

Spatial-temporal variation of the surface chlorophyll on seasonal timescale in the western Pacific during 1997-2010

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Abstract. Two dominant modes of the spatial-temporal evolution of the chlorophyll (CHL) over the western Pacific were revealed for the period from 1998 to 2010 using season-reliant Empirical Orthogonal Function (S-EOF) analysis method. The results showed that the first two dominant modes of CHL accounted for 43.8% of the total variance, corresponding to ENSO turnabout and post-ENSO years respectively. Besides, SEOF analysis was also applied to sea surface temperature (SST) and sea level anomaly (SLA). The seasonally evolving patterns of CHL on seasonal timescale was closely related to the patterns of SST and SLA associated with ENSO, with the consistent turning tendency of the principle component. To further distinguish the relationship between the seasonal evolution of CHL and ENSO, the lead-lag correlation coefficients were calculated between MEI and the principal components of the leading two modes of CHL. The first mode of CHL was primarily associated with the ENSO development and prediction while the second mode of CHL followed the peak of ENSO, and might be viewed as a response to ENSO.

1. Introduction

The western Pacific has a significant role in the evolution of El Nino and Southern Oscillation (ENSO) events. It is a complex region and at least two ecosystems coexist in the western Pacific warm pool: mesotrophic waters of the cold tongue in the eastern part of the region and the oligotrophic waters of the warm pool stand in the western part[1]. The physical forcing and biological response are highly variable over both seasonal and interannual scales. Phytoplankton is the microalgae that populate the upper layers of the ocean, transfer the carbon dioxide from the atmosphere to the ocean by photosynthetic carbon fixation and thus plays a significant role in the global carbon cycle. As the indicator of the growth condition of phytoplankton, chlorophyll concentration is also the key factor to estimate the primary production of the ocean[2].

Sea surface chlorophyll (CHL), the proxy of the ocean phytoplankton biomass and primary production, are closely associated with the ocean biological and biochemical processes. Previous studies have shown that ENSO is the strongest signal of the tropical Pacific's interannual variation and is closely related to the variation of chlorophyll concentration[3-5]. On interannual timescales the variation of chlorophyll concentration is opposite related with sea surface temperature (SST) whose



change has a close relation to ENSO events[5-7]. However, the dominant modes of chlorophyll in the western Pacific on a seasonal timescale is uncertain. The goals of this study were to identify the spatio-temporal characteristics of the leading seasonally evolving modes of chlorophyll concentration in the western Pacific (10°S-25°N, 105°E-150°W) and to determine their relationships with ENSO during 1998-2010.

2. Data and methods

Various satellite products were utilized to analyze the spatial-temporal variation of chlorophyll concentration on seasonal timescale. The seasonal SeaWiFS level3 chlorophyll concentration products from 1998 to 2010 were obtained from the NASA ocean color server. Monthly AVHRR Pathfinder version 5.0 SST between 1991 and 2009 were obtained from the Physical Oceanography Distributed Active Archive Center at the NASA Jet Propulsion Laboratory. Monthly averaged sea level anomalies (SLA) between 1993 and 2011 were distributed by AVISO. In addition, the Multivariate ENSO Index (MEI) from NOAA was used as an indicator of the ENSO variability.

In this study we applied a newly proposed method called season-reliant empirical orthogonal function (SEOF) analysis proposed by Wang Bin (2005) [8] to CHL, SST and SLA in a seasonal sequence beginning from the winter of a year to the following fall. The anomalies for December-February [D(-1)JF(0)], March-May [MAM(0)], June-August [JJA(0)], and September-November [SON(0)] were treated as yearly block, where -1 denotes the year before the year 0. Comparing with the conventional EOF and subjective time filtering methods, SEOF is an objective approach for distinguishing modes of variability that evolve with the season. In addition, we used lead-lag correlation methods to identify the relationships between the principle seasonal evolving modes of chlorophyll and ENSO.

3. Dominant seasonally evolving patterns

3.1. Dominant seasonally evolving CHL patterns

We applied SEOF analysis to the anomalies of CHL to identify the leading modes of CHL in the western Pacific. The leading two modes accounted for 24.8% and 19.0% of the total variance respectively. According to the rule of North et al. (1982), these two modes were statistically significant and distinguishable.

Figure 1 (a) and (b) present the seasonally evolving spatial patterns of SEOF1 mode and SEOF2 mode respectively. The seasonal evolutions of the two modes are clearly distinguished from each other. In general SEOF1 is characterized by a positive anomaly located in 10° S~10° N, northeast of New Guinea and is surrounded by negative CHL anomalies. From D(-1)JF(0) to MAM(0), the positive CHL anomalies intensified significantly and propagated to the east. While the negative CHL anomalies decayed rapidly from MAM(0) to SON(0), the positive anomalies still intensified and propagated to the east. By SON (0) the CHL pattern was highlighted by a westward pointing "arrowhead" shaped positive feature, centered at the equator, maximum ~160° E to 160° W [7], which resembled the pattern obtained from the conventional EOF analysis of CHL. This resemblance indicates that the SEOF1 mode of the western Pacific is stable and credible[9].

In contrast with SEOF1, SEOF2 mainly features the evolution of the negative CHL anomalies. From D(-1)JF(0) to SON(0), the negative CHL anomalies decayed rapidly. Notably, the resemblance can be observed between the patterns of SEOF1 mode of MAM(0) in figure 1 (a) and the SEOF2 mode of MAM(0) in figure 1 (b), as well as between the patterns of SEOF1 mode of SON(0) in figure 1 (a) and the SEOF2 mode of D(-1)JF(0) in figure 1 (b). The resemblance reveals that both of these modes have a connection with some important signals (e.g., ENSO) with different lead-lag correlations[9], which are discussed hereafter.

Figure 2 presents the time series of principle component (PC) of CHL. The black thick line is the time series after Spline interpolation. The first notable feature is that both of the two modes have prominent interannual variations. The second notable feature is the reversal of the variations of the two

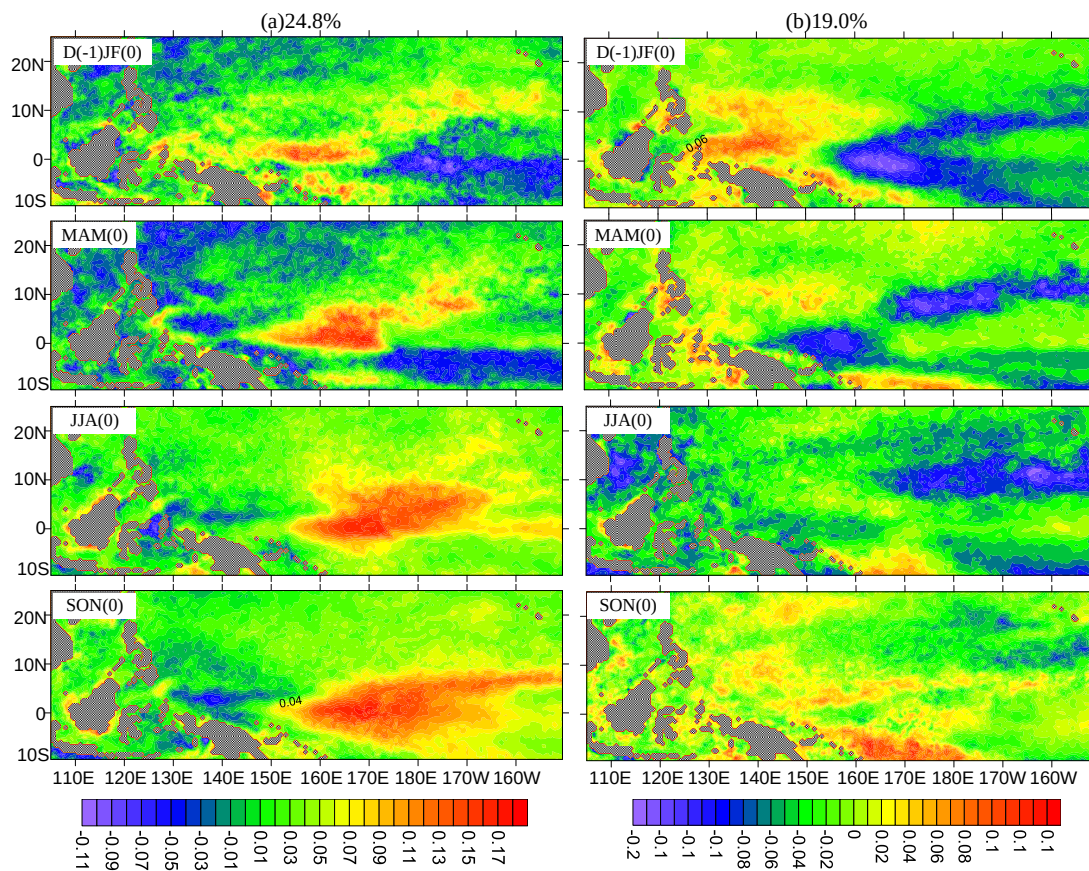


Figure 1. (a) Seasonally evolving spatial patterns of SEOF1 mode derived from the SeaWiFS chlorophyll anomalies over the western Pacific during the period 1997-2010. (b) The same as in panel(a), but for SEOF2 mode.

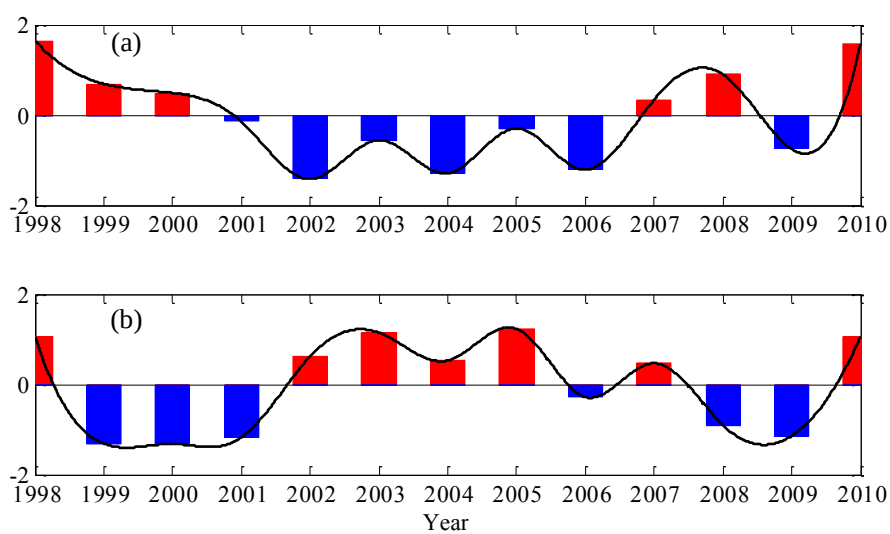


Figure 2. Normalized principal components of CHL: (a) PC1 and (b) PC2. The superimposed black thick line is the interpolated time series.

SEOF modes. The third notable feature is that the peaks correspond with the El Nino years (2002, 2004, 2006, 2009) and La Nina years (1998~2010, 2007, 2008, 2010), which indicates that CHL's seasonally evolving patterns have an association with ENSO.

3.2. Dominant seasonally evolving SST and SLA patterns

Sea surface temperature (SST) is the representative of the vertical convective mixing and the thermal stratification of the ocean and is often viewed as the indicator of nutrient availability in the upper ocean[7]. Sea level anomaly (SLA) is a proxy for surface current structure and depths of thermocline and pycnocline[7] which influence the growth of phytoplankton by impacting the nutrient-rich upwelling. Chlorophyll concentration's variation has a close correlation with the variations of sea surface temperature and sea level anomaly. To demonstrate the relationships between season-evolving variability of chlorophyll and the physical ocean motion in the western Pacific, we applied SEOF analysis to the SST (from 1991 to 2009) and SLA (from 1993 to 2011) fields in the western Pacific. The leading two modes of SST accounted for 41.3% and 20.2% of the total variance respectively and the leading two modes of SLA accounted for 37.3% and 20.7% of the total variance respectively. The principal components (PC) of the dominant seasonal evolving modes of SST and SLA are shown in figure 3, while the spatial patterns are not shown here. In fact the patterns of the first two modes of SSTA in the western Pacific are consistent with the results of Huang Fei (2010) [10], who found that the leading mode is the low-frequency ENSO mode accompanying with the Indian Ocean basin mode and the second mode is the transition mode of ENSO with the Indian Ocean dipole mode in the Pacific-Indian ocean.

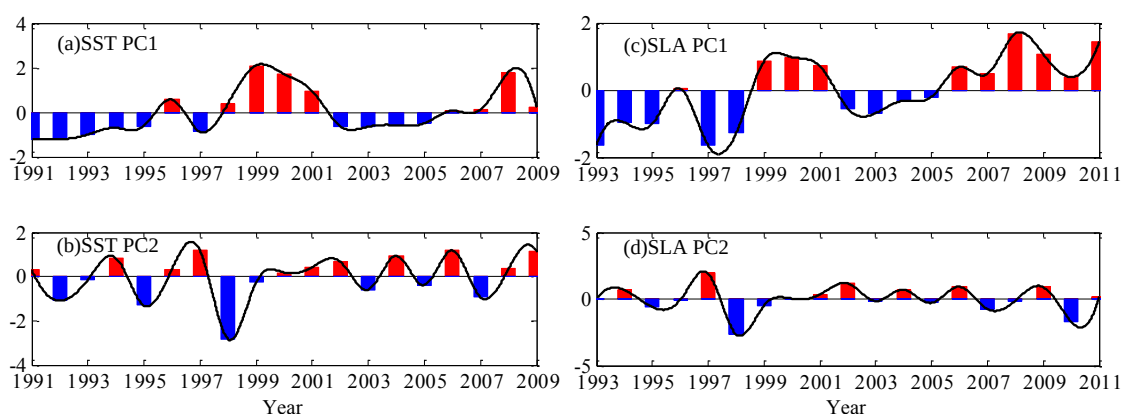


Figure 3. Normalized principal components of SST and SLA: SST PC1(a), SST PC2(b), SLA PC1(c), SLA PC2(d).

From the principal components of SST (figure 3a) and SLA (figure 3c), we can clearly see that SST PC1 and SLA PC1 are consistent with the warm and the cold phase of ENSO. Specifically, the positive values (in red) corresponding to the La Nina years (1998-2001, 2007-2008), while the negative values (in blue) corresponding to the El Nino years (1997-1998, 2002-2003, 2004-2005). Variability of CHL on the interannual timescale has a significant negative correlation with SST and SLA[1, 11, 12]. The nutrient supply is primarily influenced by the horizontal advection and vertical mixing which could be indicated by SST and SLA changes. This study clearly shows us that the seasonally evolving of CHL on seasonal timescale is closely related to the season-evolving patterns of SST and SLA associated with ENSO.

4. Relationships with ENSO

The lead-lag correlation coefficients between the principal component PC1 of CHL and MEI are presented in figure 4 (blue line), in which year(-1) denotes that MEI leads the PC1 and year(1) denotes

that MEI lags the PC1. Notably, the correlation between PC1 of CHL and MEI was positive and weak (not passing Student's t -test at the 5% significance) from MAM(-1) TO MAM(0). However, the correlation became negative and develops rapidly from JJA(0) to SON(0). From JJA(0) to MAM(1), PC1 was negatively correlated with the MEI, with the correlation coefficient passing the threshold of significance in the 95% Student's t -test. The PC1 showed a maximum negative correlation coefficient that exceeded -0.9 (statistically significant at the 95% Student's t -test significance) in SON(0) and DJF(1). After the correlation coefficient reached its peak in SON(0) and DJF(1), the correlation between them decayed rapidly.

The lead-lag correlation between PC2 and the MEI is shown in figure 4 (red line). Notably, the PC2 was positively correlated with the MEI from JJA(-1) to MAM(0), with the correlation coefficient passing the threshold of significance in the 95% Student's t -test. A maximum positive correlation coefficient occurred in DJF(0) that passed the threshold of the 5% Student's t -test significance. After the correlation coefficient reached its peak in DJF(0), the correlation between them decayed rapidly.

Based on the correlation between the two modes and ENSO, we could conclude that SEOF1 mode was primarily associated with the development of ENSO and might make a significant contribution to ENSO prediction methods. However, SEOF2 mode occurred following the peak of ENSO, and it might be viewed as responses to ENSO.

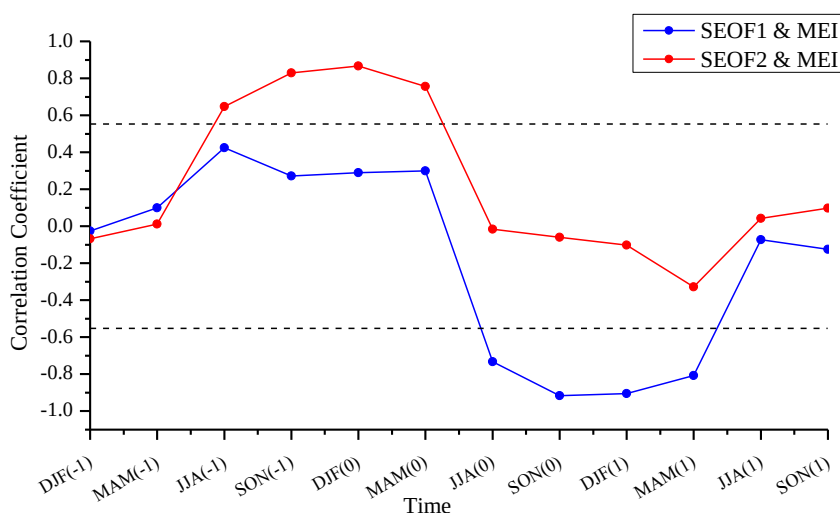


Figure 4. The blue (red) line is the Lead-lag correlations between the first (second) SEOF principal component and MEI. The dashed line indicates the Student's t -test at the 5% significance.

5. Discussion and conclusion

Two dominant modes of the spatial-temporal evolution of the chlorophyll (CHL) over the western Pacific were revealed for the period from 1998 to 2010 by means of S-EOF. The first mode is primarily associated with the ENSO development and prediction. When the CHL PC1 transfer from positive to negative the CHL in the western Pacific next year decayed from winter to fall, and it indicates the upcoming of El Nino, which happened in 2001-2002 and 2008-2009. However when the CHL PC1 transfer from negative to positive, the CHL in the western Pacific next year bloom from winter to fall, and this transition means the upcoming of La Nina which happened in 2006-2007 and 2009-2010. The variation of the second mode of CHL follows the peak of ENSO and may be viewed as a response to ENSO. During the 1997-1998 El Nino, the surface ocean became impoverished in plant nutrients and CHL were the lowest on record[13]. After 1997-1998 El Nino, PC2 turns from positive to negative, which means a recovery of CHL from 1999 to 2001. As a response to El Nino in 2002-2003 and 2004-2005, CHL PC2 transfer from negative to positive, which means CHL next year decayed from winter to fall. As a response to La Nina in 1998-2000 and 2006-2007, CHL next year

bloom from winter to fall. Both SST and SLA are the key ingredients which influence CHL's interannual variation associated with the interchange of El Nino and La Nina. The ocean's biomass variation is significantly forced by the change of ocean dynamic environments driven by ENSO.

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