# 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 extratropical transition of tropical cyclones (ET) using idealized modeling;

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 the development of new concepts and methods for the construction of synthetic tropical cyclones in operational prediction models and in ensemble forecast models;

5. To continue work on improving the quality of the operational Probabilistic Ensemble System for the prediction of Tropical cyclones (PEST) in the U. S. Navy's Automated Tropical Cyclone Forecasting System (ATCF); and to continue work on the Statistical Ensemble Prediction System STEPS;

6. To continue work on the improvement of the operational barotropic tropical-cyclone track prediction model WBAR in the ATCF System and on an ensemble version thereof;

7. To continue a study of ET in the European Centre for Medium-Range Weather Forecasts' ensemble prediction system.

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14. ABSTRACT
**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.**

15. SUBJECT TERMS

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## 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 ET with doctoral students, Ms. Doris Anwender, Mr. Michael Riemer and Ms. Helga Weindl); and Harry Weber (working on topics related to operational tropical-cyclone track and intensity prediction). The PI is working with Dr. Hongyan Zhu (University of Reading) on a modelling study of tropical cyclones, with doctoral students; Mr. Sang Nguyen and Mr. Bui Hoang Hai (Hanoi University of Science) on a comparative study of hurricane growth in a variety of model configurations and on a modelling study of midget typhoons; and with Ms. Steffi Vogl on the development of a new steady-state model for a hurricane. Wolfgang Ulrich, who has been working on the factors that govern the size of hurricanes, died tragically on 19 September after a long illness.

## WORK COMPLETED

The following papers have been accepted for publication or have appeared in print: Smith *et al*. (2005), on buoyancy in rapidly-rotating atmospheric vortices; Smith (2005a), on an accurate scheme for determining the balanced density field associated with an axisymmetric vortex; Smith (2005b) concerning the dynamics of the hurricane eye; Sampson et al. (2005), on the operational performance of the barotropic tropical-cyclone track forecast model WBAR during 2003/2004; Weber (2005a, b), on the probabilistic tropical-cyclone position and intensity prediction model PEST; Röbcke et al. (2003), on a potential-vorticity perspective of the ET of Hurricane Erin in 2001.

## RESULTS

We have shown that a near-surface cooling on the order 5$^{o}$C in the inner core of a hurricane may be accounted for simply with the assumption of gradient wind balance: it is not necessary to invoke processes such as the evaporation of spray to account for the typical observed cooling. We have devised a way to combine the simple hurricane boundary layer model of Smith (2003) with the constraint that absolute angular momentum surfaces and moist isentropic surfaces coincide above the boundary layer as suggested by Emanuel (1986). The latter assumption allows the tangential wind speed distribution above the boundary layer to be determined as part of the solution. Calculations to investigate the steady hurricane model that emerges are in progress. We have examined the evolution of an initially symmetric vortex on an f-plane using the Pennsylvania State University/National Center for Atmospheric Research fifth-generation Mesoscale Model (MM5) (Grell, et al. 1994) with minimal physics (a bulk-aerodynamic boundary-layer drag formulation, the simplest representation of latent heat release). Asymmetries develop when the first grid boxes moisten. With relatively coarse horizontal resolution (15 km) the initial asymmetry has an azimuthal wavenumber-4 pattern because of the rectangular grid, but as the resolution becomes finer, the azimuthal wavenumber of the initial asymmetry increases. This behaviour is illustrated in Fig. 1, which shows relative vorticity fields at 700 mb after 15 h of integration in the calculation with 15 km resolution and after 8 h of integration in a run with 5 km resolution. We have found that the asymmetry is not a result of barotropic instability of the initial vortex as has been suggested by previous authors (e.g. Wang, 2002), but rather a result of convective instability that is focussed in an annulas on account of the increase in surface moisture flux with increasing wind speed. Irrespective of the grid resolution, the convective cores, which are also cores of enhanced rotation, progressively merge to form a monopole vortex with a pronounced wavenumber-2 asymmetry.  Together with C. Sampson and J. Goerss of the U. S. Naval Research Laboratory (NRL), the barotropic tropical-cyclone track prediction model WBAR (Sampson et al. 2005) has been modified and updated for operational use at the U. S. Joint Typhoon Warning Center (JTWC) during the 2005 typhoon season. In particular, the model initialization procedure has been improved following a large number of sensitivity tests using NOGAPS (the U. S. Navy's Operational Global Atmospheric Prediction System) analyses and forecasts, which form the boundary and initial conditions of WBAR.

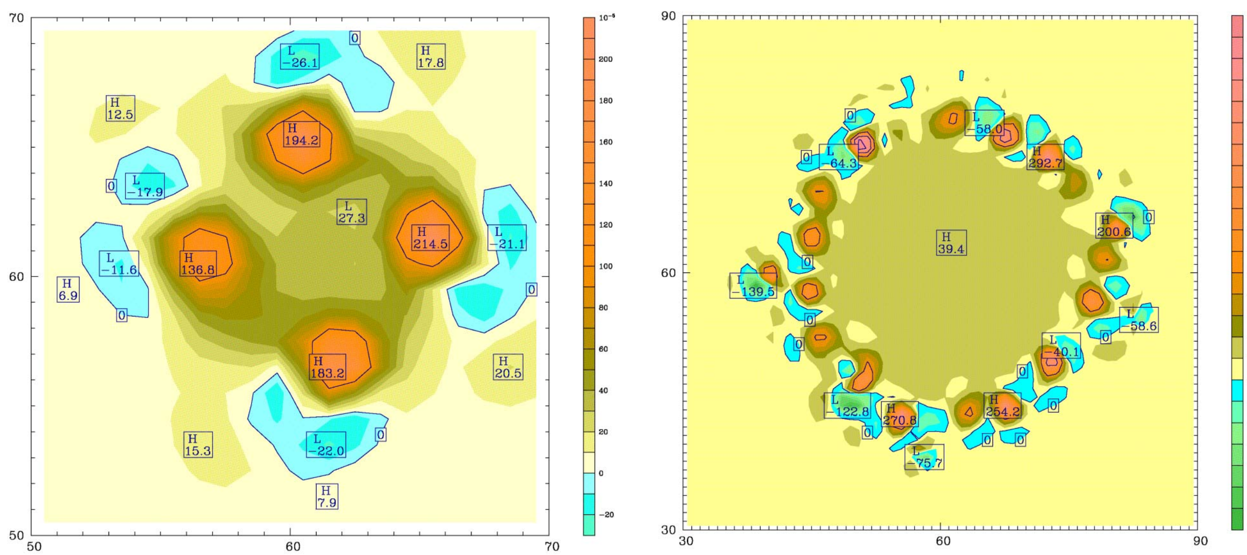


***Figure 1. Relative vorticity at 700 hPa in the core region of domain size 300 km $\times$ 300 km in  a 15 h simulation with a 15 km grid size(left panel) and an 8 h simulation with a 5 km grid size (right panel). Tick marks refer to grid points. Except for the horizontal resolution, the calculations are identical.***

The probabilistic and deterministic tropical-cyclone position and intensity prediction model PEST (Weber 2005a, b) has been implemented in the Automated Tropical Cyclone Forecast System (ATCF; Sampson and Schrader 2000) and has been used operationally for the Northwest Pacific Ocean since May 2004. With annual mean position errors of 131, 229, 336, 438 and 580 km at 24, 48, 72, 96 and 120 h prediction time, it represented one of the best deterministic position prediction models during 2004. This is shown in the homogeneous model comparisons (i. e. skill) of Fig. 2 (upper panel). With corresponding annual mean intensity errors of 7.3, 11.6, 13.6, 16.2 and 16.8 m $s^{-1}$, the deterministic PEST intensity predictions showed approximately the same skill (Fig. 2, lower panel) as all operationally-available consensus models (CON_, CONG, CONU, CONW; cf. Goerss et al. 2004). The PEST model has been modified and updated for use in the 2005 typhoon season. A paper on the operational performance of PEST during 2004 is in preparation.  We have continued our full physics idealized modeling study of ET using MM5 to explore the variability in both the structure of a tropical cyclone undergoing ET and in the interaction of the tropical cyclone with the downstream flow. We have added a tropopause perturbation to the initial conditions so that a family of extratropical cyclones develops and have included barotropic shear to give different life-cycle evolutions. The results show a modification of the midlatitude tropopause by the low-potential-vorticity outflow from the tropical cyclone. Potential-vorticity inversion is being applied to quantify this interaction.

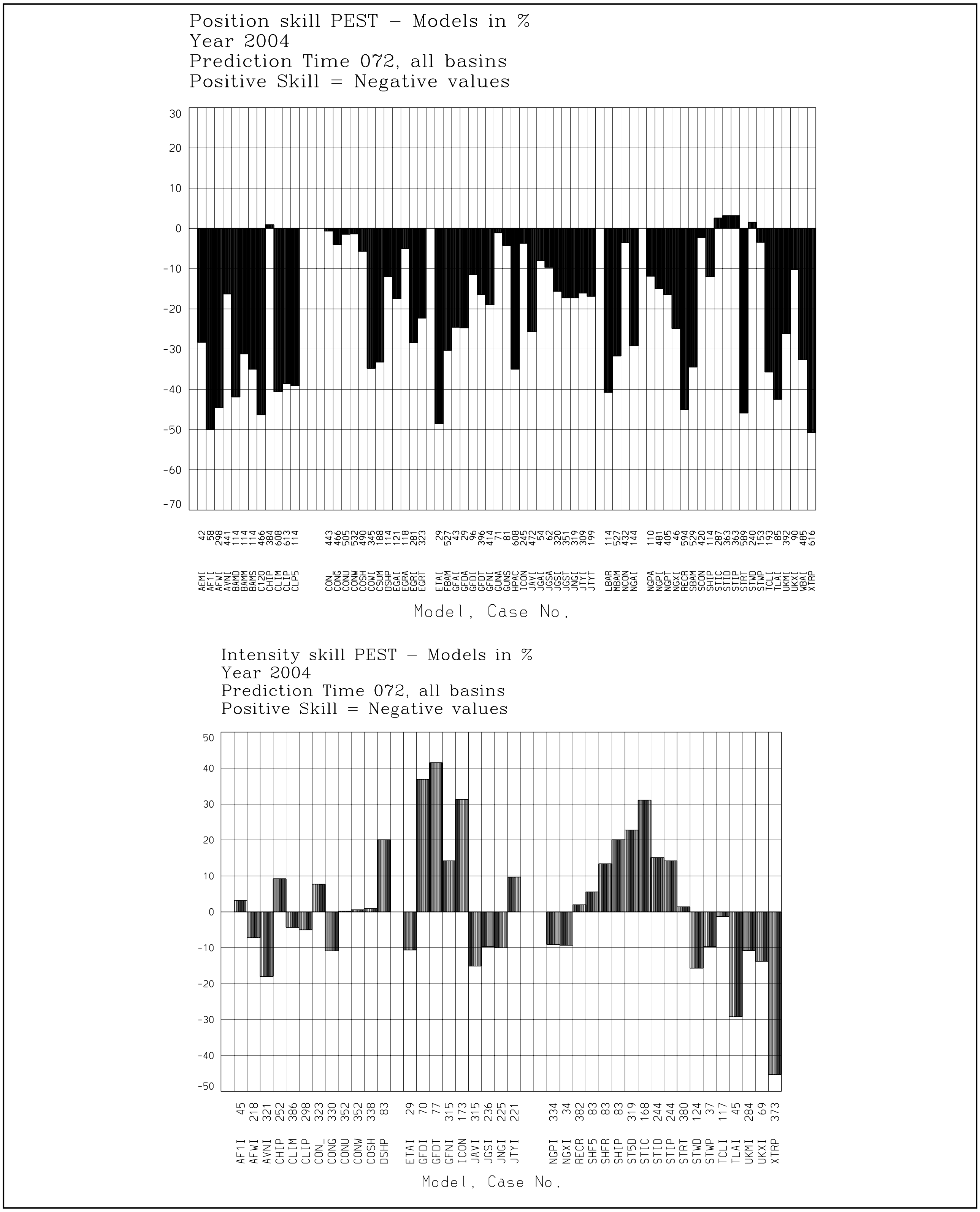


***Figure 2: Mean annual skill (relative error in %, negative values denote positive skill) at 72 h prediction time of the deterministic position (upper) and intensity (lower panel) predictions of the operational version of PEST versus all operational models during 2004.***

a) b)

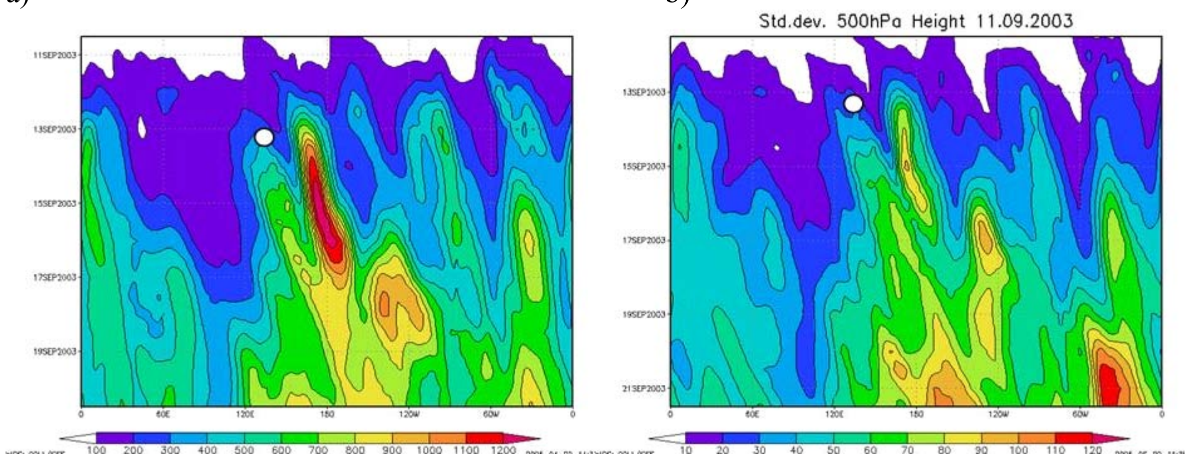


***Figure 3: Hovmöller plot of standard deviation of 500hPa height for control forecast and 50 perturbed forecasts initialized on (a) 10 September 2003 and (b) 11 September 2003.***

In order to investigate the variability of the members of the European Centre for Medium Range Weather Forecasts (ECMWF) ensemble prediction system in association with ET we have analyzed cases in the western North Pacific using the principal component (PC) analysis and clustering techniques developed by P. Harr. Increased standard deviation of the ensemble members is seen both in the region of the ET event itself and directly downstream. For example, for Typhoon Maemi in 2003 (Fig. 3), the region of increased standard deviation originating near 130$^{o}$E is due to different representations of the ET of Maemi. The mid-Pacific high standard deviation is associated with the variability of a downstream trough.

The EOF and cluster analysis applied to the forecasts of the potential temperature on the dynamic tropopause (defined as the potential vorticity = $2\times10^{-6}\ \mathrm{m^2\,K\,kg^{-1}\,s^{-1}}$ surface) verifying on 14 September and initialized on 10 September isolates five synoptic patterns associated with the ET of Maemi. Here in the interests of brevity only three of them are shown. In all of these clusters, Typhoon Maemi can be seen over the southern half of Japan, but the intensity and precise location differs between the clusters. For the smallest cluster (Fig. 4a) there is a markedly zonal midlatitude flow. Maemi is very weak and the remnants of the storm decay further because there is no trough in the midlatitude flow that Maemi could interact with. The downstream low, however, undergoes a very strong intensification at a later time. The cluster mean in Fig. 4b shows the upstream trough steering Maemi north-eastwards, and interacting with Maemi leading to a weak reintensification. At a later time the downstream low is squashed and disappears. The third cluster (Fig. 4c) shows a rapid and strong reintensification of Maemi after the upstream trough wrapped up cyclonically. Here the downstream low first intensifies moderately and then weakens. It remains separate from Maemi.

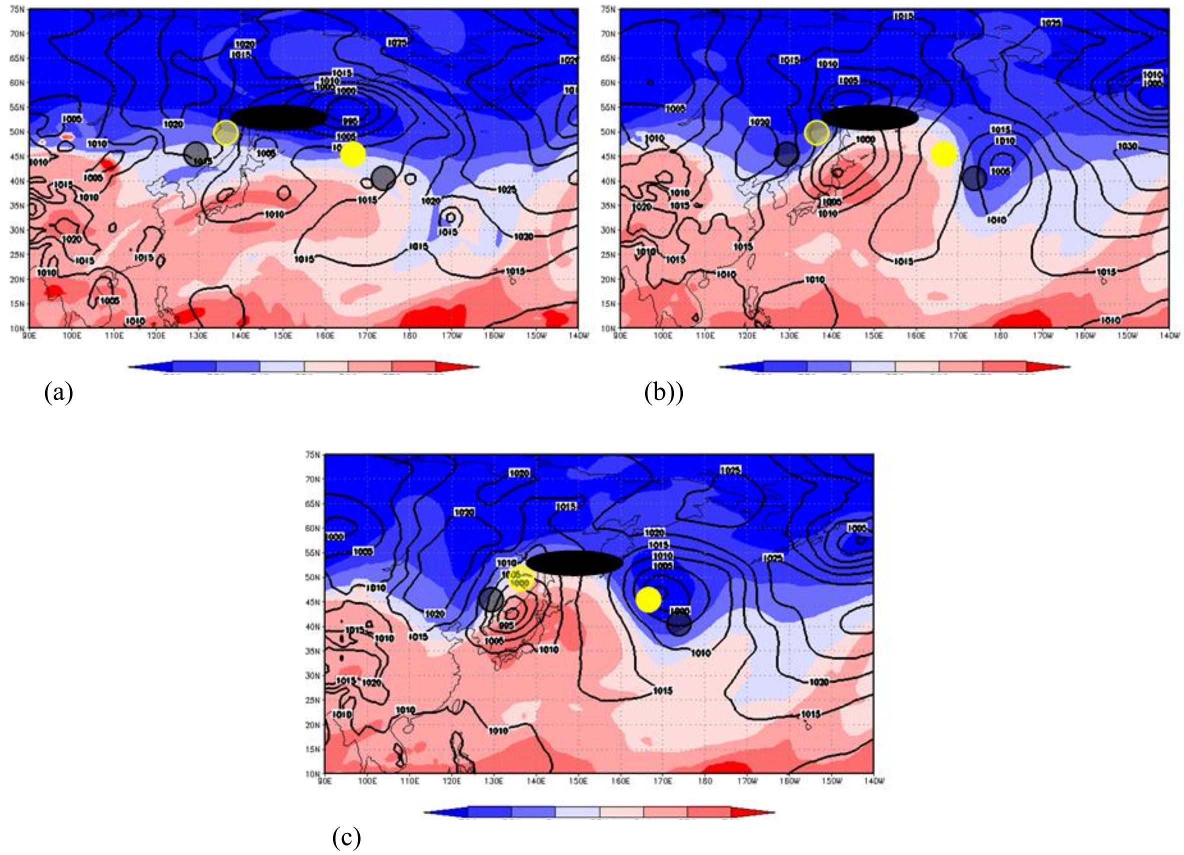


***Figure 4: Cluster mean potential temperature on the dynamic tropopause (color) and surface pressure (contours) for an ensemble forecast initialized on 10 September 2003 12 UTC, verifying 14 September 00 UTC. Clusters are shown with (a) 2 members (b) 11 members (c) 10 members. The colored shapes indicate the maxima (filled dots) and minima (shaded dots) of EOF1 (yellow) and EOF2 (black).***

**IMPACT/APPLICATIONS**

Our work on extending the boundary layer model of Smith (2003), on the consequences of gradient wind balance in hurricanes (Smith 2005a), and the MM5 simulations of idealized hurricanes and their extratropical transition are contributing to improvements of our basic understanding of storms.

Since May 2003, the tropical-cyclone track prediction model WBAR has been used operationally by JTWC as an independent model and as a member of the consensus model CONW. In the latter case, WBAR currently represents one of the models with the greatest positive impact on the general quality of the consensus forecasts (cf. Sampson et al. 2005).

The PEST model has been implemented for operational use in May 2004 and produces track and intensity guidance of high quality (cf. Fig. 1). The probabilistic position forecasts were made available to forecasters in the form of a graphical interface showing geographical strike probability regions of model prediction uncertainty in the ATCF-System.

Together with scientists from the NRL and the Australian Bureau of Meteorology Research Centre (BMRC), new methods of vortex enhancement in BMRC's regional numerical model TC-LAPS (Tropical-Cyclone Limited-Area Prediction System) are being developed in an effort to improve its track and intensity prediction of tropical depressions, tropical storms and storms undergoing extratropical transition.

The investigation of ET in the ECMWF ensemble prediction system will contribute to the development of improved diagnostics to aid in the forecasting of ET events.

## TRANSITIONS

The tropical-cyclone prediction model TC-LAPS is being used operationally since 1999 and has been incorporated recently in the consensus model used at JTWC. The track prediction model WBAR has been running operationally as an independent model and in the framework of the consensus model in the Northwest Pacific since May 2003. The probabilistic and deterministic tropical-cyclone prediction model PEST was implemented for operational use in May 2004.

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## PUBLICATIONS

Röbcke, M., S.C. Jones, and D. Majewski, 2004: The extratropical transition of Hurricane Erin (2001): a potential vorticity perspective. *Meteorol. Z.,* **13,** 511-525. [published, refereed]

Sampson, C. R., J. S. Goerss and H. C. Weber, 2005: Operational performance of a new barotropic model (WBAR) in the western north Pacific basin. *Wea. Forecasting,* [in press, refereed]

Smith, R. K., 2005a: Accurate determination of a balanced axisymmetric vortex in a compressible atmosphere. *Tellus A,* [in press, refereed].

Smith, R. K., 2005b: "Why must hurricanes have eyes?" revisited. *Weather*, [in press, refereed]

Smith, R. K., M. T. Montgomery and H. Zhu, 2005: Buoyancy in tropical cyclones and other rapidly rotating atmospheric vortices. *Dyn. Atmos. Oceans,* **40**, 189-208. [published, refereed].

Weber, H. C., 2005a: Probabilistic prediction of tropical cyclones, Part I: Position. *Mon. Wea. Rev.* **133**, 1840-1852. [published, refereed].

Weber, H. C., 2005b: Probabilistic prediction of tropical cyclones, Part II: Intensity. *Mon. Wea. Rev.* **133**, 1853-1864. [published, refereed].

**Conference papers**:

Four papers were presented at the European Geophysical Union General Assembly 2005 held in Vienna, Austria, in April 2005:

Anwender, D., P. Harr, and S. C. Jones: Diagnosing the extratropical transition of tropical cyclones using ensemble forecasts.

Jones, S. C.: The extratropical transition of tropical cyclones: a potential vorticity perspective (invited presentation).

Jones, S. C., D. Anwender, D. Majewski, M. Riemer, and M. Roebcke: The downstream impact of the extratropical transition of tropical cyclones.

Riemer, M., and S. C. Jones: Tropical cyclone - baroclinic wave interaction in idealized moist simulations.

**HONORS/AWARDS/PRIZES**

Mr. Michael Riemer was awarded a Rupert Ford Travel Award (awarded annually to young scientists who show great promise) to collaborate with Prof. D. Keyser at the State University of New York at Albany.