Interannual variability of the South China Sea in a data assimilation model

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Received 13 June 2005; revised 9 August 2005; accepted 18 August 2005; published 15 September 2005.

[1] Sea surface height (SSH) variations in the South China Sea are examined using results from a data assimilation model. After the SSH data have had the annual cycle removed, principal component analysis illustrates two distinct anomaly patterns. The first mode, strongest off Vietnam, would affect the basin-wide gyre intensity. The second mode consists of a meridional dipole feature with a nodal line around 12°N and is related to the development of the eastward jet and upwelling off Vietnam. Both EOF modes have significant interannual variations and are highly correlated to the ENSO events. The leading phase of mode 2 coefficient provides preliminary evidence for the air-sea interaction and the Pacific-East Asian teleconnection. An innovative mechanism is proposed to describe a weakened upwelling off Luzon in winter 1998. An extra-strong basin-wide warming in summer 1998 persists into fall and winter, preventing the formation of winter upwelling off Luzon in that year. **Citation:** Wu, C.-R., and C.-W. J. Chang (2005), Interannual variability of the South China Sea in a data assimilation model, *Geophys. Res. Lett.*, *32*, L17611, doi:10.1029/2005GL023798.

1. Introduction

[2] Situated at the pathway of East Asian monsoon system, the South China Sea (SCS) circulation is largely influenced by the seasonal reversal of the monsoonal winds, northeasterly in winter and southwesterly in summer. On a seasonal time scale, the surface circulation is cyclonic in winter and anticyclonic in summer. Beyond the seasonal time scale, circulation of the SCS demonstrates an interannual variation related to El Niño/Southern Oscillation (ENSO) [e.g., *Wu et al.*, 1998; *Shaw et al.*, 1999; *Ho et al.*, 2000]. For example, using TOPEX/Poseidon (T/P) altimeter sea surface height (SSH) from late 1992 to mid-1995, *Shaw et al.* [1999] showed the presence of a weaker circulation pattern during El Niño because of a weaker East Asian monsoon. Since the T/P altimeter data were too short-term to give a comprehensive description of the interannual variations, empirical orthogonal functions (EOF) analysis of these earlier studies did not consider the seasonal dependence in the SCS interannual variability. Therefore, the results of their EOF analysis include a mixture of winter and summer modes. Without this disadvantage, the analyses of *Xie et al.* [2003] and *Liu et al.* [2004] are on a single season, summer or winter, by defining a seasonal index based on sea surface temperature (SST) anomaly. Their studies have achieved to explain the interannual variability in the SCS to some extent; nevertheless, the definition of proper indices is rather subjective, and the continuation and evolution of seasonality is lacking from their analysis.

[3] In this paper, alternatively, we deal with an entire ten-year SSH time series, but removing the annual cycle signal from the data set. The residual SSH is examined in terms of EOF, using principal component analysis. In this way, the present analysis not only takes into account the seasonal dependence of the interannual variability but also keeps the continuation and evolution of seasonality.

[4] Many recent studies reveal that the ocean dynamics and horizontal advection in particular play a key part in the interannual variability in the SCS [*Metzger and Hurlburt*, 2001; *Qu et al.*, 2004; *Liu et al.*, 2004]. To further highlight the influence from the ocean dynamics on the interannual variability over the SCS, SSH field instead of SST has been selected for the present study since the oceanic dynamics is better represented by SSH rather than SST, which suffered the heavy influence from the atmosphere (e.g. surface heat flux; evaporation cooling).

2. Model Description

[5] A three-dimensional ocean model capable of altimetric data assimilation has been selected for the study. The ocean model is a generalization of the Bryan-Cox code to accommodate for a free sea surface. The integration domain of 2–24°N and 99–124°E with horizontal resolution of 0.4° and vertical resolution of 21 levels is used. Open boundaries are at the Taiwan Strait, the Sunda Shelf, and east of the Luzon Strait. The external mode velocity normal to the boundary is specified by *Wyrtki*'s [1961] bimonthly transports divided by the water depth. SSHs from the T/P or Jason-1 altimeter are assimilated into the model. Using this model, *Wu et al.* [1999] demonstrated that uncertainties associated with the wind forcing field and boundary conditions are remedied to a certain extent by assimilating altimeter data. The data assimilation model reproduces mesoscale variabilities in SSH, velocity and temperature fields, such as a dipole off Vietnam and a low/high feature off Luzon. Additional information on the model is given by *Wu et al.* [1999].

[6] The model is initialized using the January temperature and salinity profiles of *Levitus* [1982] and given the climatological forcing. After an initial spin-up period of one year, the model is forced by daily wind field and daily SST from NCEP/NCAR 40-year reanalysis project [*Kalnay et al.*, 1996] from January 1, 1992, through December 31, 2002. Assimilation of the altimeter SSH begins in October 1992,

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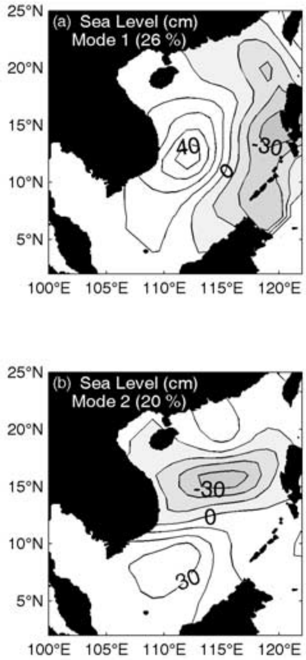

Figure 1. Spatial patterns of residual SSH EOF (a) mode 1 and (b) mode 2. Contour intervals are 10 cm. The negative contours are shaded.

when T/P altimeter data become available. Beginning in the third year, 10-year simulated SSH data over the period from January 1993 to December 2002 are used for analysis.

3. EOF Analysis of SSH

[7] While the spatial structure of the annual SSH cycle is of interest, the large annual signal could hinder the interannual timescale fluctuation. To place emphasis on the interannual variability, we remove the annual cycle signal and the subsequent analysis deals only with residual time series. An EOF analysis is applied to the residual SSH. The shallowest regions in the SCS, such as the Gulf of Tonkin, Gulf of Thailand, and Sunda Shelf, are excluded in the analysis. The resolved two leading EOF modes account for 26% and 20% of the total variance respectively.

[8] The spatial dependence of the first mode demonstrates large-amplitude oscillations centered at 12.5°N, 112°E off central Vietnam while oscillations on the eastern basin are out of phase with the western basin. Note that there is a local maximum centered at 20°N, 119°E off Luzon Strait (Figure 1a). The second mode is mainly contributed by oscillations centered at 16°N, 115°E in the northern basin, extending from Vietnam to Luzon and oscillations centered at 8.5°N, 111°E in the southern basin. This meridional dipole feature centers a nodal line around 12°N (Figure 1b).

[9] Temporal variations of SSH in each mode are shown in Figure 2. Note that the strong annual signal has been removed in the present study, thus, the values in each mode represent residual SSH and only larger values are capable of affecting the SSH pattern significantly. Graphically, mode 1 coefficient peaks in the month of December with negative values (<-0.1) in 1995 and 1998 and positive values in 1994 (>0.05) and 1997 (>0.13) (Figure 2a). Multiplying the modal amplitude (Figure 1a) by the coefficient, the local maximum off central Vietnam dominates a low in 1995, 1998 and a high in 1994, 1997. A strong low off Vietnam enhances the cyclonic gyre in the winters of 1995 and 1998 and spans the entire deep basin. On the contrary, a strong mode 1 high off Vietnam weakens the western boundary current in the winters of 1994 (not strong) and 1997 when the warming events took place in the equatorial Pacific. The weaker circulation pattern further confirms the findings from earlier El Niño events by *Chao et al.* [1996]. From model simulation of the 82/83 El Niño, *Chao et al.* [1996] show a weaker basin-wide circulation during ENSO under a weaker East Asian monsoon.

[10] Year-to-year variations are present in the mode 2 coefficient as well (Figure 2b). In contrast to mode 1 coefficient, the most significant changes in mode 2 coefficient are in the month of August. The coefficient reaches to a minimum in August 1998 (<-0.1) and maxima in August 1994, 1997 and 2002 (>0.1). Combining with spatial pattern of Figure 1b, positive values of mode 2 contribute positive anomalies to the remnant summer gyre in the southern basin and negative anomalies in the northern basin. Thus, the summers of 1994, 1997 and 2002 favor the formation of an eastward jet and upwelling off Vietnam, consisting with the climatological summer feature shown by *Qu* [2000]. On the contrary, a minimum in August 1998 implies diminishing of the eastward jet and upwelling off Vietnam. Consequently, the lack of summer cooling makes August 1998 the warmest summer on record in the SCS [*Wang et al.*, 2002].

4. Correlation With ENSO

[11] To further study the relation between SCS variability and ENSO events, Figure 3 shows the correlation between time series of each mode and Niño 3.4 SST index. Mode 1 coefficient is obviously correlated with ENSO at a one-month lag, with a correlation coefficient of 0.68 and which

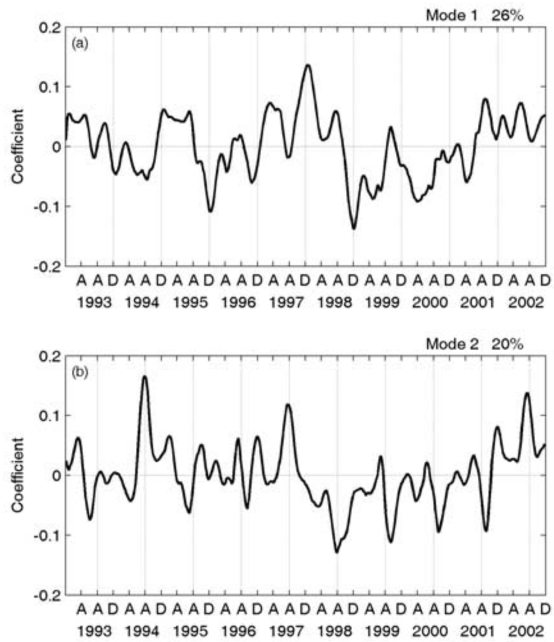

Figure 2. Temporal variations of the first two sea surface height modes.

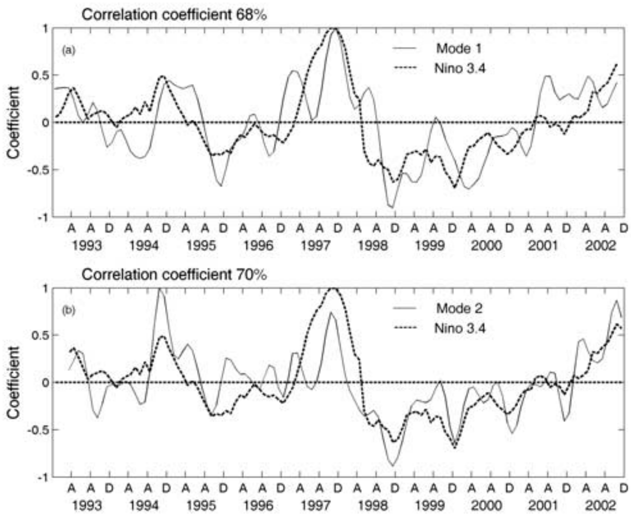

Figure 3. Correlation between time series of Niño 3.4 SST index (5°S–5°N; 170°W–120°W) (dashed line) and (a) mode 1 coefficient with time lead of one month and (b) mode 2 coefficient with time lag of 3 months. Both the coefficients and the index have been normalized for making clear comparisons.

is significant at the 95% level based on the t-distribution. There are several driving mechanisms describing how ENSO modulates the SCS climate. *Wang et al.* [2000] presented a teleconnection between the central Pacific and East Asia during the extreme phases of ENSO cycles. An anomalous lower-tropospheric anticyclone located in the western North Pacific links the warm events in the eastern Pacific and the weak East Asian winter monsoons. The weakened monsoons further give rise to a winter warming in the SCS as it took place in early 1998. Based on the ocean dynamics, *Qu et al.* [2004] pointed out that the interannual variation of transport through Luzon Strait contains a strong ENSO signal, and the associated heat advection would change the upper-layer heat content in the SCS.

[12] In Figure 3b, on the other hand, mode 2 coefficient leads Niño 3.4 index by 3 months. A correlation coefficient of 0.70 is significant at the 95% level based on the t-distribution. This 3-month leading time has not been reported by earlier studies based on the SST data [e.g., *Xie et al.*, 2003; *Qu et al.*, 2004]. The 3-month shift in phase on SSH but not on SST implies that the ocean dynamics plays a critical part in the variability since the oceanic dynamics is better represented using the SSH rather than SST. *Qu et al.* [2004] reported that the interannual variation of the upper-layer heat content also shows good correspondence with ENSO, with upper-layer heat content leading Southern Oscillation index (SOI) by 5 months. The 5-month leading phase is comparable to that of mode 2 coefficient at the present study. Both the upper-layer heat content and SSH are highly related to the ocean dynamics while less is to the SST field, further suggesting the oceanic connection plays a key part in the SCS variability.

[13] Four spatial patterns of the monthly mean SSH representative of the 97/98 event are shown in Figure 4. In August 1997, at the developing stage of El Niño, a strong dipole off Vietnam (Figure 4a) mainly contributed by mode 2 intensifies an eastward jet and upwelling there, giving rise to a significant cooling in the upper layer of the SCS. Three months later, Niño 3.4 index peaks in November 1997. The onset of the 97/98 El Niño significantly weakens the prevailing northeasterly monsoon in December 1997. With mainly contribution from mode 1, Figure 4b shows a weakened circulation but upwelling off Luzon in December 1997. In the following summer (August 1998), mode 2 coefficient prevents the formation of the eastward jet and upwelling off Vietnam, giving rise to a maximum summer warming over the SCS. This feature confirms the earlier findings that Pacific ENSO will further modulate the SCS climate and the warm SST anomaly peaks in the following summer [*Xie et al.*, 2003]. A notable feature shown in Figure 4d is the upwelling off Luzon, which normally appears in December each winter, is missing in 1998. The gridded altimeter SSH data from Center for Archiving, Validation and Interpretation of Satellite Data in Oceanography, the French Space Agency [*Archiving, Validation, and Interpretation of Satellite Data in Oceanography* (*AVISO*), 1992] confirm that the year of 1998 is the only year that upwelling off Luzon does not develop in December (figure not shown). The phenomenon deserves to be further verified and will be examined in detail in the next section.

5. Winter Upwelling Mechanism

[14] Upwelling off Luzon in winter has been recognized and studied for years [e.g., *Shaw et al.*, 1996]. Several possible mechanisms attribute to the upwelling, such as the coastline of northwest Luzon, elevated bathymetry, local wind forcing, or Kuroshio intrusion. *Shaw et al.* [1996] suggested that the upwelling is not driven by any of the factors mentioned above but containing a large, remotely forced component arising from the basin circulation based on results of a two-layer model and a general circulation

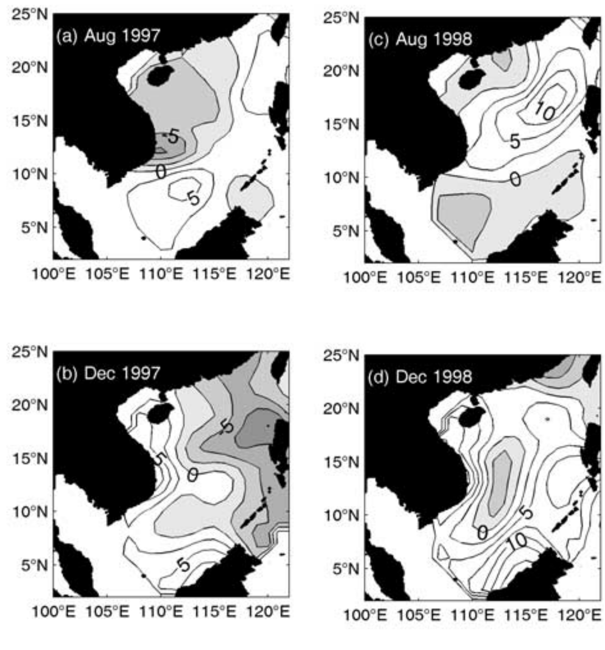

Figure 4. Spatial distribution of monthly mean SSH from data assimilation experiment in (a) August 1997, (b) December 1997, (c) August 1998 and (d) December 1998. Contour intervals are 2.5 cm, and negative contours are shaded.

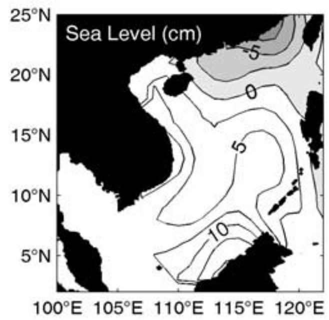

Figure 5. Spatial distribution of monthly mean SSH in December 1998. The experiment is restarted after October and thereafter is forced by daily wind of 1997 till the end of the year. Contour intervals are 2.5 cm. The negative contours are shaded.

model. Nevertheless, the remote forcing theory fails to explain the uncommon weakened upwelling process off Luzon in winter 1998. There is upwelling off Luzon in winter 1997, but not in winter 1998 although the northeasterly monsoonal winds are much stronger in winter 1998. Abnormal warming in summer 1998, the warmest summer on record, gives a clue that the cause of weakened upwelling may attribute to uncommon oceanic state over the basin.

[15] A numerical experiment is carried out to investigate this process further. The model with altimetric data assimilation is forced by daily wind of 1998 and continues to the end of October 1998. After turning off assimilation of the altimeter data and replacing wind field with those of 1997, the model is restarted and the simulation continues to the end of the year. In Figure 5, the experiment results in a similar feature off Luzon shown in Figure 4d rather than Figure 4b, indicating that the cause of upwelling off Luzon cannot be simply attributed to local or remote wind forcing. However, the winter of 1998 is the only winter that upwelling off Luzon did not show up during the 12-year period from 1992 to 2003 based on the AVISO's satellite images, suggesting that only an extra-strong and probably long persistent basin-wide warming as it took place in 1998 is capable of preventing the winter upwelling off Luzon.

6. Summary

[16] After removing the annual cycle signal, an EOF analysis is applied to residual SSH over the SCS region. The spatial dependence of the first mode indicates a western boundary current anomaly pattern, affecting the basin-wide gyre intensity. The second mode contributes to a pair of oscillations in the southern and northern basins, affecting the formation of the eastward jet and upwelling off Vietnam. Temporal variations of these two EOF modes reveal interannual variations in winter and summer, respectively.

[17] The interannual variability of both mode 1 and 2 coefficients shows great correspondence with ENSO, with mode 1 coefficient lags Niño 3.4 index by 1 month whereas mode 2 coefficient leads the index by 3 months. The fact that mode 2 coefficient leads Niño 3.4 index is probably counter-intuitive, but it provides preliminary evidence that the SCS variability is a result of the Pacific-East Asian teleconnection. *Masumoto and Yamagata* [1991] suggested that cooler SST in the SCS and warmer SST in the tropical western Pacific result in more westerly wind bursts that provide a trigger for El Niño. Pacific ENSO will further modulate the SCS climate and strong warming rises in the following summer as it took place in 1998.

[18] An innovative mechanism is proposed to explain the disappearance of the upwelling off Luzon in winter 1998. Although the wind stress curl, an important atmospheric driving force for upwelling off Luzon [*Qu*, 2000; *Metzger*, 2003], is strong in winter 1998, the abnormal basin-wide warming starting from summer is the overwhelming factor for the weakened upwelling off Luzon.

[19] **Acknowledgments.** Valuable comments given by H.-H. Hsu of National Taiwan University and the reviewers greatly improved both the presentation and discussion. Thanks extended to W.-J. Sheu for processing and plotting the model outputs. This research was supported by the National Science Council, Taiwan, ROC, under grant NSC 93-2611-M-003-002.

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