水産海洋研究　第59巻　第3号　361–370，1995

Scrutinizing the Cycles of Worldwide Fluctuations in the Sardine and Herring Populations by Means of Singular Spectrum Analysis.

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Abstract

In order to examine precisely the interdecadal fluctuation cycle of sardines and herrings, we extracted oscillatory components from time series of catch data of sardine and herring populations in each of geographically separated regions (Far Eastern, Californian, Chilean, European sardines and Pacific and Atlantic herrings) using the singular spectrum analysis (SSA). For the northern hemispheric annual surface temperature anomalies, the SSA was also applied.

It was confirmable that the populations of Far Eastern, Californian, Chilean and European sardines exhibited significantly synchronous oscillations, and so did the populations of herrings. Oscillatory relations between the sardines and herrings were out of phase. Time lags between oscillations of the populations were negligibly small, ranging from 0 to 4 years.

Temperature-fish population relations behaved in a similar manner to the fish-fish relations. Populations of sardines, and the temperature anomalies varied in phase, and herrings showed oscillations inverse to the temperature. In case of fish-temperature relations, populations of fish led the temperature by 4 to 11 years.

Global regime cycle of sardine and herring and their relations to interdecadal change of ocean-climate systems are discussed.

Sardine populations in four geographically separated regions, off Japan, California, Chile and in the southern North Atlantic, have undergone inphase long-term and high amplitude changes in abundance (Kawasaki, 1983, 1991, Lluch-Belda *et al.*, 1989). Kawasaki (1983) hypothesized that the changes have a causal relationship to long-term transpacific changes in oceanographic conditions. Kawasaki and Omori (1988) found that the population size of Far Eastern sardine and the global mean surface air temperature had fluctuated on interdecadal cycle of marked simultaneity, and insisted the latter would be responsible for the former, though the mechanism was yet to be explored. Lluch-Belda *et al.* (1989) (including the junior author, Kawasaki) insisted that the fluctuation cycles of sardine and anchovy populations cohabiting each of four separated systems of the world, the Kuroshio, California, Humboldt and Benguela system, were 180 degrees out of phase with each other. They proposed a term, regime shift, which is the phenomenon that basic structures of the climate-biogeocenotic system made up of the physical atmosphere-oceanic system, plankton community and fish community transfer discontinuously from one phese to the other, temporally on interdecacal (50–100 years) and spatially on global to basin-wide scales. Kawasaki (1991, 1992) described that two species of herrings in the northern North Pacific and in the northern North Atlantic had revealed nearly synchronous large-scale and long-term fluctuations but they had been completely out of phase with that of the sardines. The fluctuation cycles of the Pacific and European sardines are called the Sardine Cycle and those of the herrings the Herring Cycle (Kawasaki, 1991, 1992).

Accepted June 6, 1995.

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Table 1. Sources of data used.

Species	Period	Source(s)
Far Eastern sardine (*Sardinops sagax melanosticta*)	1894 – 1946	Nakai, J. (1950)
	1947 – 1951	Yearbooks of Fisheries Statistics of Japan
	1952 – 1991	FAO Yearbooks of Fishery Statistics
Californian sardine (*S. sagax caerulea*)	1916 – 1967	Radovich, J. (1981)
	1968 – 1991	FAO Yearbooks of Fishery Statistics
Chilean sardine (*S. sagax sagax*)	1962 – 1991	FAO Yearbooks of Fishery Statistics
European sardine (*Sardina pilchardus*)	1958 – 1991	FAO Yearbooks of Fishery Statistics
Pacific herring (*Clupea pallasi*)	1894 – 1951	Yearbooks of Fisheries Statistics of Japan
	1952 – 1991	FAO Yearbooks of Fishery Statistics
Atlantic herring* (*C. harengus*)	1925 – 1938	Schumacher, A. (1980)
	1946 – 1951	Schumacher, A. (1980)
	1952 – 1991	FAO Yearbooks of Fishery Statistics

*: Catch records from 1939 to 1945 which are missing were estimated by linear interpolation.

Together it is called the SH Cycle.

In the preceding papers mentioned above, data were not processed in terms of elaborate mathematical context in describing the oscillatory relation between fish populations. The purpose of this report is to make a precise mathematical analysis of the catch records of sardines and herrings and the surface air temperature records using the singular spectrum analysis (SSA), to figure out their cycles, phases and oscillatory relations, which would present an important basis for inquiring into mechanisms of the regime shift occurring on the global scale.

Materials and methods

Northern hemispheric annual temperature anomalies from 1854 to 1993 by Jones *et al.* (1994) and the catch data listed in Table 1 were used for analysis.

The singular spectrum analysis (SSA) was employed to investigate the oscillation component of time series of catch records and the annual surface temperature anomalies over the Northern Hemisphere.

SSA is expressed as following numerical formulas (Schlesinger and Ramankutty, 1994).

The eigenvalues λ_k and eigenvectors ρ_k, $k=1, \ldots, M$, of the scaled autocovariance matrix, C, a Toeplitz matrix with the first row,

$$C_{1,j+1} = (1/M)(1/(N-l))\sum_{j=1}^{N-l} X_j X_{j+l}$$

$$l=0, \ldots, M-1,$$

have been determined, where $X_j=(X(t_j)-\bar{X})/\delta$; $j=1, \ldots, N$; $\bar{X}$ is the average of detrended catch records, $X(t_j)$; δ is the standard error; and $M-1$ is the maximum number of lags l. Standardization, which is not necessarily requisite mathematically, was conducted only for the sake of easy comparison of fluctuations among species with different oscillation amplitudes. The time series for mode k is given by

$$X_k(t_j) = (1/(j-1))\sum_{i=1}^{j-1} A_{k,j-i}\rho_{k,j}$$

$$\text{for } j = 2, \ldots, M$$

$$(1/M)\sum_{i=1}^{M} A_{k,j-i}\rho_{k,j}$$

$$\text{for } j = M+1, \ldots, N-M+1, \text{ and}$$

$$(1/(M-j+1))\sum_{i=1}^{M} A_{k,j-i}\rho_{k,j}$$

$$\text{for } j = N-M+2, \ldots, N,$$

where $A_{k,j} = \sum_{i=1}^{M} X_{j+i}\rho_{k,j}$ is the amplitude, or principal comonent (PC), of mode k at time t_j (Vautard and Ghil, 1989; Ghil and Vautard, 1991; Vautard *et al.*, 1992).

For the northern hemispheric annual temperature anomalies, the standardization was not performed, and SSA was applied to the centered data.

Two detrending methods were adopted. One is to obtain residuals from a linear regression through the time series. The other is: providing the difference between successive two peaks of catch oscillation was positively related to the change in fishing intensity, the catch for respective year was rectified by multiplying $(t_i - t_j)$ *exp* (Z), where t_i and t_j are years at successive two peaks and Z is a rate of change in catch between the two peaks. The method provides for us an oscillation with a couple of peaks of leveled height. Two data sets detrended by the two different methods and original catch data, were used for SSA. To the northern hemispheric annual temperature anomalies, only the former method was applied.

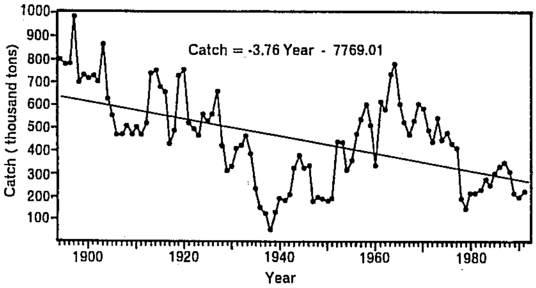

Figure. 1. Time series of catch of the Pacific herring. Anomalies from the straight line through the time series were used for singular spectrum analysis as a detrended time series.

Results

SSA results for the Pacific herring are shown in Figs. 1, 2 and 3 as an example. Catches of the her-

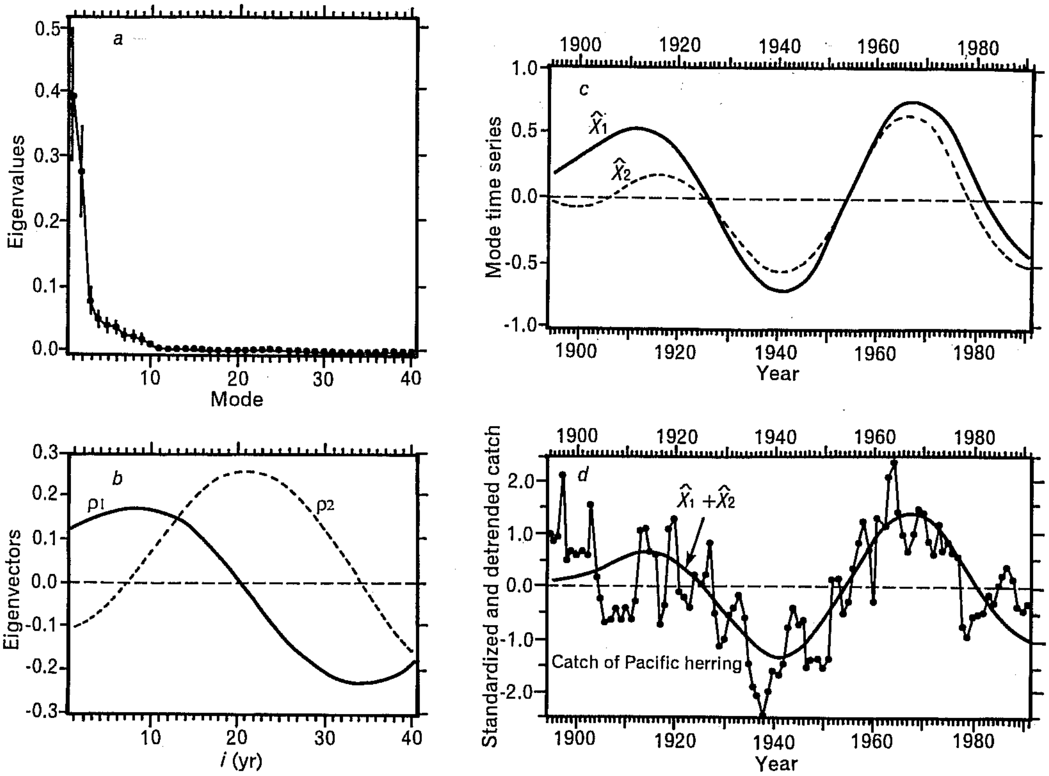

Figure. 2. a - d. Singular spectrum analysis (SSA) results for the detrended and standardized catch data of the Pacific herring. a: eigenvalues of the scaled autocovariance matrix together with the 95% confidence interval. b: eigenvectors of ρ_1 and ρ_2 (EOFs 1 and 2). c: time series of modes 1 and 2; $\hat{X}_1(t_j)$ and $\hat{X}_2(t_j)$, $j=2, ..., N$, where N is the length of the catch record (data set). d: $\hat{X}_1(t_j) + \hat{X}_2(t_j)$ in comparison with the detrended and standardized catch.

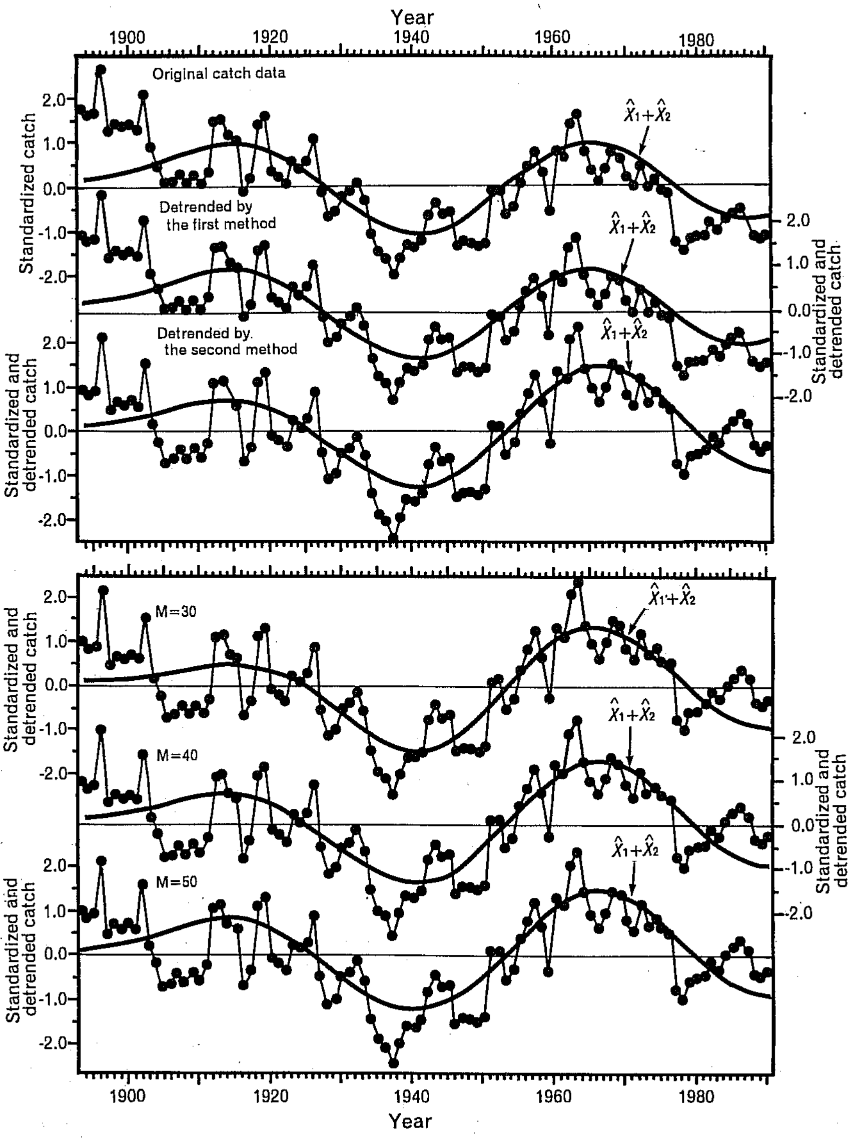

Figure. 3. Comparison of SSA results for the Pacific herring under the condition of $M=40$ between different detrending methods (top) and comparison of SSA results for the catch data detrended by the second method between different maximum time lags (bottom). For the detrending methods, see the text.

ring continued to decline from 1894 through 1991 as an overall trend as shown by a downward straight line through the time series, fluctuating cyclically with two peaks at 1920 and 1965 (Fig. 1). We also applied SSA to a series of anomalies of catch record from the straight line, and similar results were obtained for $30 \leqq M \leqq 50$ years as shown in the bottom 3 figures of Fig. 3. Figure 2 is the result for $M = 40$.

Figure 2-a shows eigenvalues λ_k together with the 95% confidence interval, $\delta\ \lambda_k = 2\ \lambda_k(2/N)^{1/2}$ (Ghil and Vautard, 1991), while N is the length of the catch record (data set) in years. Modes 1 and 2 form a pair that contribute 63.06% of the total variance (mode 1: 37.03%; mode 2: 26.03%). Figure 2-b presents eigenvectors, ρ_1 and ρ_2, each of which

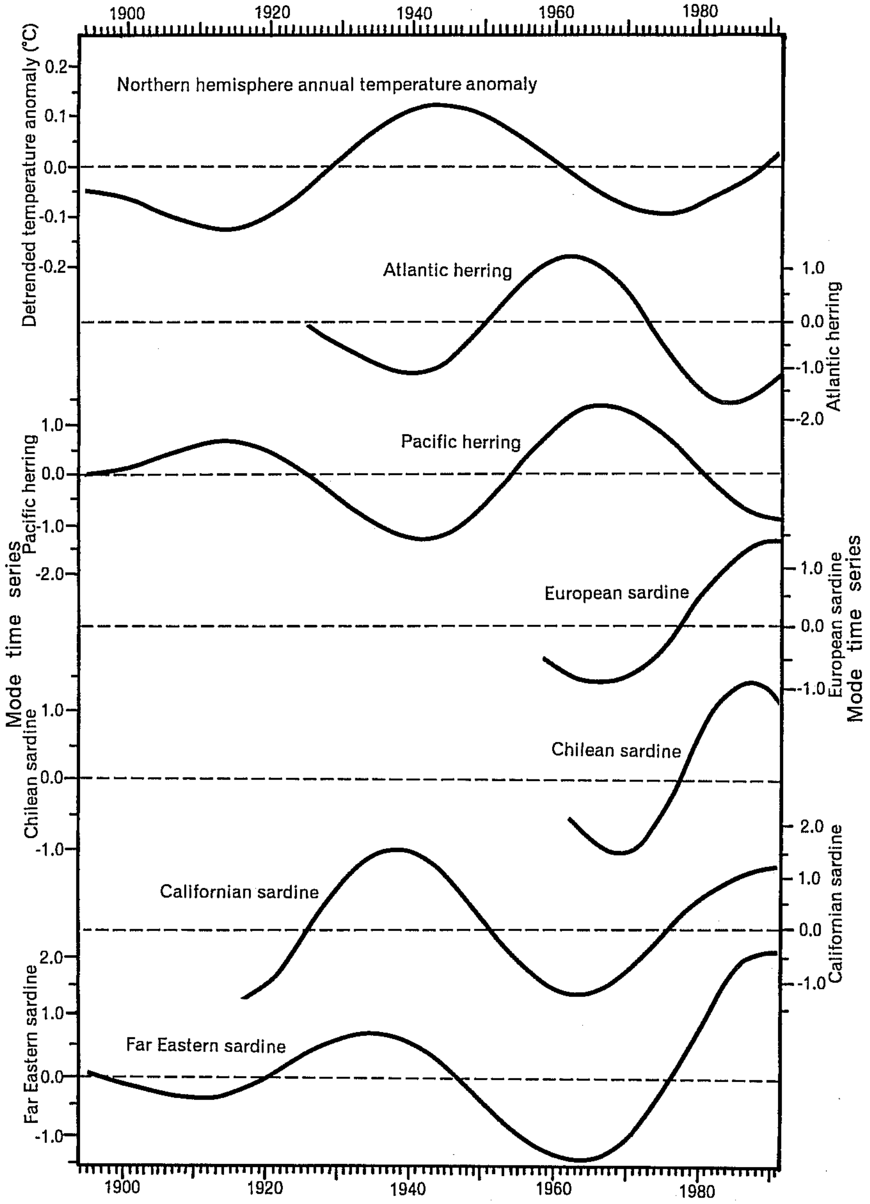

Figure. 4. SSA results for sardines and herrings and for the annual temperature anomalies in the Northern Hemisphere by Jones *et al.* (1994).

exhibits a quasiperiodic structure. Figure 2–c shows a time series of modes 1 and 2, $\hat{X}_1(t_j)$ and $\hat{X}_2(t_j), j = 2, ..., N$. In Figure 2–d, a time series of $\hat{X}_1(t_j) + \hat{X}_2(t_j)$ is compared with the detrended and standardized catch. Similar results were obtained for the three data sets, while amplitudes of oscillation were somewhat different from each other among them (see the top 3 figures of Fig. 3).

Figure 4 presents time series of $\hat{X}_1(t_j) + \hat{X}_2(t_j)$ of the Far Eastern, Californian, Chilean and European sardine and the Pacific and Atlantic herring with that of the northern hemispheric annual temperature anomalies to compare them with each other. The results for the Far Eastern, Californian

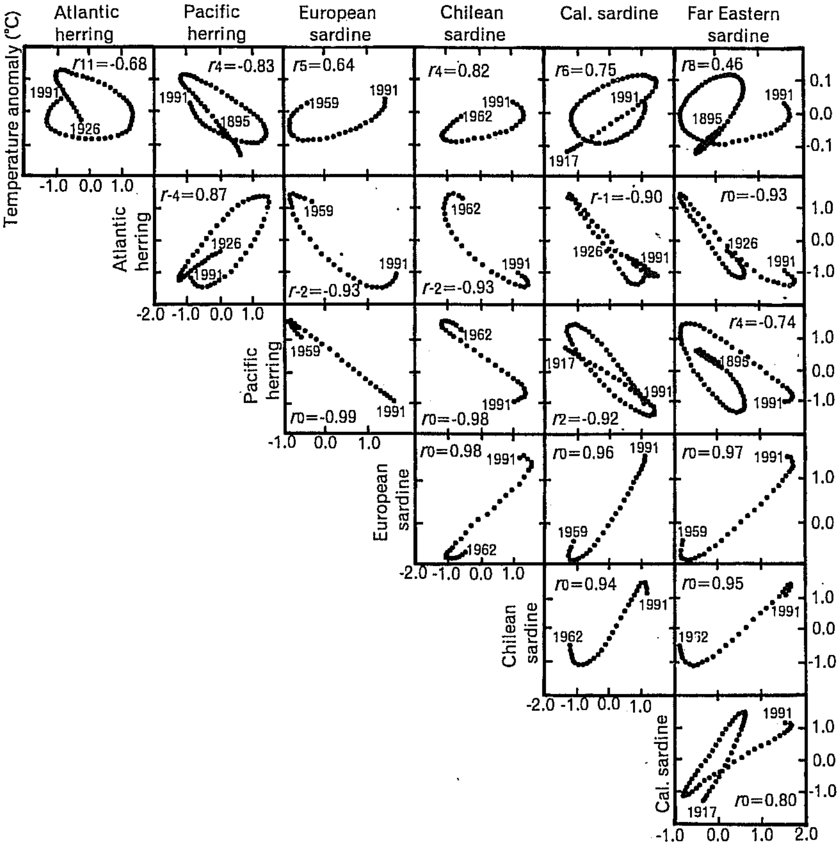

Figure. 5. Trajectories of species-species and species-northern hemispheric annual temperature anomalies relations in the field of mode 1 + 2. The cross-correlation coefficient (r_j) of species on the abcissa to species or temperature anomalies on the ordinate and the time lag (j) at the peak (the trough when inversly related) of cross-correlation coefficient plot are also shown.

sardines and the Atlantic herring are obtained by analysing the data set detrended by the first method under the condition of $M = 40$. Calculations carried out under the condition of $M = 30$, 40 and 50 resulted in similar ones and so did those for two data sets detrended by the different methods. Cumulative contribution ratios of eigenvalues of modes 1 and 2 were 66.3% for the Far Eastern sardine, 82.8% for the Californian sardine and 76.2% for the Atlantic herring. Each oscillation curve of the Chilean and European sardine in the figure is obtained for the original catch record under the condition of $M = 20$. Maximum time lags from 15 to 25 led to similar curves, and the cumulative contribution ratio of modes 1 and 2 attained 93.2% and 71.7% for respective fish. The mode time series of the northern hemispheric annual temperature anomalies is the case for $M = 40$, and the sum of eigenvalues of modes 1 and 2 was 29.1% of the total variance.

It is seen that $\hat{X}_1(t_j) + \hat{X}_2(t_j)$ of each population and the temperature anomalies have respective oscillation structures, with time scales of 40 – 52 years for the Far Eastern sardine, 50–52 years for the Californian sardine, 52–54 years for the Pacific herring, 44 years for the Atlantic herring and 58 – 60 years for the annual temperature anomalies, each of which was estimated from the interval between successive two peaks and between successive two troughs and from the duration from a peak to the succeeding trough. Because the full data set for one oscillation cycle was not available, the time scales of oscillation for the Chilean and European sardine were not estimated.

Figure 5 shows trajectories of relations of modes 1 + 2 between two fish populations and between a fish population and the northern hemispheric annual temperature anomalies. Cross-correlation coefficients of species on the abscissa to species or temperature anomalies on the ordinate were computed, and the coefficient (r_j) and the time lag (j) at the peak (or the trough when inversely related) of cross-correlation plots are also shown in the figure.

Cross-correlation between fish populations is very positive with 0–4 years' lag; 0 year for 9 combinations, 1 year for 1 combination, 2 years for 3 combinations and 4 years for 2 combinations. Coherent increase and decrease are obvious to a high degree between the sardine populations, as well as between the herring populations. It is also evident that sardine–herring relations are completely negative.

Trajectories resembling the fish–fish relations are shown also for the fish–termperature relations, though the synchronism is not so clear as the fish-fish relations. The fish catch led the temperature by 4 to 11 years and cross-correlation coefficients were not so high as the fish–fish relations.

Discussion

SSA has been used to analyze the long-term variation in air temperature in the meteorological field since Broomhead and King (1986) and Fraedrich (1986) introduced the method. The method is fully data-adaptive and fully non-parametric (Ghil and Vautard, 1991). Accoding to Vautard *et al.* (1992), SSA can easily and automatically localize in time intermittent oscillation spells, in contradiction to the classical spectrum analysis, where the basic functions are prescribed sines and cosines. The method works well for short, noisy time series without requiring numerous data points (Vautard *et al.*, 1992) and allows us to reconstruct detailedly the subset of significant components into time series of oscillation components (Ghil and Vautard, 1991). The catch records are available for only about 0.5 to 2.5 cycles and the number of data points is between 30 and 98, and the SSA is considered the most appropriate method for the present analysis.

The cumulative contribution ratio of eigenvalues of modes 1 and 2 ranged from 63.6% (the Pacific herring) to 93.2% (the Chilean sardine), which are extremely high compared to 28.7% in the SSA for global-mean surface temperature anomalies by Schlesinger and Ramankutty (1994), and attained 29.1% in case of the temperature. Such an eigenvalue pair of high-variance indicates that these modes are deterministic rather than stochastic (Ghil and Vautard, 1991). Eigenvectors are called empirical orthogonal functions (EOFs). When there exist a number of distinctive eigenvalues whose magnitude is appreciable, whereas the rests are close to zero, the modes would be a strong indication of "deterministic" parts in the subspace of eigenmodes with the rest of the modes acting as noise (Elsner and Tsonis, 1991). Schlesinger and Ramankutty (1994) revealed that, in such cases, the time series of $\hat{X}_k(t_j)$ of modes 1 and 2 is indicative of an oscillation.

The sardine populations off Japan and off California and herring populations in the northern North Pacific and North Atlantic have been extensively fished since the years before World War Ⅱ, and the fishing intensity for these fish is thought to have changed with shifts of the major fishing ground and changes in fishing gear. Although catch data should be corrected dependeing on the fishing intensity by multiplying some factor, it is, however, impossible to do it, because of lack of data on the fishing intensity for the time frame of all the time series. It would be, however, meaningful that the results of SSA for the data sets detrended by the different methods and those for the original ones coincided, possibly indicating that the variance caused by the change in fishing intensity is negligibly small compared to that in oscillation component.

Inphase long-term changes in abundance of geographically separated sardine populations and inverse oscillatory changes between sardine and herring populations were described by Kawasaki (1983, 1991, 1992) and Lluch-Belda *et al.* (1989), but strengths of these positive or negative relations have not been mathematically analyzed. By the present analysis these findings are strongly endorsed mathematically, and it is very interesting that the cycles are completely out of phase between the sardine and herring, both belonging to the same taxon but each being a member of different ecosystem.

As shown in Fig. 4, changes from downswing to upswing in global temperature occurred in 1911 and 1974 and the reverse in 1945. Polvina *et al.* (1994) analyzed physical and biological consequences of a climate event in the central North Pacific, which began in the mid 1970s, peaked in the early 1980s, and ended by the late 1980s. On the other hand, Francis and Hare (1994) examined interdecacal atmospheric and oceanic physical regime shifts in the subarctic Northeast Pacific by means of ARIMA (autoregressive integrated moving average), and observed three regimes over the period from 1925 to 1992: 1925–46 (a regime of higher temperature and lower North Pacific Index (NPI)), 1947–76 (that of lower temperature and higher NPI) and 1977–92 (that of the first one), the timing of the events coinciding with the result by Polvina *et al.* (1994) and that of the present paper. Complete inverse changes in abundance between the sardine and herring and coincidence in timing of the events occurring in the two different ecological systems, the temperate North Pacific system and the subarctic Northeast Pacific system, suggest a direct or indirect linkage between the atmospheric–oceanic physical process and biological process over the North Pacific.

The fish populations showed the oscillation phase 4 to 10 years ahead of the air temperature, which was not detected by the rough examination by Kawasaki and Omori (1988) and Lluch-Belda *et al.* (1989). This shows that the atmospheric warming or cooling itself is not directly responsible for the population change but should be regarded as an aspect of the whole structure of climate change.

Kawasaki (1994) discussed the mechanism that triggers the synchronous long-term and high amplitude cyclic fluctuation of the sardines in the world oceans, referring to Bakun (1990), Schlesinger and Ramankutty (1994) and Weaver *et al.* (1991). He argued that the long-term oscillatory variation in distribution of atmospheric pressure caused by the interdecadal shift of sinking area of the North Atlantic Deep Water (NADW) (Weaver *et al.*, 1991) will change geographical patterns of the wind stress, resulting in the variability of biological productivity (Bakun, 1990). The fluctuations in the sardine populations might have been governed by such variations as occurr in the thermohaline circulation, though the causal mechanisms have yet to be investigated. Now that coincidental cycles of sardines and herrings and their correlation to the climate change have been confirmed mathematically, our next step will be to inquire into mechanisms causing the regime shift.

Although Schlesinger and Ramankutty (1994) and Weaver *et al.* (1991) have disclosed the interdecadal oscillation of the thermohaline circulation and its impact on the global climate, which originates in the northern North Altantic Ocean, processes through which the global temperature exhibits variability remained insufficiently disclosed. Although the time lags of 4 to 11 years between the fish and the northern hemispheric annual temperature anomalies are not able to be explained today, the importance to resolve the mechanisms of the density-independent process such as that mentioned above should be focused on in the field of the population dynamics.

Acknowledgements

We thank Professor Y. Matsumiya at the Ocean Research Institute, the University of Tokyo, and the anonymous referee for making valuable comments on our draft.

References

Bakun A. (1990) Global climate change and intensification of coastal ocean upwelling. *Science*, **247**, 198 – 201.

Broomhead D. S. and G. P. King (1986) Extracting qualitative dynamics from experimental data. *Physica*, **20D**, 217–236.

Elsner, J. B. and A. A. Tsonis (1991) Do bidecadal oscillations exist in the global temperature record? *Nature*, **353**, 551–553.

Fraedrich, K. (1986) Estimating the dimensions of weather and climate attractors. *J. Atmos. Sci.*, **43**, 419–432.

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

Ghil, M. and R. Vautard (1991) Interdecadal oscillations and the warming trend in global temperature time series. *Nature*, **350**, 324–327.

Hansen, J., D. Johansen, A. Lacis, S. Lebedeff, P. Lee, D. Rind and G. Russell (1983) Observed temperature trends. *Science*, **220**, 874–875.

Jones, P. D., T. M. L. Wigley and K. R. Briffa (1994) Global and hemispheric temperature anomalies. *In.* Trends '93, eds. T. A. Boden, D. P. Kaiser, R. J. Sepanski and F. W. Stoss, Carbon Dioxide Information Analysis Center, Oak Ridge, 604–607.

Kawasaki, T. (1983) Why do some pelagic fishes have wide fluctuation in their numbers? Biological basis of fluctuation from the viewpoint of evolutionary ecology. *FAO Fish. Rep.*, **291**, 1065–1080.

Kawasaki, T. (1991) Long–term variability in the pelagic fish populations. *In.* Long–term Variability of Pelagic Fish Populations and Their Environment. eds. T. Kawasaki, S. Tanaka, Y. Toba and A. Taniguchi, Pergamon Press, Oxford, U. K., 47–60.

Kawasaki, T. (1992) Mechanisms governing fluctuations in pelagic fish populations. *S. Afr. J. mar. Sci.*, **12**, 873 –879.

Kawasaki, T. (1994) A decade of the regime shift of small pelagics–from the FAO Expert Consultation (1983) to the PICES Ⅲ (1994). *Bull. Jap. Soc. Fish. Oceanogr.*, **4**, 321–333 (in Japanese).

Kawasaki, T. and M. Omori (1988) Fluctuations in the three major sardine stocks in the Pacific and the global trend in temperature. *In.* Long–term Changes in Marine Fish Populations. eds. T. Wyatt and M. G. Larreneta. Vigo, Spain. Instituto de Investigaciones Marinas de Vigo, 37–53.

Lluch–Belda, D., R. J. M. Crawford, T. Kawasaki, A. D. MacCall, R. H. Parrish, R. A. Schwartzlose and P. E. Smith (1989) Worldwide fluctuations of sardine and anchovy stocks: the regime problem. *S. Afr. J. mar. Sci.*, **8**, 195–205.

Nakai, J. (1950) Why is there scarcely any catch of the sardine? *Kaiyo–no–Kagaku* (Sciences of the Sea), **6**, 17–24 (in Japanese).

Polvina, J. J., G. T. Mitchum, N. Graham, M. P. Craig, E. E. Demartini and E. N. Flint (1994) Physical and biological consequences of a climate event in the central North Pacific. *Fish. Oceanogr.*, **3**, 15–21.

Radovich, J. (1981) The collapse of the California sardine fishery: What have we learned? *In.* Resourse Management and Environmental Uncertainty: Lessons from Coastal Upwelling Fisheries, eds. M. H. Glantz and J. D. Thompson, Wiley–Interscience, New York, 107–136.

Schlesinger, M. E. and N. Ramankutty (1994) An oscillation in the global climate system of period 65–70 years. *Nature*, **367**, 723–726.

Schumacher A. (1980) Review of North Atlantic catch statistics, *Rapp. P. –V. cons. int. Explor. Mer.*, **177**, 8–22.

Vautard, R. and M. Ghil (1989) Singular spectrum analysis in nonlinear dynamics, with applications to paleoclimatic time seties. *Physica*, **35D**, 395–424.

Vautard, R., P. Yiou and M. Ghil (1992) Singular spectrum analysis: A toolkit for short, noisy chaotic signals. *Physica*, **58D**, 95–126.

Weaver, A. J., E. S. Serachik and J. Marotze (1991) Freshwater flux forcing of decadal and interdecadal oceanic variability. *Nature*, **353**, 836–838.

シングルスペクトル分析によるマイワシとニシンの全球的変動サイクルの精査

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マイワシとニシンの数十年のタイムスケールの周期的バイオマス変動を精査するために，極東水域，カリフォルニア沖，チリ沖，北大西洋南東水域のマイワシ，太平洋，大西洋のニシン及び北半球の地表気温の年偏差の周期成分の抽出をシングルスペクトル分析によって行った。

マイワシ間，ニシン間ではバイオマスの増大時期，減少時期は一致し，マイワシ・ニシン間では位相が逆の関係を示した。バイオマスが増大から減少あるいはその逆に変化する時の個体群間の時間差は0～4年であり，その同調性は極めて高かった。気温の周期的変動との関係では，マイワシでは気温上昇時にバイオマス増大，ニシンではその逆の関係が見られたが，バイオマスの増大，減少は気温の上昇，下降よりも4～11年早く始まることが示された。

マイワシとニシンの全球的レジームサイクル及び全球的海洋－気候系の数十年スケールの振動との関係について考察した。

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