

## **Interplay between the Indonesian Throughflow and the Luzon Strait**

### **Throughflow**

Liu Qinyan

Huang Ruixin

Wang Dongxiao

Xie Qiang

Huang Qizhou

---

Corresponding author:

Dr. Qinyan Liu

Key Laboratory of Tropical Marine Environmental Dynamics

South China Sea Institute of Oceanology, Chinese Academy of Sciences

164 West Xingang Road, Guangzhou 510301, China

Phone: 020-89023199; Fax: 020-84451672

E-mail: [qyliu66@scsio.ac.cn](mailto:qyliu66@scsio.ac.cn)

# Interplay between the Indonesian Throughflow and the Luzon Strait

## Throughflow

*Liu Qinyan<sup>①\*</sup>, Huang Ruixin<sup>②</sup>, Wang Dongxiao<sup>②</sup>, Xie Qiang<sup>②</sup>, Huang Qizhou<sup>②</sup>*

*(<sup>①</sup>Key Laboratory of Tropical Marine Environmental Dynamics, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, 510301; <sup>②</sup>Woods Hole Oceanographic Institution, Woods Hole, MA02543, USA; \*E-mail: qyliu66@scsio.ac.cn)*

**Abstract:** Analysis based on the “Island Rule” and ocean assimilation dataset shows that the interannual variability of the Indonesian Throughflow and the Luzon Strait (South China Sea) Throughflow is out of phase. Wind anomaly in the equatorial Pacific plays an important role in setting up this phase relation. During El Niño events, the westerly wind bursts intensify the Northern Equator Current and induce a northward shift of its bifurcation point. As a result, the partition of volume transport between the Kuroshio and the Mindanao Current is changed, with the Kuroshio transport decreased and the Mindanao Current increased. The undershooting/overshooting phenomena occur at the Luzon Strait and the Sulawesi-Mindanao passage, caused by variability of these two currents. Water transport from the Pacific to the South China Sea increases with the Kuroshio transport decreased, and transport from the Pacific to the Indian Ocean decreases with the Mindanao Current transport increased. Therefore, the interannual variability of the Indonesian Throughflow and the Luzon Strait Throughflow is out of phase.

**Key words:** “Island Rule”; Indonesian throughflow; Luzon Strait Throughflow; undershooting/overshooting

The Luzon Strait Throughflow (LST) carries the El Niño and Southern Oscillation (ENSO) signals into the South China Sea (SCS); thus, it works as the ocean bridge and plays an important role in regulating the circulation and heat budget in the SCS<sup>[1]</sup>. Of course, change in local wind forcing in the SCS, connected to ENSO through the atmospheric bridge, may be another important player in regulating the interannual variability of circulation in the SCS<sup>[2]</sup>. The Indonesian Throughflow (ITF) is a critically important part of the global “conveyor belt” for the thermohaline circulation in world oceans<sup>[3]</sup>. After the Pacific water enters the SCS, one part of it returns to the Pacific through the Kalimantan and the Makassar straits, and thus can effect the variability of the ITF<sup>[4-8]</sup>. The Sunda Shelf and the Java Sea may be a major passage through which the SCS plays certain role in the water exchange between the Pacific and the Indian Ocean<sup>[4]</sup>. Lebedev et al.<sup>[5]</sup> pointed out that, after the Pacific water entering through the Luzon Strait, the outflows from the SCS make a considerable contribution to the net transport of the ITF. In fact, this contribution varies from 35% in summer to 85% in boreal winter. Using a variable-grid global ocean model, Fang et al.<sup>[6]</sup> estimated the climatologic mean inter-basin water transport between SCS and its adjacent oceans and concluded that SCS can contribute about 1/4 of the ITF heat transport. The SCS circulation also

plays an important role in regulating the ITF on climatological time scales<sup>[4-6]</sup>. Using results from an Ocean General Circulation Model (OGCM), Fang et al.<sup>[7]</sup> found that there is one branch of the water exchange between the Pacific and Indian Ocean in the SCS in boreal winter, and the existence of this branch can be validated by the buoy data collected through satellites. Furthermore, Wang et al.<sup>1</sup> confirmed that LST could be thought as one branch of the Generalized ITF (GITF) on interannual time scale. Using results from a high resolution GCM, Qu et al.<sup>[8]</sup> argued that after entering the SCS water from the Pacific Ocean flows out of the SCS through the Kalimantan Strait, and returns to the Pacific through the Makassar Strait as a surface current. This current loop plays an important in the interannual variability of the ITF heat transport. The out-of-phase relation between the LST volume transport (LSTT) and the ITF volume transport (ITFT) is discernible in their figure, but the length of their simulation is 17 years only, thus it is not long enough for the study of the interannual variability. Furthermore, they did not explore the mechanism responsible for such a phase relation.

During El Niño events, the transport from the Pacific to the SCS through the Luzon Strait increases<sup>[11][9]</sup>, and that from the Pacific to the Indian Ocean decreases<sup>[10-11]</sup>. The increasing/decreasing of the LSTT can be interpreted as the southward/northward shifting of the Northern Equator Current (NEC) bifurcation point<sup>[12]</sup>. During El Niño, NEC intensifies<sup>[13][14]</sup> and the bifurcation point of the NEC shifts northward<sup>[12]</sup>. As a result, the Mindanao Current (MC) intensifies, the Kuroshio (KC) weakens<sup>[15][16]</sup>, and thus more Pacific water enters the SCS through the Luzon Strait<sup>[11][17]</sup>. Results from previous studies indicate that the decreasing of the ITFT is related to a decline of sea surface elevation difference between the Pacific and the Indian Ocean induced by the eastward migration of warm water in the western Pacific<sup>[10]</sup>. In addition, the variability of the ITFT also is closely connected to wind stress anomaly over the southern Pacific<sup>[18]</sup>. The situation in La Niña years is reversed.

As discussed above, SCS is a semi-closed basin, and it is a key domain connecting the Pacific and Indian Ocean. Therefore, it is very important to understand the interannual variability of LSTT and ITFT and the mechanisms responsible for the variability. Great efforts have been devoted to studying their variation, but some basic questions remain unanswered, such as the cause of the out-of-phase phenomenon between the ITFT and the LSTT, and the characteristics of atmosphere

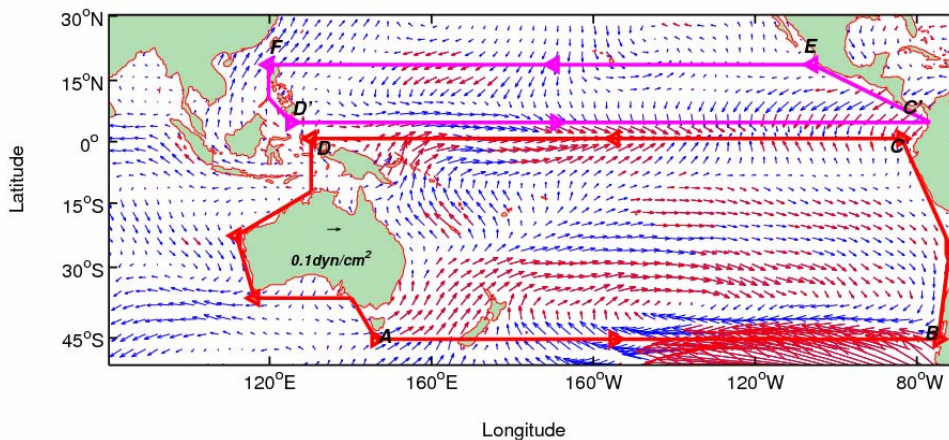
---

<sup>1</sup> Wang D X, Liu Q Y et al., Interannual variability of the South China Sea throughflow inferred from wind data and an ocean data assimilation product. *Geophys Res Lett*, accepted.

and ocean circulations associated with this out-of-phase phenomenon. The main goal of this note is to explore these topics, using the “Island Rule” and results from the oceanic data assimilation products.

## 1 Data and Methods

In this note, we use the latest Simple Ocean Data Assimilation (SODA) dataset, an assimilation products provided by the University of the Maryland, USA<sup>2</sup>, which contains two sub-datasets of the OGCM results, using different wind forcing<sup>3</sup>. These include the ocean current and wind stress supported by first dataset from 1958 to 1999 and second dataset from 2000 to 2004, and the total length of 44 years. The model region covers the globe zonally and meridionally from 75.25°S to 89.25° N. The model has a horizontal resolution of 0.5°x0.5° and is divided into 40 levels vertically with the 10m vertical spacing at surface and increasing to 100-250 m at depth below 1000m. This new version of product has topography more realistic than the Beta 7 version. In particular, the Kalimantan Strait is now opened. In this note, our analysis is based on the ocean circulation and wind stress supported by the SODA dataset. The interannual variability of the ITFT and LSTT can be described very well by the “Island Rule”<sup>[8][18][19-21]</sup>, which is formulated as the integration of the wind stress projection along the closed paths of *ABCD* and *D'CE* separately (Figure 1). Since stream function for the case with friction is approximately proportional to the stream function for the case without friction<sup>[20]</sup>, the friction influence on the interannual variability is not discussed in the following discussion.



<sup>2</sup> Carton J A, Giese B S. SODA: A reanalysis of ocean climate. Submitted to J Geophys Res-Oceans, 2006

<sup>3</sup> First dataset is the OGCM result forced by European Center for Medium Range Weather Forecasts (ECMWF) reanalysis winds from 1958 to 2001 (SODA\_1.4.2); Second dataset is the OGCM result forced by QuikSCAT scatterometer winds from 2000 to 2004 (SODA\_1.4.3).

Figure 1: The composite wind stress pattern during abnormal events and the integral path of the “Island Rule” (ABCD and D’C’EF). The corresponding latitude of AB, CD, D’C’ and EF is 45.25°S, 0.75°N, 4.75°N and 18.75°N. Red vectors denote data points above 95% significant level. Unit: dyn/cm<sup>2</sup>.

In this paper, band-pass filtering was applied to extract the interannual variability of 2~7.5yr signals from the time series anomaly after removing the climatology monthly mean.

## 2 Analyzes of the Results

High frequency and interannual signals are evident in the time series of ITFT and LSTT anomalies, estimated from the “Island Rule” and SODA dataset (integrated from the sea surface to bottom), Figure 2. The interannual variability of LSTT estimated by the “Island Rule” is consistent with that from SODA dataset (120.25°E, 17.25°N-21.75°N); the correlation coefficient with zero lag between them is 0.32, and the LSTT anomaly has a root-mean-square (RMS) value of 2.26 and 0.41 separately. The interannual variability of ITFT estimated from the “Island Rule” is also similar with the results obtained from SODA dataset (113.25°E, 8.25°S-25.25°S); the correlation coefficient with a zero lag is 0.59. The RMS of these two estimates of ITFT is 1.58 and 1.43 respectively. Results given by the “Island Rule” and the SODA dataset are comparable by the correlation (above 90% significant level.) and RMS analysis. The amplitudes of ITFT and LSTT obtained from the “Island Rule” are slightly larger than that inferred from the numerical model, and the difference is due to the omission of friction and topography when applying the “Island Rule”<sup>[21]</sup>. The correlation coefficient between ITFT and LSTT based on the “Island Rule” is -0.57 (it is -0.67 based on the SODA data); thus, the variability of ITFT on interannual time scale is out-of-phase with LSTT. That is to say, on interannual time scale LSTT decreases when ITFT increases, and *vice versa*. Therefore Qu et al’s<sup>[8]</sup> result is also true on the interannual time scale. The comparison between the “Island Rule” and SODA dataset shows that wind stress in the equatorial Pacific plays an important role in regulating the variability of LSTT and ITFT<sup>[18][19][20-21]</sup>.

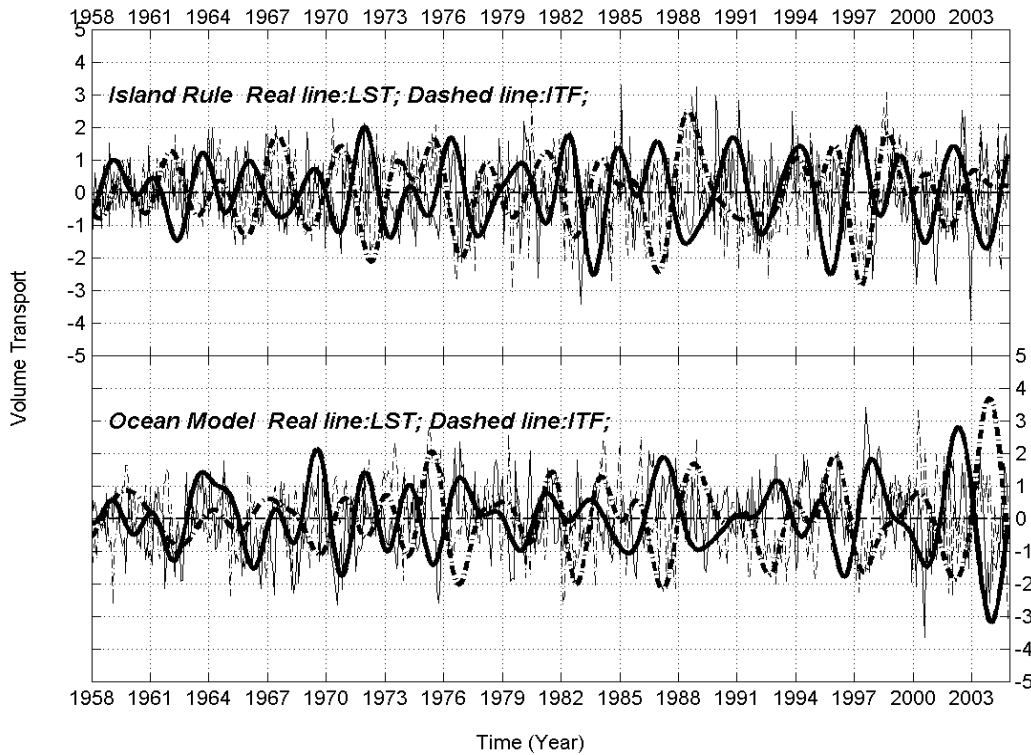


Figure 2: The normalized time series of ITFT and LSTT anomalies based on the “Island Rule” and results from SODA data. The thin solid lines are the original anomaly time series and the bold solid lines are the 2-7.5yr period band-pass filtering signals. The positive values denote the enhancement of volume transport.

### 3 The analysis of the mechanisms

#### 3.1 Change in the atmospheric wind stress

As discussed above, analysis based on the “Island Rule” and SODA dataset indicates that the interannual variability of ITF and LSTT is out of phase. Since the Pacific wind forcing plays an important role in regulating LSTT and ITFT<sup>[18][19][20-21]</sup>, what is the main cause of the interannual variability of these transports? In this section we will examine this issue by analyzing the contribution to the total volume transport for each segments of the integral path (ABCD can be divided into segment AB, BC, CD and DA, and D'CE'F can be divided into segment D'C', C'E, EF and FD').

Compared with the integrals along segments BC, DA and C'E, FD' (figures omitted), contributions along segments AB and CD (D'C' and EF) are much more important to variations of ITFT (LSTT) (Figure 3). The RMS of the integral along segment AB and CD is 1.03, 0.76 respectively. The zero-lag correlation coefficient between the integral along segment AB and ITFT is 0.88, and it is 0.85 between the integral along segment CD and ITFT. In general, wind stress change in the southern Pacific is very important to the variability of ITFT<sup>[18]</sup>; however, the role of wind stress in the equatorial Pacific cannot be neglected, as indicated by the correlation coefficient between the integral along segment CD and ITFT and the RMS of the integral along CD. The RMS along segment D'C' is 1.78, and it is 1.23 along segment EF, and the zero-lag correlation coefficient between them and LSTT is 0.82, 0.63 respectively. The RMS of the integral along segment D'C' and

the correlation coefficient with LSTT are both higher than those along segment EF, which imply that wind change along segment D'C' (that is, wind stress in the equatorial Pacific) is more important to the interannual variation of LSTT. Wind in the equatorial Pacific is very important to the interannual variability of ITFT and LSTT, as deduced from analysis of contributions along different integral paths (This can also be confirmed by the composite wind analysis during abnormal events in Figure 1).

The variations in ITFT and LSTT have a close connection with ENSO events (Figure 3). The correlation coefficient between Niño3.4 (averaging in box 5°N-5°S, 120°-170°W) SST indices<sup>4</sup> and ITFT(LSTT) based on the “Island Rule” and SODA data is -0.77(0.33), -0.62(0.45) respectively. During El Niño events ITFT decreases and LSTT increases, and it is consistent with the previous studies. We have made a collection of abnormal events to analyze the composite wind stress anomaly based on the simultaneously satisfactory of following three criteria: LSTT anomaly obtained from the Island Rule is higher than 1.5 Sv, and ITFT anomaly is lower than 1.5Sv, and the Niño3.4 index is above 0.4°C (Figure 1, the red vectors denote data points pass 95% confidence level t-test). During the abnormal events westerly wind bursts in the equatorial Pacific identifiable in the composite wind field are similar with the wind distributions during the El Niño years. Since segments D'C' and CD are very close, the integrals of wind projection along these two segments similar value, but of opposite signs; thus, their contributions to ITFT and LSTT are out of phase. As shown in Figure 3, wind stress change in the equatorial Pacific is the key factor for the interannual variability of the ITFT and LSTT. Combining Figures 1 and 3, it is readily seen that wind variation (mostly pass 95% confidence level t-test) in the equatorial Pacific is the main cause of the out-of-phase relation between ITFT and LSTT anomalies on the interannual time scale. The equatorial Pacific westerly wind bursts appear during El Niño events. As result of change in wind stress ITFT decreases<sup>[10]</sup> and LSTT increases<sup>[11][8]</sup>. The situation is reversed during La Niña.

---

<sup>4</sup>Data from [www.cpc.ncep.noaa.gov/data/indices](http://www.cpc.ncep.noaa.gov/data/indices)

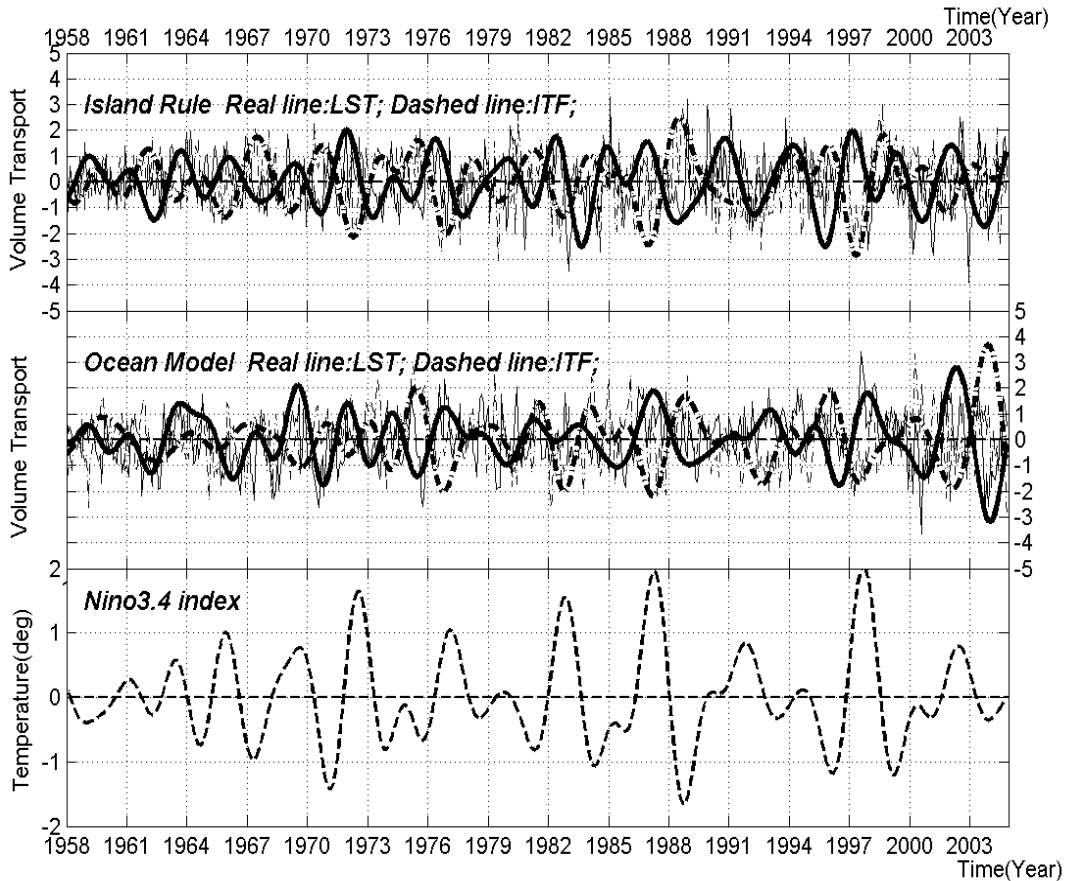


Figure 3: Variability of LST (Upper) and ITF (Middle) volume transport anomalies and the respective anomalies of line integrals along south and north segment based on the “Island Rule” (bold-solid line for the total transport, thin-solid line for the contribution due to integral along southern segment, dashed line for the integral along northern segment) and the Niño3.4 index anomaly (lower). The 2-7.5 yr period signals were extracted using band-pass filter.  $1\text{Sv} = 10^6\text{m}^3/\text{s}$ .

### 3.2 The undershooting/overshooting phenomena

As discussed above, wind stress variation in the equatorial Pacific is the main cause of the out-of-phase relation between anomalies of ITFT and LSTT on interannual time scale, and ITFT and LSTT are connected with ENSO events closely<sup>[11][10-11][22]</sup> (Figure1 and Figure3). How do wind stress changes affect the variation of ITFT and LSTT? How do the ocean circulation adjust when variation of these two transports are out-of-phase on the interannual time scale? In the following discussion, we will examine the adjustment in the ocean circulation, using indices for the equatorial Pacific current defined by Wyrki<sup>[13]</sup>, combined with the ocean dataset assimilation results.

It is well known that the variation of the NEC, North Equatorial Countercurrent (NECC) and South Equatorial Current (SEC) in the Pacific has a close connection with trade winds in the equatorial Pacific<sup>[13]</sup>. The time series of current indices anomaly of the equatorial Pacific inferred from the sea level height from Jan1975 to Dec2004 are given in Figure 4 (Positive values indicate westward transport of NEC and SEC and eastward transport of NECC)<sup>5</sup>. The zero-lag correlation coefficient between NEC indices and NECC indices is 0.74, and it is -0.48 between NEC indices and SEC indices (the sum of north and south of the equator). The zero-lag correlation coefficient

<sup>5</sup>Data from <http://ilikai.soest.hawaii.edu/uhsic/islp.html>



between NECC and SEC indices (the sum of north and south of the equator) can exceed  $-0.82$ . The positive winds curl anomaly in the northwestern Pacific enhances the westward NEC anomaly, as predicted by Sverdrup dynamics<sup>[14]</sup>, and this is accompanied by the increase of the eastward NECC and weakening of the westward SEC during El Niño. The correlation coefficient between LSTT based on the “Island Rule” and NEC indices with a zero-lag is 0.16, and the maximum coefficient is 0.62 when LSTT leads NEC indices by about 6 months. The zero-lag correlation coefficients between LSTT and NECC, SEC (north of equator) indices are 0.55 and  $-0.67$  respectively. The zero-lag correlation coefficient between the ITFT based on the “Island Rule” and NEC indices is  $-0.52$ , and it is  $-0.78$  with NECC indices and the positive correlation reaches a value of 0.48 with SEC indices (north of equator). It is readily seen that LSTT (ITFT) tends to be in-phase (out-of-phase) with NEC and NECC indices, but it is out-of-phase (in-phase) with SEC (north of equator) indices. During El Niño, LSTT increases with the anomalous westward NEC; while ITFT decreases accompanying by the anomalous eastward NECC/SEC.

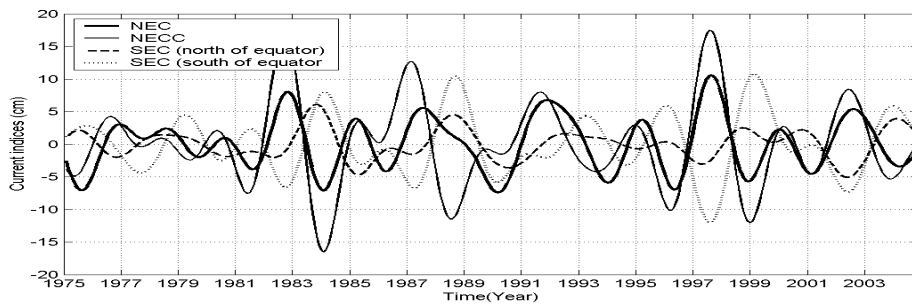


Figure 4: The time series of NEC (bold-solid line), NECC (thin-solid line), and SEC (south of equator: short-dashed line; north of equator: dotted-dashed line) indices anomalies inferred from the sea level height. Positive (negative) values indicate that the currents strengthen (weaken). Unit: cm.

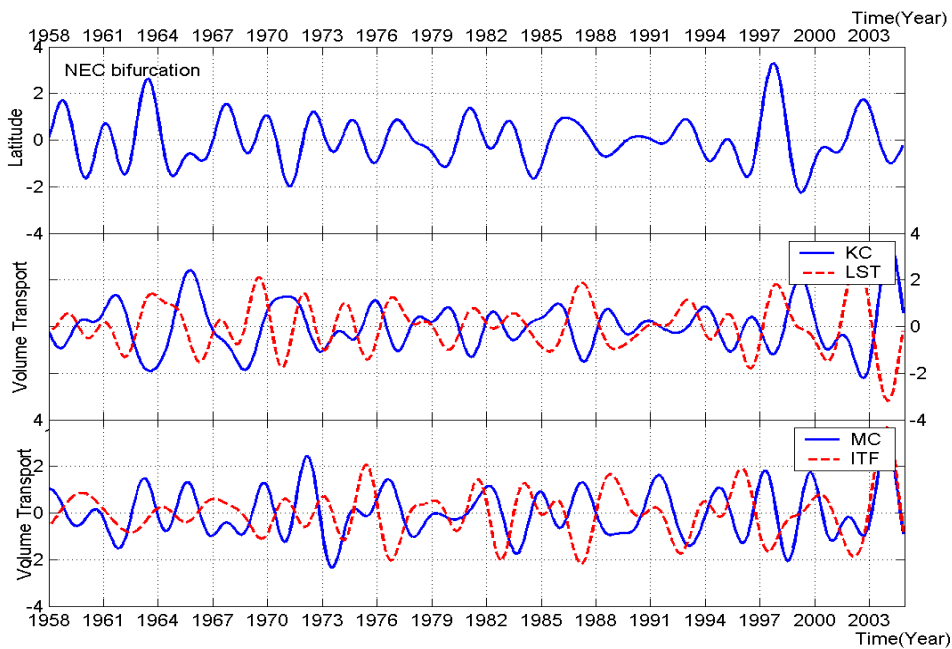


Figure 5: The normalized time series of the NEC bifurcation anomaly, the volume transport anomalies of KC, LST, MC and ITF.

Positive values denote the strengthening of currents and the northward shifting of the NEC bifurcation.

If there is a gap with a finite width in the western boundary, two possible phenomena may happen when an inertial boundary current passing flows along the western boundary. When the meridional advection of potential vorticity is strong enough to overpower the  $\beta$  effect, the inertial boundary current may leap across the gap in the western boundary. This phenomenon like “teapot” domino effect is called “overshooting” (Sheremet<sup>[9]</sup>). On the other hand, if the meridional advection term falls below a critical value  $Q_c$  (depending upon the strait width,  $\beta$  and the horizontal and vertical scales of the jet), the current will switch into the gap partly. This phenomenon is opposite to the case discussed above, and it is called “undershooting”. Yaremchuk et al.<sup>[17]</sup> pointed that the increasing of LSTT in December-January is related with the decreasing of the northward transport of KC east of the Luzon strait, corresponding to the undershooting phenomenon of this theory. A step further along this line of thinking reveals that the undershooting of KC implies an enhancement of MC, and thus the MC may overshoot the Sulawesi-Mindanao passage (124.5°E, 0.75°N-6.25°N). In fact, undershooting/overshooting processes occurring at the entrances of Luzon Strait and Sulawesi-Mindanao passage are the intrinsic elements causing the out-of-phase relation between LSTT and ITFT during ENSO years. The interannual variations of the KC transport (16.75°N), the MC transport (7.25°N) and the NEC bifurcation averaged in the regions offshore 2deg grid-points in upper 465m are given in Figure 4. The zero-lag correlation coefficient between the NEC bifurcation and the Niño3.4 index (the KC transport) is 0.54 (-0.60), and the maximum value 0.31 occurs when MC leads the NEC bifurcation by 6 months. The NEC bifurcation is out-of-phase with KC, but it is appropriately in-phase with MC, despite certain lags between the NEC bifurcation and MC. The zero-lag correlation coefficient between KC and LSTT simulated by the model is -0.59. The corresponding value between MC and ITFT simulated by the model is smaller; while the negative correlation coefficient between the MC and the ITFVT based on the “Island Rule” can reach to a value of -0.52. The out-of-phase characteristic between KC (MC) and LSTT (ITFT) is closely related to the undershooting/overshooting process; on the other hand, the out-of-phase relation between KC and MC is associated with the different speeds of baroclinic Rossby waves at their respective latitudes<sup>[14]</sup>, and this leads to the out-of-phase relation between LSTT and ITFT on the interannual time scale.

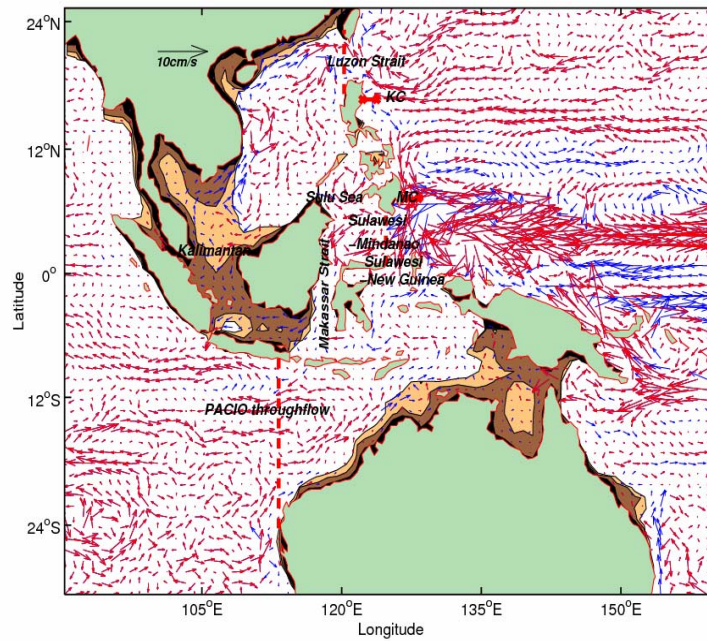


Figure 6: The distribution of the composite current anomaly in the upper 465m during abnormal events (the criterion chosen is as same as in Figure 1). The red vectors denote above 95% significant level. The domain shallower than 100m is labeled by isolines, using the topographic dataset in Matlab.

The composite anomalous currents during the abnormal events averaged over the upper 465m are presented in Figure 6, with red vectors indicating currents above 95% significant level. Thus figure shows clearly the northward shift of NEC bifurcation induced by wind stress change in the equatorial Pacific through Sverdrup dynamics<sup>[12]</sup> during El Niño events. At the same time, NEC becomes strong<sup>[13][14]</sup>, and baroclinic Rossby waves induced by changes in wind stress at different latitudes lead to the strengthening of MC<sup>[15]</sup> and the weakening of KC<sup>[16]</sup>. The weakening of the KC is in favor for the Pacific water to enter SCS, and LSTT becomes stronger; the strengthening of MC is unfavorable for the water flowing into the Indian Ocean via Indonesian pathway, and ITFT becomes weaker. When MC boosts up, NECC also builds up, but SEC trails off. During the La Niño events, the situation is the other way round, that is the NEC bifurcation shifts southward, and KC strengthens, causing a weaker LSTT; and MC weakens, resulting in a stronger ITFT. The undershooting/overshooting phenomena taking place in the Luzon Strait and the Sulawesi-Mindanao passage are induced by the adjustment of the ocean circulation, which is in turn induced by wind stress variation in the equatorial Pacific. The interplay of these dynamic processes brings about the out-of-phase relation between anomalies of ITFT and LSTT on the interannual time scale.

#### 4 Conclusion and Discussion

Results from the “Island Rule” and ocean dataset assimilation products from Jan1958 to Dec2004 indicate that the variability of ITFT and LSTT are out phase on interannual time scales. Winds variation in the equatorial Pacific is the important factor in regulating the interannual variability of ITFT and LSTT. During El Niño events, wind stress changes in the equatorial Pacific induces strengthening of NEC and the northward shift of NEC bifurcation point. As a result, the

partition of the volume transport between KC and MC varies, with the increasing of MC and the decreasing of KC. The undershooting/overshooting phenomena at the entrances of the two straits brought about the transport variations of KC and MC. A weaker than normal KC is favorable for the Pacific water to enter SCS; the stronger than normal MC is unfavorable for the Pacific water to enter the Indian Ocean, and more water returns to the Pacific interior along with NECC.

Although wind stress variation in the equatorial Pacific is the important element controlling the interannual variability of LSTT and ITFT, there are other dynamical processes that can also affect their interannual variation. The North Pacific surface water can turn into SCS through the Luzon Strait under the force of the northeast Monsoon in winter<sup>[2][23]</sup>, and during such events the dynamical role of local wind is more evident. The sea surface height difference in the western Pacific also has a definite effect on LSTT<sup>[24]</sup>. The Indian Ocean dipole mode can have an important role in regulating the transport of ITF<sup>[8][22]</sup>. For example, in 1994 wind stress anomaly in the equatorial Indian Ocean was an important factor in controlling the variation of the ITFT<sup>[25]</sup>. The out-of-phase relation between ITFT and LSTT is more distinct in some years and less distinct in some other years, and the undershooting/overshooting processes do not necessarily occur simultaneously. These complications indicate the existence of variety of the other dynamical factors. In order to understand the effect of each dynamical factor on different time scales and their contribution in modulating water exchanges between the Pacific, SCS and the Indian Ocean exactly, further studies, using higher resolution ocean model combined with the observations, is needed.

**Acknowledgement** We gratefully acknowledge the help from Dr. X. F. Meng in Ocean University of China (OUC) in providing the compute program of the "Island Rule". Discussions with Dr T. D. Qu in International Pacific Research Center (IPRC) were very helpful for the success of our work. This work was supported by the National Natural Science Foundation of China (Grant No: 40136010, 40520140074).

## References

- 1 Qu T D, Kim Y Y, Yaremchuk M. Can Luzon Strait transport play a role in conveying the impact of ENSO to the South China Sea? *J Clim*, 2004, 17: 3644-3657
- 2 Wyrtki K. *Physical Oceanography of the Southeast Asian waters*. NAGA report, 1961, vol 2, p195, Univ. Of. Cali, San Diego
- 3 Gordon A L. Interocean exchange of thermocline water. *J Geophys Res*, 1986, 91, 5037-5046
- 4 Metzger E J, Hurlburt H E. Coupled dynamics of the South China Sea, the Sulu Sea and the Pacific Ocean. *J Geophys Res*, 1996, 101(C5): 12331-12352
- 5 Lebedev K V, Yaremchuk M I. A diagnostic study of the Indonesian Throughflow. *J Geophys Res*, 2000, 105(C5): 11243-11258
- 6 Fang G H, Wei Z X, Cui B H, et al. The inter-basin water, heat and salt transport in China: the global variable-grid ocean model results. *Science in Chin (Series D, in Chinese)*, 2002, 32(12): 969-977
- 7 Fang G H, Suisanto D, Soesilo I, et al. A note on the South China Sea inter-ocean circulation. *Advance Atmospheric Sci*, 2005, 22(6): 946-954
- 8 Qu T D, Du Y, Meyers G, et al. Connecting the tropical Pacific with Indian Ocean through South China Sea. *Geophys Res Lett*, 2005, 32: L24609, doi:10.1029/2005GL024698
- 9 Sheremet V. Hysteresis of a western boundary current leaping across a gap. *J Phys Oceanogr*, 2001, 31: 1247-1259
- 10 Meyres, G., Variation of Indonesian Throughflow and the El Nino-Southern Oscillation. *J.*

- Geophys. Res., 1996, 101(C5): 12,255-12,263.
- 11 Wang D. X., Q. Y. Liu, Y Liu, et al., Connection between interannual variability of the western Pacific and eastern Indian Oceans in the 1997~1998 El Nino event. *Progress in Natural Science*, 2004, 14(5): 421-429.
  - 12 Kim Y Y, Qu T D, Jensen T, et al. Seasonal and interannual variations of the North Equatorial Current bifurcation in a high resolution OGCM. *J Geophys Res*, 2004, 109: C03040, doi: 10.1029 / 2003JC002013
  - 13 Wyrtki K, Equatorial currents in the Pacific 1950 to 1970 and their relations to the trade winds. *J Phys Oceanogr*, 1974, 4(3): 372—380
  - 14 Qiu B, Lukas R. Seasonal and interannual variability of the North Equatorial Current, the Mindanao Current, and the Kuroshio along the Pacific western boundary. *J Geophys Res*, 1996, 101(C5): 12315-12330
  - 15 Masumoto Y, Yamagata T. Response of the western tropical Pacific to the Asian winter monsoon: the generation of the Mindanao Dome. *J Phys Oceanogr*, 1991, 21: 1386-1398
  - 16 Tozuka T, Kagimoto T, Masumoto Y, et al. Simulated multiscale variations in the western tropical Pacific: The Mindanao Dome revisited. *J Phys Oceanogr*, 2002, 32: 1338-1359
  - 17 Yaremchuk M, Qu T D. Seasonal variability of the large-scale currents near the coast of the Philippines. *J Phys Oceanogr*, 2004, 34: 844-855
  - 18 Wajsowicz R C. A relationship between interannual variations in the south Pacific wind stress curl, the Indonesian Throughflow, and the west Pacific warm water pool. *J Phys Oceanogr*, 1994, 24: 2180-2187
  - 19 Godfrey J S. A Sverdrup model of the depth-integrated flow for the world ocean allowing for island circulations. *Geophys Astrophys Fluid Dynamics*, 1989, 45: 89-112
  - 20 Wajsowicz R C. The circulation of the depth-integrated flow around an island with application to the Indonesian Throughflow. *J Phys Oceanogr*, 1993, 23: 1470-1484
  - 21 Qu T D, Mitsudera H, Yamagata T. Intrusion of the North Pacific waters into the South China Sea. *J Geophys Res*, 2000, 105(C3): 6415-6424
  - 22 Li W, Liu H L, Zhang X H. The Indonesian Throughflow in an eddy-permitting oceanic General Circulation Model. *Chinese Sci Bull(in Chinese)*, 2004, 49(19): 2001-2006
  - 23 Liu Q Y, Yang H J, Li W. The zonal current and mass transport in Luzon Strait. *Acta Oceanologica Sinica (in Chinese)*, 2000, 27(2): 1-8
  - 24 Hu J Y, Kawanura H, Hong H, et al. 3~6 month variation of sea surface height in the South China Sea and its adjacent ocean. *J Oceanogr*, 2001, 57: 69-78
  - 25 Murtugudde R, Busalacchi A J. Seasonal-to-interannual effects of the Indonesian Throughflow on the tropical Indo-Pacific basin. *J Geophys Res*, 1998, 103: 21425-21441