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

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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

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 and 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. Additionally, key processes related to the development of downstream synoptic-scale circulations in response to perturbations forced by the poleward movement of a tropical cyclone are to be investigated.

Finally, an important objective is to define representative wind distributions and maximum intensities of tropical cyclones from *in situ* data obtained at times coincident with satellite overpasses. The purpose of this objective is to assess the ability to define important tropical cyclone structural characteristics via remotely-sensed observations.

APPROACH

The Tropical Cyclone Structure-2008 (TCS-08) 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. Following the field phase of TCS-08, the approach has been to analyze the life cycle of tropical cyclones by directly analyzing the observations and simulations of cases for comparison with observations.

During TCS-08, the re-intensification of Typhoon Sinlaku as a warm-core tropical system in a highly sheared environment southwest of Japan in September 2008 resulted in major structural changes with respect to the distribution of wind and convection. Sanabia (2010) and Sanabia et al. (2010) investigated the sensitivity to the structural characteristics of the post-recurvature portion of the TY Sinlaku life cycle

Determining the path(s) by which a tropical disturbance transitions into a self-sustaining tropical cyclone remains an active area of research. Observational and numerical modeling studies have helped improve our understanding of the physical processes prior to and during tropical cyclogenesis. However, the majority of these studies have focused almost exclusively on developing systems, with little emphasis on non-developing circulations. Malvig (2009) examined observations of a non-developing tropical circulation system (TCS-025) during TCS-08 and Penny et al. (2010) examined the non-development with simulations from a high-resolution numerical model.

Two hypotheses have been proposed as to how the incipient TC surface vortex forms from the tropical disturbances via an interaction with a Mesoscale Convective System (MCS). The focus in the Top-down hypothesis is on the maximum potential vorticity (PV) in the middle levels involving a large stratiform region within the MCS. The stratiform region cloud leads to cooling below the melting layer due to melting and evaporation of precipitation, and the convective updraft region provides condensation heating. The focus in the Bottom-up hypothesis is on a maximum PV in lower levels in collaboration with a strong convective updraft region. Accordingly, one distinctive feature of the

simulations of the Bottom-up process is a maximum in the latent heating profile that is lower in the troposphere in conjunction with large vertical velocities that favor spinup at lower levels. To examine the vertical distribution of latent heat release, Park et al. (2010a,b) analyzed vertical profiles of precipitation and latent heating from the space-borne precipitation radar (PR) on the Tropical Rainfall Measuring Mission satellite (TRMM) during several stages of the tropical cyclone life cycle from TCS-08 to compared with retrievals from the aircraft-based Electra Doppler Radar (ELDORA).

During the Tropical Cyclone Structure (TCS-08) field experiment, 16 ring-like mesoscale convective events developed and three of these led to Tropical Depression formations. Elsberry and Chollet (2010) examined the most dramatic of these events (termed mesoscale convective blowouts) that were defined as ring-like curved bands of more than 5° latitude diameter with radial outflow in all directions around a cloud-free area. A second unique aspect was the re-formation(s) of a convective cluster within the cloud-free area eventually became the locus of a tropical depression (TD).

The poleward movement and extratropical transition (ET) of a tropical cyclone initiates complex structural changes in the wind distribution and forcing of extreme ocean wave activity, which often lead to reduced skill from operationally produced numerical forecasts (Harr 2010). Although these extreme conditions severely impact the region of the ET, there are significant impacts downstream of the ET event due to the excitation of large-scale propagating Rossby wave-like disturbances. The approach to the primary scientific issues associated with ET and downstream impacts due to ET events is to define a framework of mechanisms, predictability, and strategies for increasing predictability. Harr et al. (2010) examined the roles of environmental factors during ET on structural changes responsible for the generation, intensification, and propagation of Rossby wave-like disturbances that often form during ET events.

WORK COMPLETED

To more thoroughly understand the mechanism for the deepening, the redevelopment of TY Sinlaku from a decaying system under (moderate-to-) high shear (0000 UTC 16 September 2008) to a warm-core typhoon (0000 UTC 18 September 2008) Sanabia (2010) and Sanabia et al. (2010) examined using European Center for Medium Range Weather Forecasts (ECMWF) model analyses and observations from the TCS-08 field program. Fortunately, the increase in convection that occurred close to the low-level TC center and was associated with the re-intensification to typhoon intensity occurred during aircraft missions conducted by the Naval Research Laboratory (NRL) P-3 and the USAF 53rd Weather Reconnaissance Squadron WC-130J. The ELDORA was operated on the NRL P-3 and provided high-resolution reflectivity, and winds from 1-17 km in the vertical. In addition to the identification of a severely tilted TC vortex, the ELDORA observations identify a series of low- and mid-level vortices associated with the convection along the eastern portion of the TC.

Throughout the evolution of TCS-025, multiple mesoscale convective systems (MCSs) were observed to form in a region between two upper-level cold low-pressure centers. Two TCS-025-related MCSs were examined with observations from Air Force WC-130J and Navy Research Lab P-3 flights. Observations were made by dropsonde measurements from both aircraft and by the Electra Doppler Radar (ELDORA) on the NRL P-3. The Advanced Weather Research and Forecasting numerical model (WRF-ARW) is used (Penny et al. 2010) to examine the roles that MCS development had in the formation of the mesoscale circulations identified in observations.

Park et al. (2010a,b) examined five TCS-08 cases in which the PR overpasses were well correlated with the ELDORA observations: TY Jangmi (Case I), pre-TD Nuri (Case II), pre-TD Jangmi (Case III), pre-Sinlaku (Case IV), and TCS-025 (Case V). These cases include the mature, pre-developing and developing phases of tropical cyclones, and a non-developing system. Using the derived three-dimensional winds, the horizontal and vertical gradient of pressure and temperature perturbations are calculated from the momentum and thermodynamic equations. Here the temperature perturbation field is calculated relative to the nearest dropsonde sounding from the US Air Force C-130 or the Taiwan DOTSTAR. The retrieved temperature field is used with the derived vertical motion field to calculate the LHR profile for comparison with the PR LHR profile.

The structural evolution of Typhoon (TY) Sinlaku during TCS-08 has been examined as it weakened under extreme vertical wind shear then re-intensified to typhoon intensity (Sanabia et al. 2010) prior to undergoing extratropical transition. Harr et al. (2010) examined the impact of forecast variability associated with the structural characteristics of the ET of TY Sinlaku on the downstream development across the North Pacific.

RESULTS

The re-intensification of TY Sinlaku was related to interaction among three mesoscale vorticies in various stages of development (Sanabia 2010, Sanabia et al. 2010). The most notable interaction occurred between the decaying low-level circulation and a vigorously growing convective cell that contained updrafts near 30 m s^{-1} (Fig. 1). Following interactions among the mesoscale vortices, re-intensification proceeded via processes consistent with axisymmetrization as multiple convective bursts rotated cyclonically and inward while a region of older convection propagated outward as a principal band. The overall re-intensification scenario is examined with respect to interactions among a variety of processes that vary from synoptic scale to convective scale. Synoptic-scale southwest monsoon flow over elevated sea-surface temperatures and high ocean heat content preconditioned the region where the critical convective episodes began. Mesoscale processes then acted to produce and re-distribute positive vorticity that defined the re-intensification of TY Sinlaku.

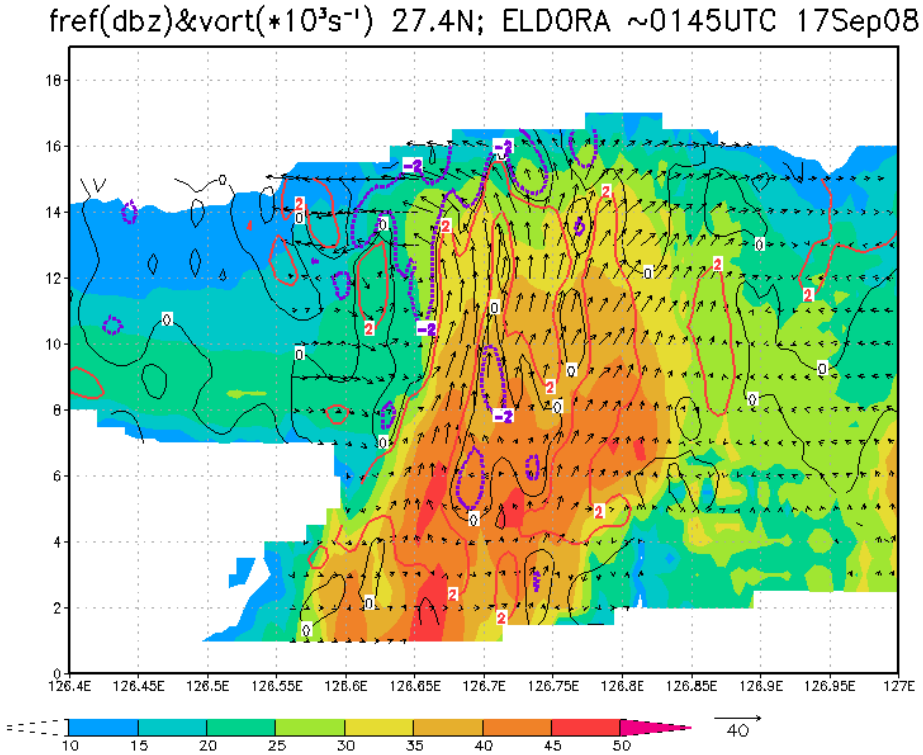

Fig. 1 Reflectivity (dBz, scale at bottom), vorticity (10^{-3} s^{-1}, positive contours in red, 0 contour in white, and negative contours in dashed purple, and wind (m s^{-1}, reference vectors below each panel) along 27.4°N, 127°E for the re-formation period of TY Sinlaku (from Sanabia 2010).

Park et al. (2010) calculated the Cumulative Frequency Altitude Diagrams (CFADs) of convective latent heating from the ELDORA reflectivity and radial winds from two periods in the northern convective region and one period in the southern convective region (Fig. 2). In the northern convective region, the less-frequent but larger magnitudes of latent heating rates have maximum values in the upper troposphere and have larger cooling rates over a deeper layer in the lower troposphere. Since this is the signature of a decaying MCS, which is consistent with the observed decay of the northern convective region in the infrared imagery over the next 6 h, this northern convective region is not favorable for TC formation. By contrast, the southern convective region was found to have maximum latent heating rates in the lower troposphere and smaller cooling rates, which is a favorable condition for TC formation. Park et al. (2010, their Fig. 7) track the infrared signature of the southern convective region to the location where the JTWC indicated Tropical Depression Nuri formed. Thus, they conclude the Nuri formation evolved directly from the low-level vortex in the southern convective burst and was not associated with the sweet spot of the easterly wave.

The 51-member ECMWF 32-day forecasts provided useful long-range guidance on the formations and tracks of the strongest typhoons during the peak of the tropical cyclone season over the western North Pacific (Elsberry et al. 2010). The ability of the 32-day ensemble prediction to identify the period of enhanced tropical cyclone activity in September 2008 was investigated. As 16 of 51 members (i.e., 31%) indicated the formation of a storm with track characteristics similar to TY Sinlaku, this case indicates some intraseasonal predictability, at least for the strong TY Sinlaku.

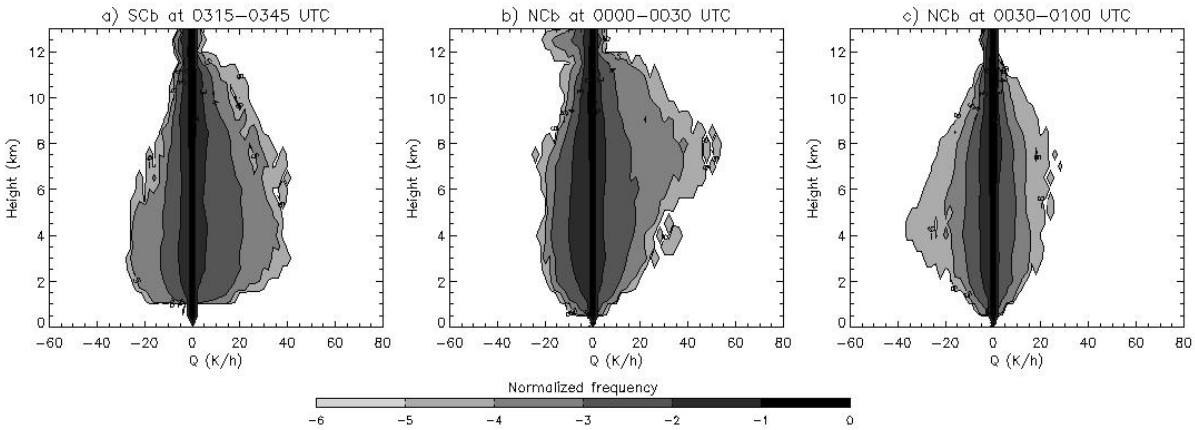

Fig. 2 Cumulative Frequency Altitude Diagram (CFAD) of latent heating and cooling rates (K/h) calculated by Park et al. (2010) from ELDORA reflectivities and radial winds from: 0315 – 0345 UTC 16 August 2008 in the southern convective region and (b) 0000 – 0030 UTC 16 August, and (c) 0300 – 0310 UTC 16 August in the northern convective region during the first research mission in pre-Tropical Depression Nuri.

Two Mesoscale Convective Systems (MCSs) in TCS025 were examined in detail by Malvig (2009). On 28 August 2008, a mid-tropospheric cyclonic circulation was associated with one MCS, but it was disconnected from the low-level circulation at around the 850-mb level, and the upper-level circulation associated with the MCS propagated southward while the low-level circulation propagated poleward. On 29 August 2008, another MCS was embedded in a broad cyclonic circulation, but the MCS was displaced to the southeast of the circulation center. Again, the circulation center propagated poleward, but the mid- and upper-level circulations associated with the MCS propagated southward. It is concluded that TCS025 did not become a tropical depression due to the lack of vertical coupling between the vortex associated with the MCS and the circulation center, so that the heat release in the MCS did not expand the column and lower the surface pressure.

Harr et al. (2010) examined the character of the sequence of downstream development forecasts from the ECMWF forecast system (Fig. 3). It is clear that forecasts of the eddy kinetic energy (EKE) distribution over the central North Pacific were quite accurate until 1200 UTC 18 September. After this time, the forecast distribution of central North Pacific EKE spreads considerably with the error increasing with increasing forecast range. At 1200 UTC 18 September, TY Sinlaku had just completed the re-intensification back to a typhoon and was just moving past southern Japan. Therefore, forecasts of downstream development are sensitive to characteristics of either the tropical cyclone, the midlatitude circulation into which the tropical cyclone is moving, or the interaction between the tropical cyclone and midlatitude flow.

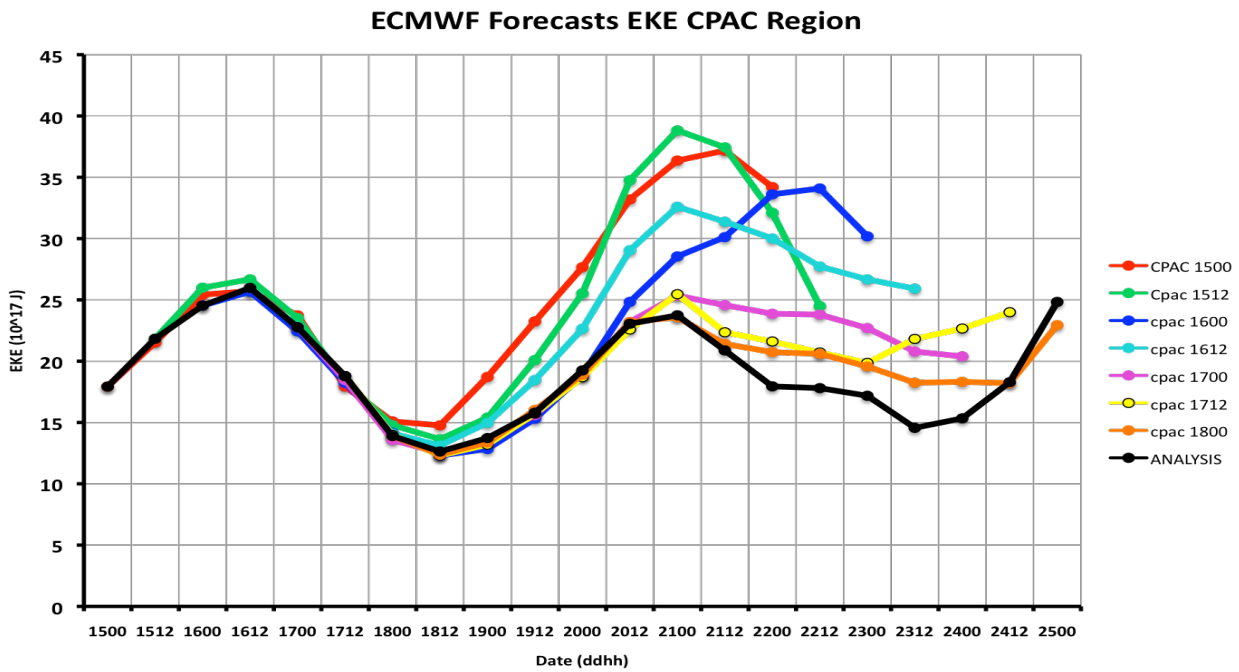

Figure 3. Analyzed (black line) and forecast (colored lines) EKE (10^{18} J) over the central North Pacific for ECMWF forecasts initiated between 0000 UTC 15 September and 0000 UTC 18 September.

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.

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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