Improving Tropical Cyclone Intensity Forecasting With Theoretically-Based Statistical Models

Year 3 (Final) 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 three-year project is focused on improving 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 was described in the Year 2 annual report. . In the third year of the project, the goals were to apply the GTE to real data from aircraft and satellite, and a develop a generalized version of LGEM with the GTE input and a new ocean parameterization. This final report summarizes results of all three years of the project, with an emphasis on year 3.

WORK COMPLETED

Progress was made on all of the third 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 2012, 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. 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 imagery was obtained for the model fit. The new 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).

The west Pacific versions of LGEM and the related Statistical Hurricane Intensity Prediction Scheme (SHIPS) were delivered to NRL in July of 2012 and real time runs began in August of 2012. These two statistical-dynamical models were run with input from several global model fields and forecast tracks to make a forecast based on a consensus of those results. This approach has proven to be successful using an older version of a statistical-dynamical intensity model (the Statistical Typhoon Prediction

Scheme). The forecasts from the new consensus based on LGEM and SHIPS is referred to at S5YY. The S5YY forecasts were made available to JTWC forecasters beginning in Mid-August of 2012. Figure 1 shows that the new S5YY forecast model improves upon the older consensus model S5XX by up to about 14% for these real time forecasts. This is a significant accomplishment, since the west Pacific intensity errors have been improving at a very slow rate (less than 1% per year on average).

Figure 1. Average intensity forecast errors for theJoint Typhoon Warning Center (JTWC), the statistical dynamical ST5D model, consensus forecasts from the ST5D model (S5XX) and new LGEM/SHIPS consensus forecast system (S5YY) (left). Also shown (right) is the improvement of the S5YY model over the S5XX, which has generally been the best performing intensity model for the western North Pacific the past few years. These results are for real time forecasts from mid-August through mid-November of 2012. The sample size is shown just above the x-axis in the left panel.

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.

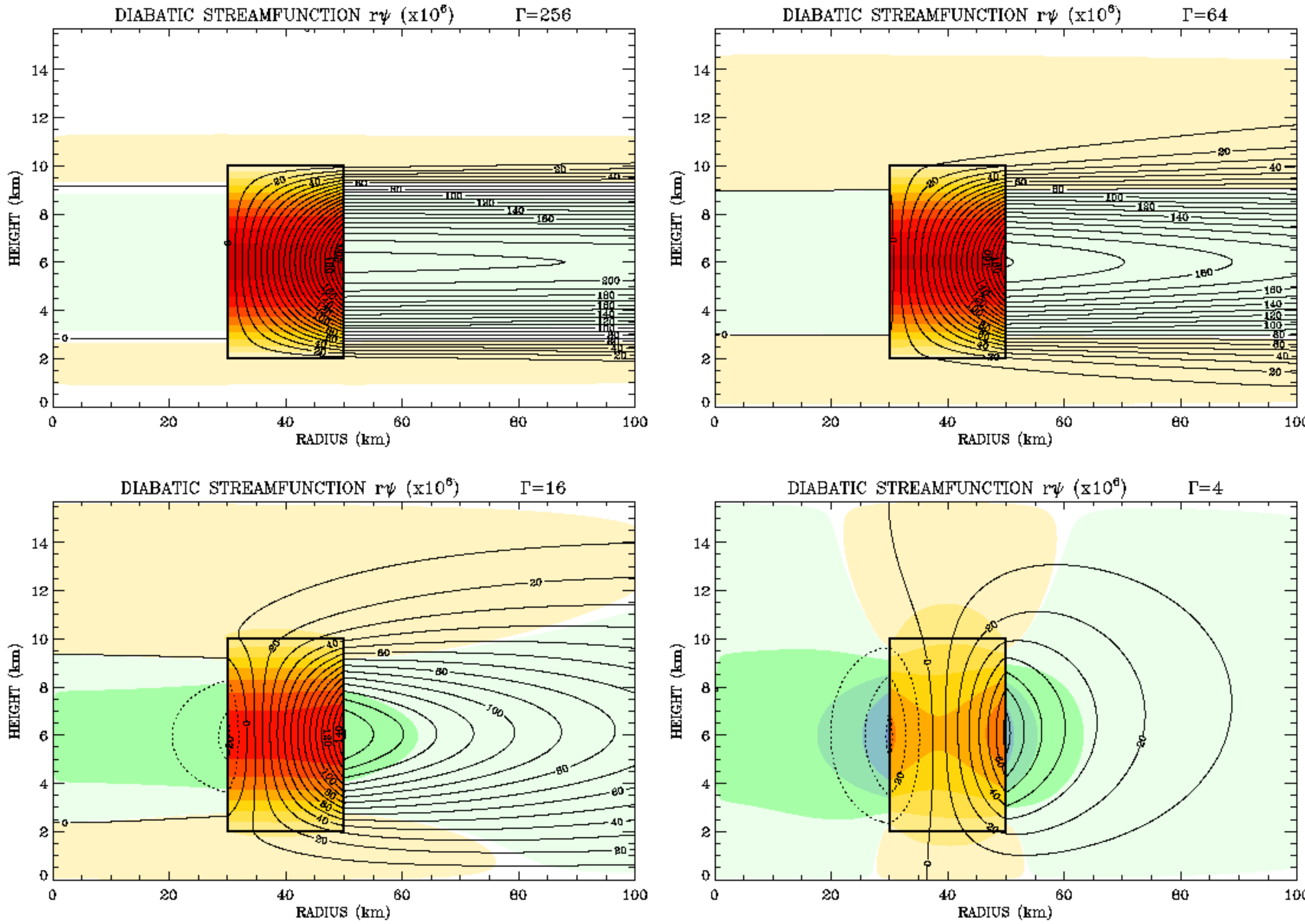

Figure 2. Line contours are isolines of $r\psi$, forced solely by diabatic heating. The sense of the circulation is counterclockwise for the dashed lines and clockwise for the solid lines. The four panels are created for z_1 = 2 km, z_2 = 10 km, r_1 = 30 km, r_2 = 50 km, $\dot{Q}_{max}$ = 100 K day^{-1}, 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.

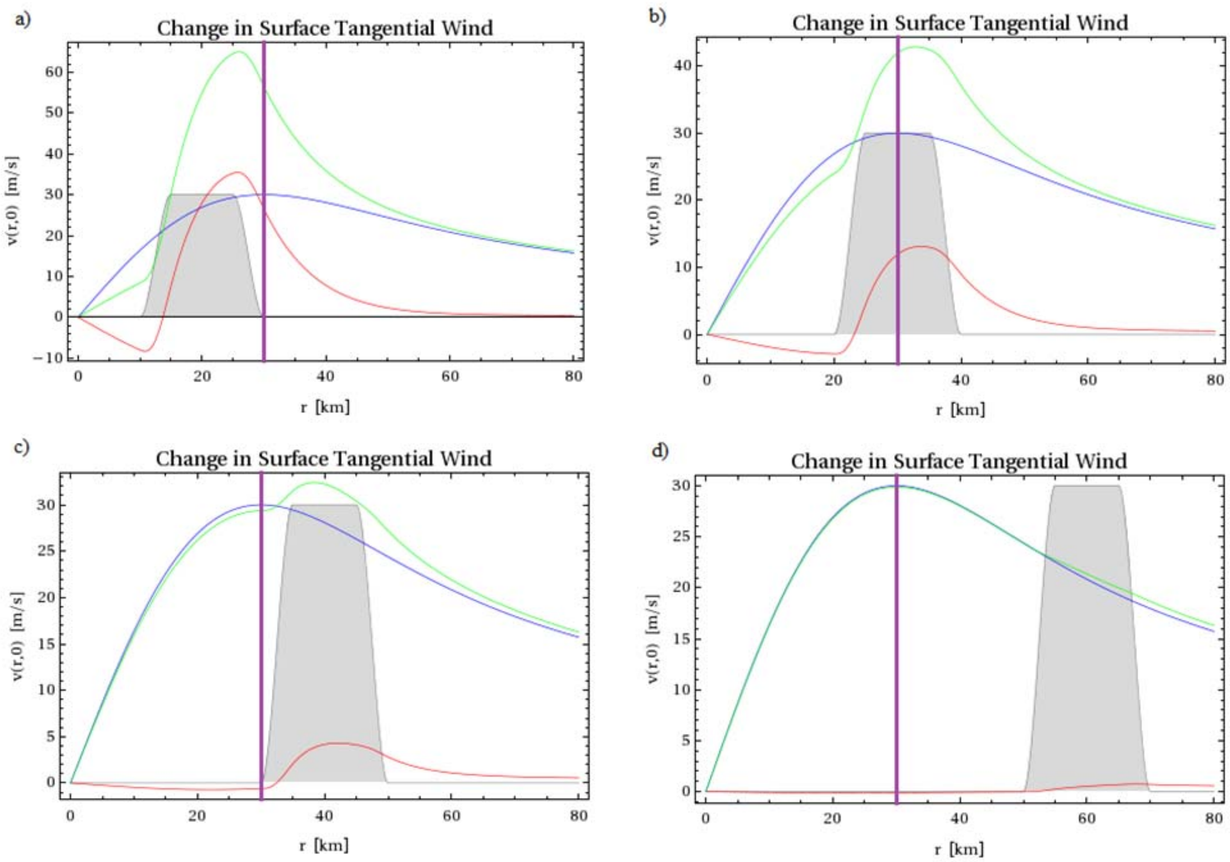

Figure 3: Initial surface tangential wind profile (blue), six hour surface tangential wind tendency (red), six hour total surface tangential wind (green), and initial diabatic heating (grey, pictured normalized to initial maximum tangential winds of 30 ms^{-1}). Radius of maximum winds (RMW = 30 km) 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 published journal article (Musgrave et al. 2012).

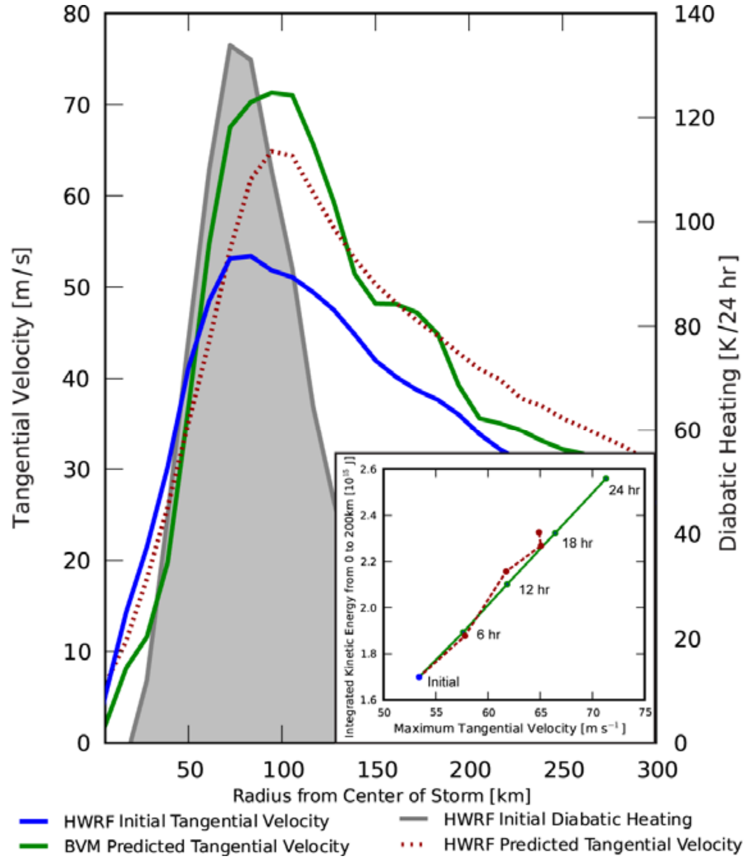

Figure 4: 78 hr forecast flight-level (700 hPa) tangential wind profile from the 1800 UTC 21 August 2011 HWRF run for Hurricane Irene (2011) used as GTE initial profile (blue), twenty-four hour total tangential wind from GTE (green), 102 hr forecast 1800 UTC 21 August 2011 HWRF run used as verification (red), and the total diabatic heating from the HWRF model (gray). Inset figure shows IKE for the 6, 12, 18, and 24 hr prediction. HWRF response (green) and HWRF model (red).

Although useful for illustration, the Mathematica version of the GTE solver is not very portable. For this reason a FORTRAN version has also been developed. This version has been 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. The forcing from HWRF is an instantaneous profile at a particular profile. To apply this forcing to the GTE, it is assumed that the forcing remains constant. A comparison of response in the HWRF model shows that the GTE solver can use the forcing from the HWRF model along with the tangential wind profile to account for the changes in intensity. Figure 4 shows an example from Hurricane Irene (2011) where the response of the GTE reflects the intensity changes seen in the HWRF model. The errors for the GTE during the 24 hr prediction are within the operational errors of the National Hurricane Center. In other examples (not shown), the GTE over-predicts changes in intensity when baroclinity, friction, and diffusive properties dominate. However, this result is expected due to the underlying assumptions used in forming the GTE. Overall, the results with the HWRF model show that the GTE is a simple and fast means of determining intensity change. The tests with the HWRF model warranted evaluation of GTE solutions with satellite-only input. For this stage of GTE evaluation, the automated objective, multi-satellite platform tropical cyclone surface wind analysis system data is used (Knaff et al. 2011) along with satellite rainfall rate estimates. Figure 5 shows the absolute mean error and bias of taking the satellite wind and rainfall rate and applying it to the GTE. As in the test with the HWRF model, the GTE over-predicts as seen in the bias for the 6, 12, 18, and 24 hr prediction. Again, this illustrates the effects of the assumptions used in the formation of the GTE.

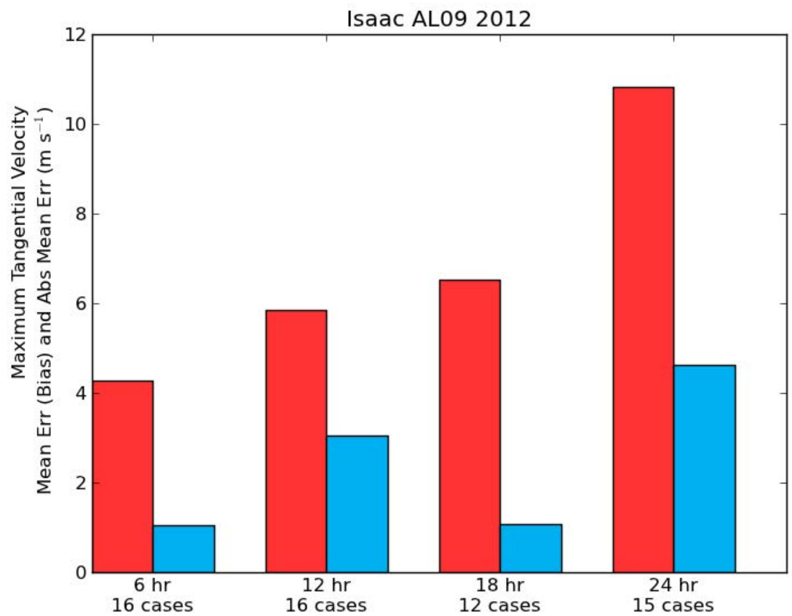

Figure 5: Mean error or bias (blue) and absolute mean error (red) for 6, 12, 18, and 24 hr predictions by the GTE using the microwave satellite data from the automated objective, multi-satellite platform tropical cyclone surface wind analysis system.

Assembly of a 5-year ocean model datasets is now complete. We computed 12 parameters for this dataset 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 are being used for investigation of potential intensity and they will also be considered as potential input for LGEM.

Knaff et al. (2012) investigated a number of questions about ocean responses to TCs using the NCODA based OHC26C and T100M in conjunction with the historical TC records. The investigation focused on composite analyses that show the type, magnitude, and persistence of upper ocean response to TC passage as a function of initial ocean conditions, latitude, translation speed, intensity, and a simplified (from TC wind radii) Kinetic Energy (KE) and then discussed possible relationships between these factors and the upper ocean response.

Previous studies suggesting a "local memory" to TC passage with respect to SSTs and SST recovery times of approximately 30-days were re-confirmed. The 10-day lagged decrease of energy in the upper ocean was observed to be between about 5 and 20 kJ cm^{-2} based on median OHC26C (Fig 6). Ten days following TC passage, the temperature in the upper 100m of the ocean also cooled between 0.3 and 0.7^{o}C (not shown). Variations in TC KE were found to play a role in cooling the upper ocean.

Multiple linear regression parameterizations for estimating 5, 10, 20 and 30-day changes in ocean heat content and SST based on routinely available data were also created using regression analysis and the composited data. Results suggest that after 10 days a typical hurricane results in a 12 kJ cm^{-2} reduction of OHC26C, cools the upper 100 m of the ocean 0.5^{o}C and cools the local SST 0.7 ^{o}C. Furthermore a significant signal of SST cooling and reduction of upper ocean energy persists through 30 days. Thirty days after the typical TC passes similar regression equation predict a lingering 7 kJ cm^{-2} anomaly of OHC26C, a 0.7 ^{o}C SST anomaly, and a 0.5 ^{o}C T100M anomaly. These simple estimates allow for an energy budget to be constructed based on the number of storms, their tracks, and their sizes.

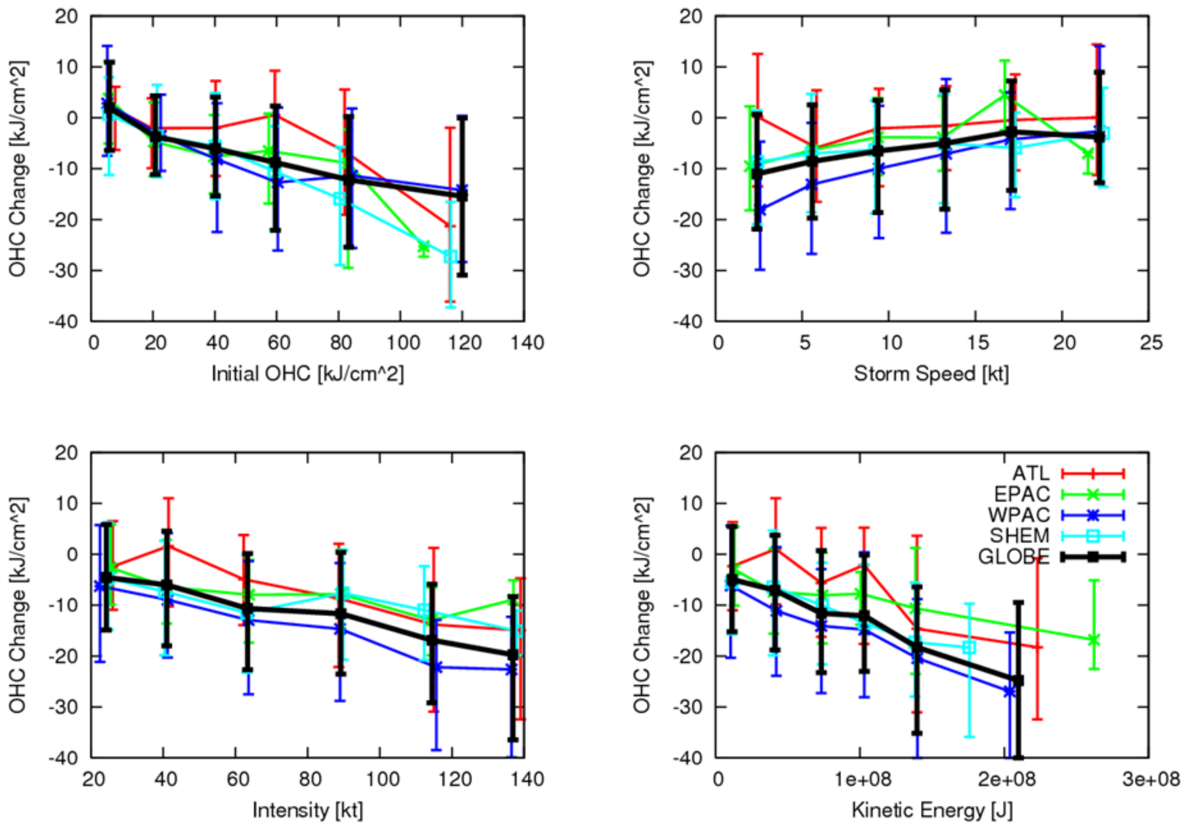

Figure 6: The 10-day OHC26C response to the passage of a tropical cyclone as a function of (top left) initial, OHC26C, (top right) storm speed, (bottom left) intensity and (bottom right) kinetic energy. Median values are indicated by the points and the bars indicate the quartiles of the distribution. Results are shown for the Atlantic (ATL, red), the east and central Pacific (EPAC, green), the northwest Pacific (WPAC, blue) and Southern Hemisphere (SHEM, magenta) TC basins as well as the global response (GLOBE, black).

The depressed ocean heat content, much like lower SST, persists for at least 30 days and possibly as long as 60 days. Our results suggest that the ocean recovers slow enough (means and medians do not recover fully in 90 days) that the inter-annual (e.g., ENSO) and inter seasonal (e.g., winter) signals mask the TC effects. Findings also suggest that there could be a negative feedback between the number and intensity of TCs and the ocean energy available for additional TCs that pass over recently TC-cooled ocean regions during a single TC season (i.e., 10 to 60 days).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 7). As was shown in Fig. 1, the consensus approach also worked very well in the new version based on the LGEM/SHIPS models.

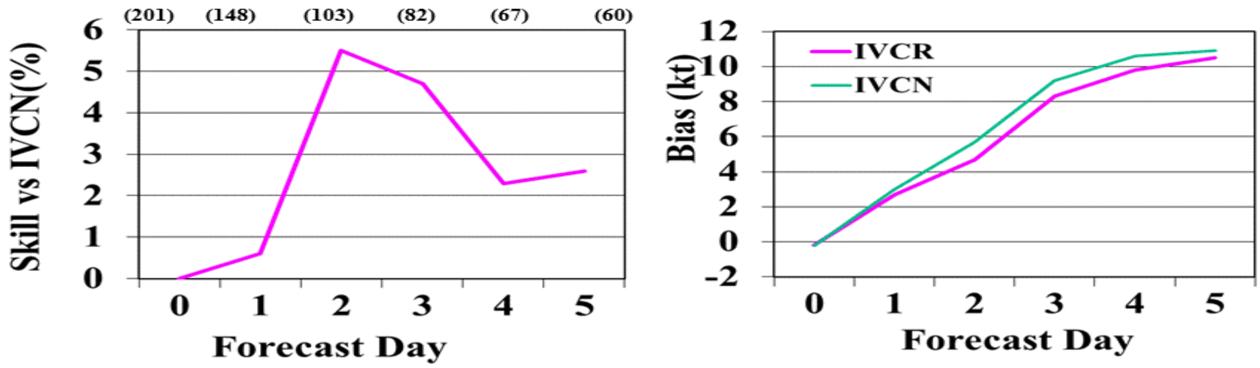

Figure 7. Preliminary 2011 Atlantic intensity forecast a) skill of experimental intensity consensus IVCR relative to IVCN, and b) bias of IVCR and IVCN. IVCN is the operational intensity consensus at NHC and IVCR is a consensus made up of all the IVCN members + COAMPS-TC + the RI aid. IVCR was run real-time at NRL for the 2011 season.

The new versions of SHIPS and LGEM developed in this project are being further improved by making additional use of the ocean input from the NCODA analyses. The current version of these models uses a simple empirical maximum potential intensity (MPI) estimate determined from the SST. A more general version has been developed that takes into account the SST and a vertical sounding. The new MPI is based on the theoretical formulation of Bister and Emanuel (2002), but also includes entrainment effects. This new MPI also includes an SST cooling algorithm that modifies the SST based on the OHC, the depth of the 26^{o}C isotherm and the storm translational speed. This version will be compared to the version that was run in real time in 2012. If further forecast improvements are realized through the new MPI formulation, that version will be transitioned to JTWC operations.

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. The new consensus intensity model is ready for operational transition, and provided improvements of up to 14% during the real time tests in 2012. 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 were involved in the data processing and programming aspects of this project, which contributed 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

The west Pacific LGEM and SHIPS intensity forecast model being developed as part of this research are being transitioned for use by the Joint Typhoon Warning Center. This transition will impact the DoD through improved forecast products. Based on the success of the 2012 demonstration, versions are also being developed for the Indian Ocean and southern hemisphere.

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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