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Interannual variability of the South China Sea throughflow inferred from wind data and an ocean data assimilation product

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[1] The Luzon Strait transport, as an index for the South China Sea throughflow, has attracted much attention recently. In this study the interannual variability of Luzon Strait transport is examined, using the Island Rule and results from ocean data assimilation. Transport variability obtained from these two approaches is consistent with each other. Assessment of contribution from each integral segment involved in the Island Rule indicates that wind stress in the western and central equatorial Pacific is the key factor regulating the interannual variability of the Luzon Strait transport, whereas the effect of local wind stress in the vicinity of the Luzon Strait is secondary. Analysis also shows that when the westerly (easterly) wind anomalies in the tropical Pacific break out, the Luzon Strait transport increases (decreases), associated with the variations in the North Equatorial Current during El Niño (La Niña) events.
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1. Introduction

[2] The South China Sea (SCS), the largest marginal sea in Southeast Asian waters, connects to the Pacific Ocean in northeast through the Luzon Strait. In the south, it connects to the Sulu, Sulawesi, Java, and Indonesian Seas through the Mindoro and Kalimantan Straits.

[3] *Wyrtki* [1961] first pointed out the intrusion of North Pacific water in winter through the Luzon Strait. Analysis of historical hydrographic data further revealed that the Philippine Sea water enters the SCS along the continental margin south of China between October and the following January [*Shaw*, 1991]. The pressure head created by the pileup of water during the northeast monsoon season may affect the Luzon Strait transport (hereafter LST [*Qu*, 2000]). Numerical experiments of *Metzger and Hurlburt* [1996] showed a cyclonic flow around the Philippines, with water entering the SCS through the Luzon Strait and leaving it to the Sulu Sea through the Mindoro Strait. The strength of this intrusion contains clear semiannual signals, stronger in winter/summer and weaker in spring/fall. Applying *Godfrey*'s [1989] Island Rule to the Luzon Strait yielded an annual mean LST estimate (from the Pacific into SCS) of approximately 4.2 Sv (1 Sv = $10^6 m^3/s$ [*Qu et al.*, 2000]). Later observations and modeling studies have arrived at a range of estimates from 0.5 to 10 Sv [e.g., *Metzger and Hurlburt*, 1996; *Qu*, 2000; *Fang et al.*, 2003].

[4] Most previous studies based on numerical models or hydrographic data emphasized the LST mean transport and its seasonal variability. The interannual variability of LST was examined only recently by *Qu et al.* [2004], and whereby the LST was revealed as a key process conveying the impact of El Niño-Southern Oscillation (ENSO) to the SCS. Further analyzing wind data and results from a high-resolution general circulation model, *Qu et al.* [2005] also revealed that the interannual variability of LST can be conveyed to the Indonesian Seas and thus has a notable impact on heat transport of the Indonesian Throughflow. However, the limited duration of the simulation, from January 1982 to December 1998, may obstruct the statistic significance. The same limitation also exists in the work by *Qu et al.* [2004].

[5] In this study we use an ocean data assimilation product and the Island Rule to investigate the interannual variability of LST over the past 47 years. Since the SCS throughflow is primarily controlled by the base-scale wind in the Pacific [*Qu et al.*, 2005], our analysis is focused on how wind stress in different parts of the equatorial Pacific contributes to the interannual variability of LST. This note demonstrates a clearly defined connection between the large-scale wind stress anomalies, variations in LST, and North Equatorial Current (NEC). Our results provide additional evidence that the throughflow in the SCS is dynamically related to the Kuroshio east of Luzon, as well as the bifurcation of the NEC.

2. Data and Methods

[6] This study is based on the Simple Ocean Data Assimilation (SODA) package (SODA_1.4.2 and SODA_1.4.3 versions (J. A. Carton and B. S. Giese, SODA: A reanalysis ocean climate, submitted to *Journal of Geophysical Research*, 2006)), which contains the monthly mean fields of temperature, salinity, and velocity. The product provides two data sets using different wind forcing. The first spans the 44-year period from 1958–2001, which complements the European Center for Medium Range Weather Forecast ERA-40 atmospheric reanalysis. The second spans the period of QuikSCAT from 2000–2004. The data domain covers almost the global ocean except south of 75.25°S. The model output has a horizontal resolution of 0.5° in both longitude and latitude and has 40 levels in vertical with

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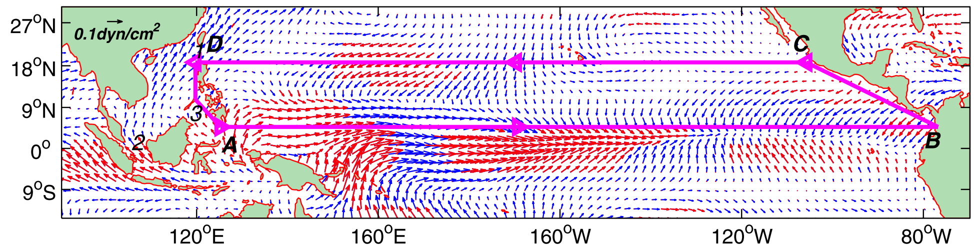

Figure 1. Path *ABCD* used in the Island Rule calculation and the composite wind stress anomaly during abnormal events, which were defined when the LST anomaly calculated from the Island Rule was larger than 1.5 Sv and the Nino3.4 index was above 0.4°C. The red vectors denote over 95% significance by t-test. Unit: dyn/cm^2. The numbers 1, 2, and 3 indicate Luzon, Kalimantan and Mindoro Straits, respectively.

spacing increasing from 10 m at surface to 100–250 m at 1000 m or below. In this note, we use the velocity and wind stress in both the first analysis from January 1958 to December 1999 and the second analysis from January 2000 to December 2004 of SODA. This version of product has a topography more refine than the Beta 7 version, and Kalimantan strait shallower than 50 m connected SCS and Java Sea is open now. The current index of NEC inferred from sea level observations [*Wyrtki*, 1974] was used to validate the model results. Band-pass filtering was applied in order to get the interannual variability of 2–7.5 yr signals for most of the time series discussed below.

[7] Based on a steady and frictionless Sverdrup theory [*Godfrey*, 1989], LST can be calculated from the line integral of wind stress projection along the closed path *ABCD* (Figure 1), LST = $T_0 = \oint_{ABCD} \tau^{(l)} dl/[\rho_0(f_D - f_A)]$, where, $\tau^{(l)}$ is the wind stress projection along path *ABCD*. The *AB* and *CD* are at 4.75°N and 18.75°N. f_A, f_D are the Coriolis parameters at the southernmost (*AB*) and northernmost (*CD*) segments of the integral path, respectively. ρ_0 = 1035 kg/m3 is the mean density of sea water. According to the Island Rule, LST is controlled by the line integral of wind stress. However, the Island Rule is valid for a steady state ocean and ideal fluid only. For a relatively narrow channel like the Luzon Strait, friction and other dynamic effects are not negligible. Local factors, such as the gap width and bottom topography, certainly affect the mean LST and its variability; however, our study here is focused on the dynamical role of wind stress in regulating the LST on interannual time scale.

3. Results

3.1. Mean LST

[8] The climatological mean transport calculated from the Island Rule, with the western segment of the integral path following the West Philippine coast rather than the East Vietnam coast, is about 12.4 Sv. Because of the friction and bottom topography influence, the LST is much reduced, falling well between 2 and 4.2 Sv, a range which is thought to be reasonable [*Metzger and Hurlburt*, 1996; *Qu et al.*, 2000]. Taking SODA zonal velocity integration from surface to bottom (near about 3000 m) along120.25°E from 17.25° to 23.25°N yields a LST estimate of about 1.5 Sv.

3.2. Interannual Variability

[9] Both high frequency and interannual signals are evident in the time series of LST calculated from the Island Rule and SODA (Figure 2, top and middle). The band-pass filtered LST calculated from the Island Rule and ocean model has a root-mean-square (RMS hereafter) value of 2.3 and 0.4 respectively, and the correlation coefficient (with zero lag) is 0.32 (over 90% t-test). Both of them are consistent in most events, although the amplitude obtained from the Island Rule without considering the friction effect is over-estimated. Many peaks in the two time series of LST occur almost simultaneously, except several events, namely 1965/66, 1979/80, 1981, 1982–1984, 1992–1994, 1998/99. The difference could be due to the approximations made use in the Island Rule, such as the omission of friction and nonlinear effects.

[10] The contribution from wind stress along each segment of the integral path is of interest to examine. As an example, Figure 2 (bottom) shows the wind stress integrals along segment *AB* and *CD*. Note that the factor $f_D - f_A$ is

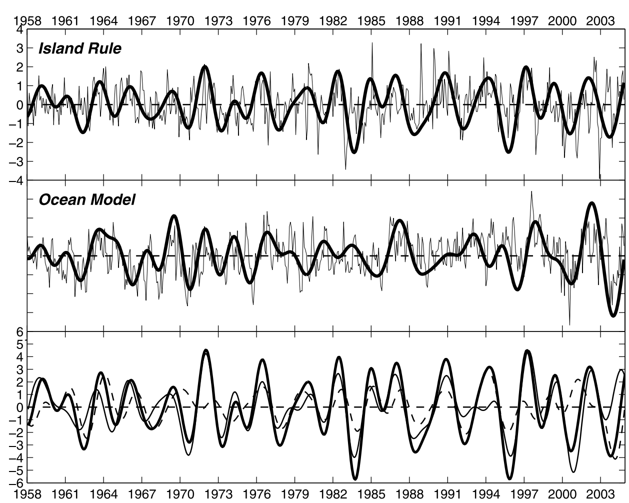

Figure 2. Normalized LST anomaly (in Sv) calculated from (top) the Island Rule and (middle) the ocean model assessment with vertical integration at the Luzon Strait and (bottom) time series of LST (bold-solid line) and its components along two major segments calculated from the Island Rule with 2–7.5 yr periods (Figure 2, bottom, thin-solid line for the southern segment, dashed line for the northern segment) from 1958 to 2004. In Figure 2 (top and middle), light solid lines are original time series and heavy solid lines after filtering by band-pass to extract the variability banded 2–7.5 yr.

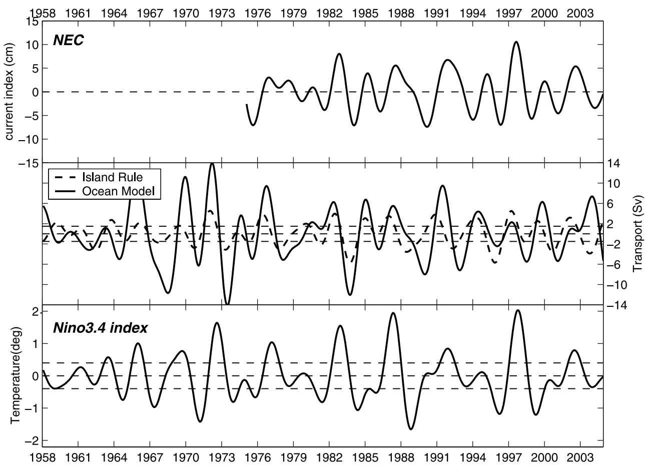

Figure 3. (top) The NEC index inferred from sea level observations (http://ilikai.soest.hawaii.edu/uhslc/islp.html); (middle) the NEC transport anomaly diagnosed from SODA (solid line) and LST anomaly calculated from the Island Rule (dashed line); (bottom) the Nino3.4 index. All data were band-pass filtered for extracting 2–7.5 yr period signals. Note that the selected years for composite analysis are defined in Figure 3 (middle and bottom), see the text for details.

fixed in these calculations. Compared with segments *BC* and *DA* (figure not included), contributions along segments *AB* and *CD* are much more important to variations of the LST. The RMS of integral along segment *AB* is 1.78, and it drops slightly to 1.23 along segment *CD*. The correlation coefficient between wind stress integral along segment *AB* and LST is 0.82, and that between the wind stress integral along segment *CD* and LST is 0.63. Further inspection of the relative contribution to the LST transport indicates that wind stress integral over the equatorial Pacific segment (*AB*) is the most important factor in general, but wind stress integral over the *CD* segment also has an important effect on the variability of LST, especially during the 1961/1964, 1967/68, 1993/94, and 2003/04 events. What is the significance of variability along *AB* and *CD* during El Niño events? This will be discussed in next section.

3.3. Linkage to ENSO

[11] The aforementioned results suggest that there is a close connection between the interannual variability of LST and ENSO. This connection is consistent with a previous study based on results from an ocean general circulation model [*Qu et al.*, 2004]. The internal oceanic connection on the interannual timescales will be addressed in this section.

[12] The NEC index inferred from sea level observations [*Wyrtki*, 1974] and the NEC transport from the SODA data (across a fixed section along 129.25°E at 7.25°N–17.75°N in upper 465 m, similar to *Qu and Lukas* [2003]) are shown in Figure 3. Both seem to be correlated to the Nino3.4 index (sea surface temperature averaging in 5°N–5°S, 120°–170°W). The signals from these time series oscillate at a coherent rhythm to a certain extent. Table 1 gives the lead or lag correlations among the NEC index, NEC transport, LST transport, and Nino3.4 index anomalies. The NEC index anomaly lags the NEC and LST transport anomalies by about 4 and 6 months, but is consistent with the Nino3.4 index anomaly with a maximum zero lag correlation of 0.67. The NEC transport anomaly lags the LST transport anomaly by 3 months but leads the Nino3.4 index by 4 months. The LST transport anomaly leads the Nino3.4 index by 6 months. The relationship among the LST, NEC and Nino3.4 index is consistent with each other during most events.

[13] In order to produce a composite event, we define the abnormal events according to the criterion that the LST anomaly calculated from the Island Rule is larger than 1.5 Sv and the Nino3.4 index is above 0.4°C. Accordingly, periods 1963, 1965/66, 1972, 1976/77, 1982, 1986/87, 1991, 1997, and 2002, were chosen as abnormal events (Figure 3). Values exceeding thresholds of ±0.4°C for Niño3.4 index are interpreted as the indication of ENSO events [*Trenberth*, 1997]. The composite wind stress is shown in Figure 1 (note that the red vectors pass the t-test at 95% significance level). We can see that the westerly wind bursts in the equatorial Pacific is attributed to the positive transport anomaly along segment *AB*. The composite transport anomaly along the equatorial Pacific also passes the t-test of 95% significance (not shown), indicative of a possibly important contribution. Such westerly bursts resemble the well-known pattern associated with El Niño. We therefore suggest that the westerly wind bursts in the equatorial Pacific is a key factor influencing the LST during El Niño events.

[14] Combining the composite wind stress anomalies (Figure 1) with the SODA-derived streamline anomalies (vertical averaged in upper 465 m, Figure 4) during the above defined abnormal events, we show that the intensification in westerly wind stress can lead to a stronger NEC, with the NEC bifurcation shifting northward [*Qu and Lukas*, 2003; *Kim et al.*, 2004]. This also corresponds to a stronger Mindanao Dome and a weaker Kuroshio transport at its beginning east of Luzon [*Masumoto and Yamagata*, 1991; *Tozuka et al.*, 2003]. When the Kuroshio transport weakens, the meridional advection of potential vorticity is not strong enough to overpower the β effect, and so the boundary current can switch into the "gap penetrating" regime easily. This behavior has been named as "teapot effect" [*Sheremet*, 2001]. Thus, the abnormal events provide a favorable condition for the Pacific waters to penetrate into the SCS through the Luzon Strait during El Niño years [*Qu et al.*, 2004; *Yaremchuk and Qu*, 2004]. The situation during La Niña is reversed, yielding a weaker LST. Most of the water entering the SCS will circulate along the western boundary of the SCS and exits through the Kalimantan Strait. One part of this outflow may return to the Pacific

Table 1. Correlation Coefficient (Lag/Lead in Month) Among NEC Current Index, NEC Transport, LST Transport and Nino3.4 Index[a]

	NEC Current Index	NEC Transport	LST Transport	Nino3.4 Index
NEC current index	-	0.59(4)	0.62(6)	0.67(0)
NEC transport		-	0.54(3)	0.42(−4)
LST transport			-	0.62(−6)
Nino3.4 index				-

[a]Positive/negative denotes the former lags/leads the latter.

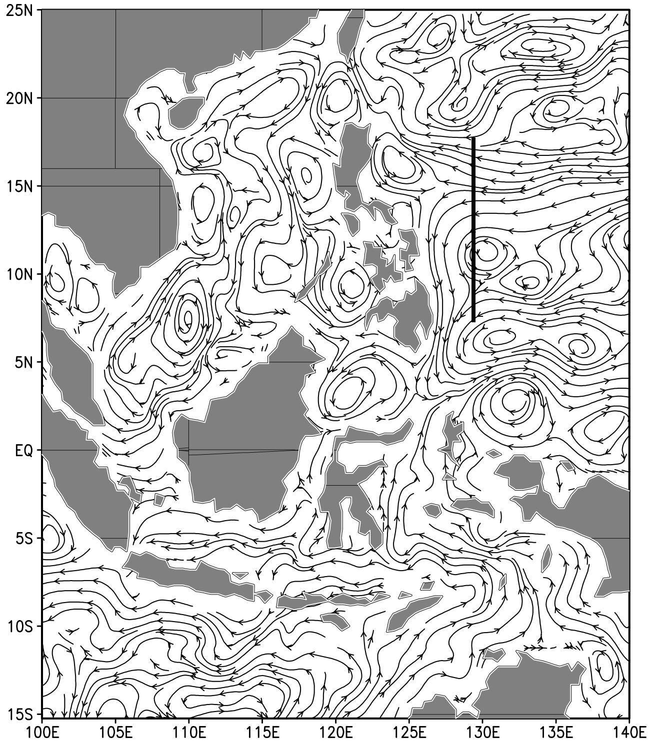

Figure 4. A composite map of anomalous streamlines averaged over the upper 465 m based on SODA during the selected years, same as in Figure 1. The NEC transport is computed by integrating the velocity across the red section (129.25°E, 7.25°N–17.75°N).

through the Makassar Strait in the upper layer, and thus has an important impact on the heat transport of Indonesian Throughflow [*Qu et al.*, 2005].

4. Summary

[15] The interannual variability of the LST can be calculated from the Island Rule. Although the amplitude inferred from the Island Rule is higher than that from the SODA outputs, presumably due to the omission of friction and topographic effect in the Island Rule, variabilities identified from these two approaches in most cases are in phase during the period of 1958–2004. The application of the Island Rule and the composite analysis demonstrate that wind stress over the southern segment over the equatorial Pacific is the key factor regulating the interannual variability of the LST. The composite analysis also reveals that the westerly wind bursts can lead to a stronger NEC and a weaker Kuroshio transport to the east of the Philippines, thus providing a favorable condition for the Philippine Sea water to enter the SCS through the Luzon Strait.

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