



North Pacific regime shifts: Definitions, issues and recent transitions

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ARTICLE INFO

Available online 6 April 2008

ABSTRACT

The many recent publications on regimes and shifts highlight the importance of decadal variability in understanding climate and ecosystems and their connectivity. This paper explores several issues in the application of regime concepts. Even the definition of regimes is unclear, as usage by different authors highlight: (1) displacement or shifts in timeseries, (2) underlying mechanisms, and (3) the distinction between external forcing and internal reorganization of ecosystems. Such differences arise, and cannot be easily resolved, because of the relatively short duration of available physical and biological timeseries, and the complexity of multivariate process in marine systems with unknown variables and relationships. Climate indices often show a rather Gaussian distribution of values with a single mean, rather than clearly separated discrete multiple states. These physical indices can be represented by a red noise long memory process, where the index can, in fact, deviate substantially from the long term mean for multiple years. If we consider changes in timeseries themselves, then climate variables for the North Pacific display shifts near 1977, 1989 and 1998. Recent variability suggests considerable uncertainty in the current state of the North Pacific. Biological variables often show a broader distribution of shifts over time, which is consistent with different types of responses to climate for different ecosystem elements and the importance of time lags in response to changes in physical forcing. Our current understanding of regime shifts is not a deterministic one, and while one can discuss amplitudes and mean duration of regimes, we cannot predict their precise timing other than to say that they will be a main feature of future climate and ecosystem states. While the authors believe that a single definition for regimes is currently not possible, the concept continues to be useful in moving the discussion of ecosystems away from the assumptions of single species and stationary processes.

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1. Introduction

“When a thing ceases to be a subject of controversy, it ceases to be a subject of interest.”

W. Hazlitt, *The Spirit of Controversy*

It is increasingly appreciated that marine ecosystems can respond to abrupt changes in climate in various ways (Bakun, 2004). These shifts, especially when persistent over multiple years, can result in major reorganization of marine ecosystems. Beamish et al. (2004) go so far as to state that management practices that ignore the impacts of such climate variability on the abundance trends of commercially important species could lead to the collapse of major fisheries. There have been over 100 papers published on regime shifts, with two major recent compilations: an ICES session in 2004 on “Regime Shifts in the North Atlantic Ocean: Coherent or Chaotic” and an issue of *Progress in Oceanography*

(Steele, 2004). PICES supported two compilations (Hare et al., 2000; McKinnell et al., 2001), as well as conducting a regime shift report (King, 2005). Other recent papers include Rudnick and Davis (2003), Duffy-Anderson et al. (2005), Hsieh et al. (2005), and Overland et al. (2006). The present volume is another contribution. While there is major interest in regimes as a codeword for decadal variability, at present there is also ambiguity and uneasiness with the term, in part due to the brevity and complexity of oceanic timeseries and in part from the multiple usages for the term. Notably, Steele (2004) states that despite the attention being focused on regimes, we lack convincing evidence that changes in ocean climate induce bi-stable modes in marine ecosystems.

The purpose of this paper is to review regime shifts as applied to physical and biological timeseries for the North Pacific; it pursues a more conceptual than analytic approach. We highlight some of the differences in emphasis and semantics noted in several recent publications and provide an update on current thinking on the character of low frequency climate variability in the North Pacific. Marked transitions have occurred in various North Pacific indices as noted in Section 3, although there is still some subjectivity in applying the label of regime shifts.

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2. Semantics and other issues of regime shifts

2.1. Definitions

The dictionary definition of “regime” is a “system of government or rule.” In French, for example, l’ancien régime referred to the system of government before the revolution of 1789. Perhaps the first explicit reference to regimes in an oceanic application was Isaacs (1976, p. 34): “the assumption is that there are some normal statistics to all kinds of (ocean) conditions. Rather, there are probably a great number of possible regimes and abrupt discontinuities connecting them.” The importance of climate/fisheries connections has been long recognized. It was a basis for the formation of ICES (International Council for the Exploration of the Sea) more than a century ago. Steele (2004) and Wooster and Zhang (2004) note that discussion of regimes began from a temporal correspondence between climate indices and population abundance such that ecosystems can, naturally, occupy alternative coherent configurations as the external world changes. As discussed by Mantua (2004), a number of studies have considered that regimes indicate different periods of quasi-stable behavior due to internally interactive dynamics. deYoung et al. (2004) more simply, defines a regime as a quantifiable quasi-equilibrium state. Finally, Bakun (2004) uses *ecosystem regime shifts* to signify drastic large time- and space-scale shifts in abundances of major components of marine biological communities and *climatic regime shifts* to signify apparent transitions between differing average climatic characteristics.

These differences in perspective relate to three separate concepts in the definition and use of regimes: *displacement*, *mechanism* and *external*. The displacement concept is based only on inspection of timeseries over relatively short periods (<50 years) where there can be sequential multi-year intervals with mean values in each interval that are statistically different, relative to their within regime variance. Adherents to the displacement viewpoint have noted the importance of such information to fisheries management, particularly if coincident shifts are seen across a large number of physical and biological variables. The PICES Study Group on Fisheries and Ecosystem Response to Recent Regime Shifts (King, 2005, p. 2) took an even more qualitative definition, “a relatively rapid change from one decadal-scale period of a persistent state to another decadal-scale period of a persistent state.”

The mechanism viewpoint focuses on the necessity to identify the underlying processes that result in the shift in particular timeseries *between discrete states*. Thus Rudnick and Davis (2003) would reserve regimes as implying multi-modal states, or more correctly a period where temporal variation in key state variables (biotic or abiotic) are concentrated near distinct dynamical attractors in a limited dimensional phase space. In this framework, it is important to distinguish between underlying processes that are non-linear/deterministic, often implying but not requiring multiple states, from processes that are relatively random and hence tend to yield more Gaussian distributions. While the latter can yield large and long-lasting excursions from long-term means and satisfy the displacement definition of regime shift, they would not constitute regimes from the mechanism viewpoint. It would seem that both viewpoints have utility, because of the general lack of both sufficiently long oceanic timeseries for assessing temporal variability in a statistically rigorous manner and sufficiently complete understanding of the processes responsible for long-lasting changes in the physical and biological environments. In any event, improved mechanistic understanding would help to increase the confidence in anticipating the evolution or trajectory of the North Pacific.

The third definition of regimes relates to the external processes involving systematic changes in ecosystems. Duffy-Anderson et al. (2005) emphasize the distinction between climate and ecosystems

by referring to any change in external forcing to the biological system, such as climate or fishing, as “regime shifts”, while changes in the state within the ecosystem are “phase transitions.” This definition points to the inconsistency between definitions of regimes. While the external definition of regimes emphasizes that all significantly changed climate forcings are regime shifts, the proponents of the mechanism definition discount most physical processes as not having true regimes, as they do not have a bimodal character. The paradox introduced by the three definitions cannot be resolved, but simply noted.

2.2. Timeseries approaches

The evolution of physical climate and ecosystems on decadal timescales is generally assessed using sample timeseries, either directly via parameters such as temperature at specific locations or abundance of a particular species, or through composites of basic timeseries such as climatic indices or estimates of species diversity. For example, a particularly well known North Pacific climate index, the Pacific Decadal Oscillation (PDO), reduces the spatial and temporal variability of sea surface temperature (SST) for the entire North Pacific into a single Empirical Orthogonal Function (EOF) spatial field and principal component (PC) timeseries. It bears noting that single indices such as the PDO can at times be inadequate for characterizing the North Pacific (e.g., Bond et al., 2003). Figs. 1 and 2 show two approaches to displaying the state of North Pacific SST variability based on the first two principal components. Fig. 2 is known as a phase space plot, which has values of the first two PCs on the X- and Y-axes, whose trajectory of points give a type of North Pacific climate state time history. Such phase space plot representations are a useful way to follow temporal trajectories as multiple climate or ecosystems indices change.

The problem of using “relatively short” timeseries when trying to infer underlying physical or biological processes from timeseries analysis alone, is illustrated by Overland et al. (2006) who tested the fit of three statistical models to the 104 year PDO timeseries. They found that one could not prove which process model was superior. A first approach assumed that the underlying model represented a multiple stable state process by construction (the square wave oscillator – SWO) which had an optimum fit with two square wave shapes at periods of 76 and 40 years (Fig. 3). [Optimum fit implies that the residuals represented no additional information—see references in Overland et al. (2006)]. The other models were a first order autoregressive model which assumes autocorrelation in the timeseries over several years and a “long memory model” which assumes low but finite autocorrelation over a longer duration (5 + years). All three models can be shown to statistically fit the observations and are equally simple. For the particular case of the PDO, a timeseries of several hundred years would be necessary to distinguish between the validity of the underlying physical process assumptions of the three models. Thus it appears difficult to determine the character of underlying physical processes from investigation of “relatively short” timeseries alone.

An issue with regard to the displacement viewpoint is that most methods lack discrimination ability near the end of the record, just when it is most important for operational purposes. A feasible approach is the probabilistic based method of Rodionov (2004) as presented in Section 3.

Multivariate approaches also show promise for overcoming some of the difficulties associated with short timeseries. The noteworthy study of Solow and Beet (2005) incorporated a multivariate approach for interacting species or groups. This approach used change points in a vector autoregressive process to examine 35 years of observations of five biotic variables for the North Sea: phytoplankton, copepods, cod, haddock and herring. Their method

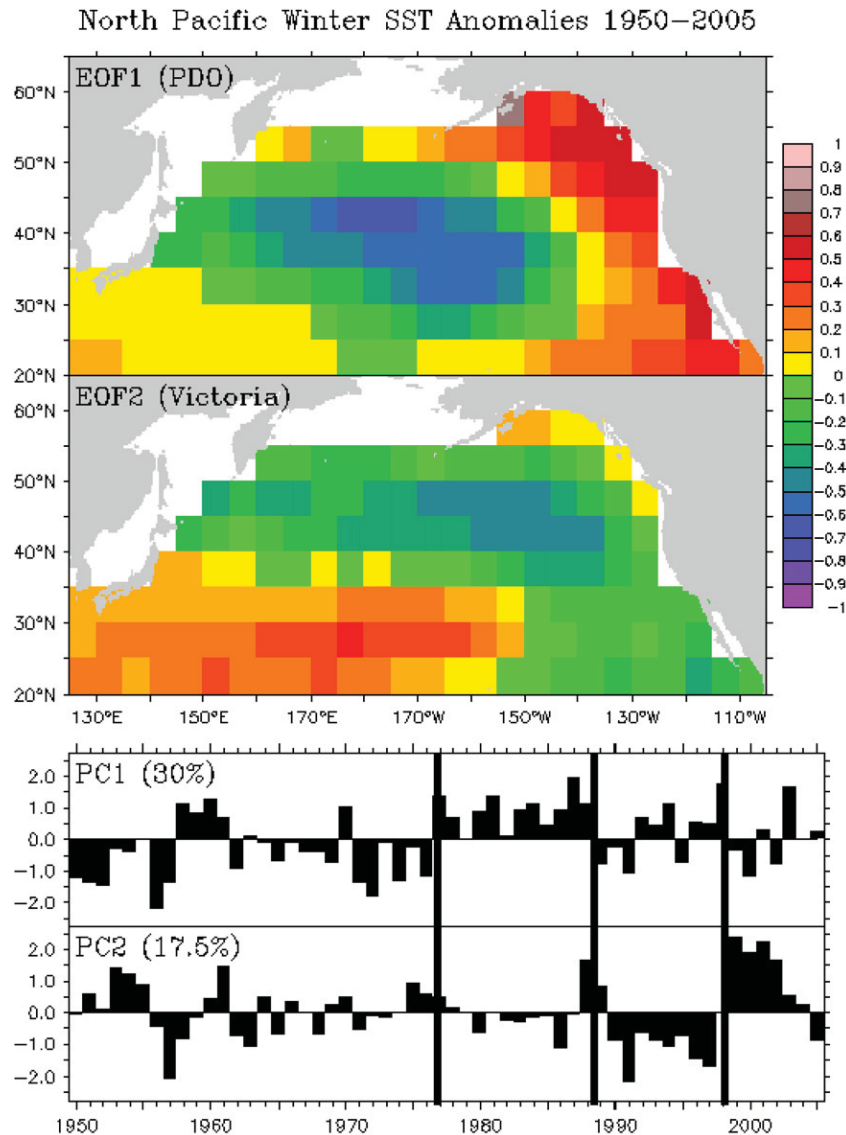


Fig. 1. The first two EOFs/Principal Components (PC) for winter (DJF) North Pacific sea surface temperature (SST). EOFs are a method of representing the variability of multiple timeseries, here SST at various grid locations, as one pattern that explains the most variance of the combined timeseries. Thus EOF1 shows primarily an east–west pattern of behavior where SST anomalies are negative in the central Pacific and positive on the eastern side. To explain additional variance, a second pattern can be calculated; for North Pacific SST, EOF2 has a more north–south dipole pattern. In the lower part of the figure the timeseries evolution of the EOFs, termed the PCs, is shown. Thus positive PC values occur in years when the SST data have the same general sign as the EOFs, and visa-versa. The percentages are the fraction of the total SST variance which is represented by each EOF. For historical reasons EOF1 is referred to as the Pacific Decadal Oscillation (PDO) and EOF2 as the Victoria pattern (Bond et al., 2003). As noted in Section 3, there appear to be displacement shifts in these timeseries near 1977, 1989 and 1998 (vertical lines), with the Victoria pattern showing more organized changes in the last two decades. The SST timeseries were not detrended for this figure.

indicates that while widespread changes occurred in the late 1980s, the record lacks a definitive, unambiguous regime shift. Since we are often interested in ecosystem or multiple trophic levels rather than single timeseries, such methods that address the stability of the abiotic/biotic correlation matrix over time should be of interest. Qualitative visual inspection methods such as stop-light plots (Link et al., 2002), ECOPATH food web models, and reduction to one or two principal components are the current levels of application. The topic of shifts in multivariate systems applied to ecosystems is a suitable area for a major advance.

2.3. Biological models and observational examples

Given the difficulties with short times series noted above, Collie et al. (2004) recommend the use of additional information such as mathematical models, to increase the understanding of shifts in

ecosystem populations. Such models, however, are often sensitive to the range of little-known parameter values. Fig. 4 shows theoretical examples of the transition from linear to non-linear behavior for a single model with different parameters, using phase space plots with abundance on the Y-axis and forcing on the X-axis. One point to note in the discontinuous solution (bottom) is that the results do not cluster around particular multiple stable states, but are spread across two functional regions.

An observational example of multiple functional relationships is recruitment/stock size of yellowfin sole in the SE Bering Sea (Fig. 5a). The relationship is apparently different for the 1980s (circles) and the 1990s (squares) because of a systematic change in the winds between the two periods (Wilderbuer et al., 2002). A second example is the depletion of the Georges Bank haddock fishery; the population did not return to previous levels after fishing was curtailed (Fig. 5b) (Steele, 2004). A third example is that Bering Sea

Phase Trajectory for Principal Components
PC-1 and PC-2 of North Pacific Winter SST

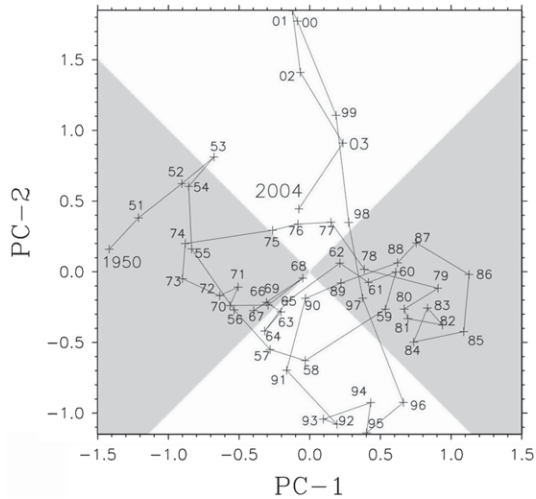


Fig. 2. Phase space plot of PDO (PC1) and Victoria Pattern (PC2) timeseries. This figure shows another way of presenting the information in the lower half of Fig. 1. For each year the magnitude of the PDO is plotted on the X-axis and the value of the Victoria pattern is plotted on the Y-axis; the numbers show the years from 1950 to 2004. With this format it is clear that the negative PDO dominated North Pacific climate in the early 1950s and early 1970s and the PDO was positive in the 1980s (gray shaded areas). That the PDO was not the primary pattern of climate variability since 1990 is shown by the relative strength of the Victoria pattern (white areas).

pollock biomass has been consistently high for most of the last 20 years. This is apparently one of four possible states (Hunt et al., 2002). This stability comes about presumably from a large spatial range, the ultimate negative feedback due to cannibalism, and other unknown causes. The work of Beaugrand (2003) and Heath (2005) show similar examples from the North Atlantic.

2.4. The complexity of hidden dimensions

A system with several but not too many interacting variables tends to have complex behavior. This behavior seems to be the hallmark of biological systems and the atmosphere at least at daily to weekly time scales. A generic example is the Lorenz model with three variables x , y , and z and three equations, which is considered as the classic of a non-linear system with multiple attractors, i.e., regions in phase space where there is an increased probability for the system to be located. This is shown by two main clusters of dots in Fig. 6a, which represent solutions to the Lorenz equations. Because different variables are plotted on each axis of a phase plot, they are often referred to as *dimensions*. What if we could observe only one variable, z for example? Variables x and y

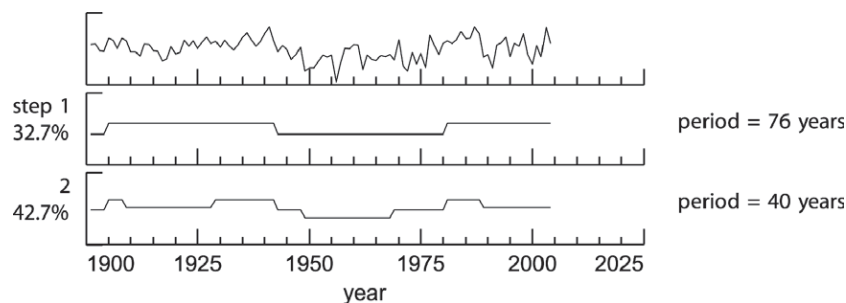


Fig. 3. Square wave model fit to the PDO. The raw PDO timeseries is shown at the top. While the two combined square wave functions series explain about 43% of the PDO variance, this multiple state model cannot be shown to provide a unique representation of the PDO from fitting 104 years of data.

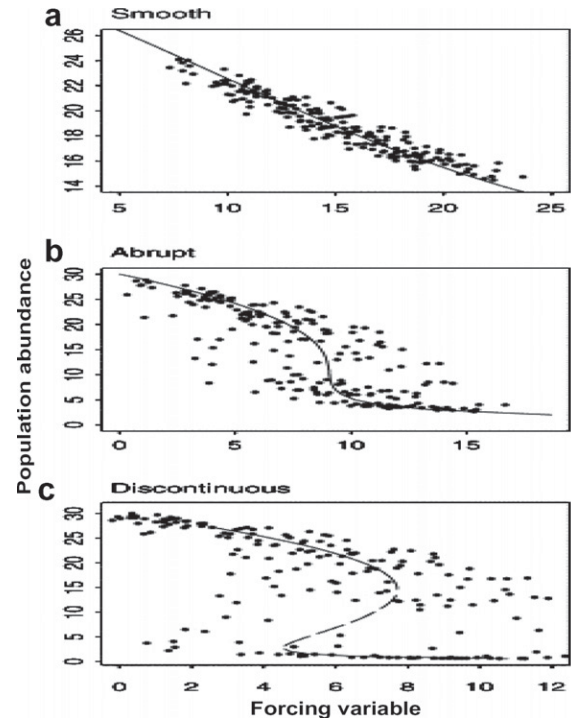


Fig. 4. Examples of linear to non-linear behavior of solutions for a single model with different parameters, using phase space plots with the abundance on the Y-axis and forcing on the X-axis. Values on each axis are arbitrary units. After Collie et al. (2004).

would be termed hidden dimensions. This case is close to the situation in observing the state of ecosystems where only some of the species are monitored. If we could only observe the distribution of z for example, there appears to be only one maximum in its distribution of values. However, in the hidden dimension, x , there are two maxima. The future value of z depends not only on the history of the value of z , which we know, but also on the values of x and y . As an analog to climate and ecosystems, this result suggests caution in making simple projections based on extrapolation of single timeseries.

Techniques exist for determining whether a process as represented by one timeseries is part of a system with few or many dimensions. Sangoyomi et al. (1996) studied the 144-year timeseries of the volume of Great Salt Lake and estimated that the dynamics were described by a system with a dimension of about four. Hsieh et al. (2005) discuss the dimensionality of 10 northeast Pacific biotic timeseries: Scripps Pier diatoms, CalCOFI copepods and three larval fish, and five salmon; and six abiotic timeseries: three California SST, the PDO, Aleutian low pressure (NPI), and the South-

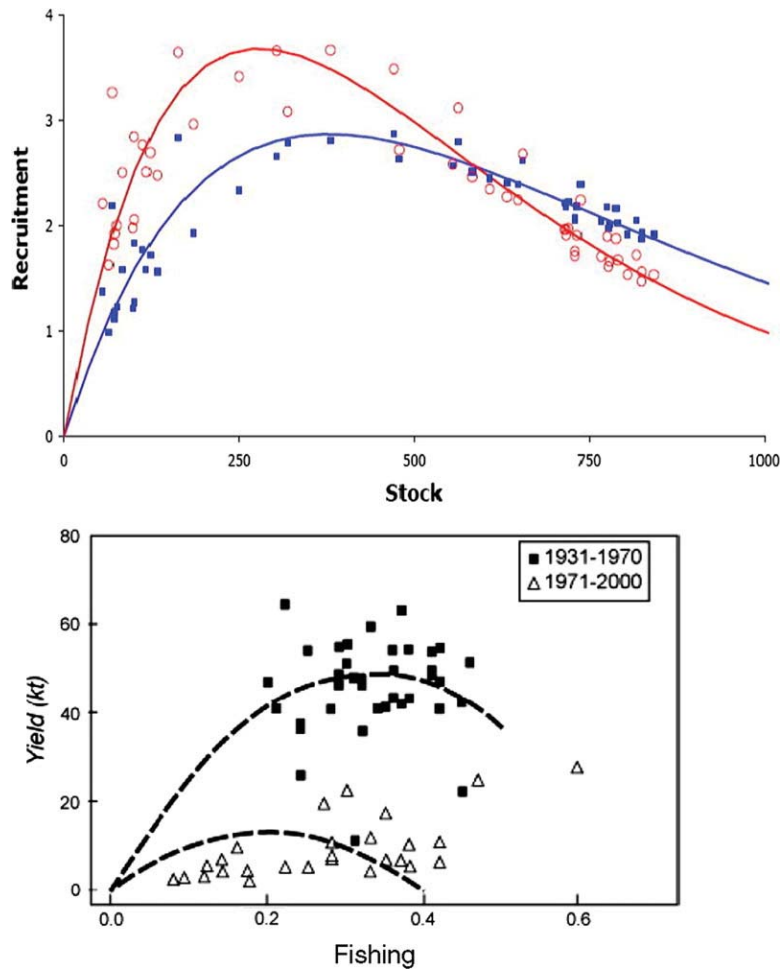


Fig. 5. (a) Stock/recruitment plot for Bering Sea yellow fin sole showing two possible states, (b) abundance/fishing effort plot for Georges Bank haddock with two apparent states based on different years.

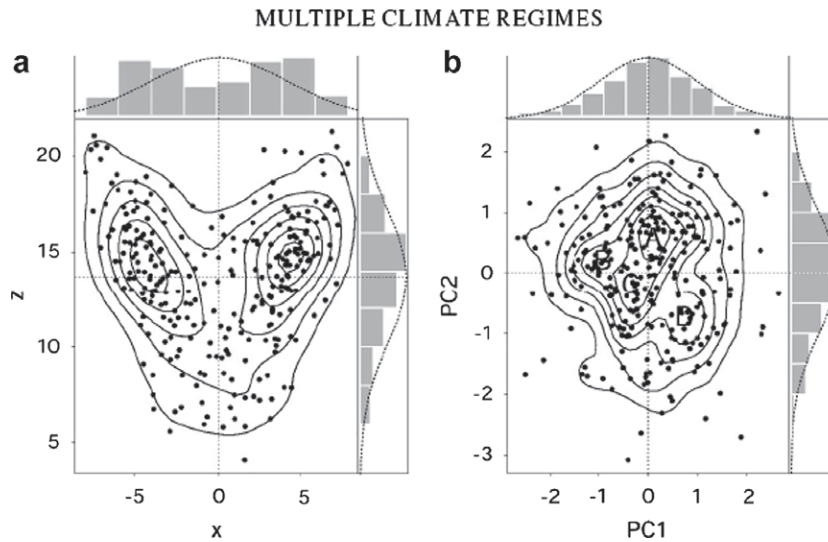


Fig. 6. Phase space plots for (a) the Lorenz system which is an example of a generic non-linear system. The dots represent possible solutions to the set of equations and the contours provide a representation of the density of the number of dots. On the top and right are histograms of the density of dots projected onto one axis. (b) Strength of the first two Northern Hemisphere climate patterns based on Principal Components of the 500 hPa geopotential heights. Dots represent the climate state in different years.

ern Oscillation Index (SOI), at various averaging intervals. All but one salmon stock timeseries had a low-dimensional behavior of 3–4, and the dimensionality for CalCOFI biological timeseries ran-

ged from 4 to 8. This implies possible multi-state behavior for North Pacific biology. Unlike the biological timeseries, the physical timeseries were judged as not deterministically non-linear, and

were consistent with a signal that would be made up of a large number of contributing factors (dimensions). One would expect a more Gaussian behavior for the physical timeseries. There is some concern over these conclusions, however, given their relatively short timeseries (Section 2.2 above and Ghil et al., 2002).

2.5. More on large scale climate

Fig. 6b is the 2-D phase space plot of the first two principal components of the atmospheric 500 hPa geopotential height field showing year to year climate variability for the entire northern hemisphere, similar to Fig. 2 for the SST in the North Pacific. While there appears to be some clustering of points in the 2-D field, the histogram of values for each axis looks rather Gaussian. Hemispheric climate has also been considered non-linear due to the apparent clustering of values (Corti et al., 1999). Essentially, the same basic data has been used to claim both a single Gaussian distribution for atmospheric processes and the presence of multiple attractors (Stephenson et al., 2004).

Fig. 7 shows the distribution functions for two North Pacific atmospheric climate indices, one for mid-level upper atmospheric circulation (Pacific North American pattern: PNA) and one for the surface pressure of the Aleutian Low pressure system (North Pacific Index: NPI). The distributions have some characteristics of multiple modes, but also an overall Gaussian shape. The statistical test of normality (Gaussian distribution) for these timeseries was positive. In contrast to the atmosphere, when autocorrelation is re-

moved from the PDO series, statistically significant regime shifts remain for the North Pacific (Rodionov, 2006).

Given the contrary information in the above two paragraphs, the discussion of short timeseries in Section 2.2, and the high dimensionality of physical variables discussed in Section 2.4, the best we can say is that time-series representing North Pacific multi-year and longer climate variability are probably not strongly non-linear. Thus for practical purposes on decadal scales, the large natural climate variability in the North Pacific appears mostly random with a regime like character to its timeseries. Some multi-year memory tendencies in the physical system may be found. In addition to this internal natural variability on decadal time scales, external forcings such as recent greenhouse gas anthropogenic contributions (Overland and Wang, 2007) or changes in solar insolation on ice age time scales will introduce persistent trends.

2.6. Two other considerations

Bailey (2000) notes that control of recruitment of pollock in the Gulf of Alaska shifted in the 1980s from physical environmental effects on larvae to biological control of juveniles through top-down predation by flatfishes and cod. It is unclear whether this example falls under the ecological regime shift paradigm or if it is more the transition of an ecological system from a state of exploitation [Bakun (2004) calls these loopholes] to one of constraints (high food web connectivity), i.e., that these changes simply represent two locations on a single stock/recruitment curve. In both the Gulf of

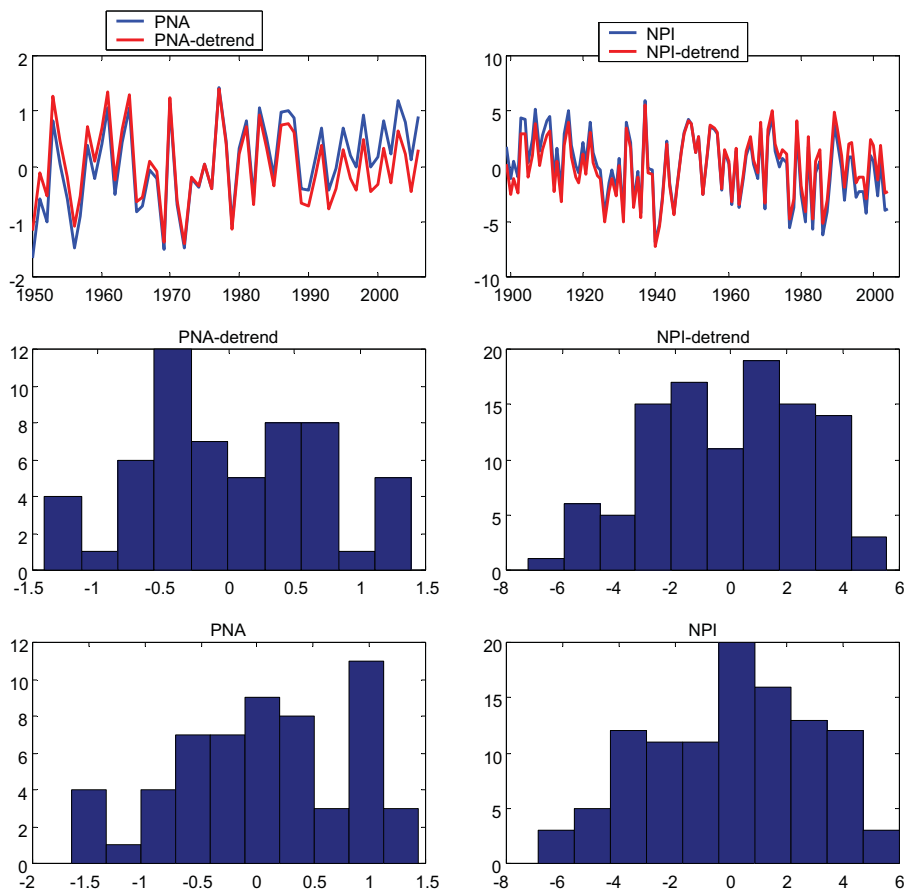


Fig. 7. (Top) Fifty five year timeseries anomalies of two wintertime (December–February.) climate indices, The Pacific North American (PNA, at 500 hPa level, arbitrary units) pattern (left) and the North Pacific Index (NPI, strength of the Aleutian low pressure system in mb) (right); raw timeseries (blue) and detrended timeseries (red). (Middle) Histogram of detrended timeseries. Units on the X-axis are the same as in Top. (Bottom) Histogram of raw timeseries. Units are the same as in Top. Correlation between the PNA and NPI for overlapping period is -0.90 (-0.86) for raw (detrended) data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Alaska and Bering Sea where pollock became dominant, it is assumed that an exploitive stage began shortly after the climate shift in the mid-1970s. Hunt et al. (2002) discuss an “oscillating control hypothesis” for pollock in the Bering Sea. Their conclusions are similar to Bailey with a major biological transition during the warm climate state after 1976.

The second consideration is geographic shifts in water masses, as exemplified by the ecosystem off of the west coast of the United States (Peterson and Schwing, 2003). Due to an increase in upwelling favorable winds after 1997 for example, there is a replacement of warm water California species with more cold water species. While there is some change in local productivity, the primary difference in state is one of water mass displacement, rather than internal reorganization or abundance change within each water mass. Do we want to call changes primarily due to geographic displacement rather than productivity changes within a single water mass, an ecological regime shift? The answer is complex because salmon spawning populations are fixed in space and thus the juveniles when reaching the ocean encounter conditions of varying productivity and community structure. Additional examples are represented by the geographic displacement of species in the northwest Atlantic during the 1930–1950s labeled as a regime shift by Drinkwater (2006) and northward shifts of species in the North Sea due to increased sea temperatures over the previous 25 years (Perry et al., 2005).

3. North Pacific displacement regime shifts

Given that displacement regime shifts are of interest, we applied the regime detection algorithm of Rodionov (2004) to selected North Pacific timeseries. As suggested in the previous

sections, selection criteria are not unique. Rodionov's approach provides flexibility by requiring a user to set a number of parameters: the target significance level p , cutoff length l , and Huber weight parameter h . The target significance level corresponds to the potential level (p 100%) of false positives. In practice, the actual significance levels (calculated using the t -test after the timing of the shifts are detected) for the overwhelming majority of the shifts are lower than p . In the case of autocorrelation in the timeseries the actual significance level is adjusted by calculating the equivalent sample size (Von Storch and Zwiers, 1999). The cutoff length l is similar to the cutoff frequency in filtering; it affects the time scale of the regimes by discounting regimes of length less than l . The Huber weight parameter improves the treatment of outliers (values greater than h standard deviations) by weighing them inversely proportional to their distance from the mean value of the regime (Huber, 2005). Using these parameters, the method utilizes a sequential approach to determine the timing of the regime shifts. The identification of a regime shift is based on calculating the regime shift index (RSI), which represents a cumulative sum of normalized deviations of the timeseries values from the hypothetical mean level for the new regime. This is the level for which the difference from the mean level for the previous regime is statistically significant according to the Student's t -test. If the RSI remains positive during all l years a shift is declared. For more details on calculating the RSI see Rodionov (2004, 2006), Rodionov and Overland (2005), and the Bering Climate website (www.beringclimate.noaa.gov), where an executable version of the algorithm can be downloaded.

As an example of the sensitivity of regime detection, the PDO timeseries was processed using two sets of parameters: (1) $p = 0.1$ and $l = 15$ yrs and (2) $p = 0.3$ and $l = 10$ yrs, both with

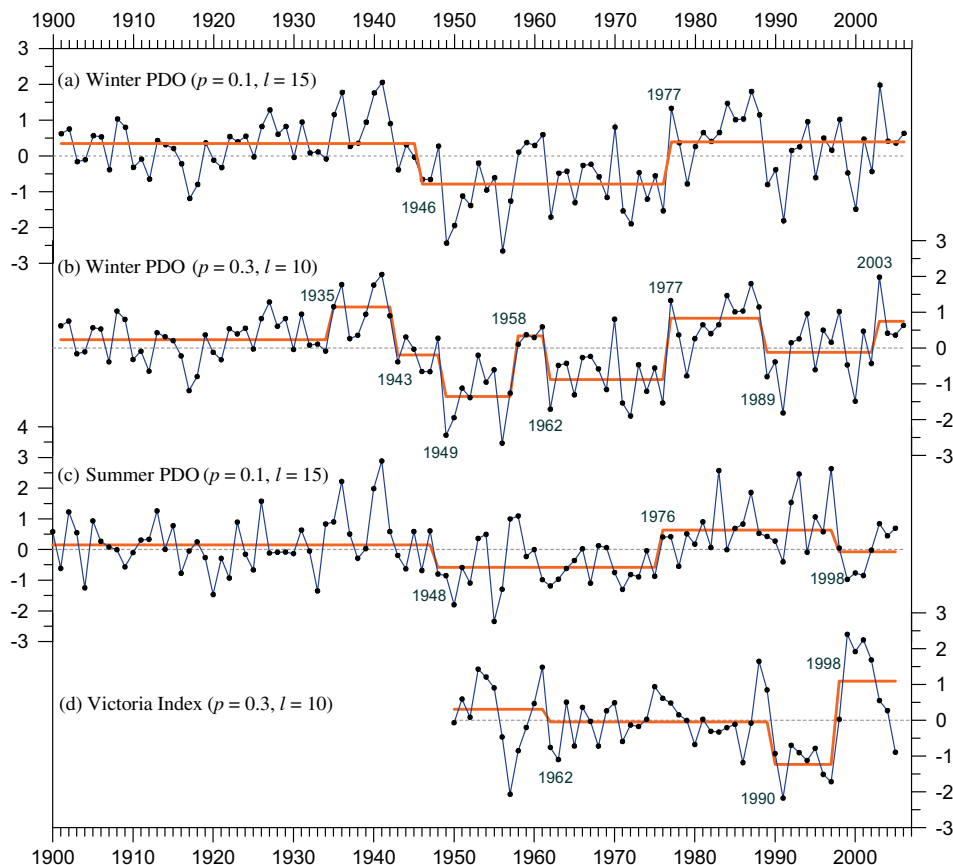


Fig. 8. Regime shifts for the PDO/Victoria Pattern with different sensitivity parameter, p , and regime length parameter, l . Timeseries here and in Fig. 9 are not detrended.

$h = 1$. For the winter PDO only the major shifts in 1945 and 1977 are selected using the first set of parameters, i.e., when the constraints are strong (Fig. 8a). With the weaker, but still substantial constraints of the second set of parameters, additional events are identified in 1958, 1989 and 2003, among others (Fig. 8b). For

the summer PDO timeseries (Fig. 8c), the shift in 1998 is selected even in the case of tight constraints. The 1998 shift is also pronounced in the second winter principal component, or the Victoria pattern (Fig. 8d). Summer SST is primarily governed by radiative processes, whereas winter SST is strongly coupled to winds and

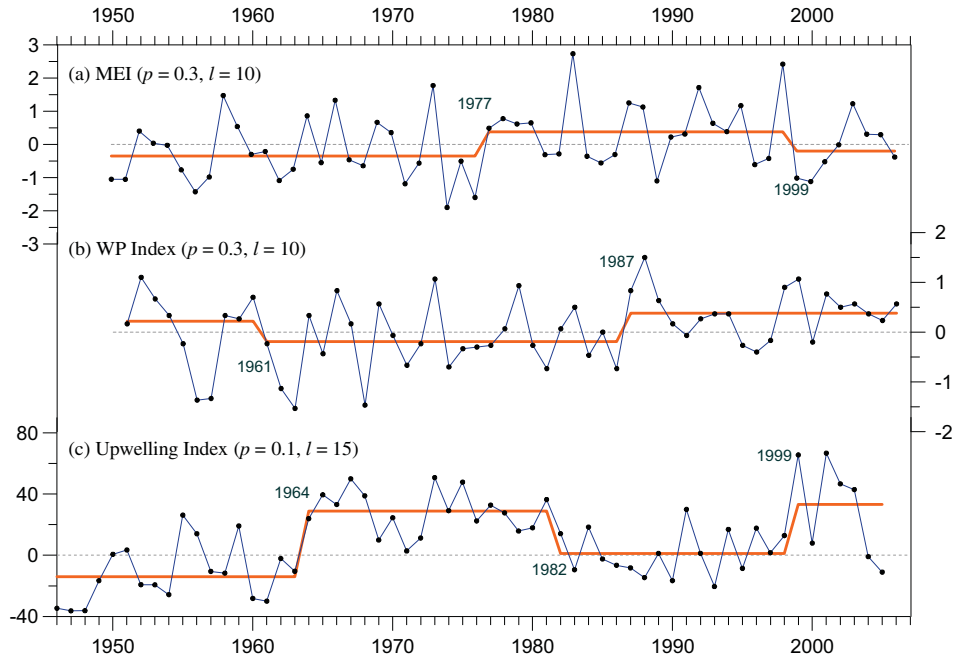


Fig. 9. Regimes for three North Pacific regional indices: the Multivariate ENSO Index, the West Pacific Index, and a west coast US upwelling index.

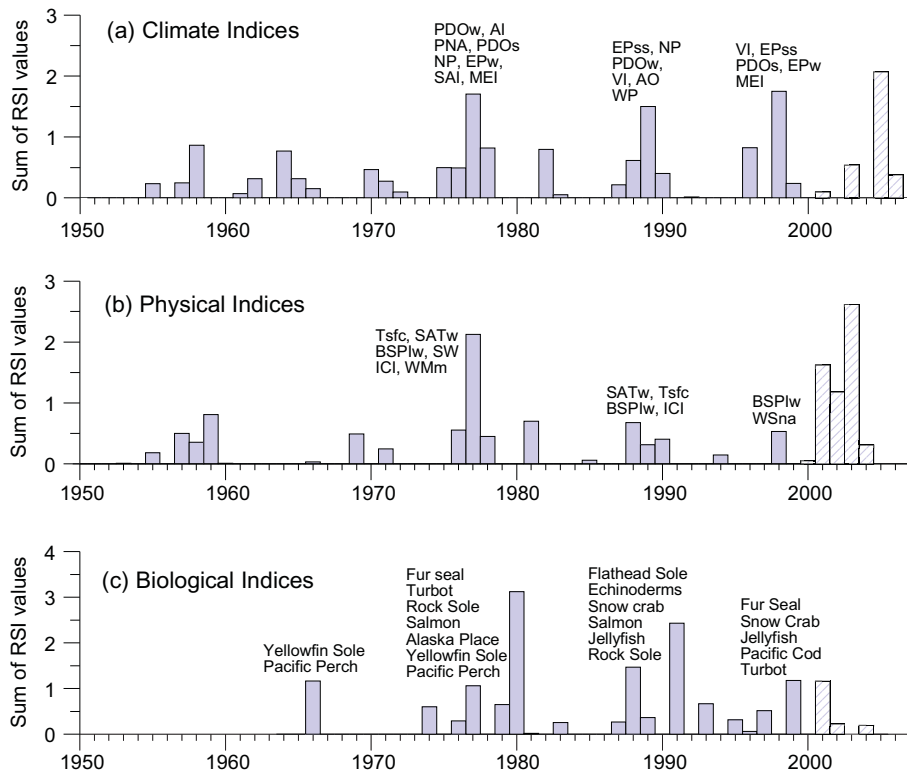


Fig. 10. Composite regime shifts for climate indices and Bering Sea physical and biological indicators. The bars beyond 2000 are shaded differently as they are tentative shifts, where confidence may increase with additional years of data.

atmospheric climate patterns. It is interesting, therefore, that the timing of the winter and summer shifts is similar. As guidance for choosing parameters p and l , selection is based on users' requirements, rather than fixed values. In contrasting Fig. 8a and b for example, does one want to consider regimes of shorter duration (5 years) with smaller magnitude? The comparison with different parameters is helpful in interpreting the sensitivity of the procedure.

Fig. 9 shows timeseries of three other indices. The Multivariate ENSO Index (MEI) includes a weak propensity for El Niños during 1977–1998. The West Pacific index (see www.beringclimate.noaa.gov for details) shows primarily interannual variability, but also a long-term trend. This and other west Pacific climate indices are more characterized by long-term trends, rather than regime type behavior as in the NE Pacific. The US west coast upwelling index for months of AMJJ and 39–48 N°, has several strong regimes bounded by 1964–1982 and 1999–2003.

Fig. 10 summarizes results for temporal shifts in basin-scale North Pacific climate indices, regional-scale Bering Sea physical

parameters, and Bering Sea biological parameters. Each bar represents a sum of individual RSI values for each timeseries at the given year. The list of variables is given in Table 1 and the detected regime shifts are presented in Appendix Tables A1, A2 and A3. Further description of the variables is given on the Bering Climate website. Note that different biological times series begin from 1956 to 1982 and end from 1997 to 2005. Thus, except for 1982–1997, there are a variable number of contributions toward the yearly RSI summary index.

For the climate indices, the highest RSI sums are clustered around three groups of years: 1976–1978, 1988–1990, and 1998–1999. In contrast, the biological shifts do not form strong groupings and imply separate responses or various time lags to shifts in physical forcing. This conclusion on biological series is different from Hare and Mantua (2000) who suggested that biological series were favored over physical series in detecting regime shifts based on principal components. The different shading near the end of the series highlights the potential for regime shifts in these years; further confirmation will increase (or not) with the addition of more years. The high RSI sums in these recent years suggest that we are in a period of uncertainty for the state of the North Pacific.

Table 1
Indices used in this study

Climate indices		
PDOw	Pacific Decadal Oscillation Index (DJF)	1901–2006
PDOs	Pacific Decadal Oscillation Index (JJA)	1900–1905
NP	North Pacific Index from (November–March)	1900–2005
AO	Arctic Oscillation Index (DJF)	1951–2006
MEI	Multivariate ENSO Index (January–February)	1950–2006
EPw	East Pacific/North Pacific Index (JFM)	1950–2006
EPss	East Pacific/North Pacific Index (AMJJ)	1950–2005
PNA	Pacific-North American Index (DJF)	1951–2006
SAI	Siberian–Alaskan Index (DJFM)	1949–2005
SI	Siberian Index (DJFM)	1949–2005
AI	Alaskan Index (DJFM)	1949–2005
WPw	West Pacific Index (DJF)	1951–2006
WPs	West Pacific Index (MAM)	1950–2005
VI	Victoria Index (DJF)	1950–2005
UI	Upwelling Index (AMJJ) along the West Coast (39–48N)	1946–2005
Physical indices		
BSPw	Bering Sea Pressure Index (DJFM)	1900–1905
BSPs	Bering Sea Pressure Index (AMJ)	1899–2005
SW	Strong winds (>9.5 m/s) at Mooring 2 (May–Mid July)	1950–2005
FW	Favorable winds at Mooring 2 (May–Mid July)	1950–2005
NSW	North–south winds at St. Paul (DJFM)	1949–2005
SATw	Surface Air Temperature at St. Paul (DJFM)	1946–2006
SATa	Surface Air Temperature at St. Paul (Annual)	1946–2005
WSna	Along-peninsula wind stress (November–April)	1951–2005
WSmj	Along-peninsula wind stress (May–June)	1950–2005
Wmm	Wind mixing at St. Paul (May)	1950–2005
WMjj	Wind mixing at Mooring 2 (June–July)	1950–2005
Tsfc	Surface temperature at Mooring 2 (January–April)	1950–2005
SBT	Summer bottom temperature in the SE Bering Sea	1982–2005
ICI	Ice Cover Index	1954–2005
Biological indices		
Salmon	Bristol Bay sockeye salmon runs	1956–2005
Jellyfish	Large medusae catch	1982–2004
Echinoderms	Echinoderms CPUE	1982–2004
Fur seal	Fur seal pups born in St. Paul Island	1975–2004
Snow crab	Snow crab biomass	1980–2004
Zooplankton	Zooplankton biomass	1965–1997
Alaska plaice	Alaska plaice recruitment	1972–2002
Pollock	Walleye pollock recruitment	1963–2004
Pacific cod	Pacific cod recruitment	1964–2004
Flathead sole	Flathead sole recruitment	1972–2002
Arrowtooth flounder	Arrowtooth flounder recruitment	1974–2001
Herring	Herring recruitment	1965–2000
Pacific perch	Pacific perch recruitment	1957–2004
Rock sole	Rock sole recruitment	1971–1999
Greenland turbot	Greenland turbot recruitment	1974–2004
Yellowfin sole	Yellowfin sole recruitment	1959–2000

4. Discussion and conclusions

We have noted the distinctions between the displacement, mechanism, and external definitions used to describe regime shifts. The first emphasizes shifts in short timeseries, the second the underlying process, and the third external forcing of biological systems. Although science strives for precision in language, it is not clear that we can put the genie back into the bottle with a single definition of regime. There is a history of associating biological regimes with changes in the physical system. This interpretation continued at the PICES-CCCC/GLOBEC North Pacific synthesis meeting in April 2006. Other parts of the community also use the external forcing definition for regime shifts for the North Atlantic (Perry et al., 2005; Drinkwater, 2006).

Based on the displacement definition we find significant shifts in multiple climate indices around 1976, 1989, and 1998 (Fig. 8). These changes would qualify as climatic regime shifts under Bakun's definition and under the external definition, in which a shift in level of a climate indicator is a prerequisite. There is no convincing evidence that these climate shifts in the North Pacific are between multiple stable states. Instead, they appear to be more consistent with a long memory process with considerable autocorrelation at multi-year time scales, which can show persistent major deviations from a single century scale mean.

Biological response to climatic regime shifts fall into several categories. The first is a change in the production/species dominance of a marine system, moving from the exploitive stage to high ecosystem connectivity. This transition may take many years and is different for different species. Biological regimes are also associated with change in the “governing rules” or functional dependencies (Rothschild and Shannon, 2004), for example multiple stock/recruit curves. These changes may be consistent with low-dimensional models with multiple attractors, but we note that these models are sensitive to the range of model parameters. The often used definition of biological regimes as “multiple stable states” needs revision, as the regime would often be a region in the variable phase space rather than at specific loci. A third notable response to a climatic regime shift is a spatial displacement of populations. This terminology has been used for the US west coast and in the Atlantic.

There is a caveat with the use of the rather qualitative definitions of regime shift mentioned in the previous paragraphs, i.e., everything can start looking like a regime, or that regime shifts

can take on mythical proportions. This is the warning from the proponents of the mechanism definition (Rudnick and Davis, 2003). There are cases where “regime shift” by itself was used as the single self-evident cause of a biological shift without further consideration of the underlying biological processes and physical connection. The debate on climate/fishing impacts on Alaskan king crab is one example (Dew and McConnaughey, 2005). However, the clear recognition of the connection between climate and ecosystems, and internal shifts of the inter-species relationships within an ecosystem, represent undeniable advances in fisheries oceanography. The use of the phrase “regime shift” has popularized these avenues of research. Our results highlight the importance of continued monitoring and mechanistic understanding in the face of environmental uncertainty.

Acknowledgements

We appreciate the support from the North Pacific Research Board for the “Indicators” Project, the NEP GLOBEC Program, and the NOAA FOCI Program. PMEL contribution number 2943. This is US GLOBEC contribution 589 supported jointly by NOAA and NSF. This paper was presented at the PICES/GLOBEC Symposium on “Climate variability and ecosystem impacts on the North Pacific: A basin-scale synthesis” held April 19–21, 2006, in Honolulu, USA.

Table A1
Regime shifts detected in climate indices

Index	<i>p</i> = 0.1, <i>l</i> = 15	<i>p</i> = 0.3, <i>l</i> = 10
PDOw	1946, 1977	1935, 1943, 1949, 1958, 1962, 1977, 1989, 2003
PDOs	1948, 1976, 1998	1916, 1934, 1943, 1976, 1998
NP	1924, 1947, 1977	1924, 1946, 1958, 1977, 1988, 1996
AO	1989, 2001	1972, 1989, 1996, 2006
MEI	None	1977, 1999
EPw	1978, 1999	1962, 1978, 1983, 1992, 1999
EPss	1970, 1989, 2004	1970, 1989, 1998
PNA	1977	1958, 1965, 1975, 2003
SAI	1978, 2005	1958, 1978, 2005
SI	2005	1966, 2005
AI	1977, 2005	1957, 1971, 1978, 2005
WPw	1998	1961, 1987
WPs	None	None
VI	1999	1962, 1990, 1998
UI	1964, 1982, 1999	1955, 1964, 1982, 1996, 2001

Years in italics are recent tentative shifts that may become more (or less) significant as additional years of observations become available.

Table A2
Regime shifts detected in the physical indices (Bering Sea)

Index	<i>p</i> = 0.1, <i>l</i> = 15	<i>p</i> = 0.3, <i>l</i> = 10
BSPIw	1924, 1947, 1977	1912, 1926, 1947, 1977, 1989, 1998,
BSPIs	1959, 2003	1910, 1917, 1928, 1959, 1969, 2000
SW	1962, 1976, 2004	1957, 1976, 2004
FW	2003	1955, 1960, 2003
NSW	1970	1953
SATw	1978, 2003	1977, 1988, 2003
SATa	1977, 2003	1971, 1977, 2003
WSna	1998	1998
WSmj	2005	2001
WMm	1976, 2005	1976, 1985, 1994, 2002
WMjj	1961, 1981	1958, 1981
Tsfc	1977, 2005	1971, 1977, 1988, 2001
SBT	2002	2002
ICI	1977, 2001	1966, 1978, 1990, 2003

Years in italics are recent tentative shifts that may become more (or less) significant as additional years of observations become available.

Table A3
Regime shifts detected in the biological indices (Bering Sea)

Index	<i>p</i> = 0.1, <i>l</i> = 15	<i>p</i> = 0.3, <i>l</i> = 10
Salmon	1979, 1997	1979, 1989, 1997
Jellyfish	1993	1991, 2001
Echinoderms	2002	1988
Fur seal	1983, 2000	1980, 1999
Snow crab	1999	1987, 1993, 1999
Zooplankton	1993	1993
Alaska plaice	1981	1977, 1981
Pollock	None	2002
Pacific cod	1976, 2001	1974, 2001
Flathead sole	1988	1988
Arrowtooth flounder	1995	1983, 1995
Herring	None	None
Pacific perch	None	1966, 1976, 1989
Rock sole	None	1980, 1991
Greenland turbot	1981	1980, 1991, 2001
Yellowfin sole	1969, 1977	1966, 1977, 1996

Years in italics are recent tentative shifts that may become more (or less) significant as additional years of observations become available.

Appendix A

See Tables A1, A2 and A3.

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