

# The Dynamics of Tropical Cyclones

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## LONG-TERM GOALS

The broad objectives of this research effort are to better understand the mechanisms that determine tropical cyclone motion, structure, and intensity change and to apply the new knowledge to improving tropical cyclone forecasts.

## OBJECTIVES

The specific objectives of the current effort are:

1. To continue our study of the dynamics of the extra-tropical transition of tropical cyclones using idealized modeling and case studies based on operational forecast models;
2. To continue a study of the factors which govern the size of tropical cyclones and the mechanisms involved in the generation of midget typhoons;
3. To continue a comparative study of tropical cyclone growth in various numerical models with the same idealized configuration;
4. To continue a study of the mechanisms responsible for inner-core asymmetries of tropical cyclones in environmental vertical shear;
5. To continue the development of new concepts for the construction of synthetic tropical cyclones (a) in global and regional operational prediction models, and (b) in tropical-cyclone ensemble forecast models;
6. To continue the development, testing, further improvement and operational implementation of the Statistical Ensemble Prediction System STEPS for the track and intensity of tropical cyclones;
7. To continue work on improving the operational barotropic hurricane track prediction model WBAR in the U. S. Navy's Automated Tropical Cyclone Forecasting system ATCF;
8. To continue work on an ensemble version of WBAR and its combination with the hurricane intensity prediction model of K. Emanuel of the Massachusetts Institute of Technology MIT;
9. To initiate a study of the extratropical transition of tropical cyclones in the ensemble prediction system of the European Centre for Medium-Range Weather Forecasts.

## APPROACH

The approach involves a mix of analytic and numerical model calculations, as well as the analysis of operational and field data. Recent findings from theoretical studies are being applied to the problem of initializing tropical cyclones in numerical forecast models. Group members in addition to the PI include: Drs. Sarah Jones (working on the effects of vertical shear on vortex evolution with diplom

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student Mr. Richard Patra and on the extra-tropical transition of tropical cyclones with doctoral students, Ms. Helga Weindl and Mr. Michael Riemer and diplom student, Mr. Matthias Röbbcke); Maria Peristeri (working on a modelling study of midget typhoons); Wolfgang Ulrich and Hongyan Zhu (working on a modelling study of hurricane-ocean interaction and on the factors that govern the size of hurricanes; and Harry Weber (working on topics related to operational tropical-cyclone track and intensity prediction). The PI is working with doctoral students, Ms. Seoleun Shin on a study of tropical-cyclone genesis and Mr. Sang Nguyen on a comparative study of hurricane growth in a variety of model configurations.

## **WORK COMPLETED**

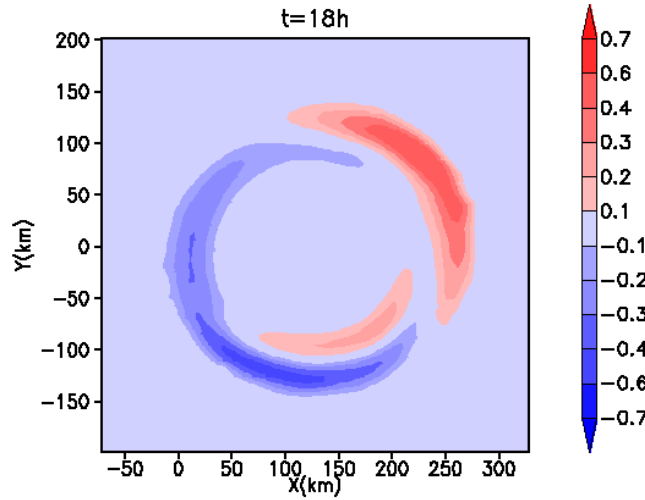
The following papers have been accepted for publication or have appeared in print: Jones *et al.* (2003), a review of the forecast challenges, current understanding, and future research priorities for extratropical transition; Jones (2003), a note on the ability of dry tropical-cyclone-like vortices to withstand vertical shear; Smith (2003), a modelling study of the hurricane boundary layer; Weber (2001), on the WBAR prediction system; Weber (2003), on the STEPS model; and Zhu and Smith (2003), a study of the effects of vertical differencing on hurricane asymmetries in a numerical model. Two papers, one explaining the concept of buoyancy in rapidly-rotating atmospheric vortices (Smith *et al.*, 2003) and one exploring the effects of ocean cooling on the inner-core asymmetries of a hurricane in a simple coupled ocean - hurricane model (Zhu *et al.*, 2003) have been submitted for publication. Progress has been made in exploring the effects of initial vortex size on vortex intensity and size in a minimal axisymmetric hurricane model. Together with N. Davidson and K. Puri of the Australian Bureau of Meteorology Research Centre BMRC, the revised initialization method of the regional tropical-cyclone prediction model TC-LAPS (cf. Davidson and Weber, 2000) has been tested successfully under semi-operational conditions and is in operational use since autumn 2002. Together with C. Sampson and J. Goerss of the Naval Research Laboratory NRL, the WBAR model has been implemented successfully in the U. S. Navy's ATCF system and runs operationally in the Northwest Pacific since May 2003.

## **RESULTS**

In Jones (2003) we have shown that a dry tropical-cyclone-vortex can remain upright for many days in moderate environmental vertical shear. The mechanism involved is that described in Jones (1995, 2000). Thus it is not necessary to appeal to the influence of moist processes to explain why tropical cyclones can resist moderate vertical shear. We have shown that a definition of the vortex center based on the PV centroid contains more information about the vortex tilt than more traditional definitions (e.g. the location of minimum central pressure or maximum potential vorticity). We have extended the dry vertical shear calculations of Jones (1995) to include an idealized representation of latent heat release in the inner core of the idealized tropical cyclone. The aim of this study is to better understand the differences between the aforementioned dry calculations, with maximum ascent to the right of the direction of tilt, and the moist calculations of Frank and Ritchie (1999), with maximum ascent to the left of the shear vector. When the stratification in the inner core of the tropical cyclone is moist stable, the pattern of vertical velocity is as in Jones (1995). For moist neutral stability, maximum ascent occurs to the left of the shear vector (Fig. 1). The mechanism responsible for these differences is under investigation.

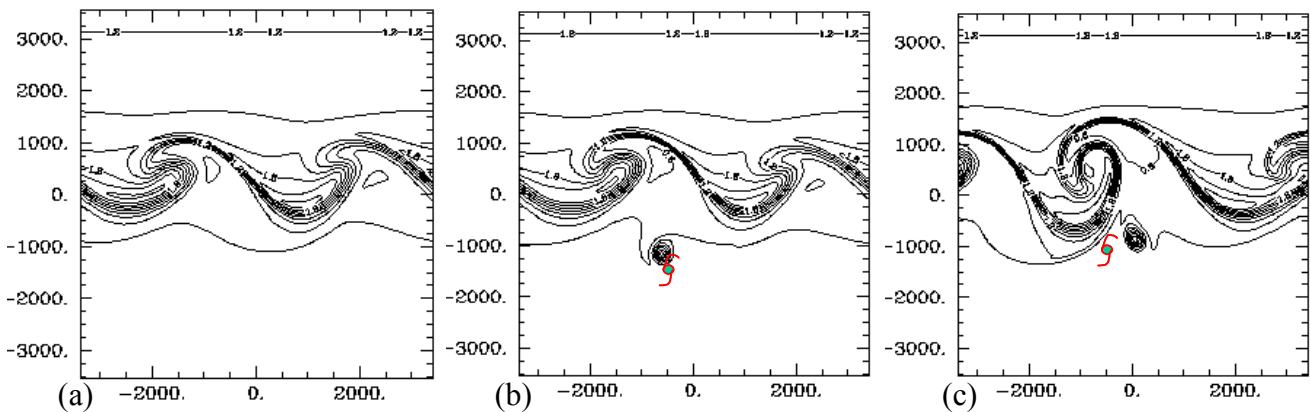
We have initiated a study of extratropical transition using forecasts from the operational global model of the German Weather Service (DWD) initialized from DWD and ECMWF analyses. A case study of

the extratropical transition of Erin (2001) indicates that the low potential-vorticity outflow from the hurricane in the western Atlantic influenced the structure of the midlatitude tropopause across the



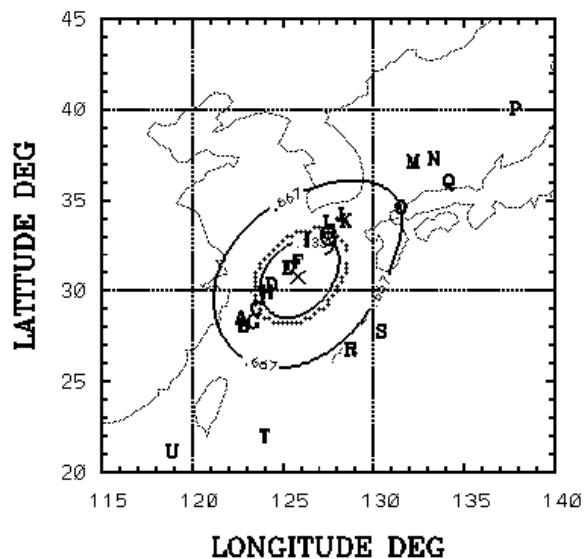
**Figure 1:** Vertical velocity for moist neutral calculation in westerly vertical shear at height of 6 km after 18 h exhibits wavenumber one structure with maximum amplitude at radius of 125 km. Maximum ascent is downshear left and maximum descent upshear right.

Atlantic and into western Europe. We hypothesize that the modification of the upper-level jet by the tropical cyclone outflow played a crucial role in the intensification after extratropical transition, and may be the source of errors in the numerical forecasts. Through our idealized study of the interaction between a tropical-cyclone-like vortex and a baroclinic wave we have demonstrated the sensitivity of extratropical transition to both the initial vortex location (Fig. 2) and the life-cycle of the baroclinic wave.



**Figure 2:** Potential vorticity at height of 4.5 km after 6 days for the interaction between a tropical cyclone (TC) and a baroclinic wave. (a) no TC (b) TC initially 1500 km south of baroclinic zone (c) TC initially 1000 km south of baroclinic zone. In (b) the TC is well to the south of the baroclinic wave and the structure of the baroclinic wave is identical to (a). In (c) the TC has moved into the warm sector of the baroclinic wave and the extratropical cyclone has a larger meridional scale.

In Zhu *et al*, 2003 we compare two representations for entrainment into the ocean mixed layer: one based on the assumption that the velocity scale for entrainment is the surface friction velocity (Method I), the other on the assumption that this scale is the magnitude of the mean velocity difference across the base of the mixed layer (Method II). The magnitude and distribution of the ocean cooling depends strongly on which method is used. Method I is more effective in reducing the heat flux from the ocean to the storm in the inner core region and leads to a greater reduction of the tropical cyclone intensity. Ocean coupling reduces the surface heat flux in the inner core, mainly in the rear-right quadrant relative to the track. As a result, the potential temperature distribution in the core region is more asymmetric in the coupled model. The region of convergence in the lower troposphere is rotated counterclockwise from the rear sector of inner core, apparently in response to the change in the temperature distribution in the middle troposphere. The region of strong upward motion in the middle troposphere shifts counterclockwise also. These changes are accompanied by changes in the divergence pattern that are mainly in the lower troposphere rather than in the boundary layer. The presence of ocean coupling has little influence on the cyclone track, unlike the case in some previous studies.



**Figure 3: Example of a probabilistic forecast with the new ensemble version of WBAR at forecast time 72 h (NW Pacific storm 21; base date/time 28 August 2002, 00 UTC). The broadly scattered letters A-U show the predicted positions of each of the 21 ensemble members (cf. text). The inner and outer ellipsoidal rings (with maximum diameters of about 400 and 1000 km) encircle the 33 and 66% integrated strike probability regions, i.e. the regions where the storm center can be expected to be in 33 and 66% of all prediction cases. The cross defines the center of the integrated strike probability distribution; the dots surrounding this center near the 33% contour mark the ring of the most probable storm position. Note that in this example, the observed position (hurricane symbol) is near this ring.**

Since May 2003, WBAR runs operationally in the U. S. Navy's ATCF system on Northwest-Pacific storms, showing a relatively high quality of performance with current mean position errors of 157, 257 and 387 km at 24, 48 and 72 h prediction time (C. Sampson, NRL, pers. comm.). The present 72-h mean position error is less than that of the U. S. Navy's Operational Global Atmospheric Prediction

System NOGAPS (by 52 km), the Aviation model (by 72 km) and the Japan Meteorological Agency's global and typhoon model (by 39 and 78 km, respectively), and a little higher than that of the Geophysical Fluid Dynamics Laboratory's model (by 2 km) and the U. K. Meteorological Office's model (by 7 km). Furthermore, the inclusion of WBAR in the consensus forecast (cf. Goerss 2000) had a significant positive impact on the performance of this method.

An ensemble version of WBAR has been developed and tested on all 2002 global tropical cyclone events (1055 cases). The ensemble has 21 members, each initialised with a different set of mass-weighted deep-layer-mean fields computed from NOGAPS analyses and predictions. At any given prediction time, a new statistical method is applied to the ensemble results, providing geographical strike probability maps as shown in the example of Fig. 3. Note that in an ensemble forecast, an exact position prediction of a given storm is not possible because the center (marked by "x" in Fig. 3) of the integrated probability distribution (the isolines in Fig. 3) does not represent the most probable position. The latter is represented rather by a ring about the center of the integrated probability distribution (marked by dots in Fig. 3) where the probability distribution is maximum. If these rings are used for a statistical evaluation of the model performance, the mean position errors reduce to 89, 155 and 235 km at 24, 48, and 72 h. The corresponding mean diameters of the 66% strike probability regions are, with 380, 676 and 984 km, comparable to those of the statistical model STEPS (Weber 2003). This shows clearly that simple models such as WBAR are capable of providing valuable probabilistic tropical-cyclone track guidance. Moreover, the computational economy of each WBAR prediction cycle is a major advantage compared with ensemble forecasts of more complex models.

The new method of statistical evaluation developed for the WBAR ensemble (see above) has been applied to the predictions of all operationally-available models used in 2002 (1857 cases in all ocean basins). Preliminary tests, carried out in the same way as described for the WBAR ensemble above, produced mean position errors of 82, 136 and 184 km (using the rings of the most probable position) and 135, 235 and 330 km (using the centers of the integrated density distributions) at 24, 48 and 72 h prediction time. It should be noted that even the latter errors are smaller than those of the consensus forecast (cf. Goerss 2000). The corresponding mean diameters of the 66% strike probability region are 284, 479 and 662 km. These excellent results recommend an operational implementation in the ATCF system.

## **IMPACT/APPLICATIONS**

The operational performance of the ATCF version of WBAR shows that it is competitive with most numerical prediction models currently in operational use in the NW Pacific, at least for cases of early-season storms. Furthermore, the WBAR predictions have a positive impact on the consensus forecast, which at present provides the best track guidance possible. Together with C. Sampson and J. Goerss of NRL, work on a further improvement of WBAR is in progress.

Currently, an ATCF-version of the probabilistic tropical-cyclone track and intensity model STEPS (Weber 2003) is being developed in collaboration with C. Sampson of NRL. Its implementation is planned for spring 2004, followed by semi-operational tests in the NW Pacific during the 2004 season. Together with P. Harr of the Naval Postgraduate School (NPS), work on a combination of STEPS with a model for the assessment of expected economic impacts of tropical cyclones at given geographical locations is planned once STEPS has been implemented and tested successfully in the ATCF system. On the basis of a statistical evaluation of the large number of NOGAPS analyses and predictions provided by J. Goerss of NRL, new and better concepts for the construction of synthetic storms in numerical prediction models are being developed and may improve tropical-cyclone prediction with numerical models. The current effort includes analyses of the structure of tropical cyclones

undergoing extratropical transition as well as the cross-storm flow contributions to observed storm translation velocities in numerical models.

With the development of an ensemble version of WBAR, the first part of the work on a combined track and intensity prediction model, carried out together with K. Emanuel of MIT, is nearing completion. In the next step, the intensity model (cf. Emanuel 1995) will be linked to the WBAR ensemble such that the intensity of a given storm is predicted as a function of the predicted positions of each ensemble member, thus providing an ensemble of intensity predictions that can be analyzed statistically.

## TRANSITIONS

The revised vortex enhancement method for TC-LAPS runs operationally at BMRC since the Australian tropical-cyclone season 2002/2003 and the barotropic track prediction model WBAR runs routinely in the framework of the ATCF system since May 2003.

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- Zhu, H., and R. K. Smith, 2003: Effects of vertical differencing in a minimal hurricane model. *Quart. J. Roy. Met. Soc.*, **129**, 1051-1069 [published, refereed].

Zhu, H., W. Ulrich, and R. K. Smith, 2003: Ocean effects on tropical cyclone intensification and inner-core asymmetries in a simple three-dimensional coupled model. Submitted to *J. Atmos. Sci.*

### **Conference papers**

The PI presented an invited paper on *Tropical Meteorology and Tropical Convection* at an international workshop organized by of the German Aerospace Research Organization Institute of Atmospheric Physics in Wessling, Germany, and one on *The Role of Convection and Buoyancy in Hurricanes* at the International Union of Geodesy and Geophysics meeting held in Sapporo, Japan. Hongyan Zhu presented a joint paper (with Roger Smith and Wolfgang Ulrich) on *Ocean Effects on Tropical-Cyclone Intensification and Inner-Core Asymmetries* at the latter meeting.

### **Theses**

Richard Patra, 2003: The role of the asymmetric vertical circulation in tropical cyclones under the influence of environmental vertical shear. Diplom thesis, University of Munich, 65 pp.