Tropical Cyclone Structure And Motion

Elizabeth A. Ritchie
Department of Meteorology, Code MR/Ri
Naval Postgraduate School
589 Dyer Rd., Room 254
Monterey, CA 93943-5114
Telephone: (831) 656-3430, fax: (831) 656-3061, email: ritchie@nps.navy.mil

Additional Principle Investigator: R. L. Elsberry
N0001400WR20176

LONG-TERM GOALS

To improve tropical cyclone track and intensity prediction through a research program combining high resolution modeling and detailed observational studies to investigate physical processes by which the motion and structure of a tropical cyclone are modified.

OBJECTIVES

The objective is to investigate the physical processes that occur as a tropical cyclone interacts with the environment such that motion and structure changes occur. Specific interactions being studied are with baroclinic environments in the tropics and in the midlatitudes during extratropical transition, and with topography as a tropical storm makes landfall. As a storm makes landfall, significant asymmetries in the low-level wind structure are expected to develop with marked impact on precipitation and wind damage patterns. During extratropical transition, radical changes to the storm structure occur as the warm core is eroded by vertical wind shear and intruding cold, dry air from the midlatitudes. Re-intensification to a strong midlatitude system is possible, and to further complicate matters, passage over islands with significant topographic features can occur during this transitioning process. In cases in which forecast models poorly predicted the motion and re-intensification of the storm during these transitional periods, better understanding of these processes should improve motion and intensity forecasts.

APPROACH

Due to the scarcity of detailed observations in regions where tropical cyclones develop and move, high-resolution, idealized modeling is combined with observations in all studies described here. The degree of physical complexity included in current mesoscale models allows detailed examination of environmental and small-scale impacts on the motion, structure, and intensity of tropical cyclones. However, caution must be taken when applying cause and effect arguments to describe the complex physical interactions that develop in these high-resolution models since they may be a product of the model parameterizations rather than realistic physical processes. Thus, a tiered approach is employed in which understanding of basic processes comes first and is built upon by gradually adding to the complexity of the modeling system, while isolating each physical process in turn. The U.S. Navy's coupled ocean-atmosphere mesoscale prediction system (COAMPS) is the primary model used in ongoing studies into landfall and extratropical transition effects on tropical cyclone motion and

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**

4. TITLE AND SUBTITLE **Tropical Cyclone Structure And Motion**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Meteorology, Code MR/Ri,,Naval Postgraduate School,589 Dyer Rd., Room 254,,Monterey,,CA,93943**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

structure. Where available, detailed observations such as those available from the ONR-sponsored TCM-92 and TCM-93 field experiments are used to verify processes examined in the model experiments.

WORK COMPLETED

Simulations using the PSU/NCAR mesoscale model investigated the possible role of mesoscale convective systems in producing tropical cyclone track deflections. New diagnostics were developed to aid in this effort. A journal article (Ritchie and Elsberry 2000) from this study was published in the Monthly Weather Review.

Simulations using COAMPS investigated the influence of topography and midlatitude baroclinic environment on the structure of TY Peter. First-guess fields and boundary conditions were provided from the Navy Operational Global Prediction System at 1-degree latitude/longitude resolution and interpolated to the high-resolution domains used in COAMPS. Additional observations including high-resolution cloud-drift and water vapor winds were assimilated into the analysis to test the impact of better resolving mesoscale features in the initial fields. Sensitivity studies were conducted by varying the degree of idealization of topography in the model.

Simulations using COAMPS investigated the structural changes that occur as a simulated tropical cyclone interacts with an idealized midlatitude baroclinic zone. Idealized initial conditions for three environments were created based on composite wind fields at each of the three steps of transformation of a tropical cyclone identified in Klein et al. (2000). The environmental mass fields were then calculated using geostrophic and hydrostatic balance. The three-dimensional tropical cyclone wind field was spun-up from analytic wind fields with the initial mass fields calculated using gradient wind and hydrostatic balance. Boundary conditions were calculated directly from the idealized fields and held constant at the initial values through the simulation. The structural changes of the simulated tropical cyclone as it interacted with each of these three environments were validated with the observed cloud structure changes. Sensitivity studies were run in which the strength of the environmental baroclinic zone was changed. A journal article (Ritchie and Elsberry 2000b) from this study is currently under review for the Monthly Weather Review. Finally, a baroclinic environment was developed into which upper-level potential vorticity anomalies were inserted and allowed to grow. A tropical cyclone was inserted into this environment and the structural changes that occurred as the tropical cyclone and upper-level wave interacted were examined.

RESULTS

New interpretations have been obtained with respect to the role that a large MCS may have played in the track deflection of TY Robyn (1993) in the western North Pacific during the ONR-sponsored TCM-93 field experiment (Ritchie and Elsberry 2000a). Interaction between a mesoscale convective vortex associated with the MCS and a simulated tropical cyclone with a structure similar to that observed in TY Robyn was modeled. The simulations show that as much as a 2 m s^{-1} deceleration in Robyn’s westward motion might have resulted due to an interaction with the mesoscale convective vortex, and then a more northward track deflection, which is similar to that observed. This study demonstrates that better analysis of mesoscale convective vortices may be important in numerical weather prediction models to obtain a correct steering current over the tropical cyclone as the majority of the steering in these simulations was located between 300 and 750 mb, a region of the atmosphere that is not well sampled by observing systems over the oceans.

The physical processes of transitioning and landfalling tropical cyclones have been investigated using COAMPS. As a tropical cyclone makes landfall, interaction with steep topography is hypothesized to produce localized extremes in low-level winds, which in turn may produce extreme precipitation events. A case study of TY Peter (1997) was used to simulate the processes that occur as a tropical cyclone makes landfall (Ritchie and Elsberry 1998; 1999). The case was further complicated as the tropical cyclone was also beginning to transition to an extratropical storm while interacting with an upper-level trough. The tropical cyclone track guidance from both the Navy's global prediction system and COAMPS was slow. After assimilating additional satellite wind, and other observations into the analyses, the high-resolution COAMPS track speed guidance improved. In addition, the simulated tropical cyclone path was very close to that observed, and rainfall patterns closely matched SSM/I data (Ritchie and Elsberry 1999). Interestingly, the majority of the rainfall (spatial distribution and intensity) occurred over the open ocean north of Japan rather than over the mountain regions of the islands. Idealized studies that simulated the same case over open ocean, and then over flat terrain, demonstrated that the majority of the rainfall occurs as a result of the baroclinic processes associated with interaction with the upper-level trough as the tropical cyclone transitions to an extratropical system rather than because of interaction with topography. However, very heavy rainfall occurred locally in association with steep orography.

Extratropical transition of tropical cyclones has been hypothesized to occur in two stages (Klein et al. 2000). The first stage, called transformation, occurs as a tropical cyclone encounters cooler air and waters and a baroclinic zone associated with midlatitude westerlies. Re-intensification subsequently occurs in some systems when, as part of an interaction with an upper-level trough, re-deepening of the system to a significant midlatitude storm takes place. An idealized study using COAMPS investigated processes associated with a mature tropical cyclone that transitions into an extratropical storm by simulating the effects of strong shear such as that found in the midlatitudes on the tropical cyclone structure. As the environmental vertical shear increases, the ability of the simulated tropical cyclone to remain coherent against the shear is reduced and the upper levels of the tropical cyclone begin to tilt. This tilting disrupts the convective processes that are important for maintaining vertical coherency of the vortex and an asymmetric pattern of convection develops to the northeast of the vortex core. At a critical vertical shear, the convection weakens in the upper-level portion of the tropical cyclone, which is then advected downstream. However, the lower portion of the tropical cyclone remains vertically coherent and upright. Whereas the central pressure of the tropical cyclone begins to rise similar to that observed, a sea-level pressure trough develops below the upper-level warm core that has been advected downstream. Thus, elongation of the sea-level pressure contours in the direction of the vertical shear also resembles observations. Sensitivity tests varying the environmental vertical wind shear are in progress to determine what tropical characteristics (intensity, size, etc.) lead to (or prevent) this vertical decoupling during extratropical transition.

The Klein et al. (2000) study identified three steps in the transformation stage of extratropical transition during which the tropical cyclone interacts with different aspects of the midlatitude, baroclinic environment. The composite wind fields of the Steps 1, 2, and 3 of tropical cyclone transformation that they calculated were used as a guide to create an idealized baroclinic environment. The tropical cyclone was then located within that environment at the location where the wind conditions matched those of the composite fields for each of the three steps of transformation. As the tropical cyclone interacted with the environment, the important structural changes were studied and verified against the observations in Klein et al. (2000) for each step. The main results were that the cloud fields and precipitation patterns (Figs. 1a, 1b) developed in a manner very similar to that observed in the Klein et al. (2000) study. Physical processes that were identified in Klein et al. (2000) to be occurring during transformation based on 1^{o} lat./long. NOGAPS analyses were generally verified in the higher-resolution, but idealized COAMPS simulations. In addition, the higher-resolution COAMPS fields allowed investigation of a hypothesis proposed in Klein et al. (2000) that it was interaction with the low-level temperature gradient associated with the baroclinic zone that produced the dry slots in the clouds, and finally the erosion of the southern eyewall convection of the tropical cyclone. The COAMPS simulations suggest that it is the interaction between the tropical cyclone circulation and upper-level environmental winds that produce deep mechanically forced subsidence into the western and southern portions of the tropical cyclone core. The subsidence not only suppresses convection in that region of the tropical cyclone, but also produces subsidence warming in the middle to low levels of the tropical cyclone. The result is a significant enhancement of the low-level warm core that may be helping to maintain the low-level wind circulation. By Step 3, when the tropical cyclone is being advected more rapidly by the mean flow, the subsidence lags the TC core, and a second low-level warm anomaly develops just upstream of the tropical cyclone core (Fig. 1c). This second warm anomaly is associated with a second surface pressure deficit and may have important consequences for the interaction of the tropical cyclone remnants with an upper-level trough and re-intensification as an extratropical cyclone.

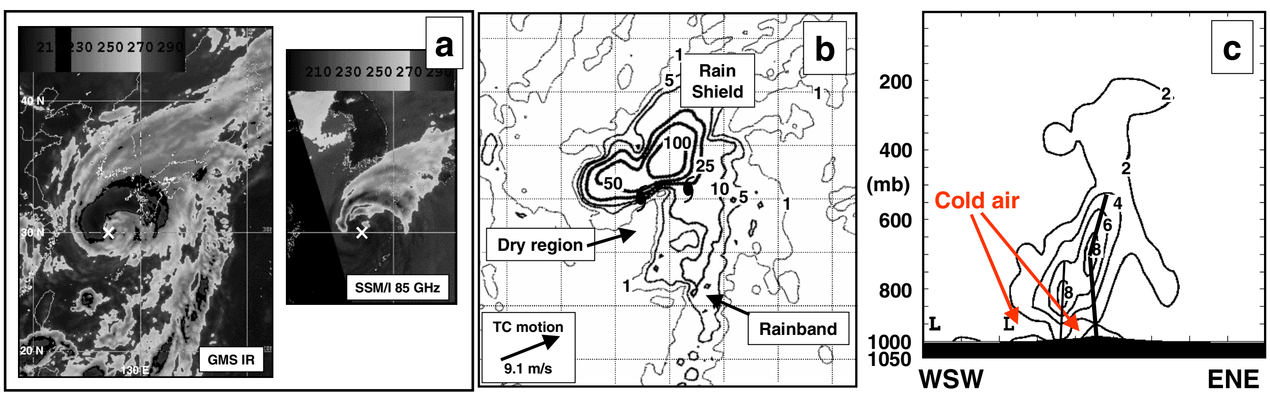

Fig. 1. Step 3 fields: a) Satellite infrared and microwave imagery near 1200 UTC 27 June 1997 (courtesy of Naval Research Laboratory – Monterey) of Typhoon Peter. A white X indicates the tropical cyclone center: b) 3-h simulated precipitation (mm); and c) vertical cross-section of temperature anomaly (2 K).

RELATED PROJECTS

1 - The simplest baroclinic environment within which a tropical cyclone can interact is that of vertical wind shear with no horizontal variation, and thus a constant, weak temperature gradient. The motion and structural development of tropical cyclones in such an environment has been numerically simulated using the PSU/NCAR mesoscale model in a related project with Prof. W. M. Frank (PSU) (Frank and Ritchie 1999; 2000). Important results include the identification of persistent patterns of asymmetric convection and rainfall in the left quadrant of the storm. The rotational motion of the storm due to storm tilt that was identified in dry simulations is reduced in simulations that include parameterizations

of convective processes, since the storm tilt due to environmental shear is almost completely eliminated in the presence of strong vertical momentum transport. In a weak environmental vertical wind shear (3 m s^{-1} over the entire troposphere), the storm is advected at 1 m s^{-1} with only a slight motion to the right of the zero-shear storm track. The model resolution has been increased to 5 km with a third inner mesh and all convective processes that were previously parameterized on the 15- and 45-km meshes are calculated using an explicit physical representation of convection scheme. Because the higher resolution model with explicitly resolved convection results in a more intense simulated tropical cyclone, it is possible to explore the parameter range of more realistic vertical wind shear values. Observational studies (e.g., DeMaria and Kaplan 1994) have shown that tropical cyclones tend to exhibit weakening when the environmental vertical wind shear exceeds about 10 m s^{-1}. Thus, three simulations with vertical wind shear values of 5, 10, and 15 m s^{-1} have been designed to explore the physical interactions between the tropical cyclone and the environment that result in eventual weakening of the tropical cyclone (Frank and Ritchie 2000). Furthermore, realistic structure has been inserted into the vertical wind shear. Thus, directional as well as differential speed shear profiles are being explored in relation to the structure and intensity of tropical cyclones.

REFERENCES

DeMaria, M., and J. Kaplan, 1994: A statistical hurricane intensity prediction scheme (SHIPS) for the Atlantic basin. *Wea. and Forec.*, **9**, 209-220.

Frank, W. M., and E. A. Ritchie, 1999: Effects of environmental flow upon tropical cyclone structure. *Mon. Wea. Rev.,* **127**, 2044-2061.

Frank, W. M., and E. A. Ritchie, 2000: Effects of vertical shear upon tropical cyclone intensity and structure. *Mon. Wea. Rev. (Revised)*

Klein, P. M., P. A. Harr, and R. L. Elsberry, 2000: Extratropical transition of western North Pacific tropical cyclones: An overview and conceptual model of the transformation stage. *Wea. and Forecasting*, **15,** 373-395.

Ritchie, E. A., and R. L. Elsberry, 1998: A study of the development of mesoscale asymmetries in tropical cyclone structure during landfall. *Preprints, 12th Conf. on Numerical Weather Prediction, Phoenix, Arizona, Amer. Meteor. Soc., Boston, MA 02108, 345-348.*

Ritchie, E. A., and R. L. Elsberry, 1999: A modeling study of the development of asymmetries in tropical cyclone structure during landfall. *Proceedings of the U.S. – Japan NR Task Committee "E" on Design for Wind Hazard Mitigation,* 24-28 May, Tsukuba, Japan.

Ritchie, E. A., and R. L. Elsberry, 2000a: Simulated impacts of a mesoscale convective system on the track of Typhoon Robyn during TCM-93. *Mon. Wea. Rev.* **128**, 2232-2251.

Ritchie, E. A., and R. L. Elsberry, 2000b: Simulations of the transformation stage of the extratropical transition of tropical cyclones. *Mon. Wea. Rev. (Revised).*

PUBLICATIONS

Elsberry, R. L., P. A. Hirschberg, P. C. Shafran, G. DiMego, and E. A. Ritchie, 2000: An observing system experiment with the west coast picket fence during STORM-FEST. *Proceedings of the 2nd USWRP Science Symposium, 27-28 March 2000, Boulder CO.*

Frank, W. M., and E. A. Ritchie, 2000: Effects of vertical wind shear on the structure and intensity of hurricanes. *Proceedings of the 24th Conference on Hurricanes and Tropical Meteorology, 29 May - 2 June 2000, Ft. Lauderdale, Florida,* 5-6.

Frank, W.M., and E.A. Ritchie, 2000: Effects of vertical wind shear on hurricane intensity and structure. *Mon. Wea. Rev., (In Review)*

Hirschberg, P. A., P. C. Shafran, R. L. Elsberry, and E. A. Ritchie, 2000: An observing system experiment with the West coast picket fence. *Mon. Wea. Rev. (Submitted)*

Ritchie, E.A., 2000: Some aspects of midlevel vortex interaction in tropical cyclogenesis. *Meteor. Monog. (Submitted).*

Ritchie, E. A., Some aspects of midlevel vortex dynamics in tropical cyclogenesis. *Proceedings of the 54th Interdepartmental Hurricane Conference, 14-18 February 2000, Houston TX.*

Ritchie, E.A., and R. L. Elsberry, 2000a: Simulated impacts of a mesoscale convective system on the track of Typhoon Robyn during TCM-93. *Mon. Wea. Rev.* **128**, 2232-2251.

Ritchie, E.A., and R. L. Elsberry, 2000b: Simulations of the transformation stage of the extratropical transition of tropical cyclones. *Mon. Wea. Rev. (Revised).*

Ritchie, E. A., and R. L. Elsberry, 2000: Simulations of the Transformation Stage of the Extratropical Transition of Tropical Cyclones. *Proceedings of the 24th Conference on Hurricanes and Tropical Meteorology, 29 May - 2 June 2000, Ft. Lauderdale, Florida,* 322-323.