

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 numerical models for forecasting 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 anomalies using a three-layer model;
2. To continue our study of the dynamical processes in tropical cyclones responsible for looping or erratic motion;
3. To continue the development of methods for (a) the introduction of synthetic tropical-cyclone-scale vortices in operational forecast models and (b) ensemble forecasting of tropical cyclones;
4. To continue our study of the dynamics of the extra-tropical transition of tropical cyclones with emphasis on idealized modelling;
5. To continue our diagnosis of hurricane track and intensity change as predicted by the Geophysical Fluid Dynamics Laboratory (GFDL) model using the technique of potential vorticity inversion;
6. To continue a numerical modelling study of tropical-cyclone - trough interaction;
7. To continue a study of the factors which govern the size of tropical cyclones;
8. To continue a numerical modelling study of mid-level typhoons;
9. To continue a numerical and theoretical study of the spin down of tropical cyclone vortices;
10. To continue collaboration with the German Weather Service (DWD) and the Australian Bureau of Meteorology (BoM) to improve the prediction of tropical cyclones with the DWD's global model and BoM's regional model TC-LAPS;
11. To initiate an idealized numerical modeling study of hurricane - ocean interaction;

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12. To continue the development and testing of a new barotropic track prediction system for hurricanes, using different initialization strategies and initial data sets from different forecast centres; and
13. To initiate collaboration with Dr. J. Goerss of the Naval Research Laboratory (NRL) with regard to the operational application of the new system.

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 and on the extra-tropical transition of tropical cyclones with doctoral student, Ms. Helga Weindl); Dominique Möller, (working on diagnosing hurricane track and intensity changes as predicted by the GFDL model); Maria Peristeri (working on a modelling study of mid-level typhoons); Lloyd Shapiro (working on potential vorticity asymmetries and tropical cyclone evolution), Wolfgang Ulrich (working with diploma student, Ms. Erica Pires, 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 tropical-cyclone track prediction, and with doctoral student Markus Adams on the sensitivity of barotropic track prediction to different initialization strategies). The PI is working with doctoral student, Ms. Hongyan Zhu, and masters student, Ms. Nguyen Chi Mai from Monash University, Australia, on the development of an idealized hurricane model and on the hurricane boundary layer.

WORK COMPLETED

The paper on the dynamics of vortices in vertical shear has appeared in print (Smith *et al.*, 2000). Two further papers describing the evolution of vortices in vertical shear have been accepted for publication (Jones, 2000a, b).

The review paper on the role of cumulus convection in hurricanes and its representation in hurricane models (Smith, 2000) is in press. The paper includes a framework in which a number of existing schemes can be interpreted and compared.

A paper describing the results of the study of tropical cyclone evolution via potential vorticity (PV) asymmetries in a dry three-dimensional model has been accepted for publication and is in press (Möller and Montgomery, 2000).

A paper describing the results of the first study of the effect of PV asymmetries and tropical cyclone evolution in a moist three-layer model including convection has been accepted for publication and is in press (Shapiro, 2000).

The paper describing the case study of hurricanes *Felix* and *Iris* (1995) has appeared in print (Thorncroft and Jones, 2000).

We have completed a sensitivity study of the new three-level, three-dimensional hurricane model on which development began in 1999. The model has an option to include three different representations of cumulus convection. A paper describing the basic model was submitted to *The Journal of the*

Atmospheric Sciences in May 2000. The paper has been conditionally accepted for publication and the revised version has been submitted. An axisymmetric version of the model has been completed also.

Preliminary diagnoses have been completed of cyclone intensity change in GFDL-model forecasts of Hurricane Opal (1995).

Preliminary results have been obtained in continuing studies of the effect of PV asymmetries and tropical cyclone evolution in a moist three-layer model.

Based on the initialization procedure of TC-LAPS, we have developed a new barotropic hurricane track prediction system. A paper describing the new model has been submitted for publication (Weber, 2000).

We have continued to collaborate with Dr. Kamal Puri at BMRC to develop and test a variety of strategies for the ensemble forecasting of tropical-cyclones, using an older version of the BMRC's regional model LAPS.

We have developed a simple two-layer ocean model to predict sea surface temperature and upper thermocline temperature. The model is designed as a lower boundary condition for the idealized hurricane model.

We have continued to collaborate with Dr. Noel Davidson of the Australian Bureau of Meteorology Research Centre (BMRC) to improve the Bureau's Tropical Limited-Area Prediction System (TC-LAPS). A paper describing the results obtained from TC-LAPS has appeared in print (Davidson and Weber, 2000). The expert system of vortex initialization used in TC-LAPS is being adapted to the DWD's new operational global forecast model and aims at improving tropical cyclone track and intensity predictions with this model.

The proceedings of the workshop that we organized in 1999 on the extratropical transition of tropical cyclones have appeared as a World Meteorological Organization report (WMO, 2000). A review paper based on discussions at the workshop will be submitted for publication in late 2000.

In collaboration with Dr. Damià Gomis at the University of the Balearic Islands, Spain, and Dr. Mike Pedder at the University of Reading, England, we organized a workshop on 'Spatial objective analysis for diagnostic studies in meteorology and oceanography', which was held in Menorca, Spain from 18-22 September 2000 and sponsored in part by ONR. The aims were to review methods of spatial objective analysis of observations in the atmosphere and oceans, with particular attention to the interpretation of features sampled by experimental survey data, such as dropwindsonde soundings in hurricanes.

RESULTS

Based on successful semi-operational tests of the new TC-LAPS model (Davidson and Weber, 2000), the model has been used operationally at the BoM since the Australian tropical-cyclone season 1999/2000. With a mean position error of 250 km after 48 h prediction time in 1999/2000, TC-LAPS ranks as one of the best track prediction model and shows skill also in predicting tropical-cyclone intensity change.

The new barotropic tropical cyclone track prediction system has been tested in 167 cases of the 1996 Atlantic Hurricane season (Weber, 2000). With mean position errors of 129, 235 and 360 km after 24, 48 and 72 h, the new system shows skill relative to CLIPER, VICBAR and the official track guidance of the NHC (see Fig. 1). The mean position errors of the new system were comparable with those of the best numerical prediction model in 1996, the GFDL-model (Fig. 1). These results were confirmed by independent tests carried out by Dr. Goerss of the NRL. Using a homogeneous set of predictions, the new prediction system performed better than all other models used in 1996 at 24 and 48 h prediction time and almost as well as the GFDL-model at 72 h (mean position error difference: 4 km). Addition of the new prediction system to a prediction ensemble (the UKMO-model, the GFDL-model and NOGAPS) produced a 10%-improvement of the track prediction in comparison with the prediction ensemble without the new system and led to a reduction of the mean position error to 102, 169 and 241 km after 24, 48 and 72 h.

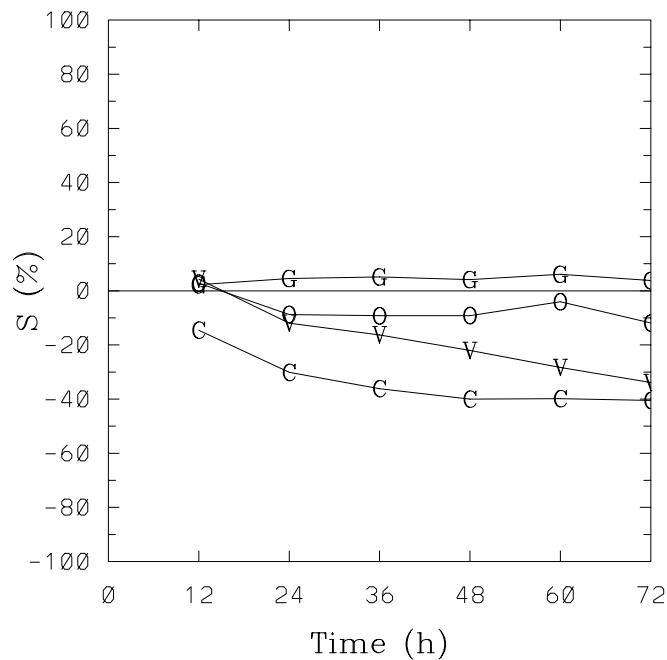


Fig. 1 Skill S in % (negative values represent better performance) versus prediction time of the new barotropic hurricane track prediction system relative to CLIPER (C), VICBAR (V), the GFDL-model (G) and the official NHC-forecasts (O). Values of S are computed using homogeneous sets of position errors for each of the other models of the 1996 Atlantic hurricane season.

We have investigated the spin-down of tropical-cyclone-like vortices in a stably-stratified fluid under the influence of surface friction. This study is relevant to the evolution of a tropical cyclone during extratropical transition. We have shown that the vortex near the surface spins down rapidly, leaving a vortex in the mid and upper troposphere that can survive for many days. Such a vortex could subsequently interact with an extratropical system resulting in extratropical development. The work on extratropical transition will be continued with studies of vortex spin-down in a model with resolved convection, idealized modeling of the interaction between tropical cyclones and fronts or baroclinic waves and an investigation of differences between extratropical transition in the North Atlantic and Northwest Pacific basins.

The new three-dimensional hurricane model has pointed to the possibility that rapid intensification of hurricanes is accompanied by a change in the character of deep convection in the inner core region from buoyantly-driven, predominantly upright convection to slantwise forced moist ascent. Both the three-dimensional and axisymmetric versions of the model have indicated a rather different dynamical picture of the hurricane boundary-layer structure compared with the conventional view. In the latter the boundary layer is seen as a quasi-steady flow in which the reduction of the tangential velocity component by friction leads to a breakdown of the horizontal force balance, leaving a net inward force in the layer. Our model calculations show that in the inner core region, the radial pressure gradient in the boundary layer is enhanced by the presence of buoyant air aloft. This allows air parcels to reach smaller radii than would be possible otherwise and permits the maximum tangential wind speed to be attained in the boundary layer, itself, instead of above the boundary layer as must be the case in the conventional view.

The completed study of vortex evolution via PV asymmetries in a dry three-dimensional model (Möller and Montgomery, 2000) established the role of radially- and vertically-propagating vortex Rossby waves in the development of a hurricane. The results confirmed that there exists an alternative means of tropical cyclone intensification to the symmetric mode. This study then relates directly to our continuing study diagnosing track and intensity change as predicted by the GFDL model. In this study PV inversion is being used to evaluate the impact of asymmetric PV anomalies, such as those associated with nearby troughs, on the development of the model hurricane vortex. Preliminary results from a case study of Hurricane Opal (1995) demonstrate some agreement between azimuthal-one wind vectors and total eddy fluxes derived from a PV inversion with the asymmetric balance theory (Shapiro and Montgomery, 1993) and those obtained from the observed fields (Persing *et al.*, 2000).

The completed first study of the role of potential vorticity (PV) asymmetries in the evolution of a tropical cyclone using a three-layer model (Shapiro 2000) confirmed the dominance of horizontal eddy fluxes at early times. It was shown that the interactions between the asymmetries and the symmetric hurricane vortex at early times depend on realistic features of the model hurricane, and not on interactions between the asymmetries and the boundary layer that possibly depend on the convective parameterization used. Continuing studies are being made of the dependence of the symmetric vortex response on the amplitude, location and structure of imposed asymmetric PV anomalies. A method has been developed for determining the vertical structure of a PV anomaly that is consistent with a diabatic source of arbitrary amplitude. Preliminary results indicate that the acceleration of a symmetric hurricane vortex is somewhat greater for a balanced initial condition than for an unbalanced forcing. In order to establish the robustness of the longer-term evolution of the model cyclone, two alternative surface-flux based convective parameterization schemes will be developed as alternatives to the present convergence-based one.

There are various models of the ocean mixed layer published, with different degrees of complexity. We have shown that the calculated SST response is essentially captured using one active layer and the upper thermocline temperature.

IMPACT/APPLICATIONS

The study of vortex spin-down has implications for the implementation of synthetic tropical cyclones in global models. When a tropical cyclone undergoes extratropical transition its structure becomes more

asymmetric and a vertical tilt may develop. If a synthetic tropical cyclone is constructed during extratropical transition the structure of the synthetic vortex will not adequately represent the real tropical cyclone structure. If the tropical cyclone remnants remain over a data sparse region, such as the North Atlantic or Northwest Pacific oceans, the subsequent forecasts may be adversely influenced by the synthetic vortex structure.

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. Intensity changes are currently forecasted by operational models with little skill.

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

The three-dimensional three-layer hurricane model will be used for 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. It has already provided new insights on the rapid intensification of hurricanes and on the dynamics of the hurricane boundary layer. Its coupling with the two-layer ocean model is expected to enhance our understanding of ocean feedback on hurricanes.

The success of the new barotropic hurricane track prediction system shows the potential of relatively simple models for providing valuable track guidance even after 48 h prediction time, in contrast to common opinion. The mean position errors produced by the new model recommend an application of the new system in operational context.

The continuing work on the initialization procedures of regional tropical-cyclone prediction models such as TC-LAPS shows the necessity of careful vortex specification and should lead to a further improvement of operational track and intensity forecasting.

TRANSITIONS

The new initialization procedure of TC-LAPS has been used operationally since the Australian tropical-cyclone season 1999/2000 and work continues to further improve the performance of TC-LAPS. In an effort to improve tropical-cyclone prediction with global models, work continues on the implementation and testing of the present vortex enhancement scheme in the new global model of the DWD.

The new barotropic track prediction system will be tested in semi-operational mode and on the basis of input fields provided by NOGAPS in collaboration with Dr. Goerss at NRL. Intensive semi-operational testing will commence in late 2000.

RELATED PROJECTS

The diagnosis of hurricane track and intensity changes in GFDL model predictions is being carried out in collaboration with the M. Montgomery group at the Colorado State University.

The work on extratropical transition of tropical cyclones is being carried out in collaboration with Dr. C. Thorncroft at SUNY, Albany and Dr. P. Harr at the Naval Postgraduate School, Monterey.

The work on the development of axisymmetric version of our new tropical cyclone model is being carried out in collaboration with by Nguyen Chi Mai, a masters student at Monash University in Australia.

The work on the vortex enhancement scheme for numerical prediction models is being carried out in collaboration with scientists of Dr. K. Puri's Group at the BMRC, especially with Dr. Noel Davidson, who is mainly responsible for the development and maintenance of TC-LAPS.

The work on the new initialization procedure for the DWD global model is being carried out in collaboration with Mr. D. Majewski and Dr. Prenosil of the DWD.

The semi-operational tests of the new barotropic tropical-cyclone track prediction system will be carried out in collaboration with Dr. Goerss at NRL. The system is being used also for experimental track forecasts of tropical cyclones in the Northwest Pacific region in collaboration with Mr. Le Cong Thanh, Ms. Do Le Thuy and Ms. Nguyen Thi Minh Phuong from the Vietnamese Hydrometeorological Service and Prof. Kieu Thi Xin and Dr. Phan Van Tan from the Meteorology Department at the Hanoi University of Science, Vietnam.

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- Weber H. C., and R. K. Smith, 2000: A monsoon depression over northwestern Australia: Part III Motion. *Aust. Meteor. Mag.*, **49**, 1-21.
- Weber, H. C., 2000: Hurricane track prediction with a new barotropic model. Submitted to *Mon. Wea. Rev.*
- Zhu, H., R. K. Smith and W. Ulrich, 2000: A minimal three-dimensional tropical cyclone model. Submitted to *J. Atmos. Sci.*

Conference papers

The following 10 papers were presented at the 24th AMS Conference on Hurricanes and Tropical Meteorology, held in Fort Lauderdale in May/June 2000:

Adams, M.: *Sensitivity studies with a new nested shallow-water model for tropical cyclone track prediction.*

Jones, S. C., and C. D. Thorncroft: *The longevity of tropical cyclone vortices after extra-tropical transition.*

Möller J. D.: *Diagnosing hurricane track and intensity change predicted by the Geophysical Fluid Dynamics Laboratory hurricane model.*

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

Nguyen, P, M. J. Reeder, N. Davidson and M. Adams: *Forecasting tropical cyclone motion near Vietnam using a nested barotropic model.*

Shapiro, L. J.: *Influence of potential vorticity asymmetries on a tropical cyclone in a moist three-layer model.*

Smith, R. K.: *Cumulus parameterization schemes for a minimal tropical cyclone model.*

Weber, H. C.: *Polygonal eye-walls in barotropic, hurricane-like vortices.*

Weindl, H., and R. K. Smith: *An investigation of the structure of hurricane Danielle (1998) using HRD dropwindsondes.*

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

Two papers were presented at the Royal Meteorological Society Conference 'Meteorology at the Millenium', which was held in Cambridge, England.

Smith, R.K. and L. J. Shapiro: *Contemporary problems on the dynamics of hurricanes.*

Zhu, H.: *A Minimal Three-Dimensional Tropical Cyclone Model*

Two papers were presented at the ONR-sponsored workshop on 'Spatial objective analysis for diagnostic studies in meteorology and oceanography', which was held in Menorca, Spain and appear as Extended Abstracts of the Workshop.

Smith, R. K.: *Estimating tropical cyclone structure from airborne surveys.*

Weber, H.: *Analysis and initialization of tropical cyclones.*

Sarah Jones presented a paper at the Cyclone Workshop, 28.8-1.9.2000 in Monterey, CA entitled: *The structure of ex-hurricanes in the eastern Atlantic*

Theses

Jakob, C., 2000: *The representation of cloud cover in atmospheric general circulation models.* Doctoral Thesis, University of Munich.

Aichinger, M., 2000: *Modellierung historischer und aktueller Windfelder von Taifunen und tropischen Stürmen im Nordwestpazifik, sowie Erstellung einer Gefährdungsanalyse für den nordwestpazifischen Raum.* (Modelling historical and contemporary wind fields of typhoons and tropical storms in the Northwest Pacific region and construction of a hazard analysis for the region). Diploma Thesis, University of Munich.

Nguyen, P, 2000: *Forecasting tropical cyclone motion near Vietnam using a nested shallow water barotropic model.* (From Dept. of Mathematics and Statistics, Monash University, Australia, supervised in part from Munich and supported in part through this contract).

Pires, E., 2000; *A simple ocean mixed layer model for coupled hurricane - ocean studies.* Diploma Thesis, University of Aveiro, Portugal (Diploma work carried out at the University of Munich under this project).