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# Interannual mode of sea level in the South China Sea and the roles of El Niño and El Niño Modoki

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[1] ENSO-scale variation of the summer ocean circulation in the South China Sea (SCS) is investigated. The interannual mode of SSH features a north-south dipole pattern that modulates the cold jet off Vietnam. During the summers before and after the El Niño, the mode has opposite signs of extrema. Strengthened circulations couple with the cold SSTAs during the El Niño developing summers; weakened circulations accompany the warm SSTAs during the decaying summers. Heat advection by the basin circulation modulates the SST variation. The impact of the 1997 El Niño on the SCS circulation contrasting that of 1994 and 2002 El Niño Modoki is assessed. With moderate SST warming but further westward shift of the low-level convergence of the atmosphere in the equatorial Pacific, the El Niño Modoki phenomenon enhanced the western North Pacific summer monsoon inside the SCS, driving stronger circulations in both the summers of 1994 and 2002. **Citation:** Chang, C.-W. J., H.-H. Hsu, C.-R. Wu, and W.-J. Sheu (2008), Interannual mode of sea level in the South China Sea and the roles of El Niño and El Niño Modoki, *Geophys. Res. Lett.*, *35*, L03601, doi:10.1029/2007GL032562.

## 1. Introduction

[2] Being the largest marginal sea in the tropics, the South China Sea (SCS) connects with two major oceans, the Pacific and Indian Oceans. The East-Asian monsoon winds, northeast in the winter and southwest in the summer, drive the general ocean circulation of the SCS, cyclonic in the winter and anticyclonic in the summer. Seasonal upwelling in the SCS is persistent but localized, and is attributed to the basin-wide circulation [*Shaw et al.*, 1996]. Off the coast of Vietnam, upwelling is manifested by a low temperature zone in June and July [e.g., *Levitus*, 1982]. The summer upwelling and the associated cold tongue are characterized by interannual variability, and play an important role in regional climate variation [*Xie et al.*, 2003]. Furthermore, the summer fluctuation persists for months and would weaken the subsequent winter upwelling off Luzon [*Wu and Chang*, 2005].

[3] The extreme phases of the El Niño–Southern Oscillation (ENSO) phenomenon have a strong modulating effect on the climate in Southeast Asia, with mature ENSO warm events often associated with weaker East-Asian winter monsoons [*Tomita and Yasunari*, 1996]. Consistent with these monsoon anomalies, the SCS responds to matured ENSO warm events with reduced winter circulation [*Chao et al.*, 1996] and anomalous warming in the sea surface temperature (SST) [*Klein et al.*, 1999]. In the subsequent summer, the surface circulation in the SCS has been reported to be weaker than normal [*Chao et al.*, 1996; *Wu et al.*, 1999] and the SST exhibits another warming peak related to ENSO [*Xie et al.*, 2003].

[4] The interannual variability in the SCS circulation was further demonstrated by *Wu and Chang* [2005]. The Empirical orthogonal function (EOF) analysis of sea surface height (SSH) anomalies during 1993 to 2002 described two leading EOF modes that are both highly correlated to ENSO: the first mode modulates the winter circulation pattern and the second mode the summer circulation. Interestingly, the second mode had an optimal correlation ($r = 0.7$) with ENSO while leading the Nino-3.4 SST anomaly index (5°S–5°N, 120°–170°W) by three months. The leading phase of this mode suggests an early impact from the developing El Niño on the SCS. The motivation of the present study is therefore set to understand the SCS circulation in the summer season preceding the mature El Niño, with focus on the atmospheric forcing. The second mode by *Wu and Chang* [2005] is adopted as the SCS summer circulation index, and is elaborated in detail in section 2. Global atmospheric conditions affecting the SCS local wind fields are addressed in section 3 with empirical analyses on NCEP reanalysis data [*Kalnay et al.*, 1996], precipitation data (GPCP) [*Huffman et al.*, 1997] and SST data (HadISST SST 1.1) [*Rayner et al.*, 2003]. Regression analyses on wind and SST fields with El Niño are presented in section 4. For the aforementioned data sets, 25-year (1979–2003) monthly climatologies were constructed and the anomalies were calculated.

## 2. El Niño-Related Circulation and SST

[5] Figure 1 shows the spatial and temporal variation of the second SSH mode. Under geostrophic balance, the mode indicates the variability of the SCS basin circulation dominated by the fluctuation of a meridional dipole with a nodal line around 12°N (Figure 1a). Since mean summer circulation in the SCS is characterized by an anticyclonic gyre in the southern basin and a weak cyclonic gyre to the north, a positive phase of the dipole mode represents an enhanced summer circulation that favors the formation of the eastward offshore flow and upwelling off Vietnam; a negative peak represents a weakened circulation with either a weak eastward offshore jet or a reversed westward onshore current (such as in the summer of 1998), and upwelling off Vietnam is unfavorable. From 1993 to

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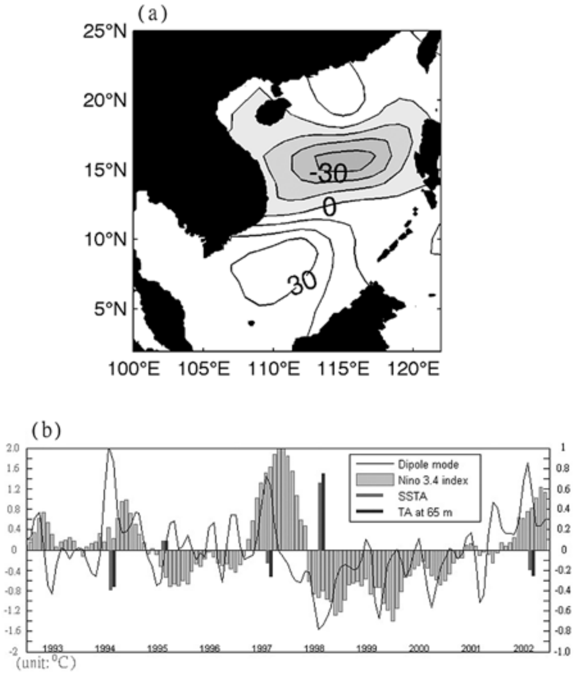


**Figure 1.** The second EOF of SSH anomaly in the SCS after *Wu and Chang* [2005, Figure 1b and 2b]. This mode explains 20% of the variance. (a) The spatial pattern, with the negative values shaded. Contour intervals are 10 cm. (b) January 1993 to December 2002 time series of the mode coefficient (solid line) and Nino-3.4 SST index (5°S–5°N;170°W–120°W) (bar area). Both the coefficient and index have been normalized. Light(dark)-grey spikes mark the July-August-September averaged SSTA (temperature at 65 m) west of Vietnam over 10°–13°N, 110°–118°E. Temperature data at 65 m are from a data assimilation model [*Wu et al.*, 1999].

2002, there were a strong El Niño event (1997/1998) and two weak ones (1994/1995 and 2002/2003). As revealed in Figure 1b, during the summers before and after the El Niño maturation, the dipole mode tends to peak in opposite phases. The conspicuous coefficient maxima (>0.7) were in August 1994, 1997 and 2002, and a minimum was in August 1998 (<−0.7). In accordance with the change in the circulation, the JJA (June, July, and August) sea water temperature anomalies at surface and 65 m averaged over the central SCS area (10°S–13°N, 110°–118°E; the "cold filament index" by *Xie et al.* [2003]) show the anomalous cooling during the summers of El Niño development and warming during the summers of El Niño decay. The temperature variation at 65 m is related to the strength of the upwelling in the central basin induced by currents associated with the basin-wide circulation. The fact that the SST variation synchronizes with the sea water temperature below the mixed layer depth indicates that the ocean heat advection is the main factor, rather than the surface heat flux, for determining the SST changes during summers. This result concurs with previous findings that the ocean dynamics, horizontal advection in particular, plays a key part in the interannual variability in the SCS [*Qu et al.*, 2004]. Our result shows that, to the first order, heat advection by the basin circulation anomaly plays an essential role in modulating the surface water temperature variation in the central basin.

[6] Considering the 1997/98 El Niño the strongest event in the 20th Century, one would have expected the strongest ocean circulation to be in the summer of 1997 and the weakest in the summer of 1998 among the three El Niño events if the El Niño was the dominant forcing for the circulation variability in the SCS. However, inspection of Figure 1b reveals that the amplitude of the dipole mode in 1997 was weaker than those in 1994 and 2002. Factors other than the strength of the El Niño may have caused this. As noted by *McPhaden* [2004], the SSTA (SST anomaly) patterns in the Pacific during the summers of 1994 and 2002 exhibited great similarity, but were different from the pattern in 1997. In both 1994 and 2002, the tropical Pacific Ocean was characterized by a SSTA tripole, with positive anomaly around the date line and negative anomalies in the western and eastern ends of the Pacific. In addition, the developing positive Indian Ocean Dipole Mode phenomenon during the summers of 1994 and 1997, which were characterized by the unusual SST cooling in the southeastern tropical Indian Ocean, might also cast impacts on the SCS. Since the SCS dipole mode is most evident in particular years as mentioned above, it is important to understand the spatial structure of the remote forcing in modifying the local wind driving the basin circulation in these years.

## 3. Anomalous Atmospheric Conditions During the Summers of 1994, 1997, and 2002

[7] To gain a dynamic insight, spatial patterns of precipitation and surface wind anomalies over the Indo-Pacific region for 1994, 1997 and 2002 are examined in Figures 2a–2c. The focus is on the feature of the monsoon circulation in July when the seasonal wind over the SCS basin is mostly strong.

[8] In both 1994 and 2002 (Figures 2a and 2c), potent westerly/southwesterly wind anomalies dominated over the SCS between 6°N and 18°N. In contrast, westerly wind anomalies in 1997 were moderate and appeared only in a narrow latitudinal band in the central SCS (Figure 2b). The band of the zonal flow anomalies over the central SCS region between 6°N and 18°N belongs to the western North Pacific summer monsoon (WNPSM) circulation, which is a Gill-type [*Gill*, 1980] Rossby wave response of the atmosphere to the convective heat source in the Philippine Sea. It is discernible in all three figures that an elongated cyclonic circulation with easterlies from the subtropical western Pacific goes to the southern part of China, then westerly in the SCS and finally the Philippine Sea. The elongated circulation, centered at 20°N, characterizes a strong WNPSM [*Wang et al.*, 2001]. Table 1 compares the magnitude of the WNPSM among summers of these three events. The monsoon magnitude is quantified as the difference of 850-hPa westerlies between regions of (5°–15°N, 100°–130°E) and (20°–30°N, 110°–140°E) [*Wang and Fan*, 1999]. Strong WNPSMs are to be occurring in the developing years of El Niño while weak WNPSMs in El Niño's decaying years [*Wang et al.*, 2001]. Clearly, this WNPSM circulation was much stronger and better orga-

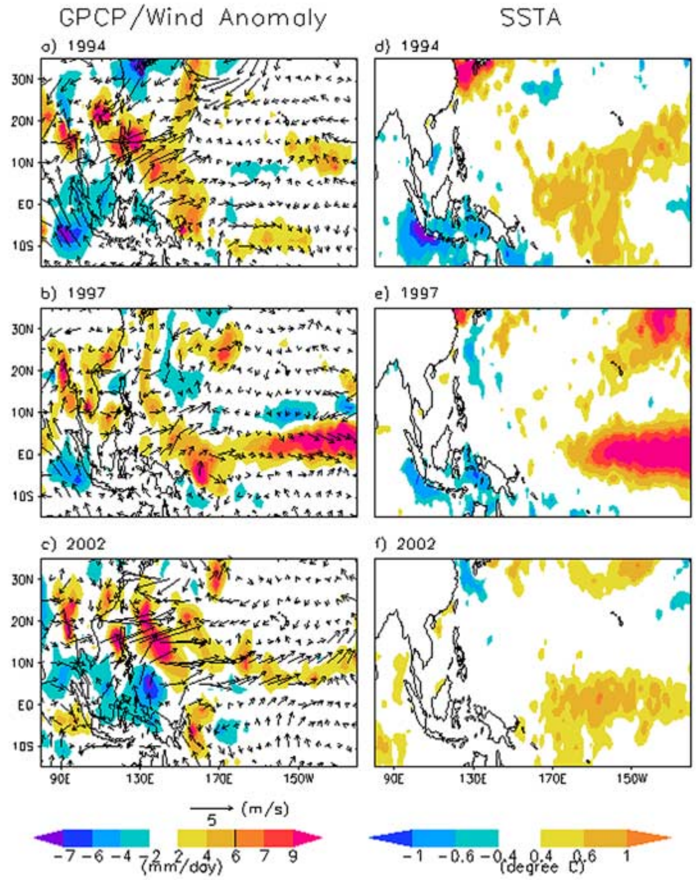


**Figure 2.** (a)–(c) July averages of precipitation anomalies (shading) overlaid with surface wind anomalies (vector) in 1994, 1997, and 2002. (d)–(f) SSTAs from HadISST for the same period.

nized, revealed as the stronger westerly wind anomalies, in 1994 and 2002 than in 1997 (Figures 2a–2c; Table 1). The intensified SCS circulations in the summers of 1994 and 2002 should have been a direct consequence of the excessive monsoon forcing during those times.

[9] Links between the strong WNPSM circulations of 1994 and 2002 and their unique SSTA patterns in the Pacific need further exploration. Figures 2d–2f show the SSTAs in parallel to Figures 2a–2c. In 1997 (Figure 2e), the tropical Pacific SSTA pattern was a dipole structure with the warming ($\sim$1.7°C) mostly located to the east of the date line. In 1994 and 2002 (Figures 2d and 2f), the tropical Pacific had a mild warming ($\sim$0.7) in the central, and negative SSTAs in the western and eastern ends. Recently, the type of El Niño with a tripole SSTA pattern has been named as ‘‘El Niño Modoki’’ (Pseudo-El Niño) [*Ashok et al.*, 2007]. The geographical difference in the warming implies that the El Niño Modoki (such as the 1994 and 2002 events) is characterized by a further westward shift of atmospheric low-level convergence in the western Pacific compared to the canonical El Niño (such as the 1997 event). This is evidenced in Figures 2a–2c: a much heavier wet zone, revealed as positive precipitation anomalies, expands from the northern SCS to the Philippine Sea and then extends to the SPCZ (South Pacific Convergence Zone) in 1994 and 2002, but less heavy in 1997. The enhanced wet convective precipitation over the Philippine Sea drove the substantially intensified monsoon circulations in 1994 and 2002. Also seen in the figures are dry zones, revealed as negative precipitation anomalies, over the tropical region between 100°–130°E during 1994 and 2002. The dry zone region indicates that the normal convections over the tropical area were suppressed. The north-south dipole of the wet convection updrafts and dry downdrafts would enhance the cross-equatorial flow for the WNPSM reinforcement in 1994 and 2002.

[10] In the southeastern tropical Indian Ocean (SETIO), the developing positive Indian Ocean Dipole Mode (IODM) phenomenon during the summers of 1994 and 1997 was characterized by a significant cooling and upwelling-favorable alongshore wind anomalies along the coast of Sumatra (Figures 2a, 2b, 2d, and 2e). Westerly wind anomalies prevailing over the SCS are linked with the cross-equatorial southeasterly flows west of Sumatra [*Wang et al.*, 2001]; in both 1994 and 1997, the southeasterly trades in SETIO

**Table 1.** June-July-August Averaged WNPSM Indices Before and After 1994–1995, 1997–1998, and 2002–2003 El Niño Events[a]

| | 1994 | 1995 | 1997 | 1998 | 2002 | 2003 |
|---|---|---|---|---|---|---|
| WNPMI | 2.53 | −3.09 | 1.44 | −6.46 | 2.06 | −1.61 |

[a]The WNPSM index (WNPMI) was defined as the difference of 850 hPa zonal wind anomalies between regions of (5°–15°N, 100°–130°E) and (20°–30°N, 100°–140°E) as by *Wang and Fan* [1999].

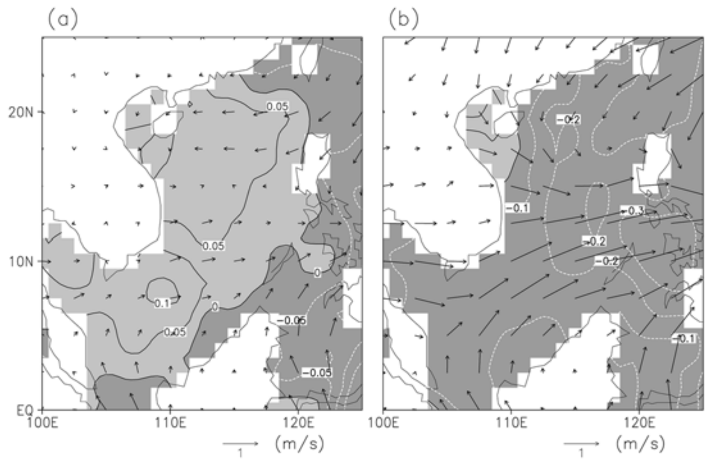


**Figure 3.** The June-July-August averaged surface wind and SSTAs derived by regression on the time series of (a) Nino-3 index and (b) EMI index. SSTA is shown in shading as negative anomaly is marked with dark grey and positive anomaly with light grey. Wind is depicted with vectors.

were strengthened and extended across the equator. Nevertheless, an enhancement in the westerly component of the summer monsoon flow extending from the Bay of Bengal eastward across the north-central Philippines appeared in 1994 (Figure 2a). This feature was weak in 1997 (Figure 2b). *Behera et al.* [1999] found that in the summer of 1994, strong convection in the northern SCS and Philippine Sea and the other ascending regions over India and the central Indian Ocean generated strong descending motions over the SETIO region (revealed as the intense negative precipitation anomalies). This regional descending implies diabatic cooling; a weak anomalous anticyclone over the South Indian Ocean was excited as the local atmosphere responded to the anomalous diabatic cooling [*Wang et al.*, 2003], and the cross-equatorial southeasterly flow off Sumatra was intensified. This enhancement was weaker in the 1997 El Niño, while the convections over East Asia were noted as less strong compared to that of the summer of 1994, therefore the induced diabatic cooling in the SETIO was limited (Figure 2e).

[11] It would be interesting to examine the condition during the 1987 El Niño, which was not under the influence of IODM and could be viewed as a pure El Niño. In the summer of 1987, the southerly anomaly was the dominant flow pattern in the SCS (figure not shown). A westerly anomaly as seen in 1994 and 2002 was not evident. Presumably, the second SSHA mode that is triggered by the strong westerly anomaly would not be as evident as in 1994 and 2002, and might be even weaker than in 1997.

## 4. Regressed Wind Field on El Niño and El Niño Modoki

[12] In this section, an attempt is made to estimate the local wind and SST fields in the SCS during summers with El Niño and El Niño Modoki conditions using regression analysis. Figures 3a and 3b show the JJA wind and SSTA patterns derived by the regression analysis on both the Nino-3 index and EMI (El Niño Modoki Index) for the period 1979–2003. Nino-3 index is a well known ENSO index defined by the SSTAs averaged over the eastern Pacific region of (5°S–5°N, 150°–90°W). EMI is defined [*Ashok et al.*, 2007] as

$$EMI = [SSTA]a - 0.5 * [SSTA]b - 0.5 * [SSTA]c,$$

where region *a* is over (165°E–140°W, 10°S–10°N), *b*: (110°W–70°W, 15°S–5°N), and *c*: (125°E–145°E,10°S–20°N). According to *Ashok et al.* [2007], the spatial patterns of the first two leading modes of the tropical Pacific SSTA resemble, respectively, with the canonical El Niño and the El Niño Modoki; and the correlations between PC (Principle Component) 1 and Nino-3 index as well as PC 2 and EMI are high. Since the correlation between the Nino-3 index and EMI is low (r = 0.13), it is therefore appropriate to use these two indices as independent predictors for the regression analysis [*Weng et al.*, 2007].

[13] The result reveals that the El Niño Modoki has a much stronger impact on the SCS. During a positive EMI phase, the regression map marks a band of potent westerly/southwesterly flow anomalies over the central SCS region between 6°N and 18°N, with the maximum wind over the deep basin (Figure 3b). The strong zonal wind jet divides the SCS with positive curl to the north and west, and negative curl to the south and east. The Ekman pumping/sucking by the anomalous wind curl geographically coincides with the oceanic SSH anomaly dipole and thus contributes to the formation of the two-gyre circulation in the basin. The result of the regressed SST pattern (shadings in Figure 3) confirms the tendency of strong cooling in the central SCS during the summer in El Niño Modoki conditions.

## 5. Summary and Discussions

[14] Previous numerical model simulations indicate that wind stress and its curl field are important factors in driving the SCS circulation [*Metzger and Hurlburt*, 1996; *Wu et al.*, 1998]; however, there was little discussion was on how large-scale atmospheric conditions affect the local wind field. This study has documented the variations of the SCS surface circulation during 1993 to 2002 while linking

the behavior to the WNPSM system during the El Niño development. Empirical analyses have been carried out to understand the El Niño and El Niño Modoki forcing, as well as the tropical eastern Indian Ocean SST cooling forcing, affect the regional-scale monsoon behavior.

[15] The reversal in the strength of the surface circulation during the summers before and after the mature phase of ENSO is a direct consequence of the magnitude change of the Southeast Asian monsoon system associated with the ENSO turnabout. During the summers of the developing phase, the El Niño Modoki inserts larger impact on the wind and current fields in the SCS even though the warming in the equatorial Pacific is mild. The essential underlying mechanism is related to the low-level convergence of the atmosphere, occurring primarily west of the maximum SSTA in the western Pacific. The maximum SSTAs during the El Niño Modoki events are not located in the eastern Pacific, but in the central Pacific around dateline. During the 1994 and 2002 El Niño Modoki summers, the low-level convergence of the atmosphere was located further to the west so that the wet convection over the Philippine Sea was greatly enhanced, leading to strong WNPSMs with potent westerly wind anomalies over the SCS. At the mean time, the significant cooling off Sumatra in the SETIO had a better coupling with the strong monsoon convection to enhance the cross-equatorial southeasterly flows west of Sumatra in the summer of 1994. The coupling was relatively weak in the summer of 1997, while the monsoon convections over East Asia were noted less strong compared to that of the summer of 1997.

[16] Our result shows that heat advection by the basin circulation anomaly plays an essential role in modulating the SST variation, especially in the central SCS basin. The temperature variation below the mixed layer in sync with the SST change gives supporting evidence for our statement. Recently, many findings report that mesoscale eddies emanated from the Luzon Strait would intermittently modulate the hydrography and the circulation in the northern SCS basin [e.g., *Centurioni et al.*, 2004; *Wu and Chiang*, 2007]. These eddies are occasionally generated when the Kuroshio intrudes into the Luzon Strait. The Kuroshio-associated mesoscale eddies exhibit interannual variability related to ENSO [*Wu and Chiang*, 2007], and their impact on modifying the circulation and surface layer temperature in the SCS deserves to be examined in more detail. The occurrence of the eddies under the canonical El Niño and El Niño Modoki conditions also requires further research.

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