Dynamic Sensitivity Analysis of Tropical Cyclone Track and Extratropical Transition

Michael C. Morgan
Nicholas Bassill (July 2006 - present)
Brett Hoover (September 2006 - present)
Dianna Nelson (May 2008 – present)

WORK COMPLETED

The work completed to date on this project includes:

1) Modifications of NOGAPS forward and adjoint code to run on a Linux PC and iMac computer.
2) Studies of extratropical transition with response functions of kinetic energy and lower tropospheric vorticity.
3) Development of tools to calculate sensitivities with respect to shearing and stretching deformation
4) Case studies of tropical cyclone steering sensitivity with the NOGAPS and MM5 adjoint modeling systems
5) Case study of extra-tropical transition with the MM5
6) Determination and investigation of the effect of choice of model microphysics and convective parameterizations on tropical cyclone structure and track.
7) Collaborations with Dr. Chris Davis (NCAR), Dr. Rolf Langland (NRL), Dr. Carolyn Reynolds (NRL), Dr. Melinda Peng (NRL), Dr. Hyun Mee Kim (Yonsei University), Dr. Chun-Chieh Wu (National Taiwan University), Dr. Eric Rappin (University of Miami)

Personnel development:

1) Nicholas Bassill (July 2006), Brett Hoover (July 2008), and Dianna Nelson (July 2008) have participated in the NCAR WRF Tutorial and are now familiar with the WRF model.
2) Brett Hoover and Michael Morgan visited NRL in Monterey to become familiar with NOGAPS forward and adjoint code.
3) Brett Hoover has written a two-dimensional, non-divergent barotropic model and its corresponding adjoint to test various hypotheses associated with adjoint sensitivity fields and aid in interpreting the results from the MM5 and NOGAPS adjoint model outputs.
4) PI has continued developing notes and text for course on atmospheric predictability and atmospheric data assimilation.
5) PI was invited to Yonsei University (May – June 2007) and Cornell University (March 2008) to give a series of lectures on use of the adjoint model for predictability of tropical and extra-tropical phenomena
6) Nick Bassill has developed a real-time WRF microphysics and convective parameterization ensemble system http://aurora.aos.wisc.edu/tropical.
7) Dianna Nelson has developed code to perform linear discriminate analysis to distinguish the large-scale environmental characteristics of developing from non-developing tropical cyclones.

Presentations (talks/posters):

Yonsei University (May 2007)
- Michael Morgan “Predictability and error growth” (invited)
- Michael Morgan “Adjoint sensitivity analysis – a practical diagnostic in a synoptician’s tool chest” (invited)

Korean Meteorological Agency (June 2007)
  Michael Morgan “An adjoint-derived forecast sensitivity study of hurricane track and extra-tropical transition” (invited)

UCLA IPAM: "Small Scale and Extreme Events: The Hurricane" (February 2007)
  Nick Bassill “WRF-ARW model forecast track sensitivities of tropical cyclone Ernesto (2006) to various parameterizations, grid spacings, and initial conditions.”

Cornell University (March 2008)
  Michael Morgan “An adjoint-derived forecast sensitivity study of hurricane track and extra-tropical transition” (invited)

AMS 28th Conference on Hurricane and Tropical Meteorology (28 April – 2 May 2008)
- Nick Bassill “Forecast track and intensity sensitivities of tropical cyclones to various parameterizations using the WRF-ARW model”
- Brett Hoover “Tropical cyclone steering as a potential vorticity advection process: the role of cumulus parameterizations in defining an optimum steering column” (poster)

WRF User's Meeting (June 2008)
- Nick Bassill "Forecast track and intensity sensitivities of tropical cyclones to various parameterizations using the WRF-ARW model"

14th Cyclone Workshop (September 2008)
- Dianna Nelson and Michael Morgan “The Predictability of Tropical Storm Alma 2008”
- Nick Bassill “Tropical cyclone intensity and track sensitivities to various cumulus and microphysics parameterizations using the WRF-ARW model: An Attempt at an Ensemble”
- Brett Hoover “The application of adjoint-derived sensitivity gradients to tropical cyclone steering: a challenge to conventional wisdom.”

Papers
Theses


Bassill, N., 2008: Forecast track and intensity sensitivities of tropical cyclones to various parameterizations using the WRF-ARW model, Univ. of Wisconsin – Madison, M.S. thesis. (in preparation)

Research narratives:

Michael C. Morgan

Over the course of the project, the PI has supervised graduate students, and collaborated with outside researchers, in the completion of research objectives related to tropical cyclone (TC) track, intensity change, and extra-tropical transition, helped with the necessary modifications of the NOGAPS model code to make it practical to run on his labs local computers, worked with students in developing response functions to study TC track and diagnose extra-tropical transition intensity change sensitivity with the NOGAPS and MM5 adjoint modeling system, and developed tools to calculate sensitivities to various kinematic response functions.

In a case study of Hurricane Floyd (1999), adjoint sensitivity calculations (using the MM5 adjoint) revealed that the lower-tropospheric kinetic energy associated with the extra-tropically transitioned Floyd was most sensitive to the lower-tropospheric vorticity ahead of the TC prior to land-fall. As Floyd moved northward along the east coast of the U.S., the vorticity ahead of Floyd became concentrated along a coastal front. As Floyd transitioned, this frontal vorticity was swept into the circulation of the transitioning cyclone – leading to a more powerful cyclone. Floyd’s track was found to be sensitive to the interaction of Floyd with a mid-latitude upper trough. The results of this work are being written up for submission this fall.

During the last year, the PI was on sabbatical leave participating in an AMS/UCAR Congressional Science Fellowship. During this time, he worked in the office of U.S. Senator Benjamin Cardin as a legislative assistant on energy and environment issues. The PI continued to advise and mentor his graduate students during this period. Brett Hoover completed his Masters’ thesis and Nick Bassill has the text of his M.S. thesis being reviewed by his thesis committee and will be fully completed by the end of this November. Work from both of their MS theses will be prepared for publication during this winter.

Working with Mr. Hoover over the last several months, the PI has suggested a response function to study TC steering that is less sensitive to TC position. This work is described below. In addition, the PI has developed tools to calculate the sensitivity to all four major kinematic descriptors (sensitivities to vorticity, divergence, shearing deformation and stretching deformation) of the two-dimensional flow field in grid point models and for the shearing and stretching deformation using NOGAPS model output. This work will prove useful in our study of extratropical transition.

The PI is working with Mr. Bassill and Mr. Hoover in developing their PhD dissertation research on topics representing an outgrowth of their thesis work that fall within the core objectives of this grant.
Dianna Nelson, who recently joined the research group, completed her qualifying exam earlier this fall, and will be working on evaluating statistical methods for understanding TC genesis and intensity change. Ms. Arwen Twitchett, of Leeds University in the UK, and funded by a World University Research Mobility Grant, is visiting out research group this fall to learn about the application of adjoint techniques in the predictability of PV streamers. The research group is working with her on a case study of a streamer event that occurred during this past September in the central Pacific during TPARC.

**Nicholas Bassill**

Much of the work performed by Mr. Bassill has been on completing research for his Master’s degree and writing the related thesis. This research has attempted to accomplish several goals. The first goal was to determine whether different cumulus and microphysics parameterizations were associated with intensity or track biases when forecasting tropical cyclones at extended ranges (up to 7.5 days/180 hours) using the WRF-ARW model. If biases were detected, the second goal was to assess the potential worth of an ensemble comprised of members using distinct parameterizations but the same model dynamical core.

Regarding the first goal, a number of intensity as well as track biases were in fact discovered. Fourteen different experiments, comprising four storms (Typhoon Cimarron (2006), Hurricane/Typhoon Ioke (2006), Hurricane Ernesto (2006), and Hurricane Lenny (1999)) were conducted. These storms were chosen to represent a wide range of forecasting challenges and basins. These experiments suggest that the Grell-Devenyi cumulus parameterization is biased towards steering storms on a more poleward track, while the Kain-Fritsch cumulus parameterization has a more equatorward bias. The Betts-Miller-Janjic cumulus parameterization lies between these two, with an earlier version of the parameterization having a distinct equatorward bias, while the current version seems to have a slight poleward bias.

Analysis shows that these biases do not occur primarily as a result of the model’s depiction of the storm-scale structure, but rather due to how the cumulus parameterizations affect the larger steering pattern, through the development (or lack-there-of) of subtropical ridges. In terms of intensity, it was found that the Kain-Fritsch cumulus parameterization produced the most intense cyclone on average. Three microphysics parameterizations were chosen for study, representing a range of complexity (the Kessler, Eta-Ferrier, or WSM6). It was found that the Kessler microphysics parameterization consistently steered storms more poleward than the other parameterizations, which again was likely due to the parameterization’s handling of the large-scale development. Since this parameterization does not include frozen processes, it is hypothesized that the lack of upper-tropospheric latent heat release through freezing results in a weaker subtropical ridge at upper levels, allowing the storm to progress poleward. The other microphysics parameterizations produced similar tracks, which were much more equatorward than the Kessler microphysics parameterization. The WSM6 microphysics parameterization produced the most intense storm on average, while the Eta-Ferrier microphysics parameterization had extreme difficulty producing a cyclone approaching a realistic intensity. This was only possible while using the most recently updated Eta-Ferrier microphysics parameterization in conjunction with the Kain-Fritsch cumulus parameterization. It is believe that this microphysics parameterization creates an unrealistic vertical potential vorticity structure which restrains intensification.

These results, in conjunction with a comparison of the global models’ performance for these storms, seem to indicate that there is some utility to using an ensemble of this model. During the past summer, Mr. Bassill focused on using this approach to make real-time tropical cyclone track, intensity, and
genesis forecasts (as well as comparing simulations using a 30 km grid spacing with a 90 km grid spacing for these topics) using the WRFV3 (ARW core). An ensemble of nine members was used (all combinations of the above three cumulus parameterizations as well the WSM6, Eta-Ferrier, and Lin et al. microphysics parameterization). Additionally, the model used was the recently released WRFV3, compared with the WRFV2, which we were previously using. Model output for this project is posted once a day, and can be viewed at http://aurora.aos.wisc.edu/tropical/WRF.shtml. Ideally, a statistical analysis of this data over the course of a full season will more specifically address the potential utility in this approach. Although the hurricane season has not ended yet, preliminary observations continue to suggest that there is some utility to this approach. Once the season ends, a more rigorous statistical analysis of the season’s data will be performed to more accurately determine this.

Presentations over the last two years can be found at http://aurora.aos.wisc.edu/~bassill

Brett Hoover

Mr. Hoover’s research has primarily been focused on the processes governing tropical cyclone (TC) motion. His Masters’ work involved an investigation of TC motion as the advection of the TC positive potential vorticity (PV) by the environmental flow. In this work, Mr. Hoover demonstrated that the motion of a modeled TC, diagnosed by performing an averaging of the wind field over some “steering column” meant to separate the environmental flow in the vicinity of a hurricane from its own symmetric circulation, is a process which strongly relates to the PV structure of the TC itself. The optimal steering column changes in depth and location in the vertical as the TC matures and the PV structure changes. Furthermore, it is demonstrated that the choice of cumulus parameterization scheme in a numerical weather prediction model can have a profound impact on TC PV structure through dictating the distribution of diabatic heating within the TC, and a track split can be observed and understood as a result of the change in TC PV structure.

Mr. Hoover has also studied the application of an adjoint model to the dynamics of TC motion. Previous research has suggested that a response function consisting of the average zonal (meridional) wind in a box appropriate for the dimensions of a steering column, centered on a TC at verification, can reveal sensitivities of zonal (meridional) TC steering with respect to the model state vector. These two sensitivity fields can then be combined into a vector that describes a perturbation to TC steering given a perturbation to some model variable. These vectors are known as “adjoint derived sensitivity steering vectors” (ADSSV).

Mr. Hoover has compiled and modified the NOGAPS adjoint model, which is an adjoint model including the moist processes of large-scale precipitation, to study the application of ADSSV to TC motion research. By running perturbation tests in a TC modeled with the NOGAPS, he has shown that the components of the ADSSV are primarily the result of perturbations in the position of the TC within the response function box; as a result, the sensitivity gradients do not correspond to sensitivities to TC steering. Instead, the sensitivities merely address the effect a perturbation to the model state has on shifting the TC slightly out of the center of the box, adding part of its own (no longer) symmetric circulation to the perturbation flow within the response function box.

Mr. Hoover has written a two-dimensional, barotropic, inviscid model run on an \( f \)-plane, along with the accompanying tangent linear model and adjoint model. Through the use of these tools, he has been able to run idealized simulations of vortices to gain dynamical understanding of sensitivity gradients for a response function used to describe the steering of a tropical cyclone. Through these simplified
tests, he can conclusively show that the response functions used in previously published work for zonal and meridional steering of TCs suffers a major fault. This fault has been identified, and a new set of response functions to define TC steering have been proposed and tested within the simplified model. This methodology has been applied to several case-studies using the NOGAPS adjoint model, and the understanding gained from the simple model aides in the otherwise difficult task of dynamical interpretation of the adjoint sensitivity gradients.

Mr. Hoover’s work has direct implications for operational targeting strategies as the newly defined response function identifies regions that have different sensitivities than those found using other techniques. The lack of robust, positive impact from assimilating observations in previously defined sensitivity regions may be the result of an improper interpretation of what those response functions are in fact measuring. A manuscript of this work has been prepared and, after a few edits, this work will be submitted to either Monthly Weather Review or Journal of the Atmospheric Sciences, in November

Dianna Nelson

Over the summer, Ms. Nelson’s research has been focused on the predictability of Tropical Storm Alma, which formed in the eastern Pacific in late May of 2008. Alma was surprising well forecast by numerical weather prediction models more than a week prior to genesis. Ms. Nelson performed a case study of Alma with an emphasis on identifying large-scale features responsible for the accuracy with which global models predicted this storm. Over the course of researching this case, Ms. Nelson identified lower-tropospheric vorticity, a Hadley cell type circulation and an anomalous zonal lower-tropospheric jet as important antecedent features to the development of this storm. Sensitivity calculations revealed the importance of barotropic energy conversions associated with deformation to the development of the cyclone. Ms. Nelson is currently investigating to see what role, if any, the Madden Julian Oscillation played in the development of Alma. She will be also expanding her research to include numerous developing and non-developing tropical vortices. Furthermore, she will employ linear discriminant analysis as a tool to determine which large-scale features would be most useful to consider when predicting tropical cyclogenesis and, more generally, tropical cyclone intensity change, over the Pacific.

Future work:

1) Application of recently developed adjoint tools to more Western Pacific tropical cyclones (particularly those from the recent TPARC experiment) to assess predictability and improved identification of potential targeting areas.
2) Analysis of ensemble forecasts for 2008 season.
3) Investigate the use of ensemble forecasts to predict extra-tropical transition.
4) Application of statistical techniques to evaluate developing vs. non-developing cyclones.