ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 27, NO. 5, 2010, 967–976

An Overview of Research and Forecasting on Rainfall Associated with Landfalling Tropical Cyclones

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(Received 14 May 2009; revised 31 December 2009)

ABSTRACT

The ability to forecast heavy rainfall associated with landfalling tropical cyclones (LTCs) can be improved with a better understanding of the mechanism of rainfall rates and distributions of LTCs. Research in the area of LTCs has shown that associated heavy rainfall is related closely to mechanisms such as moisture transport, extratropical transition (ET), interaction with monsoon surge, land surface processes or topographic effects, mesoscale convective system activities within the LTC, and boundary layer energy transfer etc.. LTCs interacting with environmental weather systems, especially the westerly trough and mei-yu front, could change the rainfall rate and distribution associated with these mid-latitude weather systems.

Recently improved technologies have contributed to advancements within the areas of quantitative precipitation estimation (QPE) and quantitative precipitation forecasting (QPF). More specifically, progress has been due primarily to remote sensing observations and mesoscale numerical models which incorporate advanced assimilation techniques. Such progress may provide the tools necessary to improve rainfall forecasting techniques associated with LTCs in the future.

Key words: landfalling tropical cyclones, heavy rainfall, research and forecasting

Citation: Chen, L. S., Y. Li, and Z. Q. Cheng, 2010: An overview of research and forecasting on rainfall associated with landfalling tropical cyclones. *Adv. Atmos. Sci.*, **27**(5), 967–976, doi: 10.1007/s00376-010-8171-y.

1. Introduction

A tropical cyclone (TC) is a cyclone generated in the tropical ocean basins with a near-center maximum wind speed ($V_{\max}$) of $\geqslant 10.8$ m s^{-1}. Landfalling tropical cyclones (LTCs) can be either a TC over land or one occurring in offshore waters approaching the land. The heavy rainfall associated with LTCs has a severe impact on lives and properties, and is thus an important topic for the TC research community. Disaster mitigation is heavily dependent on improvements in LTC rainfall forecasting ability.

Extreme disaster events are frequently caused by heavy rainfall associated with TC landfall. Indeed, the six top heaviest rainfall events on record in China are all associated with TCs. The top precipitation amount of 1748.5 mm in 24 h was caused by the landfalling Typhoon Herb (9608) at Ali Mountain, Taiwan Province during 31 July to 1 August 1996. The second top was 1672.6 mm in 24 h caused by Typhoon Carla (6718) at Xin Liao, Taiwan, on 18 October 1967. The third top was 1623.5 mm in 24 h at Ali Mountain, Taiwan, in August 2009 caused by Typhoon Morakot (0908). The fourth top was 1248 mm in 24 h at Baixin, Taiwan caused by Typhoon Gloria (6312) (Tao, 1980). The fifth top of rainfall was 1087 mm in 24 hours at Gulu/Yilan, Taiwan on 5 October 2009 caused by Typhoon Parma (0917). And finally, the sixth top, the strongest rainfall event occurring on the mainland, was 1062 mm in 24 h at Linzhuang, Henan, August 1975 caused by Typhoon Nina (7503), generating severe floods which claimed tens of thousands of people. Indeed, heavy rainfall associated with LTCs will often result in reservoir collapse, landslides, debris flow, and flash flooding, thus posing a continual threat of loss and devastation to society and human lives. In recent years, extreme weather events and calamities occurring in both Pacific and Atlantic coastal regions

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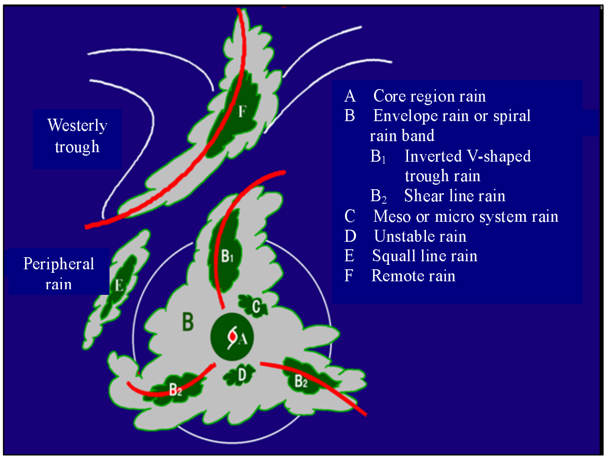

Fig. 1. LTC rainfall classification.

have been generated by LTCs, such as the super typhoons Rananim (2004), Haitang (2005), Saomai (2006) and Morakot (2009) in the Pacific, and the super hurricanes Ivan (2004), Rita (2005) and Katrina (2005) in the Atlantic, additionally, super cyclonic storm Gonu (2007) in the Arabian sea and super cyclonic storm Nargis (2008) is in Bay of Bengal. Consequently, the number one priority for scientists working in this field should be improving forecasting techniques and early warning systems for LTCs.

TC rainfall forecasting techniques are lagging behind those of the track forecast. However, significant progress has been made in recent years due to the development of remote sensing observation and the improvement of mesoscale models and data assimilation techniques. Several years ago, TC rainfall prediction was carried out mainly using empirical speculation and subjective experiences on the part of the forecasters. Today, however, techniques such as quantitative precipitation estimation (QPE) and quantitative precipitation forecasting (QPF) have been developed, improved and employed in operational applications by some of the major forecasting centers, thus greatly advancing the ability to forecast LTC-related rainfall. Nevertheless, further improvements in QPF based on a better understanding of TC rainfall mechanisms are still required.

In order to improve understanding of the structure/intensity and rainfall of LTCs, the field experiments RAINEX (Hurricane Rain Band and Intensity Change Experiment) and CBLAST (Coupled Boundary Layer Air Sea Transfer) were launched in the United States. T-PARC (THORPEX-Pacific Asia Regional Campaign) and TCS 08 (Tropical Cyclone Structure-2008) were also conducted in the western North Pacific. The objectives of these field programs are to provide a better understanding of the mechanisms behind LTC behavior and to improve forecasting. Now, one of the major objectives of an international research program, THORPEX (The Observing system Research and Predictability Experiment), is to improve high impact weather forecasting ability. Heavy rainfall produced by LTCs generates one of the highest impact type of weather event, and the forecasting techniques associated with these events is in desperate need of improvement.

In this paper, the authors describe the rain regions associated with LTCs and their corresponding systems. Next, the important physical mechanisms which affect LTC rainfall rate and distribution are discussed. The influence of LTCs on environmental rainfall, such as trough rain and mei-yu front rain, is also introduced. Finally, state of the art of research on LTC quantitative rainfall estimation and forecasting techniques is also described.

2. Classification of LTC rainfall

The present paper provides information on the primary physical mechanism and forecasting techniques of LTC rainfall. Some of the view points offered in this paper can be applied in operational forecasts.

Spiral rainbands in TCs are destroyed and deformed when the cyclone make landfall. Rainfall regions associated with a LTC can be categorized as follows (Chen and Li, 2004) (Fig. 1):

A Core region rain.

B Envelope rain or spiral rainband, in which B$_1$ is associated with the inverted V-shaped trough and B$_2$ is the rain associated with the wind shear in low layer of the LTC.

C Rain produced by meso- or microscale (tornado) systems, which usually occur in the northeast quadrant.

D Unstable rain, usually occurring in the region south of the core where upper-level cold air and lower-layer warm air superimpose each other.

E Peripheral rain associated with a squall line, which occasionally appears in front of the TC's motion direction. This mesoscale system sometimes spawns several tornadoes.

F Remote rain, which appears in front of a mid-latitude westerly trough or is associated with a topographic convergent zone away from the LTC circulation system.

The core region usually yields the strongest rainfall, especially during the landfalling stage. Inverted trough rain (B$_1$) and shear line rain (B$_2$) can be stronger than core region rain, especially during the landfall stage. The rate and distribution of remote rain depends upon moisture transport by the southeast jet flow, which in essence has connections with the LTC.

3. The physical mechanisms behind rainfall

TC rain rate not only depends upon the intensity of the LTC, but also on other complex interactions. A super typhoon may produce more intense rainfall, however many cases show that the weak remnant of the LTC under favorable conditions could result in stronger rainfall than that from super typhoons. Some crucial physical processes, such as moisture transport and latent heat release, may also play an important role in producing TC rainfall.

3.1 *Moisture supply*

Generally, a LTC would rapidly dissipate due to both the cut-off of moisture supplied by the ocean and an increase in land surface friction. Some LTCs are sustained over land due to their strong intensity, especially if there is moisture advective transport in the lower layer, which can usually be distinguished from satellite images.

Cheng (2008) studied the relationship between the moisture channel and rainfall in two groups of LTC. One group was composed of five strong rainfall cases and the others of five weak rainfall cases. Additionally, the vapor flux fields of the two groups were studied (Fig. 2) with data composite analysis. The results showed that LTC heavy rainfall occurs when a strong vapor transport channel is present (Figs. 2a and 2b), with weak rainfall occurring in the absence of such a channel (Figs. 2c and 2d). In another study by Li et al. (2005), numerical simulations of Typhoon Bilis (0010) showed that rainfall would be significantly reduced (Fig. 3b) from the control simulation (Fig. 3a) if the moisture transport was cut off.

Large amounts of water vapor can be brought by a monsoon surge. Reinforced heavy rainstorms can occur through the process of interaction between a remnant LTC and a monsoon surge with massive cloud clusters. These LTCs usually move westwards or southwestwards after landfall. Another severe tropical storm Bilis (0604), was a typical case of interacting with a monsoon surge. There was a moisture trans-

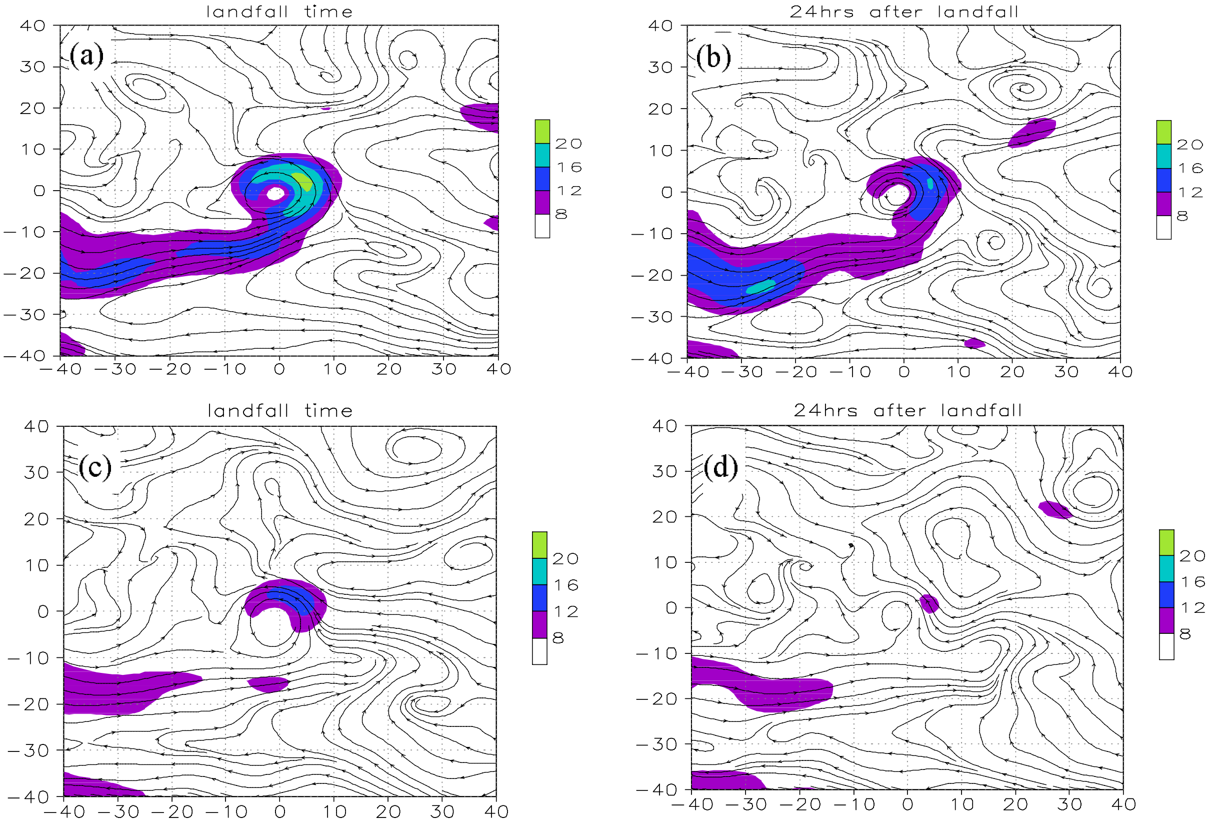

Fig. 2. Flow field and vapor flux of two groups of LTC with composite data at 850 hPa (Cheng, 2008): a, b—strong rainfall group during landfall and 24 h after landfall; c, d—weak rainfall group during landfall and 24 hrs after landfall; abscissa and ordinate represent grid numbers away from the typhoon center, the positive denotes northward and easterward and negative denotes southward and westward; TC centers located at (0,0).

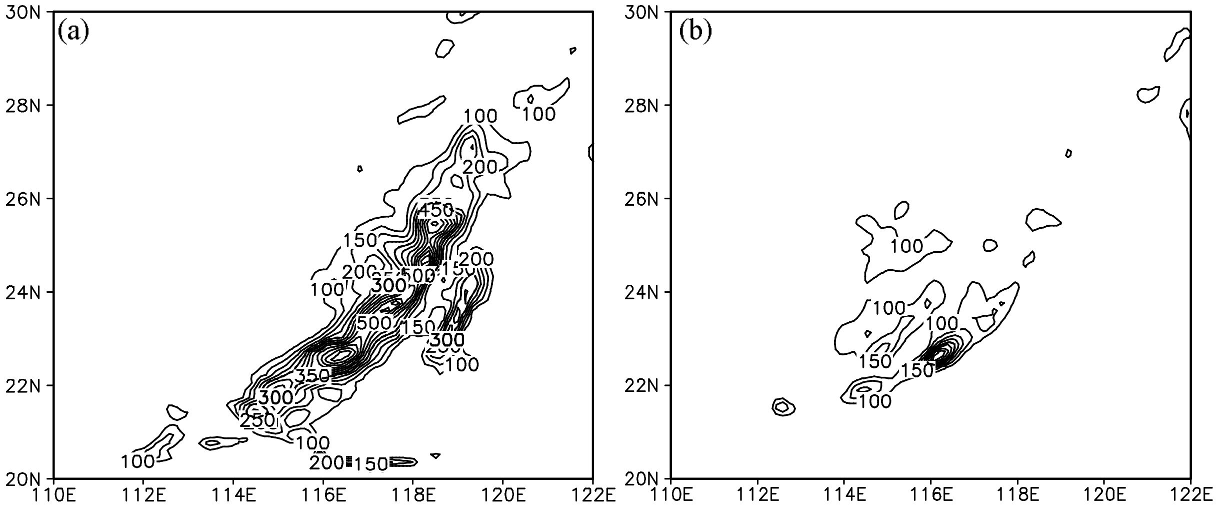

Fig. 3. The accumulated rainfall distribution (⩾100 mm) associated with Typhoon Bilis (0010) during 60 hrs of simulation (from Li and Chen, 2005): (a) control simulation with moisture transport; (b) without moisture transport.

port channel with strong vapor flux connected to the east circle of Bilis' circulation. A very strong rainfall rate and an extensive distribution of precipitation were generated by Bilis. A study by Cheng (2008) showed that considerable water vapor provided by a monsoon surge played a major role in the generation of heavy rainfall by Bilis (0604).

Another case study (Akihiko, 2006) also indicated that moisture is one of the most important factors involved in TC rainfall. Typhoon Meari (0422) made landfall in Kyushu, Japan, at 0830 LST 29 September 2004, with heavy rainfall occurring over the Kii Peninsula. A set of numerical simulations was performed using a non-hydrostatic model (JMANHM) with a grid spacing of 5 km. Two groups of different initial moisture data were employed. The results showed that the heavy rainfall produced by Meari was simulated well when using the initial conditions of a large amount of precipitable water. Weak rainfall was simulated when small amounts of precipitable water were used for the initial conditions. This suggests that moisture plays a critical role in the occurrence of heavy rainfall.

Vast expanses of water, such as lakes, rivers, and reservoirs, are also an important vapor source. A numerical investigation by Shen et al. (2002) showed that the water surface over land is favorable for decreasing the rate of decay of a LTC. They also showed that the rate of decay of a LTC over a water surface on land has a direct ratio with water depth.

As well as water surfaces (lakes, reservoirs etc.), saturated wet ground can also transfer moisture to feed back the remnant vortex and increase the intensity of a LTC and its associated rainfall. A numerical study by Kong (2002) showed that anomalous intensification of the remnants of the LTC Allison (2001) was closely related to the amount of saturated wet ground due to the continuous torrential rain caused by Allison itself. Strong convective systems developed over the warm, wet ground, and were favorable for the intensification of the remnant vortex and its rainfall.

3.2 *Extratropical transition*

Observations have demonstrated that LTCs would dissipate soon after making landfall by ground surface friction consuming their energy if they didn't obtain latent heat or baroclinic energy from mid-latitude systems. The interaction process between a LTC and the westerly trough may cause extratropical transition (ET) of the LTC. Cold air right behind the westerly trough could intrude into the vortex. The western semicircle of the LTC (north wind) would be colder and the eastern semicircle would remain warm (south wind). This changes the temperature–pressure structure of the LTC, thus producing a solenoid field. The baroclinic potential energy from the ET process would therefore be converted into kinetic energy, reviving the remnant LTC and increasing its rainfall.

Numerical experiments by Niu et al. (2005) on the rainfall of Typhoon Sinlaku (0216) were performed using the MM5 model. Results showed that the cold air which invaded into the periphery of the TC increased the rainfall amount in the area corresponding to the inverted V trough (B_1 in Fig. 1). However, when cold air penetrated into the vicinity of the typhoon center, it decreased the TC intensity dramatically and resulted in a remarkable decrease of rainfall near the TC center, while the rainfall increased still in the TC periphery and in the inverted V trough area.

A famous rainfall event occurred over Shanghai on 5 August 2001. One of its causes was a tropical depression undergoing an ET process, and it resulted in 302 mm of rain falling in 24 h (Lei, 2004). Numerical simulation (Zeng et al., 2002) showed that the "urban heat island" effect played an important role in increasing the heavy rainfall due to a cold air intrusion increasing the stratification instability of the depression. The strongest ever rainfall event over mainland China (1062 mm in 24 h) was produced by the remnants of Typhoon Nina (7503). This rain rate was much larger than the rain rate of any super typhoon during landfall, and was recorded during the ET stage. Most typhoons with ET processes will move to the north or northwest after landfall.

ET is a high impact weather process occurring in mid-latitude region, occasionally in lower latitudes, and often bringing about severe rainfall disaster. As such, the possibility exists that a TC may generate large amounts of rainfall in, for example, a lower-latitude country such as Vietnam (L. C. Duong, 2006, personal communication), if the remnant interacts with cold air. The heaviest rainfall will occur when the TC's landfall coincides with cold air (boreal monsoon) invasion, or the invasion occurs 12–24 h after landfall (Duong, 2006).

Appropriate cold air invasion would provide the LTC with baroclinic potential energy and potential instability to increase rainfall. On the other hand, rainfall of tropical cyclones would be suppressed if stronger cold air is intruded and filling up the remnant vortex.

3.3 *Topography*

Coastal and mountainous topography can influence the rainfall associated with LTCs. For example, topography-induced ascending motion on the windward slope of a mountain can contribute to an increase in rainfall. Akihiko (2006) studied the three remote rain masses occurring over the Kii Peninsula, far away (500 km east) from the landfall spot of Typhoon Meari (0422) at Kyushu, Japan, with the JMANHM model with topography removed to conduct a sensitivity experiment over the Kii Peninsula. The simulation results showed that one of the three rainfall systems related to mountainous topography disappeared, while the other two remained. The experiment demonstrates that some TC rainfall can be significantly affected by topography.

The remote rainfall of a TC can be affected by both the westerly trough in the mid latitudes (see section 4.1, below) and mountainous topography. Heavy rainfall may appear in an area far away from the center of the LTC due to the interaction between the TC and the mid-latitude trough, or the convergence between the topography and the peripheral flow of the LTC.

The asymmetric distribution of rainfall in LTCs is related to coastal topographic effects. A high rate and wide distribution of rainfall tends to occur in the region on the windward side of the shore and less rain appears on the leeward side. Thus, an asymmetric distribution of rainfall is formed due to the effect of coastal topography. When a TC makes landfall along the east coast of China, the coastlands to the north of the cyclone center would be the windward region, overlapped by the inverted V trough (B_1 in Fig. 1). This would cause rainfall to expand into a larger area on the north side of the TC center, rather than on the south side. Similarly, TC rainfall would expand into a larger area on the east side of the center than on the west side when it makes landfall along the south coast of China. On the other hand, numerical simulations (Liang et al., 2002) have shown that strong rainfall can still occur on the leeward side of the coastland if the right type of cold air is brought by the peripheral northerly winds of the LTC, which creates unstable stratification in the leeside region.

It is important to note that, although mountain ranges can increase the rainfall associated with a LTC under certain conditions, the roughness and friction of the land surface can consume the energy of the LTC and lead to its dissipation.

3.4 *Mesoscale convective systems*

Most heavy rainfall events are produced by strong mesoscale convective systems, and even microscale systems such as tornadoes. Statistical and observational studies have shown that these systems usually occur in the right front quadrant of landfalling typhoons. A number of mesoscale strong convective systems can be generated owing to the interactions between cold air, topography, and the LTC itself. Strong low-layer convergence with positive vorticity and strong potential instability and upper-level outflow divergence are favorable to the genesis and growth of mesoscale convective systems.

Mesoscale systems can be induced by a LTC interacting with the local topography. Such induced mesoscale vortices occur frequently over the Taiwan Strait when a typhoon approaches Taiwan Island of China from the east. A numerical study by Meng et al. (1996) on Typhoon Dot (9017), which crossed the Taiwan Strait, indicated that the induced mesoscale vortex from Dot was closely related to the central mountain range of the island. The low pressure area to the leeward side of the mountain wave helped the formation of the induced mesoscale leeward vortex and its corresponding heavy rainfall. Meanwhile, the topography of the Taiwan Strait and the intensity of the original typhoon also affected the formation of the induced mesoscale vortex.

The strongest torrential rain event on record over Hainan Island was caused by tropical storm Fitow (0114) as it crossed the Qiongzhou Strait to the north of the island. A numerical simulation (Duan et al., 2005) indicated that a mesoscale vortex occurred in a convergent zone between the windward mountain slope and the surrounding flow of Fitow. In this convergent zone, the lower-layer vorticity increased. Meanwhile, upper-level divergence created by Fitow became strong and the increase of unstable stratification in the middle layer due to the invasion of colder winds strengthened the vertical motion. All of these processes were favorable for the genesis of a mesoscale vortex (MSV), and rainfall increased accordingly.

Mesoscale systems also occur frequently in a remnant LTC undergoing ET processes. Certain regions of cold air provide baroclinic energy and potential instability which strengthens vertical motion and is favorable for the development of mesoscale systems. A study by Li et al. (2009) showed that when certain weak cold air intruded into the landfalling Typhoon Rananim (0414), the outcome was the emergence of a mesoscale system generated by the interaction between the north dry wind (cold air) and the easterly wet wind (warm air). The mesoscale convergent shear line was occurred in the border between the two different air flows (Fig. 4) and heavy rainfall in the remnant LTC corresponded to the mesoscale convergent shear line.

Another mesoscale system pattern is a small vortex. A numerical study by Chen and Li (2004) showed that a TC can intensify if a mesoscale vortex merges with it, with the possibility of heavy rainfall as a result.

3.5 *Boundary layer*

A field experiment on LTCs, known as the China Landfalling Typhoon Experiment (CLATEX) was implemented between July and August 2002 (Chen and Li, 2004). CLATEX acquired intensive observation data from different observational equipments in the boundary layer to study the impact of energy transfer from the boundary layer on the variation of TC behavior.

Boundary layer energy fluxes influence the intensity and rainfall of remnant vortices over land. The severe tropical storm Vongfong (0214) was a target TC for the CLATEX program. Numerical simulation of it (Yan et al., 2005) showed that latent heat flux played the most important role in the storm's intensification in the offshore water region.

In another case, the remnant of Typhoon Nina (7503) stagnated and sustained over South Henan Province for three days. Heavy rainfall and flooding made the ground under the typhoon saturated. A numerical simulation using the TC bogussing scheme was performed. The results (Li and Chen, 2005) showed that vertical fluxes of heat and momentum in the boundary layer over the saturated wet ground influenced the structure, intensity and rainfall of the rem-

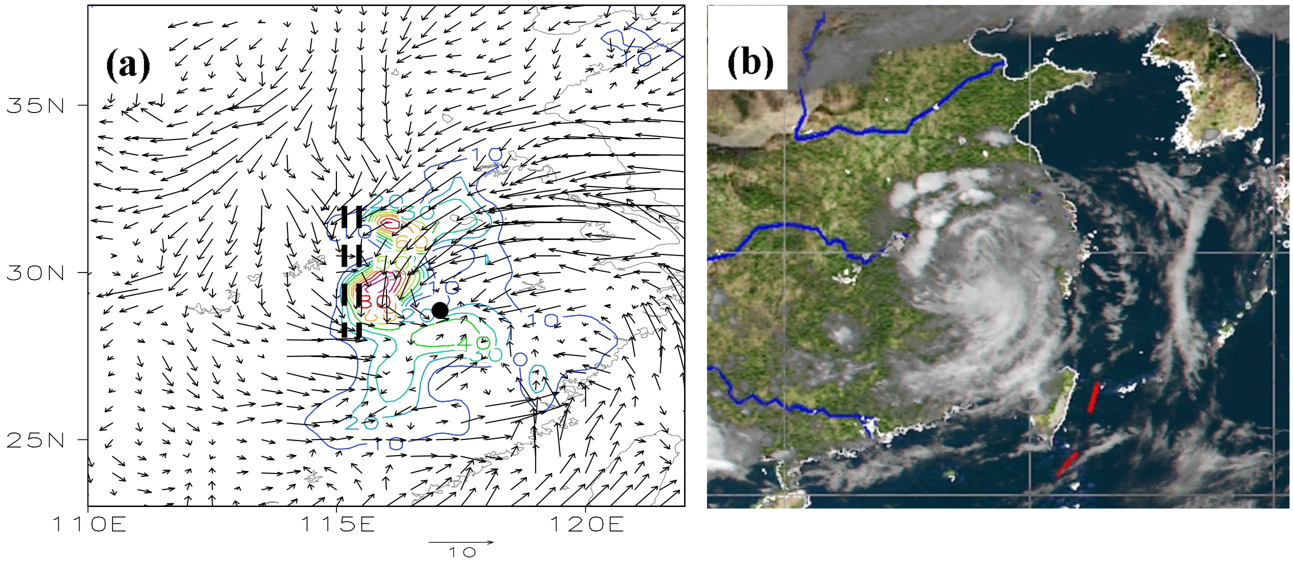

Fig. 4. Cold air intrution into super typhoon Rananim (0414). (a) Mesoscale convergent line (double broken line) and succedent 6 h accumulated rainfall in LTC remnant circulation and (b) the infrared satellite image at 1400 UTC 12 August 2004 (dot indicates typhoon center).

nant vortex greatly. Fluxes of latent heat and sensible heat were favorable for the maintenance and intensification of the typhoon remnant over land, with latent heat flux imposing the major effect on it. Heat flux in the boundary layer can also influence spiral rainbands, rainfall rate and distribution. The simulations of Typhoon Nina also showed that momentum flux can weaken the circulation of the remnant storm, with ground friction consuming the remnant's energy remarkably.

4. LTC influence on environmental rainfall change

4.1 *Interaction with the westerly trough*

A LTC or its remnant vortex may sometimes encounter a mid-latitude westerly trough. In these cases, heavy rainfall often occurs in front of the westerly trough, in the mid latitudes, far away from the center of the LTC in the lower latitudes (Fig. 5).

Typhoon Tim (9406) made landfall in Fujian Province on 11 July 1994. Heavy rainfall occurred in front of the mid-latitude trough in addition to the rainfall area generated by the typhoon itself. A numerical study by Zhu et al. (2000) demonstrated that the rainfall in the mid latitudes in front of the westerly trough was closely related to moisture transport by the strong southeasterly flow in the eastern periphery of the typhoon, which stretched the moisture channel to the area in front of the trough. A thick, wet, unstable layer with cyclonic vorticity in front of the trough was more favorable for an increase in rainfall. The study also showed that the rainfall was sensitive to the intensity of the TC and the strength of the westerly trough. Remote rainfall was produced not only by the westerly trough but also by topographic effects, as discussed above in section 3.3.

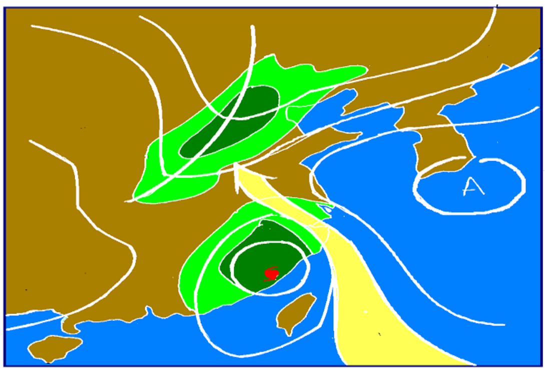

Fig. 5. Heavy rainfall occurred in front of a westerly trough due to the moisture transport in the lower layer by LTC.

4.2 *Interaction with the mei-yu front*

An observational study by Chen (1992) showed that there is a close relationship between mei-yu rainfall and typhoon activity in coastal waters. Tropical cyclones seldom appear in coastal regions when extensive mei-yu rainfall exists. Statistics (Cheng et al., 1999) show that 85% of mei-yu rainfall can be reduced, suspended or ended when a typhoon appears in southern coastal waters or makes landfall in South China.

Very heavy and extensive distribution of mei-yu rainfall along the Yangtze River and Huaihe River Basin from 18 May through 13 July 1991 ended with the occurrence and approaching of Typhoon Zeke (9106) on 9 July. It crossed the Philippines into the South China Sea and made landfall at Hainan Island on 13 July. This was the date that mei-yu rainfall ended. A numerical experiment (Cheng et al., 1999) which compared results with and without Typhoon Zeke showed that, during landfall, it could affect the moisture transportation channel from the Bay of Bengal and South China Sea to the Yangtze River Basin. Additionally, the western ridge of the subtropical high was shifted significantly northward by the typhoon. Meanwhile, mei-yu Front circulation and its energy cycle structure were destroyed by the approach of Typhoon Zeke. The suggestions, therefore, is that the appearance of a LTC in the south or southeast coastal regions of China is a strong signal for mei-yu rainfall suspending.

5. LTC rainfall estimation and forecasting

5.1 *TC rainfall estimation*

The application of remote sensing data has developed greatly in recent years. These data are quite effective in their reflection of rainfall rates and distribution. The Tropical Rainfall Measuring Mission (TRMM) was the first meteorological satellite with Precipitation Radar (PR) on board together with a TRMM Microwave Imager (TMI) and an on-board Visible and Infrared Scanner (VIRS), which can provide powerful cloud precipitation observations. In a case study by He et al. (2002) it was shown that precipitation derived from digital reflectivities of TRMM agrees well with ground radar observations.

The TC quantitative precipitation estimation (QPE) technique has been developed and put into operational use with FY-2C satellite digital products by NSMC China (You et al., 2002). The relationship between TC precipitation measured by surface observations and digital data from FY-2C has been established. Temperature of Black Body (TBB) data and cloud classification can be utilized to analyze the development and distribution of convective cloud bands and rainfall regions. SSM/I and AMSU data are also useful to estimate the potential maximum rainfall of a LTC. You et al. (2002) set up a cloud profile database with microwave data. Surface precipitation can be calculated from a cloud profile selected from the profile database which is analogous to the observed one.

Radar reflectivities have been widely used to estimate the rainfall rate and distribution of TCs. Some techniques have been developed to find the relationships between radar rainfall and true rainfall (Ji et al., 2008). Rainfall can be calculated from certain algorithms from the relationship between radar reflectivities and observed rainfall, however the algorithms vary with different radar locations and rainfall properties.

Some methodologies blending rain gauge data and radar data (Velasco-Forero et al., 2006) or satellite data have been developed to estimate rainfall rates and distributions. However, a lot of uncertainty still exists in precipitation estimation with either satellite data or radar reflectivities. The sources of these errors vary, but include both systematic and random errors. These limitations need to be overcome through further development work.

5.2 *TC rainfall forecasting*

Limited area models or mesoscale models with advanced data assimilation have become a major tool for TC quantitative precipitation forecasting (QPF). A non-hydrostatic mesoscale model (MSM) is being run by the Japanese Meteorological Agency to predict very-short-range forecasting (VSRF) of precipitation. The model provides 6-hr QPF updated every 30 mins (Tabito, 2006). The rainfall forecast is based on an extrapolation of the latest observed precipitation in the first 3 hrs and then the model results are combined with the extrapolation in the latter half. The weight of MSM-based predictions increases with the forecast time since the extrapolation accuracy rapidly decreases and the short-range forecast capacity of MSM will extend forecast time afterwards.

Another TC model (TCM), based on GRAPES (the Global and Regional Assimilation Prediction System), has been developed by the Shanghai Typhoon Institute. The model domain is 0°–50°N, 90°–170°E the horizontal resolution is $0.25°\times0.25°$, and there are 31 vertical levels, with the top at 350 000 m. Some advanced physical processes have been adopted. This mesoscale model is employed for 12–24 hr operational TC rainfall forecasting, with a certain level of acceptable error.

Rainfall ensemble forecasting systems have been designed and developed in many meteorological centers around the world, and can provide the probability of the occurrence of strong rainfall. A super ensemble prediction system based on a non-hydrostatic mesoscale model (MM5) has been developed (Feng et al., 2006) for rainfall forecasting. The multi-model perturbation scheme and multi-initial condition perturbation method have been adopted to focus on the uncertainty of heavy rainfall event forecasting in East Asia.

Statistical-dynamical approaches and empirical models are also employed in some forecasting centers to provide rainfall forecasting. A model output dynamics (MOD) method has been developed by NCHMF, Veitnam with datasets from numerical prediction models and observational rain data. MOD provides six-hourly rainfall rate and distribution forecasting. Another statistical-dynamical approach, the DSCS (dynamical-statistical combined scheme) was developed and employed by NMC China. Stepwise regression equations are used and the predictor coefficients are decided by dynamical model output based on the T213 global model (Liu et al., 2004). DSCS can provide 24-, 36-, and 48-hr precipitation forecasts for LTCs.

Statistical methods can provide a longer period (1–2 days) rainfall trend forecast or cumulative precipitation amount forecast using techniques that select analogous cases from historical data. Certain analogue criteria need to be set in order to select the analogous cases, such as season, track, landfall venue, topographic characteristics, LTC intensity, and so on. Using the right data processing techniques, the cumulative rainfall amount and its geographic distribution and other information from these analogous cases can provide a TC rainfall forecast. Statistical methods can also provide a rainfall climatic background for observed LTCs, derived from historical statistical data as a climatic background. This is very valuable for the forecasting of TC rainfall.

Real time operational forecasting of rainfall rate and distribution for LTCs can now be carried out comprehensively in many forecasting centers. Based on accurate TC intensity and track forecasting, the rainfall climactic background should be checked. Predicted results of LTC rainfall from numerous limited area models or mesoscale models and ensemble techniques etc. should be compared and verified with remote sensing satellite data, radar reflectivities, densely distributed rain gauge data, and other QPE products. In addition, a forecaster's practical experience and knowledge of empirical concepts are also valuable for rainfall forecasting. The final forecasting decision is usually made as a result of a comprehensive consideration of these QPF and QPE products.

Rainfall forecasting is not transferable to flood forecasting without a hydrological model, and there are several important uncertainties in hydrological model forecasts. Rainfall rate and distribution forecasts and surface runoff, as well as cumulative precipitation amounts, are the sensitive initial conditions for a hydrological model to predict flooding caused by a LTC. Therefore, flash flood forecasting is heavily dependent on the accurate forecasting of rainfall rates and distribution.

6. Summary

Heavy rainfall and flooding caused by LTCs are recognized as extreme weather events. The six top heaviest rainfall events in China (exceeding 1000 mm in one day) were all caused by typhoons. Fatalities and other associated disastrous consequences caused by LTC rainfall are extremely severe in China, but the science behind the behaviors of LTC rainfall is not currently understood to a great enough extent. Forecasting techniques need to be improved urgently.

In this paper, the authors have reviewed the development of research contributing to advancements in forecasting techniques for LTC rainfall. The strong vapor fluxes to LTC in lower layer or remnant of LTC interact with monsoon surge, as well as vertical transport of moisture from huge inland water surface (lake, reservoir, river, saturated ground etc) to the remnant LTC will increase rainfall remarkably. Topographic ascending effect and coastal mountain range convergence induce an asymmetric rain distribution for LTC and strengthen rain rate. Boundary layer energy transfer in a remnant of LTC increase its rainfall dramatically. Mesoscale system activities within LTC play a critical role in increasing LTC rainfall.

Remote rainfall associated with LTCs in front of a westerly trough can be produced by the interaction between the LTC and the westerly trough, and the approaching of a TC to the mei-yu Front may suspend mei-yu rainfall.

Significant progress of QPE and QPF has been made in recent years. Both remote sensing data combined with rain gauge data, as well as high-resolution mesoscale models with advanced data assimilation techniques, have become major contributors to QPF.

To date, the forecasting accuracy of LTC heavy rainfall has not reached the level necessary to meet the needs of LTC-related disaster mitigation. Observational and forecasting techniques relating to heavy rainfall caused by LTCs still require urgent improvements and significant development.

Acknowledgements. This work was financed by the National Grand Fundamental Research 973 Program of China (Grant Nos. 2009CB421504 and 2004CB418301), the Key Program of the National Natural Science Foundation of China (NSFC) (Grant No. 40730948), and the NSFC (Grant Nos. 40575018, 40675033 and 40975032).

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