Thermodynamic Constraints on Tropical Cyclone Intensity and Structure

Michael M. Bell
University of Hawai`i at Mānoa
Department of Atmospheric Sciences
Honolulu, Hawaii 96822
phone: (808) 956-2878     fax: (808) 956-2877     email: mmbell@hawaii.edu

LONG-TERM GOALS

Tropical cyclone (TC) forecast errors in intensity and structure hinder the U.S. Navy’s goal of increasing sea maneuver space for U. S. and Coalition fleet forces. Improved guidance on TC intensity change is a top priority for both the U.S. National Hurricane Center (NHC) and Joint Typhoon Warning Center (JTWC). Environmental and internal thermodynamic constraints play an important role in these forecasts, but uncertainties in the physical processes represented in forecast models limit the forecast skill. This research project seeks to improve our fundamental understanding of these constraints on TC intensity and structure to help reduce forecast error and improve Naval operations.

OBJECTIVES

Statistical-dynamical intensity forecasts that rely on environmental thermodynamic constraints are important components of the available guidance. However, the physical processes that are involved in these constraints on intensity and structure change are not fully understood. This limitation is due in part to lack of detailed full tropospheric observations, including measurements in the outflow layer of TCs. The research objective of this proposal is to use aircraft, satellite, radar, and other observations to improve our fundamental understanding of the connections between the ocean surface, eyewall convection, and TC outflow. The central hypothesis of this research is that thermodynamic constraints in both the inflow and outflow branches of the steam engine conceptual model play a major role in determining TC intensity and structure.

APPROACH

New analysis techniques and observations are being used to clarify the thermodynamic constraints in TCs. The current conceptual model of TC thermodynamics is that of a heat engine, where kinetic energy is produced through the addition of latent heat from the warm ocean surface, conversion of latent to sensible heat and kinetic energy in the mid-troposphere, and removal of heat in the upper tropospheric outflow. The maximum potential intensity and mechanical efficiency of the TC therefore depend on the thermodynamic inputs and outputs, but uncertainties in the structure of TC outflow, the connections with the inflow branch near the sea surface, and heating from convection require dedicated research. The current approach is to use a combination of numerical modeling, operational products, and research observations to obtain new insights into this problem. A dedicated field experiment called
“Tropical Cyclone Intensity 2015” (TCI-2015) was conducted in FY15 to collect new observations to achieve the research objectives.

WORK COMPLETED

The work completed in FY15 consisted of four primary research tasks: 1) idealized modeling to examine the impacts of upper-tropospheric temperatures on TC intensity; 2) full-physics model validation using new polarimetric radar observations to examine the impacts of convective heating; 3) collecting new full-tropospheric observations of TC structure and outflow as part of the TCI-2015 field experiment; and 4) collaborative research on existing TC datasets and analysis techniques. A summary of each of these tasks is summarized below.

RESULTS

Idealized Modeling of Tropopause Temperature Impacts

The “outflow temperature” in a TC represents a cold reservoir where heat is extracted from the cyclone in the steam engine conceptual model. A colder tropopause temperature therefore increases the potential intensity of a TC, and has been argued to be an important constraint on climatological TC activity (Emanuel et al. 2013). Idealized studies by Ramsay (2013) and Chavas and Emanuel (2014) using the Bryan Cloud Model (CM1; Bryan and Fritsch, 2002) model, and Wang et al. (2014) using the Weather Research and Forecasting (WRF) model have shown a significant negative correlation between tropopause temperature and simulated intensity. These studies investigated the effect of perturbing a sounding in radiative-convective equilibrium (RCE) and quantify the effects on a quasi-“steady-state” tropical cyclone. This generally involves running the model for very long periods (~100 days) to reach RCE and a steady-state TC intensity. In an effort to better understand TC intensification on relevant timescales for forecasting, we have investigated tropopause temperature impacts on shorter weather time scales of zero to ten days, rather than the more climatic time scales of previous work cited here. As a first step towards fundamental understanding we used the axisymmetric configuration of the CM1 model in an idealized set up. To initialize the model the NCEP Climate Forecast System Reanalysis (CFSR) monthly product was averaged for June, July, and August between the longitudes of 144°E and 180°E (the West Pacific basin) and separately by 5° latitude bands from 5° to 30°N. The resulting profiles are shown in Fig. 1a and have a cold-point tropopause temperature of 194.9K, 196.3K, 198.5K, 200.4K, and 201.9K for ascending latitude bands. These tropopause temperatures are very similar to those of the stratospheric temperature experiments of Ramsay (2013) using 120-day simulations with a simple radiation scheme (not shown).
Figure 1: Vertical profiles of temperature derived from the monthly mean CFSR dataset for JJA and averaged between longitude 144°E and 180°E and every 5° latitude. Cold-point tropopause temperatures are given in the legend.

Each sounding uses the same profile averaged across the five latitude-bands below 200 hPa to ensure that any differences in the simulations are due only to differences in initial tropopause temperature. Three different groups of experiments were run: 1) using no radiation, 2) using the simple radiation configuration (a scheme which relaxes back to the initial profile and is capped at 2K cooling per day), and 3) using a full physics radiation configuration (NASA Goddard scheme). At this time, only longwave radiation is considered by prescribing perpetual nighttime.

The intensities of eight-day axisymmetric TC simulations are shown in Fig. 2. Although the mean temperature profile undergoes cooling during the simulations, the difference in tropopause temperature between each latitude band remains similar at the end of the simulations (not shown). The tropopause variations do not appear to have a systematic effect on the intensity or intensification rate with this experimental setup. This conclusion is quantitatively supported when the intensity (measured by the maximum wind speed at the level of maximum wind speed) is averaged over hours 120 to 194. While previous work found a negative correlation between TC intensity and increasing stratospheric temperature, our findings suggest that there is no obvious relationship between maximum TC intensity and tropopause temperature on weather timescales using an idealized axisymmetric model. The modeled intensity is very noisy however, with large fluctuations due to the stochastic axisymmetric convection consistent with the findings of Ramsay (2013) and Hakim (2013).
Figure 2: Eight day forecasts of the maximum wind speed at the level of maximum wind speed for an axisymmetric TC in CM1r17 using (a) no radiation, (b) simple radiation which relaxes to the initial temperature profile, and (c) full radiation. Each experiment includes five simulations, initialized with the CFSR average latitude band profiles as indicated in the legend. The wind speed is smoothed with a six hour running mean.

These results are not necessarily contradictory with previous work since steady state intensity may require up to 20 days of simulation in the CM1 model (Hakim 2013). However, another recent study has argued that the TC structure at very long simulation times in axisymmetric models is unrealistic (Smith et al. 2014). Future work will expand the investigation to three-dimensional simulations, including characterization of the structure of the outflow, comparison of the outflow temperature with the tropopause and stratospheric temperature, and comparison to TCI observations.
Validation 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.

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 0.5° 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.

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. To statistically assess the accuracy of the model, Figure 3 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. The breadth of the DSDs seen in the observations (Fig. 3a,c) is not captured in the single moment schemes WSM6 (Fig. 3b,d) and Lin (not shown) due to a fixed intercept parameter. Two of the double moment schemes (WDM6 and Morrison, Figs. 3c,d) generally overproduce large raindrops, with higher frequencies of DSDs in the upper-right corner of the parameter space. The double-moment Thompson aerosol-aware bulk scheme (Fig. 3i,k) and an explicit spectral bin microphysical (SBM, Fig. 3j,l) scheme showed the best fidelity to the observed distribution, but show the presence of an unphysical high $Z_{DR}$ at moderate $Z_H$ in the upper-middle part of the parameter space. These results suggest that the modeled median drop size is too large in those regions of the TC.
There is a strong correlation (R > 0.94) between the rainfall production and the intensity of the simulated vortex. Figure 4a shows the peak accumulated rainfall on the outermost grid for each simulation, along with the combined root mean square intensity error. There is a general trend for reduced rainfall accumulation and intensity error as the sophistication of the microphysics scheme is increased. The high correlation between simulated intensity and rainfall suggests an intimate link between the latent heating produced by the microphysical scheme and the storm dynamics. The reduction in rainfall is consistent with a reduction in large raindrops as seen in Fig. 3, and is accompanied by reduced convective heating and intensity. The bulk schemes all had a high intensity bias compared to the best track, with the lowest bias found in the SBM (Fig. 4b).

While the SBM produced the most accurate intensity, best representation of the DSDs, and lowest rainfall accumulation, it required 16x the computational resources than the baseline WSM6 scheme, making it infeasible for operational use at this time. Deficiencies in the parameterization of
microphysical processes could account for the differences in the joint probability distributions of horizontal and differential reflectivity presented here. For example, a high frequency of excessively large raindrops could be the result of insufficient break-up of large drops, excessive vertical motion, overly efficient collision-coalescence, or excessive production of large ice particles such as graupel or snow that undergo melting. Future work will extend this analysis to ice particles and other polarimetric variables, such as the specific differential phase and correlation coefficient, with the goal of determining the source of model deviations from the observations. Further comparison with polarimetric radar variables from other tropical cyclones will lead to better forecasts and valuable insights into the mechanisms of hurricane intensification and heavy rainfall production.

**Figure 4.** (a) Peak accumulated rainfall over 12-hour Arthur (blue) and 18-hour Ana (green) simulations along with intensity root mean square error (red) compared to NHC and CPHC best tracks, and (b) Intensity bias for Arthur and Ana simulations using each microphysical scheme.

**TCI-2015 Field Experiment**

To further investigate the thermodynamic constraints in the boundary layer, mid-troposphere, and outflow, new research observations of full tropospheric structure are required. Typical soundings in TCs are at low-levels in the inner core due to safety concerns with C-130 and P-3 aircraft, and do not reach the tropopause in the outer core due to limitations of the G-IV aircraft. The new High Density Sounding System (HDSS) developed under ONR support was installed on the NASA WB-57 aircraft to obtain new full tropospheric observations in both the inner and outer TC core.

The PI and his research group were actively involved in the TCI field project planning and execution in FY15. The PI attended a planning meeting at the Naval Research Laboratory in Monterey in April 2015 to assist in preparations for the experiment and help design flight plans for the WB-57 aircraft. Test flights were conducted from Ellington Air Force Base in June and July, followed by research
missions during the peak of the hurricane season. The PI has been one of the primary team members in charge of data quality, assessment, and distribution to the TCI team.

An example of the HDSS sounding quality assessment is shown in Fig. 5 from co-located National Center for Atmospheric Research (NCAR) dropsondes launched by an Air Force C-130 during a test flight. The log-p skew-T diagram in Fig. 5a shows very good agreement between two nearby soundings. The fast-response temperature sensor produces very similar results to the NCAR sounding, while the slower relative humidity (RH) sensor captures the overall variability of the moisture structure at a coarser resolution. Bulk statistics in the form of percentile plots comparing ~10,000 measurement pairs within 10 m altitude and 50 km horizontally of one another are shown in Fig. 5b. The comparison suggests that the HDSS soundings are capable of producing accurate thermodynamic and kinematic measurements when compared to the well-established measurement capability of the NCAR dropsondes. The median temperature, pressure, and winds all indicate near zero bias within the accuracy of the sensor, and variability on the order of what would be expected from spatial and temporal sampling variability. The higher variability in the RH measurement difference is believed to be due to the slow sensor response, but there is no apparent bias in the average humidity over many soundings. The slight high bias in the pressure is likely due to uncertainties in the measurement height and the choice of a 10 m vertical bin for comparison.

![Figure 5](image_url)

**Figure 5.** Data quality comparison of soundings from the 25 June 2015 TCI test flight. (a) Log-p Skew-T diagram of two co-located soundings at 0123 UTC, with black lines indicating HDSS temperature and dewpoint, and red and blue lines indicating NCAR dropsonde temperature and dewpoint. (b) Percentile plot of differences between measurements co-located within 10 m altitude and 50 km horizontal distance. Red line indicates the median difference, dashed lines indicate the 25 and 75% percentile, and boxes indicate 5 and 95% percentile of the distribution.
TCI research missions in 2015 began with a successful flight into the decaying Erika due to strong vertical shear, followed by several successful flights into Marty and Joaquin. Research on the data collected during these missions has just begun and will continue in FY16. The PI’s research group took an active role in the field experiment, with daily participation in the planning and execution of the missions, with representatives from the research group present in Houston, Wallops Island, and Monterey during the field phase. The PI’s team at the University of Hawai‘i was also responsible for the data quality control during the experiment. Raw data from Yankee Environmental Systems (YES) was processed using ASPEN software to produce quick-look products that were distributed in near real-time to the NCAR field catalog for use by the TCI team. Following completion of the missions, a detailed assessment of the quality of each dropsonde was performed and made available in a spreadsheet and summary during the Daily Planning Meetings. This preliminary assessment suggests that the wind and temperature measurement quality was very high during the research missions, although a higher percentage of RH errors occurred than in the test flights due to heavy sensor wetting in the deep convective areas. The excellent datasets collected in Erika, Marty, and Joaquin will be used to investigate the full-tropospheric structure of these storms, and to further the science goals of the TCI experiment in collaboration with the science team.

Collaborative Research

Research using existing research datasets from the ONR sponsored Tropical Cyclone Structure 2008 (TCS-08) field experiment was conducted in collaboration with colleagues from NCAR and the Naval Postgraduate School (NPS) resulting in two refereed publications. The collaboration with NCAR improved the airborne radar corrections algorithm used to quality control data from the TCS08 project for use with airborne tail Doppler radars. Accurate determination of the radar pointing angle and aircraft platform motion are critical for high quality dual-Doppler wind retrievals, but the aircraft inertial navigation system has inherent uncertainties. The improved algorithm uses a generalized variational approach that can be applied to either a stationary or moving surface over either flat or complex terrain. This algorithm will help improve the quality of airborne Doppler analyses, including those potentially available from P-3 coordination as part of the continued TCI field experiment.

Collaborations with NPS yielded new insight into the genesis process through a detailed observational analysis of a non-developing disturbance from TCS-08. Despite the forecasts of most numerical models for the disturbance to intensify, it failed to organize sufficiently to be denoted a tropical depression. Detailed in situ and radar analyses of the TCS-08 observations were facilitated by the SAMURAI analysis software developed by the PI. Five aircraft missions into the disturbance revealed the evolution of an asymmetric vortex that was not vertically aligned, allowing system relative flow to import cooler, drier air into the circulation that weakened the convection. Without sufficient support from deep convection, the disturbance was not able to align in the vertical and ward off the detrimental effects of vertical shear in this case. Results from this study provide an important counter-example to the developing cases in the literature on TC genesis.

Lastly, a comprehensive review of the state of the science on TCs was conducted in FY15 as part of the World Meteorological Organization’s International Workshop on Tropical Cyclones. The PI was a co-author on several working group reports that summarize the leading ideas on TC structure and intensity change. These reports are posted online for interested researchers.
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 described in this report addresses both basic and applied research goals by improving our basic understanding of physical processes and the thermodynamic constraints on TCs, while also evaluating and validating the performance of state-of-the-art forecast models. 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 Young Investigator Program at the end of FY15 that will continue research on improving forecast model physics as the focus of the current award shifts to analyze the recently collected TCI field experiment observations. A related NSF award on precipitation processes in TCs is synergistic and complementary with the current research.

REFERENCES


PUBLICATIONS


   a. Focus Session on Objective Structure Analysis: Tropical Cyclone Structure from Coastal Radar [published]
   c. Intensity Change: Internal Influences [published]