An Overview of Tropical Cyclone and Tropical Meteorology Research Progress

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ABSTRACT

There has been much progress in the study of tropical cyclones and tropical meteorology in China in the past few years. A new atmospheric field experiment of tropical cyclone landfall with the acronym of CLATEX (China Landfalling Typhoon Experiment) was implemented in July–August 2002. The boundary layer characteristics of the target typhoon Vongfong and the mesoscale structural features of other landfalling typhoons were studied. In addition, typhoon track operational forecasting errors in the last decade have been reduced because the operational monitoring equipment and forecast techniques were improved. Some results from the research program on tropical cyclone landfall, structure and intensity change, intensification near coastal waters, interaction between tropical cyclone and mid-latitude circulation, and the interaction among different scales of motion are described in this paper. Four major meteorological scientific experiments in China with international cooperation were implemented in 1998: the South China Sea monsoon field experiment (SCSMEX), the Tibetan Plateau field experiment (TIPEX), the Huaihe River basin energy and water cycle experiment (HUBEX), and the South China heavy rain scientific experiment (HUAMEX). Although these field experiments have different scientific objectives, they commonly relate to monsoon activities and they interact with each other. The valuable intensive observation data that were obtained have already been shared internationally. Some new findings have been published recently. Other research work in China, such as the tropical air-sea interaction, tropical atmospheric circulation, and weather systems, are reviewed in this paper as well. Some research results have shown that the rainfall anomalies for different regions in China were closely related to the stages of El Niño events.

Key words: tropical cyclones, tropical meteorology, research progress

1. Tropical cyclone research and operational forecast

1.1 *Tropical cyclone landfall*

A new program of tropical cyclone landfall in China is being implemented. Under the auspices of this program, an atmospheric field experiment of tropical cyclone landfall with the acronym of CLATEX (China Landfalling Typhoon Experiment) was launched in July–August 2002. Real-time boundary layer observation data from wind profilers and other advanced equipment were acquired.

The SNR (signal-to-noise ratio) data of the wind profiler demonstrate that the turbulence layer of target typhoon Vongfong (0214) had developed up to more than 5km several hours before landfall (Fig. 1a) whereas it receded back to 1–1.5 km on the next day after landfall (Fig. 1b). The variation of the boundary layer thickness of Vongfong coincided with the turbulent layer variation. It was also found that a ground-hugging jet appeared in the right-hand sector of the target typhoon in the period of landfall.

Another important topic of tropical cyclone landfall study is the tropical cyclone sustaining mechanism. Deep and severe flood disasters often arise from the landfalling typhoons that maintain their vortices over land for an extended period of time. Chen (1998) indicated that the following factors would be favorable for a landfalling tropical cyclone to prolong its duration

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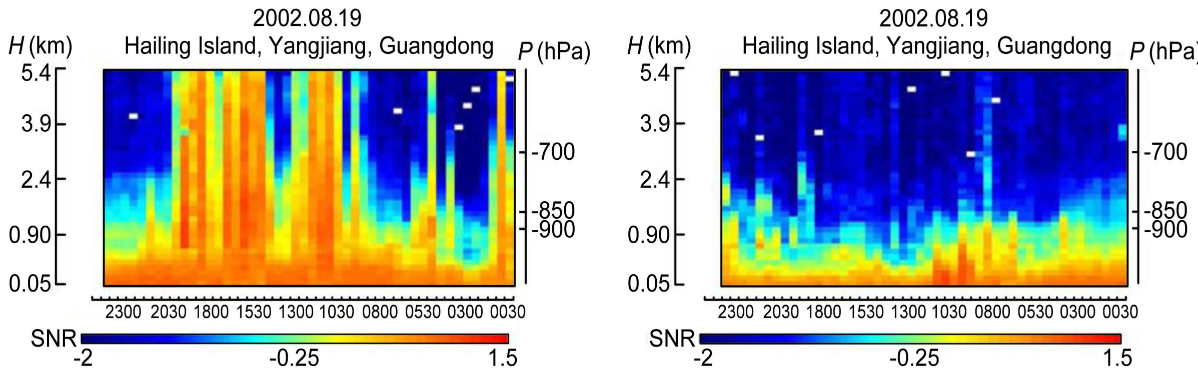

Fig. 1. The SNR (signal-to-noise ratio) data of the wind profiler demonstrate the variation of the turbulence layer before and after landfall of target typhoon Vongfong (0214) (from CLATEX). (a) The turbulence layer of Vongfong was strongly developed before it made landfall; (b) the turbulence layer of Vongfong receded one day after landfall.

over land: (1) a sustained moisture transport into the storm; (2) the overlap with an upper level strong divergence field or connected with an upper level outflow channel; (3) the experience of an extratropical transition process and the gain of a certain amount of baroclinic energy from weak cold air in the mid-latitudes; (4) the acquisition of vorticity from a mesoscale strong convective system which merges with the landfalling tropical cyclone; and (5) the presence of wet saturated land or a huge water surface of an in-land lake or reservoir that would help a landfalling tropical cyclone be sustained longer if the tropical cyclone were to be stagnant over it.

With 50 years of tropical cyclone data, the statistics of tropical cyclone intensity change and wind distribution, pre- and post-landfall were analyzed. It was found that tropical cyclones have a decreasing trend of intensity in the 12 hours before landfall. Some cyclones have been maintained over 5 days after landfall and brought severe damage to the in-land region.

Using the mesoscale model MM5, the physical processes that, under idealized conditions, lead to changes in the rainfall distribution in a tropical cyclone prior to, during, and after landfall were studied by Chan and Liang (2003). It was suggested that cutting off the moisture flux over land would have a profound effect on the tropical cyclone characteristics, while changing the sensible heat flux would have very little impact.

The interaction between the high-level cold vortex and a landfalling tropical cyclone was studied by Yu et al. (2001) and Wan et al. (2002). It was found that sometimes the cold vortex could be a favorable precondition for a tropical cyclone's abrupt intensification before landfall, while it could also cause a landfall tropical cyclone to weaken and become an extratropical cyclone quickly after it made landfall.

A set of mesoscale re-analysis data was used to analyze the physical mechanism of a tropical depression-caused torrential rainfall by Yu et al. (2002). The results show that the outburst of a southerly jet in the low layer of the troposphere triggered the explosive development of cyclonic vertical vorticity in the region with steep potential temperature surfaces in front of a moist and warm air mass. That is slantwise vorticity development. Now in the middle atmosphere, cyclonic vorticity increased notably as the air flowed from west to east and entered a region with small vertical stability. The simultaneous sharp development of cyclonic vorticity in both the lower and middle level atmosphere should be one of the causes for tropical cyclone intensification and torrential rainfall occurrence.

1.2 *Structure and intensity change*

Most tropical cyclones approaching the mainland will decrease their intensity aside from the few typhoons that would increase their intensity if some mesoscale vortex (MSV) were to merge into them. After carrying out two sets of numerical simulations with and without MSV merging, Chen and Luo (2002) showed that the MSV which merges into the typhoon plays an important role in the great decrease of central pressure and thus intensifies the typhoon. It is inferred that the MSV transfers vorticity to the core region of the typhoon and thus strengthens its intensity.

Study on the relationship between mesoscale vortices and tropical cyclone intensity shows that the interaction between them can intensify the maximum tangential velocity of the typhoon under the proper conditions (Zhou and Luo, 2002). Based on the moist potential vorticity equation and the theory of slantwise vorticity development, Yu and Wu (2001) studied the possible relationship between the abrupt intensity change of a tropical cyclone and the evolution of its equivalent potential temperature structure. Analyses show that, due to the extreme steep moist isentropic surfaces in the eye-wall region, the change of moist baroclinicity turns out to be a main reason for the abrupt changes of vertical vorticity. If the vertical vorticity increases rapidly in the moist regions, the tropical cyclone may experience explosive deepening.

Chan et al. (2001) studied the interaction between a tropical cyclone and the underlying ocean using an atmosphere-ocean coupled model. The experiment indicates that the changes in tropical cyclone intensity are sensitive to the variation of SST, and the variation of tropical cyclone intensity with SST is not linear. An SST of 27°C was found to be the threshold for tropical cyclone development. In addition, the initial depth of the ocean mixed layer has an appreciable effect on tropical cyclone intensity, which also depends on the movement of the tropical cyclone. Furthermore, the vertical structure of the ocean (vertical temperature gradient in the stagnant layer and the temperature differential between the two layers) may play a significant role in modulating the tropical cyclone intensity.

A limited-area primitive equation model was used by Duan et al. (2003) to study the effect of planetary vorticity gradient and uniform current on tropical cyclone intensity change. It was found that tropical cyclone intensity is reduced in a non-quiescent environment compared with the case of no mean flow. A tropical cyclone (TC) on a β plane not only intensifies slower than one on an f plane, its rate of intensification also varies with the direction of the mean flow. The main physical characteristic that distinguishes the experiments is the asymmetric thermodynamic (including convective) and dynamic structures when either a mean flow or a planetary vorticity gradient is introduced. The magnitude of the warm core and the associated subsidence are found to be responsible for such simulated intensity changes.

Lei (2001) discussed the dynamical equilibrium features of tropical cyclones with primitive equations under the condition of adiabatic, non-frictional, non-environmental steering. The results showed that the tropical cyclone intensity would be weakened by "ventilation flow" associated with "β gyres" and "shear gyres" with positive (negative) vertical wind shear at the high (low) level. The positive (negative) vorticity vertical convection in the high (low) level would strengthen the tropical cyclone intensity.

1.3 *Interaction between tropical cyclones and mid-latitude systems*

Tropical cyclone activities will strongly affect the intensity and distribution of rainfall associated with the Mid-latitude trough and Meiyu front. Numerical simulation (Zhu et al., 2000) showed that rainfall in front of a mid-latitude trough would increase dramatically if a typhoon would approach the south of the trough. A low level SE (southeast) jet flow in the right hand sector of the typhoon would transport an abundance of moisture to the rainy region in front of the mid-latitude trough. Another numerical simulation (Cheng et al., 1998) demonstrated that the mid-latitude torrential rainfall of Meiyu would suddenly cease if a typhoon approached the South China coastal region. Meiyu heavy rainfall along the Yangtze River was maintained by the moisture transportation from the Bay of Bengal and South China Sea. A typhoon could cut off the moisture transportation if the vortex circulation appeared around the moisture channel, and so the moisture from the Bay of Bengal and South China Sea would be drawn into the typhoon rather than be transfered to the Meiyu rain region. On the other hand, circulation systems in mid-latitudes would affect the tropical cyclone's activities as well. The tropical cyclone would undergo an extratropical transition and a restrengthening process with the influence from a mid-latitude cold wave (Xu et al., 1998). the transition process often led to tropical cyclone restructuring and strengthening with the acquisition of baroclinic energy from a mid-latitude weak cold wave (Chen et al., 2001).

Cold air associated with the westerly trough can often strengthen the rainfall produced by the tropical cyclone. The very strong rain of 275.2 mm d^{-1} in Shanghai on 5–6 August 2001 was induced by a weak landfalling tropical depression. The case study of Lei (2002) showed that the interaction between the warm moist depression and the weak cold dry air from the area behind the westerly trough played an important role in developing the local strong vertical convective motion which directly led to this heavy rainfall. On the other hand, the interaction between the strong convective cloud cluster and the tropical depression was another major function to produce this heavy rain (Qi, 2002).

Tropical cyclone motion would be influenced by an upper cold low which is cut off from a deep mid-latitude trough. The tropical cyclone could suddenly turn northwestwards and make landfall on China's east coast due to the influence from the upper cold low in the southwest area neighboring the tropical cyclone. Studies by Xu et al. (2000) indicated that whether the tropical cyclone over the west part of the western North Pacific would move westwards or recurve northeastwards is closely related to the circulation pattern over the mid-latitude Tibetan Plateau. Sixteen sets of numerical simulations were performed by Chen and

Luo (2002) with a quasi-geostrophic model on a β-plane with a topography term. The results suggested the tropical cyclone's track may have been strongly influenced by the vortices originating from the western part of the large scale terrain. Probably this kind of interaction could be one of the causes leading to the storm's unusual movement.

Using the scale discretion method, Meng et al. (2002) studied mesoscale characteristics of the interaction between a tropical cyclone and the westerly trough. Results showed that the interaction between the tropical cyclone and the westerly trough is apparently manifested by mesoscale activities. The distribution of divergence fields at lower and upper levels can be a kind of indication meaningful for the rainfall caused by the interaction between middle and lower latitude circulations.

A comprehensive study on the topic of the interaction between tropical cyclones and mid-latitude circulation systems was completed by Lei (2001). One of the results was that in mid-latitudes, tropical cyclone motion is influenced obviously by the β variation with latitude, namely the "γ effect". It was suggested that the γ effect cannot be neglected for tropical cyclone motion in the mid-latitude ocean.

1.4 *Interaction between tropical cyclones and different motion scale systems*

With a barotropic model, the interaction between tropical cyclones and mesoscale vortices was investigated by Tian and Luo (2002). It was indicated that the different initial radial location of the mesoscale vortex can cause changes in the characteristics of the perturbation relative vorticity. Other studies concerning binary tropical cyclone interaction to the south of an idealized subtropical ridge (Luo and Ma, 2001) coincide with the conceptual model of binary tropical cyclone interaction put forward by Carr and Elsberry in 1998. It was suggested in these studies that the interaction in the easterly current can lead to unusual tropical cyclone tracks, consisting of abrupt changes in direction and velocity.

Tropical cyclone motion may be influenced by some strong mesoscale convective systems (MCSs) in the peripheral area of a storm. The interaction between a typhoon and MCSs was studied with a quasi-geostrophic barotropical model (Chen and Luo, 1995). Five sets of numerical simulations were performed with an MCS in different quadrants. The experiment exhibited that the MCS in the northeast quadrant led to oscillations in the typhoon movement. On the other hand, typhoon motion could have a westward deviation from the normal track (without an MCS) if the MCS was located near the eastern sector of the typhoon.

1.5 *Tropical cyclone climate variation*

Tropical cyclone annual genesis frequency and the first landing date of tropical cyclones were analyzed by the wavelet technique. Results showed that the Morlet wavelet can disclose the significant period clearly. The main periods of annual frequency of tropical cyclones are about 7, 3, and 10 years. The main periods of the first landing date of tropical cyclones are about 5 and 10 years. Besides this, with the composite analysis method, the reasons for the anomalous frequency of tropical cyclone affecting East China were discussed. It was shown that the winter monsoon influences the frequency of tropical cyclones affecting East China. A diagnostic conceptual model was constructed to forecast the anomalous frequency of tropical cyclones. Furthermore, the latitudinal distribution of the climatic features of tropical cyclone movement in the western North Pacific was analyzed including tropical cyclone source area, active area, transition and dissipation area, and frequencies, as well as the frequency of northward motion. Some basic facts of tropical cyclone activities in different latitudinal zones were revealed as well.

1.6 *Operational forecast*

The 24-hour average error of tropical cyclone track operational forecasts has been reduced from 239.8 km in 1985 to 130.5 km in 2002 (Fig. 2). In the past decade, China has been strengthening the equipment and techniques of its monitoring and observation systems, and deploying an observing network including Doppler radars along the coastal provinces, developing satellite observing and receiving techniques, improving the tropical cyclone numerical prediction models (Country Report 2002)* and warning service systems.

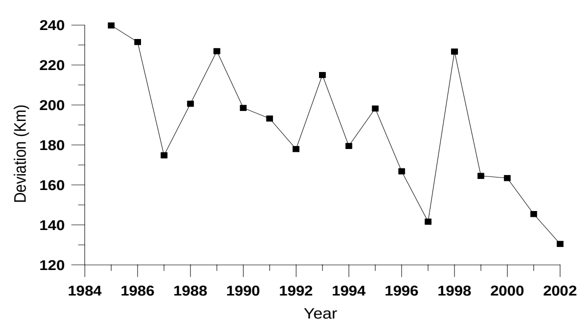

Fig. 2. 24-hour mean error during the typhoon season from 1985–2002.

*National Meteorological Center, 2002: Country Report to the 35th session typhoon committce meeting, ESCAP/WMO.

All of those works are helpful in improving the tropical cyclone operational forecasting capabilities.

In the National Meteorological Center (NMC), the tropical cyclone track prediction system was transplanted into a super computer in the summer of 2002. The initial and lateral boundary conditions were from the new medium range spectral model T213L31 rather than the former T106L19. The numerical tropical cyclone track prediction system of the Shanghai Typhoon Institute (STI) has also been upgraded, which is now running in parallel on a Galaxy super computer. The new system is based on the non-hydrostatic MM5V3, doubly nested (45 km and 15 km) with an enlarged horizontal domain.

In 2000, STI employed the ensemble technique for tropical cyclone track forecasts (Zhou et al., 2002). Starting with a barotropic model, the ensemble members were generated by perturbing the initial position and structure of the tropical cyclone. The test results show average 24-hour and 48-hour errors for track prediction of 117 km and 326 km respectively. A probability forecast method for tropical cyclone tracks was proposed. Currently, experiments with a sophisticated primitive model have been carried out.

Apart from numerical prediction models, there are several other statistical schemes being used operationally (Chen and Yu, 2003), including a consensus and a statistical-dynamical method developed by the STI and a probability ellipse method developed by the Jiangsu Meteorological Center. The consensus method uses correlation analysis to blend forecasts from four sub-models to produce a final forecast. It enables the forecasters to synthesize the forecasting tracks from different sources.

2. Research perspectives in tropical meteorology

2.1 *The South China Sea monsoon*

With the implementation of SCSMEX (the South China Sea monsoon field experiment), many meteorologists (He et al., 2001a) have tried to define various onset indexes of the South China Sea (SCS) summer monsoon. The results (He et al., 2001b) from different indexes all show that the climatic mean onset time of the SCS summer monsoon is the 4th pentad of May. The results show clearly that the atmospheric circulations show a notable abrupt change with the onset of the SCS summer monsoon, namely, the wind field in the lower troposphere, the geo-potential height field in the upper troposphere, the humidity field, and the vertical motion field all change remarkably over South Asia and Southeast Asia. The South Asian High moves rapidly from east of the Philippines to the north of the Indochina Peninsula, the trough over India and Burma intensifies, and the westerly wind over the equatorial Indian Ocean intensifies, expands, and propagates eastward and northward, together with the tropics-midlatitude interaction and eastward withdrawal of the Western Pacific Subtropical High. Those are all the large scale characteristics of the SCS summer monsoon onset. Meanwhile, the meridional temperature contrast and zonal wind shear in the low latitudes over Asia show a corresponding abrupt change. The development and behavior of the 850-hPa vortexes over South Asia and Southeast Asia play an important role in the SCS summer monsoon onset. The SCS summer monsoon onset is a part of the evolution of global atmospheric circulation from winter to summer, and has remarkable regional features.

The rainy season analyses show that there exists differences between the beginning of the subtropical monsoon rainy season and that of the tropical monsoon rainy season in East Asia from spring to summer. The former begins in early April over the region from the north part of South China to the south of the Yangtze River, and then expands southward and southwestward, and reaches the coastal regions of South China and the Indochina Peninsula in late April. The rainfall belt is mainly caused by the convergence between the northerly cold surge and the southwesterly wind along the northwest edge of the subtropical high, and by the subtropical westerly wind in winter and spring over South Asia. After the SCS tropical monsoon onset, the subtropical monsoon rainfall belt over the coastal region of South China moves back northward which is consistent with the northward movement of the subtropical high, and the early flood season comes into the first peak period. The second peak rainfall comes in the region south of the Yangtze River, that is, the frontal rainfall period over the Yangtze River and the Huaihe River regions, and then further to North China. In the mean time, the tropical monsoon rainfall belt propagates from Indochina Peninsula to India to form the tropical monsoon rainy season (Chen et al., 2000).

Both the Meiyu rainfall along the Yangtze River and the rainfall in South China in May–June are closely related to the summer monsoon activities in South China Sea (SCS). The early rainy season in South China starts in April, with the rainfall mainly caused by a cold front from mid-latitudes. The rain events are not so strong in this early stage. The heavy rainfall season is often started after the summer monsoon is set up in SCS. Rainfall in South China in the summer monsoon active period (May–June) is usually stronger and more frequent than in the other seasons.

Rainfall frequency exceeds 50% of the annual total (Zhou et al., 2003).

Recent studies show that the low frequency oscillation is stronger in summer than in winter. Usually, the SCS summer monsoon is established in the negative phase of the first strong low frequency oscillation in early summer. The low frequency oscillation over the South China Sea becomes stronger after the SCS summer monsoon onset, and the SCS summer monsoon onset is closely related to the eastward propagation of the low frequency oscillation in the equatorial Indian Ocean and to the westward propagation of the low frequency disturbance in the western Pacific Ocean. During the SCS summer monsoon period, the low frequency circulation oscillation is characterized by the meridional oscillation of the ITCZ and the zonal oscillation of the west edge of the subtropical high. The low frequency oscillation also has a close relationship with the active and break/weakening phases of the SCS summer monsoon (Lin, 1998; Song et al., 2000).

The summer monsoon onset date is earlier over the South China Sea region than over India. The onset is closely related to the reversal of the meridional temperature gradient. The peak temperature gradient and the positive temperature deviation propagate westward during the transition period from winter to summer in the low latitude regions over Asia. Case studies show that warm advection is one of the most important factors in inducing the temperature increase in the troposphere over South China before the SCS monsoon onset. The contribution of diabatic heating to the local temperature variation depends on the amount of rainfall over South China. The rapid temperature increase in the middle and high troposphere over the Indochina Peninsula before the monsoon onset is caused by the total effect of the latent and sensible heating. The distribution of the atmospheric heat sources has a close relationship with the land-sea contrast. The sensible heating contrast between land and sea is the large scale contributor for the monsoon onset. The large sensible heat fluxes are located over the Indo-China Peninsula, the northeastern part of the Tibetan Plateau, and over most of the Indian Peninsula, while the small sensible fluxes are located over the oceans. The heating effect starts earlier over the Indochina Peninsula than over the Tibetan Plateau, so that the sensible heating over the Indochina Peninsula has a notable effect on the earlier onset of the SCS summer monsoon while the Tibetan Plateau plays an important role for the maintenance of the SCS monsoon. The heating effects of the Tibetan Plateau on the summer monsoon onset over different regions of Asia are also different: this is mainly due to sensible heating during the SCS monsoon, while it is mainly due to latent heating during the Indian summer monsoon (Jiao and He, 2000; Jian and Luo, 2001; Luo and He, 1997, Shao and Qian, 2001; Wang and Qian, 2001).

2.2 *The tropical air-sea interaction*

The analyses of the SSTs over the tropical equatorial eastern Pacific show notable quasi-biennial and quasi-four-year oscillations. Zhu and Chen (2000) gave a figure of six phases of the quasi-4-year oscillation from La Niña to El Niño for SSTA and the 850 hPa wind field over the Pacific. Wu A.-M. and Ni Y.-Q. also showed a plot for five phases from La Niña to El Niño. They concluded that the occurrence of the northerly wind anomaly over the northwest Pacific and the southerly wind anomaly over the southwest Pacific causes the meridional wind convergence along the equator, and also the eastward propagation of the equatorial westerly wind anomalies to the eastern equatorial Pacific, resulting in the formation of the El Niño event. The convergence of meridional wind anomalies needs the concurrence of the anomalies of two hemispheres which must be maintained for more than half a year.

Recent studies (Li and Li, 1998) show that eastward propagating (quasi-steady) waves, whose periods are longer than 90 days, play an important role in the eastward propagation of the westerly wind anomalies and inducing the El Niño event. After the occurrence of El Niño, the intensities of the above-mentioned two oscillations decrease suddenly, and then propagate westward and induce the La Niña event. It was also found (Wu and Meng, 1998; Meng and Wu, 2000) that there is a strong positive correlation between the equatorial SSTs in the Indian Ocean and those in the Pacific, which are controlled by two Walker circulations. The two circulation anomalies look like a pair of gears existing in the equatorial Indian Ocean and Pacific Ocean. When one changes in a clockwise direction, the other changes in a counter-clockwise direction. The merging point of the two circulations propagates eastward into the Pacific Ocean, leading to the changes in SSTs and zonal winds to its east side and inducing the appearance of the El Niño event.

Some meteorologists have studied the influences of the warm pool in the west Pacific (Huang et al., 2000). They found that the SST increase occurred first over the warm pool and then propagated eastward during the 1997/1998 El Niño event. From the observation data along 137°E, it was found (Ren et al., 2001) that the large values of temperature variance were located over the region from 5° to 12°N in the sub-sea surface layer from 100 to 200 m. The temperature variations in this region occurred before the start of the El Niño/La Niña events. In winter, the sub-sea surface layer temperature has a good correlation with the local SST in this region, while in summer, it has a good correlation with the SST around Xisha Islands due to the effect of circulation.

Many scientists (Zou and Ni, 1997; Zhu and Xu, 1998; Zhang et al., 1999; Jin and Tao, 1999) studied the influences of ENSO. They confirmed that there has mainly been drought conditions in summer over East China during El Niño years. They also pointed out that the summer rainfall anomalies over China depend on the stages of the El Niño event. During the mature stage of El Niño, there exist positive rainfall anomalies over South China in autumn, winter, and spring, while negative rainfall anomalies exist over North China and South China and positive rainfall anomalies over the mid-low reaches of the Yangtze River and the Huaihe River region in summer. They also found that there are positive rainfall anomalies over the mid-low reaches of the Yangtze River and the region to the south of the Yangtze River in summer during the transition stage from El Niño to La Niña and vice versa.

Based on the SCSMEX data, it was found that there exist sudden changes in the heat capacity of the atmosphere and oceans, and also in the moisture and the momentum fluxes during the SCS summer monsoon onset. The energy is accumulated over the South China Sea before the SCS summer monsoon onset. The values of solar radiation and the latent heat flux almost deceased by half, and the net energy flux between the atmosphere and ocean was approximately zero (Yan et al., 2000; Jiang et al., 2002).

2.3 *Tropical atmospheric circulation*

Chen et al. (2001b) analyzed the interannual variations of the meridional circulation in January and July from 1961 to 1997, especially that averaged between 110° and 140°E and that of the East Asian monsoon circulation. They pointed out: (1) In addition to the annual variations of the meridional circulation, there are also notable interannual and interdecadal variations; (2) The main characteristics of the meridional circulation averaged over 110° and 140°E are that the East Asian monsoon circulation replaces the Ferrel circulation in the Northern Hemisphere in January, while it replaces the Hadley circulation in July, and the inter decadal variations are rather distinct; (3) The intensity of the East Asian monsoon circulation is influenced by the ENSO cycle.

The 1997/1998 ENSO event was a very strong one. Li and Long (2001) analyzed the relationship between the tropical atmospheric intraseasonal oscillation (ISO) and ENSO, and pointed out that the occurrence of the El Niño event in 1997 was strongly correlated with the abnormal intensification of the ISO in the central and western equatorial Pacific from the winter of 1996 to the spring of 1997. The abnormal ISO intensification in the upper layer over Indonesia was mainly due to the active convection in this region caused by the strong East Asian winter monsoon anomalies rather than due to propagation from the equatorial Indian Ocean. Other scientists also found that the zonal wind anomalies in the low layer in the west Pacific can be used as a signal to forecast the warm event (Zhai et al., 2001).

Wu and Huang (2001) studied the relationship between the circulation in the western equatorial Pacific in winter and the Asian monsoon circulation in the late spring and summer. The results show that the latter circulation and the summer rainfall over China are notably influenced from the circulation in the western equatorial Pacific in winter. The positive/negative sea level pressure anomalies and the corresponding cyclonic (anticyclonic) circulation in the western equatorial Pacific in winter will cause a stronger (weaker) summer monsoon over South and East Asia, and more (less) summer rainfall over the Yangtze River valley in China.

Some studies show that the cross equatorial currents in summer affect the SCS monsoon and the drought/flood in East China. They found that the South Africa High, South Indian Ocean High, and Australian High all have important effects on the maintenance and the intensity of the cross equatorial currents. They also found that the ocean temperature field in the North Pacific affects the intensity of the cross equatorial current. When the Somali cross equatorial flow is strong in May, the SCS monsoon will start earlier. The cross equatorial flow appears strong in the drought years over East China (Shi et al., 2001).

Based on the climate data of several decades, Song and Ji (2001) found a decadal timescale abrupt change in Asian and African monsoons in the 1960s. The results also reveal the synchronous characteristic of the decadal variations of the East Asian monsoon, the Indian monsoon, and the North African monsoon, experiencing a process from strong to weak monsoons. This demonstrates that the abrupt change of summer rainfall over the arid and semi-arid regions in Asia and Africa in the 1960s was directly related to the sudden change of the Asian and African monsoons.

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REFERENCES

Carr, L. E., and R. L. Elsberry, 1998: Objective diagnosis of binary tropical cyclone interactions for the western North Pacific basin. *Mon. Wea. Rev.*, **126**, 1734–1740.

Chan, J. C. L., Y. H. Duan, and L. K. Shay, 2001: Tropical cyclone intensity change from a simple ocean-atmosphere coupled model. *J. Atmos. Sci.*, **58**, 154–172.

Chan, J. C. L., and Xudong Liang, 2003: Convective asymmetries associated with tropical cyclone landfall. Part I: F-plane simulations. *J. Atmos. Sci.*, **60**(13), 1560–1576.

Chen, P. Y., and R. L. Yu, 2003: Review on the Northwestern Pacific tropical cyclone in 2002. *Atmospheric Science Research and Application*, **1**, 101–113.

Chen Lianshou, 1998: Decay after landfall. Tropical Meteorology Programme Report Series, Report No.59, WMO/TD-NO.875 Topic1.6.

Chen Lianshou, 2002: Observing and forecasting rainfall for tropical cyclone landfall. Tropical Meteorology Research Programme Report Series, Report No. 67, WMO/TD No. 1136, Topic 2.1.

Chen Lianshou, and Luo Zhexian, 1995: Effect of the interaction of different scale vortices on the structure and motion of typhoon. *Adv. Atmos. Sci.*, **12**(2), 207–214.

Chen Lianshou, Meng Zhiyong, 2001: An overview on tropical cyclone research progress in China during the past ten years. *Chinese J. Atmos. Sci.*, **25**(3), 420–432.

Chen Lianshou, and Luo Zhexian, 2002: The impact of the eastward shifting Dipole systems over large scale terrain on tropical cyclone tracks. *Adv. Atmos. Sci.*, **19**(6), 1069–1078.

Chen Longxun, Li Wei, Zhao ping Tan Shiyan, 2000: On the process of summer monsoon onset over East Asia. *Climatic and Environmental Research*, **5**, 345–355. (in Chinese)

Chen Yuejuan, Jian Jun, Zhang Hong, and Chen Xinming, 2001: The interannual variability of meridional circulation from 1961 to 1997 and its relation to SST anomaly. *Chinese J. Atmos. Sci.*, **25**, 79–88. (in Chinese)

Cheng Zhaohui, Kang Di, Chen Lianshou, and Xu Xiangde, 1998: Interaction between tropical cyclone and Mei-yu front. *Acta Meteorologica Sinica*, **13**(1), 35–46.

Duan Yihong, Wu Rongsheng, Yu Hui, Liong Xudong, and Johnny C. L. Chan, 2003: The rale of β-effect and a uniform current on tropical cyclone intensity. *Adv. Atmos. Sci.*, **21**(1), 75–86.

He Jinhai, Ding Yihui, Gao Hui, and Xu Haiming, 2001a: The Establish Date of the SCS Summer Monsoon and the Monsoon Indexes, China Meteorological Press, 123pp. (in Chinese)

He Jinhai, Xu Haiming, Zhou Bing, and Wang Lijuan, 2000: Large scale features of SCS monsoon onset and its possible mechanism. *Climatic and Environmental Research*, **5**, 333–344. (in Chinese)

Huang Ronghui, Zhang Renhe, and Zhang qingyun, 2000: The 1997/1998 ENSO cycle and its impact on summer anomalies in East Asia. *Adv. Atmos. Sci.*, **17**, 348–362.

Jian Maoqiu, Qiao Yunting, and Luo Huibang, 2000: The abrupt change of the circulation in low-latitudes during the period from April to June. *Climatic and Environmental Research*, **5**, 333–344. (in Chinese)

Jian Maoqiu, and He Haiyan, 2000: Evolutions of temperature fields in troposphere and corresponding thermal mechanisms in the early and late onset cases of South China Sea summer monsoon. *Acta Scientiarum Naturalium Universitatis Sunyatseni*, **39**, 97–102. (in Chinese)

Jian Maoqiu, and Luo Huibang, 2001: Heat sources over Qinghai-Xizang Plateau and surrounding areas and their relationships to onset of SCS summer monsoon in 1998. *Plateau Meteorology*, **20**, 381–387. (in Chinese)

Jiang Jing, and Qian Yongfu, 2001: Tropical circulation evolution and the onset of the South China Sea monsoon. *Journal of Nanjing Institute of Meteorology*, **24**, 83–91. (in Chinese)

Jiang Guorong, Sha Wenyu, Li Xunqiang, Xiao Yiguo, Yao Huadong, Li Jianglong, and Lu Zhanjun, 2002: The analysis of the radiation features before and after South China Sea monsoon onset. *Journal of Tropical Meteorology*, **18**, 29–38. (in Chinese)

Jin Zuhui, and Tao Shiyan, 1999: A study on the relationship between ENSO cycle and rainfalls during summer and winter in eastern China. *Chinese J. Atmos. Sci.*, **23**, 663–672. (in Chinese)

Lei Xiaotu, and Chen Lianshou, 2001: Dynamic analysis on the characteristics of tropical cyclone motion in baroclinic model. *Chinese Journal of Geophysics*, **44**(4), 467–476.

Lei Xiaotu, 2002: The impact of a tropical depression on the "01.8.5" heavy rainfall in Shanghai. *Acta Meteorologica Sinica*, **60**(6), 52–57. (in Chinese)

Lei Xiaotu, 2001: On the study of interaction between tropical cyclones and mid-latitude circulation. Doctorateal dissertation Chinese Academy of Meteorological Sciences, 175pp. (in Chinese)

Li Chongyin, and Qu Xin, 2000: Large scale atmospheric circulation evolution associated with summer monsoon onset in the South China Sea. *Chinese J. Atmos. Sci.*, **24**, 1–14. (in Chinese)

Li Chongyin, and Long Zhenxia, 2001: Transeasonal oscillation anomalies in the tropical atmosphere and the 1997 El Niño occurrence. *Chinese J. Atmos. Sci.*, **25**, 589–595. (in Chinese)

Liang Jianyin, Wu Shangsen, and You Jiping, 1999: The research on variations of onset time of the SCS summer monsoon and its intensity. *Journal of Tropical Meteorology*, **15**, 97–105. (in Chinese)

Li Guilong, and Li Chongyin, 1998: Activities of low-frequency waves in the tropical atmosphere and ENSO. *Adv. Atmos. Sci.*, **15**, 184–203.

Lin Ailan, 1998: The characteristics of low-frequency oscillation over South China Sea. *Journal of Tropical Meteorology*, **14**, 113–118. (in Chinese)

Liu Yanju, and Ding Yihui, 2000: Evolution of the atmospheric stratification and mixed layer before and after monsoon onset over the South China Sea. *Climatic and Environmental Research*, **5**, 459–468. (in Chinese)

Luo Jingjia, and He Jinhai, 1997: Asian summer monsoon establishment and SCS monsoon onset features with the causes explored. *Journal of Nanjing Institute of Meteorology*, **20**, 293–300. (in Chinese)

Luo, Z. X., and J. X. Ma, 2001: Binary tropical cyclone interaction on the south of an idealized subtropical ridge. *Acta Meteorologica Sinaca*, **59**(4), 450–458. (in Chinese)

Luo, Z. X., 2001: Effects of tropical cyclone on the short time scale evolution of subtropical high. *Acta Meteorologica Sinica*, **59**(5), 549–559. (in Chinese)

Meng Wen, and Wu Guoxiong, 2000: Gearing between the Indo-monsoon circulation and the Pacific-Walker circulation and the ENSO, Part II: Numerical simulation. *Chinese J. Atmos. Sci.*, **24**, 15–25. (in Chinese)

Meng, Z. Y., X. D. Xu, and L. S. Chen, 2002: Mesoscale characteristics of the interaction between TC Tim (9406) and mid-latitude circulation. *Acta Meteorologica Sinica*, **60**(2), 31–39. (in Chinese)

Qi Linlin, 2002: A study on heavy rainfall in Shanghai on 5–6 August 2001. Proc. First China-Japan Workshop on Heavy Rainfall Experiment and Study, 50–59.

Ren Xiaobo, Zhou Xiuji, and Chen Longxun, 2001: Climatic features of sea temperature of warm pool and relationship with SST of its adjacent regions. *Acta Meteorologica Sinica*, **15**, 257–279.

Shao Hui, and Qian Yongfu, 2001: Thermal influences of land-sea contrast and topography on summer monsoon of 1998. *Journal of Tropical Meteorology*, **17**, 45–56. (in Chinese)

Shi Ning, Shi Danping, and Yan Mingliang, 2001: The effect of cross equatorial current of South China Sea monsoon onset and drought/flood in East China. *Journal of Tropical Meteorology*, **17**, 405–414. (in Chinese)

Song Yanyun, and Coauthors, 2000: Characteristics of low-frequency oscillations during summer monsoon onset over the South China Sea. *Acta. Oceanologica Sinica*, **22**, 35–40. (in Chinese)

Song Yan, and Ji Jinjun, 2001: The interdecadal abrupt change of the African-Asian summer monsoon in the 1960s. *Chinese J. Atmos. Sci.*, **25**, 200–208. (in Chinese)

Tian, H. J., and Z. X. Luo, 2002: Numerical study on the interaction between meso-scale vortex and typhoon vortex. *Journal of Nanjing Institute of Meteorology*, **25**(2), 159–165.

Wan Q. L., W. Y. Ding, and C. X. Liu, 2002: The interaction between Vongfong (2002) and the mid-latitude system. (Manuscript)

Wang Shiyu, and Qian Yongfu, 2001: Basic characteristic of surface heat field in 1998 and the possible connection with the SCS summer monsoon onset. *Acta Meteorologica Sinica*, **59**, 31–40. (in Chinese)

Wu Bingyi, and Huang Ronghui, 2001: Winter circulation condition of the tropical western Pacific and subsequent Asian summer monsoon. *Chinese J. Atmos. Sci.*, **25**, 609–616. (in Chinese)

Wu Guoxiong, and Meng Wen, 1998: Gearing between the Indo-monsoon circulation and the Pacific-Walker circulation and the ENSO. Part I: Data analyses. *Scientia Atmospherica Sinica*, **22**, 270–480. (in Chinese)

Xie An, Liu Xia, and Ye Qian, 1998: The role of upstream equatorial westerly wind in the summer monsoon onset over the South China Sea. *Quarterly Journal of Applied Meteorology*, **9**, 129–140. (in Chinese)

Xu Xiangde, Chen Lianshou, Xie Yiyang, and Cheng Zhaohui, 1998: Typhoon transition and its impact on heavy rain. *Scientia Atmospherica Sinica*, **22**(5), 744–752. (in Chinese)

Xu Jing, and Coauthors, 2000: The impact of mid-latitude circulation over the Tibetan plateau on the track of typhoon over the northwest Pacific. *Acta Meteorologica Sinica*, **14**(3), 330–346.

Yan Junyue, Yao Huadong, Li Jianglong et al., 2000: Characteristics of turbulence structure and flux transfer on the sea surface during the onset of SCS monsoon in 1998. *Climatic and Environmental Research*, **5**, 447–458. (in Chinese)

Yu, H., X. D. Liang, and Y. H. Duan, 2002: Meso-scale diagnosis of a torrential rainfall caused by a tropical depression. Preprints 25th Conference on Hurricanes and Tropical Meteorology, San Diego, California, America Meteorological Society. 66–67.

Yu Hui, and Wu Guoxiong, 2001: Moist baroclinicity and abrupt intensity change of tropical cyclone. *Acta Meteorologlica Sinica*. **59**(4), 440–490. (in Chinese)

Yu Hui, Fei Liang, and Duan Yihong, 2002: Favorable large-scale conditions for rapid intensification of typhoon Bill (1988) before landfall. *Acta Meteorologica Sinica*, **60**, 78–87.

Zhai Panmao, Guo Yanjun, and Li Xiaoyan, 2001: A diagnostics analysis of 1997/1998 ENSO event and the role of intra-seasonal oscillation in the tropical atmosphere. *Journal of Tropical Meteorology*, **17**, 1–9. (in Chinese)

Zhou Xiuji, and Coauthors, 2003: *The Scientific Experiment in 1998 and Study on Heavy Rainfall in South China* (*HUAMEX*). China Meteorological Press. Beijing, 220pp. (in Chinese)

Zhu Yanfeng, and Chen Longxun, 2000: Study on the quasi-four year oscillation of air-sea interaction. *Acta Meteorologica Sinica*, **14**, 293–306.

Zou Li, and Ni Yunqi, 1996: Diagnosis of low frequency component of ENSO variability —Part I: Global-scale dynamic characteristics of the component. *Acta Meteorologica Sinica*, **10**, 419–429.

Zou Li, Wu Aiming, and Ni Yunqi, 2002: On the interaction between ENSO and the Asian monsoon in the scale of quasi-biennial oscillation. *Journal of Tropical Meteorologica*, **18**, 17–28. (in Chinese)

Zou Li, and Ni Yunqi, 1997: Impact of ENSO on the variability of the summer mosoon over Asia and the summer rainfall in China. *Journal of Tropical Meteorology*, **13**, 306–314. (in Chinese)

Zhu Qiangen, and Xu Jianjun, 1998: Observational study on the effect of ENSO and its interdecadal variations on the climate anomaly in eastern China. *Journal of Nanjing Institute of Meteorology*, **21**, 615–623. (in Chinese)

Zhang Renhe, Akimasa Sumi, and Masahide Kimoto, 1999: A diagnostic study of the impact of El Niño on the precipitation in China. *Adv. Atmos. Sci.*, **16**, 299–241.

Zhou X. Q., Y. H. Duan, and Y. T. Zhu, 2002: Ensemble forecasting of tropical cyclone moving: probability forecasts of moving using the ensemble production. *Acta Meteorologica Sinica*, **60**, 111–118.

Zhou Jialing, and Luo Zhexian, 2002: Numerical study on the maximum velocity reinforcement in typhoons. *Journal of Nanjing Institute of Meteorology*, **25**(2), 199–206. (in Chinese)

Zhu Hongyan, Chen Lianshou, and Xu Xiangde, 2000: A numerical study of the interaction between typhoon and mid-latitude circulation and its rainfall characteristics. *Chinese J. Atmos. Sci.*, **24**(5), 669–675.