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THE CHARACTERISTICS OF AIR-SEA HEAT FLUX EXCHANGE DURING THE GENERATION AND DEVELOPMENT OF LOCAL TYPHOONS OVER THE SOUTH CHINA SEA

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Abstract: A South China Sea (SCS) local TC (SLT) is defined as a tropical cyclone (TC) that forms within the SCS region and can reach the grade of tropical storm (TS) or above. The statistical features of the SLTs from 1985 to 2007 are analyzed first. It is found that over the SCS about 68% of the TCs can develop into TSs. The SLT intensity is relatively weak and associated with its genesis latitude as well as its track. The SLT monthly number presents a seasonal variation with two peaks in May and July to September. Based on the daily heat flux data from the Woods Hole Oceanographic Institution_Objectively Analyzed air-sea Fluxes (WHOI_OAFlux) in the same period, the air-sea exchange during the process of generation and development of the SLT is studied. Results show that the heat fluxes released to the atmosphere increase significantly day by day before cyclogenesis. The ocean to the south to the TC center provides the main energy. Along with the development of SLT, the regions with large heat fluxes spread clockwise to the north of TC, which reflects the energy dispersion property of vortex Rossby waves in the periphery of the TC. Once the SLT forms the heat fluxes are not intensified as much. During the whole process, the net heat, latent heat and sensible heat flux display a similar evolution, while the latent heat flux makes a main contribution to the net heat flux. The maximum air-sea heat exchange always occurs at the left side of the TC moving direction, which may reflect the influence of the SCS summer monsoon on TC structure.

Key words: South China Sea local TCs; composite; heat flux

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1 INTRODUCTION

The South China Sea (SCS) is one of the sea areas that are frequently affected by tropical cyclone (TC) activities. These affecting TCs mainly come from two sources: the western North Pacific (WNP) and the SCS itself. A TC generated in the South China Sea is called a SCS local TC (hereafter shortened as SLT). The SCS is small and close to the mainland, so a SLT can land on the coast quickly after its sudden generation, causing disasters to the South China coast. In addition, owing to the influences of the complex coastal topography, Tibet Plateau as well as climate systems such as East Asian Monsoon, South Asian Monsoon, and WNP subtropical high, the track of a SLT could be quite complicated, which makes it much difficult to monitor and forecast. Therefore, it is of great practical significance to study the strength and path predictors of the SLTs.

A lot of researches have been done about the air-sea interaction during the TC process. Black[1] and Bender et al.[2] pointed out that a TC-ocean system contains both positive and negative feedbacks. On the one hand, when the TC develops, the sea surface wind becomes larger and larger and the surface evaporation enhances gradually, thus the energy that enters the TC, such as latent heat, is increasing. On the other hand,

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when the TC continues to strengthen, sea surface wind stress will generate strong turbulent mixing, channeling the cold water in the thermocline into the mixed layer, resulting in significant decrease in sea surface temperature (SST). Then the latent heat and sensible heat flux into the atmosphere would be reduced to affect the ultimate intensity of the TC. Such a feedback mechanism shows that during the lifecycle of a TC, the atmosphere and the sea are exchanging heat and water vapor all the time. Especially in cyclogenesis and development stages, the TC needs a lot of energy from the ocean, whose most immediate form is the heat flux at the air-sea interface. Many scientists investigated the impact of the ocean on TC intensity via SST[3, 4] and the mixed layer[5, 6], among others, and achieved some results. However, the SST and mixed layer depth are only some of the affecting factors. They are inextricably linked with the air-sea heat flux. Chan et al.[7] pointed out that the ocean affects the TC intensity through the sea surface heat flux. Wu et al.[8] also found that the air-sea heat exchange in the South China Sea during a TC lifecycle involves extremely complex physical changes of the atmosphere and ocean, and usually leads to mutation of TC. Therefore, researches on air-sea heat exchange in TC generation and development would be of some significance to the prediction of TC intensity.

However, this subject progresses very slowly at both home and abroad due to lack of observations and data within TCs. Some scientists utilized coupled models to simulate the impact of the ocean on cyclone development[2, 9-12]. Some made case analysis based on the observed data during TC lifecycles[8, 13]. In this paper, the influences of heat fluxes on the TCs are discussed, and the distributions of heat fluxes before the generation, on-going generation and development of the SLTs are analyzed based on the synthesis method. Although many scholars have done some statistical researches on the TCs affecting the SCS, little work has been done on the SLTs only. Therefore, in order to better understand the climate background of the SLTs and lay a solid foundation for future composite study, some statistical analysis is also done in this paper.

Hence, a basic framework of this paper is as follows. Section 2 introduces the data and methods used in this study. Then section 3 presents the statistical characteristics of the SLTs. Section 4 discusses the main topic of this paper: the influence of heat fluxes on the generation and development of TCs. Section 5 gives our conclusions.

2 DATA AND METHODS

The TCs data used in this study are taken from Shanghai Typhoon Institute, China Meteorological Administration (CMA) over 1985−2006. According to the latest Chinese National Standard (GB/T19201-2006), TCs are divided into six categories, respectively, which are Tropical Depression (TD), Tropical Storm (TS), Severe Tropical Storm (STS), Typhoon (TY), Severe Typhoon (STY) and Super Typhoon (Super TY). In this paper a SLT is defined as a TC that forms within the SCS region and reaches the grade of TS or above. The geographic range of SCS is 105°−120°E, 0°−25°N.

The daily air-sea heat fluxes data are taken from Woods Hole Oceanographic Institution_Objectively Analyzed air-sea Fluxes (WHOI_OAFlux). The spatial accuracy of the data is 1°×1°. Fluxes studied in this paper include net heat flux, latent heat flux and sensible heat flux. The flux unit is W/m^2. Net heat flux is made up of latent heat flux, sensible heat flux, effective sea surface back radiation and short-wave radiation absorbed by the sea surface. For easier comparison, we define upward flux as being positive flux. At the same time the sea surface neutral winds at 10 m height are used. To eliminate the influence of seasonal factors, the data is normalized (with climatological mean seasonal cycle removed).

The main method used is composition. One is daily composite, which observes the characteristics of daily fluxes from the time 5 days before and right up to the day of generation of the LSTs. The other is grade composite, which studies the flux distributions before TCs reach certain grade. For convenience, TC stages leading up to STS, TY or STY are denoted as TS-STS, STS-TY or TY-STY in turn. In addition, we also have made two kinds of space composites, one being the composites of heat flux of various stages in the entire SCS region and the other being the composite of the heat flux of the TC circulation, which covers an area that takes the eye of TC as the center and contains 10 degrees of latitude and longitude from it.

3 STATISTICAL CHARACTERISTICS OF THE SLTS

3.1 *Grade distribution of the SCS TCs*

Preliminary statistics for the grade distribution of the SCS TCs are conducted in this work and the result shows (see Fig. 1) that during 1985−2007 there experienced 125 TCs in SCS, or an average of 5.4 per year. About 68% of them could develop into TSs. The total number of SLTs is 85, or an average of 3.7 per year. The intensity of the SCS TCs is generally weak. In all investigated TCs, TDs have the largest number (40). With the intensity increasing, the TC number is diminishing. There are 38 TSs, 27 STSs and 18 TYs. There are only 2 STYs, and no Super Typhoon ever occurred during that period.

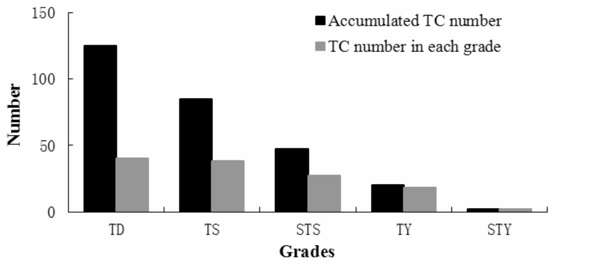

Figure 1. Distribution of grade of intensity for the SCS TCs during 1985-2007.

Figure 2 shows the tracks of SLTs at different grades of intensity. It is found that the stronger a SLT, the higher latitude it is generated on. Statistics show that the average formation latitude on which a TD, TS, STS, TY and STY is formed is 5.8°N, 16.4°N, 18.7°N, 19.1°N and 20.6°N, respectively. Taking a westward route is mostly found in the SLTs and most of them dissipate soon after landfall. The SLTs with northward or north-eastward paths usually last longer and move onto higher latitudes. With the increase of the grades, the proportion of the SLTs with the northeastward path increases significantly, suggesting a relationship between the grade of SLT intensity with the latitude it is generated on and the track it follows.

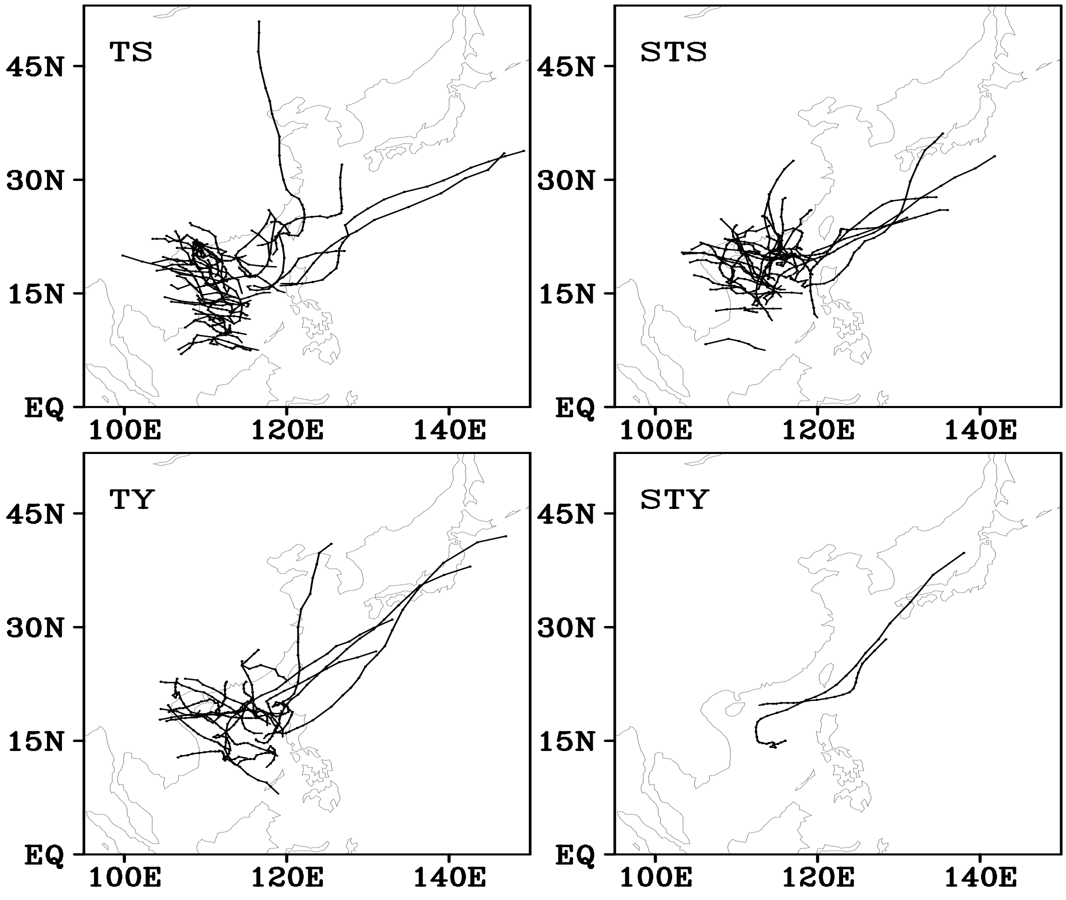

Figure 2. Tracks of the SLTs at different Grades during 1985-2007.

3.2 *Seasonal variation of the SLTs*

The monthly numbers of the TCs and SLTs in SCS are shown in Fig. 3. The frequency presents a seasonal variation with two peaks in May and July to September.

During 1985−2007, from January to March there was no TC influence in the SCS. In May the number increases suddenly and the first peak appears, which may be related to the outbreak of the SCS summer monsoon[16]. In July to September, when the WNP TCs is most frequent, the SCS TCs number reaches its second peak. Then the number decreases significantly after October.

The SLTs vary in a similar way as the TCs in the SCS. The difference is that for SLT, the number of August is less than that of July. That means the SCS TCs generated in August are relatively weak and the number of TDs is relatively large. Huang et al.[17] pointed out that though the WNP TC is most active in August, the proportion of the ST is the lowest, a result similar to the finding in this paper and work needs to be done to explain why it happens. In addition, it is important to note that besides the obvious seasonal variation, the SLTs also have an intra-seasonal oscillation with the period of two months. It may be closely associated with the intra-seasonal oscillation of the SCS monsoon[16].

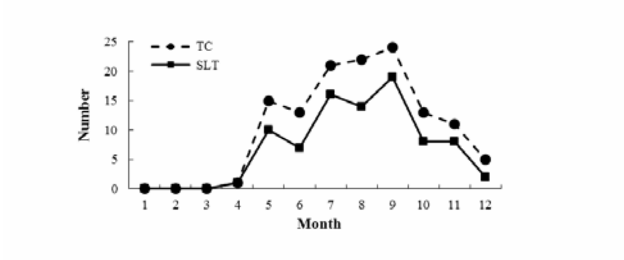

Figure 3. Seasonal variations of accumulated numbers of the TCs and SLTs in the SCS during 1985-2007.

4 COMPOSITE OF AIR-SEA FLUXES OF SLTS IN GENERATION AND DEVELOPMENT STAGES

4.1 *Distribution of composites of air-sea fluxes in SCS*

As shown in Fig. 1, the number of the SLTs in the TS-STS, STS-TY, or TY-STY stage is 47, 20, and 2, respectively. The composite daily fluxes of 5d-0d before the SLTs genesis are shown in Fig. 4. It is found that, several days before genesis the net heat flux has already been positive in almost the entire SCS. The ocean releases heat continuously into the atmosphere, though the amount is not so large. The significant area is located in the central part of the SCS near 10°N. Over time, the exothermal process strengthens and the exothermal area expands and moves northward. Two days before cyclogenensis, the area with large released amount of heat presents a concentric circle, with the center located near 12°N. After that, a high-value area extends northward with its shape getting more regular. On the day of generation, the high-value area is near 15°N. Gradually a relatively low-value area emerges close to the high-value area, just corresponding to the warm core of the TC. As shown by the black dots in Fig. 4, most SLTs form inside the contour of 40 W/m^2, suggesting that it is more likely for TCs to form over the ocean releasing large amount of energy.

In the TS-STS stage, the ocean continues to release heat, but the concentric circle is not as regular as before. In the STS-TY stage, the exothermal center slightly moves to the north, and the structure becomes looser than before. The southern SCS even has a negative zone. In the TY-STY stage, the concentric circle disappears, only leaving a strong exothermal area along the South China coast. However, the result is of no general meaning, because there are only 2 samples in this stage. From the above stages, it is drawn that after the generation, the increase of net heat flux is no longer obvious, which may be associated with the fact that strong post-cyclogenesis surface winds cause the upwelling of cold mixed-layer water and the declining of SST[1, 2, 11]. However, in all stages, all of the TCs move over ocean surface with significantly exothermal zones, which suggests that the distribution of the net heat flux may have some influence on the track of TCs.

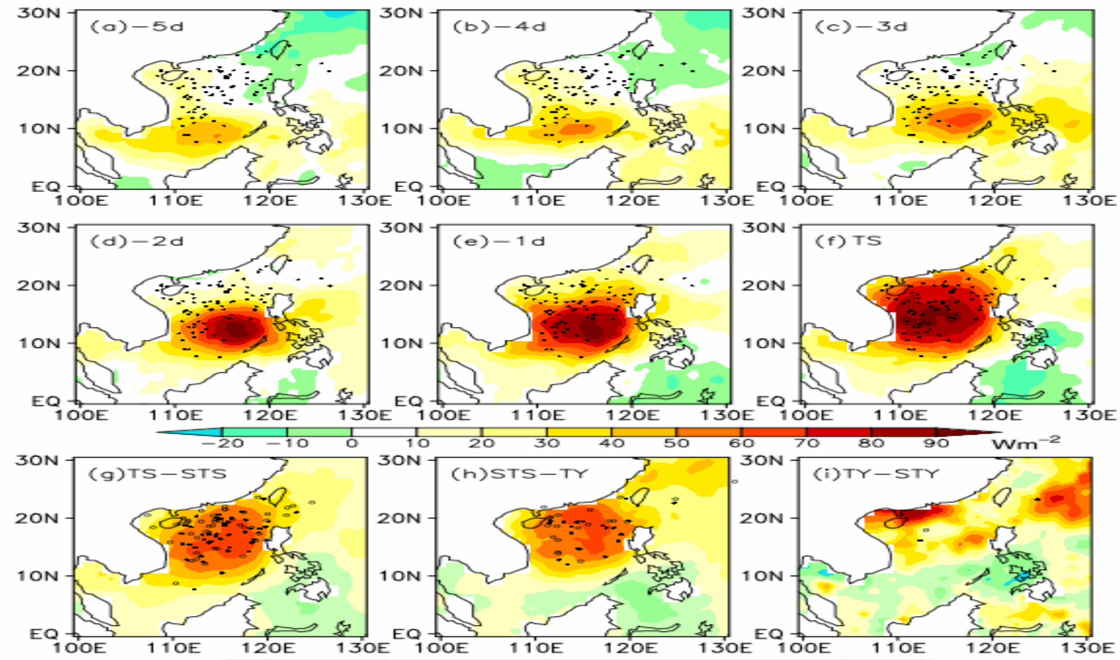

Figure 4. Distributions of net heat flux in SCS during the generation and development process of the SLTs. Solid points in (a) to (f) denote formation locations. Solid and open points in (g) to (i) denote the locations of the former and the latter grade respectively.

The distribution of the latent heat flux (Fig. 5) is similar to that of the net heat flux. Prior to the generation it gradually increases and the high-value area moves northwards. The biggest difference is that there are two high-value areas in the latent heat flux, one on the south side of the SLTs and the other along the South China coast, which may be related to the asymmetric structure of maximum wind speed in the periphery of TCs. As shown by the contours, the large wind speed area matches very well with the large latent heat flux area. Since the generation of SLTs, there has been a high-value center of wind speed along the South China coast. It may be the strong wind that results in strong latent heat exchange.

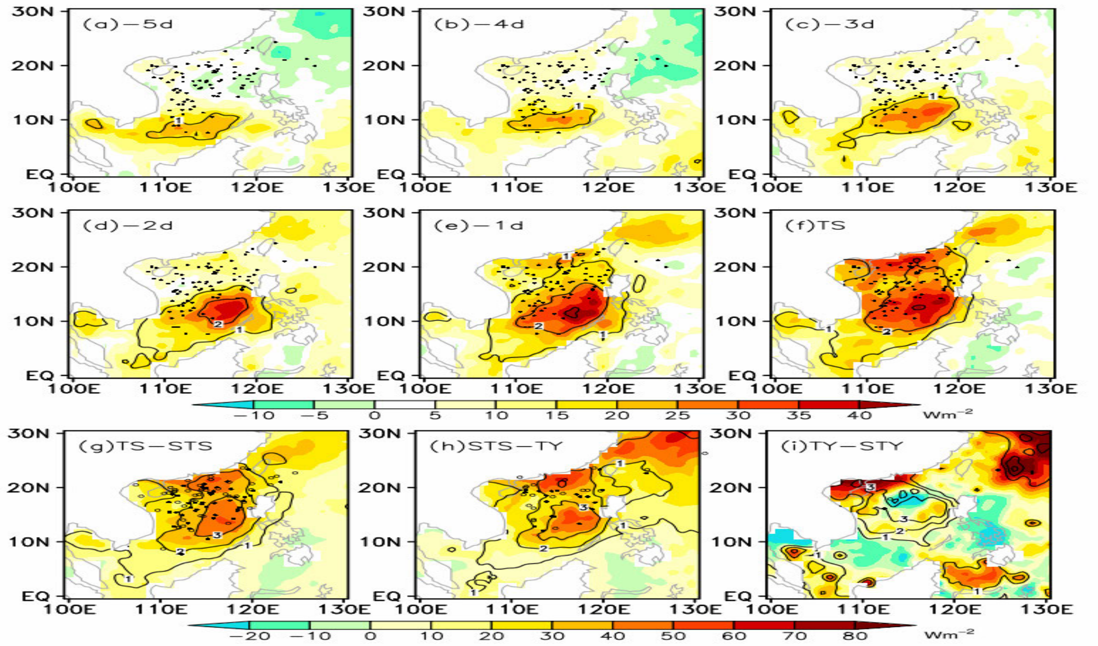

Figure 5. Same as Fig. 4 but for the latent heat flux. The added solid contours are for wind speed anomaly at 10 m above the sea surface.

The amount of sensible heat flux is significantly less than that of net and latent heat flux. It makes little contribution to the net heat exchange with the magnitude less than one-tenth of the net flux. Distribution (not shown) is more irregular than the latent heat flux, but the biggest difference is that the high-value area of sensible heat flux is almost all in the South China coast, which may be related to strong wind and shallow water in the coastal zone.

4.2 *Composite distribution of air-sea fluxes around the eye of TC*

In this section, the composite air-sea fluxes in the eye of TC are discussed. As shown in Fig. 6, several days before the TC forms, the southern positive area of net heat flux is expanding unceasingly, while the northern negative area, which is initially weak, has narrowed gradually. One day before the TC generates, the net flux is positive in almost the whole circulation with the exothermal center in the southeast quadrant. It is the ocean in the south side of the TC that provides the main energy for the TS formation. When the TS forms, the net heat flux distribution has become a relatively regular concentric circle, which is not symmetric. The high-value area is located in the south side of the eye with its center about 2 to 3 latitudes apart from it.

In the TS-STS stage, the net heat flux exchange continues to enhance and the high exothermal area moves from the south side to the southwest of the eye. In the STS-TY stage, the ocean around the eye within an area of 3°×3° releases more and more energy and the exothermal zone significantly shrinks to the center compared to the previous stage. In other words, the stronger grade of intensity the TC achieves, the more concentrated the exothermal area becomes. In the TY-STY stage, there is no obvious distribution pattern owing to the lack of enough STY samples, but the eye still appears to have a relatively low-value zone, which has been there all the time since the TC generates. On the one hand, the downdraft in the eye causes little cloud to enable the sea area underneath to obtain intense solar radiation. On the other hand, the local wind speed is always little, or even zero, making the latent and sensible heat small. These factors work together to result in the low-value zone of the net heat flux in the TC center.

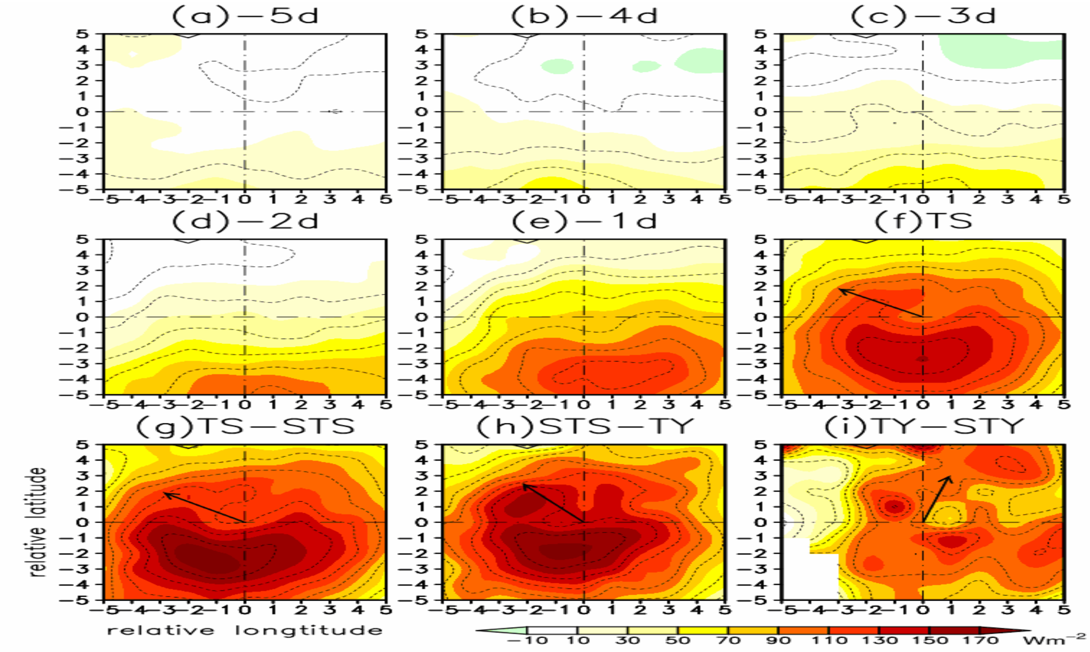

Figure 6. Distributions of net heat flux around the TC center during the generation and development process of the SLTs (shaded areas and dashed contours, with contour interval at 20 Wm^{-2}) and moving directions of the SLTs (black arrows).

The same method is used to make the composite of latent heat and sensible heat fluxes. As shown in Fig. 7, several days before the TC is generated, the latent heat flux develops in a way similar to that of the net heat flux. One day before TS (Fig. 7e), throughout the TC circulation, the ocean releases latent heat to the atmosphere, and near the eye there appears a relatively low-value zone. In the TS-STS stage, the released latent heat flux continues to increase, and the exothermal center moves in the southeast quadrant, which is not entirely consistent with the distribution of the net heat flux. It suggests that besides the latent heat flux, some other fluxes may make a large contribution to the net heat flux. In the STS-TY stage, the latent heat is decreased in the south, but is increased quite significantly in the north especially northwest of the TC. Throughout the whole process, the TC center has always been a low-value area for latent heat. Sea surface wind, humidity as well as the sea surface saturation specific humidity, etc. are important factors affecting sea surface latent heat flux. Sea surface wind field inside the TC circulation in Fig. 7 explains well such distributions of the latent heat flux during the formation and development stages of the SLTs. The distribution of the sensible heat flux (not shown) is similar to that of the net heat flux. Since the TC formation, the high-value area has been in the southwest quadrant but its magnitude is very small and has a very limited impact on the net heat flux. It is not analyzed in detail.

Generally, the strongest exchange of the air-sea heat flux happens in the right front of TC moving direction. This is because most TCs are generated in the easterly waves or Inter-tropical Convergence Zone, and move to the northwest or northeast along the edge of the subtropical high. Winds on the right side of TC are enhanced by being superimposed with the airflow on the outer edge of the subtropical high, thus the air exchanges with the sea significantly. However, the SLTs are relatively special. Arrows in Figs. 6 and 7 show that, the high-value area of the net heat flux is rotating slightly clockwise, and almost all of it appears in the left side of the moving direction. For the latent flux, it is in the left rear of the moving direction. This may be related to a particular location of the SCS. The occurrence of SLTs concentrates in May to September, when the southwest monsoon is prevailing over the SCS. On the one hand, the southwesterly airstream makes the western boundary of the subtropical high withdrawn eastward, weakening its impact on the northern airflow of the TC[18]. On the other hand, when the SLTs move northwest, the wind in the left rear quadrant is superimposed by a southwest airflow, which keeps the wind large. At the same time the southwesterly airstream brings in sufficient water vapor. That may be the reason why most intense latent heat exchange happens in the left rear of the moving direction. The hypothesis is well verified by the distribution of the wind field in corresponding figures. For example, the occurrence of TC Bilis (0604) coincides with the outbreak of the southwest monsoon though it was not formed in the SCS. When it landed, strong developed convective clouds associated with the southwest monsoon were drawn into the cyclone clouds from the south side of the TC, causing a heavy rainstorm to appear in Guangxi and other areas[19].

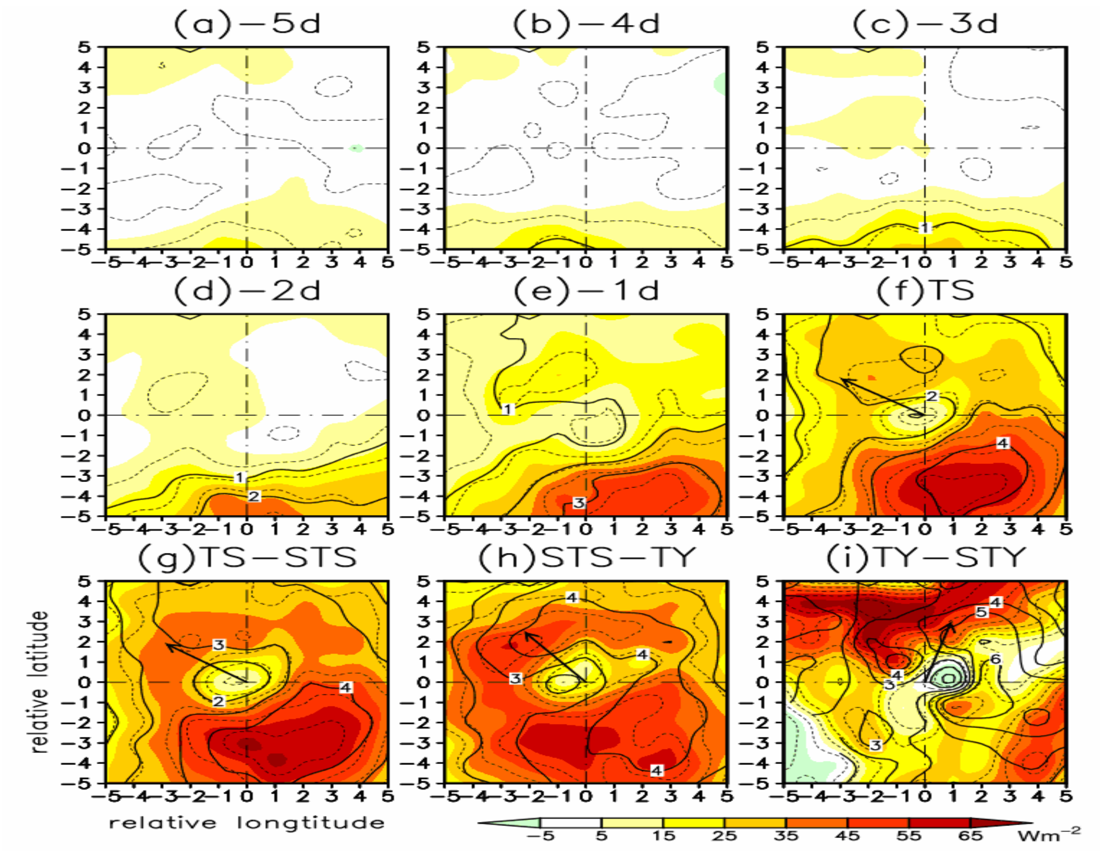

Figure 7. Same as Fig. 6 but for the latent heat flux. The dashed contour interval here is 10 Wm^{-2} and the added solid contours are for wind speed anomaly (m/s) at 10 m above the sea surface.

The distributions mentioned above are also quite consistent with the TC development process explained by CISK mechanism. That is, before the formation of the SLTs, the gradually increasing heat flux in the south side precisely corresponds to a comma-shaped cloud system in an unclosed low. The latent heat of condensation within the system continues to be released in association with the gradual development of strong convection, and low pressure continues to strengthen. When low pressure is low enough to close, the eye area forms and TC generates. With the enhancement of TC intensity, the high-value area of the heat flux within the TC circulation rotates clockwise, which suggests that TC convective clouds develop clockwise. To further validate it, the radial average of the heat flux is made for an area of 2 to 4 grids from the TC center to obtain the tangential distribution of heat fluxes in various stages of TC development (Fig. 8). It is found that, though the maximum values of net, latent and sensible heat flux for the whole lifecycle all occur in the TS-STS stage, their relatively high-value signals (shaded area) all make the first appearance in the south side (270°) of the TC, and transport clockwise and almost all spread to the north (90°).

In addition, the clockwise propagation of the heat fluxes may be related to the energy dispersion and propagation of vortex Rossby waves in the TC periphery. According to Montgomery and Kallenbach[20], the group velocity in the tangential direction along the TC periphery can be expressed as $Cg_{\lambda} = R\bar{\Omega}_0 + \dfrac{(k^2 - n^2/R^2)\beta_{eff}}{(k^2 + n^2/R^2)^2}$. Here $\bar{\Omega}_0 = \bar{V}_0 / R$ is the average symmetric vortex angular velocity at the radius R. Parameters k and n are the wave numbers respectively along the radial and tangential directions. $\beta_{eff} = \dfrac{\mathrm{d}\bar{\zeta}_0}{\mathrm{d}r}$ is the equivalent β effect of vortex Rossby waves, which is a relative vorticity gradient in the radius of the symmetric vortex in the TC periphery, similar to the β item on the planetary scale. We know that, the relative vorticity achieves its maximum near the TC center and decreases as the radius is increasing, so β_{eff} is always negative outside the eye of TC. In general, there appears only one wavenumber of vortex Rossby wave in the tangential direction around a TC eye and only in the spiral clouds band outside the radius of the maximum wind speed ($R > 1$) can the group velocity be negative. It means that, the energy of the vortex Rossby waves should disperse and propagate clockwise, which makes the TC spiral cloud bands strengthen and develop clockwise too. As a result, accompanied with the clockwise development of the TC, the high-value areas of the air-sea heat fluxes move clockwise from the south side to the north side of the TC (Figs. 6–8).

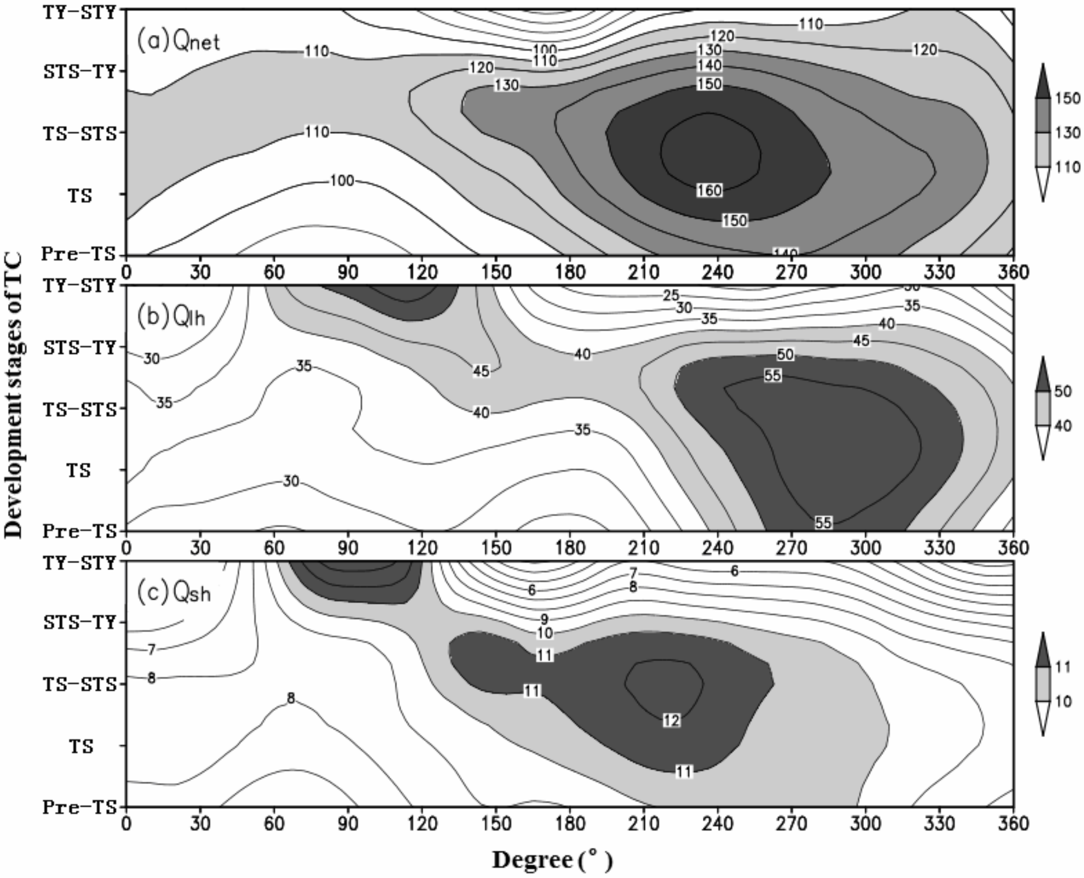

Figure 8. Tangential distributions of net heat (a), latent heat (b), and sensible heat (c) fluxes within the typhoon circulation during the generation and development process of the SLTs. Unit of heat flux is Wm^{-2}. 0º indicates the east direction, 90º the north, following an anti-clockwise rule.

4.3 *Evolutions of air-sea fluxes in the TC circulation*

The heat fluxes in each stage mentioned in section 4.2 are averaged to obtain the evolution curves as shown in Fig. 9. Similar to the results drawn from Figs. 6–8, the evolutions of the net heat, latent heat and sensible heat flux are well consistent with each other. Three days before TSs form, the exchange of net heat is the most significant, followed in turn by the latent heat and sensible heat. Then, with the genesis of TSs, the heat released by the ocean increases continuously and reaches the maximum at the TS-STS stage. It changes little in the next stage. Finally in the TY-STY stage, the released heat reduces gradually and the SLTs tend to demise. The change in the latent heat is one of the main factors that cause changes in the net heat, and it is also the main form for the ocean to release heat to the atmosphere within the TC circulation. This process is consistent with the findings of Wu[13]. The magnitude of the net heat flux is significantly greater than the sum of the latent heat and sensible heat, which suggests that the contribution of the effective sea-surface back longwave radiation should not be ignored in the development of TC. The clouds within the TC circulation are so thick that the sea surface long-wave radiation could not easily penetrate clouds to reach the outer space, but is mainly absorbed by the atmosphere and becomes part of the TC energy source. Thus, the effect of sea surface back long-wave radiation on the TC, in turn, is affected by the TC clouds. This paper mainly focuses on the influences of the heat fluxes on the TC formation and development. On the other hand, the impact of long-wave radiation does not appear until large TC clouds are already generated so that it does not play an important role in the process of TC genesis and will not be discussed in this work in detail.

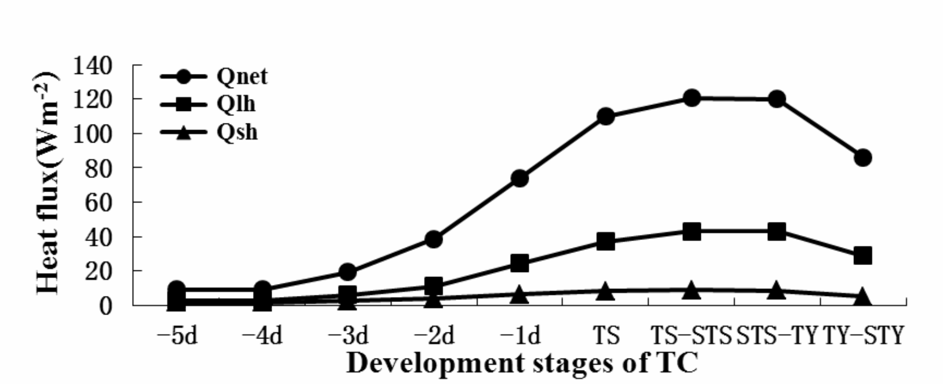

Figure 9. Evolution curves of heat fluxes with the development of TC.

5 CONCLUSIONS

Based on the daily heat flux data from the Woods Hole Oceanographic Institution_Objectively Analyzed air-sea Fluxes (WHOI_OAFlux) and the TCs data from Shanghai Typhoon Institute of CMA during 1985−2007, and using the composite method, the air-sea exchange during the process of generation and development of the SLTs is studied. The main results are as follows:

(1) About 68% of the TCs in SCS can develop into TSs. The intensity of the SLTs is weak generally, only a few of them can reach the grade of ST or above. The genesis latitude as well as the moving track of a SLT may affect its final intensity. The higher latitude a SLT forms on, the stronger intensity it can achieve. With the increase of the grade of intensity, the proportion of the northeast-path TCs increases significantly.

(2) The monthly numbers of the SCS TCs and SLTs both present seasonal variations with two peaks in May and July to September. The SLTs also present an intra-seasonal oscillation with a period of two months.

(3) The net heat flux released by the ocean is increasing day by day before the SLTs form, and the high-value area moves from the SCS center to the north of the SCS. Once the SLTs form, the distribution of the net heat flux would no longer change significantly. The distributions of the latent and sensible flux are similar to that of the net heat flux. It is easier for a TC to form over the part of the oceans where large amount of energy is released to the atmosphere.

(4) Before cyclogenesis, it is the ocean south of the TC center that provides the main energy. With the development of the TC, the ocean releases more and more energy, and the exothermal center gradually moves clockwise to the north of the TC, which reflects the energy dispersion of the vortex Rossby waves at the TC periphery. None of the net heat, latent heat and sensible heat exchange is significant near the eye.

(5) Overall, for the several days prior to the genesis to the stage of STY, the SLT has evolutions of the net heat, latent heat and sensible heat flux well consistent with each other, with the latent heat making the main contribution to the net heat. Besides the latent and sensible heat flux, the role of the effective sea-surface back radiation also cannot be negligible in the TCs development.

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REFERENCES:

[1] BLACK P G.. Ocean temperature change induced by tropical cyclones [D]. The Pennsylvania State University, 1983: 278.
[2] BENDER M A, GINIS I, KURIHARA Y. Numerical simulations of tropical cyclone-ocean interaction with a high resolution coupled model [J]. J. Geophys. Res, 1993, 98(D12): 23245-23263.
[3] JENNI L E. Sensitivity of tropical cyclone intensity to sea surface temperature [J]. J. Climate., 1993, 6(6): 1133-1140.
[4]CHEN Y J, XIE Q, MENG W et al. An experiment study on the influence of different sea surface temperature on TC Dujuan over the South China Sea [J]. J. Trop. Meteor., 2009, 25(4): 401-406 (in Chinese).
[5] MAO Q, CHANG S W, PFEFFER R L. Influence of large-scale initial oceanic mixed layer depth on tropical cyclones [J]. Mon. Wea. Rev., 2000, 128(12): 4058-4070.
[6] LI J, JIANG X P, YUAN H H, et al. The impact of mixed layer depth on the tropical cyclone [J]. Meteor., 2010, 36(4): 27-29 (in Chinese).
[7] CHAN J C L, DUAN Y, SHAY L K. Tropical cyclone intensity change from a simple ocean-atmosphere coupled model [J]. J. Atmos. Sci., 2001, 58(2): 154-172.
[8] WU D S, DENG W Z, ZHANG J F, et al. A Research on air-sea interface heat exchange under the TC over the South China Sea [J]. Atmos. Sci., 2001, 25(3): 299-341 (in Chinese).
[9] HODUR R. The Naval Research Laboratory’s Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) [J]. Mon. Wea. Rev., 1997, 125(7): 1414-1430.
[10] ZHU H, WOLFGANG U, SMITH R K. Ocean effects on tropical cyclone intensification and inner-core asymmetries [J]. J. Atmos. Sci., 2004, 61(11): 1245-1258.

[11] JIANG X P, LIU C X, QI Y Q. The simulation of TC Krovanh using a coupled air-sea model [J]. Atmos. Sci., 2009, 33(1): 99-108 (in Chinese).

[12] JIANG X P, LIU C X, MO H T, et al. The impact of air-sea interactions on TC structure [J]. J. Trop. Meteor., 2010, 26(1): 55-59 (in Chinese).

[13] WU D S. Western tropical Pacific air-sea heat flux study II: the characteristics of sea-air heat exchange under tropical cyclone status [J]. Acta Atmos. Sinica, 1996, 20(5): 533-540 (in Chinese).

[14]WU D S, ZHAO X, FENG W Z, et al. The statistical analysis to the local harmful TC of South China Sea [J]. J. Trop. Meteor., 2005, 21(3): 309-314 (in Chinese).

[15] CHEN J R. Latitudinal distribution characteristics of tropical cyclone in South China Sea [J]. J. Oceanogr. Taiwan Strait., 2007, 26(4): 465-451 (in Chinese).

[16] HUANG F, LI Y N. Relationship between the South China Sea summer monsoon onset and the tropical cyclone activity in the Western North Pacific [J]. J. Ocean Univ. China, 2010, 40(8): 1-10 (in Chinese).

[17] HUANG F, XU S B. Characteristics of super TC activity over western north Pacific and its relationship [J]. J. Ocean Univ. China, 2009, 39(5): 883-888 (in Chinese).

[18] LIN A L, WAN Q L, LIANG J Y, et al. Influence of tropical southwest monsoon on tropical cyclone Vongfong [J]. J. Meteor., 2004, 62(6): 841-850 (in Chinese).

[19] YAO S F, TANG W, HE H, et al. Southwest monsoon and the coupled tropics cyclone downpour process diagnose analysis [J]. Marine Forecasts, 2008, 25(1): 88-94 (in Chinese).

[20] Montgomery M T, Kallenbach R J. A theory for vortex Rossby-waves and its application for spiral bands and intensity changes in hurricanes [J]. Quart. J. Roy. Meteor. Soc., 1997, 123(538): 435-465.

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