The Properties of Convective Clouds over the Western Pacific and Their Relationship to the Environment of Tropical Cyclones

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LONG-TERM GOALS

The long-term goal of the proposed work is to advance our understanding of the relationship between large-scale and mesoscale environmental conditions and small but powerful convective events during tropical cyclone (TC) development and intensity changes. Our ultimate goal is to identify the necessary conditions that determine the formation and evolution of a TC.

OBJECTIVES

Using data obtained from the western Pacific region during "Tropical Cyclone Structure 2008" (TCS-08), ONR's field program, this study proposes to investigate large-scale environmental conditions, mesoscale phenomena, and small-scale convective bursts, as well as their interactions that are responsible for TC formation and intensity changes. Specific objectives include 1) characterizing the intensity of convection over the western Pacific using radar, aircraft, and satellite data; 2) deriving an accurate mesoscale environment of convective systems through the assimilation of satellite, radar, lidar, and in-situ data; 3) evaluating the quality of the global forecast system (e.g., Navy Operational Global Atmospheric Prediction System, or NOGAPS) for accurate TC analyses and forecasts; and 4) understanding the environmental factors that determine tropical cyclone formation and rapid intensification.

APPROACH

In order to achieve the research objectives of this proposal, our approach integrates observational data analysis, mesoscale data assimilation, and forecast evaluations. This includes 1) analyzing TCS-08 field data in conjunction with the available satellite data products from the NASA Aqua and Tropical Rainfall Measuring Mission (TRMM); 2) producing mesoscale numerical simulations by assimilating satellite, radar, lidar, and in-situ data into the Weather Research and Forecasting (WRF) and the

Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS®) mesoscale models; and 3) evaluating the performance of global ensemble forecasting to understand the quality of global forecasts and also study the predictability of TC formation and evolution.

People involved in this project in FY12 include the PI (Prof. Zhaoxia Pu), her graduate students (Levi Thatcher and Zhan Li), and NRL collaborators (Drs. Carolyn Reynolds and Allen Zhao).

WORK COMPLETED

Work completed in FY12 includes:

- Continuation of mesoscale numerical simulations of TCS-08 major typhoons with data assimilation. Specific efforts were made to understand the environmental conditions that influenced the formation of Typhoon Nuri (2008).

- Examination of characteristics of TC precipitation features over the western Pacific warm pool using ten years (1998-2007) of Tropical Rainfall Measuring Mission (TRMM) data.

- Progress in studying error growth in the TC environment with mesoscale high-resolution ensemble forecasting.

RESULTS

(1) *Numerical simulations of the genesis of Typhoon Nuri (2008)*

The sensitivity of numerical simulations of the genesis of Typhoon Nuri (2008) to initial conditions is examined with an advanced research version of the WRF model. Two sets of experiments are conducted using initial and boundary conditions derived from two different global analyses (NCEP Global Forecasting System final analysis and ECMWF reanalysis). The sensitivity of numerical simulations to different forecast leading times and physical parameterization schemes is also examined. Simulation results are compared with Doppler radar and aircraft dropsonde observations obtained during TCS-08. It is found that the initial and boundary conditions derived from one global analysis fail to predict Nuri's genesis, whereas the initial and boundary conditions derived from the other global analysis lead to successful numerical simulations of the formation of Nuri. The successful simulation captures the processes of Nuri's genesis and early intensification, as it produces stronger cyclonic circulation, upward vertical velocity, and a stronger gradient of vertical velocity, which leads to more rapid development of low-level vorticity.

Differences between the two initial conditions and simulations are diagnosed to understand the environmental factors that influence Nuri's genesis. Despite warm SSTs and low vertical wind shear, favorable conditions for Nuri's genesis are provided by the strong and well-organized mid-level vortex, the strong vertical motion of the upward vertical mass flux with a bottom-heavy profile, and low- to mid-level moisture. Prior to the genesis of Nuri, the formation of a low- to mid-level cold pool enhances the low-level updraft by a bottom-heavy mass flux profile along with the development of a low-level vortex inflow.

An additional set of sensitivity experiments is performed by swapping the moisture field in two initial conditions. Results show that the moisture field in the initial conditions can significantly change the simulation results in terms of the development or non-development of tropical depressions, indicating that initial moisture conditions play an essential role in Nuri's genesis. Specifically, the enhancement of mid-level moisture is favorable for convection and vortex development.

(2) Characteristics of tropical cyclone precipitation features over the western Pacific warm pool

Following the previous case studies, ten years (1998-2007) of the TRMM-derivative radar precipitation feature (PF) product are analyzed in order to determine the differences between TC-related precipitation characteristics and those of the tropical Pacific warm pool (10 to 30°N and 130 to 150°E) in general. The PF data, from the University of Utah's archive, are based on the TRMM precipitation radar's 2A25 product, where one PF consists of a single pixel or group of contiguous pixels with near-surface rainfall greater than zero. Using the PF database, the height and area of tropical background PFs versus those within 500 km of TCs are compared.

It is found that TC-related PFs are markedly more frequent from 5 to 10 km than are background tropical PFs. Figure 1 shows the frequency distribution, in percentage terms, of the two sets of PFs by height and area. It appears that both TC and tropical PFs are predominantly small and short in terms of frequency. Specifically, it is apparent that TC environments exhibit a larger population of PFs reaching 5.5 km in height and $10^{2.5}$ km^2 in area compared with the western Pacific. TC-related PFs also show a significant decrease in echoes whose tops are from 1-4 km high and around $10^{2.1}$ km^2. These patterns are found to persist throughout the 10-year period (see Figure 2). Despite the complications of the TRMM boost in August 2001, there is a consistent and marked increase in 5.5 km high PFs in TCs as compared to western Pacific in general. This difference is thus deemed not only statistically significant, but also practically significant, as it is readily seen even when comparing only a modest number of TCs.

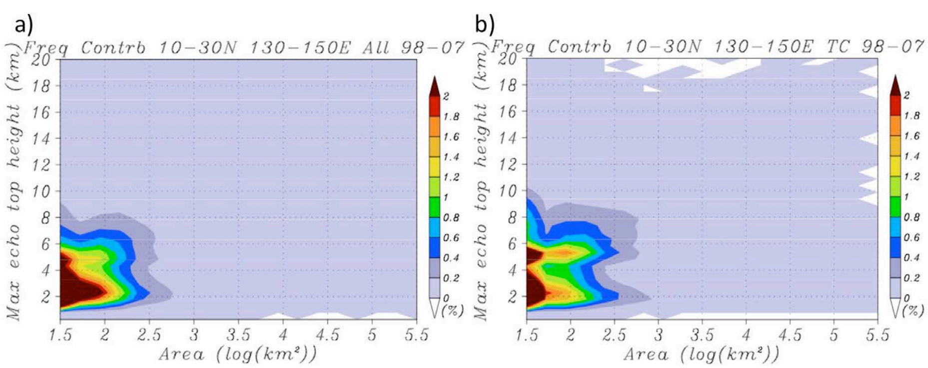

Figure 1. Comparison of frequency distribution (in percentage terms) of a) tropical PFs and b) TC-related PFs in terms of their area (km^2) and echo top height (km). The period is 1998-2007 and the spatial coverage is 130-150°E and 10-30°N.

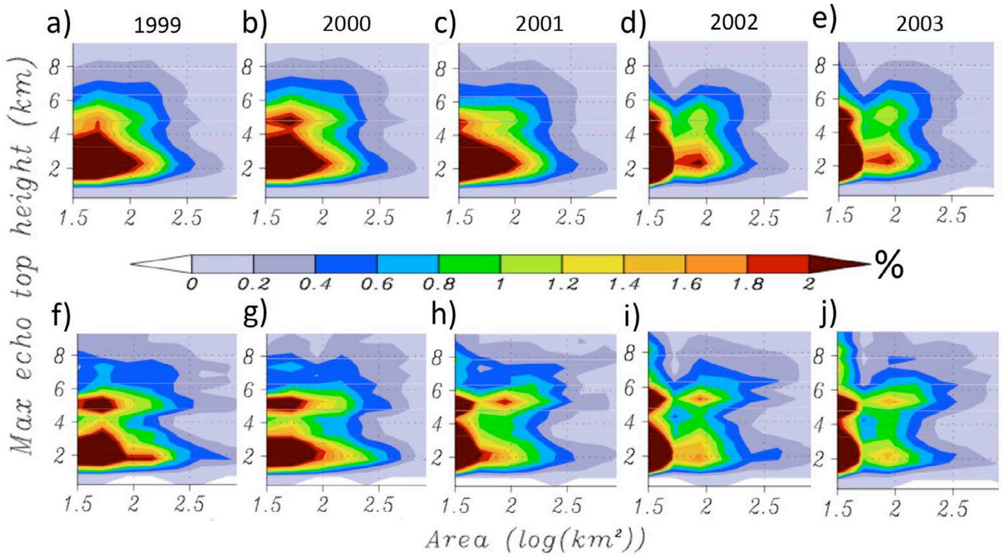

Figure 2. Yearly frequency distribution in terms of PF area (km^2) and echo top height (km) for the western Pacific tropical (a-e) and TC environments (f-j). These years are selected to show the robustness of the pattern despite the impact of the TRMM boost in 2001.

While there is a local maximum in echo frequency in both data sets (TC versus western Pacific) around 5.5 km (PFs from 5-10 km will be defined here as being cumulus congestus-like), the TC-related PFs are even more concentrated there. In other words, in TC environments, congestus-like (5-10 km high) radar echoes occur significantly more frequently than they do in the general western Pacific tropical environment. The increase in TC-related congestus is most notable around the 5-6 km height level, but it exists up to around 10 km and is persistent throughout the 10-year sample. This difference is thought to be due to enhanced levels of ice in TC environments, the enhanced stabilized melting level, and the subsequent near-0°C-level cloud-capping detrainment that occurs. *Johnson et al.* [1999, *J. Clim.*] suggested similar reasons for enhanced congestus populations in mesoscale convective system (MCS) environments but did not examine this melting-stabilization mechanism with a data sample containing many TC environments**.** We speculate that TC-only PFs from 7-9 km are partially due to the slower total detrainment of larger parcels and are also occasionally affected by midlevel dry layers that inhibit convection from reaching the tropopause.

To view PF differences in terms of their contribution to rainfall, total rainfall distributions are calculated and presented in Figure 3. It is apparent that while most of the PFs in the western Pacific are small and short, those that produce significant amounts of rainfall are tall (i.e., above 10 km) and large (i.e., over 10,000 km^2). In addition, significant differences are found between the distributions of heavy rain-bearing PFs in the Pacific tropical environment and those in the TCs of the region. Specifically, the enhanced midlevel TC-related populations exist not only in stratiform precipitation around the melting level at 5.5 km, but also from 6 to 9 km in stratiform regions, in convective precipitation, and when culling the smallest features from the data set. This increase in congestus-like echoes in TC environments aligns well with observations regarding MCSs, in which the enhanced ice present in MCS (and TC) environments creates a stabilized melting layer through cooling immediately below 0°C. This stable layer appears to enhance the detrainment of convective PFs in the TC data set at and for a few kilometers above the melting level.

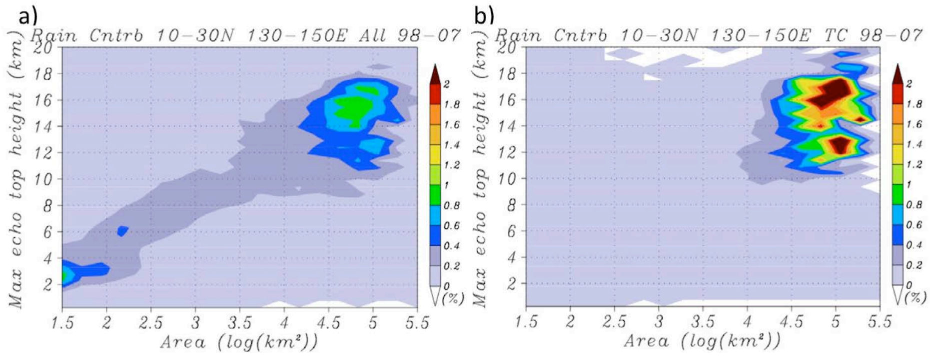

Figure 3. Comparison of PF rainfall contribution distributions (in percentage terms) of a) tropical PFs and b) TC-related PFs in terms of area (km^2) and echo top height (km).

The detailed results from this study have been published in JGR (Thatcher *et al.* 2012).

(3) Studying error growth in the TC genesis environment with mesoscale high-resolution ensemble forecasts

While many studies have used global models to examine TC genesis and intensification in ensemble-based forecasts, regional models have not been similarly employed. As a natural extension of our early efforts in evaluating global ensemble forecasts, we use ensemble forecasts generated from the WRF model at 5 km horizontal resolution to study error growth, structure, and characteristics in the vicinity of TC genesis. The first numerical experiment is performed for the forecast of the genesis of Hurricane Ernesto (2006). A control ensemble is created with the initial and boundary conditions derived from the NCEP Global Ensemble Forecast System (GEFS) with 14 members. Then, a set of mesoscale regional ensemble forecasts is created using a breeding vector method (considering its efficiency). The behavior of error structure and growth in two mesoscale ensembles is compared. The E-dimension, which is based around empirical orthogonal functions; perturbation versus error correlation analysis (PECA); and Fourier transforms are used to evaluate the results.

Preliminary results indicate that the mesoscale ensembles created using breeding schemes produce a notably higher E-dimension in the simulations than does the control ensemble. They also appear to more easily spin up TCs and increase the probability of the genesis of Hurricane Ernesto in mesoscale ensemble forecasts. More experiments and evaluations are in progress.

IMPACT/APPLICATIONS

Data assimilation, numerical simulations, and ensemble forecasting aid in understanding the predictability of TCs and the environmental conditions that contribute to TC formation and intensity changes. The findings from the study of TC-related precipitation provide an important quantitative view of the distribution and characteristics of TC and tropical precipitation features in the western Pacific.

PUBLICATIONS

(1) Peer-reviewed journal articles

- Li, Z. and Z. Pu, 2012: Numerical Simulations of the Genesis of Typhoon Nuri (2008): Sensitivity to Initial Conditions and Implications for the Roles of Environmental Conditions. *J. Geophy. Res.* (Submitted)
- Thatcher, L.,Y. Takayabu, C. Yokoyama, Z. Pu, 2012: Characteristics of tropical cyclone precipitation features over the western Pacific warm pool region. *J. Geophy. Res.,* 117, D16208, doi:10.1029/2011JD017351
- Zhang, L., Z. Pu, W.-C. Lee, and Q. Zhao, 2012: The influence of airborne Doppler radar data quality control on numerical simulations of a tropical cyclone. *Weather and Forecasting.* **27**, 231-239

(2) Conference papers and presentations

- Pu, Z., Z. Li and L. Thatcher, 2012: Examination of the roles of intense convection and moisture field in tropical cyclone formation, *30th Conference on Hurricanes and Tropical Meteorology, 15-20 April 2012*, Ponte Vedra Beach, FL
- Zhang H. and Z. Pu, 2012: Improving predictability of landfalling hurricanes through assimilation of surface mesonet observations using ensemble kalman filter methods, *30th Conference on Hurricanes and Tropical Meteorology*, 15-20 April 2012, Ponte Vedra Beach, FL
- Thatcher, L. and Z. Pu, 2012: The predictability of tropical cyclone genesis in regional ensemble forecasting: case studies with two computationally efficient perturbation methods. *CMOS Congress 2012 & AMS 25th WAF/21st NWP Conference*, May 28 – June 1 2012, Montreal, Canada.
- Pu, Z. and Z. Li, 2012: The use of satellite, radar and in-situ observations to understand the role of intense convection in tropical cyclone formation, *18th Conference on Satellite Meteorology, Oceanography and Climatology/First Joint AMS-Asia Satellite Meteorology Conference,* January 22-27, 2012, New Orleans, LA
- Zhang, H. and Z. Pu, 2012: Ensemble-Based Assimilation of Surface Observations in Improving Predictability of a Landfalling Hurricane. *16th Symposium on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS)*. January 22-27, 2012, New Orleans, LA