

# **Tropical Cyclone Intensity and Structure: Improved Understanding and Prediction. Evaluation of Existing and Development of New Techniques for Global and Mesoscale NWP Model Assessment.**

Lance Leslie

School of Meteorology, The University of Oklahoma, Norman, Oklahoma 73019, USA  
phone: (405) 325-6561 fax: (405) 325-7689 email: [lmleslie@ou.edu](mailto:lmleslie@ou.edu)

Grant Number: N00014-02-1-0181

<http://weather.ou.edu/~som/>

## **LONG-TERM GOALS**

This is the final year of the four year grant. My main objectives in this final year have been to carry out the following studies: to *publish the findings of the now completed work* on finding reliable estimates of the theoretical limits to tropical cyclone forecast errors, for both track and intensity predictions, but with emphasis on distinguishing between overall track errors, and position and timing errors at landfall; to complete the work that has addressed the problem of *identifying, quantifying and reducing* these sources of errors; to continue to *improve the initial state* specification for TCs, by the development and application of 4D data assimilation procedures, particularly with respect to the ingestion of newly emerging data sources, especially satellite, radar and scatterometer data; to *develop and implement major model changes and additions*, motivated by the very active 2004 season; in the Atlantic Ocean, the Caribbean, and the Gulf of Mexico; to complete the work on *comparing existing and new methods for the evaluation of the skill* of TC track prediction schemes, part of which is to develop new *probabilistic statistical and statistical-dynamical procedures for TC forecasting* beyond 24 hours, and also to include second order and non-linear effects; and, finally, to complete work on a specific impact of landfalling TCs, namely, *the generation of tornadoes, especially tornado outbreaks*. My goals all have implications for transitions.

## **OBJECTIVES**

As mentioned in previous section, there are six main scientific objectives of this proposal. My first objective is to publish our findings on estimating the intrinsic limits of predictability of TC cyclone behavior, for both mean absolute forecast position errors and intensity errors. As mentioned in previous FY reports, intrinsic limits of predictability for TCs exist because the equations governing the behavior of atmospheric systems, including TCs, are deterministically chaotic. Errors in initial conditions, model formulation, and boundary conditions generate errors that grow until the predictions have no skill. The first objective leads to the second, which is to carry out research directed at identifying and understanding the sources of errors in both the initial conditions and the model formulation, and to reducing these errors. This objective remains the major part of the program of numerical analysis and prediction of this proposal. My focus largely will be on TCs that are approaching or making landfall, as they are the most devastating in terms of loss of life and property. My third objective is to continuing the development of my 4D-VAR data assimilation scheme. The sub-components of the third objective continue to be to improve upon the present 4D-VAR scheme, especially its efficiency, and its ability to ingest the many emerging data sources such as the satellite and radar data. My fourth objective has been to complete an evaluation of existing schemes for

## Report Documentation Page

*Form Approved*  
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE <b>30 SEP 2005</b>	2. REPORT TYPE	3. DATES COVERED <b>00-00-2005 to 00-00-2005</b>			
4. TITLE AND SUBTITLE <b>Tropical Cyclone Intensity and Structure: Improved Understanding and Prediction. Evaluation of Existing and Development of New Techniques for Global and Mesoscale NWP Model Assessment</b>		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) <b>The University of Oklahoma, School of Meteorology, Norman, OK, 73019</b>		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 <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>code 1 only</b>					
14. ABSTRACT <b>This is the final year of the four year grant. My main objectives in this final year have been to carry out the following studies: to publish the findings of the now completed work on finding reliable estimates of the theoretical limits to tropical cyclone forecast errors, for both track and intensity predictions, but with emphasis on distinguishing between overall track errors, and position and timing errors at landfall; to complete the work that has addressed the problem of identifying, quantifying and reducing these sources of errors; to continue to improve the initial state specification for TCs, by the development and application of 4D data assimilation procedures, particularly with respect to the ingestion of newly emerging data sources, especially satellite, radar and scatterometer data; to develop and implement major model changes and additions, motivated by the very active 2004 season; in the Atlantic Ocean, the Caribbean, and the Gulf of Mexico; to complete the work on comparing existing and new methods for the evaluation of the skill of TC track prediction schemes, part of which is to develop new probabilistic statistical and statistical-dynamical procedures for TC forecasting beyond 24 hours, and also to include second order and non-linear effects; and, finally, to complete work on a specific impact of landfalling TCs, namely, the generation of tornadoes, especially tornado outbreaks. My goals all have implications for transitions.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>11</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			



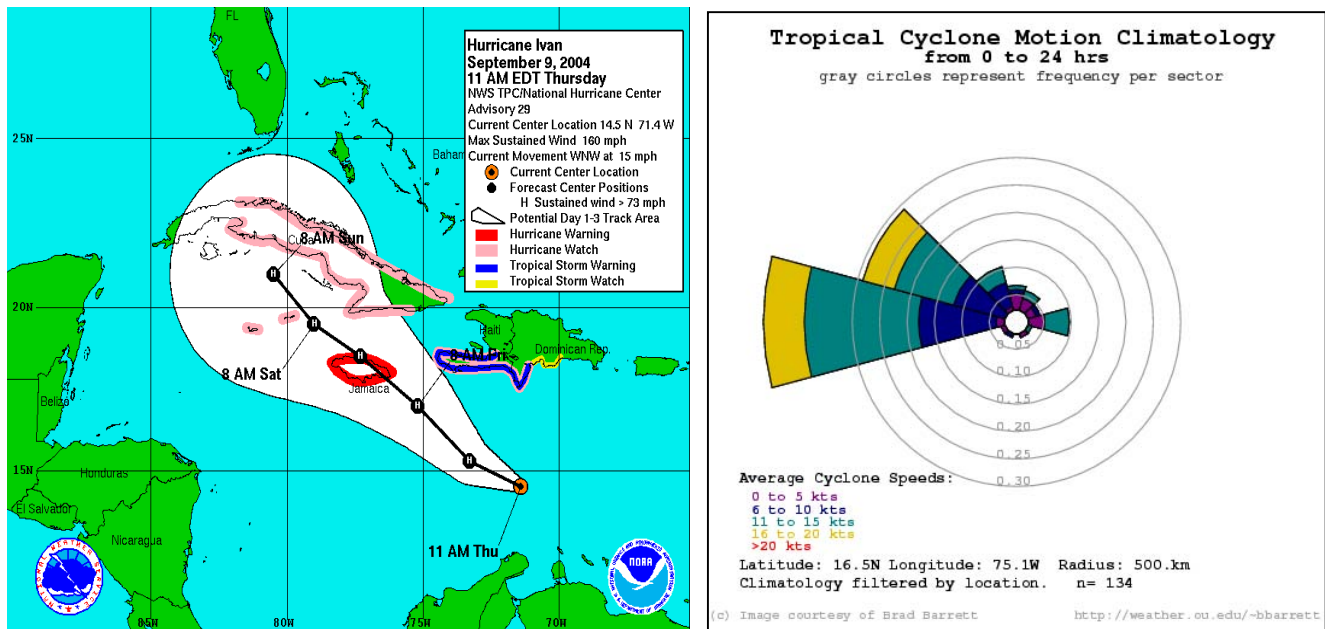
assessing NWP model performance, and to develop alternative procedures. Present methods of assessment frequently are either biased towards the NWP models or are too scale dependent, unduly rewarding smooth forecasts and penalizing detailed predictions. In particular, new assessment schemes are required for TC model forecasts, as they are not well handled by conventional measures of skill, given the many scales and the range of variables that need to be assessed. As ensemble techniques dominate forecasting systems, the need for new assessment procedures has increased. A fifth objective is the continued development of a new statistical technique for either stand-alone forecasting or to correct TC model predictions. Finally, a sixth objective was added in FY04, and has proved to be timely given the events of the 2004 hurricane season. This objective is a careful analysis of tornado outbreaks associated with landfalling TCs.

## **APPROACH**

My approach for the six goals is as follows. The methodology employed for the first goal is explained in the ONR FY01 and FY02 reports. Two distinct techniques have produced almost identical answers. One approach was to generate an ensemble of initial model states using the archived data sets from various operational global NWP centers around the world. The second technique was based purely on observational data in which the spread rate of initially close pieces of TC trajectories. These methods have now been applied to the problem of estimating the predictability characteristics of TC intensity and intensity change. The task has been massive computationally, but it is vitally important to know how close we are in practice to the limits of predictability. The second goal has been to obtain model simulations with much more realistic TC structure, intensity, intensity change and motion as TCs approach landfall. The second goal links directly with my third goal, as the approach in both cases is use my HIRES data assimilation and NWP model systems. In FY04 I continued to use 4-D variational assimilation procedures without TC bogussing, using high spatial-temporal frequency satellite derived data of various types and as many other sources of data as possible, especially radar data. Populated coastal regions are threatened each year by landfalling TCs. Therefore, it is of primary importance to acquire a better understanding of their internal dynamics in order to improve forecasting capabilities. Here, emphasis is placed on the importance of improving our knowledge of the TC's microphysical and electrical structure. Further motivation for this work comes from observational studies, which stressed the importance of more systematic monitoring of any change in TC lightning flash activity. The latter could be a very useful source to determine the distribution of the convective precipitation, particularly at landfall, where it could be used to provide advance warnings for potential flooding and severe weather originating from embedded supercells. The approach to the fourth goal has been to compare existing measures of assessment of NWP model skill with alternative measures. Initially, the alternative measures were standard, but have now been extended well beyond the existing measures. The approach to the fifth goal has been to use the Atlantic basin TC data base to generate conditional probabilities for predicting the future tracks and intensities of TCs in that basin. An example is given in the Results section below. Finally, the sixth goal is to define and develop a tornado outbreak climatology from 1953 to 2002 over the US for tornadoes associated with land-falling hurricanes. Tornadoes generated by TCs tend to be weaker and land-falling hurricanes can persist for several days. Finally, case studies that meet the outbreak definition compared against several non-hurricane related tornado outbreaks in the U.S. TC Beulah (1967) holds the current record with 117 tornadoes reported.

## WORK COMPLETED

My work on the first goal is now completed and the work has been published. Recent work has focussed on reducing mean track errors for TCs that are regarded as difficult to predict. Applying the same procedure to TC intensity predictability has also been completed, with the emphasis again being on the more difficult storms. This work has produced some intriguing and unexpected results, most notably the large variations from basin to basin. Second, development of the HIREs data assimilation and prediction system has continued, with the incorporation of new data from radar and satellite sources. This work also has been published. My third goal of understanding the factors contributing to improving the forecasts of TC intensity and structure through improvements to the NWP model have reached a new phase with the successful introduction of an improved cloud microphysics scheme. The inclusion of high quality cloud microphysics in the NWP models appears to be vital for understanding and predicting TC behaviour. This is true especially as the TCs approach landfall. Some significant findings have been made and will be presented at the 2005 AMS annual meeting. Fourth, existing methods for assessing NWP model performance have been shown to be far too simplistic and also must be extended to cover ensemble predictions, which are now becoming common-place in usage. New techniques have been tested and results also will be presented at the 2005 AMS meeting.



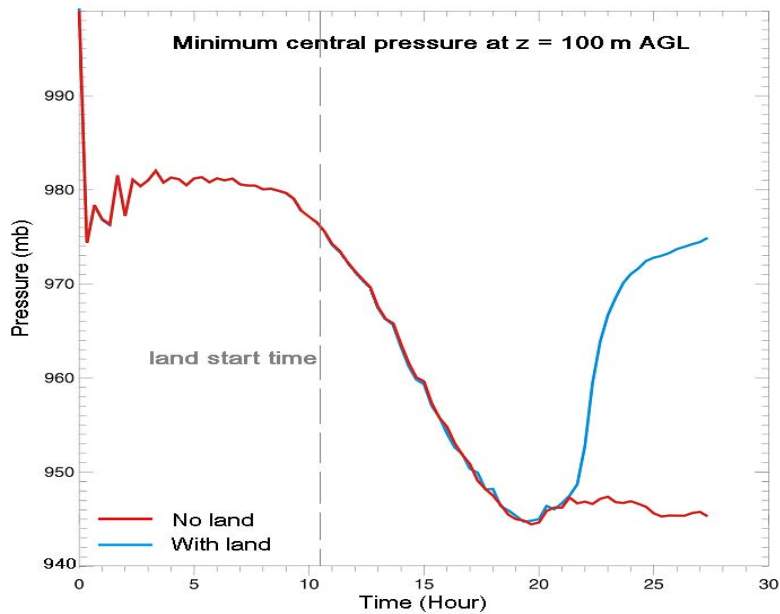
**Figure 1: The official track forecast from NHC (left), compared with the probabilistic prediction (right). The probabilistic prediction suggested a more westerly movement of Hurricane Ivan, which did in fact occur.**

Fifth, the probabilistic-statistical prediction scheme has been tested on every storm throughout the 2004 hurricane season in the Atlantic basin. It has been particularly useful in forecasting short term track directions and speeds of movement. In a number of cases, the scheme gave quite different predictions from the NWP models and the official NHC forecast. On every occasion, the probabilistic scheme was more accurate over the first 24 hours. A journal paper is in preparation on the performance of the scheme over the 2004 season, and also will be presented at the 2005 AMS annual meeting. An example is shown above (in Figure 1), for Hurricane Ivan, when located at 14.5N, 71.4W. The official

forecast moved Ivan northwest. The statistical scheme, based on 134 storms moved Ivan due west on a path that had it entering the Gulf of Mexico, well to the west of Florida. This is indeed what occurred.

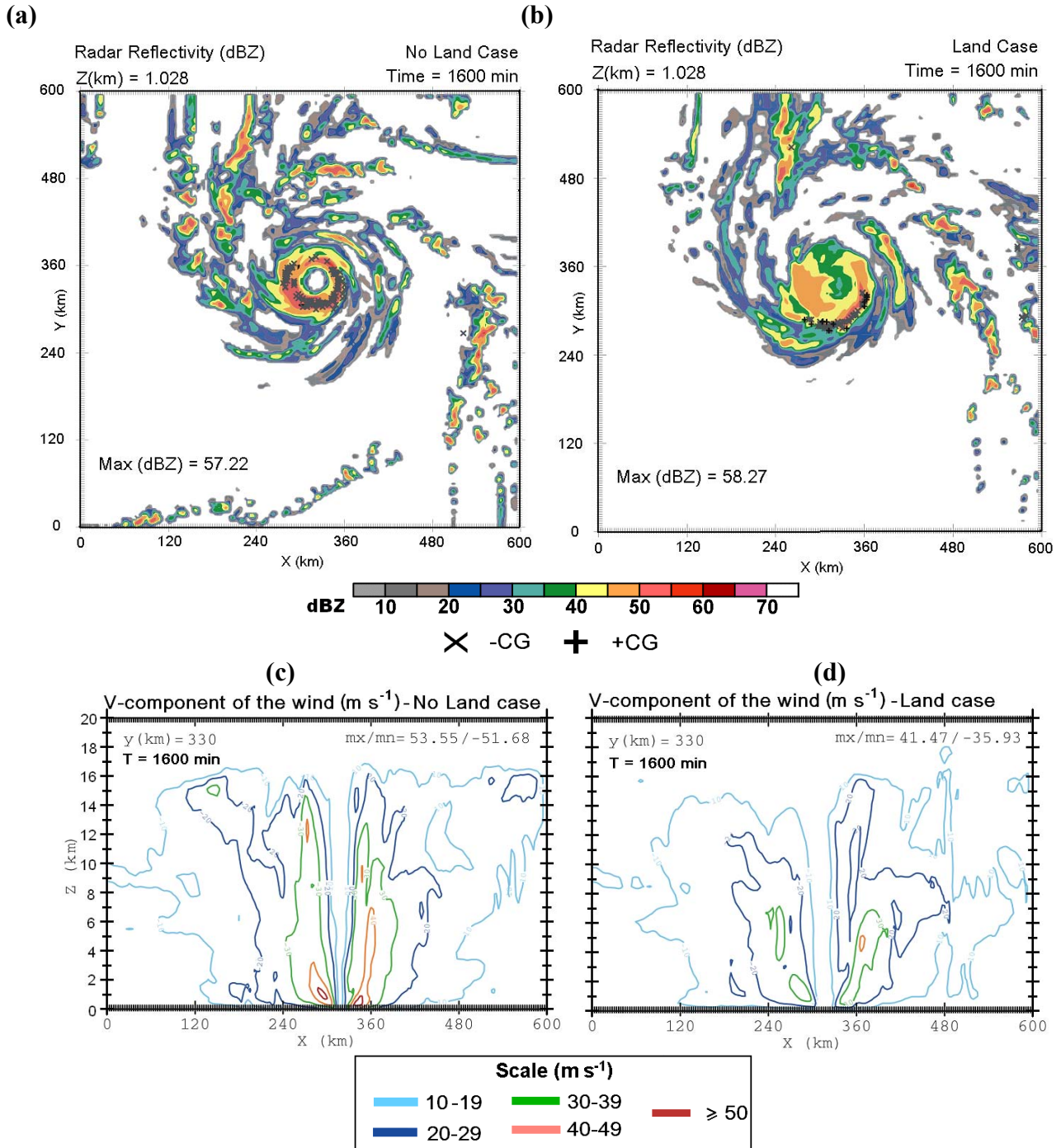
## RESULTS

Results are now complete for the first goal, which was to determine how close current NWP models are to our best estimates of the limits of predictability for mean absolute TC track errors. The major finding of FY01, FY02 and FY03 was the potential for TC track errors to at least be *halved*. A second set of results concerns the performance of the NWP systems presently at the core of my ONR research program. This model is the High Resolution (HIRES) data assimilation and prediction system. Largely using ONR support, this system has been developed over six years, for use in TC applications by the PI, various graduate students and part-time time research associates. It has continued to undergo development in FY04, especially in the area of data assimilation and representation of cloud microphysics.



**Fig. 2.** Time-height plot of pressure at  $z = 100$  m AGL for the first 27.5 hours of simulation. Blue (red) line shown for the land (no-land) case.

At 26h 40 min hours (1600 min) of simulation, the vortex shows a central pressure of 946 mb (Fig. 2, redline) and a distinct eyewall with several connecting rainbands (Fig. 3a). At that time, tangential winds are exceeding  $50 \text{ m s}^{-1}$ , with the highest gusts just within the boundary layer above ground, corresponding to a low-end Category 3 storm. Consistent with many *in situ* observations the TC eyewall exhibits an outward tilt in reflectivity and in the tangential wind profile. As the storm weakens over land tangential wind profile becomes more vertically stacked. The weakening of the TC is clearly evident for instance in the central pressure at 100m above the ground (Fig. 2, blue line) and in the tangential wind profiles (Figs. 3c and 3d), where maximum meridional (tangential) wind component are exceeding  $50 \text{ m s}^{-1}$  over the ocean, while remaining below  $40 \text{ m s}^{-1}$  once over land at the same time. The horizontal reflectivity field of the TC over land also show many interesting features consistent with *in situ* observations, namely, weaker reflectivity in and around the eyewall and the absence of a closed circular eyewall and eye near and around the storm's center (compare Figs. 3a and 3b). This is a consequence of weaker updraft mass flux in the eyewall and hence weaker divergence aloft, in turn reducing the subsidence and the subsequent warming responsible for the formation of the eye. On the other hand, when the storm evolves over open waters, more continuous convection in the eyewall and a well-defined closed circular eye are noticeable near the storm's center. Between these two convective regions, a stratiform region with weak reflectivity values is also evident. Secondary weak bands underneath the outer core stratiform region of the storm's eyewall are also found on the storm's western and eastern flank.



**Fig. 3.** (a) Horizontal cross section of radar reflectivity (dBZ) shown by 5 dBZ contour increments from 5 dBZ to 75 dBZ at  $t = 1600$  min for the no land case, and (b) the land case, at  $z = 1,017$  km. Locations of CG lightning strikes are also shown by a cross for -CG flashes and by a + symbol for +CG flashes. The flash locations were plotted for 6000 s time interval from the cross section time. Panels (c) and (d) show vertical cross section in the X-Z direction of the V (or Y) component of the wind field at  $y = 330$  km, with corresponding scale shown below.

## **IMPACT/APPLICATIONS**

In FY04, the final phase of the estimation of how close we are to the limits of track predictability on the 0-4 day time scale have now confirmed earlier work that: large TC track forecast errors remain; and that these track errors are still at least twice that which can theoretically be achieved. The patchy performance of NWP models over the 2004 season appears to have confirmed these findings. The gap between that still exists between practice and theoretical limits points to the necessity for continued understanding of TC processes and improvements in the analyses and NWP model formulation. A second impact in FY04 resulted from the continued use of careful quality controlled, high resolution, data from existing and new sources; developments in continuous (4D) assimilation; and ongoing model improvements and increased model resolutions of 5km or below. TC simulations that have many of the observed features of actual TCs will soon be routine, as suggested above in Figure 3. Also, the adjoint sensitivity techniques developed earlier continue to improve our ability to predict TC motion, structure, intensity, and intensity change. Fifth, the range of precursors of TC activity and intensity identified in FY02 in the eastern Indian Ocean, northwest Australia and the western Indian Ocean have been extended to the western North Pacific Ocean basin. These precursors were again shown to be present at the inter-seasonal level, through the intra-seasonal level, to time-scales of days and even during the life cycles of TCs. Other applications include model improvements which should increase our understanding of changes in TC structure, and associated severe weather, as they approach and make landfall; and a return to statistical schemes that provide rapid updating of probabilistic forecasts of TC track speed and direction.

## **RELATED PROJECTS**

I am a co-PI on the CBLAST grant entitled “The Impact of Air-Sea Interaction Research on Larger-Scale Geophysical Flows.” with Dr Michael Banner of The University of New South Wales. I also continue to interact with Dr Wang Yuqing, University of Hawaii, on the impact of cloud microphysics schemes.

## **SUMMARY**

This proposal aims at increasing our understanding of, and ability to predict, tropical cyclones in a number of areas. Tropical cyclones, which are also referred to as hurricanes and typhoons, are the most devastating storms on earth. As such it is vital to understand and to predict their behavior. To do so in an accurate and timely manner requires research on their motion, their structure, their intensity, especially when nearing land. To achieve these aims, a program of data collection and computer model simulations is being carried out, with the predictions being compared with observations of selected storms. Deficiencies in the initial data, the model formulation and the model predictions are then identified and research is carried out on improving these aspects. The ultimate goal, expressed succinctly is accurate, timely and reliable model predictions of TC tracks and intensity, especially for storms that threaten coastlines. This ONR funded research program will help make the School of Meteorology, University of Oklahoma, an international focal point in tropical cyclone research.

## REFERENCES

### PUBLICATIONS (2002-2004)

#### Books:

Leslie, LM (with G. Peng and Y. Shao), (2002): "Environmental Modeling and Prediction", Springer, 480pp, ISBN 3-540-67422-5.

#### Book Chapters:

Leslie, LM, (2003): "High-resolution Atmospheric Modeling. Part I: Theory". Ch. 6 in "Impact Science." Eds. J. Nicholls and B. Pailthorpe. The Tandem Group Pty. Ltd., ISBN: 1 86487 551 8, 193pp.

Leslie, LM, (2003): "High-resolution Atmospheric Modeling. Part II: Applications". Ch. 7 in "Impact Science." Eds. J. Nicholls and B. Pailthorpe. The Tandem Group Pty. Ltd., ISBN: 1 86487 551 8, 193pp.

#### Journal Publications:

Leslie, LM, and MS Speer (2004): Preliminary modelling results of an urban air quality model verifying the prediction of nitrogen dioxide, sulfur dioxide and ozone over the Sydney basin. Meteor. Atmos. Phys. DOI 10.1007/s00703-003-0062-7-0 (Online May 2004).

Le Marshall, JF, A Rea, LM Leslie, R Seecamp and M Dunn, (2004): Error characterization of atmospheric motion vectors. Aust. Meteor. Mag., 53, 123-131.

Speer, MS, LM Leslie and L Qi, (2004): Urban scale modelling: The Sydney hailstorm of 14 April 1999. Meteor. Atmos. Phys. DOI 10.1007/s00703-003-0069-0 (Online May 2004).

Leslie, LM and L Xia, (2004): A GIS framework for the Traffic Emission Information System (TEIS). Meteor. Atmos. Phys. DOI 10.1007/s00703-003-0068-1 (Online May 2004).

Mo, X, K. Beven, S. Liu, LM Leslie and Ad PJ De Roo, (2004): Long term water budget estimation with the modified distributed model LISFLOOD over the Lushi basin, China, Meteor. Atmos. Phys. DOI .10.1007/s00703-004-0084-9 (Online March 2004).

Buckley, BW and LM Leslie and MS Speer, (2004): Preliminary Climatology and Improved Modelling of South Indian Ocean and Southern Ocean Mid-Latitude Cyclones. Int. J. Climatology 24, 1211-1230.

Speer, MS and LM Leslie, (2004): Preliminary Testing of an Urban Air Quality Model for Ozone Forecasting over the Sydney Basin, Journal of the Korean Environmental Sciences Society (Accepted, In Press).

Leslie, LM and MS Speer, (2003): Modeling a coastal ridging event over south-eastern Australia. Meteor. Apps. 10, 293-294.

- Y. Shao, LM Leslie and 7 others, (2003): Northeast Asian dust storms: Real-time numerical prediction and validation. *J. Geophys. Res.*, Vol. 108, No. D22, 4691 DOI:10.1029/2003JD003667 (Online November 2003).
- Liu, S, LM Leslie, MS Speer, R. Bunker, and X, Mo, (2003): The effects of bushfires on hydrological processes using a paired-catchment analysis, *Meteor. Atmos. Phys.* DOI:10.1007/s00703-003-0614-x (Online October 22, 2003).
- Buckley, BW and LM Leslie, (2003): The impact of observational technology on climate database quality. *J. Climate*, 16, 2640-2645.
- Leslie, LM, MS Speer and L. Qi, (2003): Prediction of Extreme Rainfall for the Coffs Harbour Catchment. *Aust. Meteor. Mag.*, 52, 95-100.
- Speer, MS, LM Leslie, and L. Qi, (2003): Numerical Prediction of Severe Convection: Comparison with Operational Forecasts, *Meteor. Apps.*, 10, 11-19.
- J. LeMarshall, JF, LM Leslie, R. Seecamp and A. Rea, (2003): Remote sensing applications in meteorology: A review, *MAUSAM*, 54, 1-12.
- Leslie, LM, JF LeMarshall and WL Smith, (2002): Mesoscale initialization using advanced sounder data, *Adv. Space Res.*, 30, 2479-2486.
- Shao, Y, E Jung and LM Leslie (2002): Numerical prediction of northeast Asian dust storms using an integrated wind erosion modeling system, *J. Geophys. Res.*, 107, D24, 4814-4837.
- LeMarshall, JF, LM Leslie and WL Smith, (2002): Initialization of a NWP model using high spatial and temporal resolution satellite data, *Adv. Space Res.*, 30, 2441-2446.
- LeMarshall, JF, GA Mills, R. Seecamp, N. Pescod, LM Leslie and A. Rea, (2002): The estimation of high density atmospheric motion vectors and their application to operational NWP, *Australian Meteor. Mag.*, 51, 173-180.
- LeMarshall, JF, LM Leslie and RF Abbey (2002): Tropical cyclone track and intensity prediction: The generation and assimilation of high density satellite-derived data, *Meteor. Atmos. Phys.*, 80, 43-57.
- Leslie, LM, RF Abbey, MS Speer and TCL Skinner, (2002): Intense tropical cyclogenesis over the northwest Australian region in 1998/1999: Causal factors, *Meteor. Atmos. Phys.*, 80, 89-101.
- Morison, RP, Leslie, LM and MS Speer (2002): Atmospheric modeling of air pollution as a tool for environmental prediction and management, *Meteor. Atmos. Phys.*, 80, 141-151.
- Speer, MS, and LM Leslie (2002): The prediction of two cases of severe convection: implications for forecast guidance, *Meteor. Atmos. Phys.*, 80, 165-175.

## **HONORS/AWARDS/PRIZES**

I received one award and one honor in FY04. The award is an Australian Research Council International Linkage award. The honor is an (accepted) invitation to become a Fellow of CIMMS, School of Meteorology, The University of Oklahoma.