On the Influences of Vertical Wind Shear on Symmetric Tropical Cyclone Structure Derived from AMSU

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ABSTRACT

Axisymmetric temperatures and gradient-balanced winds associated with tropical cyclones derived from the Advanced Microwave Sounding Unit are stratified by the 24-h averaged vector difference of the horizontal wind between 200 and 850 hPa (or vertical wind shear). Using 186 total cases that are limited to tropical cyclones with intensities greater than 33 m s^{-1} (or mature) and are located over sea surface temperatures greater than 26.4°C, vertical wind shear–based composites are created. Results show that as the vertical wind shear increased, the upper-level warm-core structure associated with the tropical cyclone descended, resulting in a shallower balanced vortex. These observationally based results are presented in the context of recent mesoscale modeling results of the effect of shear on tropical cyclone structure.

1. Introduction

It has been long recognized that the vector difference of the horizontal winds between vertical levels (hereafter, vertical wind shear) tends to have a negative influence on tropical cyclone (TC) formation and intensification. While the negative effects have been well documented (e.g., Simpson and Riehl 1958; Ramage 1959; Gray 1968; Zehr 1992; DeMaria and Kaplan 1994, 1999; DeMaria and Huber 1998; and others), there have been relatively few observationally based studies discussing the structural changes within the TC that accompany increased vertical wind shear (Palmén 1956; Simpson and Riehl 1958; Gray 1968; Palmén and Newton 1969; Reasor et al. 2000; Hanley et al. 2001). This lack of observational studies is likely due to the limited number of observations, particularly in the warm core, which lies above the typical flight-level range of 925–500 hPa. Coupled with the fact that, until recently, low-level aircraft reconnaissance was the primary method to observe and study the thermodynamic structure of TCs, exactly how vertical wind shear, an upper-level process, affects the intensity and structure of a mature tropical cyclone remains an open question.

In light of this observational shortcoming and to better explore the fundamental physics of how vertical wind shear affects tropical cyclone intensity, several authors have used models, ranging from simple to complex, to bridge the gap in physical understanding (e.g., Madala and Piacsek 1975; Tuleya and Kurihara 1981; Flatau et al. 1994; Jones 1995; DeMaria 1996; Bender 1997; Peng et al. 1999; Frank and Ritchie 1999, 2001). These modeling studies point toward advective processes acting on the vortex heat and momentum fields as likely mechanisms for the observed changes in intensity. In one of the more detailed recent studies, Frank

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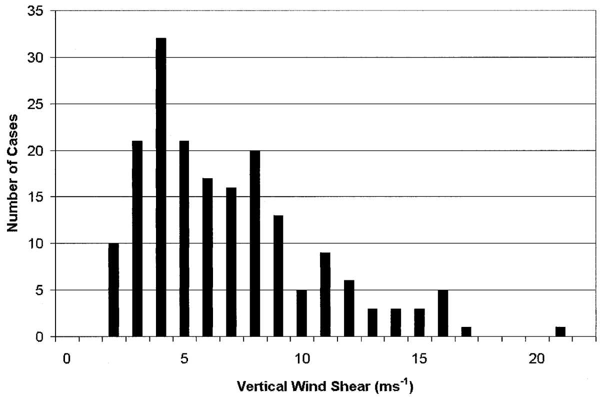

FIG. 1. Distribution of vertical wind shear with respect to magnitude used to create composites.

and Ritchie (2001) used the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) to run a series of detailed sensitivity experiments to examine the effects of vertical wind shear on TC intensity and structure evolution. Their simulations show that, over time, the upper-level warm core and circulation of the simulated TC weakens (in terms of potential vorticity and winds) from the top downward in response to vertical wind shear.

Until recently a large sample of upper-level temperature and wind observations of the near-core region of the tropical cyclone was unavailable, but this situation has changed over the last several years with the introduction of the newest generation of microwave sounders. On 13 May 1998 the first of three operationally available Advanced Microwave Sounding Unit (AMSU) instruments was launched aboard the National Oceanic and Atmospheric Administration (NOAA) satellite *NOAA-15.* The AMSU is the latest operational microwave sounder aboard the NOAA polar-orbiting satellites. It is a considerable advance over its predecessor, the Microwave Sounding Unit, with better spatial and vertical resolution (Kidder et al. 2000). Since 1998, two additional AMSU instruments have been placed in orbit aboard operational NOAA satellites (*NOAA-16* and *NOAA-17*), and their data are available for this study.

Three separate cross-scanning instruments make up the AMSU. AMSU-A1 has 2 channels (1–2), AMSU-A2 has 13 channels (3–15), and AMSU-B has 5 channels (16–20). Collectively, AMSU-A1 and -A2 are referred to as AMSU-A, which primarily is for temperature sounding and is used exclusively for this study. These soundings are determined from channels 3–14, which have frequencies in and near the oxygen microwave absorption band at 57 GHz—see Knaff et al. (2000) for more details and the individual weighting functions.

These observations and associated temperature retrievals offer a first-time opportunity to conduct a detailed observational survey of the effects of vertical wind shear on TC structure in the context of the modeling results of Frank and Ritchie (2001). However, the resolution of the AMSU observations (50-km horizontal resolution at best) will not resolve the details of near-core regions of the TC. Rather it will sense a smooth rendition of the TC's primary circulation (Brueske and Velden 2003; Demuth et al. 2004). Using AMSU observations we wish to answer the following: Does vertical wind shear result in a change in the axisymmetric TC structure inferred from AMSU data? If so, what are those changes? With these questions in mind, this note describes and discusses vertical-wind-shear-based composites of symmetric temperature and wind structure of hurricane-strength (maximum winds >33 m s^{-1} or 64 kt) TCs as derived from AMSU.

2. Data and methodology

a. AMSU temperature and gradient wind retrievals

The AMSU antenna temperatures[1] were collected in real time for all storms in the Atlantic and east Pacific basins during the 1999–2002 TC seasons and for the western North Pacific for the period May 2002–December 2002. *NOAA-15* data were available from 1999 to 2002; additional data from *NOAA-16* were collected in 2001 and 2002, and from *NOAA-17* in late 2002. Current and 12-h-old TC position estimates at 6-hourly intervals from the National Hurricane Center (NHC) and the Joint Typhoon Warning Center (JTWC) are interpolated to the time of the most recent AMSU data. Although the AMSU swaths are nearly 2200 km wide, the sample was limited to those cases where the storm center fell within 700 km of the swath center where the AMSU has greater horizontal resolution. The AMSU data were analyzed over a storm domain with a 600-km radius.

[1] Antenna temperatures are calculated from the radiance received by the antenna including both the field of view (main lobe) and sidelobe contributions. Brightness temperatures are obtained by making antenna corrections to the antenna temperatures.

TABLE 1. Mean and standard deviation (SD) statistics associated with low, moderate, and high vertical wind shear (VWS) composites made from the whole sample of mature tropical cyclones (Vmax $>$ 33 m s^{-1}, or 64 kt) and occurring over warm water (SST $>$ 26.4°C).

	N	*V*max	SD_{Vmax}	Lat	SD_{Lat}	SST	SD_{SST}	VWS	SD_{VWS}
Low	62	50.6	10.4	18.9	5.6	28.3	1.0	2.9	0.7
Moderate	62	47.2	11.2	19.5	6.2	28.6	0.9	5.9	1.0
High	62	44.9	7.7	25.3	7.5	28.2	0.8	10.8	2.8

TABLE 2. Mean and standard deviation (SD) statistics associated with favorable and less favorable VWS composites made from cases of mature tropical cyclones that had intensities between 46 and 52 m s^{-1} (or 90 and 100 kt) and occurring over warm water (SST > 26.4°C).

	N	Vmax	SD$_{V\text{max}}$	Lat	SD$_{\text{Lat}}$	SST	SD$_{\text{SST}}$	VWS	SD$_{\text{VWS}}$
Shear ≤ 7.5 m s^{-1}	22	94.3	3.9	19.8	6.6	28.4	1.0	3.7	1.8
Shear > 7.5 m s^{-1}	16	94.6	3.0	23.6	8.3	28.3	0.7	10.8	2.6

These assumptions resulted in some cases where the AMSU data swath did not cover the entire 600-km analysis domain. In these few cases, all available data are interpolated to a radial grid using a single-pass Barnes analysis with a *e*-folding radius determined from the resolution of the AMSU data as described in Demuth et al. (2004).

Prior to the temperature retrieval, corrections to the AMSU-A data were made for scan position and viewing angle (Goldberg et al. 2001). After the corrections, the resulting radiances were used as input into a statistical temperature retrieval (Goldberg et al. 2001; Knaff et al. 2000), which provided temperature as a function of pressure at 40 levels from 1000 to 0.1 hPa. Twenty-three of these pressure levels between 920 and 50 hPa were utilized for analysis. Retrieved temperatures were also corrected for the liquid water attenuation and ice-scattering effects. The retrieval of horizontal wind is performed under the assumption of hydrostatic and gradient wind balance on a constant height grid with 1-km vertical resolution. Surface temperature and lateral sea level pressure from the National Centers for Environmental Prediction (NCEP) global analysis closest in time to the AMSU swath were used as boundary conditions. More complete details concerning the temperature and wind retrievals along with what corrections and assumptions have been made for these analyses can be found in Demuth et al. (2004).

b. Case stratification

For this study, vertical wind shear is defined as the vector difference between the average 200-hPa wind and the 850-hPa wind within an annulus starting at 200 km and extending to 800 km from the storm center. Vertical wind shear values are calculated from 12-hourly global analyses. Twenty-four-hour average values of vertical wind shear ending at the AMSU analysis times are used to composite the AMSU retrievals. Twenty-four-hour averages are used based on modeling studies that indicate there is a lag on the order of 24 h between the onset of vertical wind shear and its effects on tropical cyclone structure and intensity (e.g., Jones 1995; Bender 1997; Frank and Ritchie 1999, 2001). The vertical shear values used in this study come directly from the datasets used to develop the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria and Kaplan 1999) and the Statistical Typhoon Intensity Prediction Scheme (STIPS; Knaff et al. 2004). Thus, the NCEP Aviation model (now Global Forecasting System) analyses were used in the Atlantic and eastern Pacific TC basins, and the Navy Operational Global Analysis and Prediction System (NOGAPS) analyses were used in the western North Pacific. Cases where the TC was north of 40°N or over sea surface temperatures of 26.4°C and cooler were eliminated, resulting in 186 total cases.

Using these cases, two types of composite studies

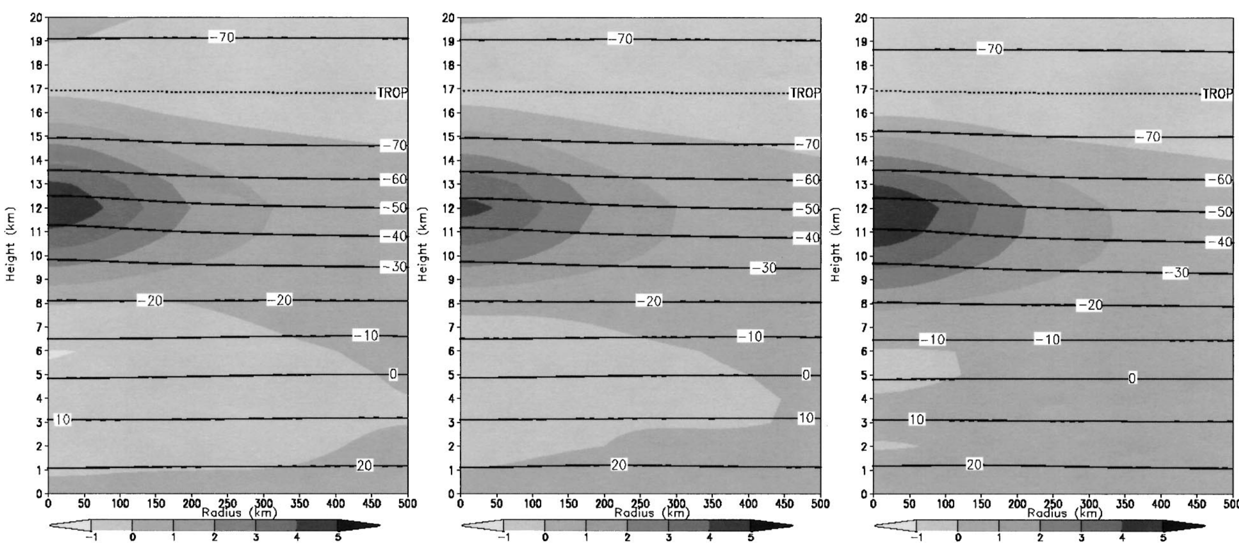

FIG. 2. Vertical-wind-shear-based radius–height cross-section composites of temperature (contours) and temperature anomalies (shaded) in °C. Shown are (left) low shear (<3.8 m s^{-1}), (middle) moderate shear (3.8 > shear > 6.8 m s^{-1}), and (right) high shear (shear ≥ 6.8 m s^{-1}).

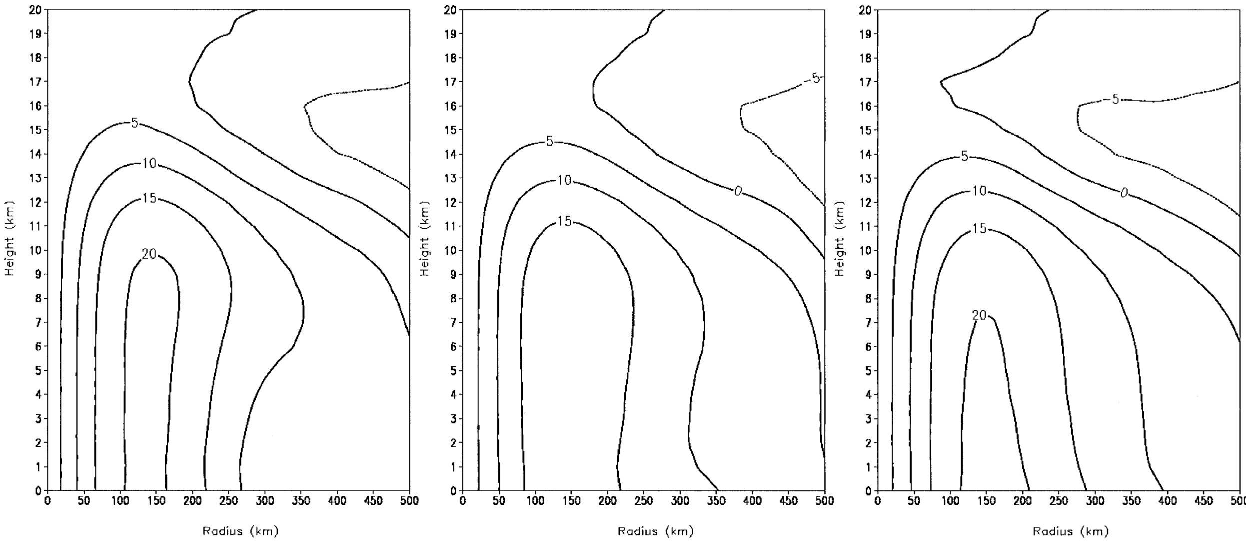

FIG. 3. Same as Fig. 2, except for balanced tangential wind (m s^{-1}).

were explored. First, three equal-sized composites using the 24-h average vertical shear were created: low shear (<3.8 m s^{-1}), moderate shear (3.8 ≤ shear < 6.8 m s^{-1}), and high shear (shear ≥ 6.8 m s^{-1}), each of which represents one-third of the sample, or 62 cases. The distribution of 24-h averaged vertical wind shear for the 186 cases is shown in Fig. 1. This distribution has a mean value of 6.3 m s^{-1} and a standard deviation of 3.6 m s^{-1} and is skewed toward lower values of vertical wind shear. Table 1 shows the statistics associated with each of these equal number composites.

A possibly more enlightening strategy is to create two composites, one for favorable vertical wind shear conditions and the other for less favorable shear conditions, using a sample of cases in a narrow range of intensities. With this approach, the effect of having a rather large range of storm intensity in each sample is removed. For this note, we chose a subsample of 38 cases that had intensities ranging from 46 to 52 m s^{-1} (90 to 100 kt). This range of intensities helps insure that the compositing subsample contains storms with the well-developed warm-core structures and will likely highlight any variations in these structures related to vertical wind shear. Since the shear values used for this study are also those used for the development of the SHIPS and the STIPS, favorable and less favorable shear conditions can be calculated using the developmental data for those models. From a correlation of intensity change with shear from the SHIPS and STIPS samples, vertical wind shear values are considered favorable (e.g., lead to intensification) when they have a value smaller than 7.5 m s^{-1} (or 14.5 kt) and vice versa. This value agrees

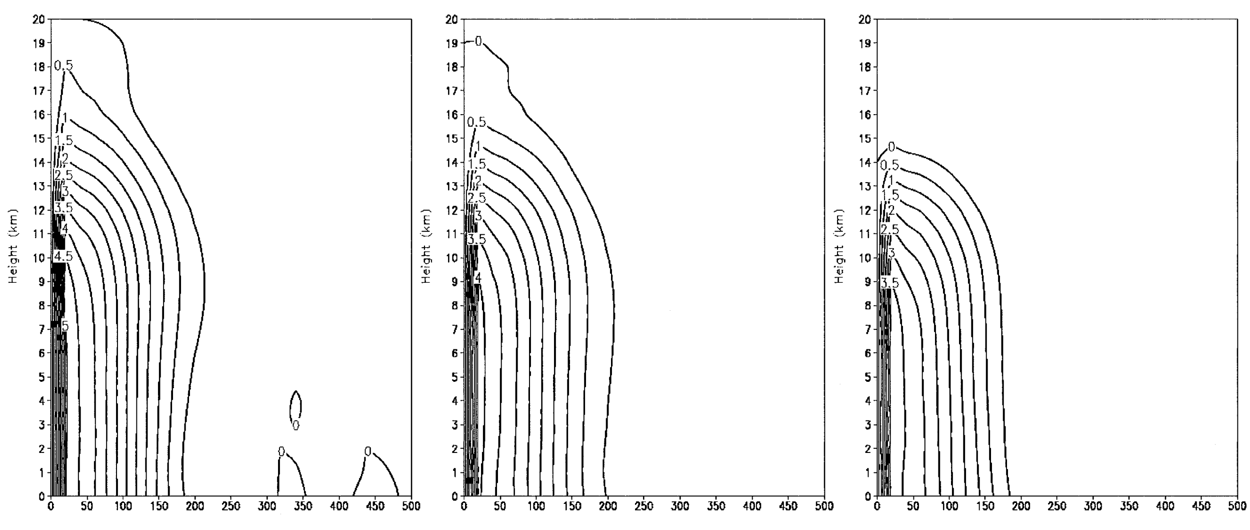

FIG. 4. Same as Fig. 2 except for vertical vorticity (10^{-4} s^{-1}).

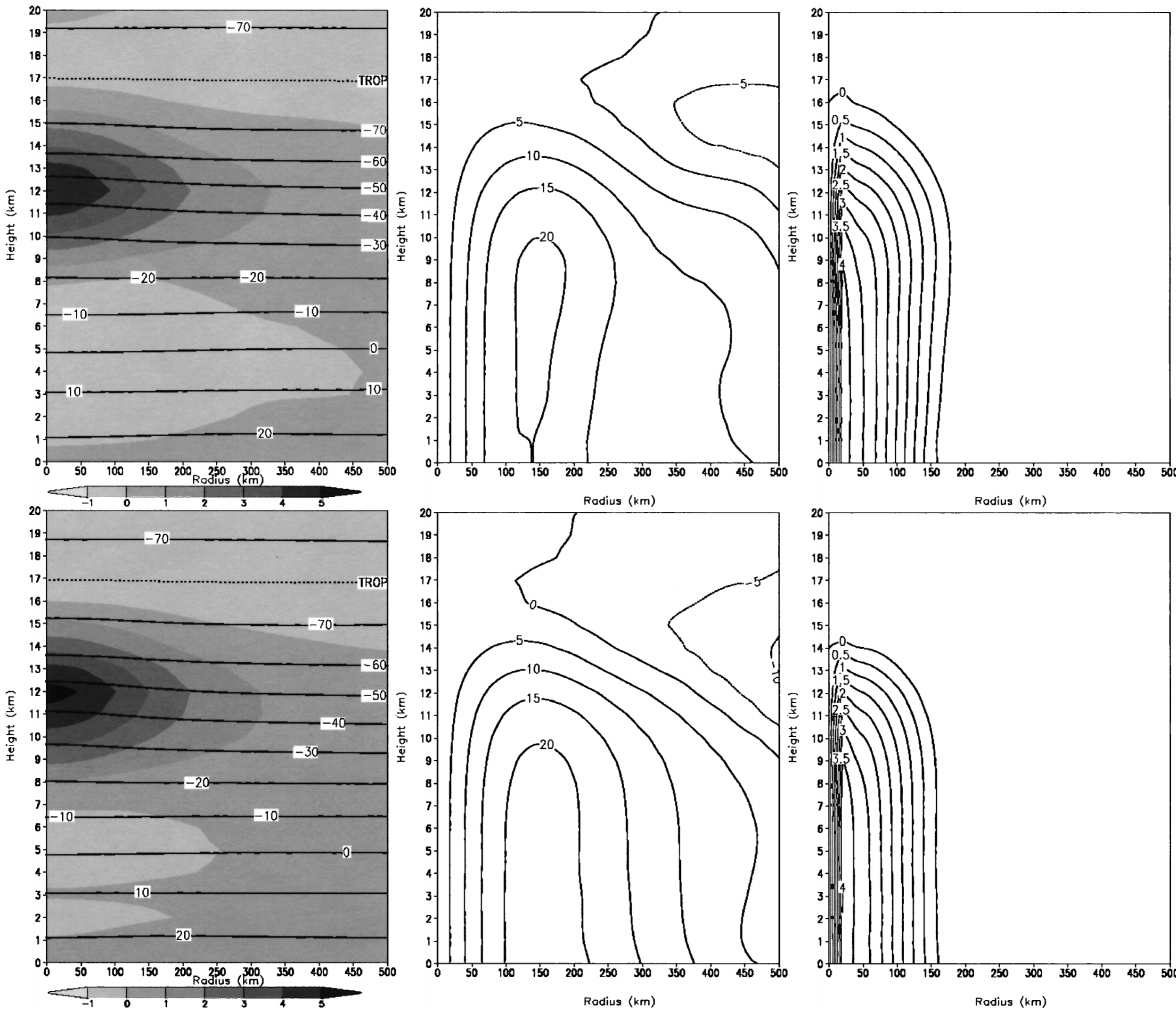

FIG. 5. Vertical shear composite results for all cases with intensities between 46 and 52 m s^{-1} (90 and 100 kt). Presented are (top) favorable and (bottom) less favorable composites, characterized by vertical wind shear values less than or equal to and greater than 7.5 m s^{-1}, respectively. Shown are composite radius–height cross sections of (left) temperature and temperature anomalies, (middle) balanced winds, and (right) vorticity. Units are the same as Figs. 3, 4, and 5, respectively.

well with values from other observational studies summarized in Frank and Ritchie (2001) and Knaff (1997), which reported values of approximately 8 to 10 m s^{-1} in the same atmospheric layers, over a variety of smaller areas. Table 2 shows the statistics associated with the favorable shear (shear $\leq$ 7.5 m s^{-1}) and less favorable shear (shear $>$ 7.5 m s^{-1}) composites.

Since compositing results will likely offer a smooth rendition of the effects of vertical wind shear on TC structure, an individual case of Hurricane Dennis (1999) is shown as it encounters increasing vertical wind shear over warm SSTs and weakens. In reviewing the AMSU sample, there were only a few cases where vertical wind shear increases were not accompanied by landfall or the storm moving over water 26.4°C and colder. In examining these other cases not affected by landfall or cold water (not shown), all showed evidence of a systematic lowering of the height of warm anomalies associated with the TC, but no single case offered a better example than Hurricane Dennis, which still was not ideal. In the case of Hurricane Dennis, storm weakening occurred over relatively warm SSTs $>$ 27.5°C. In addition, the storm's intensity estimate included aircraft observations and its location was close to the conventional observation-rich U.S. coastline, providing more confidence in both the intensity estimates and the wind shear calculated from NCEP analyses.

3. Results

Radius–height cross sections of average temperatures and temperature anomalies from the low, moderate, and

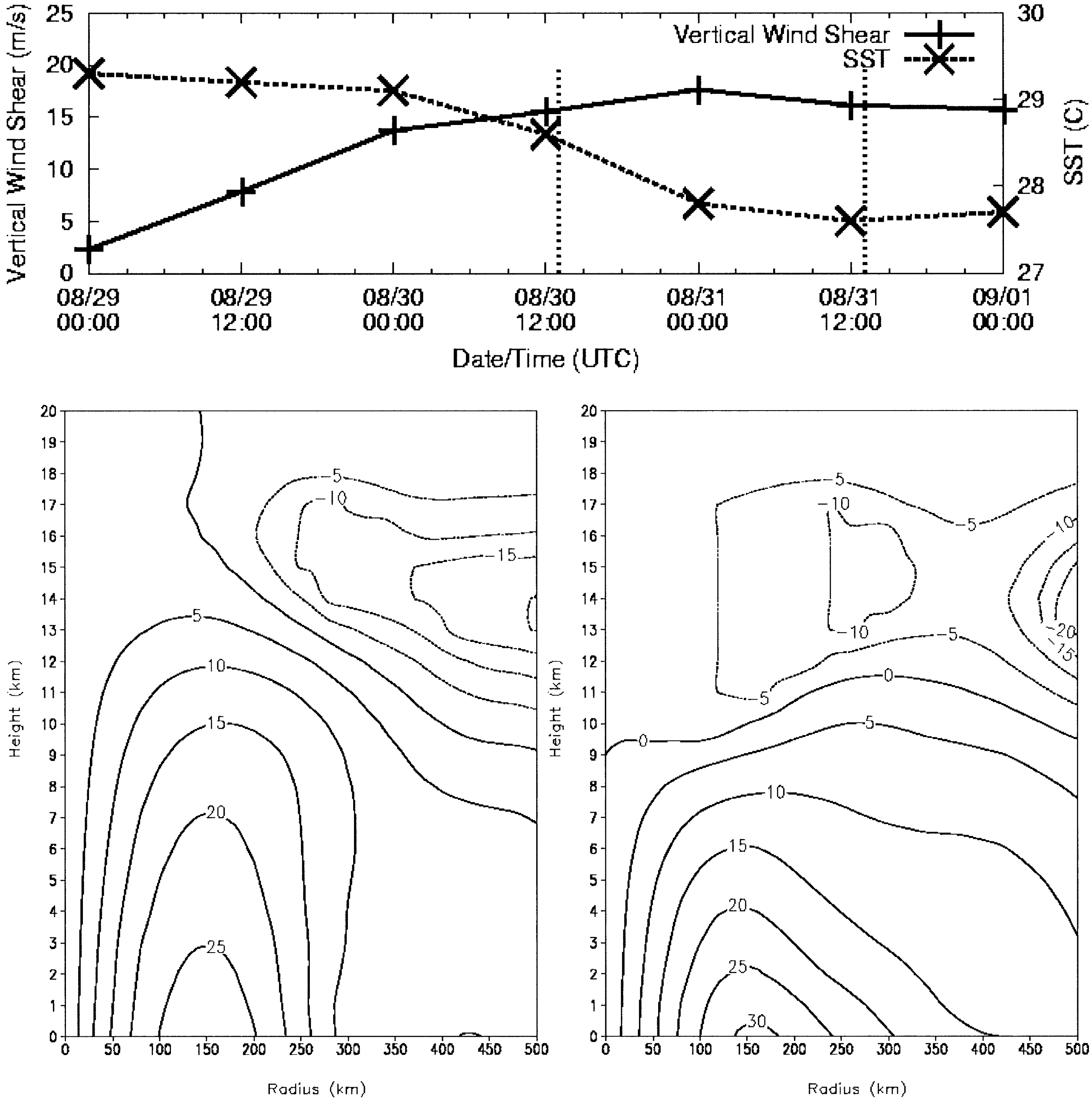

FIG. 6. An example of Hurricane Dennis (1999) showing the effects of vertical wind on its structure. (top) The time series of the vertical wind shear (m s^{-1}) and the SSTs (°C). The vertical lines indicate the times (1324 UTC 30 Aug and 1302 UTC 31 Aug) of the (bottom) AMSU-derived radius–height cross sections of tangential winds shown in from left to right.

high vertical wind shear composites are shown in Fig. 2. Temperature anomalies are calculated relative to the azimuthally and radially averaged temperature from a 500–600-km radius. Also shown is the level of the tropopause, defined here as the level where the vertical gradient of temperature reverses. Note that the tropopause is approximately at the same height in all of these composites. Differences between the three composites are rather subtle. Temperature anomalies are of the same magnitude at the upper levels, but the height of the maximum temperature anomaly decreases with increasing shear.

Consistent with the temperature anomalies shown in Fig. 2, azimuthal mean tangential winds (Fig. 3) for the low-shear composite are stronger at greater heights than for the moderate- and high-shear composites. The height differences of the vortex are slightly more pronounced between the moderate- and high-shear composites. These tangential wind profiles create distinctly different vertical vorticity profiles (Fig. 4), which show that, as shear increases, the height of the balanced hurricane vortex decreases.

The composite results shown in Figs. 2–4 suggest that the stronger the shear, the lower the warm core and associated vortex. This result, however, is somewhat complicated by the fact that some of the differences in the magnitude of temperature anomalies, tangential wind speed, and vertical vorticity field might be due to the mean intensity differences of the composites, as shown in Table 1. Given that the variation of the depth of the warm core could be a function of intensity, a smaller sample of cases with intensities ranging between 46 and 52 m s^{-1} are examined. As described in section 2, favorable ($\leq$7.5 m s^{-1}) and less favorable ($>$7.5 m s^{-1}) vertical wind shear form the basis for two composites.

Figure 5 (left) shows the radius–height cross sections of the temperature and temperature anomaly composites for the favorable and less favorable composites for storms with estimated intensities of 46 to 52 m s^{-1}. The differences between these two composites are comparable with those in Fig. 2, with the warm anomalies of the favorable composite being located at a slightly greater height. This warm-core structure again leads to tangential wind (Fig. 5, middle) and vertical vorticity (Fig. 5, right) structures that are deeper in the favorable wind shear composite. These composite results, which remove the influence of TC intensity, offer additional evidence that the effect of vertical wind shear is to erode the warm core from the top of the storm downward.

Figure 6 shows an example of Hurricane Dennis as it entered and remained in a high-shear environment. At the top of the figure is a plot of the time evolution of the vertical wind shear and SST along with the times of the two AMSU radius–height cross sections shown at the bottom of the figure. Hurricane Dennis experienced 24-h averaged vertical shear values of 12.7 and 16.4 m s^{-1}, respectively, at 1324 UTC 30 August and 1302 UTC 31 August. As the vertical wind shear increased, the vortex associated with Hurricane Dennis became noticeably shallower. The reduction in vortex depth, in general, should be more dramatic than in composite analysis, but in this case the differences are even more pronounced because of the rather abrupt change in the magnitude of the vertical wind shear from 29 to 30 August combined with the large magnitude of sustained vertical wind shear on 30 and 31 August. In fact, these two cases were both in what would have been considered high, and less favorable, shear conditions based on composite analyses defined in this study. Unfortunately, there is no AMSU analysis for 29 August, when the vertical wind shear was a minimum, for comparison with the result on 30 August. Despite these analysis shortcomings and the fact that that shear along with the entrainment of dry air contributed to the reduction of convection and subsequent weakening during the period 31 March to 2 September (see Lawrence et al. 2001), it is clear that Hurricane Dennis's warm-core structure becomes much shallower during this period of prolonged exposure to strong vertical wind shear.

4. Discussion

In the modeling study of Frank and Ritchie (2001), vertical wind was shown to erode the warm-core structure of the tropical cyclone from the top downward through downward propagating horizontal fluxes of potential temperature, consistent with the idea that upper-level asymmetries ventilate the eye as proposed by Gray (1968). The observational results, two composite analyses, and the Hurricane Dennis example presented in this note show that, as vertical wind shear increases, the warm-core vortex of the tropical cyclone becomes shallower. These results offer some much needed observational evidence that vertical wind shear acting on a mature TC causes a top-down erosion of its warm-core TC structure. While the basic results are consistent with recent modeling results (Frank and Ritchie 2001) and the concept of ventilation (e.g., Gray 1968), the symmetric analyses shown here cannot determine how this erosion occurs. Unfortunately, also beyond the ability of this symmetric analysis is the influence of the direction of the shear explored by several modeling studies (Tuleya and Kurihara 1981; Bender 1997; Frank and Ritchie 1999, 2001). Questions pertaining to effects of directional shear, storm motion, and eddy processes can be explored using the three-dimensional AMSU temperature retrievals and wind fields derived using the nonlinear balance equation, and these are the topics of future research. Nonetheless, the results shown here represent new and significant observational evidence concerning the effects of vertical wind shear on TC structure.

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