Improving Tropical Cyclone Intensity Forecasting With Theoretically-Based Statistical Models

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LONG-TERM GOALS

The goal of this research is to improve tropical cyclone intensity prediction through a theoretical study of the hurricane inner core (i.e., within 100-km), the role of ocean structure on hurricane intensity, and the incorporation of those results in a simplified intensity prediction system. The intensity prediction system will be tested in an operational framework in the western North Pacific and provided to the Joint Typhoon Warning Center (JTWC) for evaluation. The intensity model is based on the statistical-dynamical logistic growth equation model (LGEM), which has generally been the most accurate operational intensity model in the Atlantic basin during the last several hurricane seasons.

OBJECTIVES

The objectives of this project are to improve basic understanding of tropical cyclone intensity change and apply those results in a simplified intensity forecast system. The project has three basic parts, which include (1) Development of a basic version of LGEM for the western North Pacific; (2) Perform a theoretical study of warm core development using a balance model; (3) Perform ocean structure analyses using output from a sophisticated ocean data assimilation system. The results from parts (2) and (3) will then be used to guide the development of an improved version of LGEM that will be tested in real-time.

APPROACH AND WORK PLAN

This is a three-year project to improve tropical cyclone intensity prediction. The starting point for this work is to develop a basic version of the LGEM model for the western North Pacific. Versions of this model are already available for the Atlantic and eastern North Pacific and have performed very well over the last few hurricane seasons (Franklin 2009). LGEM uses a first order differential equation that confines the intensity forecast to lie between zero and an empirical estimate of the storm's maximum potential intensity. The intensity growth rate is an empirical function of storm environmental variables such as vertical wind shear and vertical instability, which are obtained from global model forecasts. The current version includes little direct information about the storm inner core or the sub-surface ocean structure. The next step is to perform a theoretical study of intensification using a simplified balance model to study warm core formation. This study will help to identify configurations of convective heating and the radial distribution of tangential wind that are conducive to intensification. In parallel with the inner core study, ocean analyses from the HYCOM/NCODA system will be used to study the relationship between surface and sub-surface ocean structure and tropical cyclone intensity change. HYCOM is the Hybrid Coordinate Ocean Model, and NCODA is the Navy Coupled Ocean Data Assimilation system. The operational LGEM model in the Atlantic and eastern North Pacific currently include ocean structure information in a very simplified manner through a vertically integrated measure of the oceanic heat content (OHC) estimated from satellite altimetry (Mainelli et al 2005). The NCODA analyses will be used to determine more general measures of OHC and estimates of the response of the ocean to forcing by the tropical cyclone surface wind. In the latter stages of this project, the insights gained from the balance model theory and ocean analysis will be used to guide an improved version of LGEM. The balance model ideas can be applied to tangential wind profiles obtained from aircraft reconnaissance data and possibly from satellite observations, along with convective heating profiles obtained from microwave satellite data and radar observations when available. The ocean parameters can be estimated from real-time HYCOM/NCODA analyses and forecasts.

The CSU PI (W. Schubert) is responsible for the overall project management and is leading the theoretical study of warm core development. The NRL co-Investigators (C. Sampson and J. Cummings) are performing the ocean structure analysis and will also participate in the testing of the generalized LGEM model. The NESDIS Co-Investigator (M. DeMaria) is developing the west Pacific LGEM and will coordinate the incorporation of the theoretical results into the generalized version.

The primary milestones in the first year include (1) developing a basic western North Pacific version of LGEM, (2) Formulating a geopotential tendency equation (GTE) appropriate for the study of tropical cyclone inner core and writing a solver using Mathematica, (3) assembly and preliminary analysis of ocean datasets. Results on these three topics are described below. In the second and third years of the project, the GTE will be analyzed over a wide range of parameters, the basic version of LGEM will be tested in real-time, new ocean parameters relevant to tropical cyclone intensity forecasting will be developed, and a generalized version of LGEM will be derived and tested.

WORK COMPLETED

Progress was made on all three of the first year milestones described above. As described by DeMaria (2009), there are two basic versions of the LGEM model. The most general version uses the adjoint of the model to fit the basic model parameters using real data. This version was fitted to a 10 year sample of storm cases, and the results are very similar to that for the Atlantic and eastern North Pacific versions. A solver for the GTE was developed using Mathematica and a preliminary investigation of the response of tropical cyclone intensity and wind structure to the diabatic heating and inertial stability profiles was performed. A preliminary ocean analysis dataset was assembled and a number of ocean parameters have been selected for initial analysis. Further details are provided in the Results section.

RESULTS

The LGEM model is governed by the logistic growth equation given by

$$dV/dt = \kappa V - \beta(V/V_{mpi})^n \qquad (1)$$

where V is the maximum wind, t is time, V_{mpi} is the maximum potential intensity, β and n are empirical constants and κ is the growth rate, which is assumed to be a linear function of storm environmental variables. The parameter V_{mpi} is determined from an empirical relationship with sea surface temperature (SST) and β, n and κ are determined by fitting the model to a large sample of cases. A 10 year sample (2001-2010) of global model atmospheric analyses and Reynolds SST fields was obtained, and preliminary results indicate that the free parameters for the western Pacific are very similar to those for the Atlantic and eastern North Pacific. This result indicates that the LGEM formulation is appropriate for the western North Pacific, and will serve as a framework for the intensity forecast system. It is anticipated that the model can be improved by making κ a function of parameters identified by the GTE study applied to observed wind and convective heating estimates, and by making V_{mpi} a function of ocean structure parameters in addition to SST.

A pair of Mathematica notebooks have been developed to determine solutions of the geopotential tendency equation (GTE) and determine the associated tangential wind tendency for a variety of initial tangential wind profiles and annular rings of diabatic heating. The notebooks are currently separated into calculation and display of results, and contain multiple initial vortex profiles with parameters that control the maximum tangential winds and the radius of maximum tangential winds (RMW), or the strength of the overall vortex. A paper is in preparation with the results of the initial theoretical profile results.

Figure 1 shows the results from one of the specified profiles, a Gaussian vortex with maximum tangential winds of 30 ms^{-1} at a radius of 30 km. When the diabatic heating occurs inside the RMW (Figure 1a) the vortex shows the strongest increase in tangential winds and the RMW contracts, consistent with theory. Diabatic heating across the RMW (Figure 1b) can serve to intensify the vortex and shift the RMW either inwards or outwards, depending on the amount of diabatic heating contained within the initial RMW. Diabatic heating located outside the RMW, but still within the vorticity skirt (Figure 1c) can also lead to an increase in the maximum tangential winds and the RMW, though the increase in maximum tangential winds is much weaker than the response to the previous two scenarios. Diabatic heating extending outside of the vorticity skirt (Figure 1d) tended to produce a tangential wind increase at the location of the heating-induced inflow maximum (not shown). Depending on the initial vortex profile and parameter specification, this sometimes led to the development of a secondary tangential wind maximum.

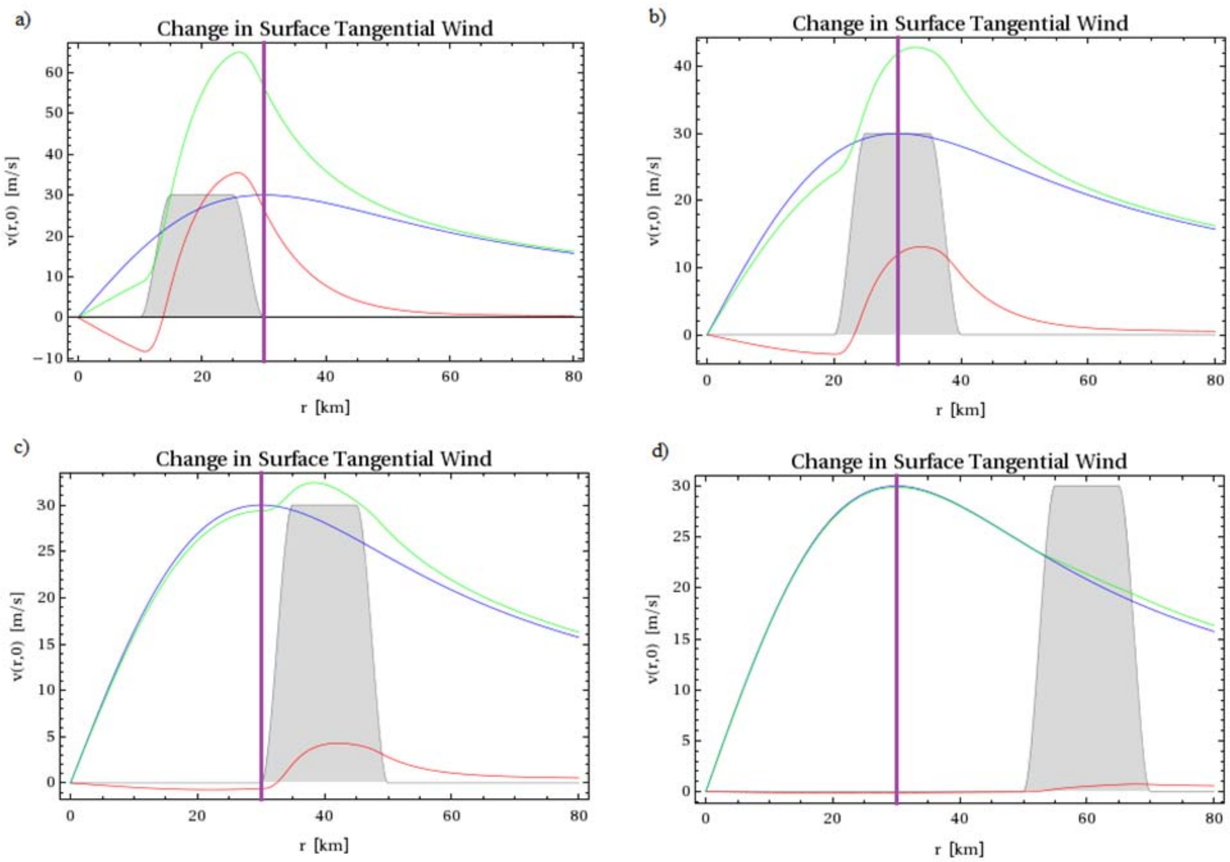

Figure 1: Initial surface tangential wind profile (blue), six hour surface tangential wind tendency (red), six hour total surface tangential wind (green), and initial diabatic heating (grey, pictured normalized to initial maximum tangential winds of 30 ms^{-1}). Radius of maximum winds (RMW = 30 km) indicated by purple vertical line. The location of the diabatic heating is a) inside the RMW, b) across the RMW, c) outside the RMW but inside the vorticity skirt, and d) outside the vorticity skirt.

Calculations of integrated kinetic energy were also added for comparison with the work of Maclay et al. (2008). Diabatic heating within or across the RMW was found to increase the maximum tangential winds more than the integrated kinetic energy, while diabatic heating outside of the RMW was found to increase the integrated kinetic energy more than the maximum tangential winds. This allows for further examination of the changes in the inner core and overall structure of the vortex.

Assembly of ocean model datasets is progressing well. We have agreed upon the following 12 parameters for this dataset:

1) OHC down to 20 deg isotherm,
2) OHC down to 26 deg isotherm,
3) Layer-averaged temp down to 100m (T100),
4) Layer-averaged temp down to maximum stability (-1/rho)*(d rho/d z),
5) Layer-averaged temp down to mixed layer,
using density difference from sfc 0.15,
6) Layer-averaged temp down to mixed layer using temp difference 0.5,
7) Sea Surface temperature,
8) Topography of OHC20,
9) Topography of OHC26,
10) Topography of maximum stability depth,
11) Topography of mixed layer depth from density difference, and
12) Topography of mixed layer depth from temp difference.

All of these parameters can be computed from the existing NCODA dataset on the GODAE server (www.usgodae.org) maintained by NRL Monterey. The top six parameters are products that represent ocean heat. The traditional OHC products integrate heat content only to the point that the 26 degree isotherm comes to the surface. This can cause problems forecasting tropical cyclones moving into colder water where the ocean may have adverse effects on tropical cyclone intensity. It is hoped that one or more of these new NCODA products will provide for better forecasting of both intensifying and decaying systems. A sample graphic for the first product (OHC down to 20 deg isotherm) is shown in Figure 2.

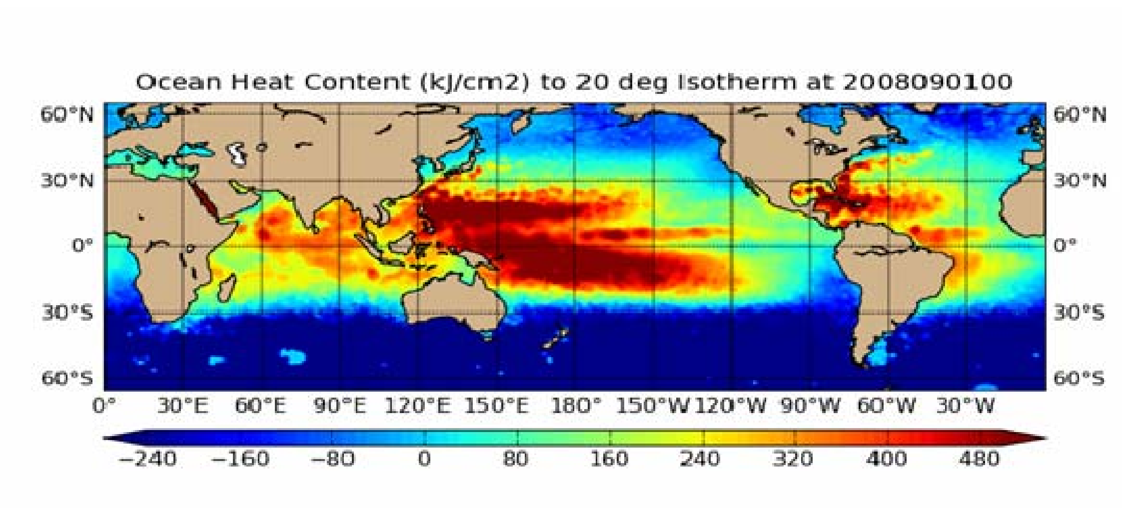

Figure 2. The oceanic heat content (OHC) using a new formulation that uses 20°C as the base temperature rather than the currently used 26°C. The new formulation reveals additional ocean structure, especially in subtropical regions.

Assembly of the ocean model datasets is progressing well. A trial run of these parameters has been completed for the period Sep 1 through Sep 15, 2008. This time period was chosen as it coincided with Hurricane Ike. The Hurricane Forecast Improvement Project was also interested in OHC products for this time, so this trial run was also provided to HFIP. Graphical loops and the entire dataset can be found at: http://www.nrlmry.navy.mil/atcf_web/nopp_ohc/may28_2010/ . Plans are to wait until January 2011 before assembling the entire dataset because doing so allows us to get a 5-year dataset of consistent NCODA products.

IMPACT AND APPLICATIONS

National Security

The project has the potential to improve operational forecasting of tropical cyclone intensity changes, which have improved very slowly over the past two decades. Better intensity forecasts will aid in mitigation procedures during tropical cyclones, including coastal evacuations and relocation of Department of Defense assets.

Quality of Life

The improved intensity forecasts mentioned above will help to reduce the impacts of over-warning during landfalling tropical cyclones, reducing economic impacts of evacuations and other mitigation procedures.

Science Education and Communication

Undergraduate and graduate students are involved in the data processing and programming aspects of this project, which is contributing to their science education. The Mathematica application developed as part of this project can also serve as an educational tool to illustrate the relationships between convective heating and wind profiles in tropical cyclones and other atmospheric vortices.

TRANSITIONS

National Security

If successful, the LGEM intensity forecast model being developed as part of this research can be transitioned for use by the Joint Typhoon Warning Center. This transition will impact the DoD through improved forecast products.

RELATED PROJECTS

This project is closely related to the Hurricane Forecast Improvement Project at CSU and the co-located Cooperative Institute for Research in the Atmosphere. Improved statistical-dynamical models and model diagnostic techniques are under development as part of that effort, with an emphasis on Atlantic tropical cyclones. See http://rammb.cira.colostate.edu/research/tropical_cyclones/hfip/ for more details.

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