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Impact of the South China Sea Throughflow on the Pacific Low-Latitude Western Boundary Current: A Numerical Study for Seasonal and Interannual Time Scales

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ABSTRACT

Prior studies have revealed that, as a part of the Pacific tropical gyre, the South China Sea throughflow (SCSTF) is strongly influenced by the Pacific low-latitude western boundary current (LLWBC). In this study, ocean general circulation model (OGCM) experiments with and without connection to the South China Sea (SCS) were performed to investigate the impact of the SCSTF on the Pacific LLWBC. These model experiments show that if the SCS is blocked, seasonal variability of the Kuroshio and Mindanao Current becomes stronger, and the meridional migration of the North Equatorial Current (NEC) bifurcation latitude is enhanced. Both in seasonal and interannual time scales, stronger Luzon Strait transport (LST) induces a stronger Kuroshio transport combined with a southward shift of the NEC bifurcation, which is unfavorable for a further increase of the LST; a weaker LST induces a weaker Kuroshio transport and a northward shifting NEC bifurcation, which is also unfavorable for the continuous decrease of the LST.

Key words: South China Sea throughflow, low-latitude western boundary current, Kuroshio, NEC bifurcation

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1. Introduction

As the largest marginal sea in the eastern Asian waters, the South China Sea (SCS) connects with the northwestern Pacific and Indonesian Seas through the Luzon Strait, the Taiwan Strait, the Mindoro Strait, and the Karimata Strait. The deepest is the Luzon Strait (>2500 m), and the shallowest is the Karimata Strait (<50 m). Wyrtki (1961) first reported an intrusion of Kuroshio water from the western Pacific into the SCS in winter, which is important to the heat and salt budgets of the SCS basin and, hence, has a great impact on SCS circulation (Qu, 2000).

The Indonesian throughflow (ITF) is the only place in the world where warm water from one tropical ocean enters another, creating a choke point of heat distribution and atmosphere–ocean interaction in the global climate system (Godfrey, 1996). The coupled dynamics of the SCS, the Sulu Sea, and the Pacific Ocean were first discussed by Metzger and Hurlburt

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(1996) using a 1.5-layer, global reduced-gravity thermodynamic Navy layered ocean model. Lebedev and Yaremchuk (2000) studied the mean seasonal cycle of the ITF using an ocean general model (OGCM) and pointed out that the Luzon Strait inflow contributes significantly to the ITF. The SCS throughflow (SCSTF), including the intrusion of Pacific waters through the Luzon Strait and outflows through the Taiwan Strait, the Mindoro Strait, and the Karimata Strait, has drawn much attention for its potential impact on climate variations (e.g., Fang et al., 2003; Qu et al., 2006). Tozuka et al. (2007, 2009) investigated the impact of the SCSTF on the Makassar throughflow using an OGCM with the SCSTF passages opened and closed both on seasonal and interannual time scales. Using satellite images and a numerical model to track the Pacific water carried by the Kuroshio, Yu et al. (2007) provided strong evidence for the existence of the SCSTF. Using an inverse modeling approach, Yaremchuk et al. (2009) presented quantitative estimates of the SCSTF and its transport distribution among the three outflow straits. The SCSTF studies, including its dynamics, variability, and potential impact on climate, were reviewed recently by Qu et al. (2009).

Because it is forced by large-scale wind in the tropical Pacific (Qu et al., 2005; Yu et al., 2007), the SCSTF is thought to be an important branch of the western Pacific circulation system. The North Equatorial Current (NEC) bifurcates into the northward-flowing Kuroshio and the southward-flowing Mindanao Current (MC) east of the Philippine coast (e.g., Nitani, 1972; Toole et al., 1990; Qiu and Lukas, 1996; Lukas et al., 1996), and this bifurcation varies on different time scales. On a seasonal time scale, the bifurcation of the NEC moves northward in winter and southward in summer with the seasonal reversal of monsoon (Qu and Lukas, 2003), which induces a change between the Kuroshio and the MC transport partitions from the NEC. The Kuroshio transport east of the Luzon Strait approaches its seasonal minimum during winter, and this situation favors the Pacific water entering the SCS (Sheremet, 2001; Yaremchuk and Qu, 2004). The possible reason for more water entering the SCS during winter is that it is harder for the Kuroshio to overcome the β effect and bypass the Luzon Strait when it is weaker; and the situation reverses in summer. For interannual time scale, the Luzon Strait Transport (LST) increases during El Niño events as the Kuroshio east of Luzon decreases; and the situation reverses in the case of La Niña events (Qu et al., 2004). This was further confirmed by Wang et al. (2006) using the island rule (Godfrey, 1989) and the Simple Ocean Data Assimilation (SODA) dataset (Carton and Giese, 2008). On the other hand, the undershooting and overshooting phenomena occur not only at the Luzon Strait but also at the Sulawesi–Mindanao passage (Liu et al., 2006; Liu et al., 2010).

Does the SCSTF impact the Pacific low-latitude western boundary current (LLWBC)? Metzger and Hurlburt (1996) have pointed out that the mean LST is actually a westward extension of the northern tropical gyre and is largely affected by model geometry. The opening or closing of the Sibutu Passage at the southern boundary of the Sulu Sea has a substantial influence on the transport of the Kuroshio and the MC east of Philippines and hence on the NEC bifurcation latitude. What happens to the Pacific LLWBC when the SCSTF is "turned off"? These issues were investigated using twin OGCM experiments in this study. The organization of this paper is as follows. A brief description of the OGCM used in this study is given in the next section. We then discuss how the SCSTF influences the Pacific LLWBC in section 3, including the Kuroshio, the MC, and the NEC bifurcation. The final section summarizes our main findings with some discussion.

2. Model and experiments

We use the LASG/IAP (State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics/Institute of Atmospheric Physics) Climate System Ocean Model (LICOM; Liu, 2002; Liu et al., 2003) to perform the twin numerical experiments. LICOM is based on the third-generation global OGCM developed at the LASG/IAP (Jin et al., 1999). Parameterization of isopycnal mixing (Gent and McWilliams, 1990), computation of the short wave radiation piercing through oceanic subsurface (Rosati and Miyakoda, 1988), and parameterization of upper-ocean vertical mixing (Pacanowski and Philander, 1981) are adopted in this version of the model. The model covers the global oceans from 75°S to 65°N, with a uniform horizontal resolution of 0.5° by 0.5°. The vertical resolution includes 30 levels, with 12 levels in the upper 300 m so that the thermocline structure can be well described. The model topography is derived from Digital Bathymetric Data Base 5 min dataset (DBDB5; available at http://www7320.nrlssc.navy.mil/DBDB2_www/), which was produced by the U.S. Naval Oceanographic Office.

Two model experiments, including a control run (CTRL) and a SCSTF-switched-off experiment (NOSCS) were conducted. For each experiment, the model's spin-up period is 320 years from the initially motionless ocean, using temperature and salinity fields from Levitus' data sets (Levitus and Boyer, 1994; Levitus et al., 1994), and was then further integrated for 43 years (1958–2000) using forcing fields of monthly-mean wind stress and surface heat fluxes from the ERA40 reanalysis data (Uppala et al., 2005). Newton cooling was adopted for the sea surface heat forcing. The global sea ice and sea surface temperature (GISST) data (Rayner et al., 1998) from the Atmospheric Science Data Center of England were used to restore SST. Real freshwater flux data was not available with which to force the model. The sea surface salinity was simply restored to the observational monthly climatology. The restoration time scales were 90 days. For the NOSCS run, main passages of the SCSTF including the Luzon Strait, the Taiwan Strait, the Mindoro Strait, the Balabac Strait, and the Karimata Strait are blocked.

3. Results

3.1 *Model performance and annual-mean circulation pattern*

The LICOM has been shown to have the ability of simulating the main features of large-scale ocean circulation, the ITF, and water exchanges between the SCS and adjacent seas (Liu et al., 2004; Liu et al., 2005; Cai et al., 2005), but the spatial resolution of the model is still coarse for the highly complex geometry of Southeast Asian waters. The simulation result of CTRL on the SCSTF and upper-layer heat status of the SCS was previously evaluated by Wang et al. (2010) using the island rule, SODA, and Expendable Bathythermograph (XBT) data. Analyses of vertical structure of NEC bifurcation, seasonal variability of the SCS circulation pattern, and interannual variability of LST indicate that LICOM can obtain a reasonable modeling result of the SCSTF and circulation in the Indo-Pacific region.

The annual-mean upper-layer currents in CTRL and NOSCS are shown in Fig. 1. The thick bars in Fig. 1a denote the Kuroshio (18°N, 122.5°–124.5°E) and MC (8°N, 126.5°–129°E) sections used for transport calculations. The model can capture the main circulation features in the western Pacific, the SCS, and the Indonesian seas. The NEC bifurcates into the northward-flowing Kuroshio, and southward-flowing MC at the western boundary. The bifurcation latitude of the NEC is depth-dependent (Qu and Lukas, 2003). On the annual average, this bifurcation latitude in the CTRL is 13.0°N at the surface, 14.0°N at 222 m, 15.2°N at 432 m, and 18.7°N at 876 m. Most of the Kuroshio waters bypass the Luzon Strait and continue northward, with only a small fraction leaking into the SCS. A strong loop current appears in the Luzon Strait when the Kuroshio passes. However, this result may have been due to the coarse horizontal resolution of the model (Metzger and Hurlburt, 2001). Annual-mean LST is 1.82 Sv (1 Sv $=10^6$ m^3 s^{-1}) in CTRL, which falls into the reasonable range of 0.5–10 Sv obtained in previous studies (e.g., Metzger and Hurlburt, 1996; Fang et al., 2003). The MC flows southward, joins the Mindanao Eddy or the North Equatorial Countercurrent partially, and the rest of it enters the Indonesian Seas to drive the ITF. The annual-mean ITF volume transport in CTRL is 14.2 Sv, which is also consistent with earlier studies (e.g., Meyers et al., 1995; Godfrey, 1996; Li et al., 2004).

As shown in Fig. 1b, the axis of the Kuroshio and the circulation pattern in the inner SCS have changed greatly as a result of the blocked Luzon Strait. In addition, the meridional velocity in the Makassar Strait has increased evidently (Tozuka et al., 2007). This may be caused by a decrease in the northward pressure gradient at the surface of the Makassar Strait after the Karimata Strait is blocked (Gordon et al., 2003; Qu et al., 2005). The Karimata Strait is one of the most important pathways connecting the SCS and the Indonesian Seas. The first observation-based estimation of Karimata Strait transport was done by Wyrtki (1961), who estimated the strait transport at $\leqslant$4.5 Sv during winter from the SCS to the Java, and at $\leqslant$3 Sv during summer from the Java Sea to the SCS. Based on recent field measurements, Fang et al. (2010) reported that the Karimata Strait transport to be 3.6 Sv (southward) from 13 January to 12 February 2008. The strait transport was estimated to be 1.7 Sv (northward) during boreal summer, and the annual mean transport was estimated to be 0.8 Sv (southward). In CTRL of our model study, the strait transport was 3.72 Sv (southward) during boreal winter, 1.86 Sv (northward) during boreal summer, with 0.82 Sv (southward) for an annual mean. These results compare well with observations. Metzger and Hurlburt (1996) noted that opening or closing the Sunda Shelf/Java Sea does not affect the transport of ITF, while Tozuka et al. (2007) suggested that the Karimata Strait outflow plays an important role in the Makassar Strait transport. Our model result seems to support this later viewpoint (not shown). Fang et al. (2010) proposed that the Karimata Strait throughflow plays a double role in the total ITF transport in their observation study.

3.2 *Impact on the seasonal variability*

Some intriguing seasonal impacts on the Pacific LLWBC emerged from the model results. Differences of upper-layer currents in CTRL and NOSCS (CTRL minus NOSCS) east of the Philippines and Mindanao Island are shown in Fig. 2. Note that CTRL minus NOSCS results in the "net effect" of the SCSTF. Model

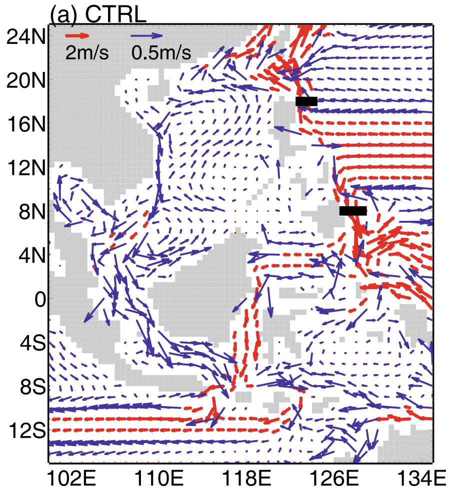

Fig. 1. Annual mean currents in the upper 303 m, with model topography in (a) CTRL and (b) NOSCS. The thick bars in (a) denote the Kuroshio (18°N, 122.5°–124.5°E) and MC (8°N, 126.5°–129°E) sections for transport calculations.

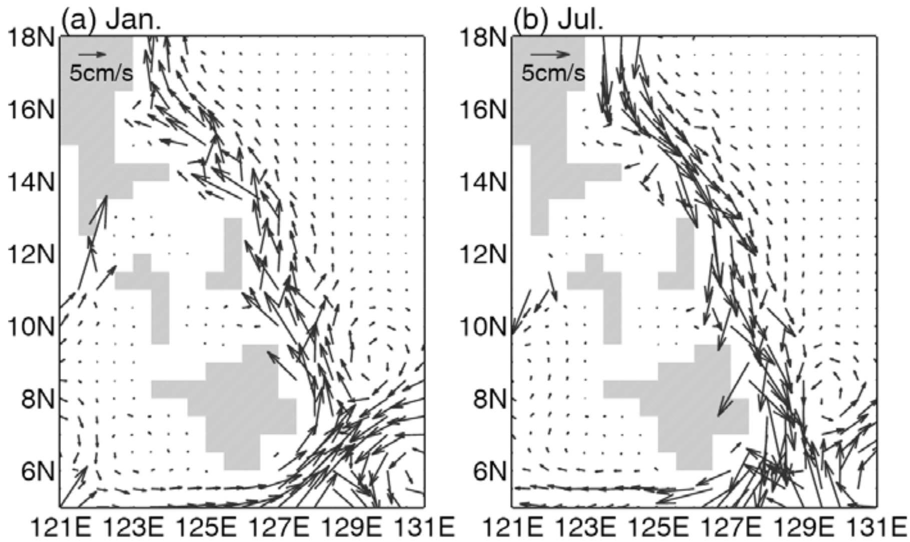

Fig. 2. Difference of currents in the upper 303 m in CTRL and NOSCS east of the Philippines and Mindanao Island in (a) January and (b) July.

results show that the SCSTF acts as a northward flow superimposing upon the western boundary of northern Pacific in January, and as a southward flow in July. The monthly mean velocity of these currents is $\leqslant$5 cm s^{-1} in the upper 303 m. Vertical profiles of meridional velocity in two experiments (not shown) indicate that differences mainly occur above 300 m.

These differences in velocity induce dramatic seasonal impacts on the volume transport of the Kuroshio and MC. Before the SCSTF is turned off (CTRL), the seasonal variability of model Kuroshio transport is comparable with previous studies: Wyrtki (1961) noted a maximum Kuroshio transport in spring and a minimum transport in fall. Qu et al. (1998) reported that most transport peaks occurred in April–June, and most bottom values took place during September–October. Yaremchuk and Qu (2004) estimated that a maximum transport of Kuroshio occurs in March and that a minimum occurs during October to November. The Kuroshio transport in CTRL reaches its maximum of 16.2 Sv in March and its minimum of 13.1 Sv in November (close value of 13.3 Sv in October). Previous model studies noted that the MC is strongest in the spring and weakest in the autumn

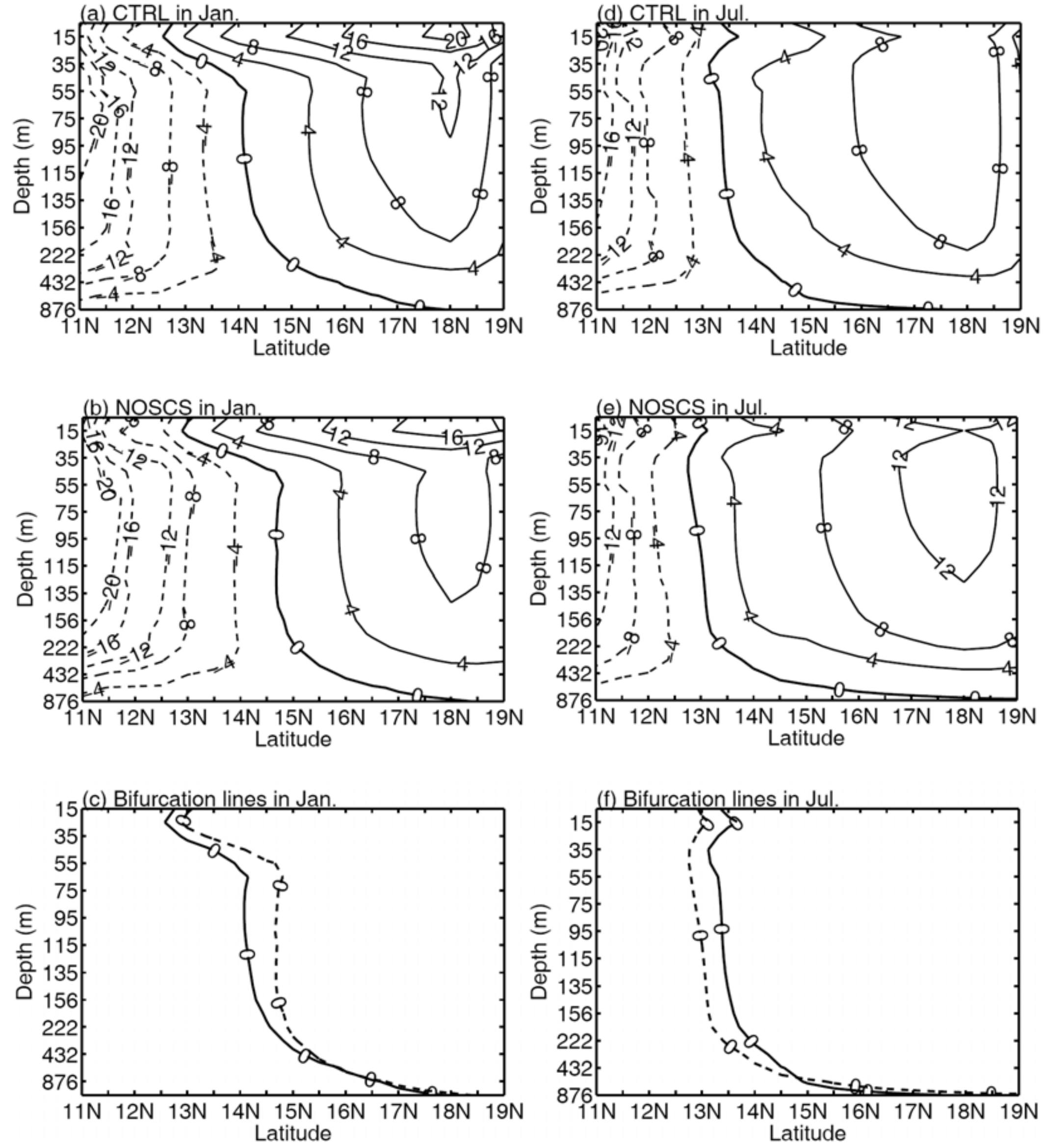

Fig. 3. Seasonal variability of meridional velocity (cm s^{-1}) averaged within a 5° (123°–128°E) band off the Philippine coast for (a) CTRL in January and (b) NOSCS in January. Positive values indicate northward flow, and the contour of zero velocity represents the bifurcation of the NEC. Two bifurcation lines of CTRL are compared in panel (c). Panels (d)–(f) are the same as panels (a)–(c), but for July.

(e.g., Tozuka et al., 2002; Qu et al., 2008). Our results in CTRL agree with these earlier studies: they show that MC transport reaches its maximum of 20.0 Sv in April and its minimum of 19.0 in September. These values are smaller compared to previous studies because we only calculated transport in the upper 303 m. Direct measurements of the MC are very limited. Base on mooring observations, Kashino et al. (2005) reported that the MC was strong during boreal summers (July–September) and weak during boreal autumns (October–December). Because of the complicated topography and the highly variable nature of the current, the MC transport varies when using different definitions. Yaremchuk and Qu (2004) assessed the MC transport at 11°N rather than at 8°N to exclude the closed cyclonic circulation associated with the Mindanao eddy and showed that maximum MC transport occurs in May and that minimum transport takes place in December. After the SCSTF is turned off (NOSCS), seasonal variability of the Kuroshio transport is much stronger—smaller in winter and larger in summer. Kuroshio transport reaches

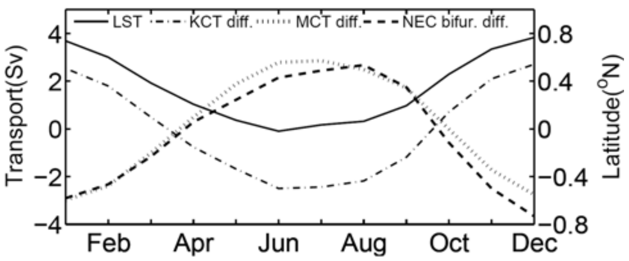

Fig. 4. Seasonal impact of the SCSTF on the Pacific LLWBC: Upper 303-m LST (solid line), Kuroshio volume transport difference (CTRL minus NOSCS; dashed-dotted line), MC volume transport difference (dotted line), and NEC bifurcation latitude difference at 55-m depth (dashed line).

its maximum of 18.0 Sv in June and its minimum of 11.0 Sv in November. The seasonal variability of the MC transport is enhanced as well. It is larger in winter and smaller in summer: the MC transport reaches its maximum of 22.6 Sv in January, and minimum of 16.6 Sv in August.

Not only the Kuroshio and MC transports but also the NEC bifurcation latitude changes after the SCS is blocked. Seasonal variability of meridional velocity averaged within a 5° (123°–128°E) band off the Philippine coast is shown in Fig. 3. Positive values indicate northward flow, and the contour of zero velocity represents the NEC bifurcation. After the SCSTF is turned off (NOSCS), the NEC bifurcation moves northward in January and southward in July; namely, its seasonal meridional migration is enhanced. In January, the largest migration occurs at 65-m in the model layer, where the difference between two experiments is up to 0.7°, from ∼14.1°N in CTRL to ∼14.8°N in NOSCS. In July, strong migrations of ∼0.5° occur in the upper layers. For example, in the 65-m layer the bifurcation latitude is ∼13.3°N in CTRL and ∼12.8°N in NOSCS. The differences become insignificant in layers 621 m and deeper in both January and July. Prior model study by Metzger and Hurlburt (1996) has shown the NEC bifurcation to be very sensitive to the topography of the region, which may partly explain the differences in CTRL and NOSCS (Tozuka et al., 2009).

The NEC bifurcation moves northward in winter and southward in summer (Qu and Lukas, 2003), accompanied by a quantitative transport change between the Kuroshio and MC. Thus, the Kuroshio transport east of Luzon approaches its seasonal minimum in winter and its maximum in summer, resulting in a seasonal maximum LST in winter and minimum in summer. Figure 4 shows the seasonal variability time series of the LST, Kuroshio transport difference, MC transport difference, and NEC bifurcation latitude difference at 55-m depth. For simplicity, we defined the westward LST and southward MC transports as positive in this study. Dramatic differences of the Pacific LLWBC volume transports and NEC bifurcation latitude are found in two model experiments. The maximum LST of 3.83 Sv occurs in December, and the minimum LST of −0.10 Sv (eastward) takes place in June. Two maxima values of Kuroshio transport difference are 2.71 Sv in December and −2.50 Sv in June. For MC transport difference, this two values are 2.86 Sv in June and −2.99 Sv in January. For NEC bifurcation latitude, the difference is 0.53° in August and −0.73° in December. The seasonal variability of these differences is in phase with the strong seasonal cycle of the LST, indicating that they are mainly induced by the closed Luzon Strait. Once again, note that the CTRL minus NOSCS means the "net effect" of the SCSTF. An intriguing feature in the twin LICOM experiments is that, from January to June, the LST decreases. Its impact on the Pacific LLWBC leads to a decrease of the Kuroshio and to an increase of the MC transport, combined with a northward shifting of the NEC bifurcation, which is unfavorable for further decrease of the LST itself. From July to December, the LST increases. Its impact leads to an increase of the Kuroshio and a decrease of the MC transport, combined with a southward shifting of the NEC bifurcation, which is unfavorable for further increase of the LST itself.

3.3 *Impact on the interannual variability*

On an interannual time scale, the NEC bifurcation moves northward during El Niño years, resulting in a minimum transport in the Kuroshio east of Luzon (e.g., Kim et al., 2004; Qu et al., 2004), further enhancing the LST (Liu et al., 2006). The situation seems to be reversed during La Niña years. The interannual variability of the SCSTF in CTRL has been evaluated by Wang et al. (2010) using SODA and island rule. Their results showed that the LICOM can obtain a reasonable interannual variability modeling of the SCSTF. The correlation coefficient of the LST anomalies and the Niño3.4 indices (http://www.cpc.ncep.noaa.gov/data/indices/) reach its maximum of 0.42 (above the 95% confidence level) when the LST anomalies lag the Niño3.4 indices for 3 months.

The composite current anomaly field during abnormal events is shown in Fig. 5. Here, abnormal events are defined when the LST anomalies in CTRL are >1 Sv and the Niño3.4 indices are >0.4°C. Model results show that the SCSTF acts as a northward flow in the upper-layer of the Philippine Sea when these positive anomalous events are selected and that it acts as a southward flow when negative anomalous events are

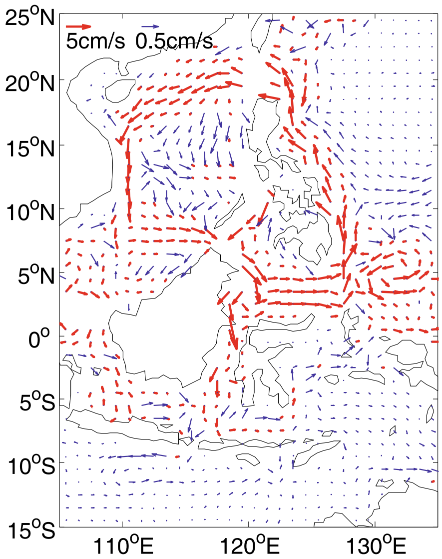

Fig. 5. Differences (CTRL minus NOSCS) in current anomaly field averaged over the upper 303 m during abnormal events, which are defined when the LST anomalies in CTRL is >1 Sv and the Niño3.4 indices are >0.4°C.

selected (not shown). Impact of the SCSTF on the current field of Pacific LLWBC on interannual time scale is similar to that of seasonal time scale given in Fig. 2.

To further confirm the interannual impact of the SCSTF on the Pacific LLWBC, anomalies of upper 303-m LST in CTRL, anomalies of upper 303-m Kuroshio volume transport difference (CTRL minus NOSCS), and anomalies of the NEC bifurcation latitude difference at 55-m depth are shown in Fig. 6. A band-pass filter has been applied to all time series to extract 2–7.5-year signals. Simultaneous correlation coefficient of the LST anomalies with the Kuroshio transport difference anomalies, NEC bifurcation latitude difference anomalies, and MC transport difference anomalies (not shown) are 0.97, −0.85, and −0.74 (above the 99% confidence level). The LST anomalies have a significant positive correlation with the Kuroshio transport difference anomalies but a negative correlation with the NEC bifurcation latitude difference anomalies. These significant correlations indicate that stronger LST enhances the Kuroshio, combined with a southward shifting of the NEC bifurcation, which is unfavorable for further increase of the LST itself. Weaker LST reduces the Kuroshio, combined with a northward shifting of the NEC bifurcation, which is also unfavorable for further decrease of the LST itself.

4. Conclusion and discussion

The twin LICOM numerical experiments show that the SCSTF has a dramatic impact on the seasonal variability of the western boundary current in the Philippine Seas. When the SCS is blocked, the seasonal variability of the Kuroshio and MC becomes stronger, and the meridional migration of the NEC bifurcation latitude is also larger. Increasing LST in winter can induce an increasing Kuroshio transport and a southward shifting of the NEC bifurcation, which is unfavorable for further increase of the LST itself. Decreasing LST in summer can induce a decreasing Kuroshio transport and a northward shifting of the NEC bifurcation, which is also unfavorable for further decrease of the LST itself. For interannual time scale, the impact of the SCSTF on the Pacific LLWBC is similar to that for the seasonal time scale. A flow chart summarizing the interaction between the SCSTF and the Pacific LLWBC both for seasonal and interannual time scales is given in Fig. 7. From this figure, the impact of the SCSTF on the Pacific LLBWC resembles "negative feedback," suggesting that the SCS basin may act as a "regulator" on the upper-layer boundary current of the western Pacific through the Luzon Strait.

The meridional velocity and volume transport differences in the two model experiments (not shown) only take place in the upper layer. The migration of the NEC bifurcation mainly occurs in the southern area (as shown in Fig. 3), where the bifurcation position has not yet reached the Luzon Strait. The topography effect alone cannot explain the differences between the CTRL and NOSCS. The existence of the Luzon Strait (and the Sulawesi–Mindanao passages) may partly explain the smaller amplitude in the seasonal variation of the NEC bifurcation latitude compared with that of the zonally integrated zero-wind-stress curl line, which varies from 11°N to 20°N (Qu and Lukas, 2003; Tozuka et al., 2009). Our model experiment results confirm that the inflow through the Luzon Strait has some kind of impact on the Kuroshio and on the NEC bifurcation at some rate. Closing the Luzon Strait may change the direction of the Kuroshio dramatically by cutting off its ridge (as shown in Fig. 1). This may affect the velocity and hence the momentum of this western boundary current in the "downstream", which may induce feedback on its "upstream". The western boundary currents are affected by the irregularity of the bottom topography and coastlines significantly. As a gap on the western boundary, the Luzon Strait may result in hysteresis when the Kuroshio passes by (Sheremet, 2001). The boundary current may either leap across the gap due to inertia or penetrate into the western basin, depending on previous

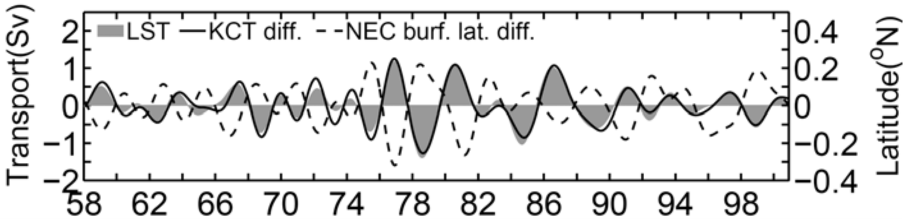

Fig. 6. Interannual impact of the SCSTF on the Pacific LLWBC: upper 303-m LST anomalies (shaded), Kuroshio volume transport difference (CTRL minus NOSCS) anomalies (solid line), and the NEC bifurcation latitude difference anomalies at 55-m depth (dashed line). Band-pass filter has been applied to all time series to extract 2–7.5-year period signals.

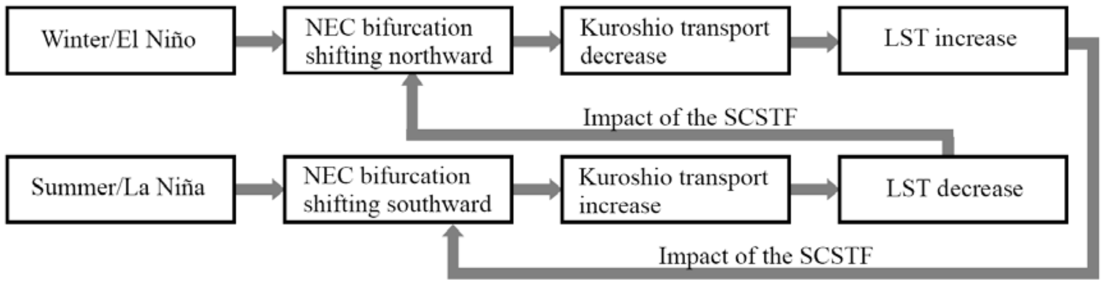

Fig. 7. Flow chart of interaction between the SCSTF and the Pacific LLWBC: in winter and/or El Niño events, stronger LST enhances the Kuroshio, combined with a southward shifting of the NEC bifurcation, which is unfavorable for the continuous increase of the LST itself. In summer and/or La Niña events, weaker LST reduces the Kuroshio, combined with a northward shifting of the NEC bifurcation, which is also unfavorable for further decrease of the LST itself.

evolution. The Kuroshio has long been recognized (Nitani, 1972) either to leap across the Luzon Strait or to penetrate into the SCS as a loop current, possibly depending on its seasonal or interannual strength variation. When the momentum feedback on the upstream occurs, the seasonal and interannual momentum variation of the Kuroshio and NEC bifurcation, depending on their historical evolution, are making contributions, especially in the upper layer with greater velocity. These factors may contribute to a dynamic interpretation of the result shown in this model study.

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