A Rotated EOF Analysis of Global Sea Surface Temperature Variability with Interannual and Interdecadal Scales

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ABSTRACT

Spatiotemporal variability of preferred global-scale sea surface temperature anomaly patterns is documented, applying a varimax-rotated empirical orthogonal function (R-EOF) analysis to monthly mean SST anomalies. The present study focuses especially on the interdecadal variability of leading R-EOF modes. It is first found that temporal variability of R-EOF1 has a quasiperiodicity of 2-5 years and coincides quite well with the occurrence of the ENSO event; hence this mode can be identified with the ENSO mode and distinguished from the other modes dominated by interdecadal variability. The authors find that R-EOF2 typically shows the dominance of interdecadal variability and signals of the ENSO phenomenon are removed. This mode is characterized by increasing Indian Ocean SST and decreasing central North Pacific SST around 40°-50°N in the recent ten or more years. A further indication is that both R-EOF3 and R-EOF4, which show the dominance of interdecadal variability, are fundamentally regarded as preferred localized modes confined only to the Atlantic Ocean. Therefore, we find the existence of two kinds of prevailing SST modes; one is a mode fluctuating between oceans, corresponding well to R-EOF2, and the other is an oscillatory mode isolated only in a specific ocean (e.g., R-EOF4).

Analysis of implications for low-frequency modes in the atmosphere showed that the Pacific/North American (PNA) mode, which prevails in the Northern Hemisphere winter, is closely related to the large-scale SST variability with interdecadal time scale rather than the ENSO time scale. Additionally, in the Northern Hemisphere summer, the Subtropical Zonal (SZ) mode, which has a north-south dipole structure over the North Pacific, corresponds fairly well to R-EOF2. It is suggested that the increasing tropical ocean SST in the recent ten or more years, especially the Indian Ocean SST, is responsible for the increase of the zonal, summertime 500-hPa geopotential heights in the low-latitude regions of the North Pacific.

1. Introduction

It is well known that the prevailing phenomenon on short-term interannual time scales is the El Niño-Southern Oscillation (ENSO) event with 2- to 5-year period. Spatiotemporal patterns of large-scale sea surface temperature (SST) anomalies over the North Pacific associated with the ENSO phenomenon were first found in the pioneering work of Weare et al. (1976). Using an empirical orthogonal function (EOF) analysis, they extracted the first mode (EOF1), which shows the SST anomaly pattern with positive anomalies over the equatorial eastern Pacific and negative anomalies over the central North Pacific around 40°N. Horel and Wallace (1981) reported that the Pacific/North American (PNA) mode, which is one of the major teleconnection patterns, is closely connected with the EOF1 of Weare et al. (1976). Kawamura (1984) further derived the leading SST mode similar to that of Weare et al., utilizing North Pacific SST data containing tropical regions. This SST mode tends to precede the geopotential heights in middle-latitude regions of the North Pacific. On the other hand, Davis (1976) and Iwasaka et al. (1987) deduced EOF1 indicating an elliptical anomaly pattern located in the central North Pacific around 40°N, applying the EOF analysis to the North Pacific SST data excluding low-latitude regions. By contrast, they showed that their EOF1 lags the extratropical geopotential height fluctuations by about one month. Similar results were also presented by Lanzante (1984) and Wallace et al. (1990), who analyzed the extratropical SST anomalies over the North Pacific and the North Atlantic. The above facts imply that the EOFs depend largely on the specific domain utilized for the analysis.

Although we focused on the analyses for the Pacific SST anomaly field, numerous observational studies on large-scale SST anomalies over the Atlantic and Indian oceans have also been performed. An elaborate review of the large-scale air-sea interaction and SST anomaly dynamics is well documented by Frankignoul (1985). In early studies the domain used for the analysis was confined to part of an ocean or one ocean because of
sparse SST data. Hsiung and Newell (1983) made the first application of EOF analysis to the observed SST field with a near-global scale and described overall features of leading modes over the entire oceans. After that, similar analyses were done by Parker et al. (1988), Nitta and Yamada (1989), and others. Their first modes tend to be distributed over the globe, which are associated with ENSO phenomenon. If we focus on the Pacific sector in their first modes, we can see the definite spatial pattern found by Weare et al. (1976). Recently, it has been pointed out that deepened Aleutian lows occurred over the period from 1977 to 1986; this fact is closely related to the warming of the tropical Pacific SST (Namias et al. 1988; Nitta and Yamada 1989; Trenberth 1990). It is seen, in fact, that the leading modes shown by Nitta and Yamada (1989) are characterized by interdecadal variability accompanying the warming of the tropical oceans. However, we do not necessarily understand the overall behavior of the interdecadal variability of large-scale SST anomaly patterns.

Although many air–sea interaction studies on ocean to global scales have been made, many problems remain to be resolved. It is possible that the El Niño mode of Weare et al. (1976) is identified with an eigenmode, although it truly consists of several independent eigenmodes, because midlatitude SST anomalies obviously differ from tropical SST anomalies influenced by the ENSO. Each unrotated eigenmode accounts for some variance in many different regions, that is, represents a considerable portion of hemispherically integrated variance (Horel 1981). However, if we consider that teleconnection patterns have a limited spatial scale, localized phenomena in the SST anomaly field may be mistakenly regarded as global phenomena by employing the unrotated EOF analysis.

The purpose of this study, therefore, is summarized as follows:

1. To reexamine spatiotemporal variability of the leading SST mode prevailing over the Pacific sector associated with the ENSO phenomenon, using the rotated EOF analysis;
2. To document overall features of preferred localized modes for the globe and explore a possible separation between signals of the ENSO variability (2–5-year periods) and of interdecadal variability; and
3. To discuss possible implications between global-scale SST anomalies and the Northern Hemisphere 500-hPa geopotential height anomalies on interannual and interdecadal time scales.

The plan of this paper is as follows. In section 2 we describe the dataset and the analysis procedure used in the present study. Section 3 offers the spatiotemporal variability of major eigenmodes derived from a rotated EOF analysis. In section 4 we discuss possible interference between the major SST modes and the geopotential height anomaly patterns. A concluding summary of the results is found in section 5.

2. Data and analysis procedure

The dataset utilized in the present study consists of monthly mean SSTs compiled at the U.K. Meteorological Office. The global SSTs are given at a spatial resolution of $5^\circ \times 5^\circ$ regular rectangular mesh extending from 30$^\circ$S to 55$^\circ$N. The period covered by the dataset extends over 34 years from January 1955 to December 1988. A more detailed explanation of the data is given by Parker and Folland (1988). Before EOF analysis, the seasonal cycle was removed at each grid point and the monthly SST anomalies were normalized by the corresponding standard deviation. Thereby the anomaly data include both intermonthly and interannual variability in the SST field. It is noted that we do not use any time filters. An initial set of unrotated EOF is found that are the eigenvectors of the matrix of correlations between all stations pairs. This corresponds to the S-mode type of principal component or EOF analysis as described by Richman (1986).

Subsequently the initial set of EOFs is transformed linearly to an alternative set of temporally uncorrelated (orthogonal) components. From the infinity of possible solutions that set of rotated EOFs is determined that minimizes the extent of regions with strong correlations between the original SST anomalies time series and the newly found EOFs. The SST anomalies time series should be correlated with as few as possible of the new set of EOFs. The mechanics of finding this type of solution are based on the concept of simple structure (Thurstone 1947; Kaiser 1958; Harman 1976; Horel 1981; Richman 1986). The procedure is called varimax-orthogonal rotation (hereafter R-EOF). There are very few studies in which the leading eigenmodes of global SST variability are deduced from the R-EOF analysis. Although the remarkable usefulness of the R-EOF analysis (e.g., factor scores are orthogonally rotated) has already been discussed by Horel (1981), Richman (1986), and other authors, its characteristics and advantages are briefly presented here in the following.

First, the R-EOF analysis can detect similar localized modes for not only the subdomains but also the full domain used for the analysis, whereas it is hard, in general, for the unrotated EOF analysis to obtain localized modes for the full domain. If no physical phenomena extend over the full domain, a disadvantage arises in identifying slightly phase-lagged localized phenomena with a phenomenon over the entire domain, extracting weak correlations between each region. Second, it is easy to interpret spatial structures of eigenmodes because loadings are distributed with larger values and values close to zero by rotating factorloadings of the initial eigenmodes. Thereby the significant anomalies are scarcely observed outside of the subdomain where a regional phenomenon is dominant. Third, we are most likely to extract two independent modes when they have similar spatial patterns because

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the R-EOFs do not retain complete orthogonality in space.

For the above reasons, the leading SST modes are identified by applying the R-EOF analysis to the monthly mean SST anomalies. We employ a cross-correlation matrix in computing eigenvalue solutions and retain up to ten EOFs of the SST anomalies, which is associated with about 40% of the total variance. Rotating the complete set of EOFs requires extensive computer time. A compromise was chosen by retaining only ten EOFs, in analogy to Horel (1981), who found that the loadings pattern of the first five EOFs remained identical if at least ten initial EOFs were rotated. The set of ten EOFs are linearly transformed using the varimax-orthogonal rotation in order to derive ten R-EOFs. Table 1 indicates the percentage variance explained by each of the first ten EOFs with and without rotation.

In order to discuss relationships with low-frequency atmospheric circulation patterns, we also utilize 5-day mean 500-hPa geopotential heights of the Northern Hemisphere compiled at the Japan Meteorological Agency. The geopotential height data are given at a spatial resolution of 10° × 10° regular rectangular mesh, extending from 20°N to 80°N; but the data are available from 60°E to 130°W only at 20°N latitude. The period covered by the dataset extends over 44 years from 1946 to 1989. We apply the R-EOF analysis to the geopotential height anomalies in the Northern Hemisphere winter (December to February) and summer (June to August) and extract the recurrent teleconnection pattern prevailing in each season.

3. Spatiotemporal variability of leading modes

Figures 1 and 2 show the spatial pattern of the first two R-EOF modes and their corresponding time coefficients, that is, factor loadings and factor scores, respectively. The spatial structure of R-EOF1 resembles those of the leading eigenmodes presented in past studies (e.g., Hsiung and Newell 1983; and Nitta and Yamada 1989), but it is seen that large positive loadings are located especially over the central and eastern equatorial Pacific, compared with other similar studies. Although significant loadings are observed over the tropical Indian Ocean in the previous unrotated EOF mode (e.g., Nitta and Yamada 1989), this R-EOF1 does not necessarily have loadings of similar magnitude there. It can be seen, furthermore, that negative loadings over the central North Pacific around 30°–35°N are not very dominant. Thus, it is considered that this mode accounts for the fundamental SST fluctuations over the equatorial Pacific and is not very strongly linked to those over the tropical Indian Ocean or the central North Pacific.

Temporal variability of R-EOF1 coincides quite well with the occurrence of ENSO events (Fig. 2). Although the leading mode shown by Nitta and Yamada (1989) describes the ENSO phenomena, it also shows the interdecadal variability accompanying the recent increase in tropical Pacific SST. On the other hand, R-EOF1 represents ENSO events having a quasi periodicity of 2–5 years, but no interdecadal variability. Moreover, there is little high-frequency variability and the persistence of the SST anomalies is rather high. Thus, R-EOF1 can be identified with the ENSO mode. However, we cannot conclude that no other eigenmodes include ENSO signals.

The spatial structure of R-EOF2 shows some noteworthy differences to that of R-EOF1. It can be seen in R-EOF2 that large positive loadings are located over the tropical and subtropical regions of the Indian Ocean, while pronounced negative loadings exist in the middle latitude regions around 40°–50°N of the North Pacific. Also, weak positive loadings exist in low latitude regions of the eastern and western Pacific. Thus, one of the essential differences with respect to the anomaly pattern is the existence of conspicuous loadings over the Indian Ocean and the central North Pacific. It should be emphasized, on the other hand, that the time component of R-EOF2 is in contrast with that of R-EOF1; namely, it is largely occupied by the interdecadal variability and scarcely corresponds to the ENSO event, although short-term interannual variability with periods from 3 to 5 years is contained in this mode to some extent.

Similarly, spatial loading patterns of R-EOF3 and R-EOF4 and their corresponding time coefficients are shown in Figs. 3 and 4. It can be clearly seen in R-EOF3 that elongated positive loadings are dominant in the high-latitude region north of 50°N and the subtropical region south of 20°N in the Atlantic; by contrast, slightly weaker negative loadings are located near the eastern coast of the North America. On the other hand, in R-EOF4 we can see large isolated positive loadings in the sub tropics of the South Atlantic. It is seen, moreover, that both modes have a definite interdecadal variability. Particularly, R-EOF4 appears to be similar to EOF6 of Parker et al. (1988), which is closely associated with rainfall in the Sahel region of Africa. In both modes we cannot see significant loadings in other regions outside of the Atlantic sector; and hence it is considered that these modes are fundamen-
Fig. 1. Spatial patterns of the leading two R-EOF modes of monthly mean global-scale SST anomalies based on data for 34 years from January 1955 to December 1988, derived from the R-EOF analysis. Contour interval is 2.0 in relative units.

Fig. 2. Time coefficients (i.e., factor scores) of the first two R-EOF modes over 34 years from January 1955 to December 1988.
Fig. 3. As in Fig. 1 but for R-EOF3 and R-EOF4.

Fig. 4. As in Fig. 2 but for R-EOF3 and R-EOF4.
tally regarded as dominant modes confined only to the Atlantic Ocean.

Thus, we found the existence of two kinds of dominant SST modes; one is a mode fluctuating between oceans, corresponding mostly to R-EOF2 with conspicuous interdecadal variability, and the other is an oscillatory mode isolated only in a specific ocean (e.g., R-EOF4).

4. Implication for low-frequency modes in the atmosphere

From the evidence cited in the previous section, it is inferred that the linkage between the SST fluctuations over the tropical Pacific and over the central North Pacific is not necessarily strong either on the ENSO time scale or the interdecadal time scale.

Although it has been reported that the Pacific/North American (PNA) low-frequency mode (see Fig. 5a) is related to the ENSO, this mode does not always coincide with the occurrence of the ENSO event (e.g., Simmons et al. 1983). Figures 6a–c show the time series of R-EOF1, R-EOF2, and PNA mode in the Northern Hemisphere winter for the interannual time scale. The ENSO event occurs in the 1957/58, 1963/64, 1965/66, 1969/70, 1972/73, 1976/77, 1982/83, and 1986/87 winters. It can be seen in this figure that the PNA mode is scarcely dominant in the 1965/66 and 1972/73 winters when the ENSO event occurs, whereas the ENSO event does not occur in winter 1980/81 when the PNA mode typically appears. Thus, we find no evident systematic implications between the ENSO mode and PNA mode for the ENSO time scale.

As documented briefly in section 1, it is argued that the tropical Pacific SST anomalies with interdecadal variability are possibly responsible for the occurrence of deepened Aleutian lows, associated with the dominance of the PNA-like mode (Namias et al. 1988; Nitta and Yamada 1989; Trenberth 1990), and thereby large-scale negative SST anomalies appear to be formed over the central North Pacific. It is found, however, that in R-EOF2 the SST anomalies over the central North Pacific are closely linked with those over the tropical Indian Ocean rather than the tropical Pacific.

Although R-EOF2 does not fluctuate in connection with the PNA mode on the short-term interannual time scales (i.e., periods of 2–5 years), we can clearly see that both modes fluctuate almost in phase with each other on the interdecadal time scale. The PNA mode is one of the preferred low-frequency modes prevailing in the Northern Hemisphere winter, but it is expected that a low-frequency mode exists that appears and dominates in the Northern Hemisphere summer, linked with the interdecadal variability of R-EOF2. It is found, in fact, that some recurrent teleconnection patterns dominating in the Northern Hemisphere summer are characterized by conspicuous interdecadal variability. Among those, the time component of the low-frequency mode shown in Fig. 5b coincides well with that of R-EOF2 on the interdecadal time scale, as seen in Fig. 6d. The summertime R-EOF2 (not shown) is also highly correlated with the low-frequency teleconnection mode. This recurrent mode has a north–south dipole structure so that positive loadings are zonally elongated over the low-latitude regions of the North Pacific; by contrast, negative loadings are located south of the Aleutian Islands. The above results imply that in the recent ten or more years the summertime 500-hPa geopotential heights increase over almost the whole domain of the low-latitude regions of the North Pacific. Furthermore, if we focus on the seasonal dependence of the major mode shown in Fig. 5b, it tends to amplify from early summer and reach a maximum

![Fig. 5. Spatial patterns of (a) the Pacific/North American (PNA) and (b) the subtropical zonal (SZ) low-frequency modes dominating in the Northern Hemisphere winter and summer, respectively. Contour interval is 0.025 in relative units. Dense and sparse cross-hatchings denote significant positive and negative anomalies, respectively.](image-url)
is strong in the interdecadal time scale rather than the ENSO time scale. Also, we can clearly see that the SZ mode and the summertime R-EOF2 are strongly correlated in the interdecadal time scale (Figs. 7c–d). It is found, therefore, that R-EOF2, which is dominated by interdecadal variability, is closely connected with each identical low-frequency teleconnection pattern prevailing in the Northern Hemisphere winter and summer.

5. Summary

We have attempted in this study to clarify overall features of spatiotemporal variability of the leading modes observed in the global monthly mean SST anomaly field using a rotated EOF (R-EOF) analysis, and further discussed possible implications with preferred low-frequency modes that are fixed geographically and appear in the Northern Hemisphere troposphere. The new findings obtained in the present study are summarized in the following.

1) It can be obviously seen in R-EOF1 that remarkable positive loadings are observed, especially over the central and eastern equatorial Pacific. However, we cannot necessarily find significant loadings over the central North Pacific and the tropical Indian Ocean, compared with past similar studies. Temporal variability of this mode has a quasi periodicity of 2–5 years and corresponds mostly to the occurrence of ENSO events. Furthermore, we can scarcely see the interdecadal variability. Thus, this mode can be identified with the ENSO mode and distinguished from other modes characterized by interdecadal variability.

2) In R-EOF2, we can see pronounced positive and negative loadings located over the tropical and subtropical regions of the Indian Ocean and the middle-latitude regions around 40°–45°N of the North Pacific, respectively. This mode typically shows the dominance of the interdecadal variability and signals of the ENSO phenomenon are considerably eliminated. Moreover, this mode is characterized by increasing Indian Ocean SST and decreasing central North Pacific SST in the recent ten or more years.

3) Both R-EOF3 and R-EOF4 show the dominance of the interdecadal variability and have significant loading extremes only in the Atlantic Ocean. It is concluded, therefore, that both modes are basically regarded as preferred modes confined only to the Atlantic sector.

4) From the viewpoint of large-scale air–sea interaction, it is found that the PNA mode, which has a multi-time-scale structure, prevailing in the Northern Hemisphere winter is closely linked with the large-scale SST variability on the interdecadal time scale rather than the ENSO time scale. Also, in the Northern Hemisphere summer the SZ mode showing a north–south dipole structure over the North Pacific corresponds well to R-EOF2 characterized by the dominance of interdecadal variability. This shows that the 500-

Fig. 6. (a) Mean time series of R-EOF1 in the Northern Hemisphere winter on the interannual time scale. Five-year running mean values are denoted by the heavy lines. (b) As in (a) but for R-EOF2. (c) As in (a) but for PNA mode. (d) As in (a) but for SZ mode in the Northern Hemisphere summer. Note that vertical axis of the panel for PNA mode is inverse.

in July (not shown); we can hence identify this mode with the Subtropical Zonal (SZ) pattern described by Barnston and Livezey (1987).

Figures 7a–d show the intercomparison of correlation between R-EOF2 and low-frequency modes appearing in the 500-hPa height anomaly field for the interannual and interdecadal components. Here the interdecadal component is simply defined as a five-year moving averaged time coefficient and the interannual component is the deviation from that moving average. As shown in Figs. 7a–b, it can be seen that the interrelationship between large-scale SST variability and the PNA mode in the Northern Hemisphere winter
hPa geopotential heights increase in the low-latitude regions of the North Pacific, associated with increasing tropical ocean SST (especially the Indian Ocean) in the recent ten or more years.

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