ADVANCES IN UNDERSTANDING AND FORECASTING RAPIDLY CHANGING PHENOMENA IN TROPICAL CYCLONES

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ABSTRACT

This review of new understanding and forecasting of tropical cyclones (TCs) is based on presentations at the *International Top-level Forum on Rapid Change Phenomena in Tropical Cyclones* in Haikou, China. The major topics are the sudden changes in tracks, rapid changes in structure and intensity, rapid changes in rainfall, and advances in forecasting and forecaster requirements. Although improved track forecast guidance has been achieved with the Australian ACCESS-TC model and in track forecasts to 120 h by the China Meteorological Administration, there is a continuing need for better understanding and improved track forecast guidance. Advances in understanding of processes related to rapid intensification (RI), secondary eyewall formation, mechanisms controlling inner-core structure and size changes, and structure and intensity changes at landfall have been achieved, but progress in prediction of rapid changes in structure and intensity has been slow. Taking into account complex interactions involved in TC-related rainfall, a prioritized list of physical processes that govern rainfall from landfalling TCs in China has been developed. While forecaster participants were generally encouraged by the progress being made, they expressed a strong desire for a transition of that new knowledge to timely and reliable forecast guidance products.

1. Introduction

This International Top-level Forum on Rapid Change Phenomena in Tropical Cyclones (hereafter the Forum) is the third of a series of workshops held in China to focus attention on landfalling tropical cyclones (TCs). Since the western North Pacific and East Asia region has the largest number of TCs around the globe, it is natural that high interest exists in this region on landfalling TCs. With the growth in population and infrastructure along the China coast, the risk from typhoons has greatly increased. Consequently, continuing research on TC landfall has been funded by the China government and the 973 Project is the latest example. A large fraction of the presentations at the Forum were a result of the 973 Project funding, and one objective of this review article is to provide a summary and wider visibility of these achievements.

It is noteworthy that this Forum has been sponsored by the Chinese Academy of Engineering. With the rapid development in China, particularly along the coastline, there has been a proliferation of tall structures. The most important meteorological conditions for these structures (and other infrastructure) near the coast is the extreme winds and heavy rainfall in landfalling TCs. One focus of the 973 Project has been in new observational tools and strategies for landfalling TCs, including Doppler radars, radar wind profilers, meteorological towers, and mobile vehicles. Dual Doppler observations have been obtained in several typhoons that will be a good data base to document the temporal and spatial variability.

Co-sponsor World Meteorological Organization (WMO) World Weather Research Program (WWRP) has put a high priority on facilitating exchange of research to improve TC

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forecasts and warnings in all countries, but especially in developing countries. Three WMO agencies have been cooperating in a five-year Tropical Cyclone Landfall Forecast Demonstration Project (TCLFDP) with the objective of improving track forecasts in the western North Pacific. This project, which is led by the Shanghai Typhoon Institute, has been able to get real-time access to forecast products from a number of the numerical weather prediction centers around the world and use them to create new guidance products.

This summary of the Forum is being published in the *Tropical Cyclone Research and Review* with the objective of highlighting research advances that are relevant to forecasters. Forecaster participation was also a key focus for the Forum since the overall objective is to reduce the impacts of TCs and saving lives through improved warnings. First, the forecasters' communication of their requests and priorities (e.g., intensity forecast improvement) helped set the program and invitation list of experts. Second, the forecasters were requested to communicate what aspects of the research presentations appear to have the highest potential for developing new guidance products and incorporation into the forecasts. While the advances in forecasting will be integrated in this summary with the research advances, the final section will examine outcomes of the Forum from the forecaster perspective.

A common theme throughout the Forum was the interaction among various physical processes or phenomena that lead to rapid changes in the TC. The focus on rapid changes is because it is during these rapid change periods that the forecast guidance is least reliable, and consequently the likelihood of large forecast errors will exist. Professor Lianshou Chen in his keynote talk (K.2) presented a flow chart (Fig. 1) to illustrate the factors that affect TC structure (S) and intensity (I) changes. However, interactions among environmental effects, inner-core dynamics, and the under-lying surface forcing are also to some degree contributing to changes in the TC motion and the rainfall. The challenge to the researcher is to understand how these various physical processes or phenomena interact to cause rapid changes, and then how to develop accurate and reliable forecast guidance products. The challenge for the forecaster is to recognize the existence of these phenomena given a sparse observational system and then to evaluate the existing forecast guidance, which may be lacking in accuracy and reliability, to predict the timing, magnitude, and duration of a rapid change. The importance of the Forum is that it was an opportunity for researchers and forecasters to exchange information on research advances and forecaster needs and requirements.

The overall objective of this review is to summarize the outcomes of the Forum in terms of research advances and forecaster needs and requirements. The focus in section 2 will be on sudden track changes. The primary focus of the Forum was on intensity changes and this will be the

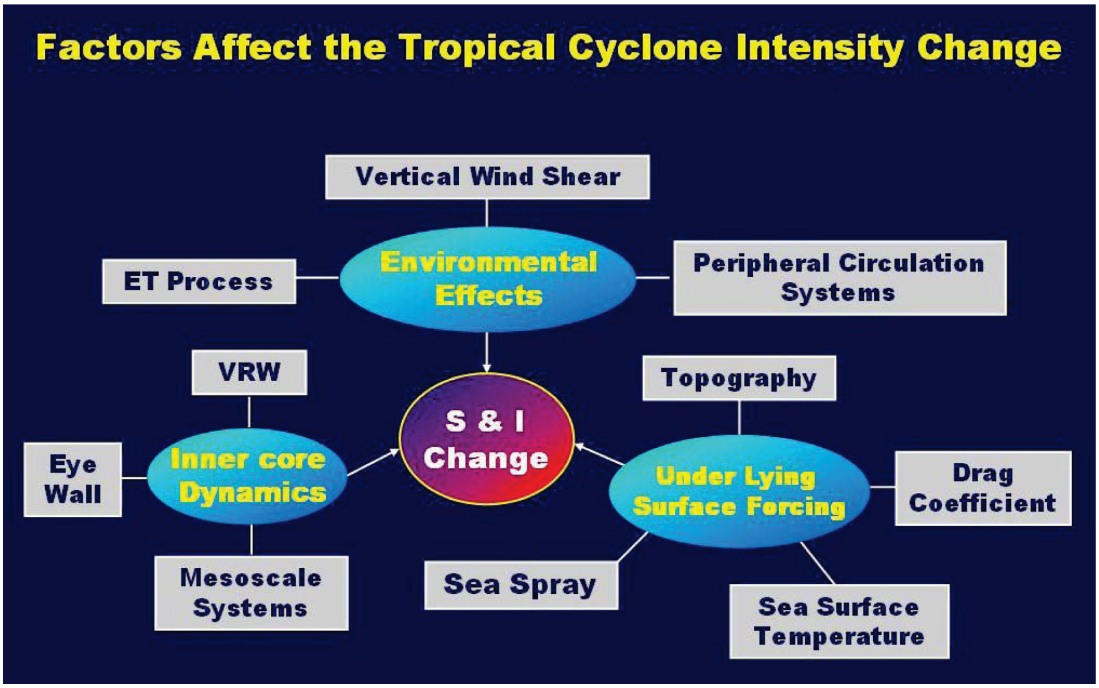

FIG. 1. Flow chart illustrating physical processes and phenomena that interact to cause structure and intensity (S & I) changes in tropical cyclones, but also may be considered to cause motion changes and rainfall distribution change (adapted from L. Chen keynote K.2).

topic of section 3. Rainfall distribution changes will be described in section 4. Finally, the forecaster perspectives will be summarized in section 5.

2. Sudden track changes

The major advance in TC track forecasting has been the reduction in track forecast errors, which has been due to improved Numerical Weather Prediction (NWP) model guidance and the use of consensus forecasting with multiple skillful NWP models (Elsberry 2007). An example of reduced track errors with the recent introduction in Australia of the ACCESS-TC model was presented by N. Davidson (K.5). For six TCs in the Australian region, the 72-h track errors were about 50% of the mean track errors over the prior five years (Fig. 2a). A reduction of 72-h errors from 300 km to 200 km was also achieved for 16 western North Pacific TCs during the 2012 season through early October 2012 (Fig. 2b).

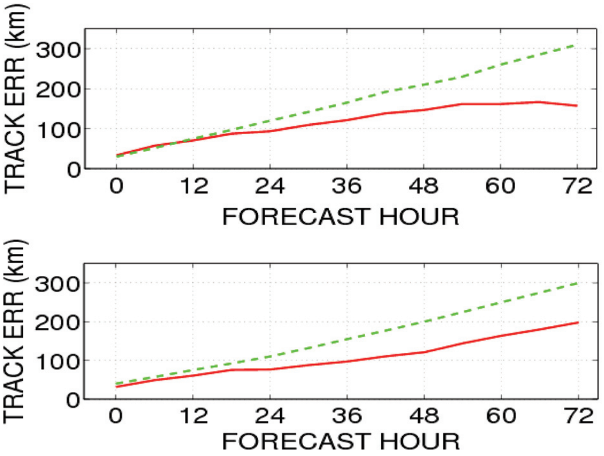

Fig. 2. Track forecast errors (km) from the Australia Bureau of Meteorology operational ACCESS-TC model for (top) six TCs in Australian region (0-35ºS, 80-180ºE) during the 2011-2012 season, and (bottom) 16 TCs in the western North Pacific during the 2012 season up to early October 2012 (provided by N. Davidson).

It was the achievement of reduced 72-h track forecast errors that led to the extension of the U.S. National Hurricane Center and Joint Typhoon Warning Center track forecasts to five days beginning in the 2003 season (Elsberry 2007). Since that time various other NWP centers have provided track guidance to 120 h. Y. Duan (K.3) presented a summary of the China Meteorological Administration (CMA) track forecast errors in the western North Pacific over the period 1991 – 2012 (Fig. 3). Note the reduction in 72-h track errors from ~420 km in 2001 to ~210 km in 2012. Even more dramatic is the reduction in 96-h track errors from ~475 km in 2008 to ~300 km in 2012. Furthermore, the 120-h track error of ~445 km during 2012 was only slightly larger than the 420 km 72-h error in 2001. Thus, track forecasts in China have been extended to five days with accuracy comparable to the 72-h errors of a decade ago.

Another track forecasting advance has been through the use of NWP ensemble models as additional track guidance and to estimate the uncertainty in the track forecast from the ensemble spread. The Northwest Pacific Tropical Cyclone Ensemble Forecast Research project has collected ensemble products from various NWP centers and provided them in near-real time to forecasters in the ESCAP/WMO Typhoon Committee. L. Qui (D.9) applied a selective consensus technique based on the short-lead time error (note

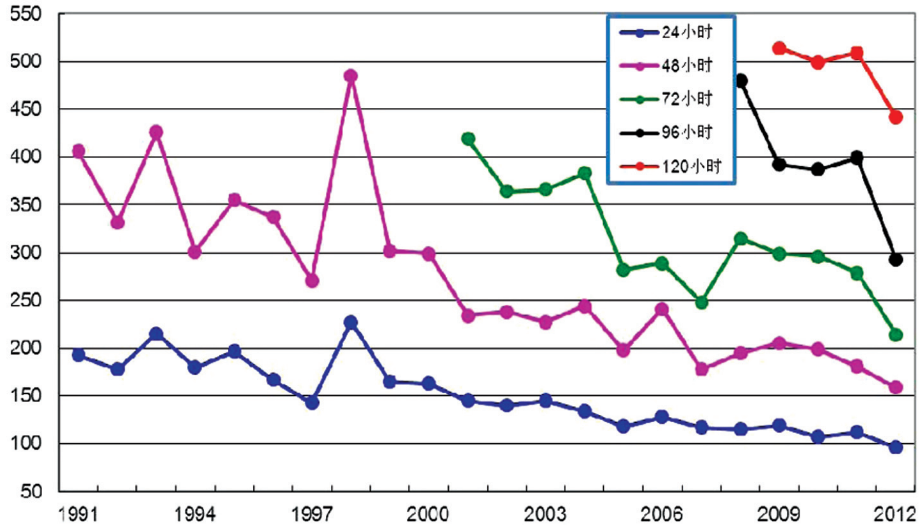

Fig. 3. Track forecast errors (km) by China Meteorological Administration forecasters for western North Pacific during 19991 – 2012 seasons. Note that 72-h, 96-h, and 120-h forecasts were first introduced in 2001, 2008, and 2009, and dramatic improvements have been achieved in 2012.

that the ensemble product is not available until synoptic time plus 12 h, when the + 6 h and + 12 h positions are known) to select some members expected to have more accurate 72-h track forecasts. Both a simple average and a weighted average of the selected tracks were evaluated for the CMA, Japan Meteorological Agency (JMA), National Centers for Environmental Prediction (NCEP), and European Center for Medium-range Weather Forecasts (ECMWF) ensembles. The weighted-mean average ensemble 24-h track error using only selected ensemble members based on the smallest short-term track errors was smaller and had a smaller standard deviation (i.e., spread) than the ECMWF high-resolution deterministic model and the CMA, JMA, and JTWC official track forecasts. However, this advantage did not extend to 48 h and beyond.

Even with these dramatic improvements in NWP track forecast guidance, the message from the forecaster participants in the Forum was that the track forecast is not a "solved problem." Presentations were made of sudden track changes in the South Indian, North Indian, and western North Pacific regions. J. Davidson (K.4) presented an extensive study of an abrupt poleward turn of Severe TC George (2007) that led to the worst 48-h track forecast in the Western Region of the Bureau of Meteorology in the last five years. One explanation for this bad track forecast is that the NWP models failed to predict the transition from a midlatitude-driven steering flow to one affected by the monsoon. Large track forecast errors with similar sharp poleward turns in the western North Pacific TCs have been attributed by Carr and Elsberry (2000) to interactions with the monsoon circulations. Such an interaction with the southwest monsoon may have also accounted for the sharp poleward track shift of Supertyphoon Megi (2010) in the South China Sea as described by C. Qian (A.7). As C. Qian illustrated, nine of the 10 best member tracks from the 51-member ECMWF ensemble 120-h forecast for Megi from 1200 UTC 17 October had an excellent representation of the sharp poleward track change. However, the remaining 42 member tracks had westward or northwestward tracks across the South China Sea. While a large spread indicates uncertainty, the natural questions of the forecasters are: How may such a large spread in ensemble tracks be factored into the official track forecast, and specifically when should the minority of tracks be accepted as guidance rather than the majority of tracks?

L. Wu (A.4) presented a composite analysis of 15 sudden north-turning cases and 14 west-turning cases that occurred in the western North Pacific during 2000-2011 and examined the influences of low-frequency monsoon circulations. Two categories of track changes were embedded in a monsoon gyre of about 2500 km in diameter on the quasi-biweekly oscillation time scale, which was also embedded in a larger scale cyclonic gyre or monsoon trough on the Madden-Julian Oscillation (MJO) time scale. The two types of track changes were closely associated with interaction between the large-scale, low-frequency circulations and the synoptic flows. In the west-turning case, the westward extension of the subtropical high led to ridging on the northwest side of the TC and the associated enhanced easterly winds largely offset the steering of enhanced southeasterly winds on the synoptic time scale. Thus, the north-turning (west-turning) sudden track changes were primarily affected by the synoptic-scale (low-frequency) steering. This may be one of the reasons for the larger track forecast errors in the north-turning case than in the west-turning case.

In summary, sudden track changes are still a big challenge for the forecasters, especially when a slow-down in the motion and then a sudden shift in direction occurs near landfall. While such sudden track changes are related to environmental steering effects (especially peripheral circulation systems such as monsoon trough, subtropical high, or another TC) as in the top part of Fig. 1, inner-core dynamics associated with mesoscale systems were also considered to be a factor in some presentations. Interaction of the TC circulation with topography such as the Central Mountain Range in Taiwan is known to lead to sudden track changes. All of these interactions are two-way, i.e., a sudden change in the track may feedback to the large-scale environment via the outflow jet and change the inner-core dynamics or the topographic interaction via an altered rainfall distribution. A request from the forecaster participants was that research be carried out to understand the sources of the large track forecast error cases.

3. Rapid changes in structure and intensity

One of the high priority objectives in this Forum was to exchange information on the rapid changes in TC structure and intensity that are one of the most difficult tasks for TC forecasters. Indeed, little improvement in the accuracy in TC intensity forecasts has been achieved by operational forecast centers around the world, which is in part due to the lack of effective TC structure forecast guidance. Whereas the track is mostly controlled by the large-scale environmental flow and synoptic-scale interactions that are fairly well predicted, the structure and intensity changes are affected by a number of physical processes that involve the inner-core dynamics and more complex interactions of the TC with the large-scale atmospheric environment and with the underlying ocean (Fig. 1; see also Wang and Wu 2004). In this section, some new or improved understanding in this important research area will be summarized and some emergent issues will be discussed.

The keynote lectures and contributed presentations can be classified into five topics: (i) Processes responsible for rapid intensification (RI); (ii) Differences in the inner-core structure between RI and steady-evolving TCs; (iii) Formation of a concentric eyewall structure; (iv) Mechanisms controlling the inner-core structure and size changes; and (v) Structure and intensity changes at landfall.

R. Elsberry (K.1) discussed the control of RI in western

North Pacific TCs by both the vertical wind shear (VWS) and upper ocean heat content (OHC). He proposed a VWS-OHC phase space in which VWS was the primary environmental control, but would facilitate discussion of the conditions when OHC would be an additional environmental control of TC intensity change. D.-L. Zhang (K.6) and Y. Wang (K.7) presented case studies of Hurricane Wilma (2005) and Typhoon Megi (2010) , respectively, in which weak or decreasing VWS and high sea-surface temperature (SST) and OHC were shown to be critical to RI. In such a pre-conditioned favorable environment, the onset of RI was triggered by convective bursts (CBs), which are defined as intense convective cells that penetrate into the upper-troposphere with maximum core updrafts over 8-10 m s^{-1}. These CBs are considered to contribute to the initial formation of the TC warm core structure in the upper troposphere by both compensating subsidence and entrainment of high potential temperature air from the lower stratosphere.

As demonstrated by Zhang (K.6) for the Hurricane Wilma simulation (Fig. 4), the warming in the upper (lower) troposphere is more (less) efficient in lowering the central sea-level pressure of a TC. Rather than an increasing number of CBs, both Zhang (K.6) and Wang (K.7) found that CBs in the inner-core region became less frequent as the simulated TC intensified rapidly. However, the areal coverage of convective precipitation increased steadily, so the upper-tropospheric warming may tend to suppress the penetration of deep convection even though strong forced convection is predicted. Although CBs have a key role in upper-level warm core development in these simulations, some questions remain as to whether they are essential for RI or are a by-product of RI.

Y. Wang (K.7) summarized his control simulation of the RI and inner-core size increase of Typhoon Megi in a schematic illustrating the key processes (Fig. 5). Given the favorable large-scale environment of small VWS and large OHC, an accumulation of CAPE occurred in the eye region of Megi that triggered CBs that led to the upper-tropospheric warming and thus the onset of RI. This upper-tropospheric warming process was enhanced by the axisymmetrization of the TC vortex and the increase in inertial stability inside the RMW. This increasing inertial stability first contributes to a rapid deceleration of the boundary layer inflow and thus stronger eyewall updrafts and convection, and secondly leads to higher efficiency of the upper-tropospheric warming in response to diabatic heating in the eyewall convection. The inner-core size increase was diagnosed by Wang and Wang (2013) in terms of the tendency equations for the azimuthal mean tangential and radial winds (inset in Fig. 5). The processes leading to the spinup of tangential wind outside the eyewall and thus the inner core size increase were a result of diabatic heating associated with active spiral rainbands.

R. Rogers (K.10) examined differences in the inner-core structure based on NOAA P-3 Doppler observations between TCs undergoing RI and non-RI or steady-evolving TCs. Intensifying TCs have a ring-like vorticity structure inside the RMW, lower vorticity in the outer core, a deeper and stronger inflow layer, and stronger axisymmetric eyewall upward motion compared with the steady-state TCs. Although little difference existed between the vertical tilts of the eyewalls between 2-7 km, the azimuthal coverage of eyewall and outer-core precipitation is greater for the intensifying TCs. The primary difference is that more active CBs, which accomplish more vertical mass flux, occur in intensifying TCs. Consistent with the earlier theoretical studies (e.g., Vigh and Schubert 2009), these CBs are preferentially located inside the RMW for intensifying TCs, while the CBs tend to be outside of the RMW for steady-state TCs. Given that the inertial stability distribution in steady-state TCs would tend to decelerate the boundary layer inflow outside the RMW, this would inhibit conditions favorable for RI.

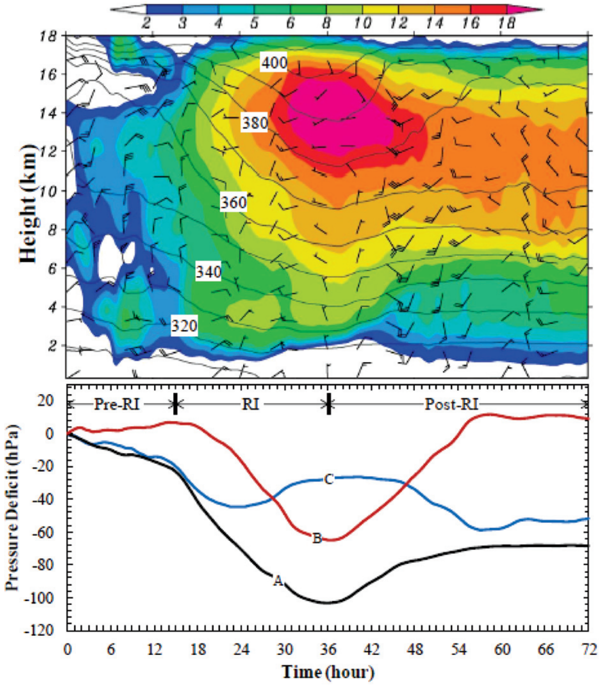

Fig. 4. (Top) Time-height cross-section of perturbation temperature (K, shaded) superposed on potential temperature (θ, contoured at intervals of 10 K) and storm-relative flows (a full barb is 5 m s^{-1}) at the eye center from the 72-h prediction of Hurricane Wilma (2005) at the 3 km resolution and 30-min intervals, where perturbation temperature is defined with respect to the (1000 km by 1000 km) area-averaged temperatures at the model initial time. (Bottom) Time series of central SLP (P_{MIN}, hPa) drop from the 72-h prediction (curve A), pressure drop estimated from the warm column above the θ = 380 K surface (curve B), and from the warm column beneath the θ = 380 K surface (curve C), where pressure drop is defined with respect to P_{MIN} at the model initial time (adopted from Zhang and Chen 2012).

Several contributing presentations at the Forum also

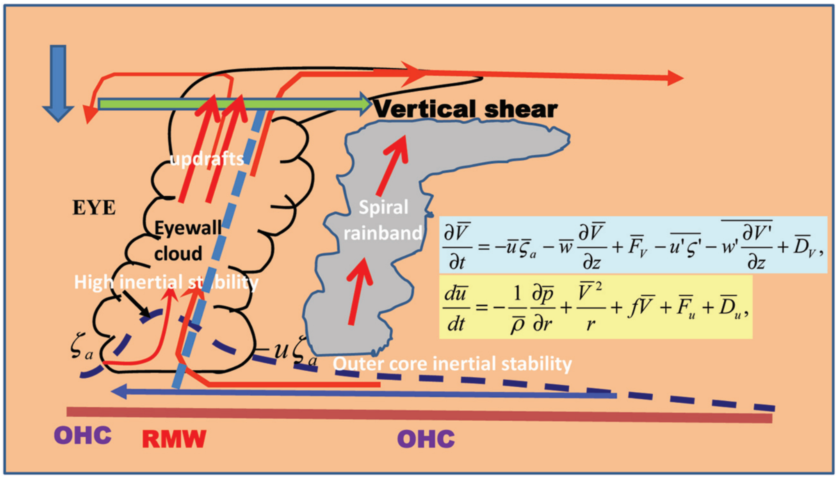

FIG. 5. Schematic of the processes related to the RI and the inner-core size increase of the Typhoon Megi as simulated by Wang and Wang (2013). Upper-level subsidence in the eye is as indicated by the large downward arrow. High inertial stability and outwardly tilted eyewall clouds with strong updrafts exist inside the RMW, and moderate inertial stability and spiral rainbands exist outside the RMW. RI is favored if environmental vertical shear is weak and the OHC is large, and the inner-core size will also increase if spiral rainbands are strong and active.

examined the role of mesoscale convection in RI. H. Yu (B.2) examined the differences in mesoscale deep convection in TC experiencing RI and those experiencing moderate intensification (MI) during 1996-2010 over the western North Pacific. H. Yu also found more active mesoscale convection with cloud-top temperatures lower than -60ºC in the inner core region during the 24 h before RI, with the strongest convection closer to the TC center than for those TCs experiencing MI. Since these results are consistent with the aircraft observations of R. Rogers (K.10) and the model simulations of Y. Wang (K.7) and D.-L. Zhang (K.6), detection of such convective activity may be a precursor of the onset of RI.

One of the major processes that can cause large/rapid intensity changes of a mature intense TC is the concentric eyewall cycle or secondary eyewall formation (SEF). Although several mechanisms have been proposed to explain the formation of the concentric eyewall structure, they do not explain all aspects of the concentric eyewall cycle. Although some high-resolution cloud-resolving models simulate the formation of concentric eyewall structure in intense TCs, these simulations are very sensitive to initial vortex structure or model physics. N. Davidson (K.5) reported an idealized simulation in which SEF was very sensitive to the initial tangential wind profile. The SEF was related to the broadening of tangential wind in which an unbalanced or net positive radial force (sum of pressure gradient force, centrifugal force, Coriolis force, and frictional force) occurs in the boundary layer and leads to a convergence zone, upward motion, and convection some distance outside the eyewall. This is very similar to the mechanism proposed by Huang et al. (2012). Y. Jiang (B.3) described a simulated SEF in Typhoon Sinlaku (2008) in which the timing and the radial location of the SEF and the duration after the SEF were quite sensitive to the choice of the PBL scheme.

Y. Wang (K.7) reported a new category of concentric eyewall structure in Typhoon Megi in which the inner eyewall appeared/developed within an existing large outer eyewall. This inner eyewall appeared to be a redevelopment of the original eyewall that had earlier dissipated over Luzon Island after Megi moved over the South China Sea (SCS), a new relatively large eyewall structure developed, and then an inner eyewall redeveloped near the storm center. As the outer eyewall contracted, the inner eyewall weakened and dissipated after about 9 h, which is a relatively short eyewall replacement cycle in the western North Pacific.

Y. Wang (K.7) noticed that Megi experienced a continuous inner-core size increase during its RI phase, which he related to the binary interaction of Megi with a large-scale low-level depression in which Megi was embedded. Both the merging of Megi with the depression and diabatic heating in active spiral rainbands enhanced by the binary interaction were considered to contribute to the inner-core size increase during the RI. Q.-H. Zhang (B.4) evaluated TC structural changes in response to the distribution of the ambient moisture field. Increased moisture in the outer-core region had a negative effect on inner-core intensification, but contributed to the maintenance of outer core strength and an increase in TC size by inducing more active convection in the outer-core region. She also found that TC size is more related to ambient moisture than TC intensity. A size-intensity phase diagram was also proposed that illustrated TC size changes are more related to ambient moisture than to intensity.

One of the distinct features of an intense TC is the ring structure of potential vorticity (PV) in the lower troposphere with maximum values just inside the RMW. Diabatic heating in the eyewall is critical to the maintenance of this PV ring structure. C.-C. Wu (K.11) indicated that the evolution of the ring structure in a 3-dimensional (3D) full-physics model is completely different from that previously found in 2-dimensional (2D) barotropic models. In the full-physics model, the ring can be maintained by convective heating in the eyewall without a significant breakdown that results in strong mixing and an end state of the monopole PV structure as in the 2D models. The PV budget analysis suggests that the e-folding times associated with the PV production and PV advection are similar while both of these processes had considerably shorter e-folding times than are associated with barotropic instability. As a result, convective heating in the eyewall likely stabilizes the PV ring structure in real TCs. In addition, other presentations at the Forum provided further evidence that VWS is a major factor in the wavenumber one asymmetries in the eyewall, but higher wavenumber asymmetries are likely tied to barotropic instability and convective-scale processes.

Changes in the structure and intensity of TCs are always rapid during landfall. Several keynote lectures and contributing presentations at the Forum provided new evidence of rapid changes in several aspects of landfalling TCs. The transition of the inflow boundary layer of a TC making landfall has some implications to both mixing and transport. L. Chen (K.2) showed evidence of the rapid deepening of the inflow boundary layer from in-situ observations of several TCs making landfall in South China. This rapid deepening even occurred near the RMW and thus was likely a result of enhanced surface friction and vertical mixing, although strong downdrafts may have contributed in some occasions.

The decay rate at and after landfall depends on local factors such as the land surface properties and topography as well as interaction with the monsoon flow, subtropical high, midlatitude weather systems, etc. S. Zhang (D.7) reported evidence of slowed weakening of TCS due to the enhanced surface latent heat flux associated with Poyang Lake. C. Ji (B.7) found that stronger TCs experience stronger VWS during landfall in Zhejiang Province with rainfall increases at and shortly after (1-2 h) landfall. If the strong VWS serves as a trigger for convective cells to develop in spiral rainbands, then an associated effect would be a broadening of the wind field in landfalling TCs. Although events of both rapid intensification and rapid decay in the coastal region are very important to operational forecasts, these events received less attention at this Forum.

Quality and consistency of real-time and best-track TC data are still issues for operational forecasts and research. For example, differences in intensity and position from different agencies may be quite large in some cases, which affects definition of RI.

Some recommendations from the Forum related to rapid changes in structure and intensity include:

- Attention needs to be given to the definitions of VWS (e.g., different area average and vertical levels) in different studies, and to evaluate the effect of the vertical profile of VWS;
- Various storm size definitions (e.g., radius of maximum wind, various wind radii, and radius of outer closed isobar) are utilized at TC warning centers and various definitions of inner-core and outer-core are used in the research community without necessarily considering dynamical constraints, so some uniformity in defining the storm size is needed;
- Storm size change predictions should be included in the evaluation of NWP model skill, and storm size specification should be included in the TC initialization;
- Additional observations of the PBL transition at landfall are needed to understand the physical processes contributing to the rapid deepening of the PBL;
- A field experiment focusing on rapid intensity changes near shore in the South China Sea should be combined with the proposed field experiment to improve TC-related rainfall prediction (see end of section 4).

4. Rapid changes in rainfall

One of the most significant impacts of TCs is the copious amount of rainfall they often produce. This heavy rainfall can lead to significant loss of life and property. For example, Typhoon Morakot (2009) caused over 600 deaths and $3 billion in damage (Zhang et al. 2010), primarily as a result of the torrential rains and flooding as Morakot slowly moved past Taiwan. Indeed, a village in Taiwan was completely destroyed by the devastating flooding accompanying Typhoon Morakot (Fig. 6). In the 30 years prior to Hurricane Katrina (2005), drowning from inland flooding was the leading cause of TC-related deaths in the United States (Rappaport 2000).

Despite the importance of accurately predicting TC rainfall, advancements from NWP models have been difficult to realize and quantify. Much of this deficiency lies in lack of understanding the physical processes that influence TC rainfall and their representation in NWP models, especially after TCs have made landfall and are well inland. Factors that govern TC rainfall distribution depend on physical processes that span multiple spatial and temporal scales (Rogers et al. 2009, Chen et al. 2010), as depicted in a schematic of rainfall regions associated with a landfalling TC (Fig. 7). These scales and associated processes include:

- Environmental scale -- monsoonal flow, frontal boundary interactions, variable static stability, inverted troughs;
- Vortex scale -- TC track and binary interactions, vortex Rossby waves and inner-rainband structures, mixed vortex Rossby wave/inertia-gravity wave structures;
- Convective scale -- convective/stratiform distribution, vertical mass flux profiles, outer rainband/cold pool forcing;
- Microphysical scale -- source/sink terms for rainwater,

FIG. 6. Before and after photographs of Shiao Lin village, Taiwan impacted by the rainfall from Typhoon Morakot (2009).

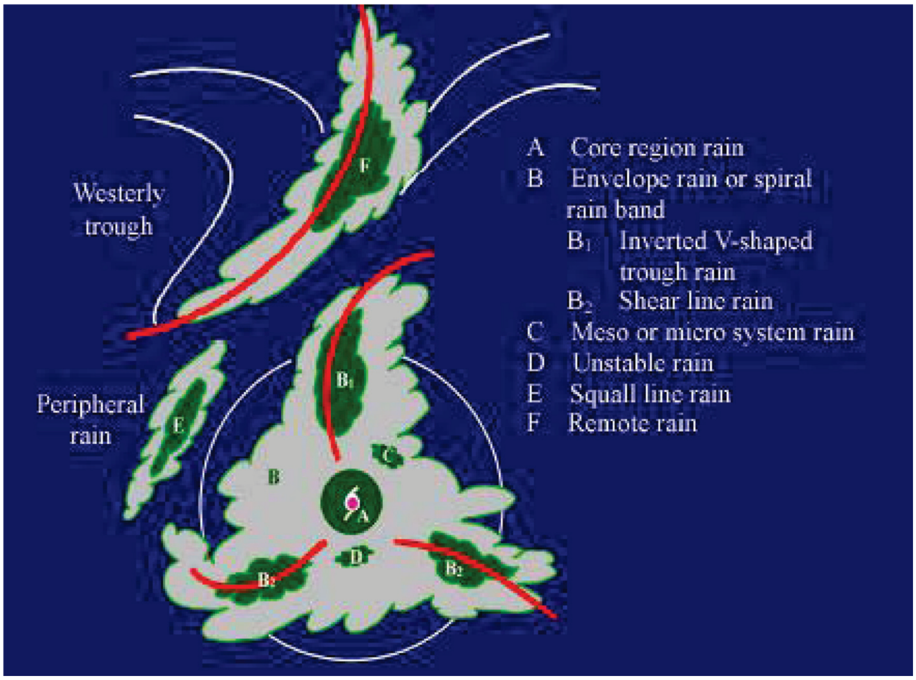

FIG. 7. Schematic of rainfall regions associated with a landfalling tropical cyclone (adapted from Chen et al. 2010).

snow, graupel, contributions from various conversion terms among microphysical species, variability with respect to characteristics of source air, such as aerosol concentrations, continental vs. maritime air.

Many of the presentations at the Forum focused on environmental scale processes. X. Cui (C.2) presented an analysis of large-scale flow fields associated with rainfall from landfalling TCs in China. Advection of moisture by the monsoonal flow around the southeast side of the TC plays a critical role in the development of heavy rainfall, particularly at large distances from the TC center. Decomposition of the flow field into irrotational and nondivergent flows indicated a predictive capability for the onset of the monsoonal flow based on predicting the irrotational flow. M. Dong (C.1) described the interaction of a landfalling TC with a cold frontal boundary in eastern China. Sensitivity tests varying the strength of the cold front led to different distributions and amounts of rain depending on the southward penetration and strength of the convergence associated with the front. The strongest (weakest) cold front penetrated the most (least), which shifted the main rainfall to the south (north). Additionally, the strongest (weakest) cold front had the weakest (strongest) convergence. For both tests the amount of rain was less than in the control run, which suggests that the control run presented the optimal distribution of southward penetration and convergence to produce the heaviest rainfall. M. Pu (C.7) presented an analysis of two cases of TC inverted troughs (see region B_1 in Fig. 7) that brought torrential rains during TC landfalls in the Yangtze-Huai River Basin. These rains occurred at a significant distance from the TC center in the presence of an upper-level trough with ageostrophic forcing, cold air advection in the mid levels, and warm air advection in low levels. This combination of factors along with moisture flux with the monsoon flow may lead to torrential rains.

Y. Li (E.5) compared two TCs with similar tracks and similar lengths of time in the vicinity of Beijing that led to vastly different rainfall amounts. Freda involved a trough interaction, mid-level cold advection, low-level warm advection, and an upslope component to the low-level flow. Matsa had none of these features and therefore had only small rain. Z. Cheng (D.5) presented a set of factors that forecasters in China should consider when predicting rainfall associated with landfalling TCs: TC intensity, range, landfall location, track, structure; water vapor transport; atmospheric stability considerations including warm and moist advection in a low-level jet, and/or cold moist advection in middle levels; and a triggering mechanism due to steady convergence and lifting.

Several presentations focused on smaller-scale (i.e., vortex- and convective-scale) processes. W. Zhong (C.5) presented a theoretical analysis of "fast" inertia-gravity waves (IGW) and "slow" vortex Rossby waves (VRW) based on the proposition that both modes can co-exist in TCs due to the presence of strong rotation (to support VRW propagation) and divergence (to support IGW propagation). This analysis verified the presence of these structures and performed various diagnostics on the expected structures based on assumptions involving the vortex basic state and assumed azimuthal wavenumber structure. An idealized simulation of rainband structures by Q. Li (C.3) using the TCM4 model investigated the structure and dynamics of inner and outer spiral rainbands. The inner rainbands were linked to vortex Rossby wave propagation, while the outer rainband propagation was related to cold pool dynamics. The horizontal distribution of convective/stratiform precipitation, vertical mass flux profiles, and diabatic heating from the simulation were consistent with recent observational studies.

J. Ming (E.3) presented a detailed study of microphysical parameterizations and the impacts of these different schemes in a WRF simulation of the intensification of Typhoon Saomai (2006). The Lin (WSM6) scheme had the strongest (weakest) heating and strongest (weakest) vertical motion. This tendency for a positive feedback with efficient cloud microphysical schemes leads to intensification of the secondary circulation and thus an intensification.

Several presentations focused on heavy rainfall events in China that occurred at a significant distance from the TC center and thus were not directly tied to rain near the TC inner core after landfall (cf. Region F, or "Remote rain", in Fig. 7). Such "rainfall reinforcement" events, which are similar to Predecessor Rainfall Events (PRE) associated with landfalling TCs in the United States, may produce torrential rainfall in conjunction with environmental conditions such as monsoonal advection of high equivalent potential temperature air, mid-level advection of cool air, interaction with an upper-level trough, and extratropical transition of the landfalling TC.

Based on these studies in China, a prioritized list of physical processes that govern rainfall from landfalling TCs has been developed:

- TC track (duration of rainfall);
- Interaction with topography (highly dependent on track);
- Interaction with environmental features (e.g., monsoonal flow, frontal boundaries, vertical wind shear, upper-level jet streaks, regions of reduced static stability);
- Inner-core structure (e.g., eyewall, rainband structure, system-scale moisture distribution (e.g., "wet" vs. "dry" storm);
- Microphysical processes (e.g., production/conversion terms of ice species, interaction of microphysical structures from different air masses as the TC moves into an extratropical environment).

An informal meeting was organized at the Forum to explore the possibility of a WMO/WWRP Research Demonstration Project (RDP) focused on improving understanding and prediction of TC-related rainfall in the western North Pacific. The first focus would be on an intercomparison of high resolution numerical models to understand the deficiencies in rainfall prediction for landfalling typhoons. This RDF effort would be coordinated with the ESCAP/WMO Typhoon Committee to include forecaster participation.

5. Forecaster perspectives

This section summarizes the key outcomes of the Forum from a forecasting perspective. Forecasters at the Forum were generally encouraged by the progress being made in modeling TCs and understanding their complex interactions. They also expressed a strong desire to see a robust process for quickly transferring that new-found knowledge to numerical models and to operations. As part of the process, forecasters would benefit from more exposure to modeling and other research studies, which would enable them to improve their conceptual models of TCs. The more skilled TC forecasters are arguably those who have acquired good conceptual models. In return, researchers may also benefit from more communications with forecasters. Worthy of consideration here would be an exercise to understand and exploit forecaster 'rules of thumb.' In TC warning centers around the world, forecasters have developed many and varied forecast aids with an operational basis that have proved useful over time. It is highly likely that understanding and modeling of the physical basis for some of these 'rules of thumb' could aid the research effort.

While significant progress has certainly been made with respect to track forecasting (section 2), forecasters believe that more research on track forecast improvement remains to be done. Consensus and ensemble techniques using global models are leading the way in TC warning centers, but real benefits also arise from high-resolution regional models and observational analysis (manual or computer). The TCLFDP at the Shanghai Typhoon Institute is an excellent example of providing easy access to multiple model outputs to the forecasters. It is important that hazardous phenomena probability forecasts are generated as an output of the process. Forecasters at the Forum put the highest priority on a more objective approach to consensus track forecasting using multiple deterministic global models and ensembles.

As indicated in section 2, forecasters need to be continually aware of the potential for bursts in the monsoon or surges in the tradewind flow that may lead to abrupt track and/or intensity changes. While the NWP models have significantly improved in predicting such changes, occasionally the forecaster may have to rely instead on observational analysis using satellite observations. Another possible cause of sudden track changes is the binary interaction of two tropical systems, with one or both being a TC. It is important for forecasters to have a good understanding of the various modes of interaction between circulations of such binary systems, because the NWP model guidance may not accurately represent the various interactions. Continued occurrence of these and other examples of large forecast errors leads to the second priority for forecasters at the Forum being the verification of the operational prognostic reasoning behind the forecast of rapid change events and preparation of detailed case studies.

As mentioned in section 2, more case studies are encouraged of the large TC track errors from the consensus and ensemble track forecasts, especially when the model guidance had a small spread and yet a large forecast error resulted. To ensure that lessons are learned from rapid change TC events, verification of the operational prognostic reasoning behind the forecast should be widely encouraged. This verification is best done soon after the event by a small dedicated group that must include the forecaster(s) engaged at the time. The next step in the process is the preparation of a detailed case study of the event that closely examines the precursors and identifies the main drivers. These case studies should be widely shared within the TC forecasting and research communities, and this new *Tropical Cyclone Research and Review* journal may be the appropriate venue for publication of such studies.

A strong consensus existed among forecaster participants at the Forum that forecasting intensity changes, and especially rapid intensification and rapid decay, is their greatest challenge. Several presentations by researchers highlighted the importance of the inner-core and convective processes within a TC in forecasting rapid change phenomena. Forecasters at the Forum put a high priority on acquiring a better knowledge of these convective bursts and concentric eyewall replacement cycles and their respective linkages to rapid intensification. Consideration of diurnal cycles needs to be factored into studies of convective bursts in TCs as this may be a real challenge to forecasters. It is often difficult to operationally decide whether or not a convective burst during more favorable early morning hours will be sustained during the day, or is in fact just part of the regular diurnal cycle. In this regard, some specialized training on how to best interpret satellite microwave imagery would assist forecasters.

Recent studies presented at the Forum have resulted in the generation of a rapid intensification index. This index would be of more value to forecasters if it was coupled to the real-time intensity and outputs from the global and high-resolution regional models. Since the index and the model output may be interrelated, this might not be a trivial exercise. Nevertheless, forecasters at the Forum put the third highest priority on development of a reliable operational rapid intensification index because of the widespread need for guidance on rapid TC intensity and size changes. A better understanding of the role of moisture and moisture fluxes in determining TC structure (intensity, size, and strength) is required. Forecasters would benefit from better guidance on bursts in the monsoon and surges in the tradewind flow that lead to rapid intensity and size changes.

Several presentations at the Forum addressed the extreme rainfall and storm tide hazards that continue to be responsible for the highest loss of life globally from TCs. As indicated in section 4, a prioritized list of physical processes governing rainfall from landfalling TCs in China has been developed. Based on this list, a question was raised as to which of the following options would maximize the improvement in TC rainfall forecasting: (i) improved observations and analysis of the environment (e.g., monsoonal flow, cold fronts, upper-level troughs and jet streaks, stability profiles); (ii) improved initialization of vortex (e.g., assimilation of radar data); (iii) higher resolution NWP models (improved rainband structure, better predictions of VRW or mixed VRW/IGW evolution, convective/stratiform partitioning and mass flux profiles); (iv) improved microphysical parameterizations (e.g., source/sink terms, higher-order schemes that may be more responsive to source air), land-surface processes, interaction of microphysics between TC air stream and midlatitude air sources; (v) ensemble-based methods (e.g., to account for spectrum of track forecasts); or (vi) the research into rainfall at large distances from TC center (PRE-type events, monsoonal flow, upper-level trough interactions, extratropical transition).

No consensus on the relative importance of these six options could be reached during the Forum. Given the importance of the TC track on the amounts and distribution of rainfall, approaches that account for track forecast variability and further improvements of the track forecast should be given a high priority. Thus, improved initialization of the large-scale environment, and adoption of ensemble-based methods to predict track forecast uncertainty, would be high priorities. Just as environmental interactions with the TC are important for structure and intensity changes (Fig. 1), forecasting of TC-related rainfall would also benefit from improved predictions of the interaction of the TC and its large-scale environment. More fundamental research into the physical mechanisms that lead to torrential rainfall at large distances from the TC center (i.e., "rainfall reinforcement" events) was recommended. While improved microphysical parameterizations and vortex initialization and increased horizontal resolution of NWP models are important, they are not expected to contribute as much as the above factors to improved forecasts of TC-related rainfall amounts and distributions.

In the Forum summary session, Jim Davidson encouraged both researchers and forecasters to focus their efforts on the 'end game', i.e., reducing TC impacts and saving lives. He also emphasized that unexpected and un-forecast TC rapid change events often lead to inadequate warnings and raise the likelihood of adverse impacts and loss of life. Because not all the presenters at the Forum were applying the same definitions of the various rapid change phenomena, Jim Davidson recommended that a small working group be established to draft a suite of definitions of TC rapid change phenomena for consideration by WMO and other relevant bodies. Finally, a critical issue for nearly all forecasters at the Forum is the lack of aircraft reconnaissance of TC in their area. The value of aircraft reconnaissance observations should never be understated. This assertion applies equally well to both the real-time needs of forecasters and to researchers undertaking modeling studies. Over the years, such data have proved invaluable in improving TC warnings and our knowledge of TC dynamics.

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