On the Calculation of Vertical Shear: An Operational Perspective

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1. INTRODUCTION

Numerous observational and modeling studies have demonstrated the role of vertical shear as an environmental control on tropical cyclone (TC) intensity change. The inverse relationship between the two quantities has been firmly established (Frank and Ritchie 2001). However, the challenges of operational intensity forecasting show that the connection between vertical shear and TC intensity is complex and that much remains to be learned about the specifics. In particular, the shear magnitude above which development ceases and weakening begins (henceforth called critical shear) is not clear. As a result, great uncertainty in TC forecasts often exists in cases where moderate to strong vertical shear is diagnosed and does not always result in the anticipated weakening. Modeling studies have also revealed extreme sensitivity in cases where strong vertical shear is present (e.g., Emanuel et al. 2004, Rhome et al. 2002, Rhome 2002), in which only slight variations in the shear magnitude can produce large differences in the forecast intensity. To confuse the issue even more, a time lag between the onset of increased vertical shear and decreasing TC intensity has been shown to range from a nearly instantaneous response up to about 36 hours (Frank and Ritchie 2001). Further, some studies have shown that small amounts of vertical shear might actually be conducive in some cases for intensification (e.g., Paterson et al. 2005). Considering previous studies have utilized varying methods for computing vertical shear, the relatively slow progress in improving operational intensity forecasts can arguably be attributed in part to uncertainties in how vertical shear is calculated.

Improved knowledge of the specific relationships between TC intensity change and vertical shear could contribute to operational intensity forecasting improvements. While upgrades to operational dynamical models will undoubtedly play a major role in such improvements, the Statistical Hurricane Intensity Prediction Scheme (SHIPS) model remains the most skillful objective intensity guidance available to the National Hurricane Center (NHC). This paper describes a preliminary examination of potential improvements to the method by which SHIPS calculates vertical shear. It is our hypothesis that an enhanced shear calculation method in SHIPS could improve its handling of the complex interaction between shear and TC intensity change.

2. EXISTING SHEAR CALCULATION METHODS

Researchers have defined the vertical wind shear vector in different ways, leading to contrasting results. First, the vertical levels or layers over which the shear is calculated have varied. Emanuel et al. (2004), Palmer and Barnes (2005), and Zehr (2003) used the classical calculation involving the simple difference between two levels, typically 850 and 200 mb as is done currently in SHIPS (DeMaria et al. 2005). Conversely, Gallina (2002) computed vector differences between the average winds in the 700-925 mb layer and those in the 150-300 mb layer. A variety of horizontal domains have also been utilized in order to identify a single value representing the shear affecting the storm at any given time. Zehr (2003) averaged the wind vector differences over an annulus with inner and outer radii at 200 and 800 km, respectively, surrounding the center of the vortex as is done currently in SHIPS (DeMaria et al. 2005). Conversely, Gallina (2002) synthetically removed the winds within 400 km of the storm center at upper levels and within 800 km at lower levels. Other studies have not removed the vortex at all, instead averaging over a storm-centered domain in an attempt to cancel out the symmetric portion of the circulation (DeMaria and Huber 1998, Rhome et al. 2002, Rhome 2002, Paterson et al. 2005). Not surprisingly, each of the aforementioned studies cites a different value for critical shear somewhere between 5 and 10 ms^{-1}. Palmer and Barnes (2002) took the calculation a step further by making a distinction between the average and maximum vertical shear over a given domain. Their results suggest that a TC can resist weakening against a maximum vertical shear value up to 15 meters per second (ms^{-1}). Only a limited amount of direct comparison has been done in order to determine which of these various methods, or others not yet tested, provides the strongest signals for intensity change.

It is not difficult to envision how changes in the SHIPS shear calculation method, with respect to the vertical levels and layers and/or the horizontal averaging domain, could lead to significantly different results from that model, depending on the characteristics of each storm, especially in moderate to strong shear environments. Consider Fig. 1 that displays a time series of intensity versus vertical shear estimated from three different methods during Hurricane Debby (2000). Shear between the 850 and 200 mb levels is calculated from the AVN (now GFS) analysis grids using storm-centered boxes (of two different sizes, 5x5 degrees and 10x10 degrees) from which the vortex has not been removed. For comparison, University of Wisconsin (UW) shear estimates for the same times are also shown; these values represent the shear between the mean winds in the 150-300 mb and 700-925 mb layers (Gallina, 2002). While each shear method accurately depicts increasing shear coincident with the onset of weakening, the magnitudes of the shear vary substantially at any given time. The smaller 5x5-degree horizontal domain produces lesser shear values than the larger domain from the same GFS wind grids, while the UW estimates are substantially smaller in magnitude, primarily owing to the vertical layer averaging but also to the

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horizontal averaging domain. Jones (2004) and Dunion and Velden (2004) similarly concluded that the average vertical shear is a function of the horizontal area over which the averaging is carried out. This can be especially problematic in situations where there is a sharp horizontal gradient in the magnitude of environmental shear near the TC, as is typical, for example, with TCs near the Saharan Air Layer (SAL) (Dunion and Velden 2004).

Given the various methods currently employed for calculating vertical shear, and considering the many permutations of vertical levels and layers and horizontal averaging domains that have not yet been tested, it is useful to determine if any of these methods would provide an operationally beneficial improvement over how SHIPS currently calculates shear. We begin to address this issue by recomputing vertical shear in several different ways, within the framework of the operational SHIPS model, and relate the results of each shear method to observed intensity changes. We also hope to stimulate increased debate and research activity on this subject by providing some insights into the strengths and weaknesses of the various methods based on experiences with particularly challenging operational cases.

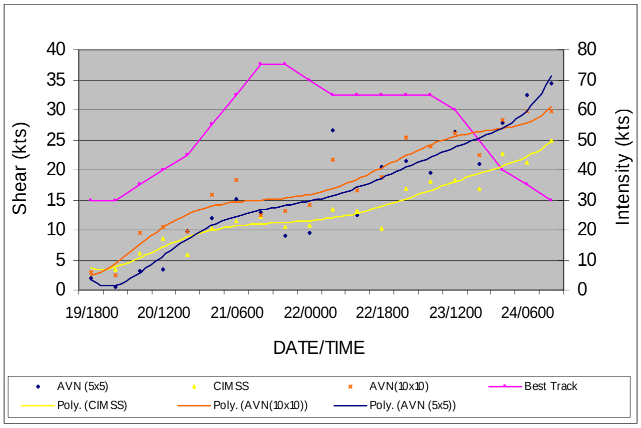

Figure 1. Times series analysis of the NHC best track intensity for Debby (2000) versus UW-CIMSS vertical shear estimate, GFS 5x5 storm centered box, and GFS 10x10 storm centered box. Blue, orange, and yellow dots represent individual shear estimates while the corresponding solid lines represent a best-fit polynomial function. The UW-CIMSS vertical shear is calculated using 700-925 mb and 150-300 mb layer averaging and synthetic removal of the winds within 400 km of the storm center at upper levels and within 800 km at lower levels (Gallina 2002).

3. DATA AND METHODOLOGY

The current operational SHIPS model uses a simple two-level (850 and 200 mb) vector difference in its computation of vertical shear. It then averages the vertical shear over an annulus of 200-800 km from the center of the TC (DeMaria et al. 2005). We compared results from the current operational shear calculation method with several other combinations of horizontal averaging domain and vertical levels/layers. Gridded GFS analyses and the latest available NHC best track intensity data from storms throughout the 2005 hurricane season were used. We directly compared results from selected storms of different depth, size, and intensity. We also examined some details of the synoptic environments to offer some physical explanations for the statistical results that differed between storms or between different phases of the same storm. *It is important to note that we analyze simply the vertical shear computation method and the resulting vertical shear estimate. No attempt is made in the present study to quantify what results, if any, an alternate vertical shear computation would have on the SHIPS intensity forecast.*

We tested two alternate methods for how the shear vector is calculated in the vertical. First, we tested a shear vector similar to the existing 850-200 mb calculation, but using layer-averaged winds rather than those from just the two levels. Specifically, we used the difference between winds averaged in the 200-300 mb layer and those averaged in the 850-700 mb layer. The reason for testing layer averaging is that the individual 850 and 200 mb level winds might over- or under-estimate the shear in cases when there are shallow but strong vertical wind speed gradients within the upper and/or lower troposphere. The levels included in the layer averages were selected to create layers centered near the traditional 850 and 200 mb levels. At present only a limited number of levels are available within the SHIPS framework and database. Clearly, more levels would be ideal in the layer-average computation, and adding those layers could be considered in the near future. However, one of our primary goals is to remain within the framework of the current SHIPS model to allow for direct application of our results to operations. Next, a shear vector calculated between the 850 and 500 mb levels (no layer averaging) was tested to examine the effects of shear between the lower and middle troposphere rather than between the lower and upper troposphere. The purpose of these tests was to identify cases when the 850-200 mb shear is unrepresentative of the winds having the greatest impact on the intensity, perhaps because the TC is a shallower system, and/or because stronger winds in the middle troposphere are impacting the system despite relatively weaker upper-tropospheric winds (or vice-versa).

The operational SHIPS model's use of the 200-800 km annulus for horizontal averaging of the shear is designed to limit the influence of the storm circulation on the shear calculation. The large size of the annulus is necessary since the SHIPS model centers its calculations on forecast points from the NHC official forecast rather than from the GFS. Since the GFS forecast of the TC center is often in a different location, the annulus must be large enough to extend beyond the model's representation of the TC circulation and predominantly sample the environment. While this is not as much of a problem at the analysis times examined in this study, the methodology was intentionally confined somewhat to remain within operational constraints. Not surprisingly, the large annulus can and does have significant drawbacks, especially when strong horizontal gradients in the vertical wind shear are present in the environment near the TC. Therefore, it is useful to examine the effects of varying the sizes of both the inner and outer radii of the annulus currently used by SHIPS. We tested varying the outer radii 400 to 800 km and the inner radii of the annulus from 0 to 200 km. Each of these various annulus sizes was applied to each of the vertical calculation methods described earlier (the existing 850-200 mb levels, the layer-averaging method centered on 850-200 mb, and the 850-500 mb levels). The result is that we analyzed 45 different shear computation methods as shown in Table 1.

Since time lags between intensity and vertical shear are known to exist, we correlated our vertical shear estimates against intensity change. Specifically, we compared each 24-hour intensity change with the vertical shear diagnosed using the various methods at the beginning of that 24-hour period. Since 24-hour intensity changes cannot be computed for the last four best track times of each TC, those times were omitted from this analysis. Additionally, storms which were short-lived (T.S. Bret, T.D. 10, T.S. Jose, T.D. 19, T.S. Tammy, T.D. 22, and Hurricane Vince) were omitted for the same reason.

850-200 mb	850-200 Layr avg	850-500 mb
SHRD82 (-.186)	*SHRL82 (-.191)*	***SHRS82 (-.238)***
SHRD72 (-.181)	SHRL72 (-.185)	SHRS72 (-.233)
SHRD62 (-.169)	SHRL62 (-.178)	SHRS62 (-.236)
SHRD52 (-.154)	SHRL52 (-.152)	SHRS52 (-.223)
SHRD42 (-.144)	SHRL42 (-.131)	SHRS42 (-.224)
SHRD81 (-.008)	SHRL81 (-.189)	SHRS81 (-.007)
SHRD71 (-.179)	SHRL71 (-.180)	SHRS71 (-.228)
SHRD61 (-.164)	SHRL61 (-.170)	SHRS61 (-.229)
SHRD51 (-.146)	SHRL51 (-.140)	SHRS51 (-.207)
SHRD41 (-.129)	SHRL41 (-.117)	SHRS41 (-.208)
SHRD80 (-.007)	SHRL80 (-.187)	SHRS80 (-.007)
SHRD70 (-.176)	SHRL70 (-.177)	SHRS70 (-.222)
SHRD60 (-.160)	SHRL60 (-.166)	SHRS60 (-.219)
SHRD50 (-.140)	SHRL50 (-.134)	SHRS50 (-.196)
SHRD40 (-.114)	SHRL40 (-.101)	SHRS40 (-.189)

Table 1. Combinations of vertical shear calculation methods used in this study. For each combination, the first four letters denote the vertical levels/layers employed (i.e., SHRD denotes the 850-200 mb levels, SHRL denotes layer averaging centered on the 850 and 200 mb levels, and SHRS denotes the 850-500 mb levels). The last two numbers denote the sizes (in hundreds of km) of the outer and inner radii of the horizontal averaging annulus. For example, SHRD82 represents the shear computation using the 850-200 mb levels with an annulus from 200-800 km. The number in parenthesis indicates the corresponding correlation coefficient (r) against intensity change, averaged over the entire 2005 season. Numbers in italics represent the highest r value in the column (for that vertical level/layer method), while the value in bold denotes highest r value of all 45 shear estimates.

4. RESULTS

The results of our study over the entire 2005 season (Table 1) show that the shear between the 850 and 500 mb levels is more highly correlated with the 24 h intensity change than is the shear between 850 and 200 mb (using either the currently employed individual levels or the experimental layer averaging). It is important to note, however, that we did not yet test a layer averaging version of the 850-500 mb shear. These results suggest that computing shear over more shallow layers in the SHIPS model might produce more representative forecast results on average.

Additionally, analysis of the horizontal averaging domain size shows that the largest annulus with the largest inner circle was most highly correlated with 24 h intensity change, regardless of the vertical calculation method. That is, the best performing annulus size, paired with the SHRD, SHRL, or SHRS vertical calculation method, was (on average) the currently operational 200-800 km annulus. The smallest annulus (0-400 km), with no inner circle intended to remove the TC vortex, exhibited the smallest correlation coefficients with respect to intensity change. Thus, on average, the best-performing method of the 45 analyzed here was the SHRS82 method: shear between the 850 and 500 mb levels with no layer averaging, when the shear was horizontally averaged over a 200-800 km annulus.

While the 850-500 mb shear method was better correlated to intensity change versus the 850-200 mb level or layer-averaged method, a comparison of only the two methods for calculating the 850-200 mb shear shows that layer-averaging does provide slightly improved results. At the time of this writing, a layer-averaged shear centered on the 850 and 500 mb levels had not yet been attempted. However, our results suggest that such a method could provide superior results and we plan to test this hypothesis.

When comparing the results from individual storms to the entire season, it becomes apparent that the relationships that show the highest correlation on average do not apply equally as well to each storm in the sample (such storm-to-storm variability is why the existing operational SHIPS model does not perform as well with some storms as with others). For example, an analysis of Hurricane Wilma (October 2005) shows that the layer-averaged 850-200 mb vertical shear method using horizontal averaging over the 200-800 km annulus (SHRL82) provides better results than any other combination tested (including any with shear between the 850 and 500 mb levels).

We also analyzed only the latter stages of Wilma, after it departed the Yucatan Peninsula and then interacted with a middle- to upper-level trough over the Gulf of Mexico. During that period, the 850-200 mb layer-averaged method using a *smaller* annulus of 200-600 km (SHRL62) provided better results (not shown) than the 850-200 mb levels (with any annulus). Analysis of water vapor imagery during this period strongly suggests that a large horizontal gradient in the environmental wind shear was in place over the Gulf to the north of the hurricane. Fig. 3 depicts GOES-12 water vapor imagery and UW-CIMSS satellite-derived winds when Wilma was over the southeastern Gulf of Mexico. The operational SHIPS 200-800 km averaging annulus is depicted by the two concentric blue rings. Note the stronger westerly winds that lie north of Wilma and within the averaging annulus. Animation of the imagery reveals that the stronger westerlies were not impacting the center of the hurricane. The large annulus appears to produce an incorrect over-estimate of the vertical shear actually affecting the storm. Moreover, the layer-averaging might produce improved results in this case since a large vertical gradient in wind speeds often exists near an upper-level jet. Supporting these conclusions is the fact that the operational SHIPS forecast during this period (using the large annulus and no vertical layer-averaging) was for Wilma to weaken as it approached Florida, largely due to shear; however, Wilma gradually strengthened during this time.

It is important to remember that the aforementioned analysis of Wilma consisted of far fewer data points or degrees of freedom than did the analysis over the entire 2005 season. Additionally, our preliminary results do not take into account any deficiencies that might exist in some cases in the GFS analysis wind fields. While this might not be a significant issue for our generalized results over the course of an entire season, the accuracy of dynamical model forecasts of the wind field (including the model forecast position of the TC circulation center) plays a major role when analyzing single storms or events. Errors in the GFS model wind fields can certainly degrade the performance of SHIPS vertical shear calculation, especially when large wind speed gradients (in the vertical or horizontal) are present. Dunion and Velden (2004) showed, for example, that strong horizontal gradients in wind shear and moisture may be underestimated in dynamical model fields during

SAL events. The combined results of this paper along with those of Dunion and Velden (2004) show that, even if an enhanced method for calculating shear in SHIPS is developed using a robust dependent analysis database, the accuracy of operational SHIPS runs will still hinge largely on dynamical model forecasts of complex shear environments.

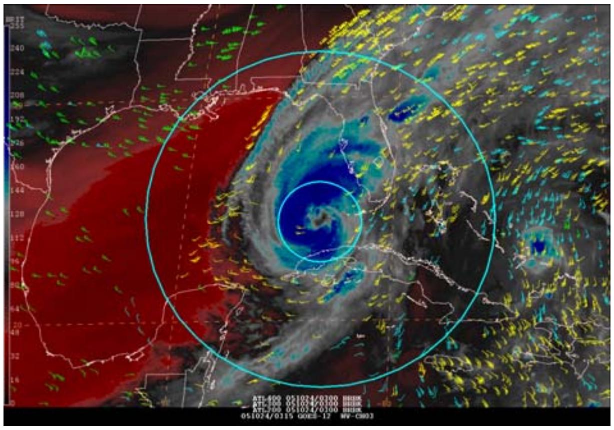

Figure 3. GOES-12 water vapor imagery of Wilma at 0315 UTC 24 October 2005. The concentric blue circles graphically depict the horizontal averaging domain (200-800 km annulus) for vertical shear as currently utilized by the operational SHIPS model.

5. CONCLUSIONS AND FUTURE WORK

Previous studies have shown the importance of vertical shear on TC intensity change, however, there has been relatively limited exploration of alternatives to how vertical shear might best be calculated, particularly given operational forecast constraints. Tremendous variance exists in the methods of computing vertical shear described in the various research papers dealing with the dynamical relationships between shear and TC intensity change. We have attempted to begin addressing this issue by exploring 45 alternative vertical shear calculation methods within the SHIPS model framework. Specifically, we correlated various combinations of the horizontal averaging annulus and vertical levels/layers with subsequent 24-hour intensity changes. Our results indicate that the 850-500 mb vertical shear vector computed (without vertical layer averaging) over a 200-800 km annulus was most highly correlated with intensity change over the entire 2005 season. Shear calculated with layer averaging centered on the 850 and 200 mb levels does appear to provide improvement on average over using the individual 850 and 200 mb levels. We did not yet test layer-averaged shear centered on the 850 and 500 mb levels. However, based on our results, we feel this might be a useful next step, so many additional combinations of vertical layers and horizontal averaging domains are currently being evaluated. Additionally, we intend to test other seasons for comparison against the 2005 results. The eventual goal could be to replace the currently utilized shear calculation method in SHIPS with one that can be demonstrated to produce more accurate results within the model's multiple linear regression framework.

We achieved different results when analyzing the various shear methods for individual storms relative to the entire 2005 season results. Of particular interest is the case of Wilma in which we found the layer-averaging of the 850-200 mb shear was more highly correlated with 24 h intensity change than the shear between the 850 and 500 mb levels. Additionally, we found that a smaller horizontal averaging annulus produced better results during the period when Wilma was crossing the southeastern Gulf of Mexico and interacted with a large middle- to upper-level trough. These results appear to be due to large horizontal and vertical gradients in the upper-level winds associated with the nearby jet stream. Operational experience with several different storms shows that situations such as this will often arise when the currently-employed SHIPS shear method will not properly represent the true vertical shear. It is important for forecasters to recognize these situations and consider the ramifications for the SHIPS forecast. Future efforts will include creating objective means to identify to the forecaster the type of shear environment in which a storm is embedded. Perhaps it would even be possible for SHIPS to dynamically select the proper shear calculation method for a given environment.

Alternatives to the traditional 850-200 mb vertical shear calculation method might produce improved results, both operationally via the SHIPS model and in other studies on vertical shear. We hope the research community will help to explore this issue further, with the goal of increasing our collective understanding of the effects of vertical shear on intensity change, and the application of that knowledge in operational forecasting.

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