Computing Deep-Tropospheric Vertical Wind Shear Analyses for Tropical Cyclone Applications: Does the Methodology Matter?

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ABSTRACT

Vertical wind shear is well known in the tropical cyclone (TC) forecasting community as an important environmental influence on storm structure and intensity change. The traditional way to define deep-tropospheric vertical wind shear in most prior research studies, and in operational forecast applications, is to simply use the vector difference of the 200- and 850-hPa wind fields based on global model analyses. However, is this rather basic approach to approximate vertical wind shear adequate for most TC applications? In this study, the traditional approach is compared to a different methodology for generating fields of vertical wind shear as produced by the University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (CIMSS). The CIMSS fields are derived with heavy analysis weight given to available high-density satellite-derived winds. The resultant isobaric analyses are then used to create two mass-weighted layer-mean wind fields, one upper and one lower tropospheric, which are then differenced to produce the deep-tropospheric vertical wind shear field. The principal novelty of this approach is that it does not rely simply on the analyzed winds at two discrete levels, but instead attempts to account for some of the variable vertical wind structure in the calculation. It will be shown how the resultant vertical wind shear fields derived by the two approaches can diverge significantly in certain situations; the results also suggest that in many cases it is superior in depicting the wind structure's impact on TCs than the simple two-level differential that serves as the common contemporary vertical wind shear approximation.

1. Introduction

Compelling observational evidence, supported by modeling studies, suggests that high values of large-scale, deep-tropospheric vertical wind shear (VWS; hereafter, VWS will refer to deep-tropospheric values, as opposed to mid- or shallow-layer values) have a generally negative impact on the formation and intensity of tropical cyclones (TCs). Early observational studies such as those by Gray (1979), Tuleya and Kurihara (1981), McBride and Zehr (1981), and Zehr (1992) noted that TC genesis and intensity modulation could be quite dependent on the magnitude of the environmental VWS impinging on the core of the storm. Frank and Ritchie (2001) looked at TC simulations in idealized environments by imposing various VWS profiles on the mean flow. Their findings concluded that VWS magnitudes in the range of $5–15\,\mathrm{m\,s^{-1}}$ produce a significant impact on TC structure and intensity.

One of the most widely utilized tools by TC analysts and forecasters in the Atlantic and eastern North Pacific basins is the Statistical Hurricane Intensity Prediction Scheme [SHIPS; DeMaria and Kaplan (1999); DeMaria et al. (2005)]. A similar model has been adapted to other basins (Knaff et al. 2005). More recently, a related logistic growth equation model (LGEM) has gained favor with forecasters (DeMaria 2009). In all of these models that rely on environmental predictors for TC intensity forecasts, VWS is consistently at or near the top in significance in terms of forecast impact. It is fairly certain that to understand and forecast the behavior of TC structure and intensity, the environmental VWS needs to be taken into account.

Given the importance of this parameter on TC intensity modulation, we look at how VWS is most often calculated, both in research studies and operational practice, and offer an alternative methodology. This alternative approach relies heavily on the distribution of tropospheric wind observations normally available over oceanic TC basins, as well as on the premise that the vertical profile of the ambient wind is important to take into account when assessing the influence of VWS on TC structure and intensity (Zeng et al. 2010).

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2. Background

Historically, the prevailing determination of VWS has its roots in early operational tropical analyses that relied on the advent of cloud-tracked wind vectors obtained from geostationary satellites beginning in the early 1970s (Menzel 2001). These atmospheric motion vectors (AMVs) were derived using primitive manual methods from sequential images to approximate observed cloud motions and thereby the predominant flow fields. Over the vast regions of the tropics, these AMVs were often the only tropospheric wind observations available to analysts, especially in the environments of TCs. In some regions of the globe, this remains true even today.

The spatial sampling of AMVs from satellites resulted in a marked improvement in the depiction of tropical flow fields, with the vast majority of AMVs a result of tracking either upper-tropospheric cirrus clouds or lower-tropospheric trade wind cumulus clouds. It became apparent that the crude methods available to attribute the derived motions to specific pressure altitudes (such as utilizing infrared cloud-top brightness temperatures) were not always reliable. Therefore, all AMVs were assigned pressure heights to approximate the predominant cloud-top occurrences in the tropics: either 850 or 200 hPa. From this information, the 850- and 200-hPa wind analyses became standards in most operational TC centers.

The emergence of animated images from geostationary satellites also illuminated an obvious observational phenomenon: TCs were often sheared apart by prevailing strong upper-tropospheric winds. This was not the first suggestion of the effects that VWS could have on TCs. Weightman (1919), Riehl and Shafer (1944), and Ramage (1959) presented perhaps the earliest ideas on how differential winds aloft could affect the development of storms. Simpson and Riehl (1958) proposed that the ventilation of the TC core by dry environmental air at midlevels could be constrained by VWS. This was followed by studies such as Gray (1968), who hypothesized that VWS could advect the warm upper-level air out of the TC core, hydrostatically raising the minimum sea level pressure. The satellite depiction of TC evolution in terms of cloud structure reinforced these ideas with strong qualitative evidence that VWS had an often controlling effect on TC intensity changes. It was perhaps more compelling than originally thought and stimulated a number of research studies on VWS and TCs over the following decades (Huntley and Diercks 1981; Merrill 1988; Zehr 1992; Jones 1995; DeMaria 1996; Bender 1997; Frank and Ritchie 1999, 2001; Schecter and Montgomery 2007; Riemer et al. 2010; Zeng et al. 2010; and many others). Despite all of these studies, our

understanding of how VWS actually works on TC intensity change, and even more basically how we should best define it, remains somewhat elusive.

In most of the above-mentioned studies, both observational and modeling, the environmental VWS was simply represented by taking the vector difference between the 200- and 850-hPa wind analyses from charts or model fields. In the early satellite era, this was considered the best available methodology, given that all of the satellite-derived AMV information was squeezed onto these two pressure levels. It was not until the 1990s that AMV processing became automated and allowed for more sophisticated methods for assigning heights to individual vectors (Schmetz and Holmlund 1992; Nieman et al. 1993; Velden et al. 1998). Despite the increased precision in AMV height assignments, and the resulting spreading of wind information in the vertical, with few exceptions the traditional method of calculating deep-tropospheric VWS by differencing just two levels remains the preferred approach both operationally and in the TC research community.

In the late 1990s, the University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (CIMSS) began deriving tropical analyses and diagnostics from locally produced, high-density AMV datasets (Velden et al. 1997, 1998). These analyses were made available in near–real time on the CIMSS tropical cyclones website, and became a popular addition to accessible tropical analyses for both the research and operational TC communities. One diagnostic product that became widely used is the CIMSS shear analysis (Pasch and Velden 1999; Gallina and Velden 2000; Gallina 2002; Rhome et al. 2006), described in more detail in the next section. The principal novelty of the CIMSS approach is that it attempts to take into account some of the vertical wind variability and structure in the VWS calculation. It is not the intent of this study to proclaim this as the best possible approach to calculating VWS for all applications used to assess TC impact, but it does suggest that in many cases it is superior in depicting wind structures affecting TCs than the simple two-level differential that serves as the common contemporary VWS approximation.

Exactly how VWS affects the TC core and intensity is beyond the scope of this paper. However, we can illustrate why the CIMSS approach may be more effective in given environmental wind regimes or, perhaps put another way, why the two-level approach may be oversimplified. Consider the two common vertical wind profiles in the tropics experienced by TCs as presented by Elsberry and Jeffries (1996) and reproduced in Fig. 1. The schematic in Fig. 1a shows a profile with a sharp and strong peak wind concentrated in a shallow layer near
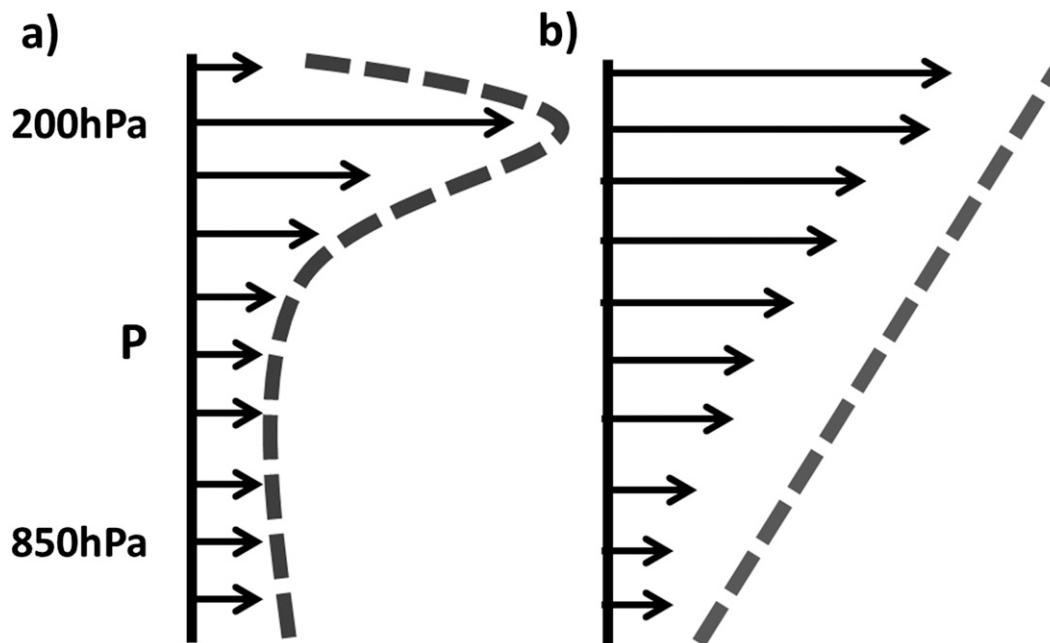
FIG. 1. Schematics of two vertical wind profiles typical of environmental flow regimes that impinge on TCs, but which provide identical 200–850-hPa wind shear values as traditionally calculated. These two profiles arise from a (a) low-latitude system with strongest upper-tropospheric winds concentrated in a shallow layer and (b) linearly distributed wind profile over a deep layer as might exist poleward of the deep tropics and associated with transient midlatitude troughs. [Reproduced from Elsberry and Jeffries (1996).]

the tropopause and relatively light winds throughout the rest of the troposphere, typical of the deep tropics. In contrast, Fig. 1b illustrates a peak wind in the upper troposphere, slowly decreasing with height in a near-linear manner, consistent with flow conditions that might exist poleward of the deep tropics associated with transient midlatitude troughs. They argued that the efficiency of the VWS to tilt the TC core and/or entrain dry air into the core and thereby impact the TC intensity could depend on the profile. While the 200- and 850-hPa wind values (and therefore the traditional two-level VWS calculation) for both profiles above may be similar, the potential for core structure–altering shear effects could be quite different. Further examples are presented in section 4.

Another aspect in which environmental VWS may impact a TC is with regard to the ability of the TC to "protect itself" from hostile upper-level flow conditions. In particular, the vertical alignment of the TC outflow with strong impinging flow could determine the impacts on the inner-core structure and ventilation. Merrill and Velden (1996) showed the importance of the three-dimensional structure of the outflow layer and its relation to TC intensity change. In particular, they stated the following: "The effects of vertical shear in the ambient flow over the depth of the outflow layer must also

be considered, as this may control whether the low-θ and high-θ (i.e., potential temperature) outflow from an intense storm are aligned in the vertical. Because outflow is apparently associated with a negative PV anomaly, the superposition (or lack thereof) of these anomalies at different θ levels may influence the strength of the induced upper-tropospheric circulation (such features as "outflow jets"), its nonlinear evolution, and the ability of the storm to sustain outflow over its full θ range for an extended period." This is illustrated in Fig. 2. Clearly, the impact of the evolving VWS interaction with the TC outflow in the above manner would depend heavily on the vertical profile of the "engaging" environmental winds. In trying to diagnose such impacts, it would appear the choice of how VWS is calculated in this evolving case could influence the interpretation.

3. Data and methodology

The CIMSS VWS analyses are based on high-density AMVs derived from a processing algorithm very similar to the operational algorithm and approach used by the National Environmental Satellite, Data, and Information Service (NESDIS). This includes the use of the Global Forecast System (GFS) model for input to sophisticated AMV height assignment and postprocessing
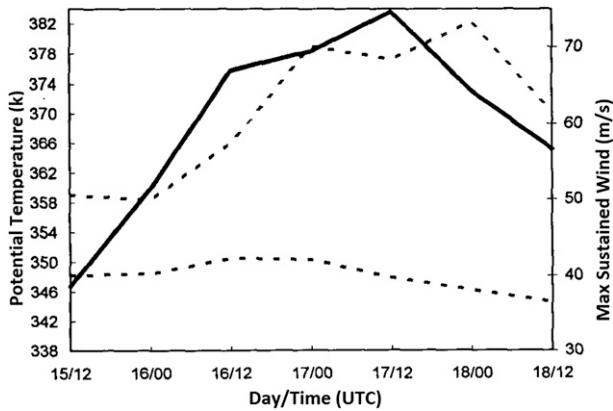
FIG. 2. Temporal changes of best-track max sustained wind (solid) and θ range (dashed) of the outflow layer at 666-km (6° latitude) radius as estimated from analyses of Typhoon Flo during September 1990. The top and bottom of the outflow layer are defined as the highest and lowest θ at which mean axisymmetric radial wind u exceeds $2 \, m \, s^{-1}$. [Reproduced from Merrill and Velden (1996).]

routines. For further details on the AMV processing, see Velden et al. (2005). To provide continuous global coverage over the tropics and subtropics, the AMV datasets are derived hourly using operational satellite imagery from Geostationary Operational Environmental Satellites (GOESs), Meteosat, and Multifunctional Transport Satellites (MTSATs). The typical spatial and height distribution of the AMVs, along with their validation in tropical applications, is discussed in Sears and Velden (2012). Generally, AMVs exhibit a clear peak in upper-tropospheric observations (150–300 hPa), which is expected given the abundance of cirrus clouds typical in the tropics. Sparse AMV coverage from below 300 to about 700 hPa can be attributed to the general lack of coherent midlevel cloud tracers in tropical systems. Transient high clouds resulting from persistent convection and cirrus canopies often prevail in the deep tropics, also prohibiting the retrieval of AMVs below. A weaker secondary maximum in AMV concentrations often exists below 700 hPa, primarily from the sampling of shallow convective clouds that are commonly observed in the low-level trade wind regimes, and away from high cloud shields.

Sears and Velden (2012) also showed that, in TC environments, the upper- and lower-tropospheric AMVs are comparable in quality with respect to typical AMV accuracies as reported by global data-processing agencies from routine monitoring versus collocated rawinsondes. This is despite the challenges imposed by anomalous TC flow fields. The greatest AMV uncertainties exist in the midlevels (between ~700 and ~300 hPa). This region is particularly vulnerable to

erroneous AMV height assignments due to difficulties in differentiating between optically thin cirrus and other midlevel clouds with similar brightness temperature values. If thin cirrus tracers fail semitransparency checks in the AMV-processing stream, they can be assigned to levels that are far too low in the troposphere. Despite quality-control procedures in the postprocessing of the AMVs, these vectors can occasionally get through to the final distributed datasets. It is primarily for this reason, and general data sparseness, that the CIMSS VWS calculation does not include midlevel analyses between 350 and 650 hPa.

The AMVs are analyzed onto gridded u- and v-wind fields using the procedures detailed in Velden et al. (1998) as part of the AMV postprocessing. Basically, the gridded wind analyses (latitude–longitude at 0.5° spatial resolution) are produced on isobaric surfaces (150, 200, 250, 300, 400, 500, 600, 700, 775, 850, and 925 hPa) using a three-dimensional recursive filter objective analysis that weights the AMVs heavily in the assimilation process (Velden et al. 1998, 2005). The operational GFS model is used to provide background fields for the analyses. Sears and Velden (2012) found that the gridded wind analyses match up well with collocated dropsonde wind values, with biases less than $1 \, m \, s^{-1}$ throughout most of the troposphere. Compared to collocated GFS analysis values, it is shown that little difference in wind variance (RMSE) exists below 500 hPa, where fewer AMVs factor in the analysis assimilation. Above 500 hPa, the AMV-aided CIMSS analyses generally show a slight improvement over the GFS. The improvements are more dramatic in the speed bias comparison. A strong slow bias is noted in the GFS model, while the AMVs hover closer to neutral. The biases in CIMSS analyses generally fall in between, however, they tend closer to the AMVs, which reflects the analysis strategy of giving strong weight to the AMV observations.

The procedure used to create the CIMSS deep-tropospheric VWS fields starts by deriving two mass-weighted layer-mean wind fields: the lower layer (700–925 hPa) and the upper layer (150–300 hPa) from the CIMSS isobaric wind analyses. These two layers were chosen based on the good AMV coverage and quality in these layers (Sears and Velden 2012). In an attempt to isolate the environmental VWS, the TC circulation (vortex region) is removed from the wind analyses by applying a gridpoint filter that operates over a prescribed radius from the TC center (empirically set at 600 km for the upper layer and 800 km for the lower layer). The procedure removes all of the grid values within these storm-centered circles (zeroes them out), then reassigns the grid values by blending the surrounding environmental wind information and gradients
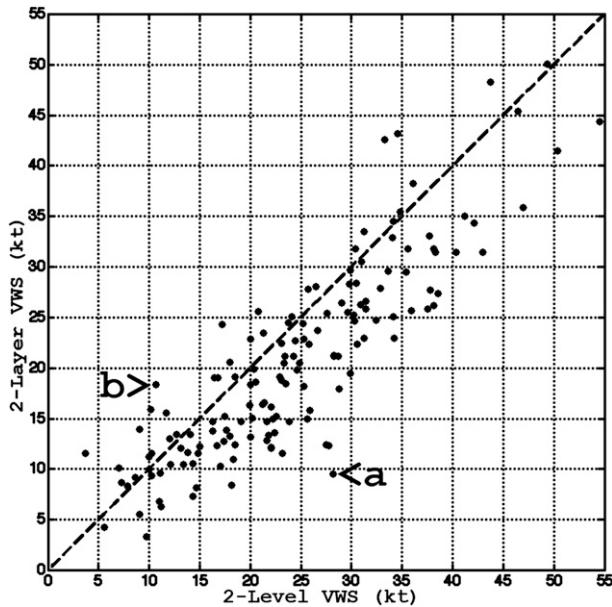
FIG. 3. Plot of VWS speed derived using the two-level and two-layer calculation approaches. The winds used in the calculations are provided from a sample of Gulfstream-V dropsondes ($N = 553$) in or near tropical disturbances taken during the 2010 PREDICT. The bias is 3.7 kt, the mean absolute difference is 5.1 kt, and the RMSD is 7.2 kt. The arrows point toward two cases highlighted in Fig. 4.

into the vortex region. In the final step of the VWS calculation method, the magnitude of the vector difference is computed from the two filtered layer-mean wind analyses to derive the VWS field. The resulting value at the storm center is used as the estimate of VWS in the evaluations presented in the next section.

4. Results

There are two prominent issues at play when examining the validity of the CIMSS VWS derivation approach: the vertical averaging methodology and the input data sources. Each of these contributions is investigated below. Other influences such as the vortex removal and averaging scheme are briefly discussed. Also shown are experiments and comparisons with the operational statistically based SHIPS TC forecast model (DeMaria et al. 2005; DeMaria 2010), which employs VWS as one of its key predictors.

a. Dropsonde comparisons

The traditional way of calculating VWS (two level) versus the CIMSS approach (two layer) is examined using wind profiles from dropsondes provided by a high-altitude Gulfstream-V aircraft investigating tropical disturbances in the Atlantic during the Pre-Depression Investigation of Cloud-systems in the Tropics (PREDICT) field

experiment in 2010 (Montgomery et al. 2012). Figure 3 shows a comparison of VWS values derived from the two approaches using 553 quality-controlled dropsonde wind profiles. A requirement of each included dropsonde is that reliable wind measurements exist from 150 to 925 hPa. From each of these profiles, a VWS is calculated using both the CIMSS two-layer approach and the traditional two-level approach. The resulting scatterplot shown in Fig. 3 indicates a decent correlation, as expected. However, there is a significant bias between the two approaches, with the two-level method exhibiting a stronger VWS in the mean [~4 knots (kt; $1 \text{ kt} = 0.51 \text{ m s}^{-1}$)]. In addition, the root-mean-square difference (RMSD) is ~7 kt, with about 14% of the compared values greater than 10 kt apart, and a few even greater than 15 kt. These differences are simply a result of the VWS calculation methodology, and exemplify how they could lead to ambiguous forecaster interpretations of the ambient environmental flow conditions when predicting subsequent TC intensity. This is especially true for VWS values of 10–25 kt, which has been shown to be the critical range for TC intensity modulation (Frank and Ritchie 1999; Gallina and Velden 2000; Rhome et al. 2006).

These differences are further illustrated by the selected dropsonde wind profiles shown in Fig. 4, which represent two of the more extreme VWS differences shown in Fig. 3. The profiles also bear a resemblance to the characteristics of the two disparate wind profiles shown in Fig. 1 based on Elsberry and Jeffries (1996). In Fig. 4a, the upper-tropospheric wind peaks at 200 hPa, and the two-level VWS calculation approach yields much higher values than the two-layer approach. In this case, the higher winds aloft are over a very shallow layer that just happens to peak at 200 hPa (one of the traditional levels used in VWS). In contrast, the profile in Fig. 4b exhibits a deeper layer of higher winds that peak in the 250–400-hPa range, and is much better represented by the layer-mean approach, thus yielding a higher VWS estimate than the two-level calculation. This scenario is often cited by TC forecasters looking carefully at animated water vapor imagery and noting the appearance of strong wind flow "undercutting" the cirrus outflow layer (normally around 200 hPa). Since the CIMSS VWS calculation approach includes wind analyses at 250 and 300 hPa, this scenario appears to be much better handled than the traditional two-level method.

In the two instances above, the dropsondes were both located upwind and in the near environment of separate tropical disturbances being followed by the PREDICT researchers. It is interesting to note that in the 5 September 2010 case (Fig. 4a) of the strong VWS with the two-level approach (27 kt) and relatively weak VWS in the
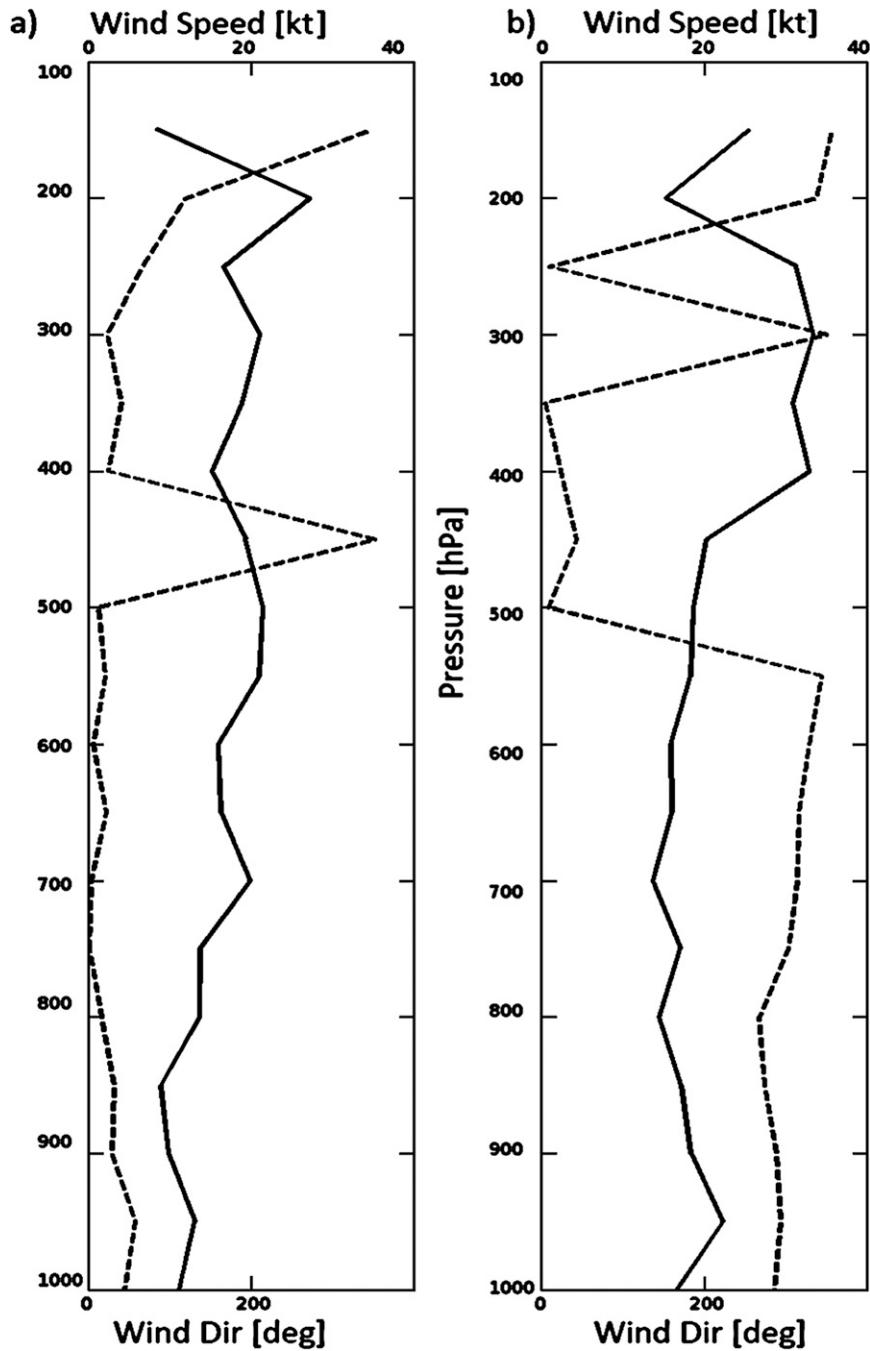
FIG. 4. Vertical profiles of wind speed (solid) and direction (dashed) produced by two dropsondes selected from the plot in Fig. 3 [points (a) and (b)].

two-layer approach (10 kt), there was slight development of the tropical disturbance over the next 24 h (National Hurricane Center 2010). In the other case, on 18 August 2010 (Fig. 4b), when there was light shear in the two-level method (11 kt) and moderate VWS using the two-layer approach (18 kt), the existing disturbance (PREDICT "pouch 27L") did not develop over the subsequent 24–72 h.

The VWS effects in these examples are anecdotal evidence since other factors may be at play in each case, but they are informative nonetheless.

b. SHIPS model comparisons

We next turn our attention to the primary contributing factors to the differences noted above, as well as how
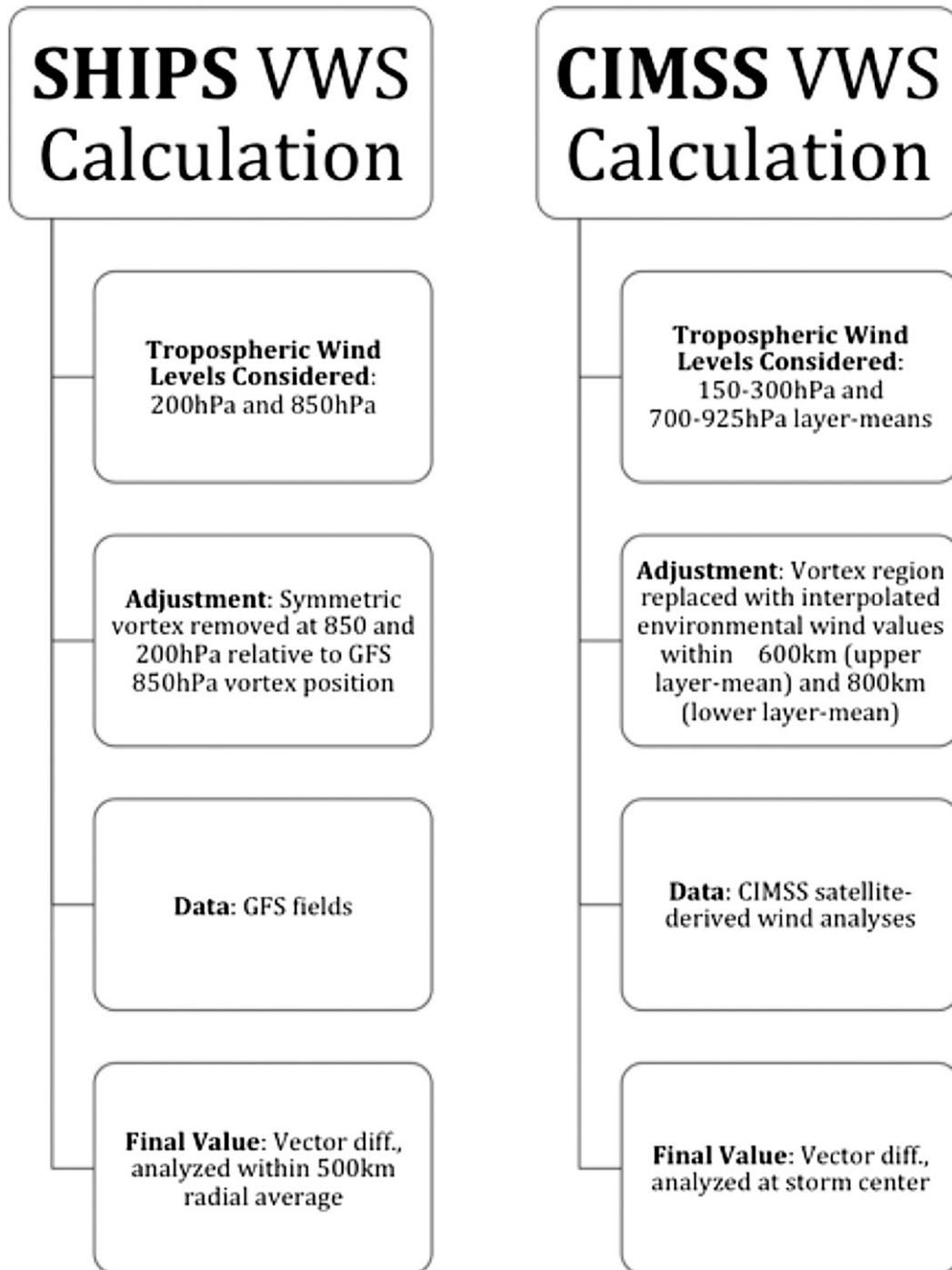
FIG. 5. Methodologies used to produce deep-tropospheric vertical wind shear for (left) SHIPS and (right) CIMSS analyses.

the results from the two approaches correlate with future TC intensity change. To help address these issues, we utilize the SHIPS model (DeMaria 2010) as a diagnostic tool. One of the key predictors in the SHIPS scheme is deep-tropospheric VWS, which is calculated

in the traditional way (two level). There are other VWS predictors that SHIPS utilizes (DeMaria 2010). The most relevant to this study is a generalized shear parameter that includes the vertical shear from all levels between 1000 and 100 hPa using a vertical integral

TABLE 1. Comparisons between CIMSS, SHIPS, and selected combination approaches to derive VWS.

Expt combination	Data VWS source and method	Benchmark VWS value	Correlation	Bias (kt)	RMSE (kt)
1 vs 4	CIMSS–CIMSS	SHIPS	0.74	−5.3	8.9
2 vs 4	GFS–CIMSS	SHIPS	0.78	−3.1	6.5
3 vs 4	CIMSS–SHIPS	SHIPS	0.86	−0.1	4.3

approach, which was added to the operational SHIPS and LGEM beginning in 2010. The generalized shear is applied as a correction to the two-level shear parameter in SHIPS. Because the primary contribution to the intensity change in SHIPS is from the two-level shear, and we are employing SHIPS strictly as a diagnostic comparison tool in this study, all further SHIPS VWS values will not include the generalized shear adjustment. The basic methodologies used to calculate deep-tropospheric VWS utilizing the SHIPS and CIMSS approaches are shown in Fig. 5. In brief, SHIPS employs the GFS model fields at 200 and 850 hPa, removes the symmetric TC vortex flow from each field, and then analyzes the average vector difference within a radial distance of 500 km from the TC center. The notable differences between the CIMSS and SHIPS approaches are the VWS calculation method and the source of the wind fields (discussed in section 2).

The two derived VWS values are compared in Table 1 using a large homogeneous sample from 2008–10 Atlantic tropical cyclones (824 cases). Using the SHIPS approach as the benchmark (GFS fields, two levels), we can see that the CIMSS approach is about 5 kt slower on average, with a root-mean-square difference between the two approaches of about 9 kt. The slow bias in the CIMSS approach is consistent with the dropsonde analysis results presented in the previous section.

To investigate this further, the CIMSS approach was modified in two ways: 1) we utilize the GFS fields to be consistent with the SHIPS and 2) we utilize the SHIPS VWS calculation method on the CIMSS wind fields. In this way, we can gauge the impact of the two notable differences in the approaches. The results in Table 1 show that by just changing the initial fields from CIMSS analyses to GFS analyses reduces the difference bias to ~3 kt. This residual is then presumed to be mainly due to the VWS calculation methodology and is very close to the

value found earlier in the dropsonde comparisons. When the initial CIMSS wind analyses are kept constant but the VWS calculation methodology is changed to that of the SHIPS procedure (including the vortex removal), the slow bias becomes negligible, and the correlations are highest. This suggests that the sensitivity to method choice is greater than the differences in initial fields used in these comparisons. It is noted that some of the differences may be due to the respective vortex removal procedures described above. However, we suspect this is not a dominant contributor since the bias with respect to the dropsonde results (no vortex removal procedure) is similar.

Another way to view the impacts of the two VWS derivation approaches is by correlating the initial VWS with subsequent TC intensity change. Figure 6 shows a comparison between the SHIPS and CIMSS approaches. For each of the sample of 824 cases, the subsequent TC intensity change is extracted from National Hurricane Center (NHC) Best Track files out to 72 h. Interestingly, the SHIPS VWS approach has a slightly better negative correlation with intensity change in the first 6–12 h. Since the near-environmental flow is likely impacting much of the TC intensity modulation at these early forecast times (DeMaria and Kaplan 1999), this could suggest that the SHIPS vortex removal approach is doing a slightly better job than the CIMSS method. After 12 h, the SHIPS correlations slowly degrade until becoming nearly flat by 42 h, while the CIMSS approach correlations steadily become stronger during this same period. Environmental flow outside the vortex region is likely playing more of an intensity modulation role during this forecast period.

c. SHIPS forecast experiments

Given these results, a set of forecast experiments on Atlantic TC cases from 2010 was conducted to assess the
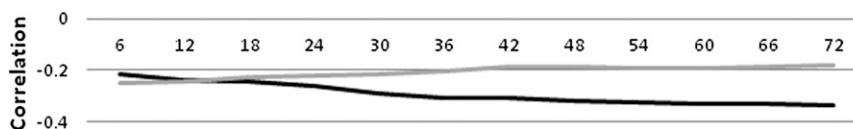

FIG. 6. Correlation of initial VWS magnitude with subsequent TC intensity change (max sustained winds from NHC Best Track files) from a sample of 824 analyses representing Atlantic TCs during 2008–10. The black line represents the CIMSS approach and the gray line the SHIPS approach.
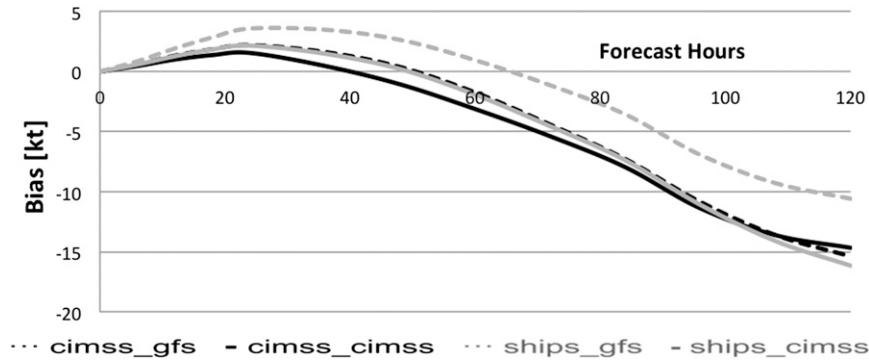
FIG. 7. SHIPS forecasts (120 h) of TC intensity (max sustained winds) based on varying inputs: 1) ships_cimss (gray, solid), the SHIPS VWS approach with CIMSS VWS analyses; 2) cimss_gfs (black, dashed), the CIMSS VWS approach with GFS analyses; 3) cimss_cimss (black, solid), the CIMSS VWS approach with CIMSS VWS analyses; and 4) ships_gfs (gray, dashed), the SHIPS VWS approach with GFS analyses. The homogeneous sample represents 283 forecasts from Atlantic TCs in 2010, and validation uses the NHC Best Track intensities.

potential impact of these alternative VWS analyses as a predictor in the SHIPS model forecasts. In this experiment, the control (CNTRL) run is similar to the operational SHIPS configuration, employing GFS-based VWS fields calculated using the two-level method, but with analyses rather than forecasts as predictor fields out to 120 h. Using analyses rather than forecasts is not, of course, demonstrable in a real-time mode; however, this is necessary to compare with the CIMSS analyses in a diagnostic sense. The other SHIPS runs involve the approaches and data sources outlined in Table 1: the SHIPS VWS approach but with CIMSS VWS analyses, the CIMSS VWS approach but with GFS analyses, and the CIMSS VWS approach using CIMSS VWS analyses. Again, this does not represent an operational demonstration, but rather an assessment of the impact of using variable analyses of VWS within an idealized SHIPS framework.

The results of the SHIPS forecasts (120 h) based on the varying configurations are shown in Fig. 7 and Table 2. The homogeneous sample represents 283 forecasts, and validation uses the NHC Best Track intensities. In terms of forecasts of maximum sustained surface winds V_{max}, the CNTRL (ships_gfs in Fig. 7) initially exhibits a high bias out to about 66 h, and thereafter a low bias. This is generally consistent with operational SHIPS forecasts of V_{max} in the Atlantic (not shown), although the low biases of the operational runs after 72 h were smaller in magnitude than those in Fig. 7. The other forecasts cluster around a tendency to reduce the initial strong bias, but increase the weak bias after about 60 h. The SHIPS run with the CIMSS analyses and VWS approach has the greatest overall impact on the results. Interestingly, the run with the CIMSS analyses–SHIPS method versus the CIMSS method–GFS analyses yields

about the same impact. While these results appear to be mixed in terms of improving intensity forecasts, it is quite probable that the inherent SHIPS biases toward the GFS fields and VWS method used in the extensive model development could be overwhelming the other signals, especially notable in the biases at the longer forecast intervals (M. DeMaria 2013, personal communication). The RMSE results shown in Table 2 indicate a slight tendency to favor the intensity forecasts using the CIMSS approaches, but none of the results are statistically significant.

5. Summary and discussion

Deep-tropospheric VWS is well known in the TC forecasting community as an important environmental influence on storm structure and intensity change. The traditional way to approximate deep-tropospheric VWS is to simply use the local vector difference of the 200- and 850-hPa wind fields based on global model analyses.

TABLE 2. RMSE for SHIPS forecasts (out to 120 h) of TC intensity (max sustained winds; kt) based on varying inputs: 1) CIMSS–GFS, the CIMSS VWS approach with GFS analyses; 2) CIMSS–CIMSS, the CIMSS VWS approach with CIMSS VWS analyses; 3) SHIPS–GFS, the SHIPS VWS approach with GFS analyses; and 4) SHIPS–CIMSS, the SHIPS VWS approach with CIMSS VWS analyses. The homogeneous sample represents 283 forecasts from Atlantic TCs during 2010, and validation uses the NHC Best Track intensities.

Method, source	24 h	48 h	72 h	96 h	120 h
1) CIMSS–GFS	11.2	22.9	30.1	37.6	43.8
2) CIMSS–CIMSS	10.8	22.2	29.7	36.1	42.3
3) SHIPS–GFS	11.0	24.1	31.4	39.9	45.9
4) SHIPS–CIMSS	11.1	23.8	30.4	39.2	45.8

However, is this rather simple approach to depict VWS adequate for most TC applications?

In this study, we compare a different methodology to generate fields of VWS as produced by the University of Wisconsin CIMSS. The CIMSS fields are derived using a three-dimensional recursive filter objective analysis operated at high spatial resolution with heavy analysis weight given to available high-density satellite-derived winds. Global model wind fields are only used as background analyses for data-sparse regions. The resultant isobaric analyses are then used to create two mass-weighted layer-mean wind analyses—one upper and one lower tropospheric—which are then differenced to produce the deep-tropospheric vertical wind shear field.

The principal novelty of the CIMSS approach is that it does not rely simply on the analyzed winds at two discrete levels, but instead attempts to account for some of the variable vertical wind structure in the calculation. This approach is strengthened by the abundance of satellite-derived winds normally available in these two layers, and the careful analysis of these winds into gridded fields. It was not the intent of this study to proclaim this approach as the best possible for calculating deep-tropospheric VWS in all assessments on TC impact, but to merely ascertain whether it represents a superior approach to the simple two-level differential that serves as the common contemporary approximation of VWS in most TC applications. We also do not consider other approach alternatives or VWS fields. For example, CIMSS also produces a midlevel shear analysis that represents the 500–850-hPa layer using a similar layer-differencing approach. In some TC cases with strong low-level environmental flow and/or midlevel entrainment, this VWS analysis may be preferable to the deep-tropospheric counterpart (Rhome et al. 2006). The SHIPS model also includes an adjustment to the two-level VWS parameter to account for shear contributions from other vertical levels. The method described in this paper is simpler than the SHIPS correction approach and has the potential to provide a similar improvement to the forecast, but with a variable that is easier to interpret physically.

The SHIPS model was employed as a diagnostic tool to compare the CIMSS VWS values to operational values and to determine the relative contributions of the VWS computation methods and data sources on correlations with TC intensity. From experiments comparing VWS values with subsequent TC intensity, there is evidence to suggest that the CIMSS analyses may represent VWS in a more constructive way. Furthermore, it appears that the improvement likely results from a combination of both superior wind analyses produced by CIMSS (Sears and Velden 2012) and the VWS calculation methodology, with the latter having a larger relative impact.

The SHIPS model was also used to produce TC intensity forecasts dependent on the various VWS fields as predictors. In this idealized set of experiments, VWS analyses were inserted into the SHIPS predictor fields at all forecast times (in operational practice, these would be forecast fields of VWS from the GFS). While the results are mixed with regard to biases in the forecasts of maximum winds, the impacts suggest a notable dependency on both the initial analyses and the VWS calculation methodology, in support of previous findings. Further work is needed to interpret these findings within the context of existing SHIPS predictor weights and biases.

Based on a comparison of the two methodologies employed to calculate VWS in TC environments using actual dropsonde wind observations, it is not too surprising that the resultant VWS estimates are generally well correlated. However, a bias does emerge, with the two-level approach yielding slightly higher VWS values on average. More importantly, there are environmental flow setups where the VWS values can diverge significantly. These situations are often characterized by variability in the vertical profiles of the ambient environmental flow acting on the TC that are not adequately being accounted for by the simpler two-level VWS approximation. Coupling this with previous studies that suggest variations in these profiles can affect TC intensity analysis and forecasts (Elsberry and Jeffries 1996; Zeng et al. 2010), it is these situations that can lead to misinterpretations of the actual strength of VWS impacting on a TC.

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