Tropical Cyclone Center Positions from Sequences of HDSS Sondes Deployed along High-Altitude Overpasses

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ABSTRACT

A method is developed to calculate the zero-wind center (ZWC) position from a sequence of Yankee High Density Sounding System (HDSS) dropwindsondes deployed during a high-altitude overpass of a tropical cyclone. The approach is similar to the Willoughby and Chelmow technique in that it utilizes the intersections of bearings normal to the wind directions across the center to locate the ZWC position. Average wind directions over 1-km layers are calculated from the accurate global positioning system (GPS) latitude–longitude positions as the HDSS sonde falls from the 60 000-ft flight level of the NASA WB-57 to the ocean surface. An iterative procedure is used to also account for the storm translation, which is necessary to put these high-frequency HDSS observations into a storm-relative coordinate system. The Tropical Cyclone Intensity (TCI-15) mission into Hurricane Joaquin on 4 October 2015 is examined here. The ZWC positions from two center overpasses indicate the vortex tilts from 1- to 10-km elevation and rotates cyclonically with height.

1. Introduction

One of the promising developments for observing tropical cyclones has been aircraft platforms capable of deploying large numbers of advanced dropwindsondes from above the cirrus canopy. For the recent NASA Hurricane and Severe Storm Sentinel (HS3) field experiments during 2012–14, the NASA Global Hawks were capable of flying near 60 000 ft (~18 km) for long periods (>24 h) while deploying as many as 80 dropwindsondes (Braun et al. 2016). This long duration and large number of dropwindsondes made it possible to either observe large areas of the tropical cyclone environment from the lower stratosphere to the ocean surface, or to repeatedly overfly the center and observe the time evolution of the tropical cyclone structure.

During the Office of Naval Research Tropical Cyclone Intensity (TCI-15) field experiment (Doyle et al. 2016), the NASA WB-57 was outfitted with the Yankee High Density Sounding System (HDSS; Black et al. 2017). As the name indicates, the HDSS is capable of very rapid deployment of dropwindsondes. In contrast to the NASA Global Hawks, the WB-57 is a manned aircraft that is also capable of flying at 60 000 ft, but for less than 6 h. The mission strategy during TCI-15 was to overfly the tropical cyclone center and rapidly deploy the HDSS sondes to observe the extreme gradients of wind, pressure, temperature, and dewpoint temperature across the inner-core region. The objective was to observe the three-dimensional structure of the outflow layer to test various hypotheses related to the role of the outflow in intensity change.

An example of the HDSS sonde deployments in Hurricane Joaquin on 4 October 2015 is presented in Fig. 1. As the WB-57 approached from the west, the HDSS sondes were deployed at 5-min intervals. Along the south-to-north overpass (hereafter pass 1) of the center, the HDSS sonde deployment rate was one every 42 s until the WB-57 reached 32°N, 66°W. Similarly, the east-to-west overpass (hereafter pass 2) of the center about 1 h later also had a sonde deployment rate of 42 s. At the WB-57 airspeed of about 400 mi h⁻¹ (647 km h⁻¹), this deployment spacing at 60 000 ft was about 4.7 mi (7.5 km). The “fastfall” HDSS sondes utilized for this mission fall to the ocean in approximately 700 s. Note
the HDSS sondes will drift with the local wind at each elevation during the fall to the surface and, thus, do not provide a vertical profile of the atmosphere variables at the deployment spacing.

If these HDSS soundings are to be analyzed in a storm-relative coordinate system, the center location must be known to an accuracy on the spatial scale of the sequence of sondes in Fig. 1. The objective of this study is to calculate the zero-wind center (ZWC) positions during both of the center overpasses in Fig. 1 from a sequence of HDSS sondes. This ZWC calculation is an adaption of the Willoughby and Chelmow (1982) technique that has been applied at the flight level of a reconnaissance or research aircraft horizontally penetrating through the eye region. Rather than a single ZWC at the aircraft flight level, this technique will provide the ZWCs at various elevations in the tropical cyclone and, thus, will reveal any vortex tilt (to be discussed in section 4).

2. Methodology for determining zero-wind centers from HDSS sondes

The Willoughby and Chelmow (1982) technique is based on changes in the aircraft flight-level wind vector directions during passes through the eye (Fig. 2). In this flight-level application, high temporal resolution (~1 s, or approximately 100 m) wind vectors are available, and as highlighted in the inset in Fig. 2, lines of positions (or bearings to the storm center) perpendicular to these wind directions intersect to accurately locate the ZWC position. As Willoughby and Chelmow indicate, this dynamic center is important for analysis of the circulation within the vortex core and may be distinct from the minimum pressure height or satellite visual or infrared center. Since the divergent component of the wind is neglected compared to the rotational component, this technique should only be applicable above the boundary layer.

Several additional factors must be considered in using the Willoughby and Chelmow technique with HDSS soundings deployed from the NASA WB-57 aircraft overflying the tropical cyclone eye at 60000 ft (Fig. 1). The capability for high-frequency deployments of the HDSS sondes is critical to deploy three or more sondes within the eye region (Fig. 2) when the WB-57 is flying at 400 mi h\(^{-1}\). While the sonde fall speeds in the upper troposphere are about 25 m s\(^{-1}\), the fall speed decreases to about 15 m s\(^{-1}\) near the surface. As indicated above, the sondes drift horizontally with the local winds at each elevation, so their latitude–longitude positions are not directly below the deployment positions along the WB-57 aircraft track, as in Fig. 2.

In the HDSS sonde deployment near the center of Hurricane Joaquin at 1800 UTC 4 October 2015 (Fig. 1),
the sonde drifts toward the north about 0.03° latitude or 3.3 km (Fig. 3a) and toward the west (Fig. 3b) about the same distance. These horizontal displacements from the vertical are small because at first the sonde is falling through the eye at a rapid speed. Later the sonde drifts farther outward from the center. For a sonde falling near the maximum wind speeds in the tropical cyclone eyewall, these horizontal displacements may be an order of magnitude larger than in Figs. 3a,b and become crucial for locating the observations relative to the center.

Another critical capability of the HDSS is the accurate (six digits after the decimal) latitude–longitude global positioning system (GPS) positions at each elevation. The Yankee processing system records position information at 0.1 Hz and the wind direction and speed are at 4 Hz. The final latitude–longitude positions in the TCI level 2 data are combined values calculated from integrating the high-resolution winds with an integration correction from the low-resolution position information (M. Bell 2016, personal communication). While the HDSS wind directions and speeds have subsequently been quality controlled after the mission by a team of TCI investigators (Bell et al. 2016), the wind directions do have some variability that leads to scatter in the bearings and thus to uncertainty in the zero-wind positions (Fig. 2). In the HDSS example (Fig. 3), most of the wind speeds above 5-km elevation are less than 5 m s\(^{-1}\) because the sonde was deployed during the overflight of the eye. Below 5 km, the wind speeds increase to 15 m s\(^{-1}\), which is consistent with the larger horizontal displacements in latitude (Fig. 3a) and longitude (Fig. 3b) below 5 km. Below 4-km elevation the wind directions (Fig. 3d) are almost constant at about 125°, which is again consistent with the northward (Fig. 3a) and westward (Fig. 3b) drifts of the sonde. This near-constant wind direction also implies near-constant bearings at 90° to the left (counterclockwise in the Northern Hemisphere) that point to a ZWC to the west-southwest of the sonde location.

Note that there is more structure and variability in the 1°-resolution wind directions (Fig. 3b), and in the wind speeds (Fig. 3a), above 5-km elevation. Clearly, vertical smoothing or filtering of these wind directions is necessary since the bearings calculated from such highly variable wind directions would not reflect the ZWC positions in the vertical. Rather than filtering the wind directions,
vertical differences in the GPS latitude–longitude positions are calculated over 1-km layers to effectively define an average wind vector over that layer. Since these vertical differences are calculated every 200 m in the vertical, bearings relative to these overlapping average wind vectors lead to ZWC positions that vary smoothly in the vertical.

As indicated above, the HDSS sondes are deployed at 42-s intervals and are displaced horizontally from a vertical fall path as a result of their drift with the local winds during the ~700 s as they fall to the ocean surface. Therefore, it is necessary to account for the movement of the tropical cyclone during the period from the first of (say) five HDSS sonde deployments to the splashdown of the fifth sonde. A first guess of the storm translation speed and directions is consequently required to put each HDSS sonde observation into correct horizontal and vertical positions relative to this moving storm. Storm-relative positions were also calculated by Willoughby and Chelmow (1982) after fitting a series of storm positions with a spline curve to translate the winds in a moving reference frame and then iteratively relocate the storm-relative centers to better fit the track.

In this HDSS application, the primary focus will be on cases in which the WB-57 made two passes over the eye region during each mission. Various sources (e.g., geostationary or polar-orbiting satellite imagery, reconnaissance aircraft, National Hurricane Center working best track) exist for a first-guess center position and storm translation speed and direction for the initial storm-relative positioning of the first sequence of HDSS sondes. During the TCI-15 field experiment, the NASA passive microwave radiometer Hurricane Imaging Radiometer (HIRAD) was also mounted on the WB-57. This instrument senses the surface wind speeds (unfortunately, not the directions) in a swath parallel to the flight track, and is most reliable for wind speeds >15 kt (where 1 kt = 0.51 m s⁻¹). Thus, a surface wind isotach analysis can be created during each tropical cyclone eye overpass of the WB-57, and the geometric center of (say) the closed 20-kt isotach should be a good approximation of the ZWC within the eye. This ZWC at the surface can provide an update of the first-guess storm translation speed and direction to be used in the HDSS ZWC procedure. If those sondes can be rapidly

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**Fig. 3.** Example of a HDSS sonde deployment at 1800 UTC 4 Oct 2015 near the center of Hurricane Joaquin with horizontal displacements in (a) latitude and (b) longitude (relative to Greenwich) as the sonde falls from 18-km elevation to the ocean surface over ~700 s. Observations each second of (c) wind speed (m s⁻¹) and (d) wind direction (*) are inferred from differences in the highly accurate GPS positions from the HDSS as the sonde falls to the surface.
processed, the technique to be described below could in practice provide a more accurate storm position and appropriate storm translation speed and direction for planning the subsequent center overflights. During the second pass over the eye, a second HIRAD surface wind center estimate will become available that can serve as a first-guess center position to calculate the storm translation vector that is required for the HDSS sondes deployed during that second overflight.

In a poststorm analysis, these two ZWCs can be improved by iteratively adjusting the storm translation vector estimates from both center overflights. The objective of each adjustment of these ZWC estimates is to obtain a storm translation speed and direction that agrees with the distance between the two ZWCs divided by the time interval between them. Within two to three iterations, these adjustments to the ZWC positions from the two center overflights should converge to a very accurate storm translation speed and direction for placing all of the HDSS observations during the mission into a storm-relative coordinate system.

When only one overflight of the tropical cyclone eye is possible because of the limited WB-57 duration in the storm, it will not be possible to apply the above iterative procedure to improve the storm translation vector to be compatible with the two adjusted ZWCs. However, the ZWC determined from the HDSS sondes deployed during that single overflight should provide high quality positioning of those limited HDSS observations relative to that ZWC. That is, the advantage of this ZWC positioning from the HDSS sondes is that the accurate GPS positions of the sondes as they fall are also being utilized to derive the wind directions to locate that ZWC.

Another special consideration is that the eye may be so small (or the WB-57 flight track is slightly off) that only one HDSS sonde was successfully deployed near the center. Typically, such small eyes occur in very intense tropical cyclones, and the vortex is vertically aligned. As that single HDSS sonde spirals down and around the inner eyewall, the turning of the wind direction may be sufficient to provide intersecting bearings at adjacent 1-km elevations that will provide ZWCs at multiple levels to validate the assumption of vertical alignment and assess the agreement between the satellite-derived center position and the ZWC.

3. Zero wind center positions on 4 October

a. ZWC positions at 3.5 and 9.5 km from pass 1

A typical application of the Willoughby and Chelmow technique, as in Fig. 2, is for the aircraft to pass through the eye of a hurricane at 700 mb or approximately 3 km. The ZWC position at 3.5 km from a sequence of three HDSS sondes near the center, which included the sonde described in Fig. 3, is shown in Fig. 4a. Six bearing lines are proportional to the wind speed. The three HDSS sondes were deployed at 60 000 ft at 1759:04 (blue lines), 1759:46 (red lines), and 1800:26 (green lines) UTC 4 Oct 2015 as the NASA WB-57 overflew the center of Hurricane Joaquin from south to north.

The ZWC position at 3.5 km from a sequence of three HDSS sondes near the center, which included the sonde described in Fig. 3, is shown in Fig. 4a. Six bearing lines extracted at 200-m intervals between 3 and 4 km are displayed for each of the three sondes. Each bearing line is normal to an average wind direction defined from the difference in the GPS latitude–longitude positions over a 1-km depth, and these GPS position differences are overlapped by 200 m to create the six bearing lines (Fig. 4a). As in Fig. 2, the intersection of these bearing lines indicates the 3.5-km ZWC is at 31.75°N, 66.52°W, and the spread of the intersections of bearing lines indicates the uncertainty in that ZWC. Unfortunately,
there were no simultaneous conventional aircraft missions to provide an independent ZWC estimate at this altitude.

Based on the HIRAD (see Braun et al. 2013 for description) surface wind speeds, staff at the NASA Marshall Space Flight Center (D. Cecil 2015, personal communication) estimated the ZWC at the surface was 31.69°N, 66.58°W. While this HIRAD position is displaced about 6.7 km to the south and 5.7 km to the east, it is uncertain whether the difference is due to the altitude differences or perhaps to a real vortex tilt. Since the estimated ZWC is calculated from three sondes deployed (at 60,000 ft) between 1759:04 and 1800:26 UTC, this ZWC might also be compared with National Hurricane Center (NHC) best-track position of 31.6°N, 66.5°W at 1800 UTC. Note that the NHC positions are provided only to the nearest one-tenth of a degree latitude–longitude, and only at 6-h intervals.

Using these same three HDSS sondes, the ZWC at 9.5 km is at 31.73°N, 66.38°W, which is about 13.3 km almost due east of the 3.5-km ZWC. Although there is more spread among the bearing intersections among these three sondes at this elevation, and the wind speeds (proportional to the bearing line lengths) are small, considerable confidence can be placed on this 9.5-km ZWC position. The implication is that the Hurricane Joaquin vortex is tilted to the east at the time of the first center overpass in Fig. 1. This vortex tilt will be discussed in detail in section 4.

b. ZWC positions at 3.5 and 9.5 km from pass 2

The second center overpass occurred almost exactly an hour later and three HDSS sondes deployed at 1900:11, 1900:53, and 1901:33 UTC were utilized (Fig. 5a). Using the center sonde that is the closest to the center (indicated by the shortest bearing lines whose lengths are proportional to the wind speed) as a basis, the most likely 3.5-km ZWC position is at the apex of the triangle formed by the bearing lines for these three sondes (i.e., at 31.88°N, 66.45°W). However, a more conservative approach would be to draw an uncertainty ellipse around the midpoint of that triangle, which would shift the position 0.02° in latitude (about 2 km) to the south. Based on the HIRAD surface wind speed distribution during the second overpass of the center, NASA Marshall Space Flight Center staff estimated the center position to be 31.87°N, 66.53°W, which is about 8.6 km to the west of the 3.5-km ZWC position based on the HDSS sondes. Again, it is uncertain as to whether these position differences are due to altitude differences or represent a vortex tilt in the lower troposphere. No NHC best-track position is available, but a linear interpolation between 1800 UTC 4 October and 0000 UTC 5 October indicates the 1900 UTC position may be near 31.8°N, 66.4°W.

A remarkable shift in ZWC positions between 3.5 and 9.5 km is observed during this second overpass (Fig. 5b). The six bearing lines from the same three sondes have larger spreads in the 9–10-km layer, but the intersections of the three sonde pairs are quite well defined near 31.98°N, 66.32°W. Thus, this 9.5-km ZWC is 0.10° of latitude to the north and 0.13° of longitude to the east of the 3.5-km ZWC position, or about 19.4 km to the northeast. The implication is that during the 1 h since the first center overpass, the Hurricane Joaquin vortex has become more tilted (to be described in section 4). Furthermore, the vortex alignment between 1.5 and 9.5 km has rotated cyclonically by approximately 41°, from an azimuthal angle of 90° (due east) during pass 1 to an azimuthal angle of 49° (northeast) during pass 2.
FIG. 6. Vortex tilt between 1 and 10 km in storm-relative coordinates from (a) pass 1 at 1800 UTC and (b) pass 2 at 1900 UTC 4 Oct for Hurricane Joaquin derived from the HDSS sonde average wind directions over 1-km layers (large red circles), as in Figs. 4 and 5, and at intermediate 200-m intervals (small colored circles). Shadow symbols on the vertical walls and on the bottom surface assist in visualizing the vortex tilt in latitude and longitude. Elevations, latitudes, and longitudes of the ZWCs are provided in the insets.
As indicated in section 2, missions in which the WB-57 makes two overpasses of the center allow a refinement in the first-guess storm translation direction and speed that is an important component in this application with a sequence of HDSS sonde deployments. Although the two HIRAD positions allow a reasonable first guess, those HIRAD positions are based on the surface wind speed distribution. A more representative level for the vortex translation may be at 3.5 km (Figs. 4a and 5a).

In the second iteration, the differences between these two positions at 3.5 km are used to define the storm translation vector, which then slightly changes the storm-relative positions and wind directions, and thus the orientations of the bearing lines that intersect to provide new estimates of the ZWCs at 3.5 km. This iterative process is repeated until the new ZWC positions from the two center overpasses converge to agree with the storm translation and speed that was used in the ZWC position determination, which typically requires only two to three iterations. In this case, the final storm translation direction/speed between the two center overpasses at approximately 1800 and 1900 UTC 4 October are 23°/9 kt based on the 3.5-km estimates, which can be compared with the HIRAD position first guess of 13°/11 kt.

4. Hurricane Joaquin vortex tilt on 4 October

An important capability of the ZWC technique applied with a sequence of HDSS sondes is to evaluate the vertical tilt of the vortex from ZWC position variations in 1-km-deep layers. A three-dimensional display of that vortex tilt estimated from 1.5 to 9.5 km is provided in Fig. 6a (large red circles). The ZWC positions from the same HDSS sonde pairs as in Fig. 4 at 200-m vertical resolution are also shown (small circles) to indicate the variability around the vortex tilts each 1 km from 1.5 km. The vortex tilts in longitude (latitude) and the vertical are shown by “shadow symbols” along the vertical wall at the back (right) and along the surface. For example, the shadow symbols along the back wall indicate the vortex tilt is largest in the longitudinal direction toward the east as in Figs. 4a and 4b. In this depiction, the vortex tilt is not confined to 3.5 and 9.5 km. Rather, the eastward tilt appears to be continuous above 1.5 km. The average tilt between 1.5 and 6.5 km is 62° from the vertical, and then the tilt increases to 80° from 7.5 to 9.5 km. Unfortunately, cloud radar observations such as in the Marks et al. (1992) and Reasor et al. (2009) studies are not available to validate these vortex tilts.

Although preliminary HDSS wind observations (or GPS latitude–longitude positions) did exist above 10 km in the level 1 TCI data fields, it is difficult to extend the ZWC analysis and vortex tilt calculation above 10 km. While this may be due to questionable data quality (values were omitted by the TCI data quality control team), the eye becomes broad and the outflow is tending toward the horizontal so that the wind directions are more variable. This combination of weaker winds at larger radii leads to more uncertainty in the ZWC estimation. Future analyses will examine this vortex tilt in relation to the vertical wind shear when these HDSS observations have been merged with the environmental observations.

A corresponding vortex tilt display from the sequence of HDSS sondes along the second center overpass is shown in Fig. 6b. While the vortex tilt between 1.5 and 6.5 km in pass 2 is slightly smaller (52° versus 62°) than in pass 1, this is because the vortex tilt from 1.5 to 3.5 km (third large red circle from bottom in Fig. 6b) is almost zero (see shadow symbols on back wall and along bottom surface). Large vortex tilt occurs above 3.5 km and the vortex tilt between 7.5 and 9.5 km is again 80° from the vertical, as calculated in pass 1.

The apparent cyclonic rotation of the upper portion of the vortex between pass 2 and pass 1 is also evident when comparing Figs. 6b and 6a. However, there is more scatter among the pairs of HDSS sondes at 200-m resolution (small circles) in the vertical in the upper levels for pass 2. This scatter is in part a result of the larger distances from the origin, as in Fig. 5b. However, the shadow symbols along the bottom surface clearly indicate a systematic northward tilt as well as a large eastward tilt.

5. Summary

These HDSS sondes deployed from the NASA WB-57 flying at 60,000 ft over Hurricane Joaquin on 4 October 2014 illustrate some of the capability to observe the three-dimensional structure of tropical cyclones. Such high temporal deployments of the HDSS sondes require accurate ZWC positions to place these observations in storm-relative coordinates. The primary objective of this study has been to demonstrate that these accurate ZWC positions can be calculated from a sequence of HDSS sondes deployed from 60,000 ft during a near-center overpass using a modification of the Willoughby and Chelmon (1982) technique. Accurate GPS latitude–longitude positions are necessary to account for the horizontal drift in response to the local winds as the HDSS sondes fall from 60,000 ft to the surface. In our ZWC technique, differences of these GPS latitude–longitude positions over 1-km layers are used to define the average wind directions (and spreads) over that layer, and then intersections of bearing lines from those wind directions define the ZWCs. This method for creating smoothly varying wind directions (and thus smoothly...
varying bearings from those directions) was found to be more successful than attempting to smooth the 1°-resolution wind directions in the level 2 TCI-15 data files.

A special feature of this ZWC positioning technique using a sequence of HDSS sonde deployments is that these ZWCs may be calculated at many levels in the vertical. A second objective of this study is a documentation of the Hurricane Joaquin vortex tilt on 4 October 2015. While vortex tilt has been demonstrated from cloud radar studies (e.g., Marks et al. 1992; Reasor et al. 2009), the precision that this ZWC technique provides will be important when relating the vortex tilt to the vertical wind shear and other properties of the flow field. Furthermore, the apparent cyclonic rotation of the vortex tilt in only 1 h is particularly interesting and is further evidence of such a rotation will be sought in other TCI-15 missions for which two center overpasses were obtained.

The ZWC positions for other missions in Joaquin and the other TCI-15 tropical cyclones (Marty, Patricia, and perhaps Erika) should be valuable for observational studies that involve storm-relative analyses or diagnostic studies. The relationships between the HDSS observations of the outflow and the Cooperative Institute for Meteorological Satellite Studies (CIMSS) rapid-scan AMVs should be revealing. Additional comparisons with the HIRAD surface wind distributions are planned both in terms of vortex tilt and the radial and tangential wind structure.

It will be productive to compare the vortex tilt (if any) in the initial conditions and forecasts of numerical models of the TCI-15 tropical cyclones. It may be challenging to incorporate these high temporal and spatial resolution HDSS observations in the numerical models. Perhaps our technique of creating layer-average wind direction and speed from overlapping 1-km layers may be useful for initializing those computer models that also represent the wind fields in layers. In this sense, the HDSS sondes offer both opportunities and challenges for understanding the role of the outflow in the intensity and structural changes of tropical cyclones.

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