Western North Pacific Tropical Cyclone Formation and Structure Change in TCS-08

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LONG-TERM GOALS

The long-term goal of this project is to develop a better understanding of mesoscale and synoptic-scale processes associated with the entire life cycle of tropical cyclones in the western North Pacific. The inability to correctly identify tropical cyclone formation over the period of 24 h – 48 h poses a threat to shore and afloat assets across the western North Pacific. Furthermore, once a tropical cyclone has formed the predictability of structure changes during intensification of tropical cyclones is very low, which is due to complex physical processes that vary over a wide range of space and time scales. Periods of reduced predictability occur throughout the tropical cyclone life cycle, which includes the decaying stage. Because decaying tropical cyclones often transition to a fast-moving and rapidly-developing extratropical cyclone that may contain gale-, storm-, or hurricane-force winds, there is a need to improve understanding and prediction of the extratropical transition phase of a decaying tropical cyclone. The structural evolution of the transition from a tropical to an extratropical circulation involves rapid changes to the wind, cloud, and precipitation patterns that potentially impact maritime and shore-based facilities.

OBJECTIVES

A primary objective is to increase understanding of the formation of a tropical cyclone from what may have been a disorganized area of deep convection or a weak pre-existing cyclonic disturbance. Over the monsoon environment of the tropical western North Pacific, pre-tropical cyclone disturbances range from low-level waves in the easterlies to large monsoon depressions. An objective of this project is to define factors that impact the large-scale atmospheric and oceanic controls on tropical cyclone formation.

A long-term goal is to understand the relative role(s) of mesoscale processes in organizing a pre-tropical cyclone disturbance such that it may begin to intensify as a tropical cyclone. A specific

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objective is to examine processes that define relative contributions of low-level vorticity in deep convective towers versus mid-level circulations embedded in stratiform regions of mature mesoscale convective systems. This objective addresses the predictability associated with the location, timing, and rate of tropical cyclone formation over the western North Pacific.

Additional objectives address the characteristic structure changes as a tropical cyclone intensifies, matures, then proceeds into extratropical transition. A particular focus is identification of key structural characteristics that limit the predictability of recurvature and the start of the extratropical transition process.

APPROACH

The Tropical Cyclone Structure-2008 (TCS-08) program and the Impact of Typhoons on the Ocean (ITOP) program resulted in direct observations of the entire life cycle of tropical cyclones over the western North Pacific. This included development and non-development of tropical cloud clusters, intensity and structure changes of mature tropical cyclones, and decay and extratropical transition of poleward-moving tropical cyclones. Additionally, several of the typhoons that were sampled exhibited intensity changes associated with varying ocean and atmospheric conditions.

A unique data set in the TCS-08 field experiment was the Electra Doppler Radar (ELDORA) radar observations of reflectivity and three-dimensional wind fields. The availability of data from ELDORA has provided the opportunity for analyses of key structural characteristics contained in deep convection in pre-tropical cyclone disturbances, outer rainbands of mature tropical cyclones, and the convective and wind distribution in the inner core of a tropical cyclone. The ELDORA high-resolution reflectivity and three-dimensional wind fields are utilized to define vertical profiles of latent heat release. Precipitation radar (PR) data from the Tropical Rainfall Measuring Mission (TRMM) satellites are also used to define vertical profiles of latent heat release. In addition, Weather Research Forecast (WRF) and Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) model forecasts of the latent heating profiles are also made for comparison with the ELDORA "ground-truth" profiles.

In addition to comparison of TRMM-PR and ELDORA, the convective environments of tropical cyclones at varying stages of development were examined by comparing rain rates derived from the Stepped Frequency Microwave Radiometer (SFMR) operated on the WC-130J aircraft during TCS-08 and ITOP with rain rates derived from the Advanced Mircowave Scanning Radiometer-Earth Observing System (AMSRE-E) and TRMM Microwave Imager (TMI). All instances that corresponded to satellite overpass within 3 h of aircraft measurements were analyzed to define the statistical characteristics of the distribution of rain rates from SFMR and satellite-based measurements

To examine the surface wind fields during various stages of tropical cyclone development regression analyses was used to define the relationships among SFMR-derived wind speeds and a variety of wind measurements based on the vertical profiles from co-located dropwindsondes. The objectives were to examine storm structure characteristics in terms of estimates of eyewall slant, inflow angle, and 10-m winds.

An analysis of the formation of Typhoon Man-yi during the dry run for TCS-08 initiated studies of both the formation and the structure of monsoon depressions in the western North Pacific. The high resolution European Center for Medium-range Weather Forecasts (ECMWF) analyses from the Year of Tropical Convection program have been utilized in a study of 43 monsoon depressions during 2009.

Satellite imagery, TRMM precipitation products, and QuikSCAT surface wind analyses have also been utilized to detect monsoon depressions and distinguish them from monsoon gyres.

WORK COMPLETED

Five TCS-08 cases [TY Jangmi (Case I), pre-TD Nuri (Case II), pre-TD Jangmi (Case III), pre-Sinlaku (Case IV), and TCS-025 (Case V)] in which the PR overpasses were well correlated with the ELDORA observations have been examined. The primary focus has been on the differences in the latent heating profiles between two developing and two non-developing tropical cyclones, which reveal important mesoscale effects. In order to fairly compare the WRF and COAMPS-TC numerical model latent heating rate profiles with the ELDORA profiles, a procedure had to be developed in which the same ELDORA radar retrieval method could be applied to the numerical model outputs.

Based on the analysis of two monsoon depressions during the TCS-08 dry run, a new conceptual model of monsoon depressions formation has been proposed that for the first time assigns an important role to three types of cross-equatorial flow from the Southern Hemisphere. Backward trajectories from the monsoon depression formation location clearly illustrate the three southerly pathways, and wave activity flux calculations provide a dynamical basis for the role of the Southern Hemisphere circulations.

The combination of the high-resolution ECMWF analyses and satellite-based products has provided an excellent data base for analyzing the horizontal structure of western North Pacific monsoon depressions. In addition to refining the definition used by the Joint Typhoon Warning Center, the analysis of 43 monsoon depressions can distinguish the structural characteristics relative to monsoon gyres.

A total of 109 outer-MCSs that occurred in the western North Pacific during 1999-2009 have been identified using satellite infrared and passive microwave. This data base has been used to develop a “climatology” of outer MCSs.

The evolution of a non-developing tropical circulation during TCS-08 (TCS-025) has been examined with respect to the relative role(s) of vertical alignment of the vortex and precipitation processes. From examination of numerical simulations using a variety of physics configurations, the rate of development is defined in relation to impacts of convective and stratiform precipitation processes on vortex tilt or the evolution of separate vortices at multiple levels in the vertical.

RESULTS

Park and Elsberry (2012) have documented from the unique ELDORA observations during the re-intensification of Sinlaku that maximum heating rates of ~ 80 K h^{-1} occurred in the upper troposphere in the region of a strong updraft and maximum cooling rates of ~ - 45 K h^{-1} are diagnosed in the lower troposphere in the region of a strong convective-scale downdraft. The southern convective burst in the pre-Nuri mission had a lower-tropospheric maximum in latent heating that was a more favorable condition for tropical cyclone formation than was the upper-tropospheric maximum in heating and lower-tropospheric maximum in cooling in the northern convective burst. Two non-developing tropical disturbances had deeper layers of more uniform heating and of cooling rates, and some evidence of more shallow cloud tops, that distinguished them from the developing cases. Park and Elsberry (2012) also document a serious deficiency in the evaporative cooling rates from the TRMM observations during all six ELDORA missions in which collocated TRMM observations were available. That is, all of the developing and non-developing cases examined had clear evidence from the ELDORA observations of saturated convective-scale downdrafts with maximum cooling rates of 25-45 K h^{-1}. By contrast, the TRMM maximum cooling rates ranged from 5 – 10 K h^{-1} and were much more limited in vertical extent than the ELDORA observations.

Park et al. (2012) have compared the latent heating and evaporative cooling rates simulated by COAMPS and by the WRF in similar convective clusters as calculated by Park and Elsberry (2012) from the ELDORA radar observations. In both the developing and non-developing cases, the radar-equivalent retrievals from the two models tend to over-estimate heating for less-frequently occurring, intense convective cells that contribute to positive vorticity generation and spin-up in the lower troposphere. The model maximum cooling rates are consistently smaller in magnitude than the heating maxima for the non-developing cases as well as the developing cases. Whereas in the model the cooling rates are predominantly associated with melting processes, the effects of evaporative cooling are under-estimated in convective downdraft regions and at upper levels. Due to the net warming of the columns, the models tend to over-intensify the lower-tropospheric circulations if these intense convective cells are close to the circulation center.

The relative frequency distributions of SFMR-derived rain rates matched the distribution of AMSR-E rain rates over low- to medium rain rates (Willis 2012). However, rain rates over 10 mm h^{-1} occurred more frequently in the satellite-based values. Because of the difference between SFMR and AMSR-E rain rates over medium intensities, the two rain rate distributions are found to be statistically different. Similar differences were found in comparisons between SFMR and the TRMM TMI-based rain rates, and in comparisons between TRMM TMI and AMSR-E rain rates. Differences between the relative frequency of rain rates larger than 10 mm h^{-1} resulted in the conclusion that the distributions of SFMR and TRMM-TMI frequency distributions and AMSR-E and TRMM-TMI are statistically different.

For the three typhoons sampled during ITOP, the location of each dropwindsonde was defined relative to the flight-level radius of maximum winds (RMW) (Cascino 2012). For all wind comparisons, the regression significance decreased for regions farther away from the RMW, which is attributed to variations in storm structure among the three typhoons. It is anticipated that an increase in sample size would improve the significance in the outer storm regimes. Nevertheless, these statistical regression results indicate that the remotely sensed SFMR surface wind measurements are accurate and consistent to measures of 10-m winds defined from dropwindsondes within a range of wind speeds between 10 m s^{-1} to 55 m s^{-1}. Outside this range some bias exists.

Lander (2004) has suggested that almost two-thirds of the western North Pacific tropical cyclones form from monsoon depressions. The new conceptual model of monsoon depression formation by Beattie and Elsberry (2012a) includes three southerly airstreams in the Southern Hemisphere that lead to cross-equatorial flows into the monsoon depression prior to formation. All of the 43 monsoon depressions in the 2009 sample had at least one of the three airstreams, which then interacted with a confluent region. In the example in Fig. 1, all three airstreams (labeled A, B, and C) are considered to have a role in the formation of the monsoon depression. Airstreams A and B originate in southerly flow between a deep trough and trailing anticyclone (labeled AC) that is a surge all the way to and across the equator where it enhances the equatorial westerlies flowing into the monsoon depression. Airstream C is a combination of southerly flow and southeasterly trade flow that has a more direct path across the Equator and into the eastern end of the monsoon depression.

Doppler-derived winds (Fig. 1) from ELDORA in a flight into TCS-025 defined a southward displacement of the circulation center with height. At the time of the aircraft mission, convection was decreasing in intensity, which is defined by the weak reflectivity values in the ELDORA domain. The circulation center below 2.5 km in height was farther to the north and not evident in the ELDORA data. The rapid decrease in convective precipitation processes and increase in stratiform precipitation processes coincide with the misalignment of the vortex in the vertical, which is hypothesized to be a primary reason for the non-development of the circulation.

Beattie and Elsberry (2012b) have documented that the elliptical shape of the monsoon depression in Fig. 1 is typical of 80% of the 43 cases. The average diameters of the 43 cases were 7.5 degrees latitude (830 km) and 10 degrees longitude (1102 km). The mean and standard deviation of the ellipticity in terms of the ratio of the latitudinal to the longitudinal diameter are 0.685 and 0.138 when only those monsoon depressions classified as non-circular are included. The importance of these large diameters and ellipticity for tropical cyclone formation is to determine where within such large monsoon depressions the tropical cyclone inner-core of say 100 km diameter will form, and how the monsoon depression structure then contributes to the outer vortex wind structure of the new tropical cyclone.

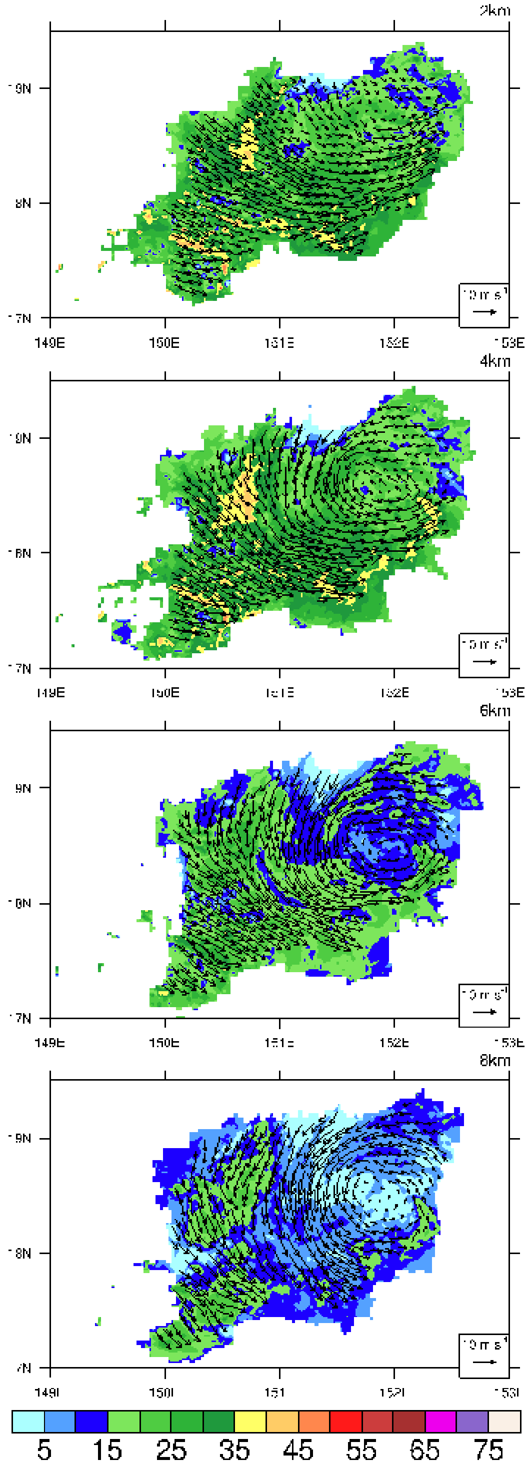

Figure 1. ELDORA Doppler radar reflectivity (dBZ, shaded) and horizontal winds (vectors) at indicated heights observed during the first NRL-P3 flight (0225W) on August 28 (0130 – 0520 UTC).

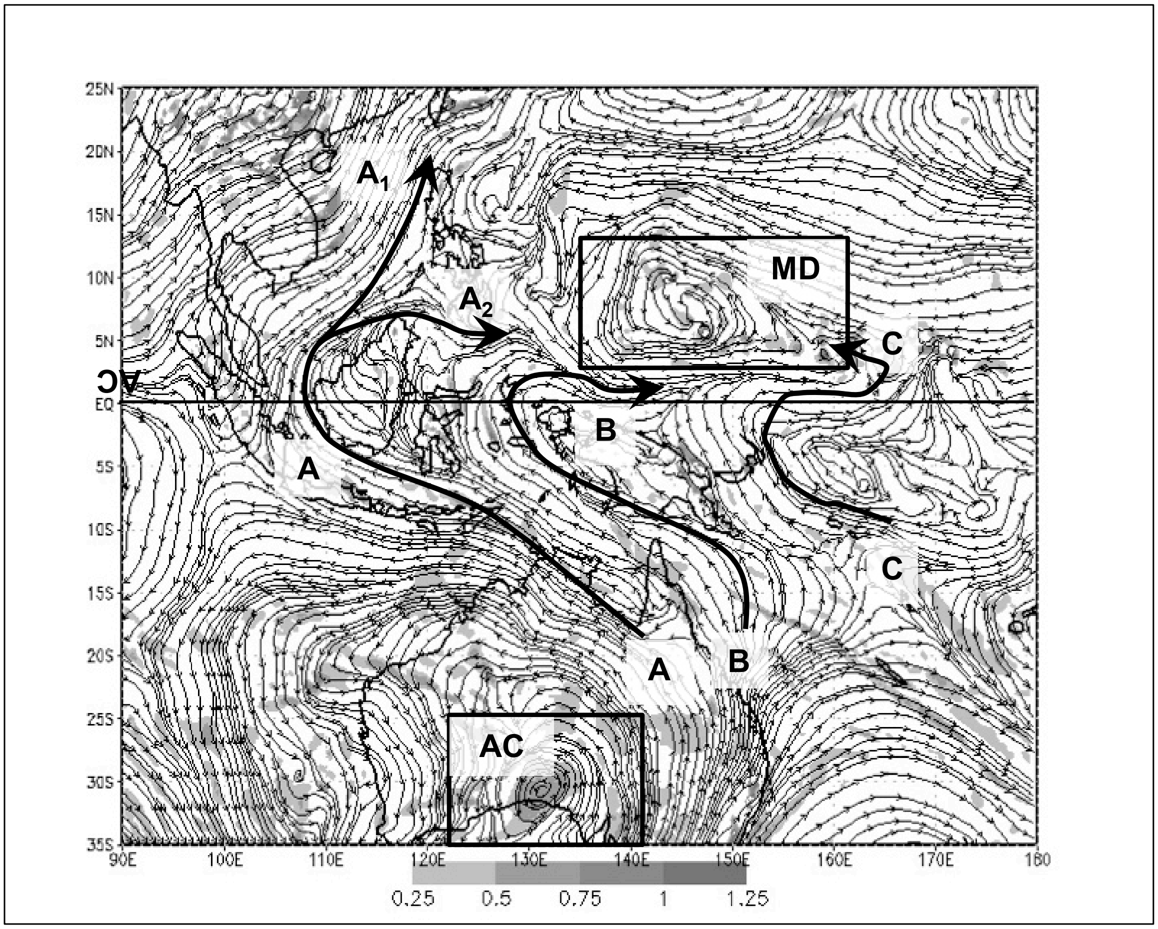

Figure 2. Streamlines and relative vorticity from the 0.25 degree ECMWF analysis at 1200 UTC 2 July 2009. Large southern box highlights the center of the Southern Hemisphere anticyclone; small northern box highlights the forming monsoon depression; the solid arrows highlight the three cross-equatorial air streams, A, B, and C, of the conceptual model.

Approximately 22% (71/322) of all western North Pacific tropical cyclones during 1999 – 2009 had at least one outer-MCS during their lifetime, and the total of 109 outer-MCSs indicates an average of 1.7 per tropical cyclone. The mean duration of outer-MCSs was 10.3 hours. Although the outer-MCSs were widely distributed in the western North Pacific, two maxima regions are noted in the South China Sea and Philippine Sea.

In a coordinate system moving with the TC centers (Fig. 2b), the mean distance of the outer-MCS centers from TC centers was 367 km. The importance of these long-lasting heavy rain events so far from the center is that they may lead to “unexpected” flooding and severe damage.

IMPACT/APPLICATIONS

The research being conducted on the comprehensive data sets gathered during the TCS-08 field program will result in increased accuracy associated with the prediction of tropical cyclone formation, intensification, and structural changes. Additionally, the unique observations of the air-ocean conditions in the environment of mature tropical cyclones over the western North Pacific provide a unique capability to identify the relative roles of environmental factors on tropical cyclone intensity change.

The documentation by Park and Elsberry (2012) of the deficiency in the TRMM evaporative cooling rates may be regarded as an opportunity to improve the diagnosis of precipitating systems throughout the tropics. Although the Shige et al. TRMM Precipitation Radar (PR) algorithm was only intended to be applied over large areas on longer time scales, the PR-derived latent heating profiles were compared with the ELDORA-derived profiles to reveal that the saturated convective-scale downdrafts have not been considered. Because all six cases indicated near-zero cooling rates, a new TRMM PR algorithm should be developed that would include the effects of saturated convective-scale downdrafts in tropical MCSs. Production of a legacy TRMM PR data set with this improvement would be useful for diagnosing tropical cyclone formations dating back to 1998, and for specifying initial and validation conditions for numerical models in the tropics. Furthermore, what could be learned from the development of a new TRMM PR algorithm could be applied to develop an appropriate algorithm for the future Global Precipitation Mission (GPM) that will diagnose precipitating systems throughout the tropics.

The demonstration by Park et al. (2012) of deficiencies in the WRF and COAMPS-TC latent heating rates may be regarded as an opportunity to address a common characteristic of non-hydrostatic mesoscale models to over-deepen tropical cyclones. Comparisons with the ELDORA observations indicate that the tilted updrafts and the saturated convective-scale downdrafts are not being accurately represented in these mesoscale models.

The demonstration of the applicability of the new conceptual model of monsoon depression formation by Beattie and Elsberry (2012a) for a large number of cases will alert the JTWC forecasters to be aware of the critical role of the southerly airstreams from the Southern Hemisphere. The documentation by Beattie and Elsberry (2012b) of the elliptical shape of monsoon depressions, and the causes of this ellipticity, will lead to better understanding of tropical cyclone formation and why some typhoons have such larger sizes.

Warnings of tropical cyclones typically focus on the high winds and heavy precipitation near the center. The documentation of long-lasting and extremely active convective systems in the outer region of tropical cyclones should alert forecasters to also consider the potential for flooding and severe damage remote from the center of a tropical cyclone.

TRANSITIONS

Following the compilation and analysis of the wide range of TCS-08 data sets, research results that identify factors responsible for the variability in tropical cyclone formation, intensification, and structure change will transition into a variety of products that will benefit operational forecasting of these tropical cyclone characteristics. These may be stand-alone products, satellite-based products, improvements to numerical models, etc. Final transition of the research will result in increased predictability associated with tropical cyclones that impact operations of the U.S. Navy across the western North Pacific.

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