

Improved Physical Parameterizations for Tropical Cyclone Prediction

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LONG-TERM GOALS

Tropical cyclones (TCs) have a significant impact on Naval operations around the globe. Ship movements are constrained to avoid forecasted TC conditions, and sortie decisions must be made well in advance of typhoon and hurricane landfalls to protect Navy assets. Inaccurate forecasts can result in unnecessary high cost preparations for a TC, or potentially cause the loss of ships. High-resolution, full physics mesoscale numerical models now play a critical role in providing forecast guidance, but TC track and intensity errors continue to exceed U.S. Pacific Command (USPACOM) target errors for optimal operational decision making. The proposed research aims to improve the parameterization of physical processes represented in numerical weather prediction (NWP) models to help meet USPACOM and Joint Typhoon Warning Center (JTWC) operational goals.

OBJECTIVES

The central objectives of this proposal are two-fold:

1. Basic research to improve our fundamental understanding of the ocean/atmosphere interface at high wind speeds and cloud microphysical processes in TCs.
2. Applied research to improve parameterizations of these physical processes for use in U.S. Navy forecast models.

The research will lead to better TC forecasts that directly benefit Naval operations through an expanded theater of operations in the Atlantic and Western Pacific and reduced costs for base sortie decisions.

APPROACH

New analysis techniques to improve our fundamental understanding of TC boundary layer structure and cloud microphysics and to validate numerical simulations have been recently developed by the PI to address the research objectives. Analysis of Doppler radar, dropsonde, aircraft, satellite and other observations will be used to test, validate, and ultimately improve the physical parameterizations used in the Earth System Modeling Framework (ESMF) that provides guidance to the Fleet. The current research focuses on the surface layer, boundary layer, and microphysical parameterizations as critical components for accurate TC intensity and structure forecasts.

WORK COMPLETED

The work completed in this project consisted of three primary research tasks: 1) Investigation of simulated hurricane drop size distributions using polarimetric radar; 2) Investigation of simulated TC boundary layer structure; and 3) collaborative research on existing TC datasets and analysis techniques. A summary of each of these tasks is summarized below.

RESULTS

Investigation of Simulated Hurricane Drop Size Distributions using Polarimetric Radar

Mesoscale numerical weather prediction models have become an invaluable tool for forecasting TCs, in part due to their ability to represent sophisticated microphysical cloud processes through computationally feasible parameterizations. The nonlinear interaction between the microphysical processes and the model dynamics through the release of latent heat makes the parameterization assumptions particularly critical for forecast accuracy (Igel et al. 2015).

Recent upgrades to the U.S. radar network from 2011-2013 now allow for polarimetric measurements of near-coastal TCs near the coast, providing a new dataset to validate cloud microphysical parameterizations used in tropical cyclone simulations. A detailed comparison between the polarimetric radar variables simulated by the WRF model were compared with real radar observations from 2014 in Hurricanes Arthur and Ana. The simulated reflectivity was calculated at 2/3 km resolution from the inner nest of four domains using a T-matrix scattering approach (Mischenko 2000) and polarimetric radar operators (Jung et al. 2006). The model was integrated for 12 hours for Arthur and 18 hours for Ana using the Global Forecast Systems FNL analyses as initial conditions. Six different microphysics parameterizations were tested that were able to capture the major features of both hurricanes, including accurate tracks, asymmetric distributions of precipitation, and the approximate intensity of the storms (not shown). However, most of the schemes produced a higher frequency of larger raindrops than observed. Results comparing all of 6 the different microphysics parameterizations with the radar observations were published in Brown et al. (2016).

A summary graphic of the comparison between the radar observations and double-moment Thompson aerosol-aware microphysics scheme is shown in Fig. 1. The horizontally polarized radar reflectivity (Z_H) is sensitive to both the size and number concentration of the raindrops, while the differential reflectivity (Z_{DR}) is sensitive primarily to the size of the drops. The combination of these two variables gives detailed information about the full drop size distribution (DSD) in a tropical cyclone. A snapshot of the Z_{DR} radar data at 2 km altitude (Fig. 1a) shows the majority of the values are below 1.5 dB, while the simulated radar data from the Thompson scheme (Fig. 1b) has many values above 2.5 dB. While the Thompson scheme showed the best fidelity of any bulk scheme to the observed radar data, this analysis revealed the presence of an unphysical high Z_{DR} at low and moderate rain rates.

To statistically assess the accuracy of the model, the bottom row of Fig. 1 shows joint probability distributions of Z_H and Z_{DR} constructed using 3 hours of radar data and the final 3 hours of each simulation. While the peak frequency of radar observations is fairly well simulated by the original Thompson scheme, the high frequency of raindrops with excessive Z_{DR} is apparent in the upper portion of the phase space. To address the discrepancy between model and observations, we collaborated with the author of the microphysics scheme Dr. Greg Thompson of NCAR to identify the deficiencies in the model physics. Further analysis indicated that the large median drop size was occurring due to poor parameterization of melting of snow in stratiform precipitation regions with low snow mixing ratios.

The Thompson scheme is single moment in snow but double-moment in rain, such that the prognostic value for the number concentration of raindrops resulting from melting snow must be parameterized. While mass is conserved, the specific DSD at each gridpoint is determined by an ad hoc melting rate parameter that had limited observational support. Additionally, a conditional statement in the code set the DSD to a default value if the snow mixing ratio was too low (below 0.005 g kg^{-1}). Experiments adjusting the melting rate parameter and default conditional were able to identify and fix the problem. Results using the modified Thompson scheme are shown in the right column of Fig. 1. The unphysical Z_{DR} has been removed in the 2 km snapshot (Fig. 1c), yielding a good match with the observed distribution. The statistical comparison is also greatly improved (Fig. 1d), and shows good fidelity to the spectrum of DSDs observed in the radar data. The analysis and improvements to the Thompson scheme were published in Brown et al. (2017). The improvements were incorporated into the WRF v.3.8.1 release as a result of this analysis and testing. The Thompson scheme has shown significant promise in forecast skill in the COAMPS-TC mesoscale model (Jin et al. 2014), and the direct impact of this work to model physics development will likely benefit the operational forecasting in the future.

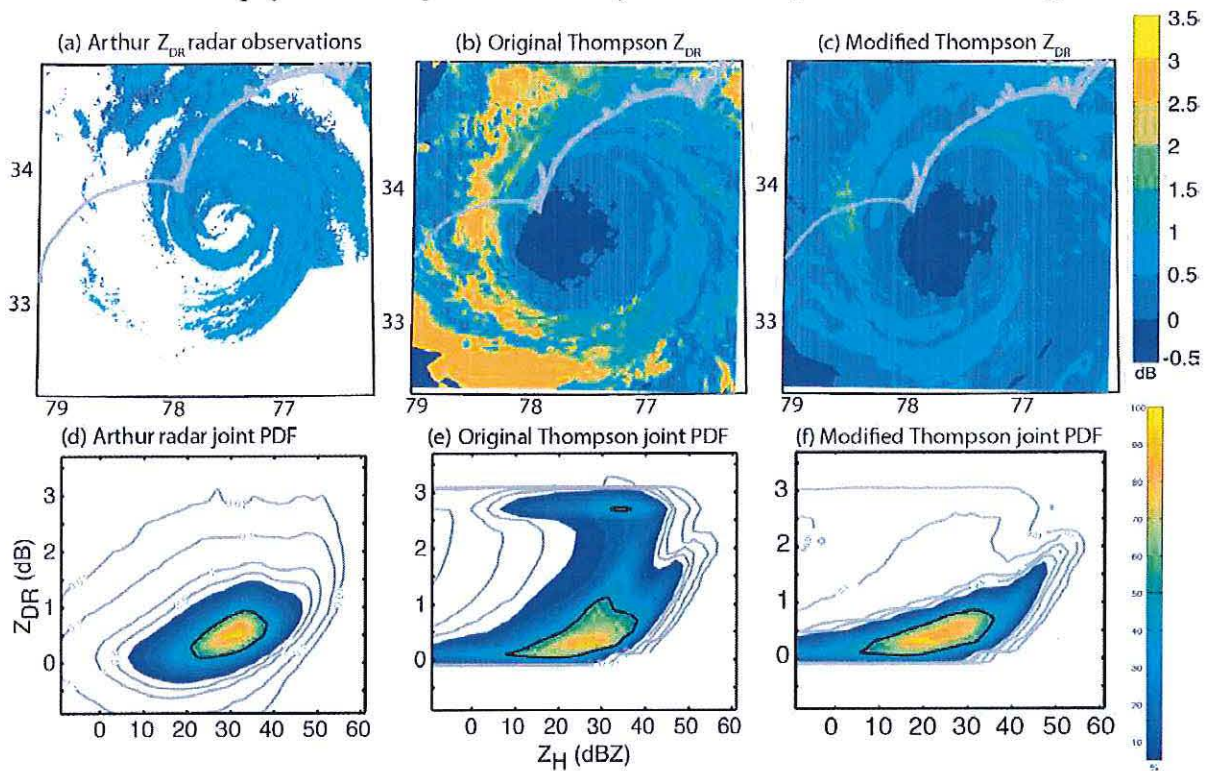


Figure 1. Radar observations for Arthur (2014) using the NEXRAD radar (left column), simulated original Thompson scheme (center) and simulated modified Thompson scheme (right). Top row shows a snapshot of Z_{DR} at 2230 UTC on 3 July 2014 at 2 km altitude. Bottom row shows the joint frequency distributions of Z_H and Z_{DR} for normalized by the maximum frequency in the dataset (percent, gray contours at 0.01, 0.1, 1 and 2.5%, black contour at 50%). Statistics from WRF are limited to below approximately 3.3 km. Z_H is binned from -10 to 60 dBz every 5 dBz and Z_{DR} is binned from -1 to 4 dB every 0.5 dB.

Investigation of Simulated TC Boundary Layer Structure

Heat, moisture, and momentum exchanges at the air-sea interface are primary processes in TC intensification and maintenance (Emanuel 1995), and the transport of momentum and heat from the surface in the TC boundary layer (TCBL) plays a critical role in determining TC intensity and

structure. All of these processes must be parameterized in NWP models, but are not well understood in TCs due to the difficulty in obtaining direct measurements in the extreme wind environment (Bell et al. 2012). To begin to address these questions, a conceptual framework of how axisymmetric dynamics within the TCBL can impact TC intensity change was developed from first principles in the form of a new, simple logistic growth equation (LGE). Although this LGE bears some similarities to the operational LGE Model (LGEM; DeMaria 2009), the difference is that our growth-limiting term incorporates TCBL structure and surface drag. The carrying capacity of the LGE—termed the instantaneous logistic potential intensity (ILPI) in this study—is used to explore the relationship between TCBL structure and TC intensity. The ILPI is defined as $(-u_m)z_m/\alpha^2 r_m C_D$, where the subscript m represents a value at the location of maximum tangential wind, u_m is the radial wind, z_m is the height, α is the reduction to the surface wind, and r_m is the radius.

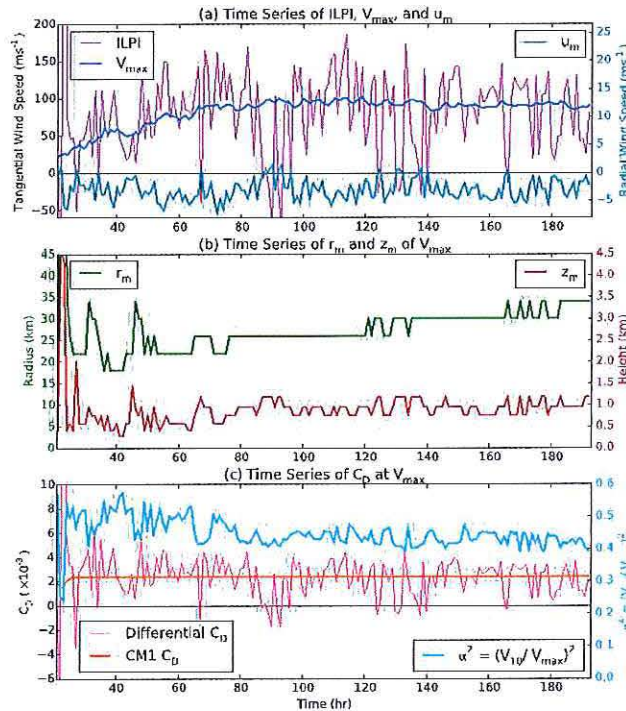


Figure 2 Time series of (a) ILPI (purple), v_{\max} (blue), and the radial wind located at v_{\max} (u_m , teal) in m s^{-1} ; (b) z_m (brown) and r_m (green) in km; and (c) the prescribed C_D (orange), retrieved C_D (pink), and $\alpha^2 = (V_{10}/V_{\max})^2$ (light blue). Shading denotes approximate times when the TC is intensifying (mint), and quasi-steady (lavender). Bold lines denote CM1 values, and thin lines represent retrieved values.

The validity of this new LGE framework was then explored in idealized numerical modeling using the axisymmetric version of Cloud Model 1 (CM1; Bryan and Fritsch 2002). Results shown in Fig. 2 indicate that CM1 exhibits changes to TCBL structure and TC intensity that are consistent with the LGE framework. Sensitivity of these results to the turbulent mixing lengths were also explored, and the general LGE relationships still hold as C_D is increased. The LGE can also be further solved for the drag coefficient (C_D) to explore the relationships between it and both TCBL structure and TC intensity. The LGE framework was also applied to new observations in the TCBL were collected from high-density dropsonde sequences in Hurricane Joaquin (2015) during the ONR Tropical Cyclone Intensity (TCI-2015) field experiment. Preliminary C_D retrievals from Joaquin indicate plausible estimates compared to Bell et al. (2012), but that additional research is required to apply the method to observations and retrieve the drag coefficient with higher accuracy. This study resulted in a completed

M.S. thesis at Colorado State University (Casas 2018) and are being prepared for publication in the peer-reviewed literature.

Collaborative Research

Research collaborations in both TCBL and cloud microphysics of TCs were conducted during the project. Collaborative work with Dr. Myung-Sook Park of South Korea investigated the effects of land on cyclogenesis near the Philippines. A case-study of Tropical Storm Mekkhala (2008) from the ONR Tropical Cyclone Structure (TCS-08) field campaign was investigated using modeling simulations with and without the Philippine land mass. When the land mass was removed the diurnal convection near the developing disturbance was reduced and the TC did not intensify. The study illustrates that boundary layer effects can be complex, and near coastal effects can significantly modify genesis and intensification. A manuscript describing these results was published in Park et al. (2017).

Collaborative work with Evan Kalina and colleagues from NOAA investigated the magnitude of ice water in TCs using polarimetric radar data. A co-located vertically pointing 10-cm radar and NEXRAD radar collected observations of Hurricane Arthur (2014), the same storm analyzed by the PI's research group in Brown et al. (2016). The vertically pointing data allows for estimates of the particle fall speed, which combined with the polarimetric radar classification can identify the type and amount of different ice species in the TC rainbands. The total ice water path from both small and large ice was estimated using the radar reflectivity and ice classification, yielding new insights into the microphysics of ice generation in TCs. A manuscript describing these results was published in Kalina et al. (2018).

IMPACT/APPLICATIONS

Tropical cyclone forecast capability is a critical aspect of U.S. Navy Fleet operations, and the current research is directed towards increasing that capability and reducing forecast errors. Reduced forecast errors will directly impact the cost of Fleet operations, and also provide positive impacts for civilians in coastal areas. The research impacts are expected to improve the representation of important physical processes in Navy NWP models used for forecast decision making. The research directly meets the Naval Science and Technology Strategic Plan goal to "Assure Access to the Maritime Battlespace", and the specific objective to "Match Environmental Predictive Capabilities to Tactical Planning Requirements." The research also directly addresses both the atmospheric prediction and air-sea interaction research missions of ONR's Marine Meteorology and Atmospheric Effects Program. It is expected that these scientific results and further research in this area will lead to continued TC forecast improvements and help meet JTWC and NHC goals for forecast skill.

RELATED PROJECTS

A related project was funded by the ONR Marine Meteorology program to continue this work at Colorado State University due to the original PI (Bell) moving to a new institution. The current report documents the progress on the first part of the award conducted at U. Hawaii and subaward to CSU. The final report on the extended project will be submitted from CSU pending the completion of the overall project.

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14. ABSTRACT
Tropical cyclones (TCs) have a significant impact on Naval operations around the globe. Forecast errors in intensity and structure hinder U. S. Pacific Command's goal of increasing maritime battlespace. High-resolution, full physics numerical models play a critical role providing weather guidance for the fleet, but there are fundamental uncertainties in the physical processes represented in Navy forecast models. The central objectives of this study are to improve our basic understanding of the physical processes that have a significant impact on TC track, intensity, and structure, and improve the parameterizations of these processes through analysis of research observations.

15. SUBJECT TERMS
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