Dynamics and Predictability of Tropical Cyclone Genesis, Structure and Intensity Change

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LONG-TERM GOALS

A long-term goal of this research is to improve dynamical prediction of tropical cyclones using ensemble methods for making analyses and forecasts. A second goal is to use the information contained in ensemble analyses and forecasts to improve basic understanding of tropical cyclone dynamics. Finally, a third goal is to use ensemble-based sensitivity analysis to target observations for tropical cyclone predictability and to assess the impact of observations on tropical cyclone forecasts.

OBJECTIVES

Specific objectives organize around the challenge of informing dynamical forecasts with observational information in tropical cyclone environments. Since these environments are atypical, traditional methods for constructing analyses from observations do not perform well. Ensemble methods naturally account for these atypical environments, and offer the opportunity for a leap forward in tropical cyclone forecast skill. Our main objective is to explore the utility of ensemble Kalman filters for creating analyses and forecasts of tropical cyclones, including genesis, intensity change, and extratropical transition. A secondary objective is to understand the intrinsic variability of tropical cyclones in the absence of environmental forcing.

APPROACH

The technical approach involves using an ensemble Kalman filter (EnKF) for experiments related to intensive observing periods (IOPs) during the Tropical Cyclone Structure project (TCS08). University of Washington graduate student Rahul Mahajan created an operational, real-time, EnKF for use during the field phase of TCS08. This system produced analyses every 6 hours and forecasts to 72 hours twice daily. Sensitivity calculations based on the ensemble data were used to help target aircraft deployment during the field campaign. Field observations (dropsondes and flight-level data) are being used to explore predictability and dynamics of typhoon Nuri, typhoon Jangmi, and typhoon Sinlaku using the EnKF with ensemble sensitivity analysis. The EnKF is cycled using the WRF model in the Data Assimilation Research Testbed (DART). A major problem with tropical cyclone applications of the EnKF has been addressed through a novel storm-centered assimilation algorithm. Basic research in

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intrinsic hurricane variability has employed a modified version of the axisymmetric cloud model of Bryan and Rotunno (2009) to simulate idealized tropical cyclones in statistical equilibrium.

WORK COMPLETED

For the four storms consider (Nuri, Jangmi, Sinlaku, and Hagupit), an 80-member EnKF has been cycled on observations (surface, rawinsondes, GPS RO, ACARS, cloud wind vectors, JTWC best track position and minimum central pressure) for 36 km and 12 km grids, including a moving 12 km grid. Dr. Mahajan made custom modifications to DART and the WRF model to allow for smooth pre-specified moves to the 12 km grid to follow the developing systems. Ensemble forecasts have been produced for the 24-hour period preceding the time when the system was named a tropical storm.

Sensitivity has been performed for each storm over the 24-hour period preceding tropical cyclogenesis. This analysis uses the EnKF analysis and forecast data to determine the sensitivity of a forecast metric to changes in the initial conditions, subject to statistical confidence testing. The ensemble approach contrasts with adjoint sensitivity, which requires an adjoint model and a new (backward in time) integration of the adjoint model to evaluate the sensitivity of each forecast metric. Moreover, the results of the statistical sensitivity analysis have been tested in the full WRF model by perturbing initial conditions using the sensitivity data, integrating the model to the forecast time, and comparing the forecast metric in the perturbed simulation to that predicted statistically. By performing the analysis for a range of initial condition perturbation amplitudes, one can “control” the intensity of the forecasted storm and, by analyzing the perturbations, discover the structures and mechanisms responsible for intensifying the storm. A challenge faced at higher resolution is the fact that convection decorrelates quickly in space and time, which dominate the sensitivity calculation, essentially by reducing the signal-to-noise ratio. We have experimented with a range of solutions to this problem, including time averaging. Another problem concerns the impact of observations, which also may introduce noise and obscure the signal of interest.

One of the findings of this research is that the impact of storm location is critical for data assimilation, even when assimilating storm location. Essentially, small changes in storm position dominate the error covariance, and therefore for the impact of new observations. In order to deal with this problem, new student Erika Navarro (Mahajan graduated Spring 2011) along with the PI developed a method that allows observations to affect fundamental storm structure; that is, analysis increments not due to position. A systematic analysis was performed using idealized three-dimensional hurricane simulations, and vortices in the shallow water equations.

Basic research has also been performed on intrinsic hurricane variability has been performed using a sequence of experiments designed to provide a large sample of this variability for statistical analysis. Initial attempts using previously established modeling frameworks failed to produce storms in statistical equilibrium. It was determined that the source problem was an assumption in past work (Rotunno and Emanuel 1987; Persing and Montgomery 2003; Bryan and Rotunno 2009) that radiation acts to damp temperature perturbations back to a prescribed sounding profile. We found that this assumption suppresses convection outside the tropical cyclone, produces an outflow jet that is too close to the storm, and produces dry air that eventually dissipates the storm. A state-of-the-art infrared radiative transfer model was introduced into the model of Bryan and Rotunno (2009). Solutions with this modified model produce storms in statistical equilibrium for over 400 days.

RESULTS

Results for typhoon Nuri reveal large ensemble variability in the developing storm position and intensity. Analysis increments due to observations reflect primarily movement of the storm location; the center is ill defined in the analysis. Sensitivity of the 24-hour forecast of storm intensity, as measured by the area-averaged 850 hPa vorticity within 300 km of the storm center, is sensitive to both the initial storm intensity as well as the surrounding environment (Figure 1). These sensitivity patterns suggest that intensity of Nuri is sensitive to the large-scale vorticity on the northwest side of the trough.

Preliminary results of perturbed initial condition experiments reveal that an initial condition that is a scaled version of the sensitivity field shown in Figure 1 yields a solution at the forecast time (24 hours, verifying 12 UTC 17 August 2008) that has a more intense storm (not shown). Repeating the process for a range of initial condition perturbations reveals that the linear approximation is valid of a wide range of intensities. Near the limit of the linear approximation, the ensemble sensitivity pattern changes the area-averaged vorticity by approximately 4×10^{-5} s^{-1}. Adding opposite-signed perturbations weakens the storm until it essentially vanishes. Further experiments show that tropical cyclogenesis is strongly controlled by the circulation near 850 hPa. Moreover, the sensitivity to moisture is weak compared to the wind field. Most important is that thesis results were found for all four storms considered.

Results on the intrinsic variability of axisymmetric tropical cyclones show that: (1) all experiments begin from rest and produce hurricanes within 10 days, with most of the development occurring within two days after the environment has been conditioned by convection; (2) Emanuel's PI (E-PI) theory accurately bounds the time-mean storm intensity (Figure 2). Transient fluctuations in storm intensity are observed to exceed the E-PI bound by more than 30%, in some cases for several days, as observed in real storms; solutions are insensitive to turbulent mixing in the radial direction (Figure 3), except for a transient spin-up storm, which exhibits sensitivity qualitatively similar to that described in Bryan and Rotunno (2009); (4) while E-PI theory provides an accurate approximation to storm intensity, the thermodynamic cycle is not well approximated by Carnot theory (Figure 4); and (5) radiative cooling is critical for triggering convection and establishing the equilibrium state, a fixed vertical cooling profile approximates well the solution with interactive radiation. Variability takes the form of convective bands that form in the environment around the storm and propagate inward producing eyewall replacement cycles. These bands have a return time of approximately 4—8 days. Predictability experiments reveal a limit of approximately three days for intrinsic storm intensity (not affected by the environment).

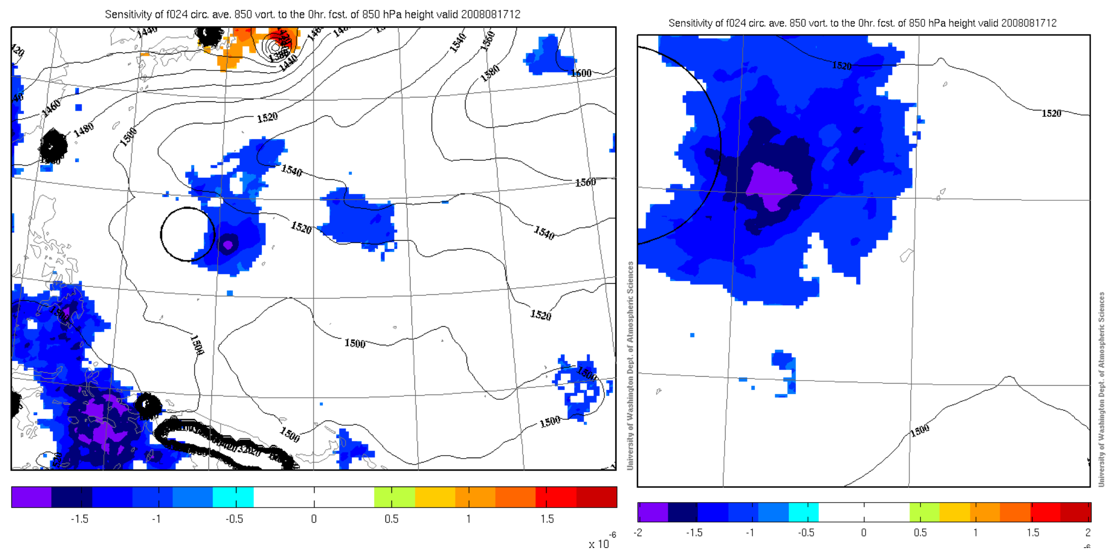

Figure 1. Sensitivity of WRF 24 hour forecasts valid 12 UTC 17 August 2008 (Nuri, pre-storm) to 850 hPa geopotential height. The forecast metric is the average 850 hPa vorticity within a circle of radius 300 km centered at 16.1N, 136.7E, denoted by the think black circle. Sensitivity is confidence tested at 95%. The 36 km domain is shown in the left panel, and 12 km domain in the right panel.

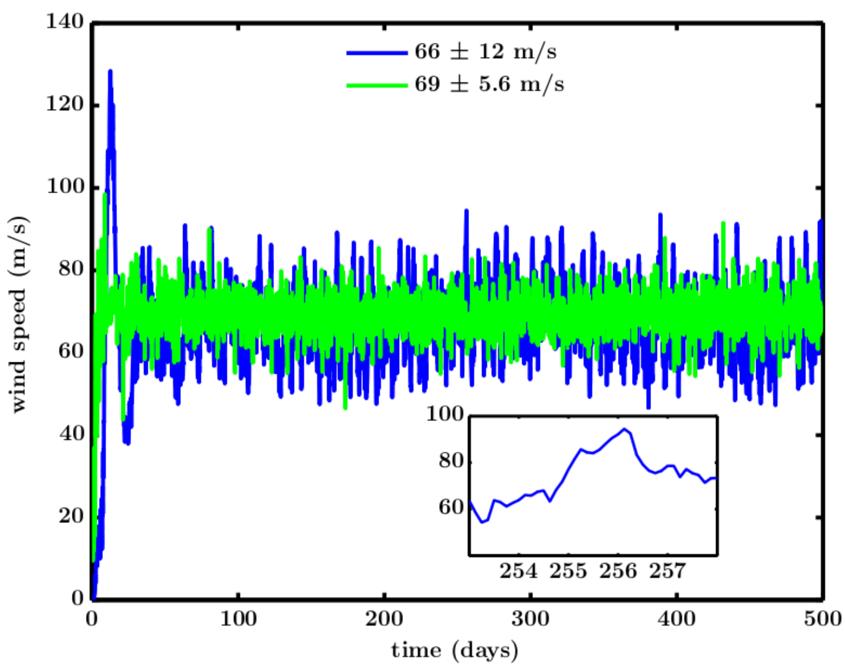

Figure 2. Maximum wind speed (m/s) at the level of maximum wind (blue line) and E-PI estimate (green line) for the control idealized axisymmetric simulation. The legend shows the time-mean values, and the inset shows a zoomed-in view of the windspeed during a 5-day period starting at day 253.

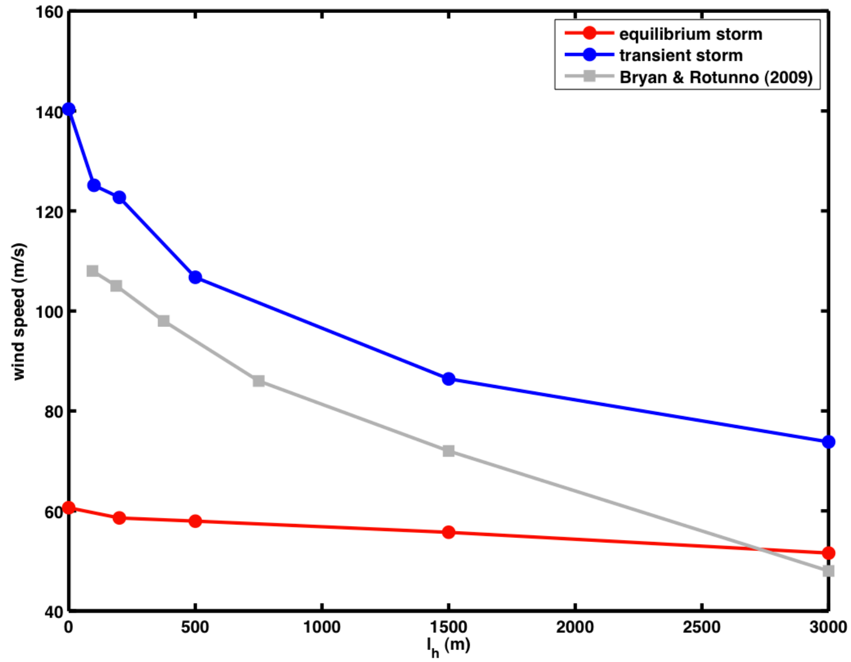

Figure 3. Sensitivity of maximum surface wind speed to radial turbulence mixing length scale, l_h. The blue curve shows the transient storm averaged over a two-day period centered on the time of maximum wind. The red curve shows the equilibrium storm averaged over days 20--120. The gray curve shows results taken from Fig. 2 of Bryan and Rotunno (2009) for a vertical mixing length scale, l_v of 200 m (same as used here), which are averaged over days 8--12.

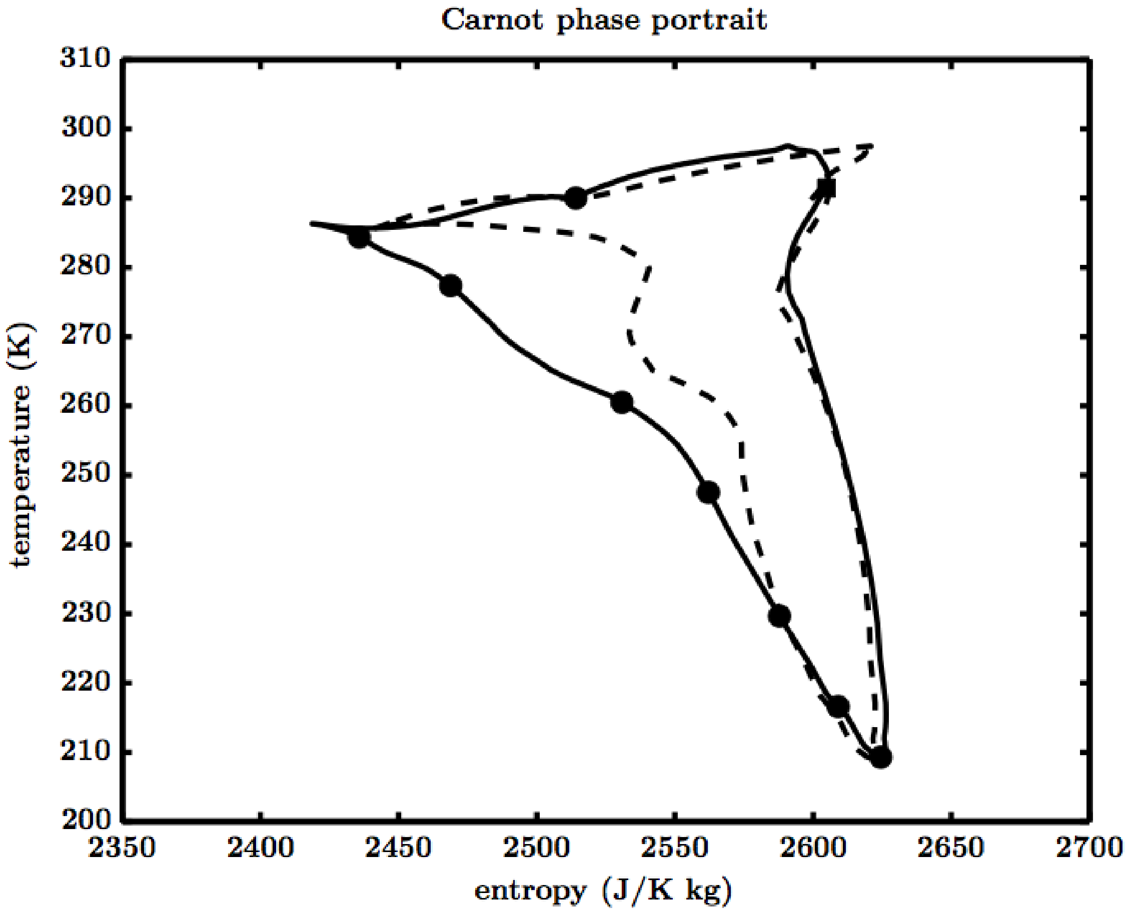

Figure 4. Temperature--entropy phase plot for the 38-day mean-state trajectory of the control simulation. A square denotes the origin of the trajectory at the point of maximum wind; filled circles show the location of the trajectory at day 1, and then every 5 days from 5 to 35 days. A Carnot cycle would appear as a rectangle on this diagram.

IMPACT/APPLICATIONS

Improvements to forecasts of tropical cyclone structure, intensity change, and extratropical transition require improvements in the initial specification of the vortex. The research in this project provides proof of concept for: (1) more-accurate vortex specification in the initial condition, (2) much reduced forecast errors for both track and intensity, (3) targeting observations near tropical cyclones and identifying high-impact observations. As a result, the impact of this research may be considerable if deployed in operational systems. Moreover, our results show that the circulation near 850 hPa is the critical factor controlling storm development for four western Pacific typhoons, and that, in the absence of environmental influences, the limit of tropical cyclone intensity prediction is about three days.

RELATED PROJECTS

None

PUBLICATIONS

Hakim, G. J., 2010: The mean state of axisymmetric hurricanes in statistical equilibrium. J. Atmos. Sci., 67, .

Hakim, G. J., 2012: The variability of axisymmetric hurricanes in statistical equilibrium. J. Atmos. Sci., 67, conditionally accepted.

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