The Dynamics of Tropical Cyclones

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LONG-TERM GOALS

The broad objectives of this research effort are to improve our understanding of the dynamics of tropical-cyclone evolution and motion using a combination of analytic techniques, observational case studies and numerical model calculations, and to apply this knowledge to improve the prediction of tropical cyclones.

OBJECTIVES

The specific objectives of the current effort are:

1. To continue our study of the physical mechanisms underlying tropical cyclone structure and intensity changes due to potential vorticity (PV) anomalies by extending studies with a three-layer model to a full-physics multi-level model;
2. To extend our diagnosis of hurricane intensity change as predicted by the Geophysical Fluid Dynamics Laboratory (GFDL) model using the method of piecewise PV inversion.
3. To apply the technique developed with the GFDL model output to other forecast models.
4. To continue our study of the dynamics of the extra-tropical transition of tropical cyclones with emphasis on idealized modelling;
5. To continue a numerical modelling study of tropical-cyclone - trough interaction;
6. To continue a study of the factors which govern the size of tropical cyclones;
7. To continue our study of the hurricane boundary layer;
8. To continue a numerical modelling study of midget typhoons;
9. To continue a numerical and theoretical study of the spin down of tropical cyclones;
10. To continue an idealized numerical modelling study of hurricane - ocean interaction;
11. To continue the development of methods for (a) the introduction of synthetic tropical-cyclone-scale vortices in global and regional operational forecast models and (b) ensemble forecasting of tropical cyclones.
12. To continue the development and testing of a new statistical hurricane track prediction system (STEPS) using an ensemble of operational numerical models;

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13. To continue collaboration with the Naval Research Laboratory (NRL) and the Geophysical Service of the German Army (AWG) with regard to an operational application of the new barotropic hurricane track prediction system WBAR;
14. To initiate a study on hurricane intensity prediction with STEPS;
15. To initiate a study of the physical mechanisms responsible for asymmetric vertical motion in the inner-core of a tropical cyclone in the presence of environmental vertical shear; and
16. To initiate a study of rapid tropical-cyclone intensification using European Centre for Medium Range Weather Forecasts archived analyses.

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 tropical-cyclone evolution, on vortex spin-down and on the extra-tropical transition of tropical cyclones with doctoral student, Ms. Helga Weindl, and in collaboration with Drs. C. Thorncroft at SUNY, Albany, and P. Harr at the Naval Postgraduate School, Monterey); Dominique Möller and Lloyd Shapiro (working on diagnosing hurricane intensity changes in numerical forecast models, as well as potential vorticity asymmetries and tropical cyclone evolution); Maria Peristeri (working on a modelling study of midget typhoons); Wolfgang Ulrich (working with doctoral student, Ms. Hongyan Zhu, on the development of an idealized coupled hurricane - ocean model), and Harry Weber (working on aspects of tropical cyclone dynamics relevant for tropical-cyclone motion and operational tropical-cyclone track and intensity prediction in collaboration with Drs. N. Davidson and K. Puri of the Australian Bureau of Meteorology Research Centre (BMRC), Mr. D. Majewski of the German Weather Service (DWD), Dr. T. Prenosil of the AWG, Dr. J. Goerss at the NRL, Ms. Do Le Thuy and Ms. Nguyen Thi Minh Phuong from the Vietnamese Hydrometeorological Service (HMS), and with Drs. Kieu Thi Xin and Phan Van Tan from the Meteorology Department at the Hanoi University of Science). The PI is working on the hurricane boundary layer, with Ms. Hongyan Zhu and Ms. Nguyen Chi Mai from the HMS on the development of idealized hurricane models.

WORK COMPLETED

The following papers have been brought to completion and have appeared in print: a paper describing the results of the study of tropical cyclone evolution via potential vorticity (PV) asymmetries in a dry three-dimensional model (Möller and Montgomery, 2000); a paper describing the results of a first study of the effects of PV asymmetries on tropical cyclone evolution in a moist three-layer model including convection (Shapiro, 2000); two papers on the evolution of tropical-cyclone-like vortices in vertical shear (Jones, 2000a,b); a paper on a minimal three-dimensional tropical cyclone model (Zhu *et al*., 2001); and a paper describing a new barotropic hurricane track prediction system WBAR (Weber, 2001a). A review paper on the extratropical transition of tropical cyclones (Jones *et al*., 2001) and a paper describing the results of the study of the balanced contributions to the intensification of Hurricane *Opal* (1995) as diagnosed from a GFDL model forecast (Möller and Shapiro, 2001) have been accepted for publication subject to revision.

The following papers have been submitted for publication: a revised version of a paper using the Zhu *et al*. model to investigate the importance of three physical processes on tropical cyclone evolution (Zhu and Smith, 2001); a paper describing an axisymmetric version of the model (Nguyen *et al*., 2001); a paper comparing an axisymmetric hurricane model with the corresponding slab-symmetric model (Ulrich and Smith); a paper describing a simple steady, axisymmetric, slab model for the hurricane boundary layer (Smith, 2001).); and a paper on the results of the new statistical hurricane track prediction system STEPS (Weber, 2001b).

A simple two-layer ocean model for predicting sea surface temperature and upper thermocline temperature has been coupled to the minimal three-dimensional hurricane model for basic studies of ocean feedback effects on hurricane evolution.

We have partially developed a piecewise technique for diagnosing the contribution of individual atmospheric features, including an upper-tropospheric trough, to the intensification of a hurricane under the asymmetric balance assumption. The technique will be applied to forecasts of Hurricane *Opal* by the GFDL model and of Typhoon *Shanshan* by the BMRC's Tropical Limited-Area Prediction System (TC-LAPS).

The current initialization procedure for TC-LAPS (Davidson and Weber, 2000) has been completely revised. Furthermore, a new initialization procedure for ensemble forecasting of tropical cyclones with TC-LAPS has been developed.

RESULTS

The effects of precipitation-cooled downdrafts in the three-dimensional hurricane model depend on the closure scheme chosen for deep convection. In the two closures in which the deep cloud mass flux depends on the degree of convective instability, the downdrafts decrease the rate of intensification during the early development stage. Nevertheless, by reducing the deep convective mass flux and the drying effect of compensating subsidence, they enable grid-scale saturation, and therefore rapid intensification, to occur earlier than in calculations where they are excluded. Convective momentum transport as represented in the model weakens both the primary and secondary circulations of the vortex, but it does not significantly reduce the maximum intensity attained after the period of rapid development. The weakening of the secondary circulation impedes vortex development and significantly prolongs the gestation period.

Differences between the solutions of the minimal axisymmetric model and those of the three-dimensional version in the same physical configuration have been explained. Vortex evolution is similar in the two models during the early stages of intensification, but the period of rapid intensification occurs earlier in the axisymmetric model due to the higher effective resolution obtained using a staggered grid. There are some marked differences at later times, when, in the three-dimensional model, asymmetric structures develop. In the axisymmetric model super-gradient winds develop in the boundary layer within a radius of about 100 km of the vortex axis at an early stage of evolution and appear to be a natural feature of the vortex boundary layer.

High-resolution solutions of the steady slab boundary-layer model show annular regions in which the tangential flow is supergradient. A new feature of these solutions is the existence of spatial oscillations in vertical velocity (with both positive and negative values) at the top of the boundary layer, inside the radius of maximum tangential wind speed above the boundary layer.

The coupled ocean has a positive feedback during the gestation period of hurricanes by supplying heat and moisture fluxes from below. For strong (mature) hurricanes the (net) feedback is a negative, because of the strong intrusion of cold water from below which lowers the sea surface temperature and thus the fluxes. This is in agreement with other studies, e.g. Schade and Emanuel (1999).

The study of the intensification of Hurricane *Opal* (1995) as diagnosed from a GFDL model forecast (Möller and Shapiro, 2001) established both the asymmetric and symmetric balanced contributions to Opal's intensification. The results of diagnosis indicated that the symmetric tangential wind acceleration in the inner core of *Opal* due to symmetric heating and friction was much greater than that from asymmetric eddy forcing. The diagnosis showed that the induced balanced symmetric secondary circulation can make a substantial contribution to the tangential momentum budget and should therefore be included in order to obtain a complete depiction of the factors responsible for the evolution of the vortex. The results imply that an unbalanced secondary circulation in the eyewall region counteracts the symmetric heating, thereby reducing its effective contribution to *Opal*'s intensification by about one half, and that gradient unbalanced regions of the vortex induce an unbalanced secondary circulation that counteracts effective momentum sinks, thereby intensifying the vortex in those regions. Moreover, asymmetric heating and friction tend to accelerate the inner core of the hurricane, opposing the deceleration induced by the asymmetric PV. The diagnostics also imply that only a fraction of the asymmetric heating and friction contributes effectively to the response.

The GFDL model forecast of *Opal* indicates that at the time of the analysis, during a period of rapid intensification, eddy forcing made a small contribution to the hurricane's lower-tropospheric near-core spinup (Möller and Shapiro, 2001). Thus, the results appear to support the conclusion that an upper-level trough in the vicinity of the hurricane was not important to its intensification, contradicting another study that came to an opposite conclusion. In order to evaluate the contribution of the trough itself, however, the technique of piecewise PV inversion is required.

The new hurricane track prediction system STEPS, based on an ensemble of all available operational numerical models, has been tested successfully using all Atlantic hurricanes in 1997-2000 (Weber, 2001b). As shown in Fig. 1 for a total average over all seasons examined, STEPS shows considerable skill relative to all available numerical models and the official predictions of the National Hurricane Center (NHC). With very few exceptions, this result is also valid in each individual hurricane season between 1997 and 2000.

IMPACT/APPLICATIONS

The three-dimensional, three-layer hurricane model has application in basic studies of tropical cyclone evolution in a variety of flow environments including cyclone behaviour in the presence of an approaching upper-level trough and has the potential to improve our understanding of the dynamics of hurricane behaviour. Its coupling with the two-layer ocean model is expected to enhance our understanding of ocean feedback on hurricanes.

The results of our PV inversion study with GFDL-model forecasts have the potential to improve forecasts of tropical cyclone motion and to better predict intensity changes by diagnosing the reasons for good and bad forecasts. Operational models currently forecast intensity changes with little skill.

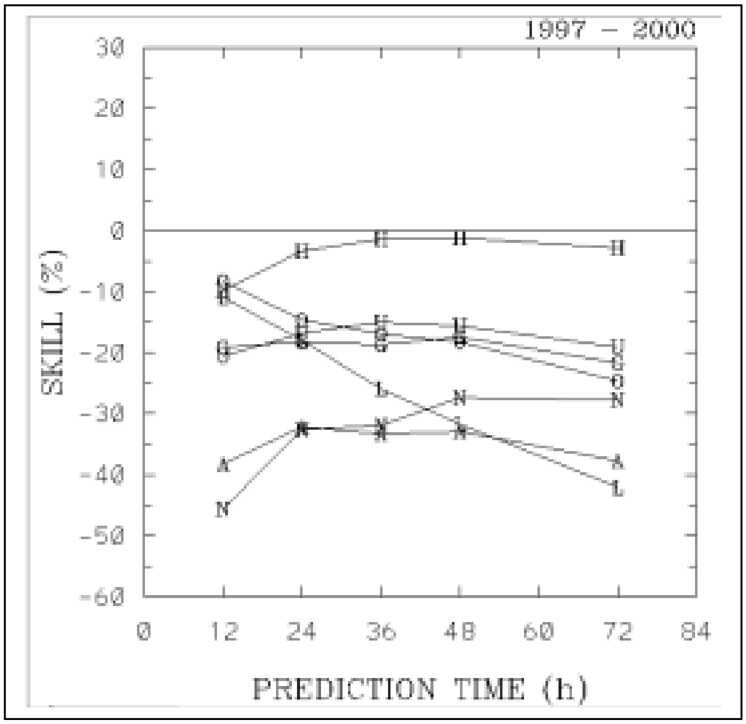

Fig. 1 Mean skill in % (defined as negative relative position error with negative values representing positive skill) versus all prediction times (12, 24, 36, 48 and 72 h) of STEPS relative to the National Centers for Environmental Prediction's Aviation model (A), the GFDL model (G), the consensus model (H) of Goerss (2000), the barotropic model LBAR (L), the U.S. Navy's global model NOGAPS (N), the NHC's official forecast (O) and the United Kingdom Meteorological Office's global model (U), averaged over all Atlantic hurricane seasons 1997-2000.

The results of the study of PV asymmetries and tropical cyclone evolution using the full-physics model have the potential to improve forecasts of rapid deepening and eyewall replacement cycles by establishing the conditions under which such processes are favoured.

The review paper on the extratropical transition of tropical cyclones provides an overview of the challenges involved in forecasting extratropical transition, summarizes our current understanding of extratropical transition and details outstanding research questions. Thus it should be of use to both forecasters and researchers in this area.

The planned operational application of the barotropic model WBAR and the statistical model STEPS may have a positive impact on the future of operational tropical cyclone track prediction.

TRANSITIONS

The revised vortex enhancement method for TC-LAPS is being tested semi-operationally at BMRC. Furthermore it is being implemented in the DWD’s global model. The new initialization method for tropical cyclone ensemble predictions with TC-LAPS is being tested also.

The new barotropic track prediction system WBAR is being tested at the NRL in semi-operational mode and on the basis of global input fields provided by NOGAPS. The system has been implemented also for operational use at the AWG.

SUMMARY

We have made much progress in understanding some basic features of tropical cyclone dynamics including the role of shallow convection, precipitation-cooled downdrafts, convective momentum transfer, the boundary layer and the role of asymmetries in tropical cyclone intensification. We have made an important step in reviewing knowledge on the extratropical transition of hurricanes. We have also made a very significant contribution to improving algorithms for hurricane track prediction by the development of the barotropic numerical model WBAR, the statistical ensemble model STEPS and the vortex enhancement procedure for the initialization of three-dimensional numerical prediction models.

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Weber, H. C., 2001a: Hurricane track prediction with a new barotropic model. *Mon. Wea. Rev.*, **129**, 1834-1858.

Weber, H. C., 2001b: Hurricane track prediction using a statistical ensemble of numerical models. Submitted to *Mon. Wea. Rev.*

Zhu, H., R. K. Smith and W. Ulrich, 2001: A minimal three-dimensional tropical cyclone model. *J. Atmos. Sci.,* **58**, 1924-1944.

Zhu, H., and R. K. Smith, 2001: The importance of three physical processes in a minimal three-dimensional tropical cyclone model. Submitted to *J. Atmos. Sci*.

Conference papers:

The following two papers were presented at the Australian Meteorological and Oceanographical Society Annual Conference, held in Hobart, Tasmania in February 2001:

H. Zhu and R. K. Smith: A minimal three-dimensional tropical cyclone model

Nguyen C. M., H. Zhu, R. K. Smith and M. J. Reeder: A minimal axisymmetric tropical cyclone model

Sarah Jones organized a session on tropical meteorology at the joint conference of the Austrian, German and Swiss Meteorological Societies in Vienna, Austria, in September 2001. The following five papers were presented in this session:

Jones, S. C.: The longevity of tropical cyclones in the mid-latitudes.

Möller, J. D.: The influence of atmospheric asymmetries on the intensity of tropical cyclones.

Shapiro, L. J.: The intensification of Hurricane Opal in a GFDL model forecast: Symmetric and asymmetric contributions.

Weber, H.: Tropical cyclone track forecasting with a barotropic model.

Weindl, H.: Numerical simulations to investigate the interaction of a tropical cyclone with an extratropical low-pressure system.

Theses

Nguyen C. M., 2001: A minima axisymmetric tropical cyclone model. (From Dept. of Mathematics and Statistics, Monash University, Australia, supervised in part from Munich and supported in part through this contract).