Improving Tropical Cyclone Intensity Forecasting With Theoretically-Based Statistical Models

Year 2 Annual Report

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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 included (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. Progress on these milestones was provided in the Year 1 annual report and the NOPP review, held in February 2011. The second year milestones include (1) testing the West Pacific version of LGEM on independent cases, (2) Applying the GTE for a wide range of input parameters, and (3) developing applications of the new ocean data for intensity prediction. Progress on the second year milestones is described below. In the third year of the project, the GTE will be applied to real data from aircraft and satellite, and a generalized version of LGEM with the GTE input and new ocean parameterization will be derived and tested.

WORK COMPLETED

Progress was made on all three of the second year milestones described above. The West Pacific version of LGEM was developed and is being evaluated on independent data collected during the latter half of 2011, the GTE equation was converted to FORTRAN and evaluated with a wide range of parameters, and the relationship between the new ocean parameters and the ocean response to the tropical cyclone forcing is being investigated. Preliminary work has also begun to test the GTE with real data. 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. An 11 year sample (2000-2010) of global model atmospheric analyses, Reynolds SST fields and geostationary satellite imager was obtained for the model fit. The NCODA ocean fields from 2005-2010 were also used to estimate the OHC. For 2000-2004, the OHC was estimated from satellite altimetry using the method described by Goni et al. (2009). Results showed that the fit of the parameter κ to the atmospheric and ocean input parameters is slightly better than that in the Atlantic and east Pacific. For the dependent sample, the intensity errors are much smaller than those from the JTWC operational forecasts, as shown in Fig. 1 below. Although there will be some degradation when the model is tested on independent cases with input that is available in real time, the dependent results suggest that LGEM has the potential to improve tropical cyclone intensity forecasts in the western North Pacific. All of the real time input data (GFS model forecast fields, IR imagery from geostationary satellites, and the NCODA ocean analyses) needed to test LGEM on independent cases has been collected at CIRA since June of 2011. The evaluation of LGEM for these independent cases is underway. It is anticipated the LGEM will be run in real time in 2012 and provided to JTWC forecasters for evaluation. In the third year of the project, LGEM will be generalized to use the GTE input and the new ocean cooling parameterization.

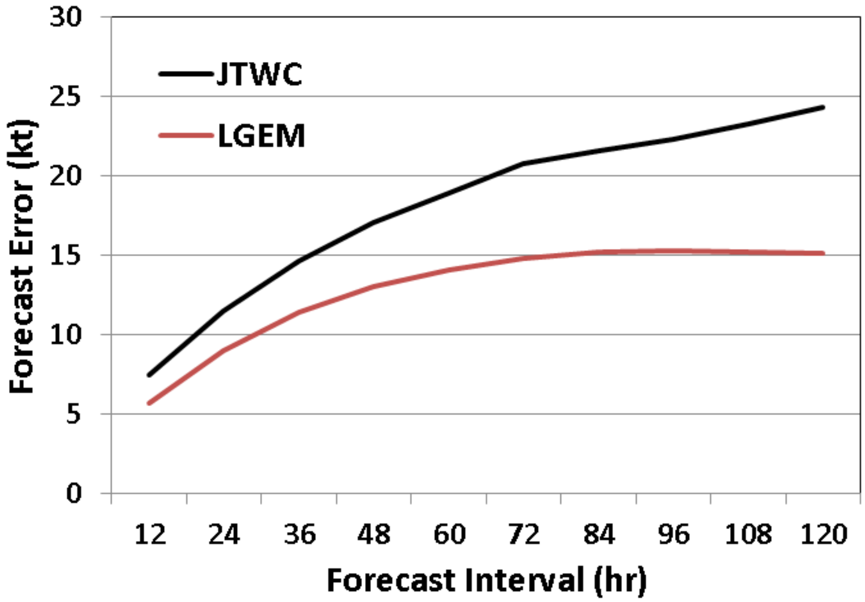

Figure 1. Average intensity forecast errors for the LGEM dependent sample (2000-2010) and the 5 year mean (2006-2010) JTWC official forecasts. The sample is not homogenous and the LGEM results are dependent, but the large difference between the LGEM and JTWC error illustrates the potential of LGEM to improve the intensity forecasts for the western North Pacific.

Schubert and McNoldy (2010) showed that the strength of the tropical cyclone vortex dramatically alters the strength and vertical influence of the secondary circulation. For strong vortices, Rossby lengths are small and Rossby depths are large, so that the secondary circulation is more vertically elongated and so horizontally compressed that some of the eyewall updraft can return as subsidence in the eye. For strong vortices, the secondary circulation associated with eyewall diabatic heating can be significantly suppressed by the large inertial stability in the interior of the vortex (Figure 2 shows r-z cross-sections of the streamfunction for four vortices of increasing intensity). The large variations of Rossby depth with vortex strength also have important implications concerning how far Ekman pumping can penetrate vertically; only strong vortices have large enough Rossby depths to allow Ekman pumping to penetrate deep into the troposphere.

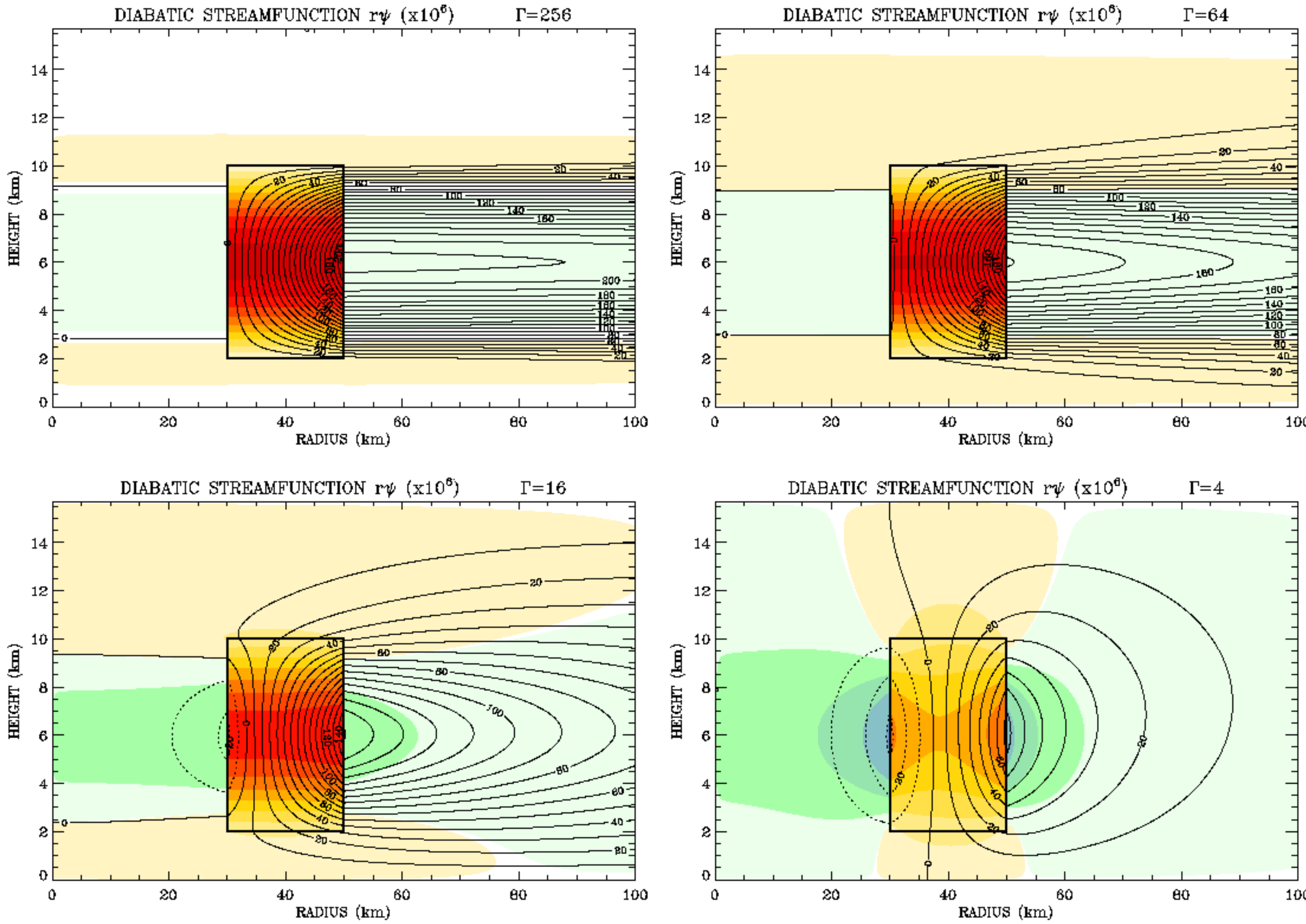

Figure 2. Line contours are isolines of rψ, forced solely by diabatic heating. The sense of the circulation is counterclockwise for the dashed lines and clockwise for the solid lines. The four panels are created for z_1 = 2 km, z_2 = 10 km, r_1 = 30 km, r_2 = 50 km, $\dot{\Theta}_{max}$ = 100 K day^{-1}, and Γ = 256 (weak), 64, 16, 4 (strong). The black rectangle indicates the region of diabatic heating. Colored contours indicate ω, the vertical pressure velocity, which is related to w by $\omega = -g\rho w$, with ρ denoting the pseudodensity. Warm colors are upward, cool colors are downward, and the contour interval is 5 hPa hr^{-1}. Please see Schubert and McNoldy (2010) for a description of the parameters.

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.

Figure 3 shows the results from one of the specified profiles, a Gaussian vortex with maximum tangential winds of 30 m s^{-1} at a radius of 30 km. When the diabatic heating occurs inside the RMW (Figure 3a) the vortex shows the strongest increase in tangential winds and the RMW contracts, consistent with theory. Diabatic heating across the RMW (Figure 3b) 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 3c) 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 3d) 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.

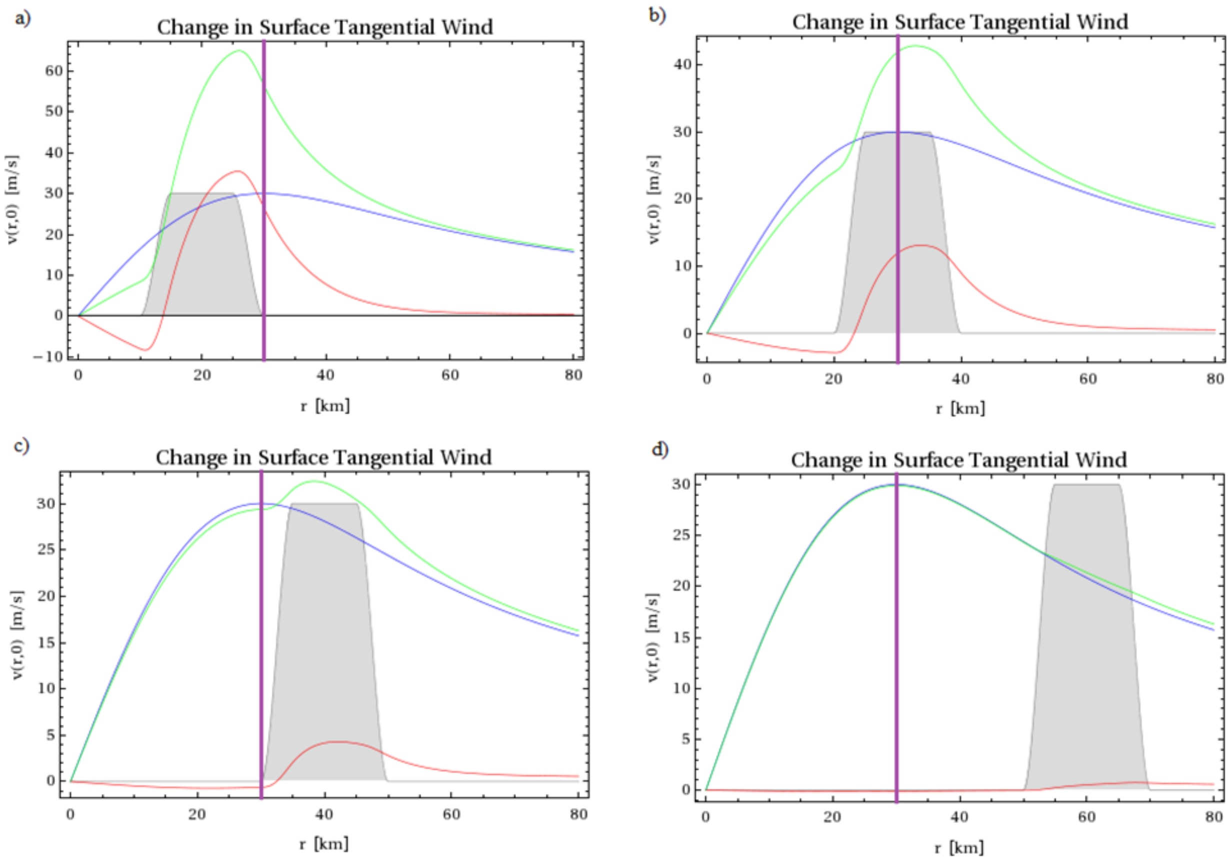

Figure 3: Initial surface tangential wind profile (blue), six hour surface tangential wind tendency (red), six hour total surface tangential wind (green), and initial diabatic heating (grey, pictured normalized to initial maximum tangential winds of 30 ms^{-1}). Radius of maximum winds (RMW = 30 km) 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 (IKE) 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. The results from the GTE and IKE work are summarized in a recently-submitted journal article (Musgrave et al. 2011).

Although useful for illustration, the Mathematic version of the GTE solver is not very portable. For this reason a FORTRAN version has also been developed. This version is being tested using input from the HWRF hurricane model as a first step toward applying it to real data. For the HWRF fields the forcing and the response to the forcing are both known, but some of the difficulties such as non-elliptic regions that will likely be encountered in real data are also present in the HWRF model output. Also, the response to the heating in HWRF is the total response, rather than the balanced response. A comparison of response in the HWRF model will provide insight into to the applicability of the GTE to real data cases.

Assembly of a 5-year ocean model datasets is now complete. We computed 12 parameters for this data-set for the entire period using the GODAE server (www.usgodae.org):

1) OHC down to 20 deg isotherm (OHC20),
2) OHC down to 26 deg isotherm (OHC26),
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.

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, which may be of limited use in TC forecasting in cool (<26 degrees) or shallow water near land. All six OHC parameters will be used for investigation of potential intensity and they will also be considered as potential input for LGEM.

The 5-year dataset has already been used to generate climatology of OHC parameters, as shown in Fig 4. Knaff et al. (2011) investigated ocean cooling responses due to TC passage and found that the ocean generally cools about 5-20 kJ cm^{-2} based on OHC26C and T100M. Simple parameterizations based on OHC and parameters routinely stored in the Automated Tropical Cyclone Forecast System (ATCF; Sampson and Schrader 2000) database have been developed. These parameterizations relate kinetic energy (computed from storm motion, intensity, and size) to ocean cooling, and could be used as sanity checks for energy budget computations.

Another aspect of the original proposal was to develop new intensity forecasts for JTWC. There are two significant developments in this regard. The first is that the SHIPS-RI probabilities have been shown to be useful in reducing mean errors and biases for consensus forecasts during RI events (Sampson et al. 2011). The second significant development is that COAMPS-TC has made a positive impact on the operational intensity consensus in the Atlantic. An intensity consensus that includes both objective aids was run real-time at NRL during the 2011 Atlantic season and the results are encouraging for both the biases and mean forecast errors (Fig 5). This bodes well for potential intensity forecast gains when SHIPS, SHIPS-RI and LGEM are developed for the western North Pacific.

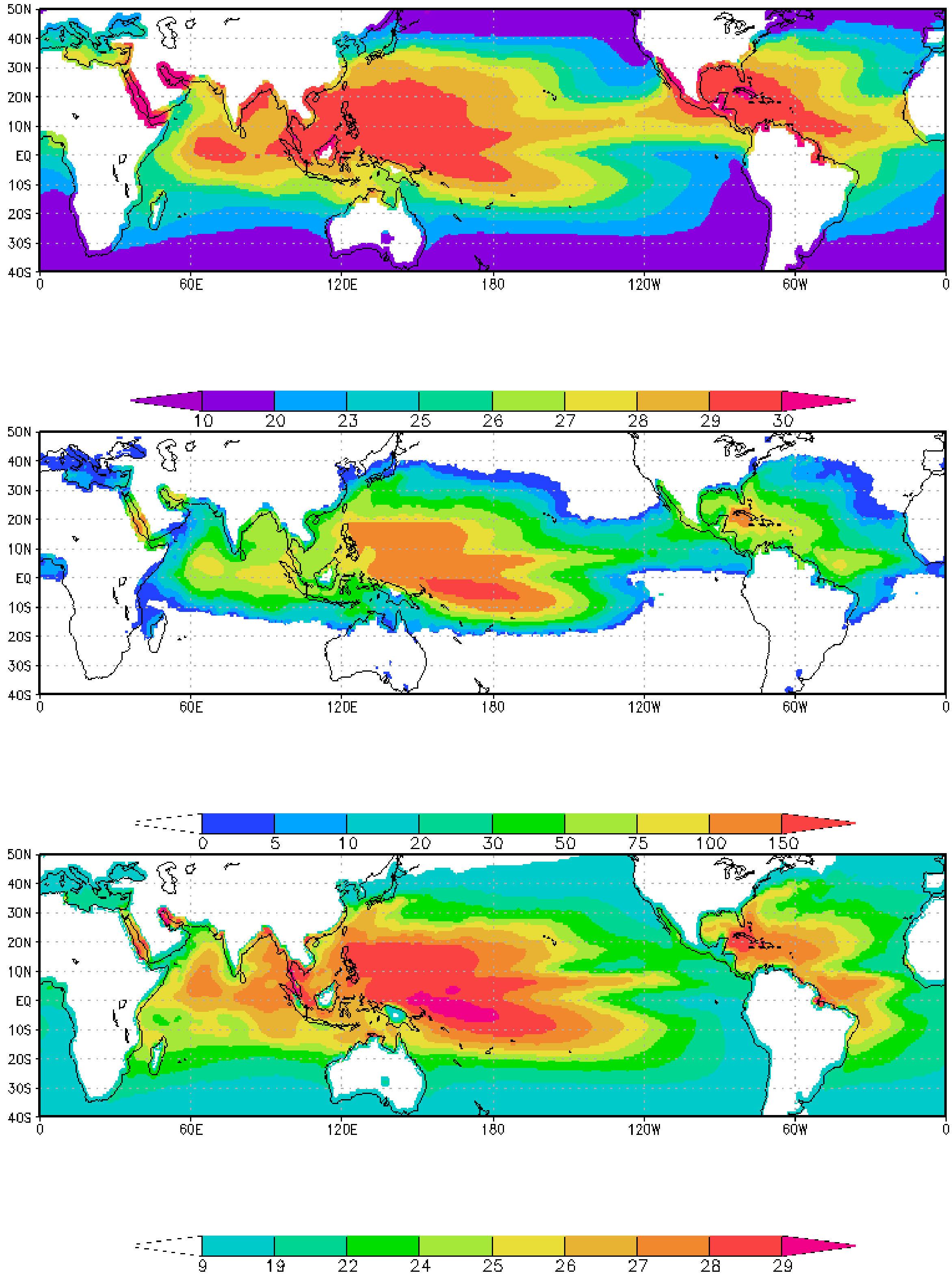

Figure 4. Panels show examples of 5-year climatological analyses of (top) SST, (middle) OHC26C, and (bottom) T100M valid on 15 September. Units are ºC for SST and T100 and kJ cm^{-2} for OHC26C.

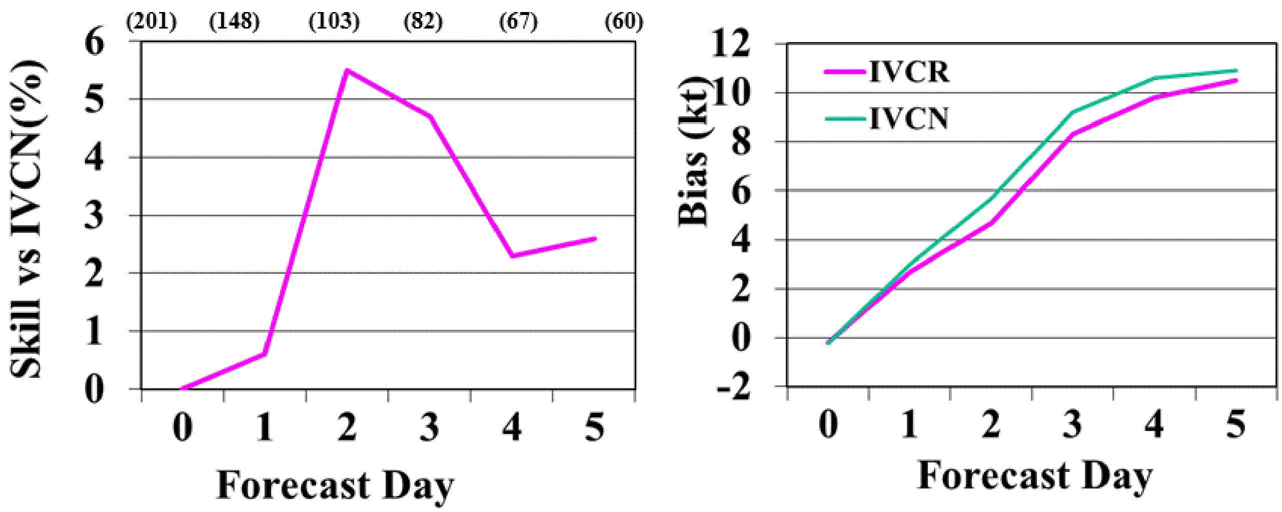

Figure 5. Preliminary 2011 Atlantic intensity forecast a) skill of experimental intensity consensus IVCR relative to IVCN, and b) bias of IVCR and IVCN. IVCN is the operational intensity consensus at NHC and IVCR is a consensus made up of all the IVCN members + COAMPS-TC + the RI aid. IVCR was run real-time at NRL for the 2011 season.

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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