The Operational Challenges of Forecasting TC Intensity Change in the Presence of Dry Air and Strong Vertical Shear

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1. INTRODUCTION

Tropical cyclone (TC) intensity changes involve complex interactions between many environmental factors, including vertical wind shear and the thermodynamic properties of the ambient atmosphere and ocean. While the effects of each factor are not completely understood, even less is known about the effects of these factors working in tandem. Emanuel et al. (2004) proposed that "storm intensity in a sheared environment is sensitive to the ambient humidity" and cautioned "against considering the various environmental influences on storm intensity as operating independently from each other." Along these lines, Dunion and Velden (2004) have examined the combined effects of vertical shear and dry air on TCs during interactions with the Saharan Air Layer (SAL). Operationally, the Statistical Hurricane Intensity Prediction Scheme model (SHIPS) (DeMaria et al. 2005) utilizes a multiple linear regression approach to account for a combination of influences from several environmental factors. However, environments with various combinations of shear and humidity pose particularly significant operational forecast challenges, not only for SHIPS but also for dynamical models and human forecasters. SHIPS remains the most skillful objective intensity guidance available to the National Hurricane Center (NHC), and improving its performance in complex environments would be of great operational benefit. This paper focuses on situations in which vertical wind shear and middle to upper tropospheric relative humidity (RH) interact in ways that the SHIPS model often does not anticipate.

Middle- to upper-tropospheric humidity in the environment of a TC, one of the predictors directly considered in the SHIPS model, is difficult to both measure and forecast. An inability to directly observe the humidity over the most of the open oceans forces forecasters and models to rely primarily on remotely sensed data, such as from water vapor channels on geostationary satellites. The available data and imagery do not provide obvious clues on how the environment will impact TC intensity. It is common to observe intense TCs completely surrounded by very dry middle- to upper-tropospheric air, whereas other storms appear to be negatively affected by similar conditions. Due largely to an incomplete specification of the initial moisture conditions, dynamical model forecasts of middle- to upper-tropospheric humidity often have large errors. Beyond the problems with observing and forecasting humidity, TC intensity forecasts become particularly challenging when dry air is accompanied by moderate to strong vertical shear.

Much of the current understanding on the response of a TC to vertical shear comes from idealized studies. It has been shown that strong vertical shear typically results in the convective pattern of the TC becoming increasingly asymmetric followed by a downshear tilt of the vortex (Frank and Ritchie 2001, Bender 1997). To keep the tilted TC vortex quasi-balanced, the diabatically-driven secondary circulation aligns itself to produce an asymmetry in vertical motion that favors stronger (weaker) vertical ascent in the downshear (upshear) direction (Jones 1995 and Zhang and Kieu 2005). This new alignment produces an increasingly asymmetric convective pattern with deep convection favored (suppressed) downshear (upshear) (Corbosiero and Molinari 2002, 2003). In the absence of other environmental forcing, the asymmetric convective pattern results in a disruption of the warm core followed by weakening of the vortex from the top down (Frank and Ritchie 2001) until reaching a steady state. The role that RH plays in this process is less clear.

More recently, a possible dynamical link between RH and vertical shear has been proposed by Zhang and Kieu (2005). Their results suggest that in strongly sheared cases, air tends to flow through rather than around the TC, as might occur with a less-sheared vortex. If their hypothesis is correct, shear allows increased entrainment of the ambient air, which, if dry, would tend to suppress convective activity. Given that the above results come from idealized studies, the concepts are difficult to apply directly in an operational setting.

The motivation of the present paper is to try to provide some initial steps toward bridging the gap between idealized studies and operational forecasting. We attempt to accomplish this in two ways: 1) through highlighting the uncertainties and operational challenges of forecasting TC intensity change in the presence of the dry air and strong vertical shear and 2) investigating the performance of the SHIPS model, and possible enhancements to that model, in cases where both strong vertical shear and dry middle- to upper-tropospheric air are present.

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2. DATA AND METHODOLOGY

Two open-ocean TCs (Irene and Nate) from the 2005 Atlantic hurricane season were selected for analysis based on the presence in those cases of moderate to strong shear but with differing humidity environments. We first performed synoptic case studies of Irene and Nate to obtain qualitative results on the impacts of shear and dry air in these cases. We utilized operationally available tools including traditional geostationary satellite imagery as well as Global Forecast System (GFS) model data to qualitatively assess the magnitude of vertical shear and RH. In an effort to also obtain more quantitative results, we analyzed vertical shear, RH, and potential intensity (POT = maximum potential intensity (MPI)–actual intensity) versus the NHC best track intensity. The quantitative estimates of RH, vertical shear, and POT were obtained from the operational SHIPS analysis of initial conditions. Our analysis includes both a simple comparison of the aforementioned parameters during the life cycle of each cyclone (section 3) along with a complimentary multiple linear analysis (section 4). Since time lags between environmental parameters and TC intensity are known to exist, we utilized intensity change rather than intensity at the initial time. That is, we computed the change in intensity occurring over the following 6, 12, 18, 24, 30, 36, 42, 48, 54, and 60 hour periods. In the analysis we considered the entire life spans of both storms, except that we omitted those intensity change time periods that would have extended beyond the last best track point for the given storm.

In addition to the conventional multiple linear regression, we examined whether an interaction effect is present between RH and vertical shear. In statistical terms, an interaction or moderation effect occurs when the effect of one independent variable (x1) on the dependent variable (Y) varies as a function of a second independent variable (x2). In our case, we tested whether the magnitude of the effect between RH (x1) and intensity change (Y) is modified by vertical shear (x2). To achieve this, we subdivided the data into weak shear and strong shear subsets and tested whether a significant difference exists in the correlation coefficients between the data subsets. Finally, we added a modifier term (RH * Shear) to the multiple linear regression equation to account for possible interaction, and we then tested for significance.

We apply our results from sections 3 and 4 to the SHIPS model output during both storms in the hopes that our results might have direct applicability to NHC forecast operations. Specifically, we aim to identify situations in which the SHIPS model might perform poorly and then examine possible improvements to SHIPS. Inaccurate forecasts by the SHIPS model can generally be attributed to the following four sources: 1) incorrect or incomplete input environmental data (e.g., shear, RH); 2) unrepresentative sampling of the environmental data (i.e., chosen horizontal areas and/or vertical levels/layers); 3) inaccurate track forecasts upon which the SHIPS model relies; and 4) regression equations that oversimplify or do not properly show the true dependence of intensity on the environmental characteristics in particular scenarios. In the present study, we focus our analysis of the SHIPS model primarily on sources 1 and 4. Further examination of sampling (source 2), with respect to vertical shear, is discussed in a separate but related paper (Rhome et al. 2006) printed in this volume. The impact of track forecast accuracy (source 3) is beyond the scope of the current study.

3. CASE STUDY SUMMARIES

Both Irene and Nate were open-ocean cyclones that never directly impacted land. This makes them well-suited for comparison in the present study since the complicating effects of land were not present. Both systems presented challenging forecast scenarios at various stages in their life cycles, and both were affected at times by moderate to strong vertical shear within varying moisture environments.

Irene's intensity changes appear to have been attributable in part to changes in vertical shear and middle- to upper-level RH (Fig. 1). The cyclone initially struggled to reach or maintain tropical storm strength during 4-10 August over the central Atlantic in an environment of moderate to strong shear and decreasing RH. Irene steadily strengthened during 11-16 August after the shear abated somewhat, even though the environment remained rather dry throughout that period. Weakening on 17-18 August was associated with increasing shear, despite the fact that middle- to upper-level RH was also increasing during that time. The shear had begun to increase on 15 August, suggesting a time lag between the onset of shear and the onset of weakening. It also seems possible that the weakening might have been more rapid had the RH in the environment not increased when the shear increased; this hypothesis is examined further in the next section.

Nate's intensity changes also appear to have been related in part to changes in shear and RH (Fig. 2). Steady strengthening took place during 5-7 September in a fairly weak shear environment. The shear more than doubled in magnitude late on 7 September and remained strong for the remainder of Nate's life span. The strengthening trend ended early on 8 September, although with some lag relative to the shear increase late the previous day. The fairly rapid weakening on 9-10 September appears to be associated not only with the continuing strong shear, but also with a decrease in RH that began on 8 September. These data suggest a possible lag between a drying environment and the onset of significant weakening, given the presence of strong shear. That is, it seems plausible that the shear-induced weakening would not have been as abrupt if the RH had not decreased. This possibility is examined further in the next section.

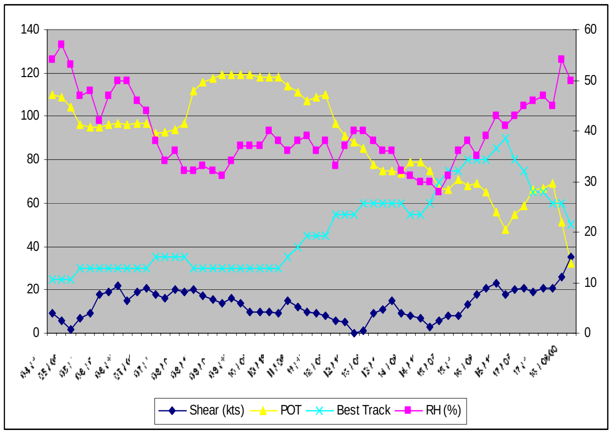

Figure 1. Time series of SHIPS vertical shear in knots (dark blue line), SHIPS 300-500 mb relative humidity (pink line), SHIPS POT (yellow line) and the NHC best track intensity in knots (light blue line) for Hurricane Irene, 4-18 August 2005. Left vertical scale depicts knots. Right vertical scale depicts relative humidity in percent.

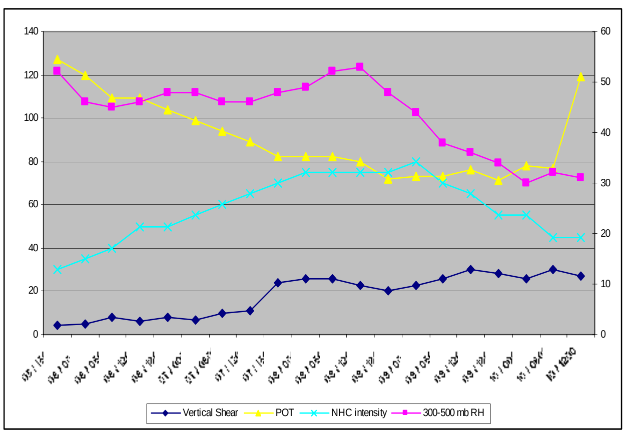

Figure 2. Same as in Fig. 1 but for Hurricane Nate, 5-10 September 2005.

The weakening phases of Irene and Nate are of particular interest for comparison, since both occurred in an environment of strong wind shear, but within differing moisture environments. Figs. 3 and 4 show water vapor images during the mature and weakening stages of Irene at 1745 UTC 16 August and 0015 UTC 18 August, respectively. Note the convective pattern which makes the transition from a well-defined eye pattern (Fig. 3) to that of a sheared system (Fig. 4). Instead of rapidly decaying under the influence of shear, Irene maintained a bursting convective pattern on 18 August, with the low-level circulation remaining on the equatorward side of the convective mass (a pattern commonly observed in the presence of vertical shear).

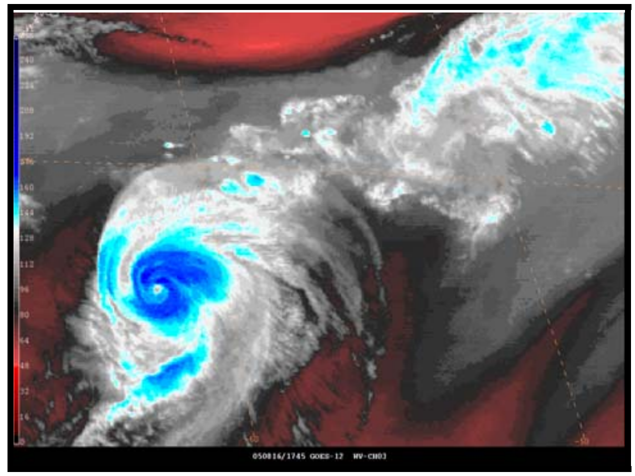

Figure 3. GOES-12 water vapor image of Hurricane Irene at 1745 UTC 16 August 2005.

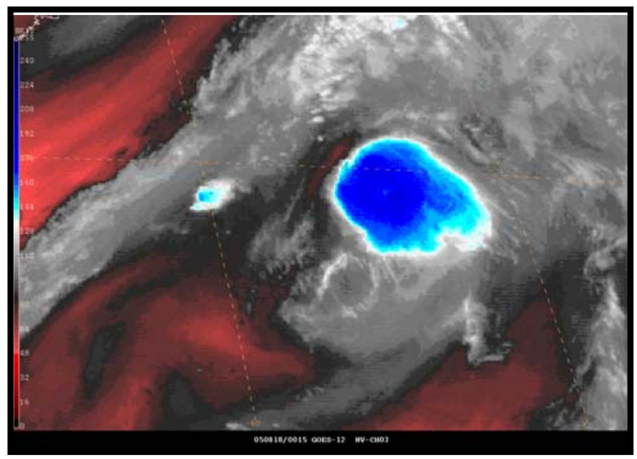

Figure 4. As in Fig. 3 but at 0015 UTC 18 August 2005.

The demise of Nate's convective pattern and its subsequent weakening between 0015 UTC 9 Sep (Fig. 5) and 1215 UTC 10 Sep 2005 (Fig. 6) occurred somewhat more rapidly than in Irene's final weakening phase. In fact, Nate's weakening was faster than both the operational forecast and the SHIPS guidance anticipated. Figs. 5 and 6 show the presence of very dry middle- to upper-tropospheric air during this period. A similar deduction can be made from Fig. 2, which suggests that Nate's weakening appears to have been related to the combined effects of decreasing RH, increasing vertical shear, and decreasing POT.

Figs. 1 and 2 show that both Irene and Nate, during their final weakening phases (shown in Figs. 3-4 and 5-6), were experiencing increasing vertical shear and decreasing POT. The primary difference between the weakening phases of the two storms appears to be the RH, which increased during the weakening of Irene (Fig. 1) but decreased during the weakening of Nate (Fig. 2). It should also be noted that Nate and Irene were at

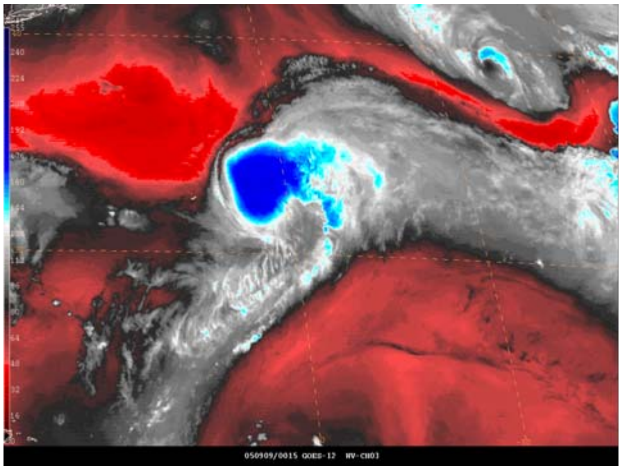

Figure 5. GOES-12 water vapor image of Hurricane Nate at 0015 UTC 9 September 2005.

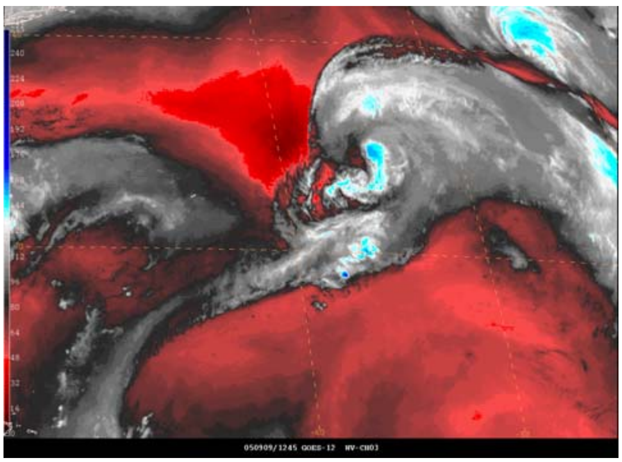

Figure 6. As in Fig. 6 but at 1215 UTC 10 September 2005.

similar latitudes (between 30ºN and 40ºN) during their weakening periods. This would seem to preclude, at least in these cases, any unique effect of latitude that has also been proposed as an important factor in determining the ability of a TC to resist shear. From this analysis, it appears that Irene and Nate were very similar during their weakening phases, except for the trends in RH values. The difference in RH between the storms appears to explain at least some of the differences seen in the evolutions of the convective patterns.

The evidence for relating the observed intensity changes in Irene and Nate to changes in shear and RH could be argued as circumstantial, demanding a more quantitative approach. It is beyond the scope of the current study to consider all possible environmental and oceanic parameters which may have affected intensity changes during these two cyclones. Therefore, in a very preliminary fashion, we next statistically examine the relationship between intensity changes and the shear and RH variables during Irene and Nate, in order to identify possible next steps for potentially improving how the SHIPS model handles such cases.

4. STATISTICAL ANALYSIS

Statistical significance was measured in our analysis using the 95% level. The results of the multiple linear regressions are shown in Tables 1 (Irene) and 2 (Nate). Table 1 shows that, while vertical shear was found to be statistically significant throughout all time intervals examined during Irene, RH was not found to be statistically significant in relation to intensity change at any time intervals. This is not to say that RH played no role in intensity change during Irene. Rather, a linear relationship between RH and intensity change was deemed statistically insignificant in this analysis.

Time period of intensity change (hr)	**R^2 RH (%)**	**R^2 Shear (%)**	**N**
6	0.007396 (.24)	**0.0625 (.002)**	55
12	0.0256 (.17)	**0.2304 (.0002)**	54
18	0.0484 (.12)	**0.5184 (.00002)**	53
24	0.0784 (.10)	**0.8281 (.000008)**	52
30	0.1296 (.07)	**1.0404 (.00003)**	51
36	0.1764 (.07)	**1.1025 (.0001)**	50
42	0.1936 (.09)	**1.1449 (.0005)**	49
48	0.1681 (.11)	**1.1881 (.0005)**	48
54	0.1089 (.22)	**1.1025 (.002)**	47
60	0.0625 (.38)	**0.7921 (.01)**	46

Table 1. Results of multiple linear regression analysis of intensity change period in hours (far left column) versus vertical shear and 300-500 mb RH for Irene 2005. R^2 values are shown for RH (second column from left) and vertical shear (third column from left), with the corresponding probability of the correlation coefficient being zero (no correlation). Values statistically significant are shown in bold. The number of data points or degrees of freedom is shown in the far right column.

Time period of intensity change (hr)	**R^2 RH (%)**	**R^2 Shear (%)**	**N**
6	0.0676 (.15)	**0.09 (.03)**	19
12	**0.2809 (.025)**	**0.4624 (.0002)**	18
18	0.4624 (.10)	**1.1449 (.0002)**	17
24	0.5929 (.20)	**2.1609 (.0001)**	16
30	0.6084 (.38)	**4.0401(.00009)**	15
36	0.3249 (.65)	**6.3504 (.00004)**	14
42	0.6561 (.56)	**6.6049 (.00009)**	13
48	0.1521 (.74)	**8.0089 (.00003)**	12
54	1.8225 (.47)	**9.3636 (.0003)**	11
60	3.0276 (.44)	**8.8804 (.0012)**	10

Table 2. Same as in Table 1 except for Nate 2005.

Slightly different results were obtained from the multiple linear regression analysis of Nate (Table 2). Specifically, RH was found to be statistically significant with respect to 12 hour intensity changes. This result is consistent with the qualitative assessment of Nate in section 3 that weakening was commensurate with falling RH values. This result also implies that a stronger linear relationship between RH and intensity change existed in the Nate (Table 2) than it did in Irene (Table 1). While interesting, these results do not answer the question of whether an interaction exists between RH and vertical shear. Recall that interaction or moderation occurs when the effect of one independent variable (x1) on the dependent variable (Y) varies as a function of a second independent variable (x2).

To test for interaction, we split the data set into strong shear and weak shear subsets. We opted to split the data at the median, producing an equal number of data points in the weak shear and strong shear subsets. However, since Nate was a relatively short-lived storm, splitting or subdividing the data produced very few data points or degrees of freedom. Therefore, it was determined that Nate and Irene would be combined to produce a larger sample size. Multiple linear regressions were then performed on the merged (Nate and Irene) data set split at 10 kt. Since we are testing whether RH has an increased effect on intensity change when strong shear is present, an additional analysis of the dataset split at stronger vertical shear values, such as 20 or 25 kt, could be useful. However, in our case, this would have significantly reduced the sample size in the strong shear subset. Results from the multiple linear regression analysis performed on the weak shear versus strong shear subsets show that RH was more highly correlated with intensity change in the strong shear subset case (not shown). This result suggests the presence of interaction between the RH and vertical shear variables. To further test the hypothesis of interaction, we added a modifier term (RH * vertical shear).

Multiple linear regressions were then performed on Nate, Irene, and the merged Nate and Irene data sets utilizing the modifier term. Results from this analysis indicate that the modifier term improved the overall model fit of the linear relationship based on the R^2 values of the overall model (not shown). One example of this was the intensity change over 24 hours in the merged Nate and Irene data set, where 8% more of the total variance was explained through the addition of the modifier term. Additionally, the modifier term was found to be statistically significant in cases where the RH term alone was not significant. Again, this suggests interaction between RH and vertical shear. Still, our analysis involves only two storms, and the statistics could be altered by outlier points or multicollinearity that results from the addition of the modifier term.

5. PERFORMANCE OF SHIPS PREDICTORS

The results of sections 3 and 4 suggest that an interaction effect may exist between vertical shear and RH. In hopes of applying this knowledge to operations through improved operational SHIPS forecasts in cases of strong shear and dry air, we further analyzed the performance of the SHIPS model in such cases. We compared our results with an analysis of the SHIPS model during Nate and Irene to analyze how the SHIPS model performed in cases where vertical shear and dry air were found to be present. In some model cycles, the error mechanism was clearly identified as external from the factors being examined in our analysis. For example, in SHIPS runs during the very early stages of Irene over the eastern Atlantic, the model received incorrect environmental input related to an inaccurate NHC forecast track (which had a significant bias to the south where the environment was much different). In the case of Nate's final weakening stages, however, it appears that a different error mechanism, related to the analysis in our study, might have been in play. Fig. 7 shows a comparison of each of the operational SHIPS forecasts versus the NHC best track intensity for Nate. Note how the SHIPS model did not accurately forecast the rapid weakening of Nate, even though the model correctly forecast a decreasing trend in RH. Specifically, the SHIPS run initialized at 0000 UTC on 9 Sep 2005 (highlighted line in Fig. 7) is especially of interest. That forecast is examined in Fig. 8, which shows the total SHIPS forecast intensity changes versus the portions contributed by the RH variable on that particular model run. Even though very dry middle- to upper-tropospheric air is clearly evident in the water vapor imagery (Figs. 1 and 2), and RH itself was forecast to decrease (and was shown to be significant in the multiple linear regression analysis), its relative contribution to the total SHIPS intensity change was minimal. This raises the question of whether the role of mid- to upper-tropospheric dry air is properly weighted in the SHIPS model when applied to certain cases. Since the SHIPS model does not currently employ a RH and vertical shear modifier term, the role of RH might in fact be incorrectly minimized.

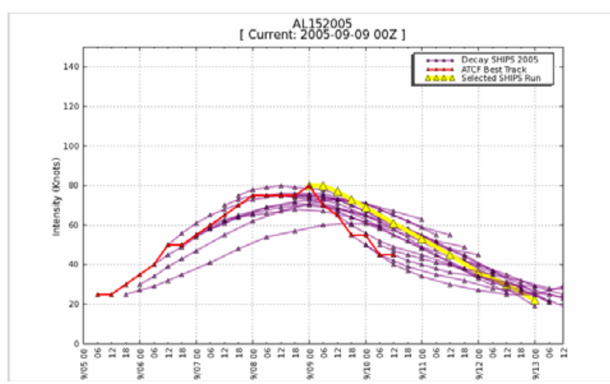

Figure 7. NHC best track intensity (red line) versus intensity forecasts from the operation decay SHIPS model (purple lines) during Nate. Yellow line indicates the selected SHIPS run that is shown in Fig. 8.

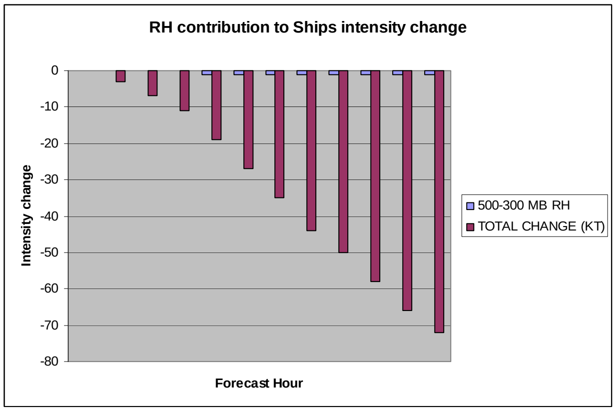

Figure 8. Total intensity change (maroon bars) versus the relative contribution to intensity change by RH (purple bar) from the SHIPS forecast initialized 0000 UTC 9 Sep 2005**.**

However, it should be noted that the lack of a modifier term is thought to be a shortcoming for SHIPS only in particular cases, since the modifier term was not found to be statistically significant during the original analysis of the entire developmental database of SHIPS (DeMaria 2006 personal communication). Therefore, from this analysis, it appears that further examination of the SHIPS model in cases where vertical shear and dry air are present is needed.

6. CONCLUSIONS

This paper has highlighted some of the operational challenges associated with forecasting TC intensity. Specifically, we have focused on the effects of strong vertical shear and dry middle- to upper-tropospheric air working in tandem. Our results suggest that previously published hypotheses on the combined role of middle- to upper-tropospheric dry air and strong vertical wind shear could be potentially incorporated into operational forecasting. Additionally, through the use of multiple linear regression, we have shown an interaction or moderation effect may be present, whereby the effect of RH on intensity change depends on the magnitude of the vertical wind shear. However, our study was limited by a small sample size, and a more comprehensive analysis is necessary to substantiate this conclusion.

How do these findings relate to improved operational forecasts of intensity change? First, our study suggests that increased forecaster scrutiny of the SHIPS model output is warranted in situations where dry middle- to upper-tropospheric air and moderate to strong vertical shear are present. Second, we believe that the results of this study could provide guidance in the ongoing development of the SHIPS model. Specifically, we propose that improved results with the SHIPS model might be achieved through the addition of conditional or separate regression equations. For example, separate SHIPS regression equations developed on weak shear and strong shear subsets might better capture the total effects of RH in different shear regimes. Another approach could be to devise a dynamic version of the SHIPS model in which forecasters supply key input parameters (e.g., the horizontal size or vertical depth of the storm) to drive the model and perhaps allow it to perform better in particular scenarios.

7. ACKNOWLEDGMENTS

The authors wish to acknowledge the input and suggestions of Dr. David Dickey, professor of statistics at North Carolina State University. Additionally, we wish to thank Dr. Michael Brennan, UCAR Visiting Scientist at the National Hurricane Center, for his comments and suggestions which greatly improved this manuscript.

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