Decadal scale regime shifts in the large marine ecosystems of the North-east pacific: a case for historical science

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ABSTRACT

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INTRODUCTION

The major goal of much current research on large marine ecosystems is an attempt to characterize the nature of order in these
systems. How do their structures and functions vary and what forces or processes drive this variability? Progress in science is
often thought to be proportional to our ability to measure. However, we only seem to improve our abilities to measure smaller
and smaller things. Several fisheries-oriented large marine ecosystem studies provide evidence of this continuing trend in
micro-measurement. In Alaskan waters, there are the NOAA Fisheries Oceanography Coordinated Investigations (FOCI); in
the California Current two ongoing programs are California Cooperative Fisheries Investigations (CalCOFI) and the Global
Ocean Ecosystems Dynamics (GLOBEC) sponsored Eastern Boundary Current Program (currently under development); and
in the northwest Atlantic there is the GLOBEC Northwest Atlantic Program. In each of these programs, you see more and
more effort being expended to measure smaller and smaller components of the marine ecosystems being studied. This is
occurring both in the physical and biological realms. A good deal of attention is being devoted to meso (e.g. eddies, jets and
squirts) and micro scale turbulence in ocean physics and techniques for measuring macro and micro scale egg and larval
dynamics in biology. Models focused at the individual level (IBM or individual based models) represent an active area of
current research (e.g. DeAngelis and Gross 1992). Unfortunately, there seems to be little effort to go the other way in terms of
scale.

What seems to be happening here is an inherent tendency to apply the more "scientific" experimental-predictive (reductionist)
approach to the study of large marine ecosystems. The questions then become, can the techniques of controlled experiment and
the reduction of natural complexity to a minimal set of general causes be applied to the

unraveling of the nature of order in
ecosystems? Can all time scales be treated alike and adequately simulated in the laboratory? Or might the nature of ecosystem
dynamics be better understood by rooting our science in the reconstruction of past events themselves - in their own terms -
based on narrative evidence of their own unique phenomena?

So it is a concept and understanding of order in large marine ecosystems that we are after. In this paper, we attempt to use the
techniques of the historical-descriptive approach to doing science in the context of our own and other research on climate
change and biological production in the Northeast Pacific Ocean. In particular, we explore attempts to detect and understand
rapid shifts in the abundance and distribution of two major components - salmon and zooplankton - of the large marine
ecosystem of the Gulf of Alaska. But, first, we briefly explain the historical-descriptive approach to science--its basic tenets, an
example of how it has been applied in the field of fisheries oceanography, and why we have found it useful in trying to unravel
order out of chaos in the functioning of large marine ecosystems of the Northeast Pacific. And so part of this paper is a review
of scientific method, part is a review of specific scientific activities, and part involves new scientific findings as yet unreported.
Our hope is that the combination provides a clear rationale for the application of historical science to the problem of
characterizing certain aspects of the nature of order in large marine ecosystems.

HISTORICAL SCIENCE

All science is concerned with developing an understanding of order in the natural world. The two kinds of science discussed in
this paper use different methods to arrive at that understanding. On the one hand, the stereotype of the "scientific method" or
"hard" science is associated with experimental/predictive science. The underlying assumption is that certain laws of nature are
invariant with respect to space and time, and that order in the natural world can be understood by probing the way various
components of a natural system behave with respect to these laws. If only we can study the system in enough detail, filtering out
extraneous variability, reducing system processes to their "fundamental" behaviors, then by reconstitution of the parts we can
reconstruct the essence of the system being studied. On the other hand, basic to historical/descriptive science is the assumption
of contingency. A historical explanation does not rest solely on direct deductions from the laws of nature; it also takes into
account an unpredictable sequence of antecedent states, where any major change in any

step of the sequence would have
altered the final result. The final result is therefore dependent, or contingent, on everything that came before.

The problem is that because of its assumptions and methods, historical science has been labeled as less rigorous than
experimental science. Distinctions have been made between "hard" and "soft" science and a hierarchy has developed. It seems
that much of this concern about historical science has to do with its strong reliance, particularly in its early stages, on the
structure of empirical relations between variables without much regard for whether or not mechanistic connections actually exist.
Rigler (1982) deals with these concerns in ecology and Brown and Katz (1991) in documenting the history of teleconnections
research in the field of meteorology. The authors of both papers come to the conclusion that an inability of empirical science to
provide reliable predictions or forecasts of future states of both ecological and connected weather systems has led to a general
resistance to historical science. Rigler (1982) asserts that this is not the fault of method; rather it is due to the fact that
"long-term abundance of species in systems subject to anthropogenic or other changes is not predictable." Brown and Katz
(1991), on the other hand, show that some of the failures of early teleconnections research were due both to an inability to
understand underlying physical causes of empirical relationships, and to a general lack of appreciation by physical scientists of
the complexities that arise in any empirical approach (e.g., autocorrelation and multiplicity).

The question now becomes, how does historical science work? It seems to us that it involves a three step process. The first
step is observation. Next a holistic model is developed under the realization that not all of the numerous assumptions made are
correct. The model is an initial picture of how things might fit together, and is merely a useful framework for testing various
hypotheses relating to the problem being addressed. At this stage one is not sure which suppositions are empty conjecture and
which, in retrospect, might be regarded as valuable insights.

Finally, one reverts back to historical observation to look back in time to see if narratives can be developed which would
support or not support the model.

So, in fact, what happens in the realm of historical science is not that cause must be directly seen from a particular experiment
or analysis in order to qualify as a scientific explanation of a particular model or theory,

but rather that a model is supported by
the piecing together of historical evidence from disparate sources.

In the words of Gould (1989), historical science is a "search for repeated pattern, shown by evidence so abundant and so
diverse that no other coordinated interpretation could stand, even though any item, taken separately, would not provide
conclusive proof."

An example which, we feel, exemplifies the use of historical science in unraveling order from chaos in the structure and
dynamics of large marine ecosystems, involves the paleoecological study of the dynamics of Pacific sardine (Sardinops sagax)
and northern anchovy (Engraulis mordax) populations in the California Current ecosystem. The fundamental questions being
explored are the nature of fluctuations of these pelagic fish populations and, in particular, the relative effects of man on these
fluctuations. The major motivation for this investigation was the precipitous increase in the early 20th century and similarly sharp
decline several decades later of the California sardine population and fishery. Linked to this was a rapid increase in northern
anchovy biomass which seemed to immediately follow the sardine collapse (Smith 1978). The analysis of historical fishery
statistics (1920 - present) and resource surveys which began just after the sardine collapse (1950 - present) was able to
document one "event" in an unknown universe of pelagic fish fluctuations in the California Current ecosystem. Arguments have
raged for decades over whether the sardine collapse was caused by overfishing or whether it was a response to environmental
fluctuations and/or competition for food resources with anchovies. The debate was joined by the research of Soutar and Isaacs
(1974) who determined that the annual layered (varved) sediments in the Santa Barbara Basin off southern California provide a
natural historical record of pelagic fish populations in the region. As a result, they developed a time series of fish scale counts
for small pelagic species, including Pacific sardine and northern anchovy. These data constituted the first continuous time series
of fossil fish and offered a fairly clear picture of the variability of California Current sardine and anchovy populations for more
than a century. Their main findings were that in the past both sardines and anchovies had experienced large natural fluctuations
which were clearly unrelated to fishing and that abrupt shifts in population abundance, similar to those observed in the 20th
century, are not uncommon.

The question then became, what were these fluctuations related to? The research of Baumgartner et al. (1992) opened a door
to the answer in their extension of Soutar and Isaacs (1974) Santa Barbara Basin fossil fish time series to over 16 centuries. In
performing spectral analyses, they divided the variability of sardine and anchovy fossil records into high-frequency (<150 years)
and low-frequency (>150 years) components. At the high-frequency part of the spectrum they found that both anchovies and
sardines have fluctuated at a period of approximately 60 years and that only anchovies have fluctuated at a period of about a
century. At the low-frequency end of the spectrum, they found that anchovies appear to fluctuate with a longer period than do
sardines. They also found a weak positive correlation between the two species at the low frequency level thus questioning the
hypothesis of competitive exclusion of sardines by anchovies. Finally, in comparing the low-frequency dynamics of sardine and
anchovy biomass with a proxy for global climate (tree-ring widths of bristlecone pine, limited principally by temperature), T.
Baumgartner (pers. comm.) found general similarities in the responses of all three smoothed time series, each reflecting the five
distinct low-frequency climate epochs of the last 1700 years: warm period (A.D. 300-700), cold period (A.D. 700-1000),
Medieval Warm Period (A.D. 1000-1350), Little Ice Age (A.D. 1400-1800), current warm period (A.D. 1800 - present).
The implication is that both sardines and anchovies respond similarly to very long period extrinsic forcing related to large-scale
climate change.

And so, through the application of historical scientific methods to the question of causes of sardine and anchovy fluctuations in
the California Current ecosystem, new models of the dynamics of large marine ecosystems are beginning to arise. In particular,
this case exemplifies the relationship (Gould 1987) between time's cycle (the regular periodic fluctuations at the high-frequency
level) and time's arrow (response to low-frequency global climate change).

SALMON AND ZOOPLANKTON IN THE NORTH-EAST PACIFIC

One of the real difficulties we seem to have in coming to grips with ecosystem properties has to do with our inability to deal
with scale, defined by Ricklefs (1990) as the characteristic distance or time associated with variation in natural systems.
Clearly, many linked processes that affect ecosystem structure and dynamics occur on different time and space scales. Levin
(1990, 1992) and Carpenter (1990) provide some clues on scientific directions that we might point ourselves in order to begin

to come to grips with these problems associated with scale. Levin (1990, 1992) suggests that quantitative modeling is a useful
tool for developing an understanding of how information is transferred across scales. He says that "the essence of modeling is,
in fact, to facilitate the acquisition of this understanding, by abstracting and incorporating just enough detail to produce observed
patterns." Carpenter (1990) proposes that because of the nature of ecosystem dynamics, in many cases manifesting themselves
in abrupt "sledgehammer blows" in the words of Schindler (1987), the classical domain of replicate experimental science is not
available to the ecosystem analyst. He goes on to recommend a number of relatively new statistical approaches that show
promise for the analysis of large-scale ecosystem properties (e.g., intervention analysis, a time series method designed to detect
abrupt discontinuous shifts in time series, and empirical Bayesian analysis which allows one to reach quantitative conclusions
from the combined results of different studies). Levin (1992) adds to the list some powerful new methods of spatial statistics
that provide the capacity to describe how patterns change across scales. They both point out that ecosystem scientists (and
managers) must look to modern developments in quantitative modeling and statistics if they want to deal seriously with
fundamental ecosystem properties associated with scale. It is clear that only through the methods of historical science are we
going to be able to begin to sort out questions of pattern and scale in marine ecosystems.

Two examples drawn from recent research trying to understand rapid shifts in the abundance and distribution of two major
components - salmon and zooplankton - of the large marine ecosystem of the Gulf of Alaska tend to bear this out. The
underlying question being addressed in both cases is: does climate cause rather rapid shifts in the organization of marine
ecosystems and, if so, on what time and space scales can these effects be measured?

SALMON PRODUCTION

The first example concerns salmon production in the northeast Pacific and is drawn from our current research. The impetus for
our research was the observation of a number of physical and biological phenomena that transpired in the mid-1970's. The
major physical phenomenon was the now well-documented climatic regime "shift" that occurred in the North Pacific during the
winter of 1976/77 (Trenberth 1990, Miller et al. 1994). A second phenomenon, slightly delayed in time, was the dramatic
increase in catches of almost all the major salmon stocks of Alaskan origin. Perhaps not coincidentally, many West Coast

salmon stocks (notably Oregon coho, Pearcy 1992) entered a state of decline from which they have not yet fully recovered.

Using the time series analysis technique of intervention analysis, Hare and Francis (in press) demonstrated that salmonid production in Alaska alternates between regimes of low and high production, and that the timing of the transitions from one regime to another (intervention) are nearly synchronous across different species as well as across a large part of the spatial range of salmon in Alaska. A highly significant positive intervention was found to occur in the mid to late 1970s, and a smaller negative intervention was found in the late 1940s-early 1950s.

In the tradition of historical science, Francis (1992) and colleagues have proposed a very rough and highly speculative model of how atmosphere, ocean, and marine biological production are linked in the Northeast Pacific, resulting in low-frequency shifts in fisheries production of the major domains described by Ware and McFarlane 1989). Based on earlier speculation by Hollowed and Wooster (1992), we proposed that

a) There are two mean states of winter atmospheric circulation in the North Pacific which relate to the intensity and location of the winter mean Aleutian Low (Emery and Hamilton 1985, Hollowed and Wooster 1992).

b) Oceanic flow in the Subarctic Current and the resultant bifurcation at its eastern boundary into the California and Alaska Currents is fundamentally different in these two states.

c) The patterns in Alaskan salmon production tend to indicate long interdecadal periods of oscillating "warm" and "cool" regimes: early 1920s to late 1940s/early 1950s (warm), early 1950s to mid 1970s (cool), mid 1970s to present (warm).

d) The hypothesized out-of-phase behavior of the long-term production dynamics of the Alaska Current and California Current salmonids (Francis and Sibley 1991) and zooplankton (Wickett 1967) is related to effects of these two states of winter atmospheric circulation on the dynamics of the Subarctic, California, and Alaska Current physical oceanographic systems (Chelton and Davis 1982, Chelton 1984, Tabata 1991) and, subsequently, on biological processes at the base of the food chain.

Following up on Hare and Francis (in press), we report here on an application of the methods of time series analysis to

developing an understanding of the spatial and temporal dimensions of the relationship between salmon production and
atmosphere/ocean physics. In this example, we use two physical and four biological time series. The physical time series are
winter (November-March) air temperatures at Kodiak Island (KWA) in the northern Gulf of Alaska, a proxy for winter sea
surface temperatures in the region ($r2 = 0.47$ between winter SST at 590 N 1490 W and KWA), and the North Pacific Index
(NPI), used by Trenberth and Hurrell (1994) to index the intensity of the winter Aleutian Low pattern referred to earlier. The
salmon (biological) time series are Western and Central Alaska sockeye salmon catch and Central and Southeast Alaska pink
salmon catch. The time frame of all the time series is 1925-1992. The two salmon species have very different marine (and
freshwater) life histories. After spending either one or two years in freshwater, sockeye generally spend either two or three
years in the ocean before returning to freshwater to spawn (Burgner 1991). Pink salmon, on the other hand, enter the ocean
only a few months after emerging as fry in their natal streams and spend only one full year at sea before returning to freshwater
to spawn (Heard 1991).

The salmon data used in this study were compiled from a variety of sources. Catch data from 1925-1991 were taken from
ADFG (1991), 1992 catch data from Pacific Fishing (1994). Collectively, the four groupings accounted for more than 80% of
total Alaskan salmon catches (by number) for the period of study. The catch data were adjusted to account for incidental catch
of Alaska origin salmon and U.S. catch of non-Alaska origin salmon. Incidental catch data through 1989 were taken from
Shepard et al.(1985), Harris (1989), and the Pacific Salmon Commission (1991). Data for 1990-1992 were computed by
using the average interception ratio for 1985-1989. Between 1952 (start of the Japanese mothership fishery) and 1992 (demise
of high seas salmon fishing), estimated interceptions of Alaska origin sockeye averaged 6.6% of the western and central Alaska
origin sockeye catch, topping 20% in several years. Based on Harris (1989), we assigned 75% of the intercepted fish to
western Alaska, the other 25% to central Alaska. The change in the catch time series for Western Alaska sockeye is illustrated
in Fig. 1. By comparison, changes to the three other time series were minor, rarely accounting for a change of more than 5%
(not shown). True production data (catch plus escapement), while preferable to work with, are not available for many Alaska
salmon runs. However, catches are believed to mimic production, at least for very large runs, such as those used in this analysis

(Beamish and Bouillon 1993). We were able to test this assumption by regressing 1950-1984 run size estimates (Rogers 1987)
on our catch time series. The results (Table 1) support our use of the time series we assembled as a means of analyzing
historical variability in salmon production.

In essence, we use a sequence of time series analysis methods to determine patterns in individual time series, the time scales at
which variability seems to be most pronounced, the manner in which this variability manifests itself (e.g. sledgehammer blows or
gradual shifts) and the manner in which the variability in multiple time series are related. We report here on a series of steps
taken to gain this insight.

First, in light of the significant interventions discovered by Hare and Francis (in press) in four Alaskan salmon time series (a
negative intervention around 1950 and a positive and larger positive intervention in the late 1970s), we tested for similar
interventions in the two physical time series (KWA and NPI). As a first step, however, we tested for a relationship between
KWA and NPI. To do so, we fit autoregressive integrated moving average (ARIMA - Box and Jenkins 1976) models to both
of the time series and computed residuals. The purpose is to remove autocorrelation within the time series which can have the
effect of suggesting a lead/lag relationship between two time series when none actually exists (Katz 1988). In the case where
potential feedback might exist between the two time series, such as between oceanic and atmospheric processes, separate
ARIMA models are fit to the time series, i.e., "double prewhitening" (Wei, 1990). When the influence of one time series on
another can only be unidirectional, such as SST on salmon production, the ARIMA filter for the casual time series is used to
prewhiten both time series (simple prewhitening). With the effect of autocorrelation removed, cross correlations at different time
lags are then computed between the prewhitened time series to see how they relate in time. The KWA time series had
significant autocorrelation at lag 1, leading to the following ARIMA model:

(1) $KWA_t = 0.34 \ KWA_{t-1} + a_t$

The NPI was a random time series (i.e., no significant correlations with itself at any lag), thus its ARIMA model consists only of
its mean:

(2) $NPI_t = -.45 + a_t$

The cross correlation function (CCF) for the doubly prewhitened physical time series are given in the top half of Fig. 2. KWA
and NPI are highly correlated at lag 0 and not significantly correlated at any other lags. Next, interventions in the two physical
variables at times similar to those in the salmon reported by Hare and Francis (in press) were explored. The most significant
interventions were found in 1947 (a positive step in winter atmospheric pressure (p <.01) and a negative step in winter air
temperature (p < 0.01)) and 1977 (a negative step in NPI (p < 0.01) and a positive step in KWA (p <.01)) in both time
series. These results are plotted in Fig. 3. Three regimes of physical activity are observed over the time period of sampling:
1925-46, 1947-76, 1977-92. The lower panel of Fig. 2 then gives the cross correlations at different time lags between the two
residual time series once the effects of the interventions were removed, i.e., subtracted from the original time series. Subtraction
of the intervention effect reduced the KWA series to white noise as the interventions accounted for most of the lag 1
autocorrelation in the time series. The significant cross-correlation between KWA and NPI at lag 0 still remained. The
implication is that these two physical time series reflect similar dynamics of variability at both the regime level and at higher
frequencies, and that the strong relationship between them does not derive from the fact that both are responding to a change in
climatic regimes.

Next, when cross correlations between the atmosphere/ocean physics (NPI, KWA) and salmon time series (prewhitened by
the specific physical time series ARIMA model) are computed, they are significant at specific time lags which tend to pinpoint
when in the salmonid life histories the biological response is happening. In Fig. 4, the CCF is shown for KWA with each of the
four salmon time series. The only significant cross correlations are at lag 2 for Western Alaska sockeye (KWA leads sockeye
catch by 2 years), lags 2 and 3 for Central Alaska Sockeye, and lag 1 for both pink salmon time series. Since Western Alaska
sockeye spend predominantly two years in the ocean, Central Alaska sockeye are divided between 2 and 3 years in the ocean,
and all pink salmon spend one year in the ocean prior to spawning or being caught, it is clear that whatever impact the physics
has on salmon production occurs during their first year in the ocean.

Basically the same picture emerges with the NPI, though the relationships are less clear cut (Fig. 5). The sockeye salmon show
significant lag relationships not only at 2 and 3 years but Central Alaska sockeye also at 4-6 years. Western Alaska sockeye

also shows significant relationships at negative lags of 2 and 3 years. The probable explanation for this is the strong
autocorrelation within the salmon time series themselves. Western Alaska sockeye contain a mix of 4, 5, and 6 year cycles, thus
one would expect to see significance within the CCF at lags equal to the natural cycle. The Central Alaska sockeye is
borderline non-stationary (evidenced by the slow decline in its autocorrelation function), which implies that successive catch
years are highly related to each other, thus the CCF would be expected to display the same behavior. The two pink salmon
time series illustrate the same behavior as the Central Alaska salmon with several lags appearing to be significantly related to
NPI. Unlike the KWA ARIMA filter, which removed the lag 1 autocorrelation in the salmon time series prior to calculation of
the CCF, no filtering was done with the NPI. The lack of filtering with the NPI is the primary reason for the difference in the
two sets of CCFs.

The final step was to test whether the apparent lag relationships between the physics and biology were due to covariability at
the interannual time scale and/or at the regime (interdecadal) scale discussed earlier. To test this, we fit intervention models to
the salmon time series with interventions occurring at appropriate lags from the physics (2 years for Western Alaska sockeye
and 1 year for Central Alaska pink). Details of the intervention model fitting procedure are summarized in Hare and Francis (in
press). Significant interventions (p < 0.01 for all cases) were found for Western Alaska sockeye in 1949 and 1979 and for
Central Alaska pink in 1948 and 1978 (Fig. 6). The fact that highly significant interventions occur in both the physics and
biology at appropriate time lags implies that all appear to be responding to the same low-frequency (regime scale) phenomena
and that there is good agreement as to when these regime shifts transpired.

Finally, modified time series were formed by removing the effect of the estimated interventions. Cross correlations were then
computed for the modified physical and salmon time series. The results are illustrated in Figs. 7 (KWA) and 8 (NPI). For three
of the salmon time series the lag cross-correlations are all reduced to non-significance. The situation for Western Alaska
sockeye is different, however. Removal of the intervention effect has no impact on the lag 2 relationship between KWA and
catch (Fig. 7, top panel) In addition, a lag -3 relationship was added. This suggests to us that, at the interannual time scale,
winter air temperature in the northern Gulf of Alaska could be related to Bristol Bay sockeye production 2 years later. The lag

-3 relationship most likely derives from the 5 year cycle in Bristol bay sockeye production (Eggers and Rogers, 1987). The
notion that ocean temperature is an important factor in Bristol Bay salmon production has been advocated by Rogers (1984),
though he hypothesized that the link operated during the final winter at sea (lag 0 relationship with KWA). Removal of the
intervention changes the entire nature of the cross correlation relationships between NPI and Western Alaska sockeye.
Significant cross correlations now occur at lags 1 and -3 (Fig. 8, top panel). Once again, it is our feeling that this has to do with
the inherent but somewhat irregular cyclic nature of Western Alaska sockeye salmon production. This certainly deserves closer
investigation and is one focus of our current research.

The implications of this analysis are that there are very significant and coherent linkages between relatively sudden interdecadal
shifts in North Pacific atmosphere and ocean physics and a marine biological response as evidenced by indices of Alaskan
salmon production. These linkages are consistently timed in such a way to indicate that salmon production is affected fairly early
in the marine life history, thus adding more support to thoughts on this subject summarized by Pearcy (1992). The lack of
coherent and consistent covariation at the interannual time scale implies that there is no single direct mechanistic relationship at
this scale between the physics (winter Aleutian Low pattern, SST in coastal Gulf of Alaska) and the biology (Alaskan salmon
production). The only exception involves sockeye salmon production in the E Bering Sea. As mentioned above, these
relationships will receive closer scrutiny in a later paper. The overall implication of this analysis is that the decadal-scale link
between climate variability and salmon production is most likely carried by other, yet unidentified, processes.

ZOOPLANKTON PRODUCTION

The second example concerns zooplankton in the NE Pacific and the possible effects of advection (wind-driven Ekman
transport) on variation (at different time scales) in levels of production. Two seminal papers shed a good deal of light on the
nature of both interannual and interdecadal variations in zooplankton of this region. Wickett (1967) studied the interannual
variation in zooplankton volumes off California, in the western Bering Sea, and at Ocean Station P (500 N 1450 W) in the
central Gulf of Alaska during the 1950s and early 1960s. By studying the relative abundances of zooplankton in these regions
and relating them to zonal and meridional components of surface winds in a region

upstream of the bifurcation of the Subarctic
Current, he found that a major cause of zooplankton variation downstream of the division point (bifurcation of the Subarctic
Current into the California and Alaska Currents - Fig. 9) is the change in the proportion of surface-layer, wind driven water
(Ekman transport) that is swept southward (escaping) out of the subarctic circulation. The implication is that zooplankton and
nutrients are carried with the surface waters and that forcing conditions (surface winds) which favor a high "escapement" of
subarctic water into the California Current will increase zooplankton production in that region and decrease it in the region of
the Alaska Current.

Brodeur and Ware (1992) analyzed zooplankton collections, taken with similar sampling methodology, from the subarctic
Pacific from two time periods (1956-62 and 1980-89). They discovered that there are large and highly significant interannual
and interdecadal fluctuations in the summer biomass of zooplankton in the North Pacific subarctic gyre. The interannual
variation can be clearly related to the intensity of the winter winds in the northern Gulf of Alaska (Fig. 10 - top panel). The
mechanism that is proposed to underlie the interpretation of these phenomena has to do with variation in the circulation of the
subarctic gyre in the NE Pacific - a speeding up and slowing down of the Subarctic and Alaska Currents. This would affect
both Ekman pumping at the center of the gyre, leading to increased upwelling and divergence in the center, and advection
(transport of nutrients, phytoplankton, zooplankton) around the circumference of the gyre. This hypothesis is supported by the
observation that in both decadal regimes, the spatial pattern of zooplankton in the Alaska Gyre showed generally low biomass
throughout the region under low winter wind conditions and a ring-like structure of high zooplankton biomass around the outer
gyre under high winter wind conditions. The interdecadal variation, however, does not appear to be related to the intensity of
these winter winds and was left unexplained by Brodeur and Ware's analysis. What is clear is that there was a significant
increase in zooplankton biomass between the late 1950s to early 1960s and the 1980s.

DISCUSSION

So what does all of this historical analysis reveal about the issue of scale and the relationship of biological production to physical
forcing in the NE Pacific?

1) There are large interannual and interdecadal fluctuations in both salmon and zooplankton production (biomass) in the
subarctic Northeast Pacific.

2) Clear linkages occur at the interdecadal (regime) scale between patterns in atmosphere and ocean physical variables and
corresponding patterns in salmon production. Generally, these linkages do not appear to hold at the interannual time scale.

3) Clear linkages occur at the interannual scale between patterns in atmospheric variability and zooplankton production. These
linkages do not appear to hold at the interdecadal (regime) scale.

4) The magnitudes of both salmon and zooplankton production seem to be inversely correlated between the region of the
California Current (subarctic escapement area) and the Alaska Current.

It appears that although the time patterns of a number of atmosphere and ocean physical variables and salmon production are
very coherent at the decadal (regime) scale, these same variables show little or no coherence in their patterns at the annual
scale. To us this implies a lack of direct mechanistic connection between salmon production and these physical processes. This
would imply, for example, that neither winter SST nor winter storm activity in the North-east Pacific directly affects salmon
survival during its early ocean life, with the possible exception of Britol Bay sockeye salmon. On the other hand, it does appear
that the intensity of winter storm activity in certain parts of the North Pacific does directly affect interannual variability in
zooplankton production throughout the region. In addition, both the intensity and the direction of winter winds near the
bifurcation of the subarctic current seem to impact interannual dynamics of relative zooplankton production in the regions of the
California and Alaska Currents. A direct mechanistic connection is implied here.

The major question which arises as a result of the scale-related findings of these two historical analyses is whether or not the
observed decadal-scale shifts in North-east Pacific salmon and zooplankton production are responses to the same physical
forcings. If one examines Fig. 10 (bottom panel) which relates NPI to zooplankton biomass, one sees very different, but highly
significant, correlative patterns occurring in the two regimes (the sign of the correlation reverses between the early and late
regimes). As a matter of fact, within each of the regimes, the correlations between NPI and zooplankton biomass are as high as
those between Ekman Transport at 600 N and zooplankton biomass. This indicates to us

that while the intensity of winter
storms in the North Pacific is clearly related to interannual variability in Gulf of Alaska zooplankton production, it does not
directly cause the observed regime scale change which appears to be of a much larger magnitude. Existing zooplankton data
do not allow determination of the exact timing of the shift. However, it is our guess that, if we had a continuous time series of
zooplankton production in the Gulf of Alaska of similar length to that for salmon catch, we would find significant discontinuities
or interventions occurring in the late 1940s and late 1970s, as we did in both the atmosphere/ocean physical and salmon catch
time series. In the tradition of historical science, this leads us to speculate that either similar physical mechanisms, with dynamics
which vary at the decadal scale, are affecting regime scale shifts in both zooplankton and salmon production, or zooplankton
production is affected by shifts in atmosphere/ocean physics and, in turn, affects salmon production during their early ocean
coastal phase. It is clear, in particular from the zooplanton analysis, that these climate-driven regime shifts cause major
reorganizations of ecological relationships over vast oceanic regions.

In the words of Margalef (1986), the subarctic North Pacific is periodically perturbed by energy "kicks" which tend to disrupt
or decouple a number of ecological relationships within the ecosystem. These rapid and infrequent shifts in the physical structure
of the ocean (and coupled atmosphere) tend to result in significant shifts in the structure and dynamics of certain components of
the ecosystem. We speculate that, at least during the past half century, both North-east Pacific zooplankton and salmon have
responded similarly to these kicks. The important point to be made is that it is only through application of the methods of
historical science that we are going to be able to further our understanding of how and on what scale these processes operate.

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TABLE 1. Results of regressions of corrected catch statistics with the four regional salmon stocks used in
this analysis (see text for details).

 Stock

r^2

Western Alaska sockeye
.86
Central Alaska sockeye
.96
Southeast Alaska pink
.99
Central Alaska pink
.97

FIGURE CAPTIONS

Figure 1. Original and corrected Western Alaska sockeye salmon catch time series. Corrected series contains estimates of high
seas catch of Western Alaska origin fish.

Figure 2. Cross correlation functions (CCFs) and 95% confidence bands for Kodiak winter air temperatures and North Pacific
Index (Trenberth and Hurrell, in press) for 1925-1992. Upper panel gives CCF when the series have been doubly prewhitened
for autocorrelation. Lower panel is CCF for the two time series when the effect of the 1947 and 1977 interventions have been
removed.

Figure 3. Time history (dashed lines) and intervention model fits (solid lines) for physical variables used in this study.

Figure 4. Cross correlation functions (CCF) and 95% confidence bands for Kodiak winter air temperature (KWA) and each of
the four salmon time series. Simple prewhitening with the KWA ARIMA filter was done to all series prior to computation of the
CCF.

Figure 5. Cross correlation functions (CCF) and 95% confidence bands for North Pacific Index (NPI - Trenberth and Hurrel,
in press) and each of the four salmon time series. Prewhitening of the series prior to computation of the CCF was not necessary
as the NPI was a white noise time series.

Figure 6. Time history (dashed lines), intervention model fits (thin solid lines) and estimated interventions (thick solid lines) for
salmon time series.

Figure 7. Cross correlation functions (CCF) and 95% confidence bands for Kodiak winter air temperature (KWA) and each of
the four salmon time series after removal of intervention effects. Prewhitening of the series prior to computation of the CCF was
not necessary as the modified KWA series was a white noise series.

Figure 8. Cross correlation functions (CCF) for North Pacific Index (NPI - Trenberth and Hurrell, 1994) and each of the four
salmon time series after removal of intervention effects. Prewhitening of the series prior to computation of the CCF was not
necessary as the modified NPI series was a white noise series.

Figure 9. Relevant large-scale upper-level physical oceanography of the Subarctic North Pacific.

Figure 10. Relationship between zooplankton production and wind stress (measured as Ekman transport) at 60° N, 149° W in
the northern Gulf of Alaska (top panel) and North Pacific Index (bottom panel). After Brodeur and Ware (1992).