9C.4 ENHANCEMENTS TO THE OPERATIONAL SHIPS RAPID INTENSIFICATION INDEX

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1. Introduction

Although some modest improvements have been made in tropical cyclone intensity guidance models over the past decade, predicting changes in tropical cyclone intensity remains a very challenging problem, especially for cases of rapid intensification (RI). In recent years, a statistically based rapid intensity index (RII) that employs large-scale predictors from the SHIPS model has been developed for operational use at the National Hurricane Center (NHC) for both the Atlantic and eastern North Pacific basins (Kaplan et al. 2010). Although the current operational RII uses only information from the large-scale environment as well as some gross measure of inner-core organization, the RII has exhibited some skill when validated for the 2008 and 2009 Hurricane seasons as will be discussed in more detail in section 2. Nevertheless, the skill of the RII is fairly low in the Atlantic and only in the low to moderate range in the E. Pacific basin underscoring the difficulty of predicting RI particularly in the Atlantic basin.

While the large-scale conditions help to set the stage for RI, the actual intensification process itself is related to the storm's inner core. Thus, this paper will explore the potential to improve the operational RII by including predictors derived from three new sources of inner-core information. The first of these three sources is the time evolution of inner-core structure as deduced from GOES infra-red (IR) imagery. Although some basic parameters from GOES IR imagery such as counts of cold cloud pixels are already included in the RII, the time evolution of the inner-core structure is not. In a recently completed study, complex principal component analysis was applied to tropical cyclones and consistent IR cloud-top patterns related to RI were found (Knaff 2008). The second source is microwave derived total precipitable water (TPW). Previous research utilizing the SHIPS model has shown that TPW is statistically correlated with intensity change (DeMaria et al. 2008). Thus, this study will seek to employ TPW to improve the RII. Finally, inner-core surface fluxes of heat and moisture will be tested for their ability to improve the RII. Estimates of surface fluxes can be obtained by utilizing GFS surface temperature and relative humidity fields and the sea-surface temperature (SST) determined from the SHIPS inner-core SST cooling algorithm (Cione et al. 2005). In this paper, a new version of the RII that includes real-time predictors based upon the above three new sources of inner-core information will be developed and evaluated against the current operational RII.

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2. Background

The SHIPS RII has undergone numerous changes since it was first provided in real time to the National Hurricane Center (NHC) during the 2001 Atlantic Hurricane Season. The original version (Kaplan and DeMaria 2003) compared the t=0 h magnitude of five large-scale predictors from the SHIPS model (DeMaria et al. 2005) to thresholds that had been determined previously from a sample of rapidly intensifying Atlantic basin systems to estimate the probability of rapid intensification (defined as a 24 h change $\geq$ 30 kt over the next 24 h). In succeeding versions, two GOES satellite-derived predictors were added to the index (bringing the total number of predictors used to seven) and several of the predictors were averaged over the entire 24-h period. The rapid intensity threshold was also lowered slightly to 25 kt and a version of the index was developed for the E. Pacific, since the original RII was developed exclusively for the Atlantic basin.

More recently, the method for deriving the index was modified so that that the contributions from each of the predictors represented a scaled value between 0 and 1 rather than either a 0 or 1 as had been employed in the original threshold version. These scaled values were subsequently weighted to determine the relative importance of each to rapid intensification utilizing linear discriminant analysis. Finally, an 8^{th} predictor determined from satellite altimetry data was added and the index was re-derived for additional rapid intensity thresholds (i.e., 30 and 35 kt). This discriminant analysis version of the RII was declared operational by the TPC/NHC prior to the 2008 Hurricane season. A more complete description of the methodology used to derive the current operational RII can be found in Kaplan et al. (2010). Table 1 shows the RI predictors that are included in the current operational version of the RII.

Previous 12-h intensity change
850-200 mb vertical shear from 0-500 km radius
200 mb divergence from 0-1000 km radius
850-700 mb relative humidity from 200-800 km radius
Percent area from 50-200 km covered by -30° C IR brightness temperatures
Std. dev of 50-200 km IR brightness temperatures
Potential intensity (Current intensity – maximum potential intensity)
Ocean heat content

Table 1. Predictors used in the operational Atlantic and E. Pacific RII.

Fig. 1 shows the mean relative weights of the RI predictors for all three RI thresholds (25-kt, 30-kt, and 35-kt) that were determined based upon linear discriminant analysis for the 1995-2008 developmental dataset. The figure indicates that the relative weights of some of the predictors vary both within and between basins since the weights of each of the predictors would be one if they were of equal importance. Table 1 indicates that the RII uses information that is primarily related to the large-scale environment with relatively little information related to the inner-core, save for some gross information deduced from GOES IR imagery. Nevertheless, Fig. 2 shows that the operational 2008 and 2009 RII forecasts exhibited some skill relative to climatology when verified for all 24-h forecasts times for which a system remained both over-water and either tropical or subtropical using the methodology described in Kaplan et al. (2010).

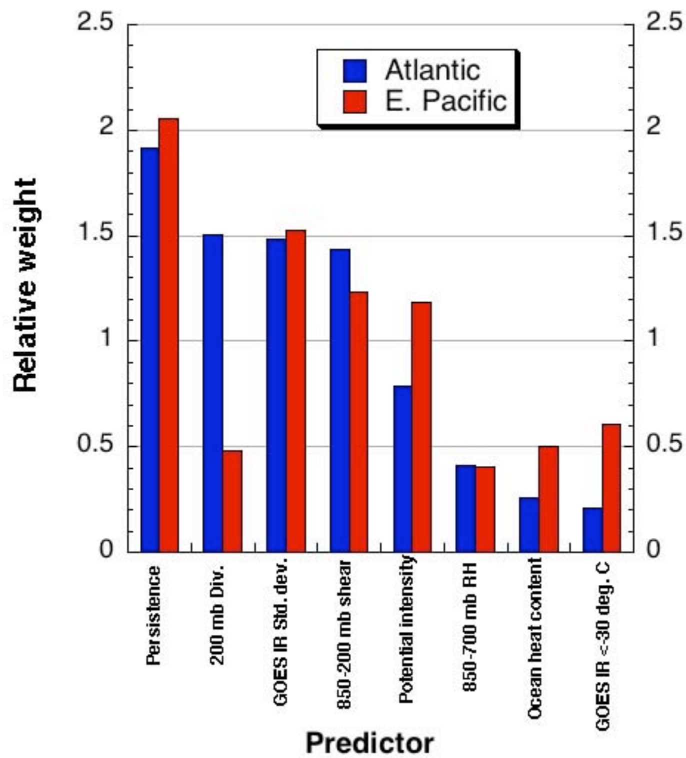

Fig. 1. Mean discriminant weights of the RI predictors for the Atlantic and E. Pacific versions of the RII for 1995-2008 developmental samples.

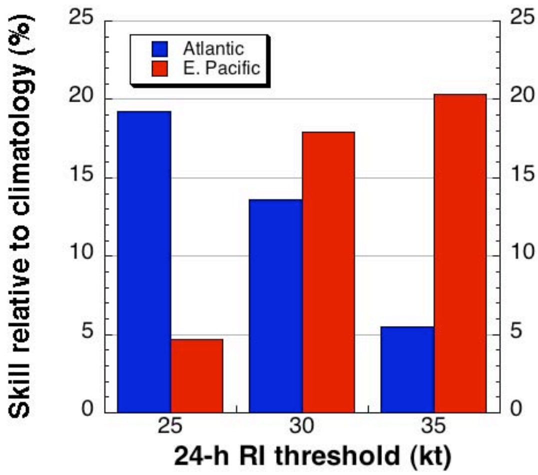

Fig. 2. The skill of the operational Atlantic and E. Pacific 2008-2009 RII forecasts.

In addition to exhibiting skill when used in probabilistic manner discussed above, Fig. 3 shows that the RII performed well relative to the other “early” operational intensity guidance in terms of the probability of detection, false alarm ratio, and Peirce skill score for a homogeneous sample of cases from the 2008 and 2009 Hurricane seasons. The Peirce skill score is used to evaluate contingency type forecasts and is 1 for a perfect forecast and 0 for random or constant forecasts (Wilks 2006). It is worth noting that the RII and the other intensity guidance exhibit considerably more skill predicting RI in the E. Pacific basin than they do in the Atlantic basin.

It is important to note that since the RII provides only RI probabilities and not a yes or no answer as to whether RI will occur, the statistics shown in Fig. 3 were obtained by applying the RI cutoff probabilities that had been previously determined for the 1995-2006 developmental sample to assess when to forecast RI to the operational 2008 and 2009 RII probabilities. These cutoff probabilities are 29.8,20.3 and 20.6 % in the Atlantic basin and 35.2%, 30.6% and 28.3% in the E. Pacific basin for the 25-kt, 30-kt and 35-kt threshold respectively. For the other operational intensity guidance, RI was forecast if the magnitude of the 24-h forecasted intensity change exceeded the corresponding RI threshold (i.e., 25, 30, or 35kt). Further details about the methodology used to obtain the Fig. 3 results can be found in Kaplan et al. (2010).

The aforementioned results suggest that the RII and some of the more recently developed models like LGEM (DeMaria 2009) and the 3-D dynamical HWRF model (Surgi et al. 2008) appear to have some limited skill in predicting RI. In attempt to assess the impact of the availability of this guidance on recent operational RI forecasts, the probability of detection, and false alarm ratio of the operational NHC RI forecasts were assessed for the periods 2006-2007 and 2008 and 2009 for both the Atlantic and E. Pacific basins. Fig. 4 indicates that NHC’s ability to predict RI has improved somewhat during the past few years as is indicated by the decrease in false alarm ratio and the maintenance or increase in the probability of detection between the periods 2006-2007 and 2008-2009. Thus, the availability of the aforementioned intensity guidance may have contributed, in part, to the observed improvements in recent operational RI forecasts.

3. Methodology

a. Development of new Atlantic predictors

As noted above, the current operational RII includes predictors that are gross measures of the large-scale as well as some fairly simple GOES IR predictors that provide a measure of the overall organization of the inner-core. Thus, some additional predictors derived from three new sources of information: principle components of GOES-IR imagery, TPW derived from microwave SSM/I imagery, and boundary-layer predictors derived from GFS analyses are developed and tested for their ability to improve the operational RII using the methods described below.

i. Time evolution of GOES IR imagery

The CIRA Tropical cyclone IR image archive for the period 1995-2008, was employed to perform Empirical Orthogonal Function (EOF)/Principle Component Analysis on storm-relative, direction-relative imagery. Using the first 9 EOFs, predictors for the SHIPS database were created. These included the six-hour averages of the first nine EOFs, the standard deviations, and the regression coefficients associated with these six-hour periods. These predictors were added to the SHIPS developmental database for testing with respect to rapid intensification.

ii. Total Precipitable water

The TPW was derived using microwave imagers (SSM/I, TMI, and AMSR-E) every 6 hours for the timeframe 1995-2008. All data in the region 0-60° N and 0-100° W was supplied by the Naval Research Laboratory (NRL) and employed to compute several storm-relative TPW predictors. These predictors included the TPW azimuthally averaged from r=0 to r=100 km, the TPW azimuthally averaged from r=100 to r=200 km, % TPW less than 45 mm in radii r=0 to

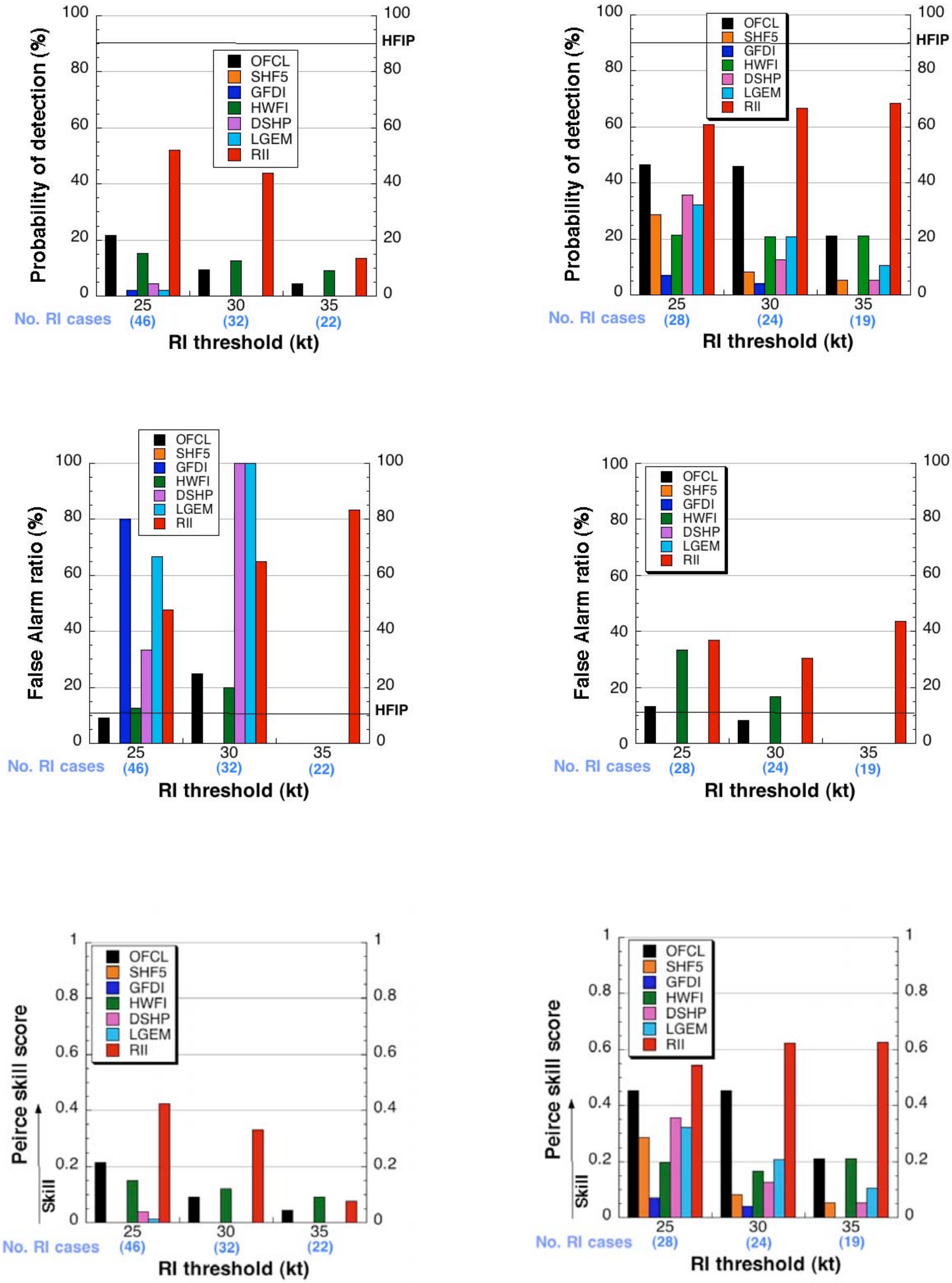

Fig. 3. The probability of detection, false alarm ratio, and Peirce skill score for the RII and operational intensity guidance for the 2008 and 2009 Hurricane season for the Atlantic (left panel) and E. Pacific (right panel) basins. For more complete definitions and a description of the above models consult Kaplan et al. (2010).

r=200 km and r=400 to r=600 km in the N, W, S and E quadrants, the %TPW less than 45 mm, r=0 to r=200 km and r=400 to r=600 km, front, left, back, right quadrants (storm motion relative quadrants), the %TPW less than 45 mm, r=0 to r=500 km, 90° quadrant centered upshear, TPW averaged r=0 to r=500 km, 90° quadrant centered upshear, and TPW averaged r=0 to r=500 km. The above predictors were added to the SHIPS database for testing in the new experimental RII.

iii. Boundary-layer predictors

Atmospheric temperature and moisture data obtained from the NCEP GFS analyses and sea-surface temperature (SST) estimates derived from the Reynolds gridded SST analysis and an inner-core cooling algorithm (Cione et al. 2005) were used to compute air-sea temperature and moisture differences and to estimate surface sensible and latent heat fluxes within the storm's inner-core region. A series of boundary-layer predictors were computed both directly from the GFS data as well as by first applying the empirical relationships developed by Cione and Uhlhorn (2003) to the GFS and SST fields.

b. Selection of predictors

As a first step at screening the above predictors for their ability to increase the skill of the operational RII, each was subjected to statistical significance testing for a homogenous sample of Atlantic cases from the 1995-2008 sample. Those predictors whose mean values for the developmental RI and non-RI samples were shown to be statistically different (at $\geq$ 99.9% level based upon a standard 2-sided t-test) were tested for their ability to increase the skill of the operational RII. This was accomplished by substituting the statistically significant predictors for select predictors in the existing operational RI shown in Table 1. Specifically, the new TPW predictors were tested as replacement to the 850-700 mb relative humidity (RH) predictor since both are measures of atmospheric moisture, while the GOES-IR PC predictors were tested as replacement for the two existing inner-core GOES predictors since they are all measures of inner-core organization as deduced using GOES IR imagery. Finally, the new boundary-layers predictors were tested in place of the potential intensity and heat content predictors since these predictors are all related to boundary-layer processes.

Sensitivity tests were then performed to determine if any of the new predictors increased the skill of the RII when they were substituted for predictors in the existing operational version that are listed in Table 1. The change in skill of each of the new predictors was then assessed by comparing the average skill of the experimental RII to that obtained using the current operational predictors using the methodology described in Kaplan et al. 2010 for the three RI thresholds that are used in the current operational RII (25-kt, 30-kt, and 35kt) as well as an additional RI threshold of 40 kt RI threshold for the Atlantic and E. Pacific basins.

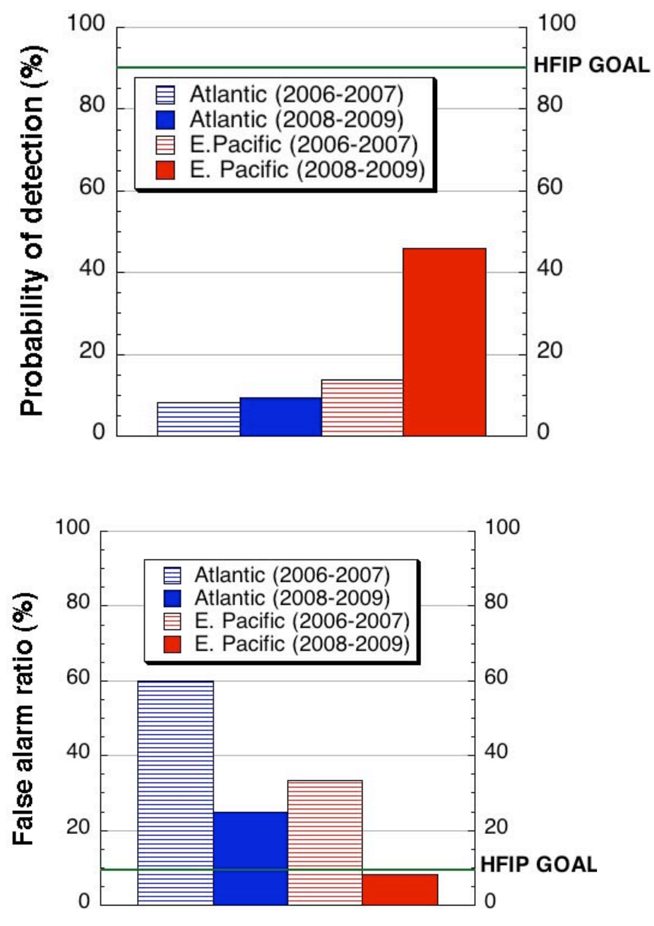

Fig. 4. The NHC operational probability of detection and false alarm ratio of RI forecasts for the periods 2006-2007 and 2008-2009 for the 30 kt RI threshold for the Atlantic and E. Pacific basins. The HFIP goals are also depicted.

Based upon the above sensitivity tests, three new predictors were selected to replace those in the existing operational version. The first of these three new predictors is the percentage of the area within 500 km radius 90° upshear of the storm center with TPW <45 mm at time t=0 h. This predictor is used as a replacement to the 850-700 hPa RH in the new experimental version of the Atlantic RII. Rapid intensification is favored when this predictor is small and hence the amount of dry air that is being advected into the storm circulation is relatively small. The cutoff of 45 mm as a delineator for dry air is based upon the results of Dunion (2009). Figure 5 shows an example of the distribution of TPW around several storms during the 1995 season. The blue and green areas represent regions where TPW <45 mm and thus the atmosphere is relatively dry between the surface and about 500 hPa (where ~90-95% of the contribution to TPW comes from) while the orange and red areas (>45 mm) represent regions where TPW exceeded that threshold and thus the atmosphere is relatively moist.

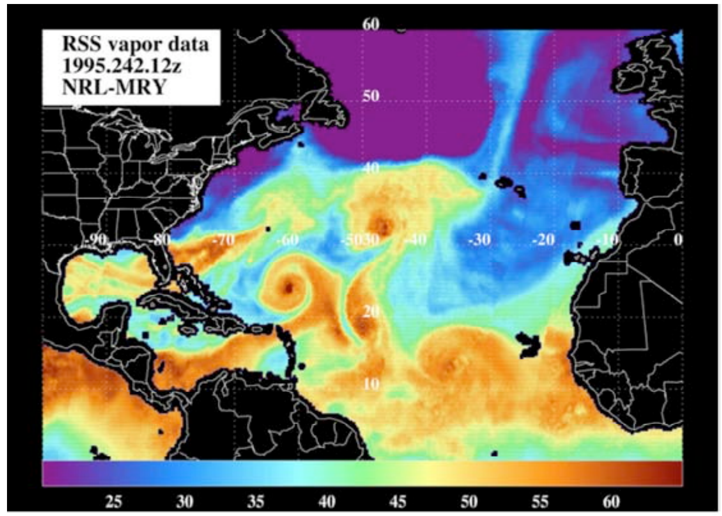

Fig. 5. Total precipitable water (TPW) during a select day during the 1995 Hurricane season. Data courtesy of RSS and NRL-Monterey.

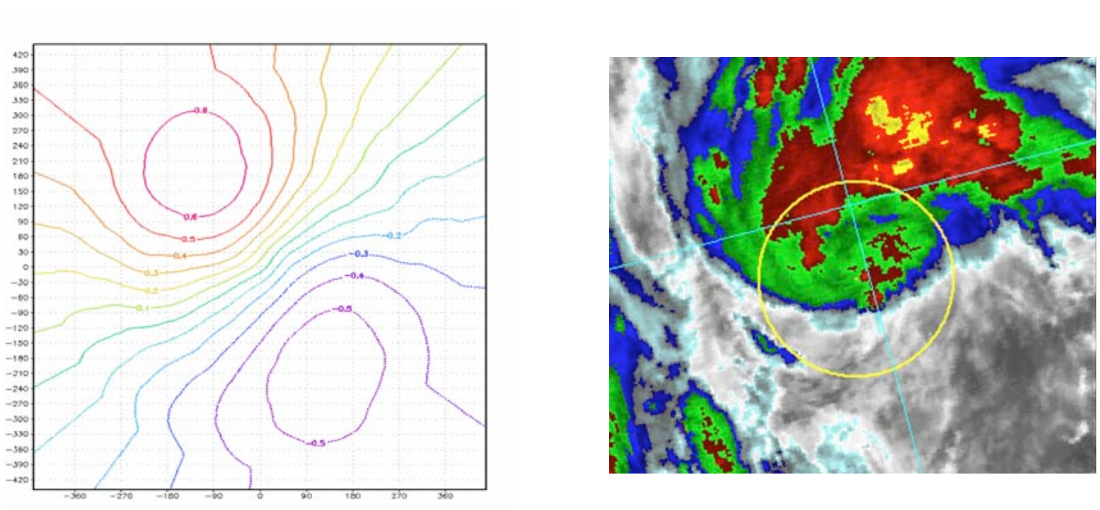

Fig. 6. Preferred pattern of PC2 (left) and an example of the corresponding GOES-IR representation for Hurricane Wilma at 1745 UTC on 17 October (right). The yellow circle denotes a circle with a radius of 440 km. The direction of motion is to the top-center of both diagrams.

Another one of the new RI predictors is the second principle component (PC2) computed from the GOES-IR imagery following the methods described in Knaff (2008). This predictor is used as a replacement for the percent area covered with GOES-IR brightness temperatures <-30° C in the new experimental version of the Atlantic RII. Figure 6 shows the favored overall pattern of the EOF of PC2 as an example of what the GOES-IR imagery looked like just prior to the episode of RI that Hurricane Wilma underwent during the 2005 Hurricane Season. The image shows that convection tends to be enhanced in the left front quadrant (when the storm motion is toward the top-center of the image) and suppressed in the right rear quadrant near the time that RI commences. This pattern often precedes axisymmetrizaton of the IR imagery (Knaff 2008).

The last new predictor is the inner-core dry air predictor that is given by:

$$(q10_{layer} - q10)*Vmx \quad (1)$$

where q10 is the inner-core specific humidity at 10 m obtained using the GFS ambient 200-800 km radius 1000 hPa temperature (T) and RH, $q10_{layer}$ is the 10 m specific humidity obtained using the ambient 200-800 km radius 1000 mb T and the layer-mean RH between 1000 hPa and 500 hPA, and Vmx is the NHC maximum sustained wind at t=0 h. The value of q10 is obtained by bringing the 1000 hPa air down to the surface (dry adiabatically if unsaturated at 1000 hPa and moist adiabatically if air is saturated) and then allowing the air to cool assuming that the RH reaches 95% as the parcel spirals into the storm core. The value of $q10_{layer}$ is obtained following the same methodology but using the 1000 hPa T and the layer-mean RH between 1000 and 500 hPa instead of the RH at 1000 hPa. Although this predictor was tested in place of the potential intensity and ocean heat content predictors that are currently used in the operational RII, it was ultimately used as a replacement to ocean heat content since it increased the skill of the RII when substituted for this predictor but not when it was substituted for the potential intensity predictor. It should be noted that small values of the inner-core dry air predictor, indicating less potential for dry air to mix down to the surface, are favored for RI. Table 2 shows the predictors used in the new experimental Atlantic RII.

Previous 12-h intensity change
850-200 hPa vertical shear from 0-500 km radius
200 hPa divergence from 0-1000 km radius
Total precipitable water
PC-2 from GOES-IR principle component analysis
Std. dev of 50-200 km IR brightness temperatures
Potential intensity (Current intensity – maximum potential intensity)
Inner-core dry air predictor

Table 2. Predictors used in the new experimental Atlantic RII.

In addition to replacing the three old operational RI predictors with three new ones described above, the scaling methodology that was used for the potential intensity and persistence predictors was modified slightly from that used previously in the operational RII since sensitivity tests showed that doing so improved the overall skill of the model for the developmental sample. Specifically, the peristence and potential predictors were scaled so that they were most favored for RI if their magnitude was equal to that of the average of all of the RI cases and then decreased for values above and below those values. Although these changes decreased the weights of these predictors (particularly the peristence predictor) it incresed the weights of the other RI predictors and resulted in an overall increase in skill of the RII when tested using both the old and new predictors in both the dependent and cross-validation tests conducted.

4. Results

Figure 7 shows the average relative weights of the RII predictors for all four RI thresholds (25-kt, 30-kt, 35-kt and 40-kt) that are determined from linear discriminant analysis (see Kaplan et al. 2010). The percentage of the weight of the three new RI predictors to the total of the weights of all eight RI predictors was also computed and

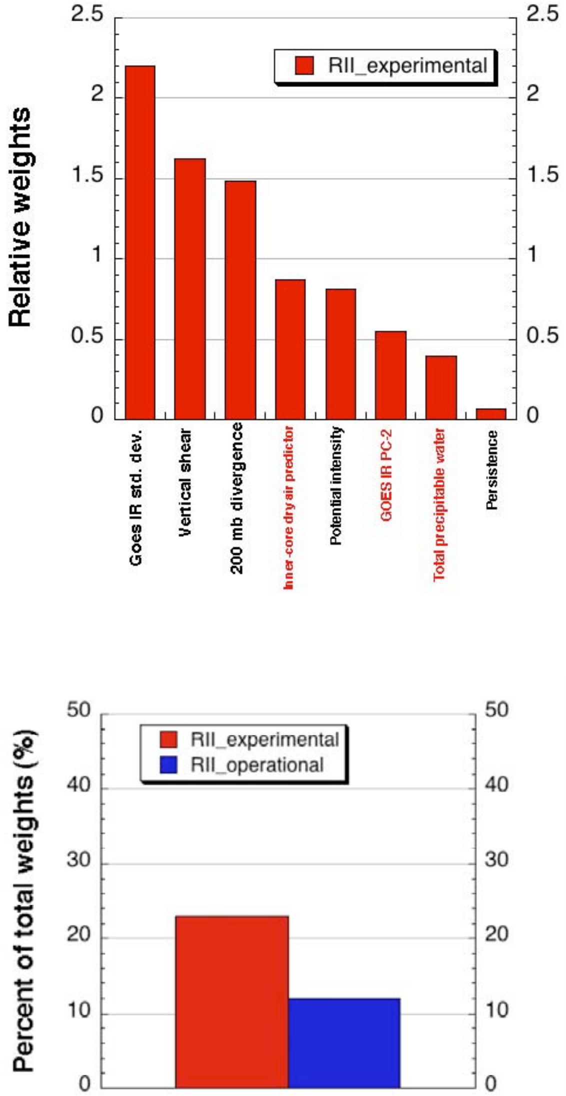

Fig. 7 Average relative weights of the RI predictors for the 25-kt, 30-kt, 35-kt and 40-kt RI thresholds for the new Atlantic experimental RII (the new predictors are higlighted in red) for the 1995-2008 developmental sample (top) and percentage contribution of three new replacement (red) and corresponding replaced operational (blue) RI predictors to the sum of the weights of the eight RI predictors that are used in the new experimental and old operational RII (bottom).

then compared to the weights of the three predictors that they replaced. These percentages were obtained by summing the weights of the three replacement (operational) RI predictors and then dividing those by the sum of the relative weights of all eight RI predictors used in the replacement (operational) RII. It can be seen that the new predictors (denoted in red) represent about 24% of the total weight of the eight RI predictors while the old operational predictors are only about 12%. The level of skill of the new experimental Atlantic RII index was compared to that of the current operational RII by performing a cross-validation for the 1995-2008 sample. To accomplish this, each of the 14 years that comprised the 1995-2008 sample were excluded one year at a time and the RII was re-derived and then re-run on cases from the excluded year.

The results from all 14 of the years were then combined to get the skill of each version of the RII for the 14 year sample. Figure 8 shows the skill of the RII for the 1995-2008 cross-validated sample. The figure shows that the new experimental RII is more skillful than the current operational verson for all of the RI thersholds save for the 40 kt threshold. Although slightly lower skill was obtained for the 40 kt RI threshold for the new experimental version of the RII, there were only 64 RI cases in the entire sample so this result may change when additional cases from the 2009 season are added to the sample. Nevertheless, the new experimental version of the RII increased the mean skill mean skill of the RII by about 3% over the operational version which represents roughly a 24% relative improvement for the 4 RI thresholds studied.

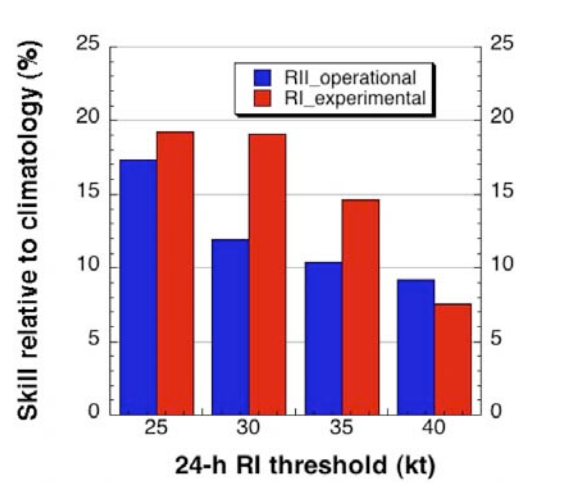

Fig. 8. Cross-validated skill of the current operational and new experimental RII for the 1995-2008 Atlantic sample.

Moreover, the skill of the new experimental RII is about 7% higher than the old operational version for the 30-kt RI threshold which represents a 60% relative increase in skill. Although ocean heat content is not currently included as one of the predictors in the new experimental RII, recent results suggest that it may be possible to increase the skill of the experimental RII by including it. Specifically, when ocean heat content was included as an additional predictor in the new experimental

RII the mean absolute dependent (cross-validated) skill increased by 1.5% (0.5%) for the 4 RI thresholds. The possibility of including ocean heat content as an additional predictor in the new experimental RII will be investigated further when the experimental RII is re-derived using data from the 2009 Hurricane Season in preparation for testing during the latter part of the 2010 Atlantic Hurricane Season.

5. Summary and future work

The operational 2008 and 2009 RII forecasts exhibited some skill in both the Atlantic and E. Pacific basins for the 2008 and 2009 Hurricane seasons although the skill was only on the low side in the Atlantic and in the low to moderate range for the E. Pacific basins. Nevertheless, an evaluation of operational NHC forecasts from the 2006-2007 and 2008-2009 season suggest that NHC's operational ability to forecast RII has improved some (particularly in the E. Pacific basin) during recent years which is likely due in part to the availability of the RII and some other new models like LGEM and the 3-D dynamical model HWRF which also appears to have some limited skill in predicting RII.

A new experimental version of the RII was developed for the Atlantic basin. This version included three new predictors, total precipitable water, the second principle component from an EOF analysis of GOES-IR imagery, and an inner-core dry air predictor deduced from GFS relative humidity analyses between 1000 and 500 mb in place of low-level 850-700 mb RH, areal-coverage of -30° C brightness temperature, and ocean heat content. It was shown that this version increased the mean skill of the RII by an average of 3% (24% relative improvement) for the 4 RI thresholds examined while also increasing the skill by 7% (60% relative improvement) for the 30 kt RI threshold for the cross-validated 1995-2008 Atlantic basin sample.

In the future, the new experimental RII will be re-derived utilizing the updated SHIPS database that includes cases from the 2009 season and the possibility of including ocean heat content as an additional predictor will be explored. The revised version of the experimental RII will then be tested in near real-time during the latter part of the 2010 Hurricane season. The potential of developing additional RI predictors from microwave imagery (see Velden et al. 2010) and lightning data (Knaff et al 2010) will also be explored as part of the GOES-R Risk Reduction Program. Finally, an experimental version of the RII analogous to the version that is being developed for use in the Atlantic basin will be developed for use in the E. Pacific basin and the potential for deriving a version of the RII for longer lead times (e.g., 48 h) will be explored.

Acknowledgements

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