankton bloom that contributes substantially to total annual primary production (Niebauer et al. 1981).

Spring blooms typically consist of chlorophyll-rich diatoms. This burst of primary production leads to increased zooplankton populations and therefore favorable growth and survival conditions for animals at higher trophic levels. As nutrients become depleted later in summer, phytoplankton community succession commonly occurs. Dinoflagellates, relatively small phytoplankters with lower chlorophyll content than diatoms, tend to predominate under nutrient-limited conditions.

In addition to seasons, important ocean changes occur on shorter and longer time scales. Atmosphere-ocean variations are coupled (Horel and Wallace 1981; Trenberth and Hurrell 1994); climate has a profound effect on the ocean and, in turn, the ocean has a great influence on climate. Moreover, ocean conditions in one region of the world, such as the equator, can be "teleconnected" to another region, such as the North Pacific, by an alternating pattern of high and low atmospheric pressure systems. Mechanisms and ramifications of these interrelationships are topics of vigorous research.

One important phenomenon of climate-ocean variability is the El Niño/Southern Oscillation (ENSO) that occurs about every 2-7 years (Mysak 1986). At the equator, El Niños are typified by relaxed trade winds and the eastward progression of a deep pool of warm, nutrient-poor water across the Pacific. Off Peru, El

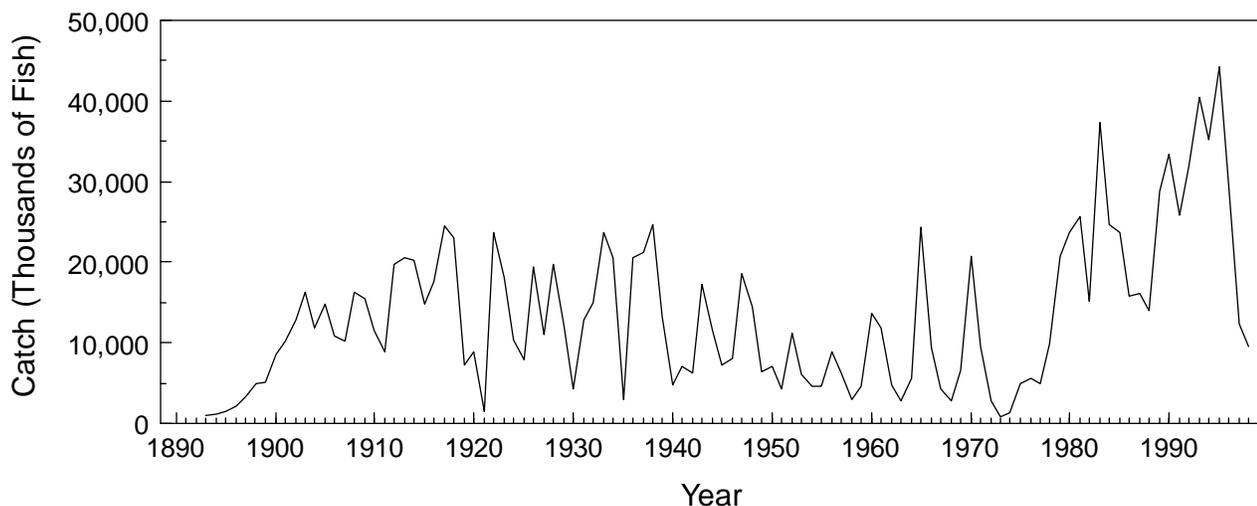


Figure 3. Commercial catches of Bristol Bay sockeye salmon during 1893–1998 (Herman Savikko, ADF&G, Juneau, unpublished data). Data for 1998 are preliminary.

Niños have profound effects on marine ecosystems (Cushing 1982). Warm ocean temperatures force many anchovetas *Engraulis ringens* to the south in search of cooler waters. Others that do not migrate die from lack of food and temperatures beyond their tolerance limits (Mann and Lauzier 1991). Recruitment declines, probably due to sharply reduced primary production associated with upwelling of warm, nutrient-poor water. Guano-producing sea bird populations collapse as adults abandon their chicks and fly to the coasts of Ecuador and Chile in search of prey.

ENSO events are not limited to the equatorial region. For example, at the equator shifts in climate and ocean due to El Niño are propagated by teleconnections that cause major shifts in climate in the North Pacific (Mysak 1986; Emery and Hamilton 1985). Often, but not always, stronger Aleutian Lows are associated with El Niños. Recent research suggests that shifts in the Aleutian Low are associated, not only with climate

variability in the central Pacific, but also in northeast Asia (J.E. Overland, Pacific Marine Environmental Laboratory, Seattle, Washington, personal communication). A North Pacific Index (NPI), calculated as the area-weighted sea level pressure over 30–65° N, 160° E–140° W (Trenberth and Hurrell 1994) indicates variability in the strength of the Aleutian Low (Figure 4). Deeper low pressures are revealed by lower values. Whereas the period 1947–1976 was typified by weak lows (mean NPI anomaly was 1.06), the period 1977–1988 was typified by strong Aleutian Lows (mean NPI anomaly was –1.87). After a brief reversal in 1989–1991 (mean NPI anomaly was 2.40), intermediate Aleutian Lows have generally occurred during 1992–1998 (mean NPI anomaly was –0.63). Mantua et al. (1997) termed these decadal climate shifts as the Pacific Decadal Oscillation (PDO), and they developed another index of the PDO as a function of North Pacific sea surface temperatures.

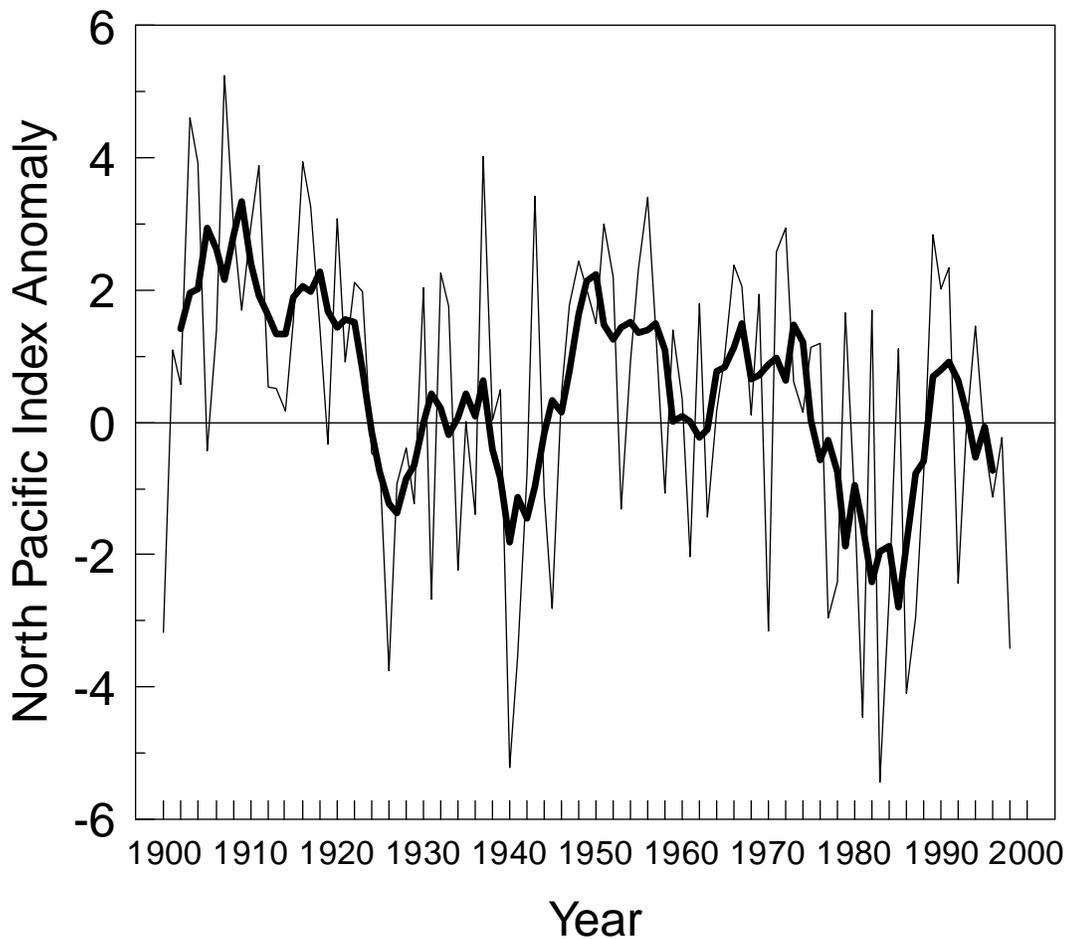


Figure 4. Annual anomalies (thin line) and 5-year running average (heavy line) of the North Pacific Index during winter (November–March average) from the long-term (1899–1998) average (Trenberth and Hurrell 1994).

## DECADAL CLIMATE SHIFTS AND SALMON PRODUCTION

Periods of stronger Aleutian Lows are typified by increased winter storms, more nutrients mixed into the surface layers, higher coastal sea levels, faster ocean circulation around the Gulf of Alaska, and northward movement of warmer water into the region (Emery and Hamilton 1985; Mysak 1986). These conditions favor higher primary productivity in spring and increases in zooplankton biomass in summer (Venrick et al. 1987; Brodeur and Ware 1992; Sugimoto and Tadokoro 1997). Regime shifts between periods of weak and intense Aleutian lows have been linked to periods of low and high salmon catches, respectively (Beamish and Bouillon 1993; Hare and Francis 1995; Mantua et al. 1997). Density-dependent growth curves for Bristol Bay sockeye salmon also shifted synchronously from smaller to larger sizes at age (Rogers 1984). The recent period of high salmon productivity followed a regime shift in the late 1970s. The most common hypothesis is that increased salmon production is related to improved feeding conditions.

## UNPRECEDENTED ECOSYSTEMS CHANGES IN 1997 AND 1998

The North Pacific and Bering Sea responded to the 1997/98 El Niño in some ways typical of other El Niño events but some aspects were unprecedented. A multivariate ENSO index shows that the 1997/98 El Niño developed more quickly than any other El Niño in history (Wolter and Timlin *in press*). Only the 1982/83 El Niño had a higher index of strength, but the 1997/98 El Niño was unique in that it featured 2 peaks: August–September 1997 and February–March 1998.

The National Climate Data Center reported that July 1998 continued this year's record-breaking trend for the highest global mean temperature anomalies since reliable records began in 1880. There appears to be a synergistic relationship between this global warming trend and El Niños (Livezey et al. 1997). Over recent years, El Niño events have become more frequent as global temperature continues to increase. As indexed by mean global surface temperatures, the 1997/98 El Niño was the strongest on record. Thus, extreme regional climate–ocean anomalies associated with El Niño are being exacerbated by global warming.

Regionally, sea surface temperatures from the coast of British Columbia to the eastern Bering Sea were up to 5–6°C higher than average during August

and September 1997, and surface temperatures continue to be about 2.0°C above average through summer 1998. Since January 1998, deep ocean temperatures off Seward, Alaska, have been 1.5–2.0°C higher than normal. So, temperatures have increased, both at depth and at the surface.

As with other El Niño events, there were unusual sightings of southern species of fish and mammals. Pacific white-sided dolphins *Lagenorhynchus obliquidens* were seen from Southeast Alaska to the northern Gulf of Alaska. An albacore *Thunnus alalunga* fishery developed off Kodiak Island. Anecdotal reports indicated the offshore walleye pollock *Theragra chalcogramma* fleet in fall 1997 shifted operations 1.5 times farther north in the Bering Sea than usual. Northern anchovies *Engraulis mordax* were reportedly found in the stomachs of salmon caught off Yakutat. A yellowfin tuna *Thunnus albacares* and several ocean sunfish *Mola mola* were seen in the northern Gulf of Alaska.

In addition, there were a number of first-time records: Sitka Sound Pacific herring *Clupea pallasii* spawned earlier than ever before, and the fishery, therefore, recorded its earliest opening in history. One of the most unprecedented observations included the apparent first-recorded occurrence of aquamarine waters in the eastern Bering Sea starting in July 1997 (Schumacher et al. 1998; Stabeno 1998; Vance et al. 1998). This color was due to a rare bloom of coccolithophores *Emiliania huxleyi*, a phytoplankter more typical of nutrient-limited subpolar waters (Raymont 1980). These phytoplankters secrete calcium carbonate platelets, which collectively turn the water into a milky turquoise color.

Coccolithophore blooms occur where the water is highly stratified (the mixed layer depth is very shallow, only 10–20 m thick) and where light intensity is high and nutrients are low (e.g., phosphate). These very conditions were favored by extremes in the atmosphere in 1997. Very weak winds coupled to unusually strong solar radiation created a very shallow mixed layer in the eastern Bering Sea in summer 1997 (Schumacher et al. 1998; Stabeno 1998). Associated with this was a lack of flow of nutrient-rich waters onto the continental shelf. Although sea ice was normal in southward extent in the 1997/98 winter, it melted and retreated northward very rapidly in spring, precluding a more stable ice edge that normally leads to plankton blooms. An inner ocean front near Nunivak Island, normally a site of strong production, was not well developed (Vance et al. 1998). These unusual combination of conditions, never before observed, are thought to be due to the unparalleled alignment of the strong 1997/98

equatorial El Niño, decadal variability, global warming, and other atypical regional conditions. These factors severely restricted nutrient supplies to the base of the food web in 1997. Even more remarkable, a second coccolithophore bloom, observed as early as February, continued into summer 1998 and was more extensive than 1997's. Turquoise water was observed from Bristol Bay north through the Bering Strait to the Chukchi Sea. As pointed out by Schumacher et al. (1998), many of these features were predicted by a team of U.S. ocean scientists who gathered in 1995 to consider the effects of global warming on the Bering Sea.

These remarkable 1997/98 conditions also led to significant mortalities of seabirds (Vance et al. 1998; NOAA 1998). Reports of massive seabird die-offs began in August 1997. Short-tailed shearwaters *Puffinus tenuirostris* died from the western Gulf of Alaska to the Chukchi Sea. A die-off of black-legged kittiwakes *Rissa tridactyla* was reported on the Alaska Peninsula, and common murre *Uria aalge* died in western Alaska. Corpses were conspicuous in areas of turquoise water. Shearwaters, at 20–30% underweight, were dying of starvation. Foraging birds appeared to avoid turquoise water where they probably had difficulty seeing prey under poor water visibility. The lack of nutrients that favored the coccolithophore bloom may also have adversely affected productivity of other species, such as euphausiids, that are common food of shearwaters.

### ARE RECENT ECOSYSTEM CHANGES LINKED TO SALMON RUN FAILURES IN 1997–1998?

The conventional view, that most salmon mortality occurs in the early life, was originally based on corroborating research focused on freshwater factors, but 1980s research revealed similar importance for early marine life (Percy 1992). Now the roles of ocean factors on juvenile and adult growth and survival are active topics of current research. Density-dependent growth (Rogers 1980; Walker and Myers 1998) and environmentally induced changes in predation (Rogers 1984; Hare and Francis 1995) may occur in maturing salmon in their final year at sea.

Several indicators implicate marine stressors in reduced survival of some western Alaska salmon in 1997 and 1998. Returning Bristol Bay sockeye salmon were smaller than average for their age in both years, particularly in 1998. Whether these reduced sizes at age were associated with a decadal-scale shift in

salmon production (Rogers 1994) remains to be determined. Typically, smaller-than-average fish are associated with strong runs; density-dependent growth or changes in marine environmental conditions are commonly postulated as causes (Helle and Hoffman 1995). The combination of smaller-than-average sockeye salmon and weak runs in 1997 and 1998 implies that ocean conditions were unusually poor for growth and survival. Perhaps prey availability declined so sharply that some fish may have starved, and the survivors had limited food for growth. Conversely, perhaps prey availability was adequate but ocean temperatures accelerated salmon metabolic rate beyond the limits for growth and survival. Welch et al. (1998) proposed that thermal requirements limit the ocean distribution of sockeye salmon because metabolism exceeds energy intake at higher temperatures. Processors of the Yukon River salmon reported lower chinook salmon weights in 1997 and 1998. Yukon River chum salmon returned 1 week late, and chinook salmon returned 7–10 d late. The striking tardiness of these runs in 1998 was not due to the usual cause, a late ice breakup, but was more likely due to slower-than-average swimming speed of smaller-than-average salmon.

There was also evidence of altered migration pathways. Yukon chum and chinook salmon adults stayed offshore in 1998 rather than return, as typical, along the coast. The pattern of entry into the north, middle, and south mouths of the Yukon River was also abnormal. For sockeye salmon, catch rates in the Port Moller test fishery were much higher than expected in 1997 and 1998, given the weak runs; so, migration altered pathways may have led to higher gear vulnerability than experienced prior to 1997. Shifted migration pathways of several British Columbia sockeye salmon runs in response to ENSO events have been well documented (Mysak 1986). Finally, anecdotal evidence suggests higher parasitism and predation. Returning chinook salmon, for example, reportedly had higher occurrences of sea lamprey bites and a naturally occurring protozoan infection, *Ichthyophthirius multifiliis*. Although these anecdotal observations need to be substantiated, if true, they could indicate population stress; fish under stress are believed to be less vigorous and more vulnerable to predation. Taken together, these indicators suggest a major role of the marine environment on western Alaskan salmon runs in 1997 and 1998.

It is premature to draw conclusions about the full suite of potential factors that may have led to poor salmon returns in western Alaska in 1997 and 1998. Strong runs of salmon to other river systems do not support the notion of catastrophic, basin-wide ecosystem changes. Analysis of recent return-per-spawner

data for different river systems may provide considerable insights. If relationships between salmon production and indices of Aleutian Low or Pacific Decadal Oscillation continue to hold, then perhaps the dominant role of early marine factors may be upheld. On the other hand, deviations from those relationships may lend additional support that unusual marine environmental conditions of 1997 and 1998 played an important role in the reduced production of western Alaska salmon. Some researchers speculate that there was a shift in the late 1980s or early 1990s to a new regime unlike those previously observed (Noakes 1998).

Readily observed changes in seabird and salmon populations may provide hints about the magnitude of changes currently occurring in the marine ecosystem. The apparent shut down of nutrient pumps in the Bering Sea and the prevalence of coccolithophore blooms may have profound implications. Large phytoplankton cells,

such as diatoms, are associated with efficient energy transfer and shorter food chains typical of productive regions of the world's oceans (Ryther 1969). Not only do coccolithophores contain low chlorophyll content, they are small and covered with calcium platelets. Due to their small size, additional trophic links may be necessary to pass energy to higher-level consumers. Energy is lost at each trophic level due to energetic costs of digestion, assimilation, conversion, and storage. Thus, changes in the phytoplankton community in 1997/98 may have had important ramifications throughout the system. Process-oriented studies in the North Pacific and Bering Sea are urgently needed. Investigations on plankton dynamics and early life histories of fish and shellfish should be undertaken so that mechanisms for subsequently observed changes in fish, shellfish, bird, and marine mammal populations can be understood.

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