

Environmental Vertical Wind Shear with Hurricane Bertha (1996)

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ABSTRACT

Hurricane Bertha (1996) was influenced by vertical wind shear with highly variable direction and magnitude. The paper describes a unique method for determining the vertical tilt of a tropical cyclone vortex using satellite and aircraft data. Hurricane Bertha's vortex tracks at three levels are shown during a period of intensification just prior to landfall. During this period, the hurricane vortex becomes more closely aligned in the vertical. Changes in asymmetries of satellite infrared (IR) cold cloud areas are shown to be related to the vortex alignment. Environmental vertical shear measurements throughout Hurricane Bertha's life cycle are presented using IR cloud asymmetries and numerical model analyses. Intensification periods are associated with more symmetric IR cloud measurements. The directions of the IR cloud asymmetric orientations are compared with numerical-model-derived vertical shear directions. The changes in the vertical shear analyses are discussed with respect to observed intensity change, and other potential influences on intensity change. A trough interaction and the warm ocean influence of the Gulf Stream were observed with Hurricane Bertha. Correlation coefficients indicate weak correlations among vertical shear quantities and intensity change. Slightly higher correlations are shown with IR cloud asymmetry measurements versus numerical-model-derived vertical shear quantities.

1. Introduction

Tropical cyclones are commonly observed to weaken when they encounter vertical wind shear imposed by the environmental wind. When this occurs, satellite images show asymmetric distributions of deep convective clouds located downshear and shallow low-level clouds exposed on the upshear side. In fact, this shear pattern is recognized as one of the four basic cloud patterns of the Dvorak technique for assigning tropical cyclone intensity using satellite images (Dvorak 1984), and the intensities indicated by that pattern are generally below hurricane intensity. When the low-level circulation center can be seen in the shallow clouds, over warm tropical oceans, it seems clear that the vertical wind shear forcing is inhibiting intensification. However, when the environmental vertical wind shear is weaker, and intensification is observed, the role of vertical shear is less clear. It seems reasonable to assume that since only a small number of tropical cyclones attain their maximum potential intensity (Merrill 1988; Holland 1997; Emanuel 1997), that the vertical wind shear influences may often be a limiting factor. Furthermore, the vertical shear influences are fundamentally important to understanding tropical cyclone intensity change.

DeMaria and Huber (1998) provide a historical perspective on our understanding of the effect of vertical wind shear on intensity change, and there are recent theoretical and numerical modeling efforts that address the problem (Jones 1995; DeMaria 1996; Bender 1997; Frank and Ritchie 1999). Forecasters consider an assessment of vertical wind shear from satellite imagery and winds, and a more quantitative evaluation from numerical model forecasts when making an intensity forecast (Avila 1998). Statistical intensity forecast models indicate that two-level vertical shear measurements averaged over large areas provide useful information for intensity forecasting (DeMaria and Kaplan 1994, 1999; Fitzpatrick 1997).

To avoid any confusion, the "vertical shear" of interest that influences intensity change is the "environmental" vertical shear. "Point" values of vertical shear may be quite different, and are strongly influenced by the tropical cyclone circulation, whereas the environmental value is averaged over a large area centered on the tropical cyclone. The tropical cyclone circulation tends to average out, due to its axisymmetry, leaving the environmental wind profile. The deep layer mean of this profile has been referred to as the steering flow and is well related to the tropical cyclone motion. Similarly, it is the deep-layer tropospheric vertical shear that is related to intensity change. Historically, this vertical shear has been discussed and measured in the context of a two-level model (DeMaria 1996), with the upper

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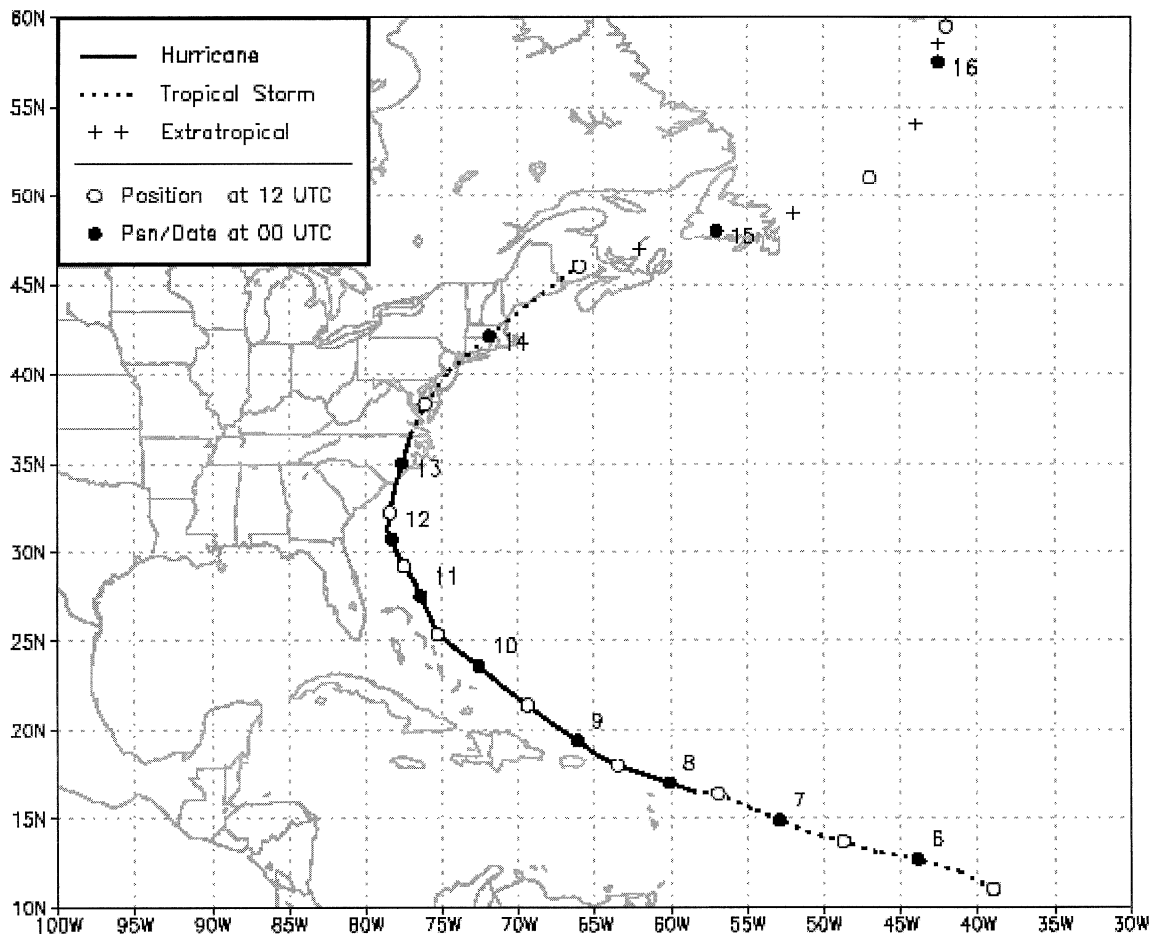


FIG. 1. Hurricane Bertha's track, 5–15 Jul 1996. "Best track" positions are plotted at 6-h intervals with 0000 UTC positions labeled by the day of Jul 1996.

and lower wind vector difference commonly given by a level (or layer) near 200 hPa, and a level near 850 hPa.

Satellite image measurements can be used to assess the influence of environmental vertical wind shear on a hurricane. Two application methods are illustrated in this paper. 1) The cloud asymmetry is quantified using IR images to compute the centroid of a cloud area defined as pixels colder than a specified temperature threshold. The direction and distance of that point from the surface center location provides a measure of asymmetry. 2) The cloud motions viewed in animation are used to locate circulation centers that can be tracked, with approximate height assignments based on IR temperatures. For this study, aircraft observations and multispectral, rapid interval satellite imagery were combined to track the hurricane circulation center at three levels.

Hurricane Bertha (1996) was chosen for this case study because it had multiple intensity maxima and appeared to be influenced by vertical wind shear with highly variable direction and magnitude. The main objective is to compare the satellite-based measurements with the

conventional numerical model analysis vertical shear computations. The satellite images provide high temporal resolution in comparison with twice-daily numerical model analyses.

Hurricane Bertha's track (Fig. 1) was generally toward the west-northwest, passing north of Puerto Rico. It then turned northward and made landfall in North Carolina at 2000 UTC 12 July 1996. Its intensity¹ reached 100 kt (51.4 m s^{-1}) maximum surface² wind speed and 960-hPa minimum sea level pressure (MSLP). The winds were at least hurricane intensity for about 5½ days. Bertha's intensity, plotted as MSLP in Fig. 2, shows three intensity peaks (MSLP minima). Intensification occurred on 7–8 July, becoming more rapid around 1200 UTC 8 July, and reached a maximum at 0600 UTC 9 July. After some slight weakening, a small reintensification was observed on 10 July. The intensity

¹ "Intensity" is defined as an estimate of the hurricane's maximum surface² wind speed, based on available observations. It is expressed in intervals of 5 kt ($1 \text{ kt} = 0.514 \text{ m s}^{-1}$). The associated minimum sea level pressure is also often used as an indicator of intensity.

² "Surface" wind speed is a 1-min-average wind at a height of 10 m.

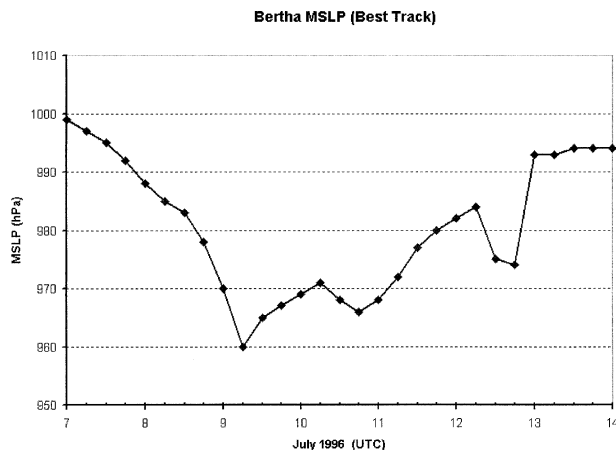


FIG. 2. Hurricane Bertha's intensity as MSLP (hPa) from best-track data.

then decreased substantially on 11 July, but an abrupt intensification occurred just prior to landfall on 12 July. The "best track" data (Figs. 1 and 2) include center locations and intensities, both as maximum surface wind speed and MSLP. The best-track analysis is based on all available data and information (Jarvinen et al. 1984). It is important to note that with Hurricane Bertha, the routine aircraft reconnaissance flights began at about 1000 UTC 7 July 1996 and continued until landfall.

2. Observations of tilted circulation center: 11–12 July 1996

The enhanced IR images in Fig. 3 illustrate the appearance and variability of Hurricane Bertha's asymmetric cloud patterns. The IR cold cloud area in Fig. 3a is predominantly west of the center. In contrast, on the following day, nearly all high (cold) clouds are lo-

cated in a semicircle east-southeast of the hurricane's surface center (Fig. 3b). Note in Fig. 2 that a small minimum in MSLP occurred at 1800 UTC 10 July, as the orientation of the cloud asymmetry changed markedly as shown in Fig. 3. Another intensification period occurred on 12 July and detailed observations and analysis during that period were used to track the circulation center at three levels.

a. Analysis

The satellite images at 2015 UTC 11 July (Fig. 4a) and 0545 UTC 12 July (Fig. 4b) show that Hurricane Bertha's circulation center is defined by the low-level clouds. A few hours later at 1132 UTC 12 July (Fig. 4c) the center is once again surrounded by deep convective clouds. During the 24-h period prior to Hurricane Bertha's landfall at 2000 UTC 12 July, rapid changes occurred in the satellite-observed cloud patterns.

Intensity changes during that time were well observed by aircraft reconnaissance. Between 1200 UTC 11 July and the time of landfall, there were 16 aircraft measurements of Bertha's MSLP, either by dropsonde or extrapolation of flight-level pressure. Those observations, plotted in Fig. 5, depict the reintensification of Hurricane Bertha that occurred rather quickly as the MSLP fell from 985 to 974 hPa between 0830 and 1257 UTC. The associated increase in maximum surface wind from the best-track intensity data was from 70 to 90 kt (36–46 m s⁻¹). An observation of 991-hPa MSLP early on 12 July was suspect and was disregarded in the best-track data. It has also been omitted in Fig. 5. The final MSLP observation (Fig. 5) very close to the time of landfall indicates a slight weakening (MSLP increase). However, it is assumed that Hurricane Bertha maintained its intensity with 974-hPa MSLP and 90-kt (46

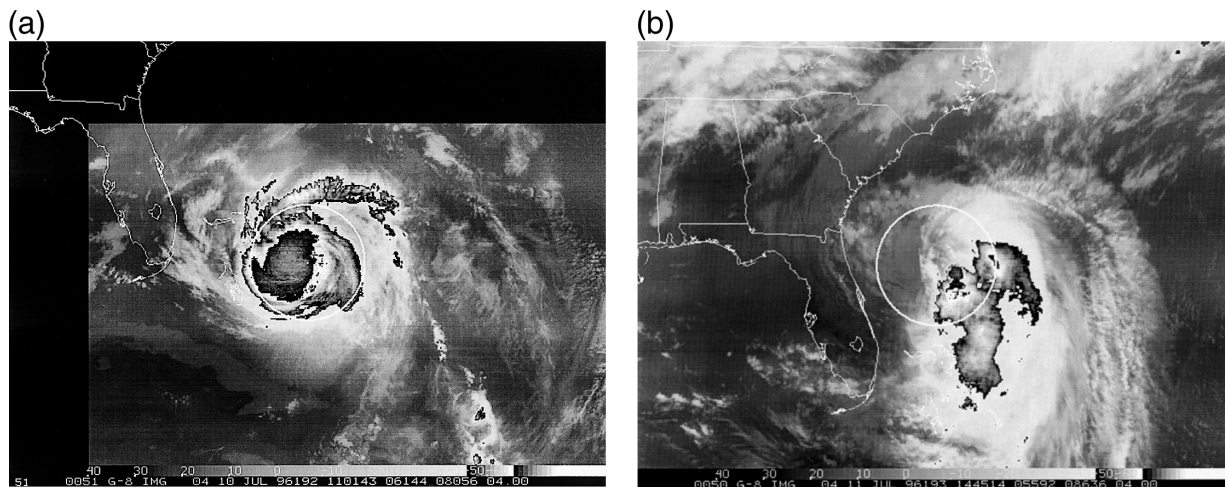


FIG. 3. Enhanced IR images for Hurricane Bertha: (a) 1101 UTC 10 Jul 1996 and (b) 1445 UTC 11 Jul 1996. The enhancement assigns linear black to white shades for IR temperature from -50° to -69°C , and the same enhancement again for IR temperatures colder than -70°C . The circle is at 222-km radius from the hurricane center.

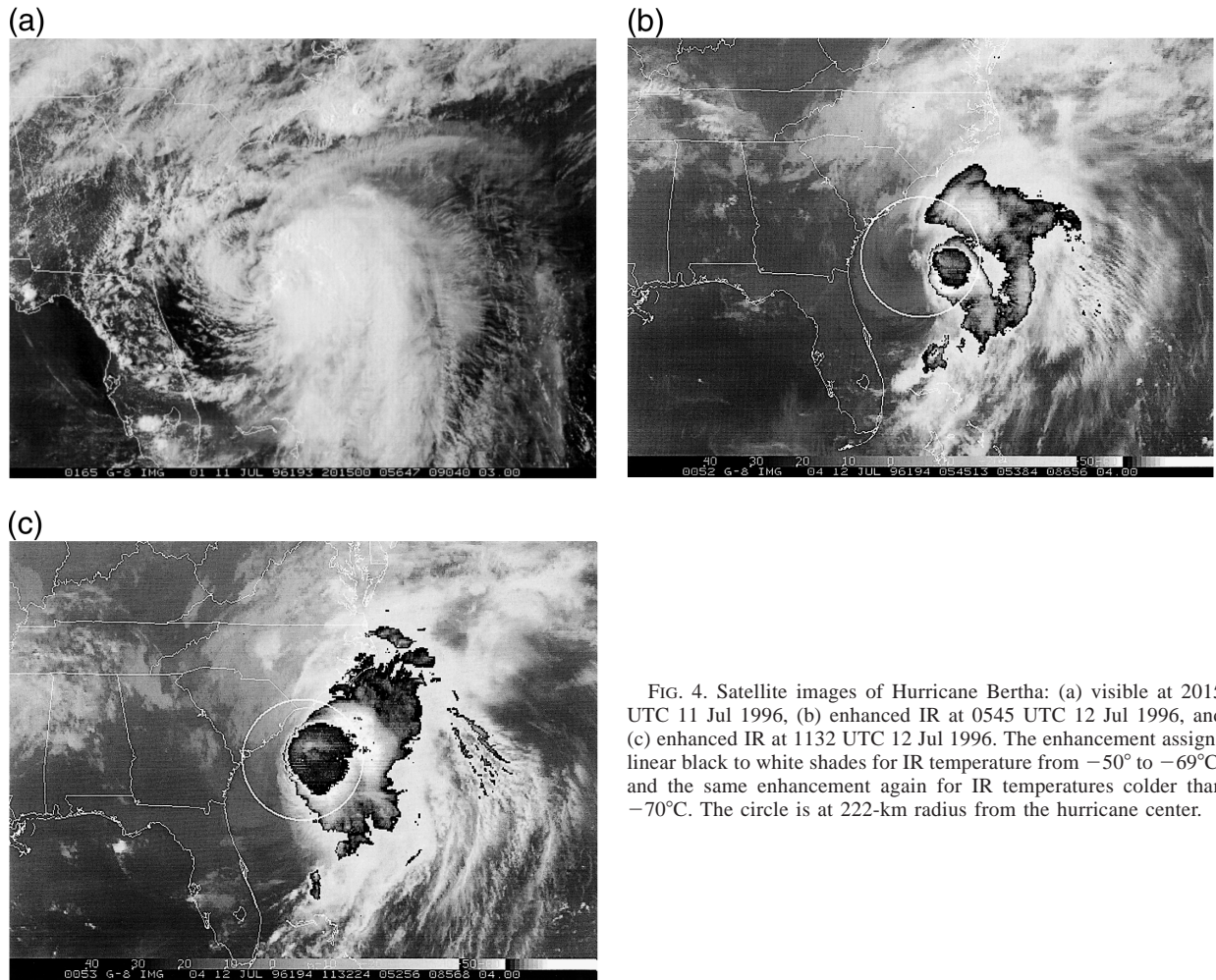


FIG. 4. Satellite images of Hurricane Bertha: (a) visible at 2015 UTC 11 Jul 1996, (b) enhanced IR at 0545 UTC 12 Jul 1996, and (c) enhanced IR at 1132 UTC 12 Jul 1996. The enhancement assigns linear black to white shades for IR temperature from -50° to -69°C , and the same enhancement again for IR temperatures colder than -70°C . The circle is at 222-km radius from the hurricane center.

m s^{-1}) maximum wind up to time of landfall (Pasch and Avila 1999).

The aircraft reconnaissance provides not only MSLP measurements but also accurate center locations at flight

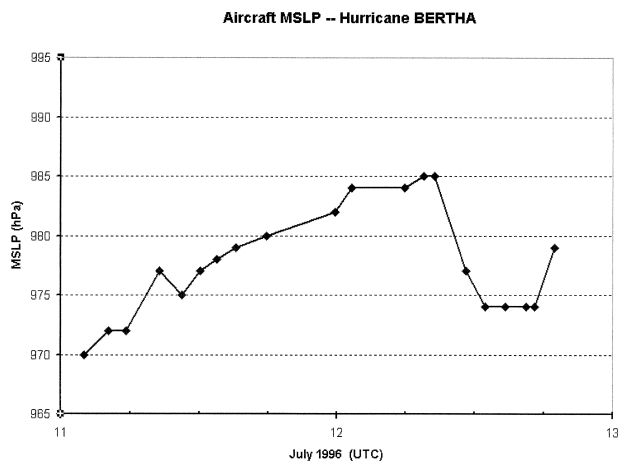


FIG. 5. Aircraft observations of Hurricane Bertha's MSLP (hPa).

level (700 hPa, approximately 3 km). Animation of Geostationary Operational Environmental Satellite (GOES) visible images (daytime) and channel 2 ($3.9 \mu\text{m}$) images (nighttime) along with Dvorak (1984) center fixing methods were used to track the low-level center. Since IR cloud-top temperatures for the shallow nearly over-cast clouds near the center were in the 13° – 17°C range, it is assumed that the center that was tracked is likely representative of the layer below 2-km height, and is assigned an approximate height of 1 km. Animation of IR images during this period revealed a cyclonic circulation center in the high clouds. This provided a track of the upper-level center. The IR temperatures associated with that circulation center (Figs. 3 and 4) indicated a level of approximately 15 km. Rapid scan (5-min interval) images were available from 0000 to 1800 UTC 12 July for satellite-derived center fixes.

Satellite images from multispectral rapid interval GOES along with aircraft center fix data, have been combined to obtain the track of Hurricane Bertha's center at three levels of approximately 1-, 3-, and 15-km height. The tracks were interpolated to 6-h intervals

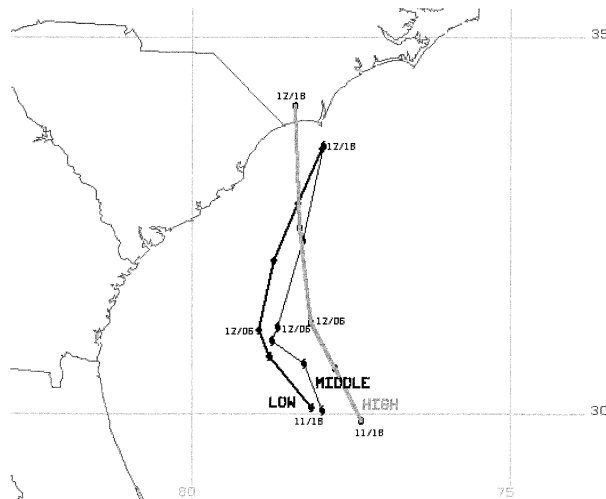


FIG. 6. Tracks of Hurricane Bertha's center from 1800 UTC 11 Jul through 1800 UTC 12 Jul 1996 at three levels in the atmosphere (low, 1 km; middle, 3 km; high, 15 km).

from 1800 UTC 11 July through 1800 UTC 12 July just prior to landfall (Fig. 6). The tracks labeled “low” and “high” are derived from satellite imagery, while the track labeled “middle” is from aircraft flight-level center fixes. Table 1 lists the directions and distances of the circulation center displacements in the vertical using the three levels (low, 1 km; middle, 3 km; and high, 15 km). The analysis reveals that Hurricane Bertha's center is tilted generally toward the east with height through all three levels, from 1800 UTC 11 July through 0600 UTC 12 July. The tilt increases to a maximum near 0000 UTC and then begins decreasing. At the 0000 UTC maximum, the low-level center is located 104 km to the west-northwest of the upper-level center. A rapid change to a more vertical alignment occurs with the middle- and upper-level centers aligning first followed a bit later by the lower- and middle-level centers. An additional entry in Table 1 at 1500 UTC is shown to better depict the changes. The changes in the circulation center displacements through the three levels appear to occur along with an abrupt change in hurricane motion from a north-northwest to a north-northeast track, near 0400 UTC. The intensification period coincides fairly closely

with the minimum in separation distances of the centers. By 1800 UTC 12 July the upper-level center is again becoming more separated from the lower and middle levels, but in a different direction, with the low-level center to the south-southeast of the upper-level center. During the period from 1200 to 1800 UTC the orientation of the tilt changes to one that is along track in the lower troposphere with the midlevel center slightly ahead of the low level, and the upper-level center displaced to the north-northwest. It should be noted at this time the high-level clouds were dissipating and the upper-level center was broader, thus adding some uncertainty to its exact location at this time.

The three-level analysis (Fig. 6 and Table 1) is intended to illustrate the changes with time of the approximate magnitude and orientation of the tilted hurricane vortex. The uncertainties and potential errors in the satellite center fixes and height assignments are likely too large to obtain precise measurements, and are likely not well suited for applications such as numerical model initialization or validation.

The validity of the analysis was corroborated by aircraft reconnaissance center fix observations at 1118 and 1257 UTC on 12 July. At those times, the surface center was reported to be located 37 km (20 n mi) to the south-southwest of the flight-level center. At 1440 UTC a 19-km (10 n mi) displacement was reported and, with the observations following, no displacement was reported. This is in general agreement with the analysis based on low-level satellite center fixes. Modification of the low-level track in Fig. 6 based on this information would bring it slightly closer to the middle-level track between 1200 and 1800 UTC on 12 July. The best-track center positions are aligned parallel and east of the low-level track in Fig. 6, and agree more closely with the aircraft flight-level positions.

During this analysis period, cloud asymmetry measurements were computed by locating the centroids of cloud areas with IR temperature less than -60°C , within 444 km of the hurricane center, using individual GOES images at 30-min intervals. The -60°C threshold was arbitrarily chosen to define an area large enough that it persists through the analysis period, but yet small enough to identify the areas of deep convective cloud.

TABLE 1. Hurricane Bertha's circulation center displacement directions and distances, through three atmospheric levels, with approximate heights: low, 1 km; middle, 3 km; high, 15 km. The directions are given as that from which the vector is directed from the first to second level. For example, the first entry, 287° at 18 km, for “low to middle” indicates the low-level center is 18 km toward 287° (i.e., WNW) from the midlevel center.

Date	Time (UTC)	Low to middle		Middle to high		Low to high	
		Direction ($^{\circ}$)	Distance (km)	Direction ($^{\circ}$)	Distance (km)	Direction ($^{\circ}$)	Distance (km)
11 Jul	1800	287	18	294	64	292	82
12 Jul	0000	283	55	292	50	287	104
12 Jul	0600	263	29	276	50	271	79
12 Jul	1200	237	53	143	8	227	53
12 Jul	1500	237	28	144	39	180	47
12 Jul	1800	225	5	145	71	148	72

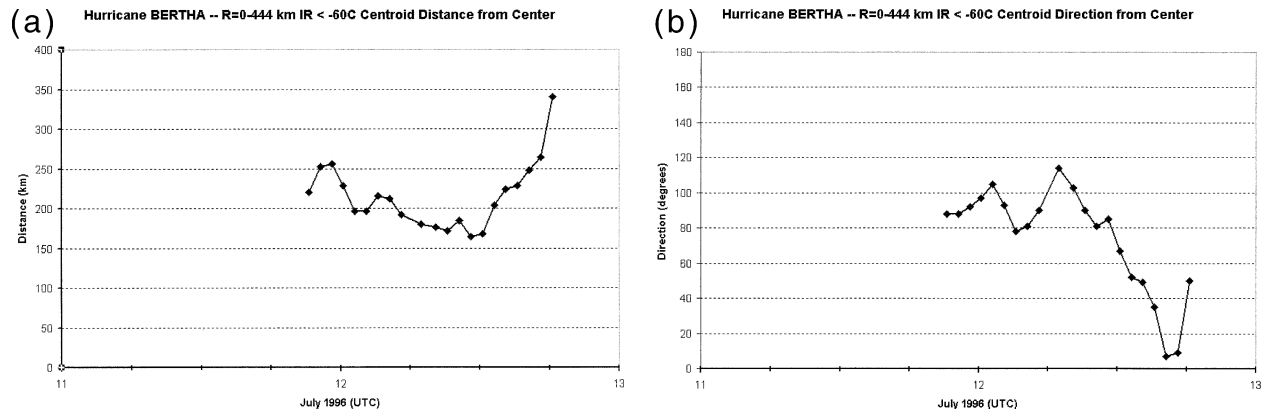


FIG. 7. Centroid locations of cloud areas with temperature less than -60°C within 444-km radius of hurricane center, computed from 30-min interval GOES images, according to (a) distance (km) from hurricane center and (b) direction ($^{\circ}$) from hurricane center. Date and timescale match Fig. 5.

Experience with this type of analysis has shown results to be rather insensitive to the exact threshold used through a range of cold IR temperatures. The distances and directions of the centroid locations from the surface center are plotted in Fig. 7. The minimum distance occurs at 1115 UTC 12 July, with the IR cloud area less than the -60°C centroid located 164 km to the east of the center. This coincides with the 8-km minimum displacement between the middle- and high-level circulation centers at 1200 UTC in Table 1. The orientation of the IR cloud asymmetry is west to east, but following the minimum, the direction shifts toward a nearly south to north orientation. This coincides with the displacement of the middle- and high-level centers along a southeast to northwest direction.

The IR cloud asymmetries exhibit changes closely related to the changes in the vertical alignment of the circulation centers. However, the cloud asymmetries suggest that a component of westerly vertical shear persists throughout the analysis period. The relationship between IR cloud asymmetry and vertical shear computed from numerical model analysis is explored further in section 3.

b. Discussion

Two other notable environmental influences were taking place during the 12 July intensification period: 1) Hurricane Bertha crossed the Gulf Stream and 2) Hurricane Bertha was interacting with a weak upper-level trough that approached from the west-northwest and changed the hurricane's direction of motion.

The narrow band of warmer sea surface temperatures known as the Gulf Stream is a well-recognized oceanic feature. The potential for oceanic influences on intensity change seems clear due to the fact that energy flux from warm oceans is the primary energy source for the formation and maintenance of tropical cyclones (Palmen 1948; Leipper and Jensen 1971). Hurricane Opal (1995) was influenced by the warm-core ring in the Gulf of

Mexico (Shay et al. 2000). Hurricane Bertha clearly exhibited enhanced deep convection as it passed over the Gulf Stream as can be seen by comparing IR images in Figs. 4b and 4c.

Trough interactions like the one that occurred with Hurricane Bertha have been shown to often be associated with hurricane intensification periods (Hanley et al. 2001; Kaplan et al. 1997). Bosart et al. (2000) describe a "jet-trough-hurricane interaction in a low shear environment" associated with the rapid intensification of Hurricane Opal (1995), and provide a detailed discussion of hurricane-trough interactions with additional case studies (Molinari and Vollaro 1990). For example, Hurricane Elena's (1985) trough interactions resulted in an erratic track with two intensity maxima along the Gulf Coast.

Despite the potential influences of the Gulf Stream and the trough interaction on Hurricane Bertha's re-intensification of 12 July, the observed intensity changes (Fig. 5) can also be explained by hypothesizing that they were forced by changes in the environmental vertical shear. This is based on the assumptions that 1) Hurricane Bertha's tilted circulation center changes in response to environmental vertical shear and 2) that the re-intensification period occurs due a vertical shear minimum, coinciding with the circulation centers becoming more closely aligned in the vertical.

3. Environmental vertical shear measurements with Hurricane Bertha (1996)

a. IR images

IR cloud asymmetries were quantified by computing the centroid of all clouds with IR temperature colder than -65°C in a 222-km radius circle centered on the surface center. The distance and direction of the centroid location from the center provide a measurement of the asymmetry and are plotted as time series in Fig. 8. For this analysis, the computation was performed every 6

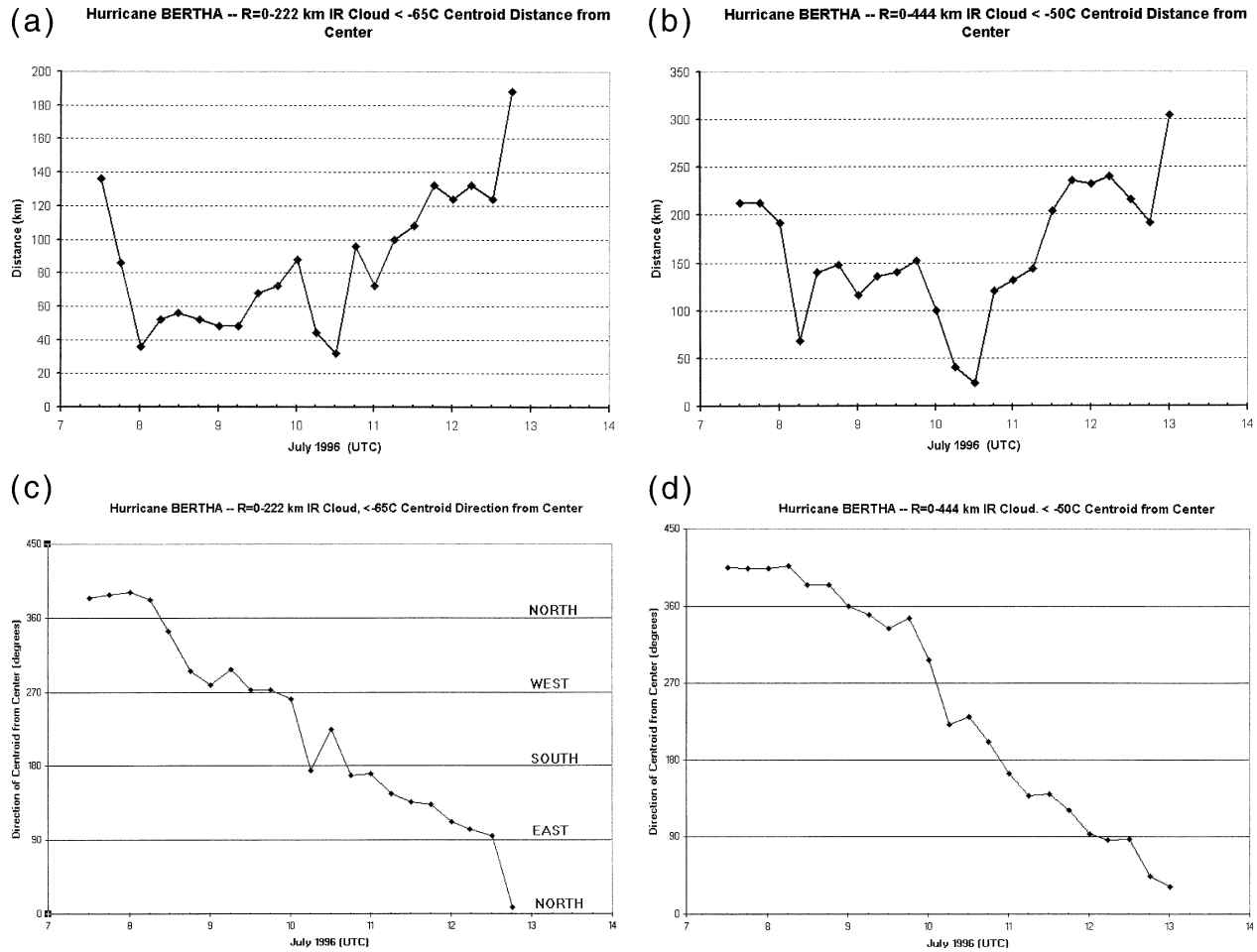


FIG. 8. Time series of IR cloud area centroid distance from Hurricane Bertha's surface center. The 6-h-average IR images are used. (a) The IR temperature less than -65°C in a 222-km radius circle, (b) IR temperature less than -50°C in a 444-km radius circle, (c) direction of centroid from center (e.g., 90° indicates the centroid is east of the center, 180° south, 270° west, etc.), IR temperature less than -65°C in a 222-km radius circle, and (d) direction of centroid from center, IR temperature less than -50°C in a 444-km radius circle.

h on IR average images. Those images were derived by relocating and registering each 30-min IR image to the surface center prior to averaging over a 6-h period. The image averaging removes some of the short timescale variability and gives a clearer picture of the cloud pattern. Figure 8 is comparable to Fig. 7, except that the analysis period is expanded to Hurricane Bertha's entire life cycle and 6-h interval IR-average images are used instead of 30-min individual images.

Figure 8 includes another analysis using a temperature threshold of -50°C and a 444-km radius circle. The distance and direction of the cloud centroids from the surface center are plotted as time series. Both asymmetry measurements are shown since one of the objectives is to evaluate the use of different areas and IR temperature thresholds for IR asymmetry quantities. It is noted that with Hurricane Bertha (Fig. 8) the two measurements roughly depict the same thing. The relationships between the IR asymmetries (Fig. 8) and the environmental vertical wind shear, as quantified by nu-

merical model analyses, are discussed in sections 3b and 4.

Weak vertical shear environments are associated with small displacements of the IR cold cloud centroid from the center, while very asymmetric cloud patterns have large displacements, indicating high vertical wind shear. The direction of the vertical shear is toward a downshear IR cold cloud centroid location. Therefore, with strong westerly shear (i.e., increasing westerly wind component with height), IR cold cloud centroids tend to be located toward the east. For example, the IR asymmetries at 0000 UTC 12 July clearly indicate vertical shear with a strong westerly component, since the displacements in Figs. 8a and 8b are large and both IR cold cloud centroids are located to the east of the center (Figs. 8c and 8d).

Hurricane Bertha's main intensification period is 7–8 July (Fig. 2), with an increase of intensification rate around 1200 UTC 8 July, reaching an intensity maximum (MSLP minimum) at 0600 UTC 9 July. The IR

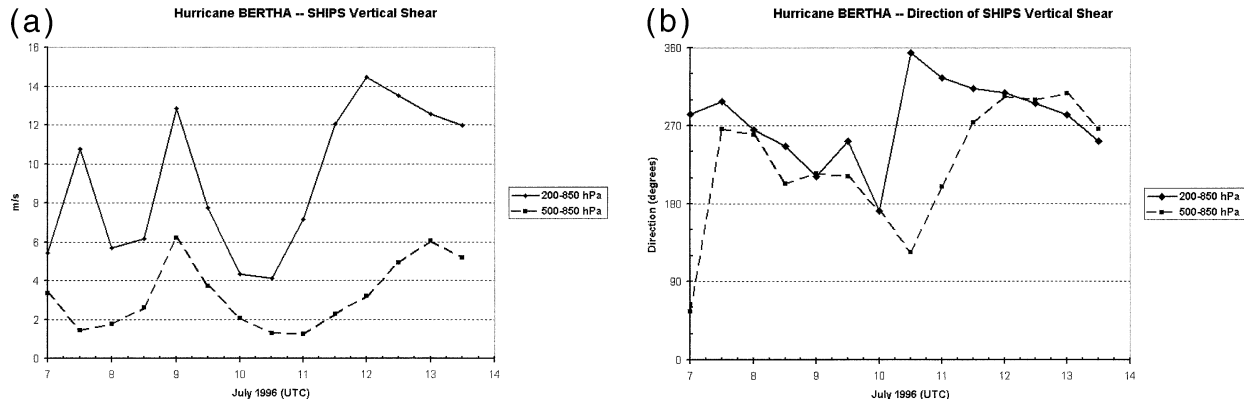


FIG. 9. SHIPS vertical shear (a) speed (m s^{-1}) and vertical shear (b) direction for 200–850 and 500–850 hPa. The SHIPS routine averages the winds at 200–800-km radius from the hurricane center using the AVN initial analysis.

asymmetries out to 222-km radius (Fig. 8a) show a large decrease on 7 July and remain small (less than 60-km IR centroid displacement from surface center) through its initial intensification period. The directions are toward the northeast on 7 July shifting to an orientation toward the west-northwest at the intensity maximum. This suggests that southwesterly vertical shear decreases and turns to a more easterly direction during Hurricane Bertha's main intensification period. The larger area asymmetries (Fig. 8b) show similar characteristics, except that the directions shift only slightly from northeast to northwest.

Gradual weakening takes place during the period 0600 UTC 9 July–0600 UTC 10 July. This is accompanied by an increase in asymmetric cloud pattern (Fig. 8a). The cold IR cloud area becomes displaced to the west of the center. The larger cloud area (Fig. 8b) shows a small increase in asymmetry.

The reintensification period on 10 July occurs along with a decrease in IR cloud asymmetry (Figs. 8a, 8b). As the IR asymmetries reach minimum values and increase again on 10 July, there are also large changes in direction (Figs. 8c, 8d). Between 1200 UTC 9 July and 1200 UTC 11 July the direction of the IR cloud centroid (area $< -65^{\circ}\text{C}$, at $R = 0\text{--}222$ km in Fig. 8c) changes from west to southeast, while the one in Fig. 8d (area $< -50^{\circ}\text{C}$, at $R = 0\text{--}444$ km) changes more than 180° to a southeast orientation. This suggests that a large rapid change in environmental vertical shear direction may be associated with a minimum in vertical shear magnitude.

During 11 July, both measurements of IR asymmetry are increasing, and both directions become oriented toward the southeast, indicating increasing northwesterly vertical shear, and Hurricane Bertha's intensity shows a steady weakening trend (Fig. 2). A slight decrease in IR asymmetry is noted in Fig. 8, associated with the 12 July intensification period discussed in section 2. It is not well depicted by the measurements in the 6-h average images, because it happened on short timescales, and was followed quickly with an overall decrease in

cold cloud area associated with Hurricane Bertha's landfall.

In general, Hurricane Bertha's IR asymmetry analysis indicates that intensification occurs when deep clouds are more symmetrically distributed about the center, while weakening periods are associated with large asymmetric IR cloud measurements. It is interesting to note that the IR cloud asymmetries rotate completely around Hurricane Bertha's center during the 6-day analysis period. This may likely be an unusual occurrence uniquely associated with Hurricane Bertha.

b. Model analysis

Numerical models objectively analyze operationally available wind observations, which include radiosondes, aircraft, and satellite wind vectors. In addition, they retain information from previous analyses to help quantify, for example, the tropical cyclone wind field. Even though available observations may at times be sparse, the analysis provides a quantitative and consistent assessment of the environmental vertical wind shear (Molinari et al. 1992).

Environmental vertical wind shear quantities are derived from the National Centers for Environmental Prediction (NCEP) global spectral model, known as the Aviation Model (AVN), and used as input to the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria and Kaplan 1999). SHIPS vertical shear speeds and directions at the initial analysis time (12-h interval) of Hurricane Bertha are plotted in Fig. 9. The SHIPS analysis spatially averages the wind vectors between 200- and 800-km radius from the hurricane center, and computes the vertical wind shear speed and direction from the vector difference of the 200- and 850-hPa averages. In the same way, a lower-tropospheric shear vector is also computed by subtracting the 850-hPa wind field from that at 500 hPa.

With Hurricane Bertha, SHIPS vertical shear quantities begin with low values associated with the initial intensification period, then increase to a maximum at

0000 UTC 9 July. They decrease to low values on 10 July, and then increase to even higher values by 0000 UTC 13 July, near the time of landfall. In general, the trends are similar for both 200 – 850 and 500 – 850 hPa, with lower values at 500 – 850. However, it is noteworthy that on 7 July, the 500 – 850-hPa shear direction is easterly, while it is westerly at 200 – 850 hPa. During the later time periods, the two shear quantities have similar directions.

The SHIPS vertical shear maxima at 0000 UTC 9 July in both the 200 – 850- and 500 – 850-hPa quantities (Fig. 9a) coincide with the onset of weakening. However, the increasing trend of SHIPS vertical shear appears to precede the onset of weakening suggesting a lagged response of the intensity change to vertical shear.

The reintensification on 10 July occurs with SHIPS vertical shear returning to lower values. The weakening on 11 July occurs as the 200 – 850-hPa SHIPS vertical shear increases to higher values. The SHIPS vertical shear remains at relatively high values at 1200 UTC 12 July and 0000 UTC 13 July in association with the reintensification period.

Comparison of the 200 – 850-hPa SHIPS vertical shear directions (Fig. 9b) and the orientation of the IR asymmetries (Figs. 8c,d) suggest that they are related. Following 1200 UTC 10 July, the 200 – 850-hPa SHIPS shear directions gradually change from northerly to westerly. During the same period through 1200 UTC 12 July, the IR asymmetries change from a north–south orientation to a west–east orientation. At other times, relationships between the directional shear indicators are less clear. This is particularly true when the vertical wind shear is weak.

4. Correlations

Undoubtedly a larger sample is needed to establish relationships between the IR cloud asymmetries and the numerical analysis vertical shear quantities. Also, there may likely be other influences on IR cloud asymmetry measurements in addition to environmental vertical shear. For example, a tropical cyclone's intensity and structure are known to influence the cloud patterns. In addition, sea surface temperature and thermodynamic conditions effect the size of the cold IR cloud areas. Both of those factors contribute to the IR temperature scene and may modify the IR cloud centroid locations.

Some aspects of the relationships between the vertical shear datasets and Hurricane Bertha's intensity are noted in the correlation coefficients, R , in Table 2. Boldface font identifies R with 90% confidence level using the Student's t test. The correlations are listed for both types of vertical shear indicators: IR cloud asymmetry and SHIPS vertical shear wind speed. Following that, the vertical shear datasets are paired with intensity, as measured by MSLP. The correlations with intensity change over 6-, 12-, and 24-h periods are also given in Table

2. Each intensity change period is assigned the time that corresponds to the end of the period.

The numerical-model-derived vertical shears are related to the cloud IR asymmetries and the correlations are higher with the 200 – 850-hPa SHIPS vertical shear than with the 500 – 850-hPa quantities (Table 2).

The larger area IR cloud asymmetry measurements are well related to intensity (Table 2). Such a relationship should be expected based on how cloud patterns are known to be related to intensity (Dvorak 1984).

Higher correlations between vertical wind shear and intensity change, as opposed to current intensity, are expected (DeMaria and Kaplan 1994, 1999). The correlation coefficients in Table 2 also show this. Note that the correlation coefficients between intensity change and IR cloud asymmetries are higher than with the SHIPS vertical shear. This suggests that IR cloud asymmetry measurements should be examined further as to their potential for incorporation into statistical intensity forecast schemes.

Theoretical and modeling studies (Jones 1995; Frank and Ritchie 2001; Bender 1997) have shown that vertical wind shear changes lead resultant structure and intensity changes by up to 24 h. To explore this with the datasets from Table 2, correlation coefficients were computed using the intensity change data with lags up to 24 h. The intensity change applies to the period ending at the time used for the correlation computations. The data lags are with respect to that time. Table 3 lists the two highest correlation coefficients with each vertical shear indicator from all three intensity change categories (6, 12, and 24 h) using lagged data out to 24 h. These correlation coefficients that relate to future intensity change are generally higher than those in Table 2. The IR cloud asymmetries appear better related to short-term (6–12 h) future intensity change, while the SHIPS vertical shears tend to lead intensity change by 12–24 h.

5. Discussion

The environmental vertical wind shear with Hurricane Bertha was observed to undergo major changes both in magnitude and direction, which influenced the hurricane's intensity. The changes in the vertical alignment of Hurricane Bertha's circulation centers at three levels illustrated in section 2 are important in understanding the intensification period of 12 July. The timescales on which changes are observed in the tilted centers and the IR cloud asymmetries suggest that 12-h interval numerical model analysis may be insufficient to reliably capture the important changes. If useful indicators of the environmental vertical shear can be extracted from the IR image data, improved diagnosis of ongoing changes may be a possible aid in short-term forecasting and may improve our understanding of intensity change. Rapid changes can be measured by 30-min interval IR images.

TABLE 2. Correlation coefficients R . Boldface font identifies R with 90% confidence level using the Student's t test.

Indicators of vertical shear		R	n
$R = 0\text{--}222\text{-km}$ IR cloud $< -65^\circ\text{C}$ centroid distance from center	SHIPS 200–850-hPa vertical shear speed	0.655	12
$R = 0\text{--}222\text{-km}$ IR cloud $< -65^\circ\text{C}$ centroid distance from center	SHIPS 500–850-hPa vertical shear speed	0.376	12
$R = 0\text{--}444\text{-km}$ IR cloud $< -50^\circ\text{C}$ centroid distance from center	SHIPS 200–850-hPa vertical shear speed	0.702	12
$R = 0\text{--}444\text{-km}$ IR cloud $< -50^\circ\text{C}$ centroid distance from center	SHIPS 500–850-hPa vertical shear speed	0.408	12
Intensity and vertical shear			
Intensity, best-track (MSLP)	$R = 0\text{--}222\text{-km}$ IR cloud $< -65^\circ\text{C}$ centroid distance from center	0.260	22
Intensity, best-track (MSLP)	$R = 0\text{--}444\text{-km}$ IR cloud $< -50^\circ\text{C}$ centroid distance from center	0.593	23
Intensity, best-track (MSLP)	SHIPS 200–850-hPa vertical shear speed	0.117	13
Intensity, best-track (MSLP)	SHIPS 500–850-hPa vertical shear speed	0.062	13
Intensity change and vertical shear			
6-h change of MSLP	$R = 0\text{--}222\text{-km}$ IR cloud $< -65^\circ\text{C}$ centroid distance from center	0.284	22
6-h change of MSLP	$R = 0\text{--}444\text{-km}$ IR cloud $< -50^\circ\text{C}$ centroid distance from center	0.384	23
6-h change of MSLP	SHIPS 200–850-hPa vertical shear speed	0.113	13
6-h change of MSLP	SHIPS 500–850-hPa vertical shear speed	0.157	13
12-h change of MSLP	$R = 0\text{--}222\text{-km}$ IR cloud $< -65^\circ\text{C}$ centroid distance from center	0.247	22
12-h change of MSLP	$R = 0\text{--}444\text{-km}$ IR cloud $< -50^\circ\text{C}$ centroid distance from center	0.348	23
12-h change of MSLP	SHIPS 200–850-hPa vertical shear speed	0.190	13
12-h change of MSLP	SHIPS 500–850-hPa vertical shear speed	0.031	13
24-h change of MSLP	$R = 0\text{--}222\text{-km}$ IR cloud $< -65^\circ\text{C}$ centroid distance from center	0.442	22
24-h change of MSLP	$R = 0\text{--}444\text{-km}$ IR cloud $< -50^\circ\text{C}$ centroid distance from center	0.319	23
24-h change of MSLP	SHIPS 200–850-hPa vertical shear speed	0.333	13
24-h change of MSLP	SHIPS 500–850-hPa vertical shear speed	0.078	13

It seems clear that environmental vertical shear is an important influence on tropical cyclone intensity change. When the vertical shear increases substantially, intensification is limited, and with larger increases of vertical shear, weakening is observed. Decreases in vertical shear may allow reintensification to occur. However, it has not been shown that the vertical shear influence can be reliably quantified and consistently related to observed intensity change.

Satellite-derived indicators that relate to environmental vertical wind shear may provide important information for short-term forecasting applications. Quan-

ties derived from numerical model vertical shear have been shown to be useful with statistical forecast models (e.g., SHIPS; DeMaria and Kaplan 1999). However, numerical-model-derived vertical shear quantities that more closely relate to observed intensity changes in a consistent way are lacking. The SHIPS vertical shear values are computed over very large areas out to 888 km from the storm's center. Model-derived quantities over smaller areas, with additional levels, may be better related to hurricane center vertical alignment and inner-core IR cloud asymmetry. To establish the relationships between the vertical shear measurements and intensity

TABLE 3. Two highest correlation coefficients with each vertical shear indicator from all three intensity change categories (6, 12, and 24 h) using lagged data out to 24 h. Boldface font identifies R with 90% confidence level using the Student's t test.

Indicator	Lag	R	n
$R = 0\text{--}222\text{-km}$ IR cloud $< -65^\circ\text{C}$ centroid distance from center	24-h MSLP change with 6-h lag	0.585	22
$R = 0\text{--}222\text{-km}$ IR cloud $< -65^\circ\text{C}$ centroid distance from center	12-h MSLP change with 6-h lag	0.510	22
$R = 0\text{--}444\text{-km}$ IR cloud $< -50^\circ\text{C}$ centroid distance from center	24-h MSLP change with 12-h lag	0.299	23
$R = 0\text{--}444\text{-km}$ IR cloud $< -50^\circ\text{C}$ centroid distance from center	12-h MSLP change with 6-h lag	0.298	23
SHIPS 200–850-hPa vertical shear speed	24-h MSLP change with 24-h lag	0.369	13
SHIPS 200–850-hPa vertical shear speed	12-h MSLP change with 24-h lag	0.324	13
SHIPS 500–850-hPa vertical shear speed	6-h MSLP change with 12-h lag	0.378	13
SHIPS 500–850-hPa vertical shear speed	24-h MSLP change with 24-h lag	0.195	13

changes, a larger sample and more rigorous testing are needed.

Perhaps the main conclusion from this case study is that evaluations of vertical shear, using IR images and satellite cloud motions, are shown to be useful. The IR asymmetries measure the response of the clouds to the environmental vertical shear. The frequent time intervals of the IR images allow improved diagnosis of rapidly changing tropical cyclone structure and environmental forcing. The higher correlation coefficients associated with the IR asymmetry measurements, compared with the SHIPS quantities, suggest that they may be useful for incorporation into statistical intensity forecast schemes. The satellite techniques illustrated in this study need to be tested with larger data samples to further explore their application as short-term intensity forecast aids. Searching for numerical-model-derived vertical shear quantities that more closely relate to the satellite measurements should be a primary research objective.

Unanswered questions remain about the role of vertical wind shear on intensity change and our ability to consistently quantify its influence. Hurricane Bertha's reintensification on 12 July, as described and discussed in section 2, is an excellent example. Observations show three potential influences on the intensity change: an environmental vertical shear decrease, the deep warm ocean water associated with the Gulf Stream, and an interaction with an external upper-level circulation (trough interaction). What is the relative importance of each of those environmental influences in forcing the observed reintensification and how are they interrelated?

Undoubtedly, trough interactions influence the environmental wind shear, and in some cases the associated increased vertical wind shear will cause tropical cyclones to weaken. However, as some trough interactions occur, tropical cyclones are observed to intensify (DeMaria et al. 1993; Molinari et al. 1995; Bosart et al., 2000; Hanley et al. 2001). The question of "good trough" versus "bad trough" is discussed by Bosart et al. (2000). The vertical wind shear influences and the aspects of trough interactions favorable for intensification must be reliably measured and quantified in order to better understand the environmental influences on intensity change.

It has been shown that the underlying ocean provides the primary energy source for the tropical cyclone and that the sea surface temperatures effectively provide an upper bound on intensity (Miller 1958). More recently, the interactions between the hurricane's winds and the oceanic heat content have been observed, and it has been shown that deep ocean layers need to be considered to accurately assess the ocean's forcing on intensity change (Shay et al. 2000). Clearly, the difference between a tropical cyclone's current intensity and the intensity it could have, given its underlying oceanic heat content is an important consideration for predicting intensity. In fact, the potential intensity based on an empirical relationship with sea surface temperature and the current

intensity are critical input parameters to the SHIPS intensity forecast (DeMaria and Kaplan 1994, 1999). Since it is also known that large environmental vertical wind shear inhibits intensification, the vertical shear can be viewed as a limiting influence on the potential for intensity change. The potential is prescribed by the intensity and structure of the tropical cyclone itself, and the underlying ocean. The unanswered questions to this approach involve quantifying the relationship and finding the best way to reliably and consistently measure the environmental vertical shear.

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