# Dynamical Control of Rapid Tropical Cyclone Intensification by Environmental Shears

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## LONG-TERM GOALS

The long-term goal of this project is to advance our understanding of the fundamental mechanisms of formation and explosive intensification of tropical cyclones (TCs). Of particular interests are the roles and interactions of the environmental shears and TC internal dynamical processes in changing TC intensity and TC formation.

## SCIENTIFIC OBJECTIVES

Improve our understanding of the physical processes by which (a) 3-D environmental shears, in particular the low-level meridional shear and upper-level vertical shear affect inner core structure and intensity, and (b) the mesoscale vortices, outer spiral rainbands, inner spiral rainbands, and the eyewall interact and affect TC development and intensity change.
General questions to be addressed include: (a) How is the asymmetric structure generated in association with the environmental forcing? (b) How does the change of the structure affect TC intensity? (c) What are favorable environmental conditions for the tropical cyclone formation and rapid intensification in the western North Pacific? (d) How do changes in the environment control the movement and formation in the western North Pacific region?

## APPROACH

Our approach is to combine observational analysis, numerical modeling, and diagnostic analysis of the physical mechanisms. This strategy include:

1. Analyzing observed data to identify environmental controls and internal structure changes in the (a) rapid development of tropical depressions into a tropical storm (TS formation), and (b) explosive intensification of tropical storms;

2. Designing and performing numerical experiments with a realistic hurricane model (TCM3) to reveal major processes by which the environmental forcing affects the structure and intensity.

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14. ABSTRACT
**The long-term goal of this project is to advance our understanding of the fundamental mechanisms of formation and explosive intensification of tropical cyclones (TCs). Of particular interests are the roles and interactions of the environmental shears and TC internal dynamical processes in changing TC intensity and TC formation.**

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3. Developing diagnostic tools for studying energetics, potential vorticity, angular momentum, and heat and moisture budgets. The budget diagnostics will help elucidate internal dynamic processes in the core region that could alter the thermodynamic efficiency of the TC intensification.

4. Conduct real case and climate simulation of the TC track and intensity using MM5 and focusing on the western North Pacific region.

## WORK COMPLETED

This project has involved an integrated effort of a group of people (PI, Co-PIs and graduate students, Justin Ventham, Kevin Mallen, Bo Yang, Bing Fu, and Tom Dunn). Major works that have been completed or have a draft manuscript in preparation for publication are summarized here.

1) Large scale flow patterns and their influence on the intensification rates of western north Pacific tropical storms
2) Analysis of Rossby wave energy dispersion in TC genesis in the western North Pacific
3) Some issues related to TC initialization with bogus data assimilation
4) Re-examining tropical cyclone near-core radial structure using aircraft observations: Implications for vortex resilience.
5) Impacts of air-sea interaction on TC motion and intensity
6) The effect of internally generated inner core asymmetric structure on tropical cyclone intensity

## RESULTS

### 1. Large scale flow patterns and their influence on the intensification rates of western north Pacific tropical storms

Large-scale environmental flow patterns around future intensifying tropical storms are identified with the goal of finding the most favorable low-level flow fields for rapid intensification. The analysis is, based on the hypothesis that aspects of the horizontal flow may affect tropical cyclone intensification at the early stage. A new initial intensity-based definition of rapid intensification is proposed and is used to define very rapid, rapid and slow 24hr intensification periods from weak tropical storm stage (35kts). By using composite analysis and scalar EOF analysis of the zonal wind around these subsets, a form of the lower level (850mb) monsoon confluence pattern is found to occur dominantly for the very rapid cases. Overall differences in the flow fields for slow and rapid subsets are less significant at lower levels (850mb). At 200mb the importance of the location of the incipient tropical storm directly under a region of flow splitting into the mid-latitude westerlies to the north and the sub-equatorial trough to the south is identified as a common criterion for the onset of rapid intensification [as well as an eastward extension of outflow south of the TUTT]. The total 200mb slow composite exists in an upper level environment with north-easterlies over the lower level tropical storm, and without outflow to the north. Cases that rapidly intensified form 60kt initial intensity are also shown to exhibit a signal for preferred confluence patterns occurring for very rapidly intensifying storms within the subset. Cases in which interaction with an upper level trough to the north-west occurred prior to intensification are identified and the sequence of events is found to be very similar to the prior

Atlantic tropical cyclone-trough interaction studies, where a small scale potential vorticity anomaly approaches but never quite crosses the tropical cyclone circulation below. This provides more confidence in the possible universal occurrence of this sequence of events, as has been well studied in the Atlantic

**2. Analysis of Rossby wave energy dispersion and cyclogenesis.**

The structure and evolution characteristics of Rossby wave trains owing to TC energy dispersion are revealed based on the QuikSCAT and TRMM TMI data. Among 34 cyclogenesis cases analyzed in the western North Pacific during 2000-2001 typhoon seasons, 6 cases were associated with the Rossby wave energy dispersion of a pre-existing TC. The wave train is oriented in a northwest-southeast direction, with alternating cyclonic and anticyclonic vorticity circulation and a typical wavelength of 2500km. A new TC is observed to form in the cyclonic circulation region of the Rossby wave train through a scale contraction process. Not all TCs have Rossby wave trains in their wakes. The occurrence of the wave train depends, to a certain extent, on the TC intensity (size) and the basic flow. For those TCs that have the Rossby wave train, not all wave trains finally lead to the generation of a new TC in the wake. It depends crucially on the large-scale background field that includes the effect of ISO. A strong low-level convergence, a positive mid- to low-level vorticity and a deep moisture layer are among favorable large-scale conditions.

**3. Some issues related to TC initialization with bogus data assimilation**

Issues on the initialization and simulation of tropical cyclones (TCs) have been studied based on observing systems simulation experiments (Yuqing Wang in collaboration with C.-C. Wu). In particular, experiments have been carried out to assess: (1) what are the most critical parameters for the so-called bogus data assimilation; and (2) how the current procedures on the bogus data assimilation can be further improved. Two key findings are established from this study. (1) The assimilation of wind field is more effective than the assimilation of pressure field. This is because the scale of the TC vortex is much smaller than the radius of Rossby deformation and thus the geostrophic adjustment favors the pressure field to adjust to the wind field. Our results suggest that a better initial condition in the wind field is critical to the simulation of TCs; (2) Inclusion of the initial TC movement during the data assimilation window can help improve the track prediction, particularly at the early integration period. This method sheds some light on the improvement of TC simulation based on the bogus data assimilation.

**4. Tropical cyclone near-core radial structure: Implications for vortex resilience**

Recent theoretical studies, based on vortex Rossby wave (VRW) dynamics, have established the importance of the radial structure of the primary circulation in the response of tropical cyclone (TC)-like vortices to ambient vertical wind shear. Linear VRW theory suggests, in particular, that the degree of broadness of the primary circulation in the near-core region beyond the radius of maximum wind (RMW) strongly influences whether a tilted TC vortex will realign and resist vertical shear or tilt over and shear apart. Fully nonlinear numerical simulations have verified that the vortex resiliency is indeed sensitive to the initial radial structure of the idealized vortex. This raised the question of how well the "true" nature of a TCs' resiliency is represented by idealized vortices that are commonly used in some theoretical studies. In this paper the swirling wind structure of TCs is re-examined by utilizing flight-level observations collected from Atlantic and eastern Pacific storms during 1977-2001. Hundreds of radial profiles of azimuthal-mean tangential wind and relative vorticity are constructed from over five thousand radial flight leg segments and compared with some standard idealized vortex profiles. This analysis reaffirms that real TC structure is characterized by relatively slow tangential wind decay in conjunction with a skirt of significant cyclonic relative vorticity possessing a negative radial gradient. This broadness of the primary circulation is conspicuously absent in some idealized vortices used in theoretical studies of TC evolution in shear. The relationship of the current findings to the problem of TC resiliency is discussed.

**5. Impacts of air-sea interaction on TC motion and intensity**

The influence of TC-ocean coupling on TC motion and intensity is investigated through idealized numerical experiments with a coupled TCM3-ocean model. It is found that the symmetric sea surface cooling is primarily responsible for the weakening of TC because the asymmetric circulation induced by the asymmetric SST anomalies is weak and shallow. The track differences between the coupled and uncoupled runs are generally small due to competing processes. The asymmetric SST anomalies decrease surface heat fluxes in the rear but increase the fluxes in the front. As such, the enhanced diabatic heating is located to the southern side for a westward-moving TC, tending shift the TC southward. On the other hand, the weakening of the TC outer flow strength leads to weakening of the beta drift, which leads to a more northward propagation.

**6. The effect of internally generated inner core asymmetric structure on tropical cyclone intensity**

In an *f*-plane quiescent environment, the internal dynamics of a tropical cyclone (TC) can generate axially asymmetries in the inner core region. The effect of these internally generated inner core asymmetries on TC intensity is investigated through comparison of the results obtained from a three-dimensional (3D) TC model (TCM3) and its axisymmetric version (2D). Both the 3D and 2D models have identical model structure and use the same set of parameters; both are integrated from the same initial conditions. Thus the differences between the two runs are interpreted as the results of the TC asymmetries. The results show that the presence of asymmetries in the 3D run reduces the TC final intensity by about 15%. Such an intensity reduction is explained in terms of the effects of the inner core asymmetries on the TC symmetric structure and thus the intensity. In the 2D run, the convective heating in the eyewall generates an annular tower of high potential vorticity (PV) with relatively low PV inside the eyewall. Under the tilted eyewall the downdrafts induced by evaporation of rain and melting of snow and graupel make the subcloud-layer inflows dry and cool, which lowers the boundary layer equivalent potential temperature (EPT), thus increasing the entropy difference between the air and sea in the vicinity of the radius of maximum wind (RMW). The increased air-sea entropy deficit leads to a greater final intensity. On the other hand, in the 3D run, significant inward PV mixing from the eyewall into the eye results in a less tilted eyewall, which in term limits the drying and cooling effects of downdrafts in the subcloud layer and reduces the air-sea entropy deficit under the eyewall, thereby reducing the TC intensity. The angular momentum budget analysis shows that the asymmetric eddies tend to reduce the strength of the primary circulation in the vicinity of the RMW.

## IMPACT/APPLICATIONS

The 4-D VAR assimilation method studied by Wu et al. (2005) sheds some light on the improvement of TC simulation based on the bogus data assimilation. The novel approach of assessing the tropical cyclone track change in the GCM predictions of the future climate change can be applied to multi-model ensemble prediction of the future change of TC tracks.

## TRANSITIONS

TCM3 tropical cyclone model has been installed at the National Taiwan University. Our state-of-the-art cloud microphysics package has also been successfully implemented into our IPRC regional climate model and updated at BMRC operational forecast system. Our coupled model has been used by Florida State University to investigate the air-sea coupling process and its impacts on TC intensification.

## PUBLICATIONS

The following publications during FY 2005 are supported or partially supported by this grant.


Li, T., 2005: Origin of summer synoptic-scale wave trains in the western North Pacific. *J. Atmos. Sci*., in press.

Li, T., and B. Fu, 2005: Tropical cyclogenesis associated with Rossby wave energy dispersion of a pre-existing typhoon. Part I: Satellite data analyses. *J.Atmos.Sci*., in press

Li, T., X. Ge, B. Wang, and Y. Zhu, 2005: Tropical cyclogenesis associated with Rossby wave energy dispersion of a pre-existing typhoon. Part II: Numerical simulations. *J.Atmos.Sci*., in press..

Li, T., and B. Wang, 2005: A review on the western North Pacific monsoon: synoptic-to-interannual variabilities. *Terrestrial, Atmospheric and Oceanic Sciences*, **16**, 285–314.

Mallen, K. J., M. T. Montgomery, and B. Wang, 2005: Re-examining tropical cyclone near core radial using aircraft observations: Implications for vortex resilience. *J.Atmos.Sci*., **62,** 408-425.

Tam, C.-Y. and T. Li, 2005: The origin and dispersion characteristics of the observed summertime synoptic-scale waves over the western Pacific. *Mon.Wea.Rev*., in press.

Ventham, J., and B. Wang, 2005: Large scale flow patterns and their influence on the intensification rates of western north Pacific tropical storms. *Mon.Wea.Rev.,* (revised).

Wu, C.-C, K-H Chou, Y. Wang, and Y-H Kuo, 2005: Tropical cyclone initialization and prediction based on four-dimensional variational data assimilation. *J. Atmos. Sci*., (revised).

Wu, L., B. Wang, and S. A. Braun, 2005: Impacts of the sir-sea interaction on tropical cyclone motion and intensity. *J. Atmos. Sci*., in press.

Yang, B., Y. Wang, and B. Wang, 2005: The effect of internally generated inner core asymmetries on tropical cyclone intensity, *J. Atmos. Sci*., (revised).

**Submitted Manuscripts**

Yang, B., B. Wang, and L. Wu 2005: How do meridional shears of environmental flows affect tropical cyclone intensification? Part I: Basic mechanism. Submitted to *J. Atmos. Sci*..

**DISSERTATION AND THESIS**

**Ph D**:
**Justin Ventham,** Fall 2005, Department of Meteorology, University of Hawaii
Dissertation title: **Large scale environmental wind patterns and the intensification rates of western north Pacific tropical storms**
Advisor: Bin Wang