ICES Journal of Marine Science, 62: 328–332 (2005)
doi:10.1016/j.icesjms.2005.01.013

Application of a sequential regime shift detection method to the Bering Sea ecosystem

Sergei Rodionov and James E. Overland

Rodionov, S., and Overland, J. E. 2005. Application of a sequential regime shift detection method to the Bering Sea ecosystem. – ICES Journal of Marine Science, 62: 328–332.

A common problem of existing methods for regime shift detection is their poor performance at the ends of time-series. Consequently, shifts in environmental and biological indices are usually detected long after their actual appearance. A recently introduced method based on sequential t-test analysis of regime shifts (STARS) treats all incoming data in real time, signals the possibility of a regime shift as soon as possible, then monitors how perception of the magnitude of the shift changes over time. Results of a STARS application to the eastern Bering Sea ecosystem show how the 1989 and 1998 regime shifts manifest themselves in biotic and abiotic indices in comparison with the 1977 shift.

Keywords: Bering Sea, ecosystem, regime shift, sequential analysis, t-test.

Received 1 April 2004; accepted 8 December 2004.

S. Rodionov: Joint Institute for the Study of the Atmosphere and Oceans, Box 354235, University of Washington, Seattle, WA 98195-4235, USA. J. E. Overland: NOAA/Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115-6349, USA. Correspondence to S. Rodionov: tel: +1 206 5266211; fax: +1 206 5266485; e-mail: Sergei.Rodionov@noaa.gov.

Introduction

Regime shifts are defined as rapid reorganizations of ecosystems from one relatively stable state to another. In the marine environment, regimes may last for several decades, and shifts often appear to be associated with changes in the climate system. In the North Pacific, climate regimes are typically described using the concept of Pacific Decadal Oscillation (PDO), a term established by Mantua *et al.* (1997). Those authors demonstrated that shifts in the polarity of the oscillation correspond to shifts in salmon production in the North Pacific Ocean.

Because the lifespan of such regimes is much longer than the transition time, there is opportunity for so-called “nowcasts”. Knowing that there has been a regime shift would allow fisheries scientists to adjust their management advice depending on what regime is established. Although the idea seems attractive, there are two major issues to be resolved: (i) poor understanding of ecosystem response to climate shifts, and (ii) timely detection of the shifts. Here we address the second issue.

Several methods have been developed to detect discontinuities in time-series (for comprehensive reviews, see Easterling and Peterson, 1995; Lanzante, 1996). Some are automated; others require a preliminary visual inspection of the time-series. They also differ in their sensitivity to trends, outliers, and other forms of non-normality, as well as in their ability to handle single or multiple shifts. However, all the methods have a common problem: the drastic deterioration of the test statistics toward the ends of time-series. This means that a substantial quantity of data has to be accumulated before they can be applied, although by the time sufficient data are available, there is a good chance that another, more recent shift has already occurred. Obviously, this uncertainty undermines the value of a nowcast.

In an attempt to overcome this problem, Rodionov (2004) developed a new method based on sequential t-test analysis of regime shifts (STARS). Here we describe the main features of the method and discuss preliminary results of its application to the Bering Sea ecosystem.

Method

Let $x_1, x_2, \ldots, x_i, \ldots$ be a time-series with new data arriving regularly. When a new observation arrives, a check is performed to determine if it represents a statistically significant deviation from the mean value of the current regime. If it does, that year is marked as a potential change point c, and subsequent observations are used to confirm or reject this hypothesis. The hypothesis is tested using the regime shift index (RSI), which is calculated for each c:

$$\mathrm{RSI}_c = \sum_{i=c}^{c+m} \frac{x_i^*}{l\sigma_l}$$

where m = 0, …, $l-1$ (i.e. number of years since the start of a new regime), l being the cut-off length of the regimes to be tested, and σ_l is the average standard deviation for all one-year intervals in the time-series. RSI represents a cumulative sum of normalized deviations x_i^* from the hypothetical mean level for the new regime ($\bar{x}_{\mathrm{new}}$), for which the difference, diff, from the mean level for the current regime ($\bar{x}_{\mathrm{cur}}$) is statistically significant according to a Student's t-test:

$$\mathrm{diff} = \bar{x}_{\mathrm{new}} - \bar{x}_{\mathrm{cur}} = t\sqrt{2\sigma_l^2/l}$$

where t is the value of the t-distribution with $2l-2$ degrees of freedom at the given probability level p. If, at any time from the start of the new regime, RSI becomes negative, the test fails and a zero value is assigned. If RSI remains positive throughout $l-1$, then c is declared to be the time of a regime shift at the level $\leq$p. The search for the next regime shift starts with c + 1 to ensure that its timing is detected correctly even if the actual duration of the new regime is $<$l year.

In a previous version of the program, Rodionov (2004) used a running window of a fixed size equal to 2l (i.e. [c − l, c + l], centred at c). In this case, the average value for the current regime $\bar{x}_{\mathrm{cur}}$ is calculated for the period (c − l, c). If a transition from one regime to another is gradual, the program might not detect it, because $\bar{x}_{\mathrm{cur}}$ is also changing as the window slides along the time axis, so the difference between the new arriving observations and $\bar{x}_{\mathrm{cur}}$ may not be statistically significant to become a potential change point and trigger the calculation of RSI. In the new version used here, $\bar{x}_{\mathrm{cur}}$ is calculated for the period from the previous regime shift to the point immediately before the current point in time. As a result, a stepwise function of regimes is produced in almost all cases, whereas the previous version of the program could detect abrupt regime shifts only. To improve the performance at the beginning of time-series, the testing for a regime shift starts not from x_{l+1} as in the previous version, but from x_2. The average value $\bar{x}_{\mathrm{cur}}$ is still calculated for the entire initial period [1, l], but if a regime shift occurred prior to i = l, it is detected.

Table 1. RSI values for pollock recruitment (p = 0.1; l = 5 years; non-zero values of i, c triggered calculation of RSI; only for the years highlighted in bold did values remain positive and a regime shift was declared; final values are in italics; testing is still in progress for 2001).

i, c	m = 0	m = 1	m = 2	m = 3	m = 4
1978	0.51	0.45	0.44	0.21	*0.57*
1979	0	0	0	0	*0*
1980	0	0	0	0	*0*
1981	0.1	0	0	0	*0*
1982	0	0	0	0	*0*
1983	0.15	0	0	0	*0*
1984	0	0	0	0	*0*
1985	0.1	0.29	0.52	0.67	*0.12*
1986	0	0	0	0	*0*
1987	0	0	0	0	*0*
1988	0	0	0	0	*0*
1989	0.34	0.24	0.05	0.37	*0.09*
1990	0	0	0	0	*0*
1991	0	0	0	0	*0*
1992	0.07	0	0	0	*0*
1993	0.07	0.19	0.07	0	*0*
1994	0.12	0	0	0	*0*
1995	0	0	0	0	*0*
1996	0	0	0	0	*0*
1997	0	0	0	0	*0*
1998	0	0	0	0	*0*
1999	0	0	0	*0*	—
2000	0	0	*0*	—	—
2001	0.08	*0.14*	—	—	—
2002	*0*	—	—	—	—

Table 1 illustrates the results of calculations for recruitment (at age 1) of walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea. Data are available for the years 1963–2002, but to save space here, RSI values are listed only since 1978, when the first shift was detected. All non-zero values in the second column (m = 0) indicate the years during which calculation of the RSI was triggered. Only for three years (1978, 1985, 1989) did RSI values remain positive right up to m = l − 1, and the regime shift was declared (testing for a possible shift in 2001 is still in progress). The last RSI values in each row are the final ones. If there are sufficient data, Table 1 can be used to evaluate the probability of a regime shift, if the RSI reaches a certain value by m = 1, 2, … l − 2 (Rodionov, 2004).

STARS can be tuned to detect the regimes of certain time scales and magnitudes. The time scale to be detected is controlled primarily by the cut-off length. Figure 1 illustrates that as the cut-off length is reduced, the time scale of regimes detected becomes shorter. Both the cut-off length and probability level affect the statistically significant difference between regimes, and hence the magnitude of the shifts to be detected.

Because time-series are normalized and the method is fully automatic, it can be applied easily to a large set of variables. In this case, the final RSI is the average of the RSI for each variable in the set. It is important to note that there is no need to reverse the sign of some time-series to ensure that all shifts occur in the same direction. This problem was experienced by Hare and Mantua (2000) in

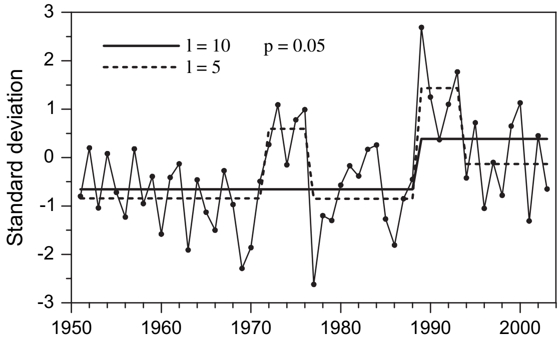

Figure 1. Regime shift detection in the Arctic Oscillation index for different values of the cut-off length.

their analysis of 100 physical and biological time-series in the North Pacific. Rudnick and Davis (2003) demonstrated that the procedure of sign reversal artificially enhances the chance of identifying existing shifts and may even lead to spurious shifts being identified.

STARS was originally written in Fortran, then converted to VBA for Excel. It is available for download at www.BeringClimate.noaa.gov.

Application to the Bering Sea ecosystem

STARS was applied to a set of indices describing the ecosystem of the eastern Bering Sea. (www.BeringClimate.noaa.gov describes data sources and discusses the relevance of each index; the data can be downloaded.) Currently, 45 indices are available, divided into five groups: climate (16), atmosphere (11), ocean (6), fishery (11), and biology (3). Here, the last two groups were analysed together. If not stated otherwise, cut-off length was set to l = 10 years and probability level at p = 0.1. A brief description of the results for each group follows, with the emphasis on the most recent shifts, but owing to space limitations, graphic illustration is provided only for the group of climate indices.

The highest RSI value for the climate indices was obtained for 1943 (Figure 2), with a major contribution coming from the PDO index. The second strongest shift occurred around 1976−1977. In addition to the PDO, this shift was prominent in the Aleutian Low Pressure Index (ALPI), a North Pacific Index from the National Center for Atmospheric Research (NPI_{NCAR}), and in the Pacific−North American (PNA) index. The shifts in 1989 and 1998 were less pronounced and the PDO played only a secondary role. This is consistent with the conclusion of Bond *et al.* (2003) that North Pacific climate variability during the past 10−15 years deviates from typical PDO variability, which dominated much of the twentieth century. Among the indices considered, the shift of 1989 was most prominent in the Arctic Oscillation (AO) index (Figure 1), which may have contributed to the relative cooling in the Bering Sea after an exceptionally warm period over the years 1977−1988 (Overland and Adams, 2001).

The 1998 shift was first portrayed as a sign reversal in the PDO (Minobe, 2002). However, Bond *et al.* (2003) showed that the shift was not as much in the PDO but rather in the second principal component of sea surface temperature (SST). Figure 2 shows that the shift was particularly strong in the North Pacific Index from the Climate Prediction Center (NPI_{CPC}) and East Pacific Index (EPI). Changes in both indices reflect strengthening of the Subtropical High in recent years, which resulted in cooling in the California

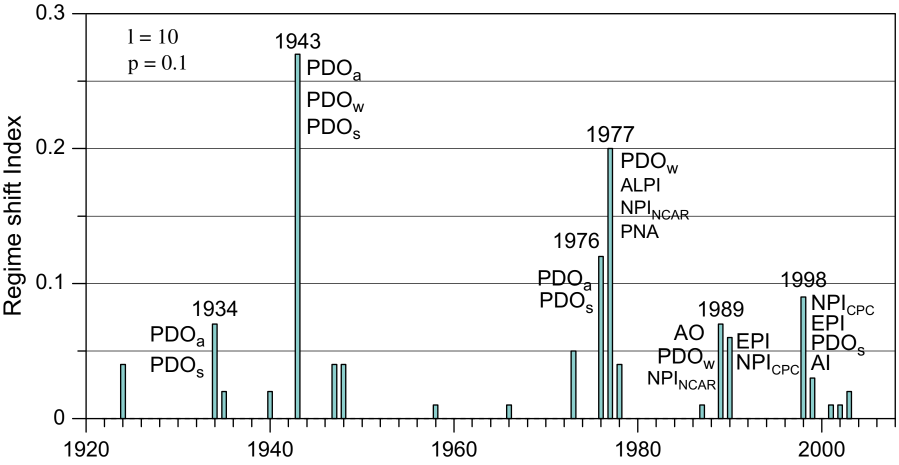

Figure 2. Regime shift index values for the group of climate indices (PDO, Pacific Decadal Oscillation; subscripts a, w, and s, annual, winter, and summer values, respectively); ALPI, Aleutian Low Pressure Index; NPI_{NCAR}, North Pacific Index from National Center for Atmospheric Research; NPI_{CPC}, North Pacific Index from Climate Prediction Center; PNA, Pacific−North American index; AO, Arctic Oscillation; EPI, East Pacific Index; AI, Alaskan Index).

Current region. Peterson and Schwing (2003) reported substantial changes in that region since 1998, for instance an increase in zooplankton biomass and a switch from warm- to cold-water species dominance. At the same time, the Bering Sea continued to experience anomalously warm climate conditions (Bond *et al.*, 2003).

The highest RSI value for the atmospheric group of indices was in 1977, with the largest contribution coming from winter and annual sea surface temperature (SAT) and winter sea level pressure (SLP) averaged over the Bering Sea. The latter also experienced abrupt shifts in 1989 and 1998, which means that a cyclonic regime dominating in the years 1977–1988 was followed by an anticyclonic regime in the years 1989–1997, to be replaced by another cyclonic regime in 1998. Average SLP after 1998 is even lower than during the previous cyclonic regime. Also, starting with 1997, there was a sharp decrease in (i) the index of windspeed in the months May–July favourable for successful larval feeding of walleye pollock (Megrey and Hinckley, 2001), and (ii) the index measuring the rate of summer (June and July) wind mixing.

Although the shift of 1977 was very strong in oceanographic indices, the maximum RSI value for this group was in 1983. The shift of 1983 was primarily associated with a decrease in winter (January, February, and March) SST south of the Pribilof Islands, after a very warm period of 1977–1982. At Mooring 2 (57°N 164°W), this cooling became noticeable in 1988. Recent years, however, were anomalously warm in the Bering Sea, as for instance reflected in a sharp decrease in the Ice Retreat Index in 2000. The values from that year on indicate that there was practically no ice in the vicinity of Mooring 2 after March 15, while mid-March typically is the time when ice just starts retreating from this area. The fast rise in summer bottom temperatures in the southeastern Bering Sea after the anomalously cold summer of 1999 is also worth noting.

Unlike the abiotic indices, RSI values for the biotic indices were not concentrated around certain years, suggesting that different species experienced shifts in different years. Most shifts were between 1977 and 1992. Species for which shifts were timed closely with those in the abiotic indices include Pacific herring (*Clupea pallasi*), sockeye salmon (*Oncorhynchus nerka*), and walleye pollock (Figure 3). There was a statistically significant shift in herring recruitment in the late 1970s, starting with the two extremely strong year classes of 1977 and 1978. Although there appears to have been a shift back to poor year classes in 1989, recruitment data are available only until 1991, and a final judgement cannot be made. Bristol Bay sockeye salmon showed a major upward shift in 1979. The average run during the years 1979–1997 was 41 million, about twice as high as in the preceding period (1956–1978). This favourable regime lasted until 1997, when a new low-level regime was established with an average run of 25 million. When a cut-off length l of 10 years was applied to pollock recruitment, no shifts were identified. For l = 5 years, the period 1985–1988 was singled out as a separate regime, and the shift of 1978 was significant. A possible shift to poor year classes in 2001 can also be seen.

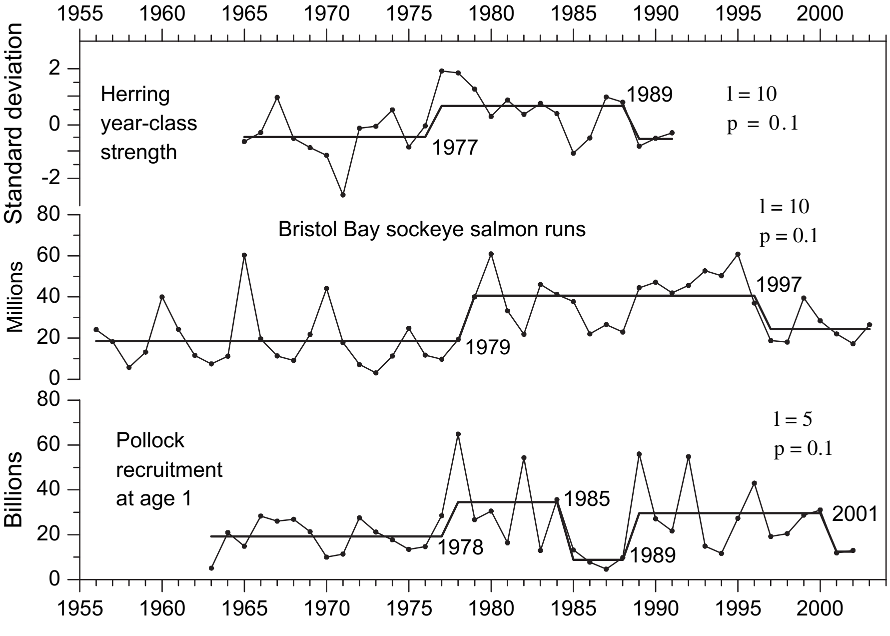

Figure 3. Regime shifts in herring year-class strength (top), sockeye salmon runs (middle), and pollock recruitment (bottom).

Discussion

Sequential analysis of regime shifts provides a new approach to regime shift detection and monitoring. Its main advantage is the ability to process data in real time, signalling the emergence of a potential shift and measuring changing confidence in the evidence for a shift as new data arrive. The method does not require initial visual inspection of a time-series and *a priori* hypothesis about the timing of the shift. It can process time-series with multiple shifts and handles input regardless of whether data are presented in the form of anomalies or absolute values.

In applying STARS to available indices for the Bering Sea ecosystem, the following picture emerges. The 1977 shift was the second strongest for the group of North Pacific climate indices (after 1943) and the strongest for a combined group of atmospheric and oceanic indices pertinent to the Bering Sea for all records of observations stretching back to the first decades of the twentieth century. Among the biological indices, a shift occurred at about that time in herring recruitment (1977) and Bristol Bay sockeye salmon runs (1979), and to a lesser extent in pollock recruitment (1978). The 1989 shift was less pronounced and particularly noticeable in the AO index. The regime of 1989–1997 was characterized by a relative winter cooling and reduced cyclonic activity. Shifts to poor year classes around that time were detected for herring (1989). The 1998 shift in the climate indices was stronger than the 1989 shift. Beginning with 1998, the winter cyclonic activity in the Bering Sea increased sharply, even exceeding the activity observed during the regime 1977–1988. Owing to anomalous spring warming, ice retreated earlier. A shift to lower runs of sockeye salmon occurred in 1997. Despite the coincidences in the timing of abiotic and biotic shifts, RSI values among all the biotic indices investigated were rather evenly distributed between 1977 and 1992 and not concentrated around certain, dominant years, as in the abiotic indices.

Acknowledgements

We thank two anonymous reviewers for their detailed comments and suggestions. This publication is funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement No. NA17RJ1232, Contribution No. 1099, and represents NOAA's Pacific Marine Environmental Laboratory Contribution No. 2764 and GLOBEC Contribution No. 501. We appreciate the support of the North Pacific Research Board and the NOAA NPCREP and GLOBEC Programmes.

References

Bond, N. A., Overland, J. E., and Stabeno, P. 2003. Recent shifts in the state of the North Pacific. Geophysical Research Letters, 30: 2183–2186.

Easterling, D. R., and Peterson, T. C. 1995. A new method for detecting undocumented discontinuities in climatological time series. International Journal of Climatology, 15: 369–377.

Hare, S. R., and Mantua, N. J. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography, 47: 103–146.

Lanzante, J. R. 1996. Resistant, robust and non-parametric techniques for the analysis of climate data: theory and examples, including applications to historical radiosonde station data. International Journal of Climatology, 16: 1197–1226.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., and Francis, R. C. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society, 78: 1069–1079.

Megrey, B. A., and Hinckley, S. 2001. Effect of turbulence on feeding of larval fishes: a sensitivity analysis using an individual-based model. ICES Journal of Marine Science, 58: 1015–1029.

Minobe, S. 2002. Interannual to interdecadal changes in the Bering Sea and concurrent 1998/99 changes over the North Pacific. Progress in Oceanography, 55: 45–64.

Overland, J. E., and Adams, J. M. 2001. On the temporal character and regionality of the Arctic Oscillation. Geophysical Research Letters, 28: 2811–2814.

Peterson, W. T., and Schwing, F. B. 2003. A new climate regime in Northeast Pacific ecosystems. Geophysical Research Letters, 30: 1896.

Rodionov, S. 2004. A sequential algorithm for testing climate regime shifts. Geophysical Research Letters, 31: L09204.

Rudnick, D. I., and Davis, R. E. 2003. Red noise and regime shifts. Deep-Sea Research, 50: 691–699.