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SURFACE OBSERVATIONS IN THE TROPICAL CYCLONE ENVIRONMENT OVER THE SOUTH CHINA SEA

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Abstract: In this paper, the observational data from Marine and Meteorological Observation Platform (MMOP) at Bohe, Maoming and buoys located in Shanwei and Maoming are used to study the characteristics of air-sea temperature and specific humidity difference and the relationship between wind and wave with the tropical cyclones over the South China Sea (SCS). The heat and momentum fluxes from eddy covariance measurement (EC) are compared with these fluxes calculated by the COARE 3.0 algorithm for Typhoon Koppu. The results show that at the developing and weakening stages of Koppu, both these differences between the sea surface and the near-surface atmosphere from the MMOP are negative, and data from the buoys also indicate that the differences are negative between the sea surface and near-surface atmosphere on the right rear portion of tropical cyclones (TCs) Molave and Chanthu. However, the differences are positive on the left front portion of Molave and Chanthu. These positive differences suggest that the heat flux is transferred from the ocean to the atmosphere, thus intensifying and maintaining the two TCs. The negative differences indicate that the ocean removes heat fluxes from the atmosphere, thus weakening the TCs. The wind-wave curves of TCs Molave and Chanthu show that significant wave height increases linearly with 2-min wind speed at 10-m height when the wind speed is less than 25 m/s, but when the wind speed is greater than 25 m/s, the significant wave height increases slightly with the wind speed. By comparing the observed sensible heat, latent heat, and friction velocity from EC with these variables from COARE 3.0 algorithm, a great bias between the observed and calculated sensible heat and latent heat fluxes is revealed, and the observed friction velocity is found to be almost the same as the calculated friction velocity.

Key words: tropical cyclones over the South China Sea; temperature and specific humidity difference; wind-wave

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1 INTRODUCTION

As is well known, the air-sea interaction plays a very important role in the genesis and development of tropical cyclones (TCs). The ocean provides energy for TC genesis and development. Meanwhile, dramatic oceanic responses to TCs occur within the upper layer of the ocean. This strong air-sea interaction usually takes place within the air-sea boundary layer of TCs. However, due to the lack of low-level observation, it is quite difficult to understand deeply the detailed characteristics of the air-sea boundary layer and its effect on the intensity change of TCs. In the past ten years, with the increase of observational data over the ocean and the implementation of special experiments (e.g. the Coupled Boundary Layers Air-Sea Transfer experiment), significant progress has been made in the observational research of the air-sea boundary layer of TCs. Studying the marine surface observation from 37 hurricanes between 1975 and 1998, Cione et al.[1] found that the difference between sea surface temperature (SST) and near-surface atmospheric temperature (TA) increased from 0.15°C to 2.42°C at 3.25° to 1.25° latitudes from the hurricane center, and 90% of the observed cooling occurs here with the sea surface at 27°C at least. The surface specific humidity decreased 1.2 g/kg at 4.5° to 1.75° latitudes from the hurricane center. They argued that downdrafts may be acting to dry and cool through evaporation in the near-surface environment. Analyzing dropsound data, Barnes and Bogner[2] supported the hypothesis proposed by Cione et al.[1] that downdrafts may be

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dried and cooled by the near-surface air. Later Cione and Uhlhorn[3] studied the relationship between the storm intensity and the difference between SST inside the hurricane and SST in the forefront of the hurricane environment. They pointed out that this difference influences the intensifying and maintaining processes of TCs under certain conditions. These results indicate that changes of the marine and meteorological variables within the air-sea boundary layer may have a direct influence on the intensity changes of TCs to a certain extent.

In China, with the marine observational data increasing, knowledge has been gained about the air-sea boundary layer characteristics of TCs. For example, Liu et al.[4] used the data from Argo buoys to analyze the variations of sea temperature in TCs in the Western North Pacific (WNP) from 2001 to 2004, and the results showed that the drop of sea temperature was especially significant 50 to 150 km away from the right side of the best track of the TC. Applying the data for the TCs processed from Marex Buoy of the South China Sea (SCS) Branch of the State Oceanic Administration, China, Wu et. al.[5] and Wu et. al.[6] studied the heat flux at the air-sea interface of TCs. Results of both studies showed that the air-sea interface heat exchange of TCs is very strong; latent heat flux is the main contributor to the heat. The negative sensible heat flux occurred within the TC circulation in summer, and sensible heat flux of the TC significantly increased in autumn. Wu et. al.[6] further pointed out that both water temperature and air temperature tend to fall within the TC circulation and air temperature decreases obviously. However, because of the lack of maritime observational data, knowledge about the air-sea boundary layer during the TC processes is still at an early stage. Consequently, observational analysis and theoretical research need to be carried out on the characteristics of marine and meteorological variables within the boundary layer during TC processes and on how it affects TC intensity.

In this paper, in order to understand the air-sea boundary layer in the offshore areas of the SCS, data from the Marine and Meteorological Observation Platform (MMOP) at Bohe, Maoming and the buoys offshore Shantou and Maoming will be used to investigate the distributional characteristics of the air-sea temperature and specific humidity differences under the influence of TCs and the wind-wave relationship in TCs. Heat and momentum fluxes from eddy covariance measurements for typhoon Koppu are compared with the fluxes calculated with the COARE 3.0 algorithm.

2 DATA AND TC WEATHER PROCESSES

2.1 *Data and methods*

Data from the MMOP and offshore buoys are used in this paper to analyze the variation characteristics of near-surface marine and meteorological elements under the influence of TCs over the SCS between 2009 and 2010. The MMOP is located about 6 km south of Bohe Port of Maoming with water depth at 14 m. The total height of the platform is 53 m. The upper part of the platform is a 25-m long steel tower and its lower part consists of a foundation that supports steel tubes, and a triangular platform. It mainly comprises a 30-m tower, which is used to measure air-sea flux and the atmospheric boundary layer, a 10-m marine and meteorological tower, and underwater oceanic observation equipment. Elements observed on this platform mainly include 5 layers of wind, temperature and humidity, as well as SST, rainfall, atmospheric pressure, and fluxes from eddy covariance measurement. The Maoming buoy is located about 100 km south of the coast of Diancheng Town, Dianbai County, where the water depth is about 50 m. The Shanwei buoy is mounted 5 km away from the coast of Honghai Bay, Shanwei, where the water depth is about 25 m. Observational data from the buoys mainly include 2 layers of wind, temperature and humidity, as well as atmospheric pressure, rainfall, wave height, wave direction, wave period, and SST, at a depth of 50 cm. We also use the 6-h best tracks and intensities of TCs from *Yearbook of TCs* edited by Shanghai Typhoon Institute (STI) of China Meteorological Administration.

Table 1 describes the observational elements and data intervals from the MMOP and the two buoys in this research. The height of SST measurement at the MMOP is different from that of the buoys. Infrared radiometers at the MMOP are used to measure the sea surface skin temperature, while traditional observations of the buoys are to monitor water temperature at the depth of 50 cm. For composite analysis of air-sea temperature difference, it is necessary to correct the SST measured at the MMOP. In SST observation, different detecting approaches can result in different forms in which SST is presented. Infrared radiometers are usually used to measure temperatures at depths of the micrometer-order under the sea surface; microwave radiometers are used to measure temperatures at depths about 1 mm under the sea surface. For the buoys, SST is usually directly measured with instruments at various water depths from centimeters to meters[7]. Donlon et al.[7] argued that the difference between sea surface skin surface and SST from the buoys is –0.17±0.07krms when the 10-m wind speed is greater than 6 m/s. So, we can convert, via this relationship, the sea surface skin temperature from the MMOP in TCs to the SST recorded by the buoys.

Table 1. Data description of the Marine and Meteorological Observation Platform and buoys for this research.

	Observational heights	Atmospheric Variables	Oceanic Variables	Data Averaging periods	Data recorded intervals
Platform	13.4m, 16.4m, 20m, 23.4m & 31.3m	Wind speed wind direction temperature Relative Humidity pressure(only 13.4 m)	Sea surface skin temperature	1 min	1 min
	27.3m, 35.1m	sensible flux, latent flux and frictional velocity by eddy covariance measurement			
Buoy	10m, 15m	Wind speed wind direction temperature Relative Humidity pressure(only 10m)	Sea surface temperature (50cm depth)	1 min	10 min

Table 1 also shows that the atmospheric temperatures and specific humidity of Maoming and Shanwei buoys are at 10 m and 15 m heights, respectively, while the observational height of the lowest level of the MMOP is 13.4 m. In order to investigate the contrast of air-sea temperature and specific humidity, the atmospheric temperature measured at 13.4 m will be converted to the temperature at 10 m by using the dry adiabatic rate of temperature (0.0098°C m^{-1}), while the atmosphere specific humidity at 10 m on the MMOP is gained by extrapolating the 5-layer atmospheric specific humidity data.

In this paper, there is a general investigation of the observational data from the MMOP in Bohe, and buoys in the offshore areas of Maoming and Shanwei for nine cases of TC processes in the SCS (i.e. Molave (0906), tropical storm Goni (0907), Mujigae (0913), Koppu (0915), Chanthu (1003), Lionrock (1006), Fanapi (1011), and Megi (1013) between 2009 and 2010. Quality control is applied to the data. (1) For the observational data, which is located 300 km from the TC center, those that are missed or incorrect are eliminated. (2) In view of the effect of TCs, we have also eliminated data at the time when the central minimum pressure of TC is greater than 998 hPa. With this processing and quality control, there are six cases of TCs that meet our preset conditions.

2.2 *Introduction to tropical cyclone cases*

Through general investigation of the observational data of SCS TCs from 2009 to 2010, we found that observational data of four cyclones, namely Molave (0906), tropical storm Goni (0907), Koppu (0915), and Chanthu (1003), were quite satisfactory. The best tracks and intensity of these four TCs are respectively shown in Figures 1 and 2. Typhoon Molave, tropical storm Goni, and typhoon Chanthu all originated from the West Pacific east to the Philippine's islands and then moved towards the west or northwest into the South China Sea. The genesis of typhoon Koppu was in the north of the Philippines, and later it was strengthened into TC in the South China Sea. When typhoon Molave landed in the coastal area of Dapeng Peninsula (Nan'ao Town) of Shenzhen, Guangdong province at 1650 Coordinated Universal Time (UTC) July 18, 2009, the central maximum wind speed reached Level 13 on the Beaufort scale (38 m/s) and the central minimum atmospheric pressure was 965 hPa. After landing, it moved between northwest and west and gradually weakened, and storm warning was lifted at 1800 UTC July 19 (See Figure 2a). Tropical storm Goni landed in the coast of Taishan, Guangdong province at 2220 UTC August 4, 2009 and then weakened into a tropical depression in the early morning of August 6. After it strengthened into a tropical storm again at 0600 UTC August 7, it weakened into a tropical depression again at 0000 UTC August 9, and warning signals were lifted at 0900 UTC August 9. Tropical storm Goni is not strong; its maximum wind speed was just 23 m/s, which belongs to the level of tropical storm (see Figure 2b), but the best track of tropical storm Goni was very winding (see Figure 1). After landing in the western Guangdong, it went westwards into Beibu Gulf, and then looped over the western coast of Hainan province for almost an entire day before gradually weakening and disappearing, completing a long life span of about 10 days (See Figure 1). Koppu originated from the West Pacific near the Philippines and then moved westwards into the SCS, strengthened into a TC in the offshore area of Guangdong at 0900 UTC September 14, and landed in the coastal area of Beidou Town, Taishan at about 2300 UTC September 14. At the time of its landing, the central minimum atmospheric pressure was 970 hPa and the maximum wind speed was Level 12 (wind speed 35 m/s). After landing it weakened quickly and became a tropical depression at 1600 UTC September 15 in Guangxi, and continued to weaken into a depression trough at 2100 UTC September 15 (Figure 2c). Chanthu developed into a

TC at 0900 UTC July 21, 2010, landed in Wuchuan, Guangdong at 0545 UTC July 22 with a Level-12 maximum wind (35 m/s) near the center and a minimum pressure of 970 hPa at the center, weakened into a tropical depression in western Guangxi at 0500 UTC July 23, and warning was lifted at 1200 UTC July 23.

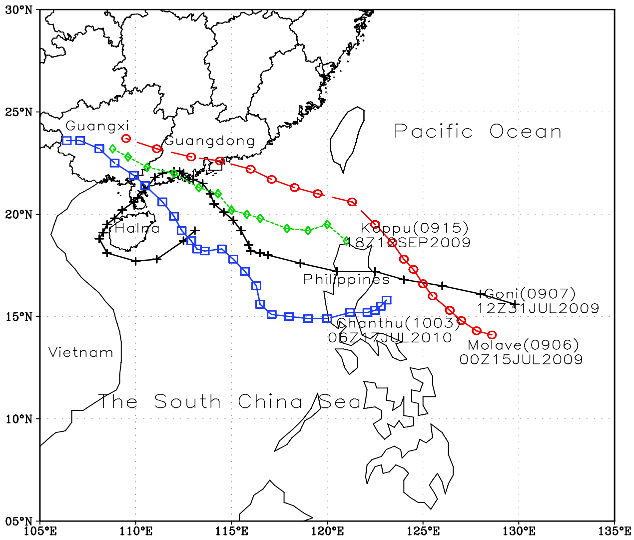


Figure 1. The 6-h best tracks of four TCs, Molave (red line with open circles, from 0000 UTC 15 July to 1200 UTC 19 July 2009), tropical storm Goni (black line with crosses, from 1200 UTC 31 July to 1200 UTC 9 August 2009), Koppu (green line with diamonds, from 1800 UTC 12 September to 1800 UTC 15 September 2009), Chanthu (blue line with open squares, from 0600 UTC 17 July to 1200 23 July 2010).

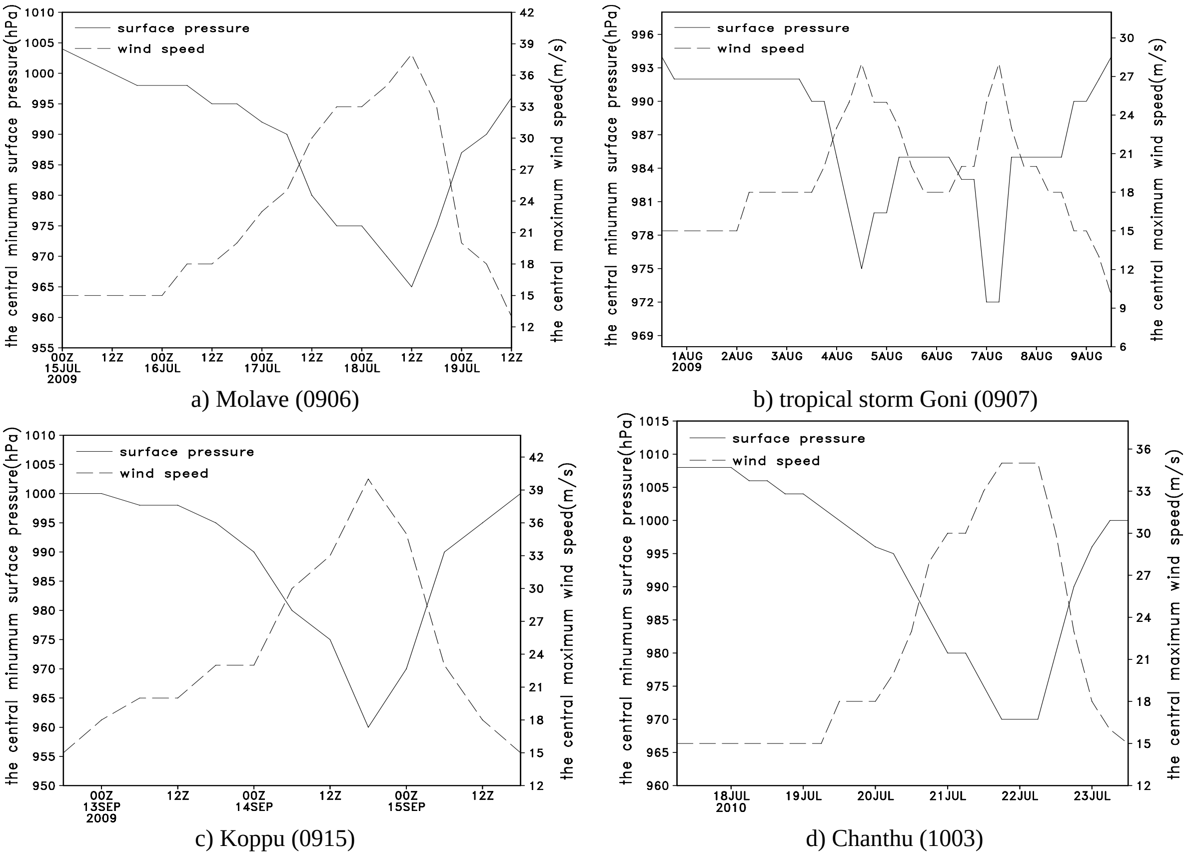


Figure 2. The 6-h central minimum surface pressure (solid line) and central maximum wind speed (dashed line) of the four TCs best track. a: Molave; b: tropical storm Goni; c: Koppu; d: Chanthu. The abscissa is for time in UTC, units in hour).

3 AIR-SEA THERMODYNAMIC CHARACTERS IN THE TROPICAL CYCLONE ENVIRONMENT OVER THE SOUTH CHINA SEA

3.1 *Radial distribution characteristics of air-sea temperature and humidity difference*

Observational results, numerical simulation, and theoretical studies have all shown that the flux exchange at the air-sea interface has direct impacts on the intensity change of a TC. The momentum flux (τ), sensible heat flux (H_s), vapor flux (E), and latent heat flux (H_l) at the air-sea interface can be generally estimated by using the bulk transport formula. Positive values mean that the flux is transferred from the sea to the atmosphere.

$$\tau = \rho_a \overline{w'u'} = \rho_a u_*^2 = \rho_a C_d SU \tag{1}$$

$$H_s = \rho_a C_{pa} \overline{w'T'} = \rho_a C_p u_* \theta_* = \rho_a C_{pa} C_h S(\theta_{sea} - \theta_a) \tag{2}$$

$$E = \rho_a \overline{w'q'} = \rho_a u_* q_* = \rho_a C_E S(q_{sea} - q_a) \tag{3}$$

$$H_l = \rho_a L_v \overline{w'q'} = \rho_a L_v u_* q_* = \rho_a L_v C_E S(q_{sea} - q_a) \tag{4}$$

where u_* is the friction velocity; θ_* and q_* mean the turbulence scale of the potential temperature and specific humidity; C_d, C_H, and C_E are the drag coefficient, the Stanton number, and the Dalton number, respectively; ρ_a is the air density, C_p is the specific heat at constant pressure, L_v is the latent heat of evaporation, and U is the near-surface wind speed. θ_{sea} and θ_a denote the potential temperature of the sea surface and the potential temperature of the atmosphere, respectively. q_{sea} and q_a denote the specific humidity near the sea surface and the specific humidity of the atmosphere, respectively, which indicates the vapor situation near the sea surface and the atmosphere. Eq. (2) can be rewritten as the following formula.

$$H_s = \rho_a C_{pa} \overline{w'T'} = \rho_a C_p u_* \theta_* = \rho_a C_{pa} C_h S(T_{sea} - T_a)(\frac{1000}{p})^{R_d/c_p} \tag{5}$$

Eq. (4) and Eq. (5) show that there is a very close relationship between the sensible heat and latent heat fluxes at the air-sea interface and the contrast between sea-air temperature and specific humidity. The symbol of these differences determines the direction in which sensible heat and latent heat fluxes are transferred at the air-sea interface.

The 6-h TC positions and the air-sea temperature differences from the MMOP in Bohe, Maoming and the simultaneous Shanwei and Maoming buoys are used to analyze the radial distribution of air-sea temperature differences of six TCs that took place in 2009 and 2010 (See Figure 3). Figure 3 shows that the difference between SST and near-surface air temperature is from –14°C to 0.9°C, which is less than 300 km from the TC center. There is no clear relationship between the air-sea temperature and the distance from the TC center. This result does not match the finding by Cione et. al.[1] that the difference between SST (sea surface temperature) and TA (surface atmospheric temperature) increased from 3.25° to 1.25° latitude by This paper also analyzes the contrast of SST and surface atmospheric temperature derived from observational data of each tropical cyclone (Figure not shown). The results show that the differences between SST and TA of both tropical storms Goni and Koppu from the MMOP were negative, and the maximum temperature difference was –14°C, probably because the platform was located in the shallow water offshore. Another possible cause for these radial distribution characteristics of air-sea temperature difference is that the sample number we used for analysis was significantly fewer than that of Cione et al.[1]

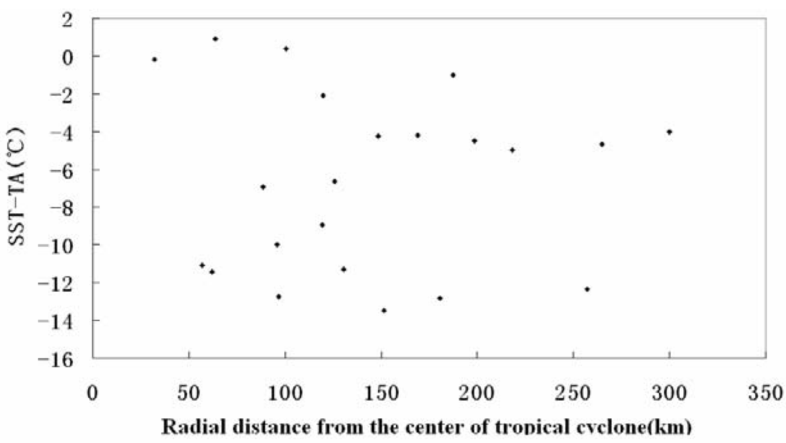


Figure 3. Differences between SST and TA as the function of radial distance from the center of TC.

Analyzing the difference of SST and TA and the difference of sea surface specific humidity and surface air humidity from the MMOP of Maoming during the Goni and Koppu processes, we can find that (Figures

5b and 5c) these differences were always negative within 300 km from the centers of both TCs (See Figures 4b and 4c). These facts mean that the sensible heat and latent heat fluxes—transferred from the atmosphere to the sea wherever the fluxes data—are located in a TC circulation. In the intensifying period of typhoon Koppu (i.e. before 0600 UTC September 15, 2009, in Figure 2a), the transfer of the sensible heat and latent heat fluxes in the MMOP is from the atmosphere to the sea. For tropical storm Goni, at its weakening stage from 0000 UTC August 5 to 0000 UTC August 6, the fluxes of sensible heat and latent heat from the atmosphere to the sea have a positive effect on TC weakening, while the MMOP is located in the W-SW phase within 200 km from the TC center, which is on the left or left rear portion of the TC along its best track. During the re-strengthening stage of tropical storm Goni, it was unfavorable for its strengthening. The sensible heat and latent heat fluxes are transferred from the atmosphere to the sea, while the MMOP was located on the right side of the TC.

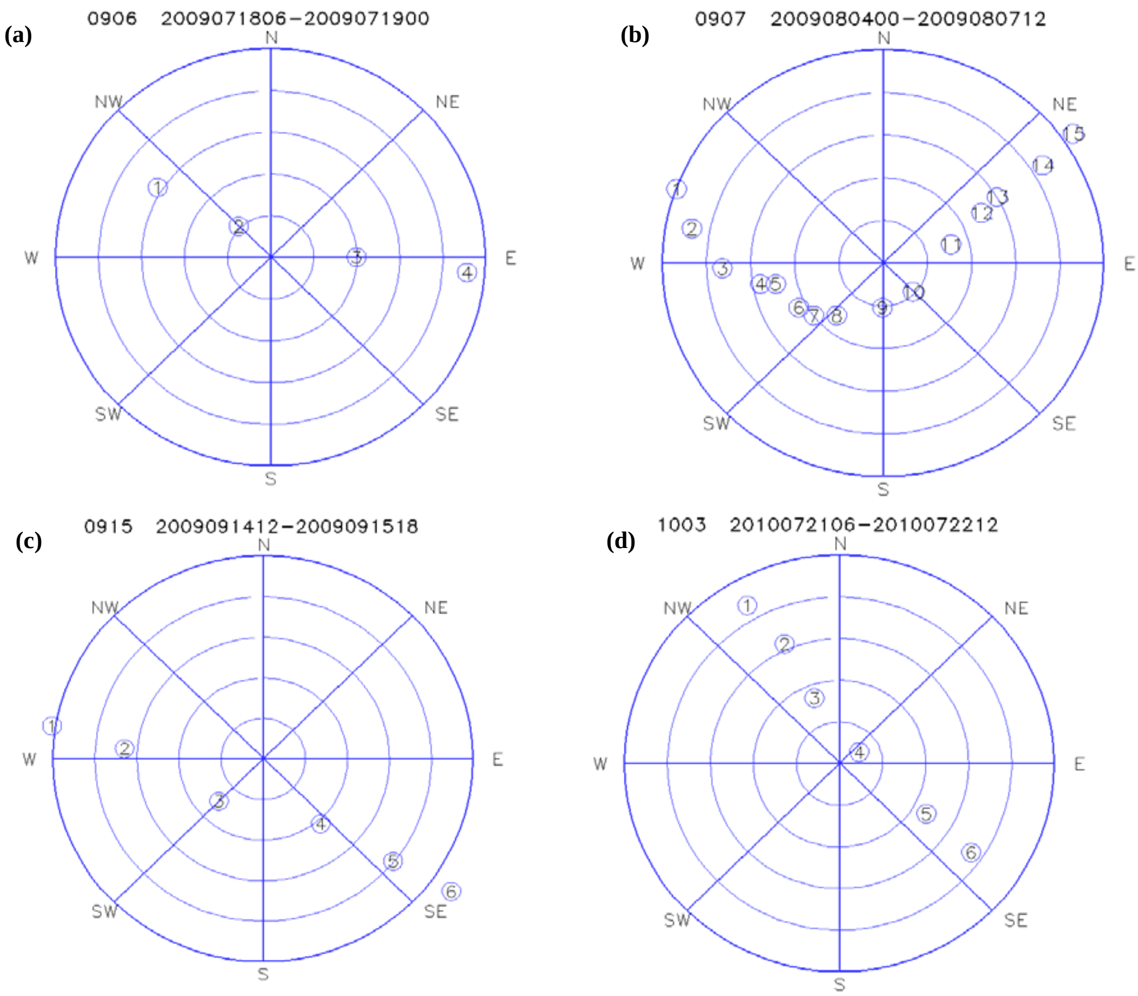
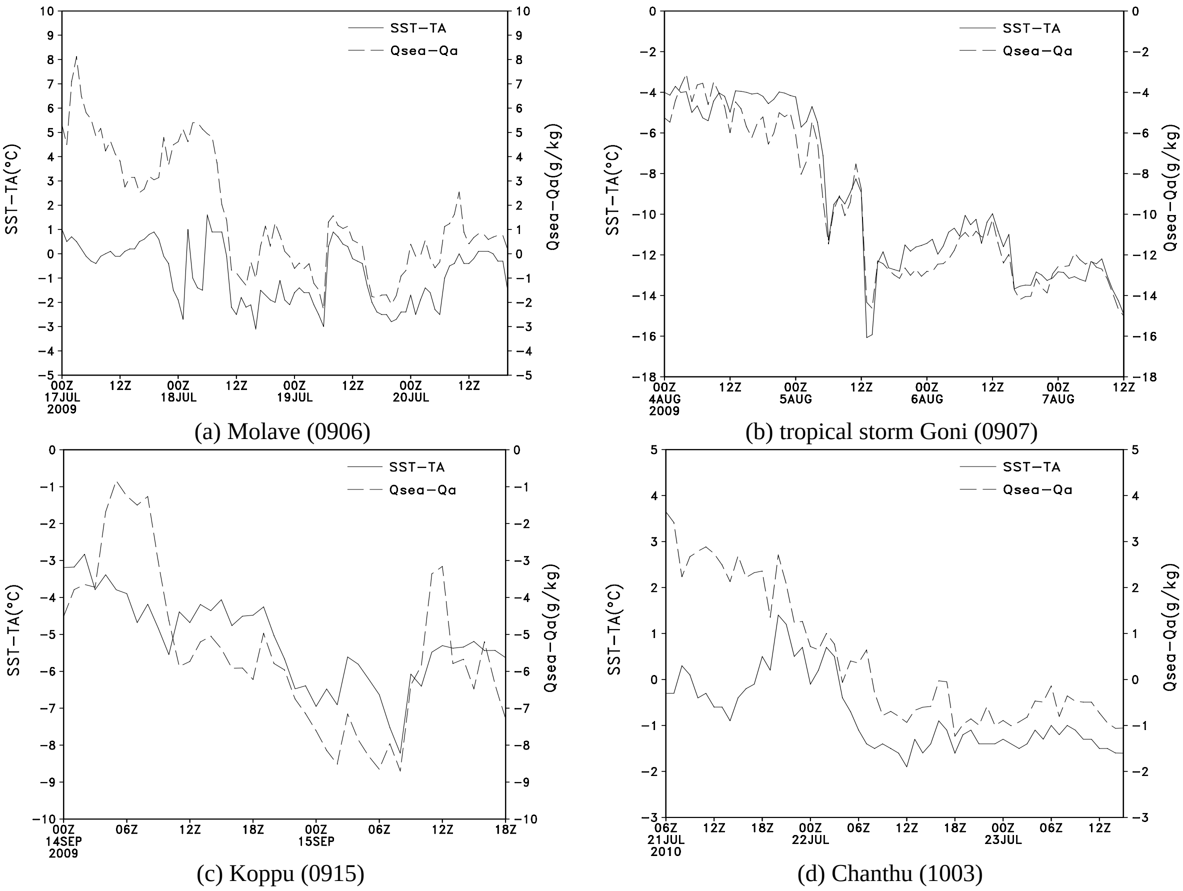


Figure 4. (a): ①-④ respectively stand for the position of the Shanwei buoy with respect to the center of typhoon Molave at intervals of 6 hours from 0600 UTC July 18 to 0000 UTC July 19, 2009. (b): ①-⑮ respectively stand for the position of MMOP at Maoming with respect to the center of tropical storm Goni at intervals of 6 hours from 0000 UTC August 4 to 1200 UTC August 7, 2009. (c): ①-⑥ respectively stand for the position of MMOP at Maoming with respect to the center of typhoon Koppu at intervals of 6 hours from 1200 UTC September 14 to 1800 UTC September 15, 2009. (d): ①-⑥ respectively stand for the position of the Maoming buoy with respect to the center of typhoon Chanthu at intervals of 6 hours from 0600 UTC July 21 to 1200 UTC July 22, 2010. (The center of each large circle is the center of the TC. Circles around this center respectively stand for distances of 60, 120, 180, 240, and 300 km from the TC center. The characters represent the different phases with respect to the TC. N stands for north, S for south, W for west, E for east, NW and NE respectively for northwest and northeast, and SW and SE respectively for southwest and southeast.)

Figure 4a shows the position of the Shanwei buoy with respect to the center of typhoon Molave at different time, and Figure 5a presents the difference of SST and TA and the difference of sea surface specific humidity and surface air humidity from the Shanwei buoy. During the strengthening stage of typhoon Molave (i.e. 0600 UTC July 18, 2009 and 1200 UTC July 18, 2009, in Figure 2a), the Shanwei buoy was located in the W-NW phase of the TC circulation and between 60 and 180 km from the TC center, and here the difference between SST and TA and the difference between sea surface specific humidity and surface air humidity are positive, indicating that the sensible heat and latent heat fluxes are transferred from the sea to the atmosphere. The results imply that these positive differences on the left front of typhoon Molave along the best tracks can cause the development of typhoon Molave. From 1800 UTC July 18 to 0000 UTC July 19, 2009, the Shanwei buoy was located in the easterly phase 120 to 274 km from the central typhoon Molave, which was in the weakening stage. During the same period, the difference of SST and TA from the Shanwei buoy was negative and decreased to –3°C, and both positive and negative values of the difference of sea surface specific humidity and near-surface atmospheric specific humidity were observed, ranging between –2 g/kg and 2 g/kg. This indicates that in the easterly phase (i.e. on the right side) of the TC, the sensible heat flux from air to sea favors the weakening of typhoon Molave, and it is difficult to understand how the difference of sea surface specific humidity and atmospheric specific humidity affect the TC intensity change because of the uncertain direction of latent heat fluxes.

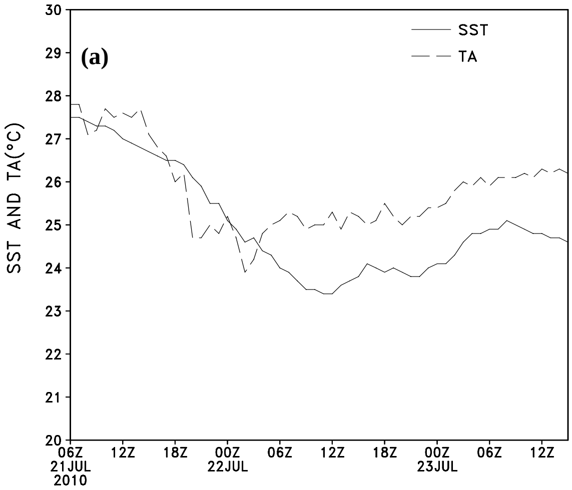


(a) Molave (0906) (b) tropical storm Goni (0907)

(c) Koppu (0915) (d) Chanthu (1003)

Figure 5. Temporal variations of the difference of sea surface temperature and surface air temperature (solid line) and temporal variations of the difference of sea surface specific humidity and surface air humidity (dashed line).

Figure 4d shows the position of the Maoming buoy with respect to the center of typhoon Chanthu. And the difference of SST and TA and the difference of sea surface specific humidity and surface atmospheric specific humidity from this buoy are shown in Figure 5d. From 0600 UTC to 1200 UTC July 21, 2010, there are nearly negative differences between SST and TA and positive difference between sea surface specific humidity and near-surface atmospheric specific humidity (See Figure 5d), while the Maoming buoy was located in the NW-N phase 262 to 188 km from the center of typhoon Chanthu, which is in the front of it along the best track. Between 1800 UTC July 21 and 0000 UTC July 22, 2010, the Maoming buoy was located within 120 km from the TC center and the difference between SST and TA and the difference between sea surface specific humidity and surface air humidity are both positive. This means that the ocean supplies sensible heat and latent heat for the atmosphere, which maintains the TC intensity during the period. From 0600 to 1200 UTC July 22, 2010, the Maoming Buoy was located on the right back of the moving direction of typhoon Chanthu, 120 km from its center. During the period, data from the Maoming buoy show that the air-sea temperature difference was negative, and the air-sea humidity difference was almost negative except for a few times. It indicates that the transfer of sensible heat and latent heat fluxes from the atmosphere to the sea has a positive effect on the weakening of TC intensity.



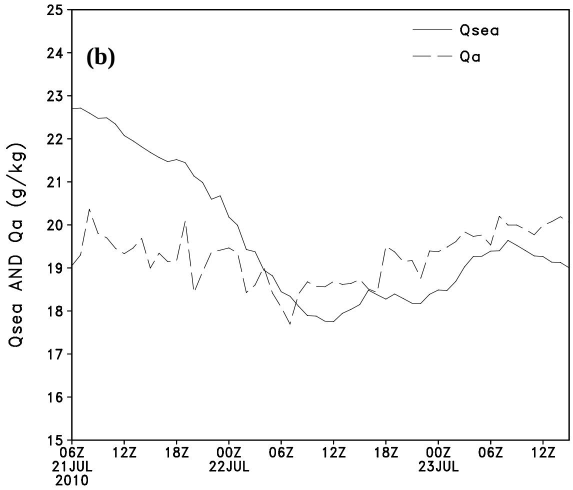


Figure 6. a) Sea surface temperature (solid line) and 10-m atmospheric temperature (dashed line); b) sea surface specific humidity (solid line) and 10-m atmospheric humidity (dashed line).

In summary, for both Molave and Chanthu, the sensible heat and latent heat fluxes are transferred from the sea to the atmosphere in the foreparts of the TCs along their best tracks within 120 km from the TC centers or in the right of their best tracks within 60 km from the TC centers, favoring the strengthening and maintenance of TC intensity. The sensible heat fluxes of both TCs also are transferred from the atmosphere to the sea in the right of the TCs along their best tracks between 120 km and 300 km from their centers. But the latent heat fluxes of both TCs show significantly different behaviors. During the typhoon Chanthu process, the transfer of latent heat fluxes from the atmosphere to the sea has a positive effect on the weakening of TC intensity, while the latent heat flux of typhoon Molave has both positive and negative values, which makes it difficult to estimate the effect on the change of TC intensity. During the intensity variation of tropical storm Goni and typhoon Koppu, the observational data from the MMOP indicates that both the sensible heat and the latent heat fluxes are transferred from the atmosphere to the sea and only the magnitude of the heat fluxes changes.

3.2 *Cooling effect of TCs*

Figure 5d shows that from 1800 UTC July 21 to 0000 UTC July 22, 2010, both the air-sea temperature difference and humidity difference were positive under the influence of typhoon Chanthu. To gain further knowledge of the causes for this phenomenon, the temporal variations of SST and TA are investigated in the same way as that for the sea surface specific humidity and surface atmospheric specific humidity during the period of typhoon Chanthu (Figures 6a and 6b). Between 1800 UTC July 21 and 0000 UTC July 22, 2010, both the SST and 10-m atmospheric temperature were decreasing. And the cooling rate of the atmospheric temperature is significantly greater than that of the sea surface temperature, resulting in the positive difference between SST and TA. As to the air-sea humidity difference, the sea surface specific humidity was significantly greater than the surface atmospheric specific humidity before 0600 UTC July 22 and the air-sea specific humidity difference still remained positive although the difference was decreasing with time. Investigation of the temporal variation curves of SST and humidity and the distances of the Maoming buoy from the TC center at corresponding points of time indicates that the decreases of both SST and atmospheric temperature are in the left and near the center of the TC, accompanied by significantly reduced sea surface moisture. That means the sea surface was cooling and drying. Figure 6a shows that the cooling of minimum sea surface temperature lagged behind the attainment of maximum wind speed, while the cooling of minimum air temperature correspond well with the attainment of maximum wind speed. It is suggested that the cooling effect lasts for a longer time on the sea surface than in the atmosphere.

3.3 *Relationship between air-sea temperature difference and surface wind speed*

By examining the relationships between the air-sea temperature differences and 2-min average wind speed at 10-m height from the buoys in Shanwei and Maoming during typhoon Molave and typhoon Chanthu (Figures 7a and 7b), we found that when the wind speed was less than 10 m/s, the air-sea temperature differences of both TCs varied with time in almost the same pattern and there was no clear relationship between air-sea temperature and wind speed. As the wind speed increased from 15 m/s to 35 m/s, the air-sea temperature difference of typhoon Chanthu changed from –1°C to 1°C and a linear relationship was exhibited between air-sea temperature difference and wind speed (Figure 7b). Korolev et al.[8] and Pudov[9] suggested that average air-sea temperature varied from 1°C to 5–6°C as surface wind speed increased from 12 to 25 m/s. It can be inferred that when the surface wind speed is high, the air-sea temperature difference varies as the function of surface speed in TCs over the South China Sea, which is the same as that in the Atlantic hurricanes. However, there is a significant contrast in the magnitude of air-sea temperature difference as the function of wind speed. Therefore the relationship between air-sea temperature difference and wind speed still needs to be validated with lots of observational data. From Figure 7 we can also see that as the wind speed increased, the variation of air-sea temperature difference with wind speed was irregular during typhoon Molave and did not reflect the characteristics shown by typhoon Chanthu, probably because the Shanwei buoy was located near the coastline and its water depth was only about 20 m.

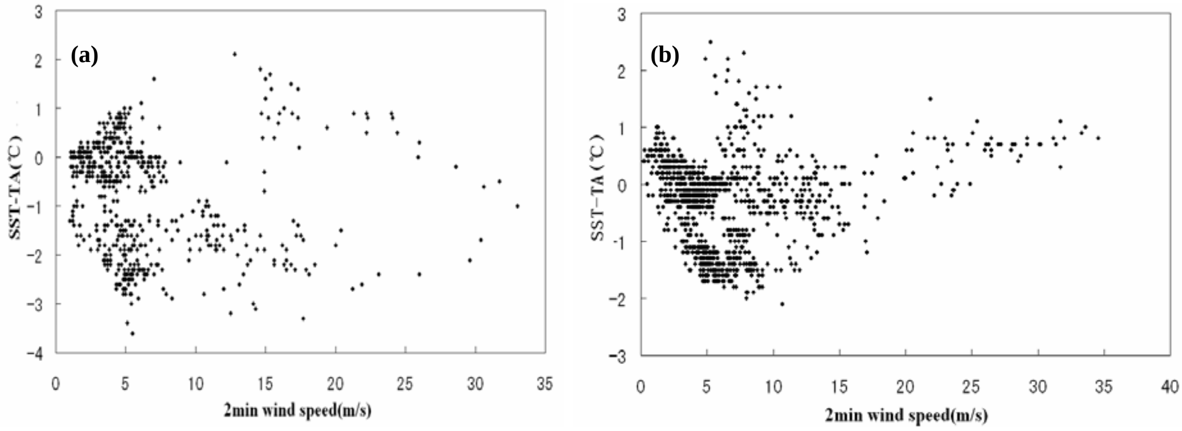


Figure 7. Differences between SST and TA as a function of 2-min wind speed. a) Typhoon Molave from the Shanwei buoy; b) typhoon Chanthu from the Maoming buoy.

4 RELATIONSHIP BETWEEN WIND AND WAVE IN TROPICAL CYCLONE ENVIRONMENT

Figure 8 shows the relationship between significant wave height and 2-min average wind speed at 10-m height under the influences of typhoons Molave and Chanthu. From the diagram we can see that there is a very significant correlation between the significant wave height and 2-min average wind speed detected by the Maoming buoy under the influence of typhoon Chanthu. After polynomial fitting, the correlation coefficient can be up to 0.8921. The relationship between significant wave height and 2-min average wind speed detected by the Shanwei buoy under the influence of typhoon Molave is quite dispersive, and the correlation coefficient obtained through polynomial fitting is 0.7464, which is significantly smaller than that of the Maoming buoy. In a way, this indicates that the relationship between significant wave height and wind speed in the offshore area is quite complex. Figure 8 indicates that when the wind speed is less than 25 m/s, the relationship between significant wave height and wind speed is nearly linear, and significant wave height increases monotonically with wind speed. When the wind speed is greater than 25 m/s, the significant wave height barely increases and even tends to remain unchanged. This coincides with the fact that the drag coefficient of the sea surface stops increasing or even decreases[10] when the wind speed is higher than 25 m/s, indicating that the slight increase of wave height under high wind speed is probably one of the causes for the sea surface drag coefficient to stop increasing.

5 COMPARAING EDDY COVARIANCE MEASURED FLUXES WITH COARE 3.0 COMPUTED FLUXES

The eddy covariance measurement (EC) heat fluxes and friction velocity is compared with the heat fluxes and friction velocity calculated with the COARE 3.0 algorithm[11] during the typhoon Koppu process (see Figure 9). Both the sensible heat flux and latent heat flux calculated with COARE 3.0 are negative, and the latent heat flux is significantly greater than the sensible heat flux. This agrees with the conclusion proposed by Wu et. al.[6], which is "latent heat flux is the greatest contributor to TCs and negative values of sensible heat flux will occur in the tropical cyclonic circulation in summer". The sensible heat and latent heat directly measured by EC had both positive and negative values during the TC period. The sensible heat flux is 1/10 of the value calculated with COARE 3.0 and the latent heat flux equals 1/2 of the value calculated with COARE 3.0. It can be inferred that there is a great difference between the directly measured air-sea heat flux and the heat flux calculated with COARE 3.0. For the friction velocity from measurement and calculation, however, both their temporal variation (in Figure 9c) and their scatter diagram indicate that there is a good correlation between the directly measured friction velocity and the friction velocity calculated with COARE 3.0, and the value calculated with COARE 3.0 is slightly larger.

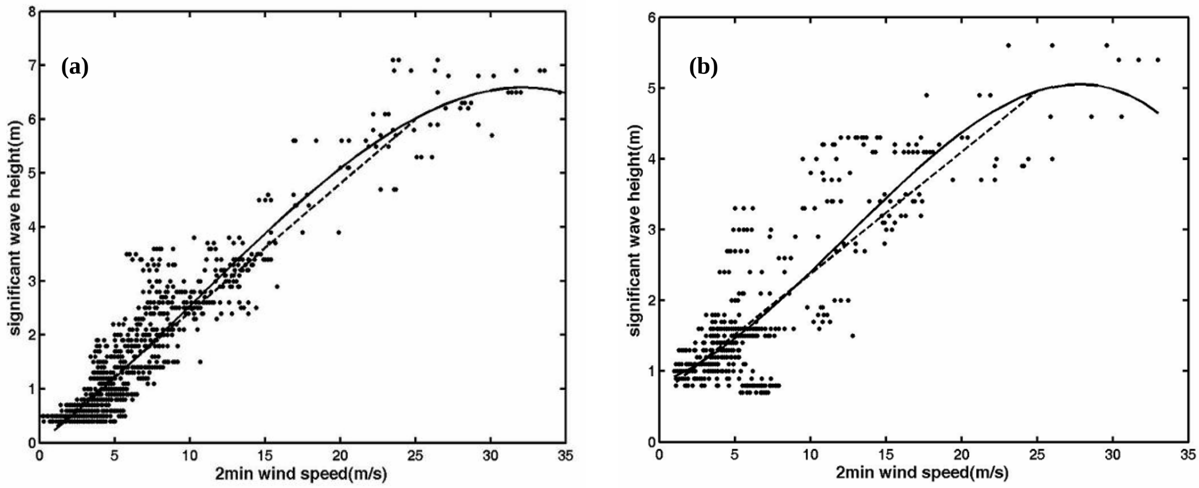


Figure 8. a) Significant wave height as the function of wind speed of typhoon Chanthu by using the Maoming buoy; b) significant wave height as the function of wind speed of typhoon Molave by using the Shanwei buoy. Curves are the polynomial fitting lines, with $y= -0.0002x^3+0.0058x^2+0.2135x+0.0139$ (Figure 8a), $y = -0.0003x^3+0.0107x^2+0.0785x+0.8360$ (Figure 8b). Beeline is the linear fitting line, $y = 0.2480x+0.0393$ (Figure 8a), $y=0.1723x+0.6500$ (Figure 8b).

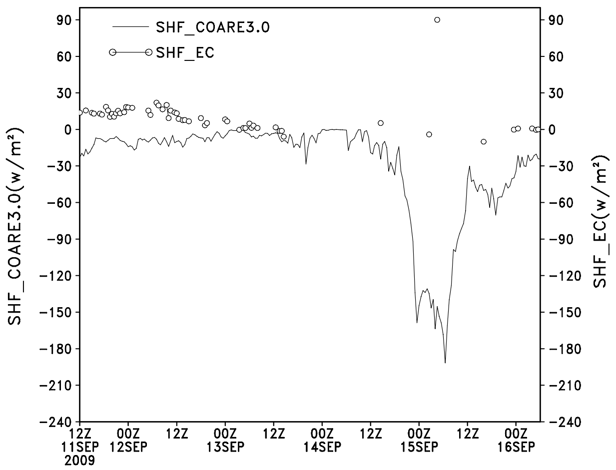
In summary, the difference between the moment flux directly measured by EC and the moment flux calculated with COARE 3.0 is significantly smaller than their heat difference. The directly measured sensible heat and latent heat fluxes have the same transferring direction as the sensible heat and latent heat fluxes calculated with COARE 3.0. It is shown that heat flux is transferred from the sea to the atmosphere, but there is a huge difference in the values between the directly measured heat fluxes and the calculated heat fluxes. Therefore, in the absence of the eddy covariance measurement, we can use the plus-minus status of the flux calculated with COARE 3.0 for a qualitative discussion of the flux transferring direction between the sea and the atmosphere. In other words, we can study the issue of flux exchange between the sea and the atmosphere by using the air-sea temperature difference and humidity difference, which determines the transfer directions of sensible heat and latent heat fluxes in COARE 3.0 formulas.

6 DISCUSSION AND CONCLUSION

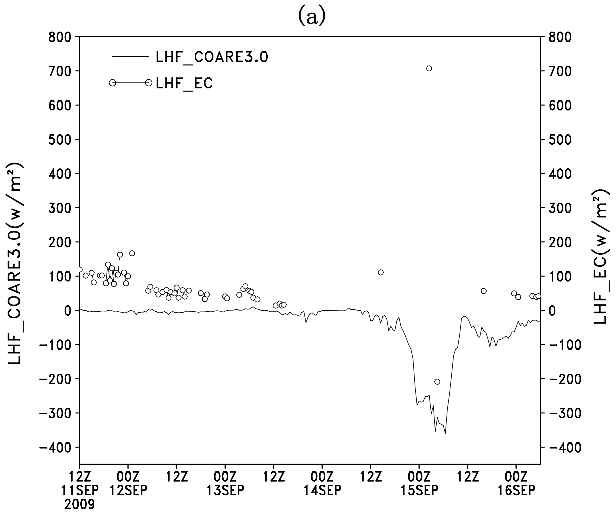
From comparison of the directly measured fluxes from EC and fluxes calculated with COARE 3.0, it is suggested that the air-sea temperature difference and humidity difference are good indicators of the direction in which heat flux is transferred between the sea and the atmosphere. This also provides evidence for the discussion of the issue of heat flux transfer determined by the air-sea temperature difference and humidity difference in Section 3. The comparative analysis of the friction velocities derived from both methods has revealed that the difference between friction velocities from EC and calculated with COARE 3.0 algorithms is far less than the difference in the heat flux.

Analysis of the air-sea temperature difference and specific humidity difference in the TCs indicates four points as follows. (1) The relationship between air-sea temperature difference and the distance from TC's center, which is derived from analysis of 6 TCs, may disagree with the relationship derived by Coine et. al., probably because the MMOP is in a shoal area and the sample number is not enough to study. (2) The study of data from the buoys in Shanwei and Maoming indicates that there is a nearly linear relationship between air-sea temperature difference and wind speed during the influence of TCs. And this has almost the same trend as that of air-sea temperature and wind speed proposed by Korolevet et. al.[8] and Pudov[9]. (3) Analysis of data from the Shanwei and Maoming buoys indicates that positive values of air-sea temperature difference and specific humidity difference frequently occur on the left front of TCs within 120 km from the centers of TCs or in the right of TC along their best tracks within 60 km from TC centers. That shows that the transfer of heat fluxes from the sea to the atmosphere in these areas that has a positive effect on the strengthening and maintenance of TCs. The main reason for the occurrence of positive air-sea temperature difference is that the SST and the air temperature in the lower atmosphere fell simultaneously during the TC processes and the decrease of atmospheric temperature is more significant than that of SST. (4) Analysis of data from the Shanwei and Maoming buoys shows that there are negative values of temperature difference and specific humidity difference between sea surface and near-surface atmosphere on the right side of TCs along their best tracks 120 km from the center of TCs. And it is revealed that the heat was transferred from the atmosphere to the sea in such areas.

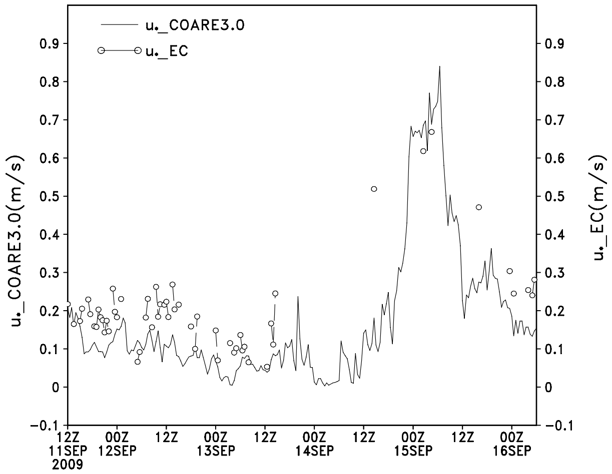
Studying the relationship between significant wave height and 2-min average wind speed measured by the buoys shows that the significant wave height no longer increases monotonically with wind speed but changes slightly when the wind speed is greater than 25 m/s. This coincides with the fact that the sea-surface drag coefficient stops increasing under high wind speeds.



(a)



(b)



(c)

Figure 9. a) Latent heat flux from the eddy covariance measurement (solid line) and calculations with the COARE 3.0 algorithm (open circles); b) sensible heat flux from the eddy covariance measurement (solid line) and calculations with the COARE 3.0 algorithm (open circles), c) u_* from the eddy covariance measurement data (open circles) and COARE 3.0 (solid line). (SHF_EC is for the sensible heat flux from EC, LHF_EC the latent heat flux from EC, SHF_COARE3.0 the sensible heat flux calculated with COARE3.0, and LHF_COARE3.0 the latent heat flux calculated with COAER3.0, and u_*_EC and u_*_COARE3.0 respectively stand for u_* from the eddy covariance measurement and u_* from calculation with COARE 3.0.)

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