A global analysis of multimode sea surface temperature pattern

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Abstract

The variability of the air-sea system in the low-frequency time domain can be decomposed into several systematic climate modes, namely, the decadal variability (DV) mode, the ENSO Southern Oscillation (ENSO) mode, the annual cycle (AC) mode, the semiannual cycle (SC) mode and the intraseasonal variability (ISV) mode. The combination of these primary modes in the air-sea system orchestrates a complex climate system. The multimode low-frequency variability in SST is investigated based on 22 a SST records from 1982 through 2003. The variation of SST in the past two decades undergoes a different combination of these dominant climate modes over different regions, which leads to an interesting new classification of the global ocean based on the relative importance of these modes. The new classification can provide ideal locations for better monitoring of these low-frequency modes in the scientific proof sense. Moreover, two no-annual variation and 14 no-semiannual variation oceanic points, termed annual and semiannual amphidromies, have been well defined in the AC and SC phase maps. The formation of these nodal points is attributed to the couplings of climate modes in EOF analysis results.

Key words: multimode variability of SST, new classification, annual and semiannual amphidromies

1 Introduction

The variability of the air-sea system orchestrates a complex climate system of the earth, and this variability gives rise to an array of naturally occurring dynamical modes at different time scales. These modes are important attributes of climate changes and the future climate variation can be manifested as the variability of some leading modes of the climate system. This variability in the low-frequency time domain can be decomposed into some systematic modes ranging from intraseasonal to decadal time scales. Among them, the decadal variability (DV) with a period of more than 10 a, the ENSO Southern Oscillation (ENSO) with a period ranging from 2 to 7 a, the annual cycle (AC) with a period of about 1 a, the semiannual cycle (SC) with a period of about 6 months, and the intraseasonal variation (ISV) with a period ranging from 20 to 90 d, are of the dominant time scales in the climate variation. Therefore, these three quasi-periodic modes, DV, ENSO and ISV, as well as two periodic modes, AC and SC, are the issues of the utmost concern in oceanography and meteorology, in particular, the former three quasi-periodic modes, which have been extensively studied and documented in the past decades since they were identified (Bjerknes, 1966; Mantua et al, 1997; Madden and Julian, 1971).
ation of an air-sea signal at a given location thus can be approximately expressed as

\[ S(t) = S_0 + S_{DV}(t) + S_{ISNO}(t) + \tilde{S}_{AC}(t) + \tilde{S}_{SC}(t) + \xi(t) + \varepsilon(t), \tag{1} \]

where \( S_0 \) is the climatological mean; \( S_{DV}(t), S_{ISNO}(t), \) and \( \tilde{S}_{AC}(t) \) are corresponding to the DV\(^-\), EN\(^+\), SO\(^-\), and ISV\(^-\) induced variability, respectively; \( S_{AC}(t) \) and \( S_{SC}(t) \) are the AC and SC components, respectively; \( \xi(t) \) and \( \varepsilon(t) \) represent lower and higher-frequency residues, respectively. Here \( S_{AC}(t) \) and \( S_{SC}(t) \) can be further expressed as

\[ S_{AC}(t) = A_1 \cos \left( \frac{\pi t}{T_1} + \varphi_1 \right), \tag{2} \]

\[ S_{SC}(t) = A_2 \cos \left( \frac{\pi t}{T_2} + \varphi_2 \right), \tag{3} \]

where \( T_1 \) is 12 months; \( A_1 \) and \( A_2 \), and \( \varphi_1 \) and \( \varphi_2 \) are the corresponding amplitudes and initial phases of AC and SC component, respectively.

Among these primary modes, the AC is the dominant mode because the major forcing of the air-sea system comes from the seesaw of solar irradiance between two hemispheres although sometimes ISV and DV are also significant. But the relative importance of these primary modes varies from space to space, as well as from one parameter to another, which can be well supported by the interannual, annual, and semiannual components of global oceanic precipitation and oceanic water vapor studied by Chen et al. (2003) and Chen (2004). Their results show that the ratios of the interannual variation (IV), AC, and SC of oceanic precipitation and water vapor are 1.94:1.91:1, and 1.5:4.2:1, respectively, which suggests that the IV and the AC are almost of the same importance in the oceanic precipitation variation, while the AC is much more significant than the IV and the SC in the oceanic water vapor variation. Previous results imply that the relative dominance of the low-frequency variation modes is of interest in our understanding of the air-sea system.

As one of the most important geophysical parameters of the ocean affecting the atmosphere and a critical indicator of the state of the earth's climate system, the SST is essential for climate monitoring, research and prediction. Although SST is usually selected in investigating the aforementioned five modes, to our knowledge, a systematic study of SST variation in the low-frequency time domain has not been addressed, especially for the spatial dependence and the relative dominance of these primary modes. In this study, only three low-frequency modes, IV, AC and SC will be discussed based on 22 a SST data, and hopefully several interesting findings presented in this study can provide some valuable information for better understanding the multimode low-frequency variability in the SST in particular, and the long-term climate change in general.

2 Data and methods

Monthly gridded SST data in the ocean with \( 1^\circ \times 1^\circ \) in spatial resolution are derived from Physical Oceanography Distributed Active Archive Center (PO DAAC), NASA/JPL. The National Centers for Environmental Prediction (NCEP) Reynolds Optimally Interpolated SST version 2 (O I SSTV2) products consist of weekly and monthly global SST fields. Both in situ and satellite derived SSTs from the NOAA advanced very high resolution Radiometer (AVHRR) are blended in O I SSTV2. The satellite derived SSTs are from the Multichannel SST products that have been constructed operationally the five-channel AVHRR by NOAA’s environmental satellite. Twenty-two year data spanning from January 1982 through December 2003 have been compiled in this study. Much more detailed reports related to O I SST V2 were addressed by Reynolds and Smith (1994), Reynolds et al. (2002). O I SST V2 product has been extensively applied for long-term cli-
mate studies in the scientific community due to its relative long-term records.

Three advanced statistical methods, fast fourier transform (FFT), harmonic analysis (HA), as well as empirical orthogonal function (EOF), also known as principal component analysis (PCA), have been used in identifying the multimode characteristics of low-frequency variability of SST during the past two decades. These three advanced statistics are used widely in climate studies. The FFT is normally used to identify signals with different frequencies, and the EOF is popularly employed to study the spatio-temporal variability of geophysical variables with independent modes, while the HA is normally used in the tidal prediction or to isolate regular periodic climate modes (Hsu and Wallace, 1976a, b). Except for the aforementioned three advanced statistics, some fundamental statistics are also used in this study.

3 Results

3.1 Identification of multimode SST variation

One-dimensional FFT has been employed for each grid point of the whole analysis domain and the relative importance of each signal at each grid point in terms of its corresponding power density has been derived. The first dominant mode of each grid point is presented in Fig 1a. An interesting finding of Fig 1a is that the global ocean can be classified into four different regions, namely, AC-controlled region (red, I), SC-controlled region (purple, II), AV-controlled region with a period from 2 to 7 a (green, III), and an ENSO-like-controlled region with a period of more than 7 a (blue, IV). Although a majority of oceans are dominated by the AC, another three regions still can be clearly defined in the tropical oceans. For a further examination of the space-dependence of multimode SST variations over these four oceanic regions, time series and its associated spectral structure based on area-averages of four regions are plotted in Figs 1b—i, respectively. The characteristics of SST variation over these four regions are discussed in the following paragraphs.

The first region is a typical solar controlling domain with a pronounced sine curve in time series and an opposite phase structure in two hemispheres (see Fig 1b). The Northern Hemisphere (NH) is not only much warmer than the Southern Hemisphere (SH) in the area mean context, but also has a much higher annual range than that of the SH. It seems that only AC exists over this region, but the spectral analysis result illustrates it is lightly modulated by the SC too (see Fig 1f). It is well known that the DV is also significant in the North Pacific and the North Atlantic, characterized by the Pacific decadal oscillation and North Atlantic oscillation (Hurrell, 1995), respectively, but it has not been identified in our results due to the relative short data records used in this study.

The second region is strongly controlled by the SC. It reaches its first maximum in May and second maximum in October—November (see Fig 1c). A salient feature of this bimodal structure in a calendar year is that the first maximum is much higher than the second one, while there is not too much difference between two minimums. The distribution of this SC-controlled region is also very interesting. The largest one is located in the Arabian Sea, where the thermal and thermodynamic processes are strongly controlled by the seasonal monsoons. The monsoon-induced upwelling and shoaling thermocline can lead to two minimum SSTs appearing in summer and winter, respectively, which can be confirmed by two cold oceanic seasons appearing in August and the next January—February in Fig 1c. Even though the SST variation is controlled by the strong monsoon over this region, the annual solar irradiance still has a deep impact on it, which can be supported by its corresponding spectrum in Fig 1g. The modulation
of AC over this region also can contribute to the interpretation of the much higher maximum SST in the first half of a year than that of the second half of a year. Note that the Asian-Pacific monsoon domain occupies most of the North Indian Ocean and the North Pacific Ocean (Wang and Lin, 2002), why only Arabian Sea is pretty controlled by the SC, instead of the AC? The SST variation is strongly forced
by the annual solar irradiance, as well as the seasonal monsoons. If solar forcing is stronger than monsoon forcing, then the AC is more prominent than the SC component and vice versa. The second SC-controlled region is distributed over the western equatorial Pacific, and over this region, the SST is mainly forced by the sun crossing the equator twice a year, which is consistent with the expected pattern that the SC should be dominant over the AC for incoming solar irradiance. The last SC-controlled region is identified over a limited band of the equatorial Atlantic region. This banded zone may be attributed to the solar migration across the equator twice a year too, however, the location seems consistent with the ITCZ determined by the oceanic water vapor in the Atlantic (Chen and Lin, 2005). Whether this SC-controlled region is associated with the ITCZ climate processes and how do they interact on each other deserve further studies in future.

The third region is strongly controlled by the ENSO mode and slightly modulated by the AC and SC components (see Figs 1d and h). It is interesting that this region is presented over the central equatorial Pacific, rather than the eastern equatorial Pacific, where the IAV is more energetic. Six El Niño events, 1982/1983, 1987/1988, 1991/1992/1993, 1994/1995, 1997/1998, 2002/2003, and four La Niña events, 1984/1985, 1988/1989, 1995/1996, and 1999/2000 have been clearly displayed in Fig 1d. The maximum SST range between El Niños and La Niñas can reach 3°C over this region. The AC and SC components are of the same significance in magnitude over this region (see Fig 1h).

Some small sporadic regions with a period of more than 7 a appear over the equatorial Pacific. A joint illustration of the time series and its corresponding spectrum suggests that it is an ENSO-like mode, but is strongly modulated by the SC component since most of these grid points of this region are located at the transitional band between the SC and ENSO mode (Figs 1e and i). The plot of time series seems to capture a whole DV signal after 1988, which suggests that this region is an ideal location for monitoring DV.

3. 2 Annual, semiannual and interannual components of SST variability

Since the AC, the SC, and the ENSO are the primary components of SST variability in the low-frequency time domain during the past two decades, their spatial amplitude distributions are informative for our further understanding of these multimode characteristics of SST variability. HA is performed to extract the AC and SC components from the 22 a dataset, and the interannual amplitude is also calculated based on the standard deviation of annual average.

The amplitude of AC component is presented in Fig 2a. The pattern is characterized by (1) obviously asymmetric structure in the NH and the SH. In the NH, the annual dynamic zone is converged within 30° 60°N and its corresponding maximum has a continent preference, while in the SH, the dynamic belt is located over the subtropical region and has a much lower value than that in the NH; (2) the smallest annual amplitude is identified over the western and central equatorial Pacific, where the SC and ENSO are much more energetic than the AC (see Fig 2a); (3) the eastern equatorial Pacific cold tongue region is also found to have a distinct seasonality of SST, even though this region is always closely connected with the large IAV in the SST. This strong AC variation in the eastern equatorial Pacific has been documented by much literature (Wang, 1994; Xie, 1994; Chang and Philander, 1994; Fu and Wang, 2001). As far as the SC amplitude is concerned, large amplitudes have been observed over the Arabian Sea, the Okhotsk Sea and the Grand Banks. Another salient feature of SC amplitude pattern is that the SC energetic regions are only
located in the NH, in particular the North Pacific (see Fig 2b). The interannual amplitude pattern well captures the characteristics of ENSO over the central and eastern equatorial Pacific and the maximum center has been observed over the coast of Peru and Ecuador (Fig 2c). Other significant IAV regions are identified over the North Pacific and the northwest Atlantic. The relative importance of the AC, SC and IAV of SST variability can be quantified in terms of the global mean amplitudes and the ratio of them is roughly estimated to be 6:1:1:1, which suggests that the AC overwhelmingly dominates the SST variation, while the SC and the IAV are of the same significance in magnitude.

![Fig 2](image)

Fig 2 Spatial distributions of the amplitude (in °C) for (a) annual, (b) semiannual, and (c) interannual variability of SST. Two annual SST amphidromes and fourteen semiannual amphidromes are highlighted by the white dots in (a) and (b), respectively.

3.3 Annual and semiannual amphidromes

As a scientific term in oceanography, "amphidrome" is normally connected with ocean tides. An amphidrome refers to a point where there is almost zero amplitude due to the canceling of tidal

waves and it can be determined by the cotidal and corange plots of the tidal system. In fact, the annual and semiannual variations of the coupled air-sea system have some similar properties to those of the tidal system. Recent studies documented by Chen and Quartly (2005) illustrate that these no-anual variation points, namely, annual amphidromes, do exist in the ocean. Their results based on radiometer-derived SST and altimeter-derived sea level anomaly data suggest that the annual amphidrome is a common feature on the global scale and at least eight annual sea level amphidromes and two annual SST amphidromes have been identified in the ocean. A further study by Zhang et al (2006) illustrates that the annual sea level amphidrome is not only a phenomenon in the global ocean, but also can be well identified in the South China Sea by using a higher spatio-temporal resolution sea level product. The existence of two annual SST amphidromes can be further confirmed by the annual phase pattern derived by the HA analysis of OI SST V2 data, as presented in Fig 3a. The general feature of the AC phase distribution is hemispherically divided as expected except for part of the north Indian Ocean where it follows a SH phase pattern in the SST variation. Two annual amphidromes, PI and A1, are clearly located in the central equatorial Pacific and Atlantic and present a cyclonic rotation pattern around PI and an anticyclonic pattern around the A1, respectively. Their existence strongly modulates the phase structure along the equatorial region, where a rotating structure is observed, rather than a regular transitional belt from the SH to the NH, and it also suggests the annual variation in time is characterized by a rotary phase pattern in space.

Following the successful identification of annual SST amphidromes, we are inspired to examine the similar features of SC component of SST. The SC phase

![Fig 3](image_url)

**Fig 3.** (a) Phase maps for annual component a and semiannual component b. Two annual SST amphidromes and fourteen semiannual amphidromes are highlighted by the white dots in a and b, respectively. The phase refers to the calendar month during which the annual and semiannual amplitudes reach their maximums.
map is shown in Fig 3b. The phase distribution of SC is much different from the AC pattern. Most of oceans over the tropical region have their peaks in April and May, and over the extratropical region they peak in February. Focusing on the regions where their phases vary very significantly, at least 14 SC SST amphidromes can be identified in the global ocean and they are highlighted by the white dots in Fig 3b. P1 and P2 are evident and symmetrically distributed in the North Pacific and the South Pacific, with a salient rotary phase structure around them. A1 and A2, II and II, B and I4, 15 and 16, behaving like twins and sharing some cophase lines but with an opposite rotary pattern around them, are distributed in the Atlantic Ocean and Indian Ocean, respectively. A3, A4 and A5 present a triangle structure, which forms an interesting pattern over the southeast Atlantic Ocean. 17 is located on the south coast of Madagascar, sharing some cophase lines with 14 and having a cyclonic pattern around it. For a further examination of the existence of these annual and semiannual SST amphidromes, they are projected over their corresponding amplitude maps in Figs 2a and 2b. Clearly one can see that these no-annual and no-semiannual variation points do locate over the regions where the amplitudes of AC and SC are very small.

Different from a tidal amphidrome, which is caused by the Kelvin wave dynamics and has a mature theory to explain it, the global annual and semiannual amphidromes in the ocean are just some new issues and the physical processes implied behind them are not clear up to now. The formation of these annual and semiannual amphidromes in different oceanic variables vary from one parameter to another, and each individual amphidrome distributed over different locations in the same variable may be different from space to space; therefore to explain the complex dynamical processes involved in them is a hard task in our knowledge. The next paragraph is hopeful to explain them in fundamental sense by using the EOF analysis results.

The first six modes of EOF results are presented in Fig 4 and the explained variances of them are 85.25%, 3.33%, 2.24%, 1.36%, 0.72%, and 0.51%, respectively. As expected, the first mode is the solar controlling pattern, with opposite PC structures in two hemispheres and captures highs as the annual amplitude map in Fig 2a. Regular sine curve with a period of 12 months in EOF time series confirms this dominant factor in controlling the SST variability (see Fig 4g). Note that two annual amphidromes are just located over the zero contour curves in the tropical region (see Fig 4a), which suggests that their formation is closely connected with the transition of seasonality between two hemispheres. EOF2 accounts for only 3.3% of the total variance, but it is very significant in the eastern tropical Pacific and Asian monsoon region, and its EOF time series also shows an obvious annual cycle slightly lagging the phase of EOF1 (see Fig 4b and h). Therefore, the whole annual variations of SST are strongly controlled by the first two EOF modes and since both of them have an obvious annual cycle, thus, when both of them are of equal amplitude and have an opposite phase, the net seasonality of SST should be zero and an annual amphidrome can be developed. Another interesting finding is that two annual amphidromes locate just around the intersections of the zero contour curves of EOF1 and EOF2 (see Fig 4b), which implies that they are formed in the regions where both EOF1 and EOF2 are not significant in magnitude, therefore when these two weak annual variation regions overlay together, an annual amphidrome can be formed. EOF3 is a typical SC pattern. The tropical region is out of phase with the mid- and high-latitude ocean and the global pattern is consistent with the phase distributions in Fig 3b. Except for P1, II, II, A1, and A2, other SC amphidromes are also located around the zero contour curves in the SH (see Fig 4c), which suggests that
Fig. 4. The first six modes of EOF results derived from 22 a SST data. The locations of two annual amphidromes and 14 semiannual amphidromes are highlighted by the white dots in (a), (b), (c), (e), and (f). The thick black curves in a--f refer to the zero contours. PC patterns and EOF time series are normalized by their corresponding standard deviations.

The formation of SC amphidromes may be consistent with that of AC amphidromes explained by EOF1 and EOF2. It deserves to examine the following EOF patterns. EOF4 is an ENSO pattern (Fig. 4d and j), which has been reported widely by previous documents. EOF5 and EOF6 together can contribute 23% in variance and both of them have a strong SC period (Fig. 4k and l). Furthermore, one can find that SC amphidromes, P1, II, E, A1, and A2, which are not identified over the zero contour curves of EOF3 (Fig. 4c), do surprisingly appear over the zero contour curves of EOF5 and EOF6 (Fig. 4e and
Therefore, the formation of these SC amphidromes is attributed to the coupling of EOF3, EOF5, and EOF6. It goes beyond our knowledge to explain all the thermal and thermodynamic processes involved in each EOF SST pattern, but it indeed closely connects with the formation of these SST amphidromes.

4 Summaries and remarks

The multimode low-frequency SST variability has been discussed in this study. First, the whole global ocean can be well classified by the first relative dominant mode in the low-frequency time domain and each individual region has different combinations of these primary modes of SST variation. The new classification of this kind illustrates these primary modes of SST variations, AC, SC, ENSO, and ENSO-like mode, are of strongly spatial dependency, and furthermore, it also presents ideal locations for the monitoring of these different variation modes. Second, SST variation is overwhelmingly controlled by the AC component, and slightly modulated by the SC and IAV modes. The relative importance of the AC, SC, and IAV in terms of global mean amplitude is approximately 6:1:1:1, which suggests that the SC and the IAV are of the same significance in SST variability. Thirdly, inspired by the successful identification of annual SST amphidromes that were firstly addressed by Chen and Quarty (2005), 14 SC amphidromes are further well-defined firstly by the SC SST phase pattern. The formation of the AC and SC amphidromes is fundamentally interpreted by the coupling of different SST EOF modes. The identification of these amphidromes is of significance in monitoring the IAV and the DV because they are free from interference of energetic AC and SC signals in theory.

The multimode low-frequency variability is not only a phenomenon associated with the SST in the ocean, but also a common feature existing in other key oceanic variables such as sea level anomaly, thermocline depth, as well as other geophysical atmospheric parameters such as precipitation, water vapor, sea level pressure. A clear understanding of these global multimode patterns of different variables in the air-sea system is helpful to convey some information of the coupling of the ocean and atmosphere in the low-frequency time domain in particular, and the long-term climate change in general. Moreover, we speculate that the annual and semianual amphidromes are not only a common feature in the ocean, but also a global phenomenon in the air, which hopefully will be identified and confirmed in some atmospheric variables in our future studies.

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References

Bjerknes J A. 1966 A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature. Tellus, 18: 820[829
Chen Ge 2004 A 10-yr climatology of oceanic water vapor derived from the TOPEX microwave radiometer. Journal of Climate, 17: 2 541[2 557