A LONG-TERM, HIGH-QUALITY, HIGH-VERTICAL-RESOLUTION GPS DROPSONDE DATASET FOR HURRICANE AND OTHER STUDIES

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A long-term, high-quality, high-vertical-resolution GPS dropsonde dataset is created from NOAA hurricane flights and consists of 13,681 atmospheric profiles for 120 tropical cyclones.

A hurricane is one of the most devastating extreme weather phenomena threatening the United States. In the United States, between 1980 and 2012 over $1 trillion was spent providing disaster relief aid after 151 weather disasters: overall damages and costs reached or exceeded $1 billion for each disaster (www.ncdc.noaa.gov/billions/). Of those 151 events, 33 of the disasters resulted from tropical cyclones, and they accounted for ~50% of the total damage in dollars. Early warning, adequate preparation time, and evacuation time rely on accurate forecasting of hurricane tracks and intensities, and these forecasts depend on accurate measurements of hurricane winds and thermodynamic structure.

A dropsonde is a scientific instrument dropped from research aircraft or other platforms in the air and descends through the atmosphere by a parachute to make measurements of pressure, temperature, relative humidity (RH), and horizontal wind speed and direction profiles at any location over the globe, especially over ocean and remote regions, where other in situ measurements are hard to make. The National Center for Atmospheric Research (NCAR) GPS dropsonde system called the Airborne Vertical Atmospheric Profiling System (AVAPS) was developed in the 1990s and is the only operational dropsonde system in the world capable of providing research-quality, high-resolution, reliable atmospheric profiles in hard-to-reach locations. This system consists of an onboard data acquisition and processing system and the dropsonde itself. The GPS dropsonde is currently manufactured by Vaisala, Inc., under license from NCAR, and is also known as Vaisala dropsonde RD94 (Hock and Franklin 1999; Vaisala 2014). The dropsonde includes a pressure, temperature, and humidity (PTU, also PTH) sensor module; a GPS receiver for wind measurements; and a 400-MHz telemetry transmitter to transmit data from the sonde to the onboard receiving system (see Fig. 1 in Hock and Franklin 1999). Based on Vaisala (2014), the accuracy of pressure, temperature, and RH is 0.4 hPa, 0.2°C, and 2%, respectively. The horizontal wind measurement from the u-blox GPS receiver is estimated to be 0.1 m s^{-1}. The aircraft data system includes a narrowband 400-MHz telemetry receiver, which allows simultaneous operation of up to eight dropsondes in the air. During the last 18 years (1996–2013), the dropsonde system has improved significantly, including a complete redesign of the system (known as AVAPS II) in 2008 and development of miniaturized dropsondes for deployment from superpressure balloons, unmanned aerial vehicles (UAVs), and high-altitude aircraft during recent years. Major milestones in AVAPS advancement and scientific impact during its lifetime are summarized in Table 1.

Since 1996, GPS dropsondes have been routinely deployed during hurricane reconnaissance and surveillance flights to help predict hurricane tracks and intensities. The reconnaissance flights are conducted in the hurricane inner and outer core regions, while the surveillance aircraft fly outside of the immediate environment of tropical cyclones. During the first season of National Oceanic and Atmospheric Administration (NOAA) Gulfstream-IV (G-IV) jet aircraft missions for hurricanes in 1997, about 150 dropsondes were released from the aircraft at 150–200-km intervals in the environment of tropical cyclones (TCs; Aberson and Franklin 1999). This first set of dropsonde observations improved mean hurricane-track forecasts from the Geophysical Fluid Dynamics Laboratory hurricane model by as much as 32% and intensity forecasts by 20% during the critical first two days of the forecast (Aberson and Franklin 1999). The track forecast improvements were comparable to those accumulated over the past 20–25 years at that time (Aberson and Franklin 1999). Mean track forecast improvement as a result of synoptic surveillance dropsondes during 1999–2005 is summarized in Fig. 1. The improvement is above 10% during 0–48 h in the Global Forecast System (GFS) model (Fig. 1). This result is consistent with the finding in Aberson (2010). The dropsonde data have also been found to play an important role in understanding the characteristics of hurricane dynamic and thermodynamic structures (e.g., Franklin et al. 2003; Molinari et al. 2012; Zhang et al. 2013). For example, Franklin et al. (2003) analyzed 630 dropsonde profiles from hurricane reconnaissance flights during the 1997–99 seasons and documented, for the first time, the mean vertical profile of wind speed in the hurricane inner core from the surface to the 700-hPa level with unprecedented accuracy and resolution. In addition to routine hurricane flights, the dropsonde is also often deployed to study winter storms, TCs in different ocean basins, strong convection systems, and other severe weather events to ultimately improve their forecasting. A study of dropsonde impact during the 1999 NOAA Winter Storm Reconnaissance (WSR) program documented that the dropsonde data significantly improved the forecasts in 18 of the 25 storms targeted by NOAA aircraft (Szunyogh et al. 2000). However, the WSR program has been cancelled recently due to minimal impact in recent years, perhaps because of other improvements in the data assimilation systems (Hamill et al. 2013). The impact of dropsonde data on typhoon-track forecasts has been also studied extensively (e.g., Wu et al. 2007; Aberson 2011; Chou et al. 2011; Wu et al. 2012). For example, the typhoon-track forecast error in four numerical weather prediction models was reduced by 20%–40% consistently as a result of dropsonde data collected during The Observing System Research and Predictability Experiment (THORPEX) Pacific Asian Regional Campaign (T-PARC) in 2008 (Weissmann et al. 2011).

In spite of the scientific importance of the dropsonde data collected from all of these missions and projects mentioned above, the data reside in different locations, have different formats and varied levels of data quality, and in many cases have limited metadata. Such heterogeneity between datasets hinders composite analysis of TCs and limits the application of the dropsonde data for broader scientific use.

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TABLE 1. The list of major milestones in AVAPS advancement and scientific impact during 1995–2012.

Years	Milestones	Impact
1995	• The first GPS dropsonde system (referred as to AVAPS) was under development at NCAR. • Dropsonde uses Vaisala PTH module RSS903 and GPS codeless receiver GPS-111/121 for winds. • A single version software supported up to four simultaneous dropsonde soundings, the first for atmospheric sounding systems, and operations on many different aircraft platforms.	• The GPS dropsonde development made it possible to obtain vertical profiles of wind and thermodynamic parameters within nearly all portions of the hurricane with unprecedented accuracy and resolution.
1996	• The AVAPS development was completed. • First deployment of system on NOAA G-IV for test flights. • NCAR licenses AVAPS technology to Vaisala, Inc.	• The ~150 sondes from the first G-IV mission resulted in a 30% improvement in 24–36-h hurricane-track forecasts (Aberson and Franklin 1999).
1997	• First supported field campaign for Fronts and Atlantic Storm Track Experiment (FASTEX), which used over 800 dropsondes released from three different aircraft. • NOAA began operational hurricane missions with the AVAPS on both G-IV and P3.	• The first deployment of GPS sondes in the eyewall of Hurricane Guillermo on 2–4 Aug 1997 illustrated the complex variability of boundary layer structure in the hurricane (Hock and Franklin 1999).
2005	• GPS receiver is changed to u-blox TIM-LF receiver (from GPS-121) to increase wind solution from 2 to 4 Hz and improve its reliability.	• The usage of u-blox GPS receiver increases the wind sampling from 2 to 4 Hz to detect more detailed structure and to make the last wind data point closer to the ocean surface.
2006	• GPS receiver is changed to u-blox TIM-4P from TIM-LF to improve its reliability.	• AVAPS II significantly reduces the percentage of the GPS wind loss (two-thirds) and the time to obtain the winds in the beginning from ~30 to ~1 s.
2008	• Major redesign of AVAPS system: it is renamed as AVAPS II. • Improvement includes u-blox TIM-5P GPS receiver for winds, Vaisala RSS904 module for PTH, a more robust telemetry system resulted in higher percentage of GPS data per sounding, latest technology for electronics and firmware, reduction in mass of dropsonde, ability for eight simultaneous soundings. • AVAPS II software user interface retained the same basic look and feel to the dropsonde operator, thus minimizing the trouble and expense of retraining experienced flight crews.	• The capability of eight simultaneous soundings makes it possible to sample the atmosphere in much higher horizontal spatial resolution.
2010	• Significant internal enhancement of the software to allow remotely controlled operation via satellite communications link for use on the unmanned NASA Global Hawk aircraft and super-pressure balloons (driftsonde system). • Development of mini dropsonde with smaller size and lighter weight for NASA Global Hawk and a fully automated remote control aircraft system. A slightly different version of this sonde is also used for driftsonde.	• The development of mini dropsonde, completely automatic operations, and new platforms extend the dropsonde's vertical dimension to the upper tropospheric–lower stratospheric (UTLS) regions, lengthen its deployment duration, and increase its spatial coverage and thus expand to new scientific areas.

DATA SOURCES, QUALITY ASSURANCE AND CONTROL, AND VALUE-ADDED PRODUCTS. Raw dropsonde data for this study were collected during NOAA hurricane reconnaissance and surveillance flights from 1996 to 2012 and were obtained from the NOAA/Hurricane Research Division (HRD) online GPS-dropsonde data archive (www.aoml.noaa.gov/hrd/Storm_pages/sondeformat.html). The NOAA/Aircraft Operations Center (AOC) runs the AVAPS program for NOAA. The dropsonde data available through the NOAA/HRD site were collected by HRD, National Hurricane Center (NHC), and the U.S. Air Force (USAF), three of the biggest users of the AVAPS dropsonde system.

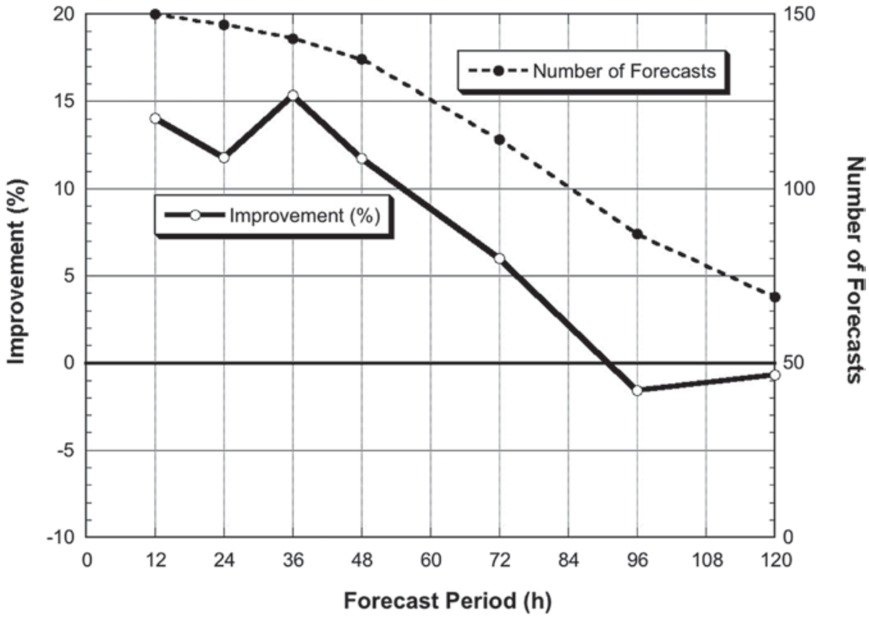

Fig. 1. Improvement of mean hurricane-track forecast in the GFS model as a result of assimilating synoptic surveillance dropsondes during 1999–2005. Number of forecasts is also given.

The dropsonde data contained in this archive were collected from three separate aircraft. The NOAA N42RF and N43RF are P3 aircraft and the NOAA N49RF is a G-IV. The P3 aircraft make measurements from the inner and outer cores (0- to about 200-km radius) and from the middle–lower troposphere (1–5 km) to the surface. The atmospheric data outside of the immediate environment of TCs come primarily from the NOAA G-IV flying at ~14–15-km altitude. Note that during 1996–2012 about 6,000 soundings were collected from USAF, but they are not processed and included in this archive.

The data quality assurance (QA) begins with the cumbersome task of renaming all of the sounding files according to date and time of launch. The files were originally archived only by sonde identification (ID) number. The next step is to identify and categorize the files according to dropsonde GPS type (u-blox or GPS121). This is necessary because a new dropsonde with an improved full GPS receiver (u-blox), capable of making more accurate measurements of position and velocity, was introduced in 2005. Prior to that, GPS121 dropsondes were used. The GPS121 receiver computed the 3D velocity. However, the 3D position was computed using precise drop location from the AVAPS aircraft data system and integrating the velocity to obtain position with each individual measurement from the dropsonde. From 2005 through 2007, both sonde types were deployed by different aircraft in different storms. The implication of having varying dropsonde types is that quality control of the GPS data must be handled differently. Finally, before data quality control could begin, the data files were categorized according to the aircraft from which they were collected.

Data quality control of the sounding data is an extensive, multistep process that includes evaluating the data products using a variety of visualization tools and statistical methods to identify and correct data quality issues caused by launch detect errors, sensor offsets or bias, accelerated descent rates, and failure of the sensors to accurately transmit data from flight-level altitude to the ocean's surface. Each raw sounding data profile must be individually evaluated to determine if the data contain any features that warrant further investigation. Appropriate corrections are then applied. Metadata files are created for each aircraft flown in each of the storms and include documentation detailing specific data quality issues found in individual data files and explain subsequent corrections, if any are applied. The variables, pressure, temperature, and RH, are calibrated values from measurements made by the dropsonde, which are all subjected to quality control. The dewpoint is calculated from the quality-controlled RH and temperature. The geopotential altitude is calculated from the hydrostatic equation, typically from the ocean's surface upward. Dropsondes that fail to transmit useful data to the surface must be identified so that geopotential altitude can be integrated from flight level down. The descent rate of the sonde is computed using the time-differentiated hydrostatic equation. Wind speed and direction are quality controlled, but the GPS horizontal position (latitude and longitude) is not. Following evaluation of the raw data and subsequent steps to resolve data quality issues, each of the dropsonde profiles is processed through the Earth Observing Laboratory (EOL) Atmospheric Sounding Processing Environment (ASPEN) software, which further analyzes data quality and performs smoothing and filtering to remove suspect data points. The

ASPEN configuration used to process this dataset is given in the dataset readme file. Following ASPEN, histograms of all variables are evaluated to examine the distribution, range, and characteristics of each parameter. Profile plots of the quality-controlled soundings are visually evaluated for outliers or any other obvious issues, and time series plots are used to evaluate the consistency of soundings launched during each flight and to examine the variability of soundings from different missions. These standard procedures are used to ensure the highest-quality set of soundings within and near a large and varied sample of TCs are provided to the community. In addition to pressure, temperature, humidity, and wind speed and direction profiles, three value-added profiles, the vertical air velocity and the radius and azimuth angle of each dropsonde location, are computed as described in detail below and added to the dataset.

The vertical air velocity is computed as the difference between the actual dropsonde fall rate and that in the still air (Wang et al. 2009). The still-air fall rate is computed based on the balance between the gravity and the drag force, and it is a function of the weight of the dropsonde, the drag coefficient (0.61 for dropsonde), and the area of the parachute (Hock and Franklin 1999; Wang et al. 2009). The sonde weights of 350 and 322 g are used for AVAPS-I and AVAPS-II sondes, respectively. A square parachute of 26 cm × 26 cm is used. A 20-s low-pass filter is applied to the calculated vertical velocity to remove occasional spikes. Both directly calculated and filtered velocities are saved in the data. The uncertainty in the vertical air velocity is estimated to be on the order of 1 m s^{-1}, and the velocities with magnitudes less than 1 m s^{-1} should not be used without careful examination (Wang et al. 2009).

For each sonde, the radius of the observation was determined by the spherical distance from the storm center to the sonde location. Azimuth was determined trigonometrically from the latitudes and longitudes of the storm center and the sonde. The effects of lateral motion of the sonde were included, so that the radius and azimuth varied with height for each sonde. The storm center was defined by the 6-hourly NHC best-track position linearly interpolated to 1-min resolution. In reality, the storms do not move linearly. Rather, the purpose of the high time resolution was to prevent artificial jumps in center position and thus in sonde position on small time scales.

The final quality-controlled dropsonde dataset includes 13,681 dropsonde soundings from 1996 to 2012 for 120 storms. The numbers of soundings and storms for each year are shown in Fig. 2. There were maximum numbers of soundings (2,306) and storms (13) in 2005 (Fig. 2). The record number of soundings per storm (653) was deployed in Hurricane Ivan (2004). The majority of soundings were dropped over the Atlantic Ocean (Fig. 3). The sondes were dropped either from NOAA P3 aircraft in the inner or outer core region from the middle to lower troposphere or NOAA G-IV in the surrounding regions from the upper troposphere (Fig. 3). Figure 4 shows one example of sonde locations dropped between 1700 UTC 28 August and 0000 UTC 29 August 2005 from NOAA P3 and G-IV aircraft for Hurricane Katrina. The number of dropsondes in each 100-km radial bin and each 30° azimuthal bin is displayed in Fig. 5. The dropsondes were most frequently located within 100 km to the tropical cyclone center (Fig. 5), and the number of dropsondes gradually decreased with increasing radius. The broad radial distribution of dropsondes has enabled composite studies to be done on various spatial scales ranging from the TC inner core (Zhang et al. 2013) to the outer regions of the TC and the environment (Molinari et al. 2012). The

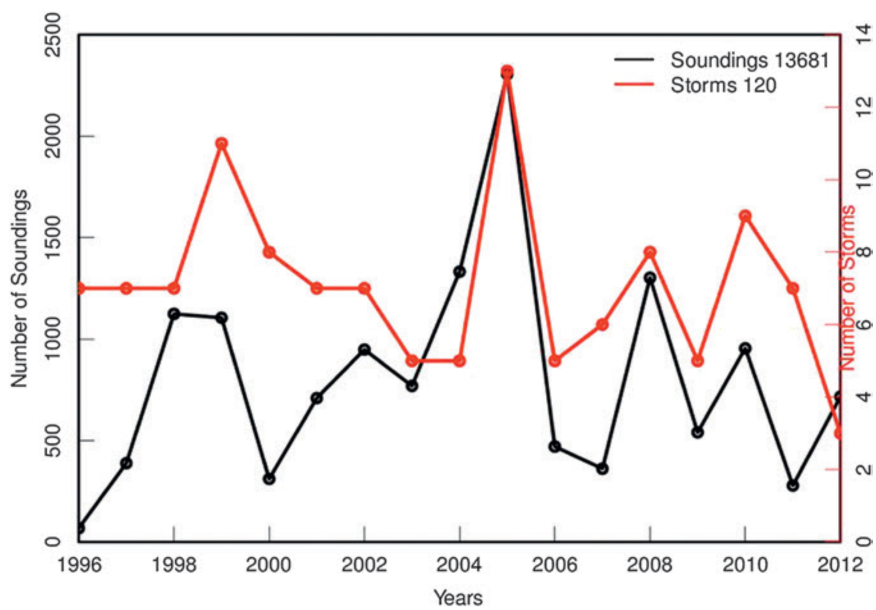

Fig. 2. Numbers of soundings (black line) and storms in each year from 1996 to 2012 included in the final dataset.

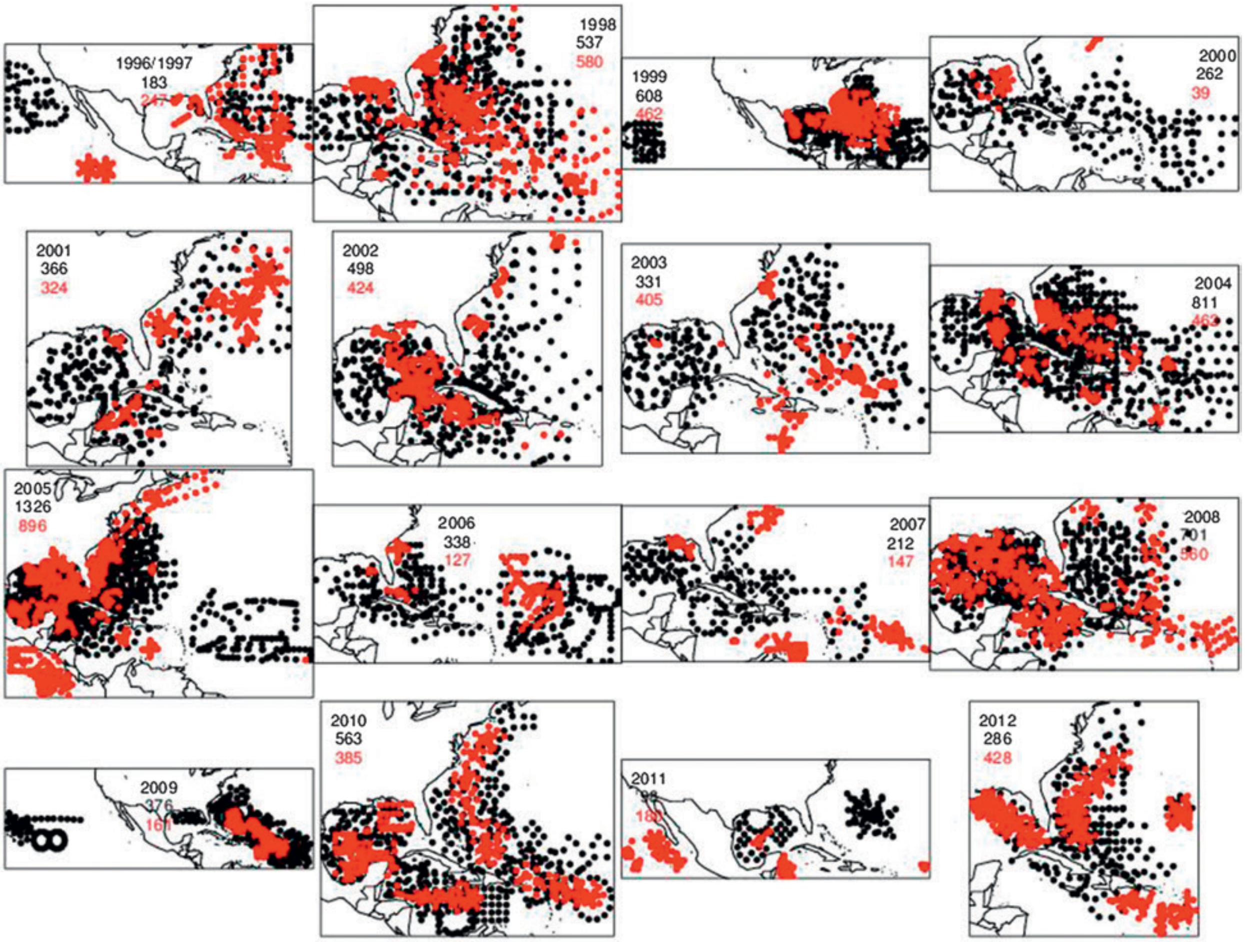

Fig. 3. Maps of dropsonde locations from NOAA G-IV (black dots) and P3 (red dots) for each year. Total number of soundings for each year is given in the legend.

azimuth distribution of dropsondes is rather asymmetric, with a maximum in the northern quadrant and a minimum in the southern quadrant (Fig. 5).

The QC dropsonde data include high-quality and high-vertical-resolution profiles of pressure, temperature, RH, wind speed and direction, vertical velocity, sonde location (longitude, latitude, and altitude), and radius and azimuth angle relative to the storm centers. The thermodynamical and wind data are available at 1/2- and 1/4-s resolution, respectively, corresponding to ~5–15 m and ~3–8 m from the surface to 16-km altitude. The final dropsonde dataset is in EOL sounding file format that includes a header, with detailed project and sounding information, and 17 columns of high-resolution data. The EOL format is an ASCII text format and is described in detail in the readme file on the dataset website. The files are broken out into directories by year, storm name, GPS sensor type, and aircraft type. The dataset along with the readme file is available for free download online (www.eol.ucar.edu/content/noaa-hurricane-dropsonde-archive).

SCIENTIFIC HIGHLIGHTS. Dropsonde data have been used extensively for hurricane and other studies. In the introduction, we summarized the milestones of dropsonde data's impact on hurricane studies. Several scientific applications of this long-term dropsonde dataset are highlighted below based on preliminary analysis of the data. They not only demonstrate the scientific value of this dataset but also illustrate potential scientific discovery in the future as a result of this dataset.

Composite profiles of GPS-derived wind measurements in TCs in the Atlantic basin were constructed from 3,101 dropsonde profiles from this dataset (Fig. 6). Selection criteria consisted of all drops from NOAA P3 aircraft only. A large fraction of the dropsondes from P3 aircraft were dropped into storms that were not hurricane status or storms that changed categories during the process of dropping, so they were excluded in this analysis. Only storms that maintained their status through the entire drop (e.g., did not fluctuate in intensity) were used. If there was any

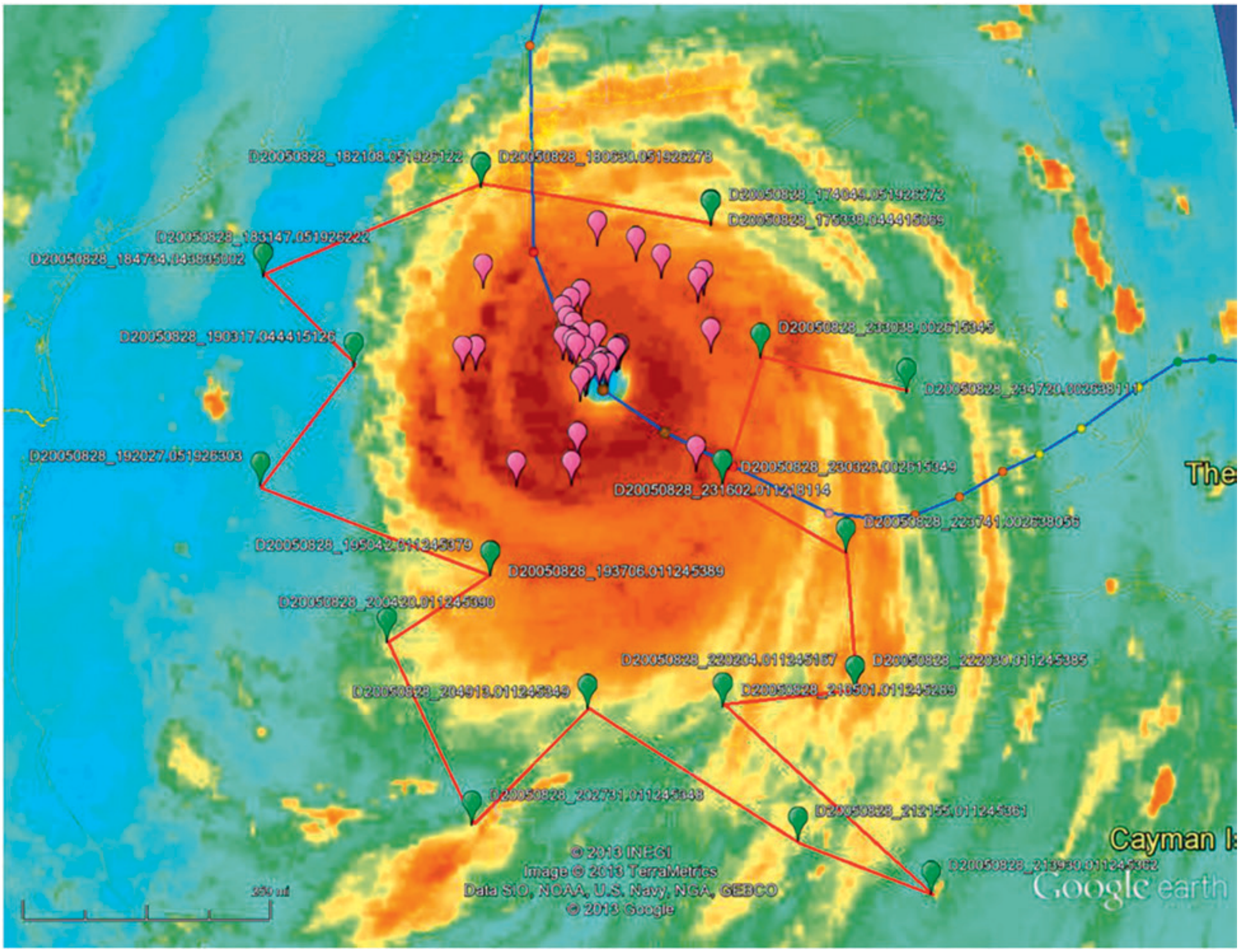

Fig. 4. Dropsonde locations from NOAA P3 (magenta balloons) and NOAA G-IV (green balloons) between 1700 UTC 28 Aug and 0000 UTC 29 Aug 2005 for Hurricane Katrina. The blue line is the hurricane track. The background color image shows the satellite water vapor image.

question of ambiguity in intensity, the sondes were not included. Mean profiles of wind speed stratified according to hurricane intensity are shown in Fig. 6. Composites were constructed by averaging individual profiles with a rough mean vertical bin resolution of 25 m, and we applied a conservative smoothing routine to reduce the profile noise. The total sample encompasses data for 667 category 1 storms, 710 category 2 storms, 670 category 3 storms, 908 category 4 storms, and 146 category 5 storms. No attempt was made to stratify drops according to radial distance within each intensity class. Regardless, these mean profiles show robust differences between the five hurricane-intensity classes. All profiles reveal significant shear in the boundary layer and low-level wind maxima between 500 and 1000 m above ground. The difference in mean profile wind speed between individual storm categories is remarkably linear, particularly with regard to the lower-tropospheric wind maximum. In all categories, there is a tendency for wind speed to weaken significantly above 3–4 km. Interestingly, secondary maxima appear around 4 km in two of the stronger categories (categories 3 and 4). It is uncertain whether the absence of this feature in the category 5 wind profile is related to physical processes or to a limited sample size. This type of composite-based analysis just scratches the surface of what can be done using this high-resolution vertical structure information.

Dropsonde data have often been used to study changes in the TC structure in response to environmental vertical wind shear (e.g., Molinari et al. 2012; Zhang et al. 2013). Shear has been shown to have a negative influence on the TC-intensity change (e.g., DeMaria et al. 2005) through several proposed mechanisms. One hypothesized mechanism is the thermodynamic modification of the inflow layer by downdrafts induced by asymmetric convection outside the inner core (Riemer et al. 2010, 2013). To assess this, the position of each dropsonde was

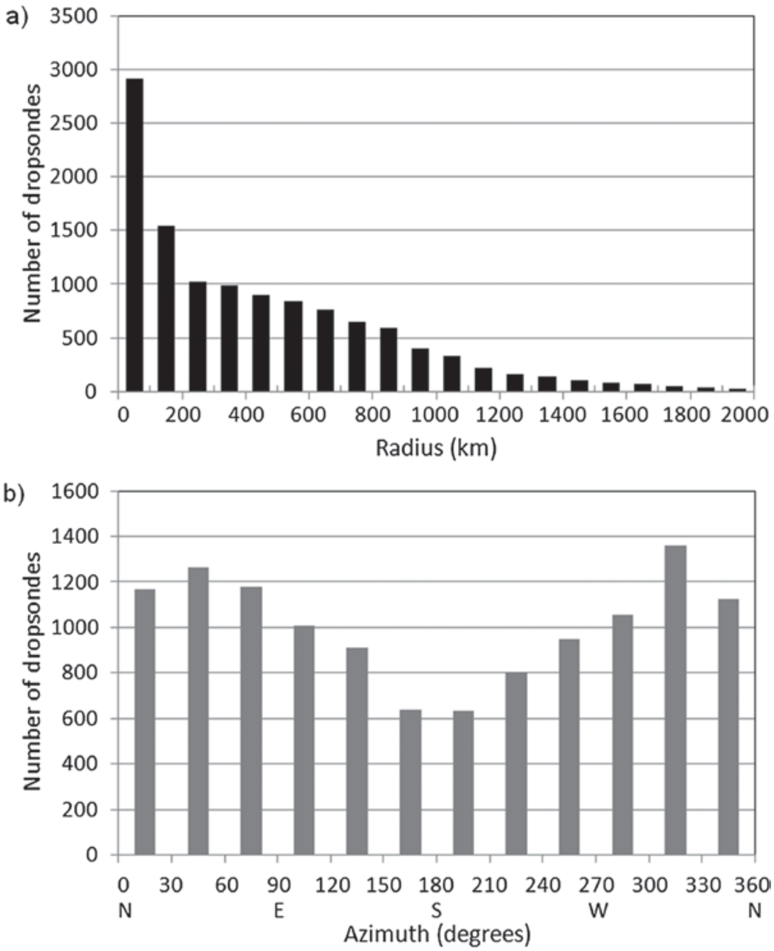

Fig. 5. (a) Number of dropsondes in each 100-km radial bin. (b) Number of dropsondes in each 30° azimuthal bin. The azimuthal direction follows meteorological convention (i.e., 90° denotes a dropsonde that is east of the tropical cyclone center).

rotated with respect to the environmental vertical wind shear following Corbosiero and Molinari (2002). The environmental shear was taken from the Statistical Hurricane Intensity Prediction Scheme (SHIPS) database (DeMaria et al. 2005). Figure 7 shows the mean equivalent potential temperature (θ_e) in each shear-relative quadrant in the 75–200-km radii region, which in general falls well outside the eyewall. Only sondes released when ambient shear exceeded 6 m s^{-1} are included. Note that the number of dropsondes reporting data decreased rapidly above 2-km height (Fig. 7). These results are compared to similar fields shown within the eyewall region by Zhang et al. (2013). In the lowest 1 km for both studies, θ_e reaches a minimum in the downshear-left quadrant and a maximum right of the shear vector. This likely reflects the influence of low-θ_e downdrafts left of shear and surface flux–induced boundary layer recovery right of shear (Molinari et al. 2013; Zhang et al. 2013). Figure 7 shows that these anomalies extend up to 3-km elevation and out to 200 km from the center. Dropsondes can be divided up by a combination of radius, ambient shear magnitude, tropical cyclone intensity, and/or intensity change to further elucidate the role of vertical wind shear in TC structure.

The hurricane boundary layer (HBL) has long been known to play an important role in storm development and intensification (e.g., Emanuel 1986; Braun and Tao 2000; Smith et al. 2009; Bryan and Rotunno 2009). Understanding of the HBL structure becomes increasingly important as efforts have been made toward developing high-resolution numerical models in order to improve the hurricane-intensity forecast (e.g., Gopalakrishnan et al. 2013; Rogers et al. 2013). However, the HBL has been the least observed part of a storm until now, especially its turbulence structure (Black et al. 2007; Zhang et al. 2008; Zhang 2010). With the advent of the GPS dropsonde (Hock and Franklin 1999; Franklin et al. 2003), the mean boundary layer structure has been progressively studied, mostly the boundary layer structure in an individual storm (e.g., Bell and Montgomery 2008; Barnes 2008). Recent composite analyses of GPS dropsonde data (Zhang et al. 2011, 2013) from multiple hurricanes at various stages of their life cycle have provided a more comprehensive representation of the HBL. In spite of those efforts using the dropsonde data to study the HBL, it still remains imperative to include more dropsonde soundings, such as those from this study, to understand the HBL processes, improve its representation in numerical models, and ultimately increase our ability to better forecast hurricanes.

Vertical profiles of temperature and specific humidity are two key parameters that characterize the environmental conditions for electromagnetic (EM) wave propagation in the atmosphere, represented by the modified index of refraction *M* (Bean and Dutton 1966). The data source for this purpose generally comes from numerical simulations and/or mostly by rawinsonde measurements based on ships,

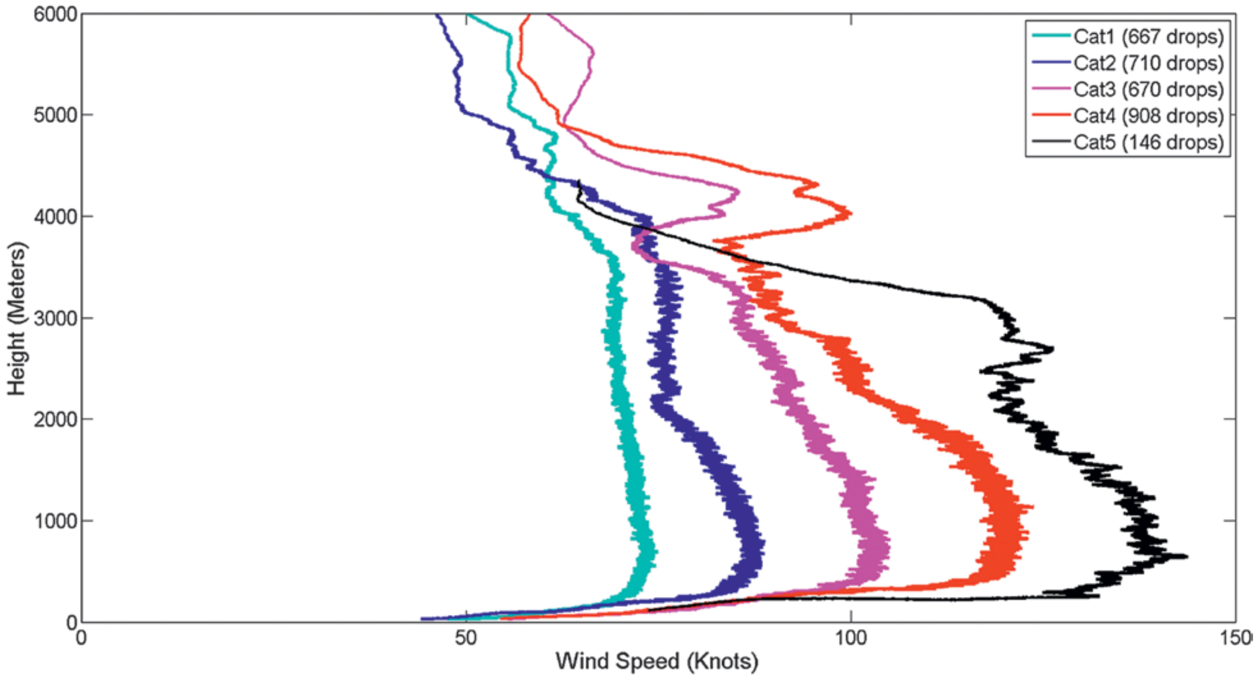

Fig. 6. Mean wind speed profiles for hurricane categories 1–5 computed from 3,101 dropsonde profiles. The number of soundings used for each category is given in the legend.

islands, or land. While rawinsondes provide direct measurements of the atmospheric temperature and moisture, it is generally difficult to use the measurements for identifying surface-based ducts or evaporative ducts over the ocean because of ship or island contaminations unless an top-down sampling approach is adopted. Although the sensor technology between dropsondes and rawinsondes are similar, the near-surface sampling of the descending dropsonde is normally made in an undisturbed environment away from potential flow distortions such as those near a ship. Hence, dropsonde measurements have the potential to represent the near-surface altitudes better than the ascending rawinsonde carried by balloons. The hurricane dropsonde dataset provides the best opportunity to assess the application of dropsonde measurements to EM propagation study and to identify the radar signal ducting environment in the vicinity of significant tropical disturbances. In this effort, we computed M from temperature, humidity, and pressure profiles from all available soundings in this data archive. The vertical gradients of M were used to define different duct layers based on the criteria outlined in Zhu and Atkinson (2005) and many other references. Figure 8 gives a general overview of the different duct types occurring in a hurricane environment. Here the elevated duct layers were separated into elevated low ducts (duct heights less than 2 km) and high ducts (duct heights higher than 2 km). The high-level ducts have minimum influence on radar propagation and communication but may have an adverse effect on the inversion of GPS radio occultation data (Ao 2007). Figure 8 shows that ~50% of the soundings show the presence of a duct layer below 2 km, which is against the general notion that the atmospheric environment in a hurricane is not in favor of development of ducts. However, similar results were found by Ding et al. (2013) using a much smaller dataset. The ducting layer characteristics were also categorized in the storm-relative environment for the objective of identifying the storm-relative regions critical to radar and communications performance. These characteristics are related to the cyclone track and other storm-related factors using the best-track products archived by NOAA. Statistical analysis methods are used to quantify the characteristics of ducting conditions in different quadrants of a hurricane relative to its motion. However, no preference of ducting was identified in any quadrant of the hurricanes. More extensive analyses can be found in Ziemba (2013).

Satellite data play an important role in monitoring and predicting TCs as a result of lack of in situ data over the ocean. However, because of the exact same reason, satellite data over the ocean are not well calibrated and validated. NOAA Products Validation System (NPROVS; Reale et al. 2012) provides a daily compilation and archive of collocated conventional

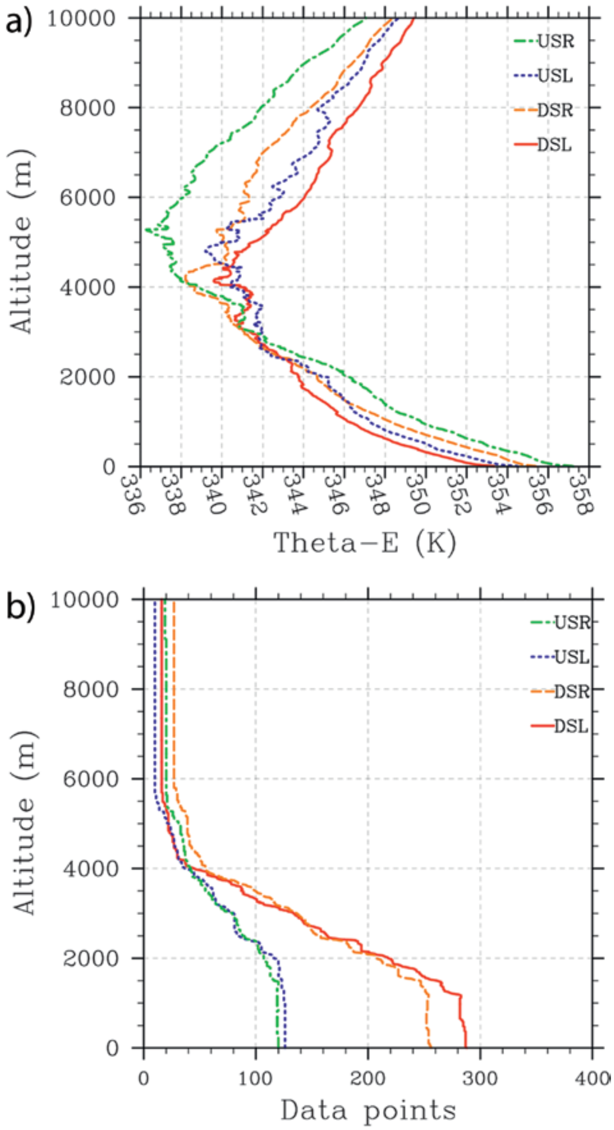

Fig. 7. (a) Mean equivalent potential temperature of the 75–200-km radii region in the downshear-left (DSL; solid red), downshear-right (DSR; dashed orange), upshear-left (USL; dotted blue), and upshear-right (USR; dashed–dotted blue) quadrants in tropical cyclones embedded in greater than 6 m s^{-1} of ambient vertical wind shear. (b) Number of data points at each vertical level in each quadrant.

radiosonde (raob) and environmental satellite (SAT) products, which include dropsonde (DROP) observations routinely available for assimilation into NOAA/National Centers for Environmental Prediction (NCEP) GFS forecast models. Wang et al. (2013) used NPROVS to collocate 10 satellite products with the unprecedented dropsonde data collected during the 2010 Concordiasi field experiment over Antarctica to validate satellite products. The plan is to compile a dataset containing collocated SAT and DROP temperature and humidity profiles during 2010–12 from the quality-controlled dropsondes data from this study. Note that NPROVS started to operate in 2010. Then we will conduct comparisons of SAT products for temperature and humidity against DROPs to validate the satellite products in TC environments. Numerical weather prediction products contained in NPROVS can also be evaluated against the dropsonde data to understand their performance. Additional comparisons against nearby conventional raob can also be included to better understand unique contributions by DROPs in the context of satellite data validation.

CONCLUSIONS. A GPS dropsonde is a scientific instrument deployed from research and operational aircraft, manned or autonomous, that descends through the atmosphere by a parachute. The GPS dropsonde was developed in 1995 by NCAR and is currently manufactured by Vaisala, Inc. The dropsonde provides high-quality, high-vertical-resolution (~5–15 m) profiles of atmospheric pressure, temperature, relative humidity, and wind speed and direction from the aircraft flight level to the surface over the hard-to-reach areas. Since 1996, GPS dropsondes have been routinely dropped during hurricane reconnaissance and surveillance flights to help predict hurricane track and intensity. From 1996 to 2012, NOAA has dropped over 13,000 dropsondes inside hurricane eyes and eyewalls and in the surrounding environment for 120 TCs. All dropsonde data have been collected, reformatted to one format, and consistently and carefully quality controlled using state-of-the-art QC tools. Three value-added products, the vertical air velocity and the radius and azimuth angle of each dropsonde location, are generated and added to the dataset. As a result, a long-term (1996–2012), high-quality, high-vertical-resolution GPS dropsonde dataset is created and made readily available for public access (www.eol.ucar.edu/content/noaa-hurricane-dropsonde-archive). It includes 13,681 quality-controlled dropsonde soundings from 1996 to 2012 for 120 storms.

The dropsonde data collected during hurricane reconnaissance and surveillance flights have significantly improved TC-track and TC-intensity forecasts and enable researchers to better understand the characteristics of TCs. Previous studies have shown that dropsonde data alone have improved the hurricane-track forecasting by as much as 32% and the hurricane intensity by 20% (Aberson and Franklin 1999). The wind measurements throughout the depth of the troposphere made by the dropsonde are required to

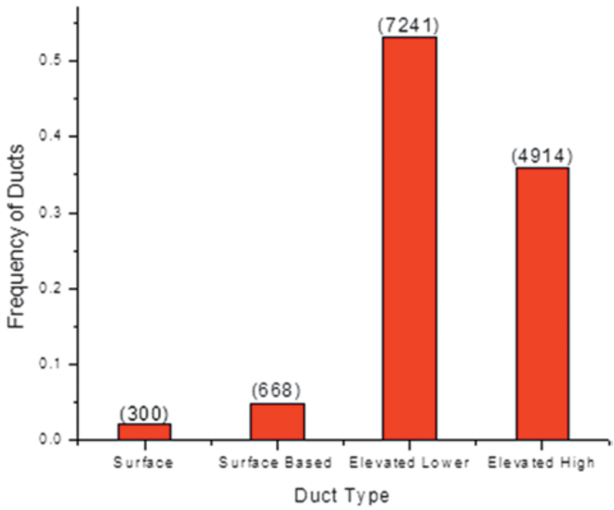

Fig. 8. Frequency occurrences of various duct types in hurricane environment from all hurricanes with dropsonde measurements as well as storm-track data. The numbers in parentheses denote the number of dropsondes with the specific duct type. The "elevated lower" category refers to elevated ducts below 2 km. The "elevated high" category refers to a single elevated duct layer above 2 km.

specify the environment flow surrounding the hurricane eyewall, which determines the hurricane motion (Franklin et al. 2003). The milestones of dropsonde data's impact on hurricane studies are summarized in the introduction. Various scientific applications of the long-term dropsonde dataset from this study are highlighted in the "Scientific highlights" section, including characterizing TC structures, studying TC environmental interactions, identifying surface-based ducts in the hurricane environment that affect electromagnetic wave propagation, and validating satellite temperature and humidity profiling products. We strongly believe that the applications of this dataset still wait to be discovered by forecasters, researchers, and the general public in the years to come.

The extensive and comprehensive QA and QC procedures for dropsonde data are summarized in this study. They can be applied to other dropsonde data collected over the years. We plan to find the support to expand our dropsonde dataset in the future by including dropsonde data from the U.S. Air Force, National Aeronautics and Space Administration (NASA), field projects, Taiwan typhoon surveillance flights, and other countries. From 1997 to 2012, the U.S. Air Force has collected over 6,000 dropsonde profiles. During last 23 years (1990–2012), the dropsonde system has been deployed to 41 field projects around the globe and dropped over 8,000 soundings, which includes ones from an unmanned, high-altitude aircraft (Global Hawk) and stratospheric superpressure balloons. The Taiwanese Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOSTAR) collected 1,051 soundings from 2003 to 2012 for 49 typhoons (Wu et al. 2005). The inclusion of these dropsonde data in our archive will further increase the value of the dataset and expand its applications.

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REFERENCES

Aberson, S. D., 2010: Ten years of hurricane synoptic surveillance (1997–2006). *Mon. Wea. Rev.,* **138,** 1536–1549, doi:10.1175/2009MWR3090.1.

——, 2011: The impact of dropwindsonde data from the THORPEX Pacific Area Regional Campaign and the NOAA hurricane field program on tropical cyclone forecasts in the Global Forecast System. *Mon. Wea. Rev.,* **139,** 2689–2703, doi:10.1175/2011MWR3634.1.

——, and J. L. Franklin, 1999: Impact on hurricane track and intensity forecasts of GPS dropwindsonde observations from the first-season flights of the NOAA Gulfstream-IV jet aircraft. *Bull. Amer. Meteor. Soc.,* **80,** 421–428, doi:10.1175/1520-0477(1999)080<0421:IOHTAI>2.0.CO;2.

Ao, C. O., 2007: Effect of ducting on radio occultation measurements: An assessment based on high-resolution radiosonde soundings. *Radio Sci.,* **42,** RS2008, doi:10.1029/2006RS003485.

Barnes, G. M., 2008: Atypical thermodynamic profiles in hurricanes. *Mon. Wea. Rev.,* **136,** 631–643, doi:10.1175/2007MWR2033.1.

Bean, B. R., and E. J. Dutton, 1966: R*adio Meteorology. NBS Monogr.,* Vol. 92, National Bureau of Standards, 435 pp.

Bell, M. M., and M. T. Montgomery, 2008: Observed structure, evolution, and intensity of category 5 Hurricane Isabel (2003) from 12 to 14 September. *Mon. Wea. Rev.,* **136,** 2023–2036, doi:10.1175/2007MWR1858.1.

Black, P. G., and Coauthors, 2007: Air–sea exchange in hurricanes: Synthesis of observations from the Coupled Boundary Layer Air–Sea Transfer experiment. *Bull. Amer. Meteor. Soc.,* **88,** 357–374, doi:10.1175/BAMS-88-3-357.

Braun, S. A., and W.-K. Tao, 2000: Sensitivity of high-resolution simulations of Hurricane Bob (1991) to planetary boundary layer parameterizations. *Mon. Wea. Rev.,* **128,** 3941–3961, doi:10.1175/1520-0493(2000)129<3941:SOHRSO>2.0.CO;2.

Bryan, G. H., and R. Rotunno, 2009: The maximum intensity of tropical cyclones in axisymmetric numerical model simulations. *Mon. Wea. Rev.,* **137,** 1770–1789, doi:10.1175/2008MWR2709.1.

Chou, K.-H., C.-C. Wu, P.-H. Lin, S. D. Aberson, M. Weissmann, F. Harnisch, and T. Nakazawa, 2011: The impact of dropwindsonde observations on typhoon track forecasts in DOTSTAR and T-PARC. *Mon. Wea. Rev.,* **139,** 1728–1743, doi:10.1175/2010MWR3582.1.

Corbosiero, K. L., and J. Molinari, 2002: The effects of vertical wind shear on the distribution of convection in tropical cyclones. *Mon. Wea. Rev.,* **130,** 2110–2123, doi:10.1175/1520-0493(2002)130<2110:TEOVWS>2.0.CO;2.

DeMaria, M., M. Mainelli, L. K. Shay, J. A. Knaff, and J. Kaplan, 2005: Further improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting,* **20,** 531–543, doi:10.1175/WAF862.1.

Ding, J., J. Fei, X. Huang, and X. Cheng, 2013: Observational occurrence of tropical cyclone ducts from GPS dropsonde data. *J. Appl. Meteor. Climatol.,* **52,** 1221–1236, doi:10.1175/JAMC-D-11-0256.1.

Emanuel, K. A., 1986: An air–sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.,* **43,** 585–605, doi:10.1175/1520-0469(1986)043<0585:AASITF>2.0.CO;2.

Franklin, J. L., M. L. Black, and K. Valde, 2003: GPS dropwindsonde wind profiles in hurricanes and their operational implications. *Wea. Forecasting,* **18,** 32–44, doi:10.1175/1520-0434(2003)018<0032:GDWPIH>2.0.CO;2.

Gopalakrishnan, S. G., F. Marks, J. A. Zhang, X. Zhang, J.-W. Bao, and V. Tallapragada, 2013: A study of the impacts of vertical diffusion on the structure and intensity of the tropical cyclones using the high-resolution HWRF system. *J. Atmos. Sci.,* **70,** 524–541, doi:10.1175/JAS-D-11-0340.1.

Hamill, T. M., F. Yang, C. Cardinali, and S. J. Majumdar, 2013: Impact of targeted Winter Storm Reconnaissance dropwindsonde data on midlatitude numerical weather predictions. *Mon. Wea. Rev.,* **141,** 2058–2065, doi:10.1175/MWR-D-12-00309.1.

Hock, T. F., and J. L. Franklin, 1999: The NCAR GPS dropwindsonde. *Bull. Amer. Meteor. Soc.,* **80,** 407–420, doi:10.1175/1520-0477(1999)080<0407:TNGD>2.0.CO;2.

Molinari, J., D. M. Romps, D. Vollaro, and L. Nguyen, 2012: CAPE in tropical cyclones. *J. Atmos. Sci.,* **69,** 2452–2463, doi:10.1175/JAS-D-11-0254.1.

——, J. Frank, and D. Vollaro, 2013: Convective bursts, downdraft cooling, and boundary layer recovery in a sheared tropical storm. *Mon. Wea. Rev.,* **141,** 1048–1060, doi:10.1175/MWR-D-12-00135.1.

Reale, T., B. Sun, F. H. Tilley, and M. Pettey, 2012: The NOAA Products Validation System (NPROVS). *J. Atmos. Oceanic Technol.,* **29,** 629–645, doi:10.1175/JTECH-D-11-00072.1.

Riemer, M., M. T. Montgomery, and M. E. Nicholls, 2010: A new paradigm for intensity modification of tropical cyclones: Thermodynamics impact of vertical wind shear on the inflow layer. *Atmos. Chem. Phys.,* **10,** 3163–3188, doi:10.5194/acp-10-3163-2010.

——, ——, and ——, 2013: Further examination of the thermodynamic modification of the inflow layer of tropical cyclones by vertical wind shear. *Atmos. Chem. Phys.,* **13,** 327–346, doi:10.5194/acp-13-327-2013.

Rogers, R. F., and Coauthors, 2013: NOAA's Hurricane Intensity Forecasting Experiment: A progress report. *Bull. Amer. Meteor. Soc.,* **94,** 859–882, doi:10.1175/BAMS-D-12-00089.1.

Smith, R. K., M. T. Montgomery, and N. Van Sang, 2009: Tropical cyclone spin-up revisited. *Quart. J. Roy. Meteor. Soc.,* **135,** 1321–1335, doi:10.1002/qj.428.

Szunyogh, I., Z. Toth, R. E. Morss, S. J. Majumdar, B. J. Etherton, and C. H. Bishop, 2000: The effect of targeted dropsonde observations during the 1999 Winter Storm Reconnaissance program. *Mon. Wea. Rev.,* **128,** 3520–3537, doi:10.1175/1520-0493(2000)128<3520:TEOTDO>2.0.CO;2.

Vaisala, 2014: Vaisala dropsonde RD94. Vaisala Rep., 2 pp. [Available online at www.vaisala.com/Vaisala%20Documents/Brochures%20and%20Datasheets/RD94-Dropsonde-Datasheet-B210936EN-A-LoRes.pdf.]

Wang, J., J. Bian, W. O. Brown, H. Cole, V. Grubisic, and K. Young, 2009: Vertical air motion from T-REX radiosonde and dropsonde data. *J. Atmos. Oceanic Technol.,* **26,** 928–942, doi:10.1175/2008JTECHA1240.1.

——, T. Hock, S. A. Cohn, C. Martin, N. Potts, T. Reale, B. Sun, and F. Tilley, 2013: Unprecedented upper air dropsonde observations over Antarctica from the 2010 Concordiasi Experiment: Validation of satellite-retrieved temperature profiles. *Geophys. Res. Lett.,* **40,** 1231–1236, doi:10.1002/grl.50246.

Weissmann, M., and Coauthors, 2011: The influence of assimilating dropsonde data on typhoon track and midlatitude forecasts. *Mon. Wea. Rev.*, **139,** 908–920, doi:10.1175/2010MWR3377.1.

Wu, C.-C., and Coauthors, 2005: Dropsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR): An overview. *Bull. Amer. Meteor. Soc.*, **86,** 787–790, doi:10.1175/BAMS-86-6-787.

——, K.-H. Chou, P.-H. Lin, S. D. Aberson, M. S. Peng, and T. Nakazawa, 2007: The impact of dropwindsonde data on typhoon track forecasts in DOTSTAR. *Wea. Forecasting,* **22,** 1157–1176, doi:10.1175/2007WAF2006062.1.

——, S.-G. Chen, C.-C. Yang, P.-H. Lin, and S. D. Aberson, 2012: Potential vorticity diagnosis of the factors affecting the track of Typhoon Sinlaku (2008) and the impact from dropwindsonde data during T-PARC. *Mon. Wea. Rev.*, **140,** 2670–2688, doi:10.1175/MWR-D-11-00229.1.

Zhang, J. A., 2010: Estimation of dissipative heating using low-level in situ aircraft observations in the hurricane boundary layer. *J. Atmos. Sci.*, **67,** 1853–1862, doi:10.1175/2010JAS3397.1.

——, P. G. Black, J. R. French, and W. M. Drennan, 2008: First direct measurements of enthalpy flux in the hurricane boundary layer: The CBLAST results. *Geophys. Res. Lett.*, **35,** L14813, doi:10.1029/2008GL034374.

——, R. F. Rogers, D. S. Nolan, and F. D. Marks Jr., 2011: On the characteristic height scales of the hurricane boundary layer. *Mon. Wea. Rev.*, **139,** 2523–2535, doi:10.1175/MWR-D-10-05017.1.

——, ——, P. Reasor, E. W. Uhlhorn, and F. D. Marks, 2013: Asymmetric hurricane boundary layer structure from dropsonde composites in relation to the environmental vertical wind shear. *Mon. Wea. Rev.*, **141,** 3968–3984, doi:10.1175/MWR-D-12-00335.1.

Zhu, M., and B. W. Atkinson, 2005: Simulated climatology of atmospheric ducts over the Persian Gulf. *Bound.-Layer Meteor.*, **115,** 433–452, doi:10.1007/s10546-004-1428-1.

Ziemba, D. A., 2013: Ducting conditions for electromagnetic wave propagation in tropical disturbances from GPS dropsonde data. M.S. thesis, Dept. of Meteorology, Naval Postgraduate School, 78 pp.