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RESEARCH PROGRESS ON THE STRUCTURE AND INTENSITY CHANGE FOR THE LANDFALLING TROPICAL CYCLONES

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Abstract: Landfalling tropical cyclones (LTCs) include those TCs approaching the land and moving across the coast. Structure and intensity change for LTCs include change of the eye wall, spiral rain band, mesoscale vortices, low-layer shear lines and tornadoes in the envelope region of TC, pre-TC squall lines, remote rain bands, core region intensity and extratropical transition (ET) processes, etc. Structure and intensity change of TC are mainly affected by three aspects, namely, environmental effects, inner core dynamics and underlying surface forcing. Structure and intensity change of coastal TCs will be especially affected by seaboard topography, oceanic stratification above the continental shelf and cold dry continental airflow, etc. Rapid changes of TC intensity, including rapid intensification and sudden weakening and dissipation, are the small probability events which are in lack of effective forecasting techniques up to now. Diagnostic analysis and mechanism study will help improve the understanding and prediction of the rapid change phenomena in TCs.

Key words: research progress; TCs; structure and intensity changes

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1 INTRODUCTION

The structure and intensity of tropical cyclones (TCs) may have great changes in their different life stages. The greatest change of TC structure and intensity in its life span usually appears when it approaches the land or moves across the coast. Squall lines in front of TC, tornadoes in the right front quadrant of TC and remote rain bands may occur with landfalling TCs.

More TC structure change may appear when TCs move across the coast. TC eye wall would expand and become loose. The spiral structure of its rain band will become indistinct. Tornadoes and other mesoscale vortices as well as mesoscale wind shear may appear in different quadrants of TC remnants, which may produce heavy rain. Most of the remnants would dissipate over land due to ground friction. A few of them may revive when they interact with a mid-latitude trough and even produce heavier rainfall than they do in the landfalling stage.

Some landfalling TCs in the southeast coast of China may re-enter the sea again such as East China Sea, Yellow Sea, Bo Hai Sea and South China Sea. Some remnants of those typhoons may re-intensify after entering the sea. The sea surface temperature (SST) of those areas is usually lower than 26°C. The main mechanism of remnant intensification is the extratropical transition process.

The impact of TC structure and intensity change is not only on their associated maximum winds but also on the rate and distribution of TC rainfall, even in the storm surge. Study (Chen and Luo[1]) shows that the asymmetric structure of TC would influence its motion conspicuously. It is obvious that the TC structure and intensity change is an important area in TC research. However, the forecast capabilities of TC structure and intensity are much more lagged behind than those of track and precipitation. A key research program of China National Science Foundation provides an opportunity for us to focus research in this area for four years to improve the understanding of TC structure and intensity change.

2 INFLUENCING FACTORS OF THE STRUCTURE AND INTENSITY CHANGE

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TCs are subject to different influences from the ocean and atmosphere. The influencing factors can be categorized into three aspects (Figure 1).

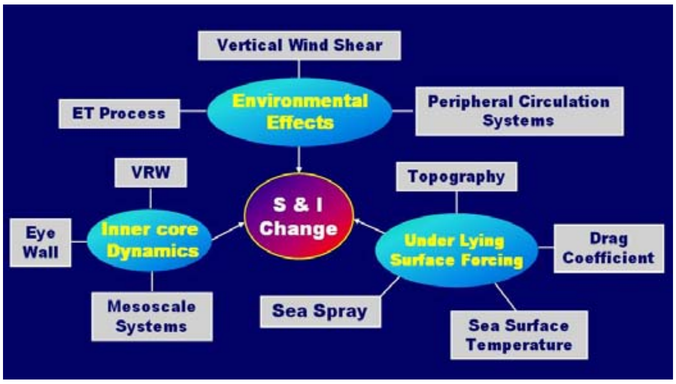

Figure 1. The diagram of factors affecting tropical cyclone structure and intensity.

2.1 *Environmental effects*

It's well known that the most important influence of environmental atmosphere on TC formation and intensity change is the vertical wind shear (VWS). TCs usually do not form under the effect of strong VWS. Study of Zeng et al.[2] shows that the influence of VWS on TC intensity change depends upon not only the magnitude of VWS, but also the wind direction of VWS, TC strength and position (different latitudes) etc.

Many peripheral weather systems (Figure 1) may influence TC intensity change. One of them is jet stream. Low-layer jets connect with TCs in the southeast quadrant. This is an important channel to transport moisture, vorticity and momentum to increase the intensity of TCs. Upper-level jets may enhance TC outflow and upper-level divergence, thus helping to strengthen TCs. Mesoscale vortexes and synoptic cloud clusters appearing in the peripheral area of TC not only affect the motion direction of TC but also its structure and intensity. TCs may intensify if the peripheral systems merge with them. Another important influence from the peripheral circulation is monsoon surge. The TC or its remnant could be reinvigorated by the interaction between the remnant and monsoon surges through providing plenty of moisture and energy to intensify the remnant. A typical example is the severe tropical storm Bilis (0604) which made landfall at Fujian province on 14 July 2006 and encountered a monsoon surge in the south of China. Widespread torrential rain occurred and devastated social infrastructures.

Extratropical transition (ET) of TC may occur when a TC or its remnant moves northward. ET is usually a result of the interaction between the TC and mid-latitude westerly troughs. The TC or its remnant will gain baroclinic potential energy due to the intrusion of proper cold air from the westerly trough. The TC or its remnant may increase its intensity because potential energy can be transformed into kinetic energy. Typical structure change of ET is cold in the west semicircle and warm in the east semicircle where heavy rainfall may occur.

2.2 *Inner core dynamics*

The variation of eye wall is intimately related to TC intensity change. A severe TC is usually corresponding to a compact and tight eye wall. As dry and cold continental air is drawn into the TC as it approaches land, it will cause the eye wall to expand and become loose. Correspondingly, the intensity of the TC will decrease.

A concentric eye wall may greatly modify the change in TC's inner structure and intensity. Concentric eye walls frequently appear in strong TCs in the western North Pacific. They usually form through the formation of mesoscale convective systems and their encircling around the inner core eye wall. The outer mesoscale convective ring prevents the moisture and energy from being transported to the inner eye wall, resulting in the decay of the inner eye wall and the growth and evolution of the outer convective ring. Consequently, the intensity of strong TCs begins to decrease. A previous study suggested that the interaction between wave-flow and vortex Rossby wave (VRW) may affect the formation of concentric eye walls (Qiu and Dan[3]).

Mesoscale convective systems (MCSs) inside the TC circulation such as small vortices and wind shear (Li et al.[4]) as well as the strong convective systems may modify TC structure significantly. The MCSs extensively existing in the peripheral area may act like a "moat" to inhibit the moisture and energy transport, leading to TC dissipation.

Vortex Rossby waves (VRW) is another mechanism of vortex structural change. Study shows that there is a close relation between the growth of unstable energy in the VRW region and the development of the inner core convective motion (Zhong et al.[5]). This is also a clue in exploring the dynamical conditions for rapid intensification of TCs. It is also shown that the VRW may affect the formation of eye walls and spiral rain bands.

2.3 *Underlying surface forcing*

SST is a foundation for TC formation and intensity change. Many rapidly intensifying processes usually appear when TCs enter oceanic areas with high SST, e.g. as it is higher than 30°C. Famous Hurricane Katrina (2005) rapidly intensified in the middle of Gulf of Mexico from Category 1 to Category 5 with the SST at 30°C. In contrast, TCs usually dissipate rapidly when they move into cold ocean water with SST lower than 25°C. Other observational facts suggest that TCs may weaken when they move across a cold water trail left by a preceding TC. TCs may weaken due to ocean upwelling if they slow down or stagnate. A field program named ITOP (Impact of Typhoon on Ocean of the Pacific) in 2010 is to study the ocean response to the TCs, especially the sea surface cooling due to upwelling caused by TCs. Interactions between the ocean and the atmosphere is a basic physical process to influence the TC formation and structure. Some observational studies show that the ocean heat capacity (OHC) has better correlation with TC intensity change than SST. A thick warm layer of the upper ocean with higher OHC would have less influence from TCs. Fast-moving TCs may have less influence on SST.

There are few observations on the distribution of ocean surface waves which are related to TC surface wind stress through affecting the frictional drag and sea spray processes. Recent research by Zeng et al.[6] with a new boundary parameterization scheme indicates that drag coefficients would decrease in the situation of wind speed exceeding 40 m/s. The decrease of the drag coefficient will increase the tangential wind speed near the core region and strengthen the warm core, which will consequently increase TC intensity. Another research on sea spray with a Weather Research Forecast (WRF) model suggests that the sea spray may strengthen the dynamic effect of the boundary layer, increase near-surface wind speed and convergence. That process suggests that the sea spray may intensify TC.

Topographic forcing may cause structure and intensity change of the TC greatly as it is approaching land or moving across the coastline. Topographic influences can start when a TC moves into the sea water above a continental shelf. Shallow sea storm surge and sea spray would be strengthened. Sea water and coastal topography should be considered in examining structural change of TCs. The basic influence of topography on TC remnants is frictional energy consumption. The remnant usually dissipates over land due to frictional effect. On the other hand, topographic effect may help generate some mesoscale systems, such as small vortices, wind shear, etc, in the peripheral of TC, which may lead to torrential rainfall due to the structural change of TC. Frictional effect of land surface may increase the radial wind convergence and cause strong convection that is favorable for TC to alleviate its decaying. TC peripheral wind distribution will produce leeward and windward low-pressure centers near mountain ranges, which would have different effect on the structural change of the TC remnant. Different underlying surface properties, such as mountainous region, champaign land, and vast inland water surface, will have different influences on the TC structure change. For example, huge reservoirs or lakes may somewhat prolong the TC maintenance through providing energy and decreasing the friction, which may enhance the convective systems and rainfall.

3 RAPID CHANGE PHENOMENA OF TC STRUCTURE AND INTENSITY

3.1 *Rapid intensification of TC over offshore water*

Statistics shows that most TCs weaken gradually when they approach the land. Only 12% of them intensify rapidly (Zhu et al.[7]). The following processes are favorable for the rapid intensification of TCs.

3.1.1 MESOSCALE VORTICES MERGING

Numerical experiments implemented by Chen and Luo[7] demonstrate that the TC may intensify rapidly when a mesoscale vortex merges with it. The main cause is that the TC gains the vorticity suddenly from the mesoscale vortex in the merging process. The TC intensifies prominently with its merging with a small vortex (Figure 2).

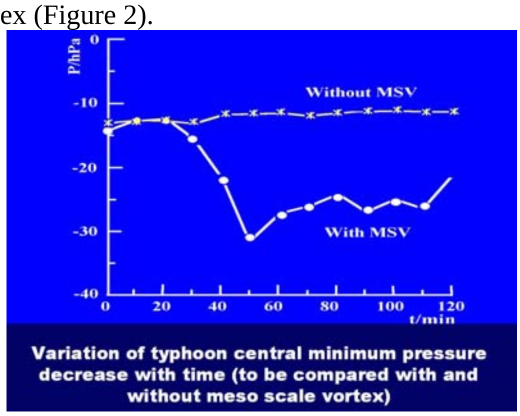

Figure 2. TC intensity change with and without mesoscale vortex merging into it.

Occasionally, binary TCs could be merged, becoming a single circulation system with a pair of eye wall rotating around each other. The intensity of the merged system will increase dramatically. This process could lead to rapid change not only in the motion direction but also the structure and intensity of the TC.

3.1.2 BINARY TROPICAL CYCLONE INTERACTION

Binary TCs often appear in coastal waters, such as Saomai (0608) and Bopha (0609), Morakot (0908) and Goni (0907). When two TCs are close enough, the interaction between them will start. Typical interactions between binary TCs, like Morakot and Goni (Figure 3), may change the structure and intensity of both TCs. Xu et al.[9] suggested that the intensity of Morakot and its associated rainfall rate increased dramatically due to Goni transporting plenty of moisture and energy to it with its southwest flow. Finally, Goni was gradually dissipating over the South China Sea.

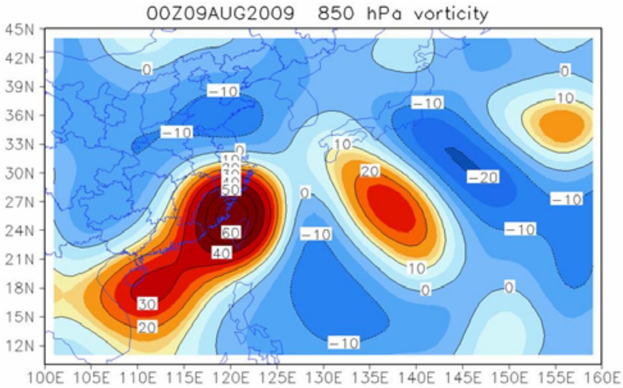

Figure 3. Interactions between Morakot (0908) and Goni (0907).

3.1.3 WATER VAPOR TRANSPORT

Composite data analysis of two groups of intensifying and weakening TCs demonstrates that the intensifying TC group has a vapor transportation channel while the weakening TC group does not. It shows that the moisture transportation is an important factor for TC intensification. An important process for TCs to gain considerable moisture is the interaction between it and the monsoon surge. Monsoon is a major weather system in China. In particular, the east and the south of China and their surrounding oceanic regions are frequently affected by monsoon. A large amount of cloud clusters with high humidity surge moving northeast may encounter a TC when they approach the continent. Monsoon surges, composed of wet cloud clusters, can be drawn into TCs, providing latent heat to intensify them in the interaction process. A typical case of interaction between TC and monsoon surge is severe tropical storm Bills (0604). It gained great quantities of moisture from the monsoon surge (Figure 4) to prolong its life span over land, resulting in heavy rainfall continuously and great calamities in the south and middle of China (Zhang et al.[10]).

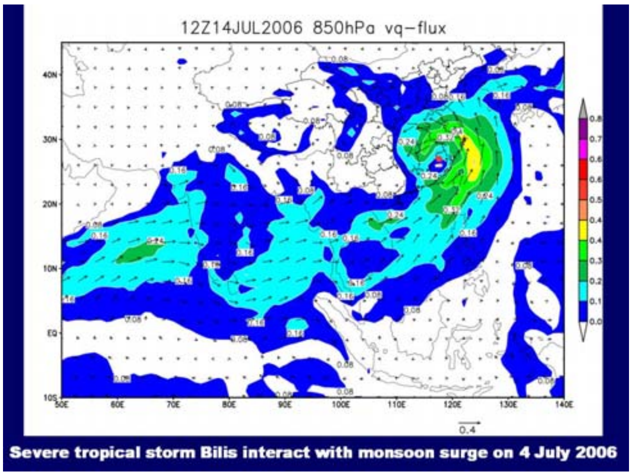

Figure 4. Interactions between Bilis (0604) and the monsoon surge.

3.1.4 UPPER LEVEL OUTFLOW EFFECT

When TCs move into an area south of an upper-level jet stream, upper-level divergence and out-flow of the TCs may be strengthened, which would be favorable for TC intensification.

3.1.5 SEA SURFACE TEMPERATURE

SST would affect TC structure and intensity significantly when a TC moves into a high SST area such as 30°C. This is also a favorable condition for TC rapid intensification.

3.2 *Rapid weakening of TC in offshore area*

Super typhoons may dissipate suddenly, which will cause the failure of track forecasting.

One environmental condition that suppresses TC development is strong vertical wind shear (VWS). Zeng et al.[2] suggests that the VWS in different layers with different wind directions would have different effects on TC structure and intensity. It is also suggested that westerly wind shear may have a stronger effect on TC intensity than an easterly wind shear.

The outbreak of continental cold waves may affect the TC in offshore areas, especially in the northern part of South China Sea in autumn. The cold air can be drawn into the TC, destroying the eye wall and dissipating the TC.

In the northern part of South China Sea, when a typhoon is approaching the coast of the south of China in late autumn, strong cold and dry air from the mainland may intrude into the offshore typhoon. Under this condition, a “hollow core” structure may occur with the absence of an inner-core maximum wind ring because the eye wall has been destroyed by cold, dry air. The northern peripheral winds near the cold front are much stronger than in the core region. This phenomenon usually happens in late autumn, just before TC dissipation.

In many cases, TC dissipation is affected by cold ocean water. Strong typhoon Babs (9810)—with maximum wind of 50 m/s in the ocean near the Philippines—decreased rapidly to 15 m/s as it moved into an area of cold sea surface (SST<25°C). It dissipated over the cold sea water.

Low SST could be produced by the TC itself when it slows down or stagnates or loops. The response of local sea that is covered by a TC is the occurrence of an up-welling current from deep ocean mixed layers, which will decrease the SST. TCs weaken during the interaction between the atmosphere and the ocean.

3.3 *Squall line associated with TCs*

Squall lines may appear in front of a TC that is with strong convection and instability stratification. A pre-TC squall line is a special structural phenomenon of TC. Sometimes squall lines compose of small-scale convective systems, even tornadoes, which may cause extreme weather when they move across the coast.

Squall lines are not a necessary structural part of TCs. Some TCs are associated with squall lines while others are not. Study by Meng and Zhang[11] suggests about 43% of the landfalling TCs in China are associated with pre-TC squall lines. Rich moisture, instability and low-level mesoscale frontogenesis and convergence zone preceding a TC are important influencing factors for the formation and development of pre-TC squall lines (Figure 5).

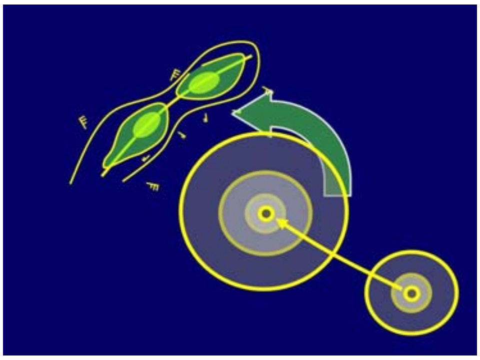

Figure 5. Schematic diagram of squall line formation.

Numerical simulation suggests that the formation of the pre-TC squall lines are closely related to the approaching of the parent TC (Meng and Zhang[10]). Though convections are still initiated, they are not organized into a long-lasting squall line when the TC is removed. Other experiments also demonstrate that the position, strength and movement of the pre-TC squall line are also related to the TC's behavior.

3.4 *Revival of remnants of landfalling TC*

After landfalling, most TCs will dissipate over land but a few of them would revive to bring about more rainfall and damage than in the landfalling stage. Statistics in Dong et al.[12] show that only 9.7% remnant of a landfalling TC will revive in the mainland of China. Thus, it is a small probability event.

This work also suggests that the revived TCs have two main tracks, moving either northward or westward (Figure 6). Diagnostic analyses and numerical experiments suggest that the interaction between the remnant of a TC and mid-latitude westerly troughs is a major mechanism for the remnant revival (Dong et al.[13]). The interaction process would lead to ET in the remnant through gaining potential energy from the cold air. Potential energy could be transformed to kinetic energy to reinvigorate the decaying remnant. The case study suggests that the moisture channel connected with the northward remnant is another favorable condition for the revival.

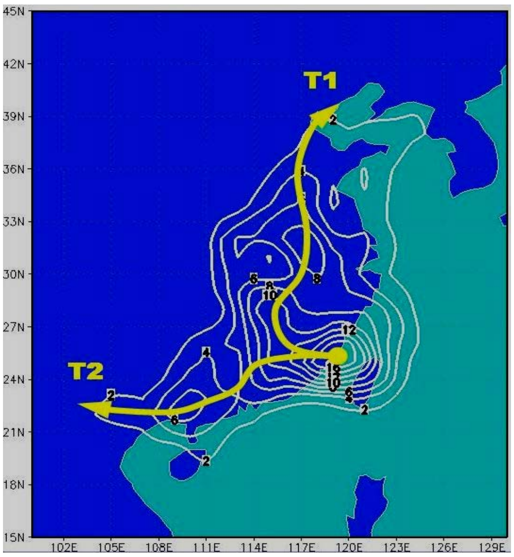

Figure 6. Two favorable tracks for TC revival[12].

On the other hand, diagnostic analyses also suggest that the interaction between TC remnants and monsoon surges could change the structure and intensity of the TC to prolong the existence of the remnant overland. Wet cloud clusters drawn into the remnant provides latent heat energy to increase its intensity and to help produce heavy rainfall. It is suggested that the remnant could interact with mid-latitude troughs or interact with the monsoon surge, which would be favorable for the remnant of a landfalling TC to revive.

3.5 *Remote rain band of TC*

TCs may create a rain band in front of and away from the TC. This rain band may bring about heavy precipitation. Here in this work, this phenomenon is called Tropical-cyclone Remote Precipitation (TRP) (Figure 7). Statistics indicate that only 14.7% of the

TCs have the TRP (Cong et al.[14]). A number of TRP events have extensive heavy rain that may persist for more than one day.

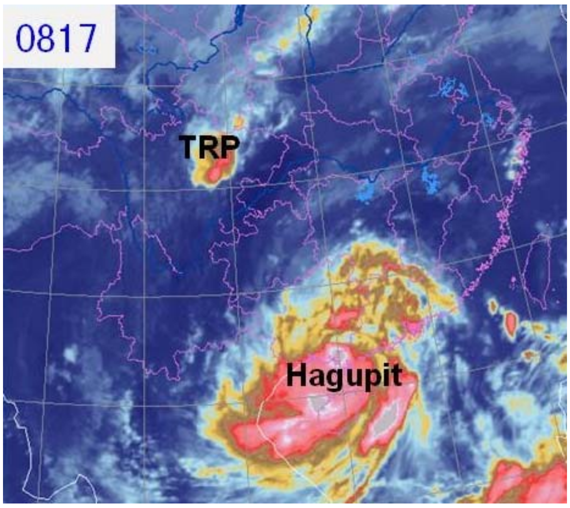

Figure 7. Infrared satellite image of 0230 UTC 24 September 2008 which displays the TRP phenomenon with typhoon Hagupit (0814)[14].

Diagnostic analyses suggest that the TRP rain band is a result of interaction among TCs, westerly troughs and topography. It is formed through moisture transportation via southeast peripheral flows on the eastern quadrant of the TC to the area in front of a westerly trough. Composite analyses of two groups of data with and without TRP indicate that the westerly trough and upper-level divergence in front of the trough and a lower-layer moisture transportation channel connected with the TC are favorable for the occurrence of the TRP phenomenon.

Numerical experiments suggest that the TRP are closely related to the TC, westerly troughs and topographic effects. Sensitivity numerical simulations demonstrate that the TRP will remarkably decrease if the TC is removed or the intensity of TC is decreased (Cong et al.[15]). It is also shown that the westerly trough plays an important role in producing the TRP event. The stronger the westerly trough is, the heavier rainfall of TRP will be. Besides, topography such as mountain ranges also has positive effects on the TRP.

The TRP phenomenon appears not only in China, but also in the United States and Japan, with a similar formation mechanism (Wang et al.[16]).

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