Radial-Vertical Profiles of Tropical Cyclone Derived from Dropsondes

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RADIAL-VERTICAL PROFILES OF TROPICAL CYCLONE DERIVED FROM DROPSONDES

By

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ABSTRACT

The scopes of this thesis research are two folds: the first one is to construct the intensity-based composite radial-vertical profiles of tropical cyclones (TC) using GPS-based dropsonde observations and the second one is to identify the major deficiencies of Mathur vortices against the dropsonde composites of TCs. The intensity-based dropsonde composites of TCs advances our understanding of the dynamic and thermal structure of TCs of different intensities along the radial direction in and above the boundary layer where lies the devastating high wind that causes property damages and storm surges. The identification of the major deficiencies of Mathur vortices in representing the radial-vertical profiles of TC of different intensities helps to improve numerical predictions of TCs since most operational TC forecast models need to utilize bogus vortices, such as Mathur vortices, to initialize TC forecasts and simulations.

We first screen all available GPS dropsonde data within and round 35 named TCs over the tropical Atlantic basin from 1996 to 2010 and pair them with TC parameters derived from the best-track data provided by the National Hurricane Center (NHC) and select 1149 dropsondes that have continuous coverage in the lower troposphere. The composite radial-vertical profiles of tangential wind speed, temperature, mixing ratio and humidity are based for each TC category ranging from “Tropical Storm” (TS) to “Hurricane Category 1” (H1) through “Hurricane Category 5” (H5). The key findings of the dropsonde composites are: (i) all TCs have the maximum tangential wind within 1 km above the ground and a distance of 1-2 times of the radius of maximum wind (RMW) at the surface; (ii) all TCs have a cold ring surrounding the warm core near the boundary layer at a distance of 1-2 times of the RMW and the cold ring structure gradually diminishes at a higher elevation where the warm core structure prevails along
the radial direction; (iii) the existence of such shallow cold ring outside the RMW explains why
the maximum tangential wind is within 1 km above the ground and is outside the RMW, as
required by the hydrostatic and gradient wind balance relations; (iv) one of the main differences
among TCs of different intensities, besides the speed of the maximum tangential wind, is the
vertical extent of near-saturated moisture air layer inside the core. A weaker TC tends to have a
deep layer of the near-saturated moisture air layer whereas a stronger TC has a shallow one; (v)
another main difference in the thermal structure among TCs of different intensities is the
intensity and vertical extent of the warm core extending from the upper layer to the lower layer.
In general, a stronger TC has a stronger warm core extending downward further into lower layer
and vice versa. The features (iv) and (v) are consistent with the fact that a stronger TC tends to
have stronger descending motion inside the core.

The main deficiencies of Mathur vortices in representing the radial-vertical profiles of TC
of different intensities are (i) Mathur vortices of all categories have the maximum wind at the
surface with a much straight axis in the vertical; (ii) none of Mathur vortices have a cold ring
outside the warm core near the boundary layer; (iii) Mathur vortices tend to overestimate warm
core structure in reference to the horizontal mean temperature profile; (iv) Mathur vortices tend
to overestimate the vertical depth of the near-saturated air layer near the boundary layer.
CHAPTER ONE

INTRODUCTION

1.1 Motivation

Tropical cyclone (TC) typically occurs on a scale of several hundred kilometers in the warm ocean. Lots of building damages and financial loss are caused by TCs annually. Since the convective activity and devastating winds concentrated in the inner-core region and the outer-core region are important for potential cyclone wind damage, torrential rainfall, and powerful storm surges. Therefore, the precise study and forecast of TC are needed.

Forecast of track and intensity for mature tropical cyclones requires accurate representation of TC vortex in the model initial condition for numerical weather predictions. The accuracy of the initial condition depends on the quality, frequency, and spatial resolution of observation, and the method to involve the observational information into the model, as well as the forecast model itself that provides the first guess for data assimilation. Bogusing (Mathur, 1990, Kurihara et al., 1993, 1997; Bender et al, 1993; Singh et al., 2005) and data assimilation (Navon et al. 1992; Bennett et al., 1996; Zhao and Braun, 2001) are techniques usually applied in the hurricane initialization to improve the track and intensity predictions. In the present time with the development of satellite, the derived products have begun to be assimilated for hurricane initialization, which makes a substantial improvement in tropical cyclone track prediction (Velden et al, 1992; Krishnamurti, 1995; Leslie, 1998; Zou and Xiao, 2000; Xiao et al, 2000).

Since most observations come from satellites usually only give a decent estimate of hurricane horizontal structure since the retrieval products typically have a very low resolution in the vertical. Therefore a key problem that remains for TC initialization is the lack of observations, especially the observations in the boundary, which is one of the major factors
limiting the accurate prediction of tropical cyclones. From 1997, National Oceanic and Atmospheric Administration (NOAA) hurricane research aircraft began deploying global positioning system (GFS) based dropsonde in the hurricane eyewall and surrounding regions (Hock and Franklin, 1999). These sondes represent a radical amelioration in design and performance from the Omega navigation based dropsonde which rarely worked in heavy precipitation and lacked winds measurement below about 500 m (Franklin and Julian, 1985). Along with the dropsonde observations operated in the Atlantic and Eastern Pacific, the Dropsonde Observations for Typhoon Surveillance near Taiwan Region (DOTSTAR) program operated in the Western Pacific Ocean began in 2002.

Although satellite radiances provide thermodynamic retrievals, little atmospheric wind information is directly obtained from observations. Dropsonde measures the vertical profiles of wind, temperature, and humidity between flight level and sea surface with a high vertical resolution. Therefore, the development of dropsonde has made it possible to obtain the dynamic and thermodynamic fields within nearly all portions of the hurricane with unprecedented accuracy and resolution. The error of the forecast hurricane intensity and track could be reduced accordingly, as the observations from lower troposphere could provide a preference for hurricane structure study and model initialization verification.

1.2 Previous Studies Using Dropsonde Data

Dropsonde observations have already been made many applications as they are applied in various aspects of hurricane study. Dropsonde can provide the instant features from single storm and the averaged characteristics from multiple storms. Studies are mainly concentrated on the
understanding of inner-core structure and hurricane boundary features, as well as improvement of hurricane track prediction and verification of model simulations.

Much research on dynamic and thermodynamic properties for hurricane inner core has been done using dropsonde data. Prior to 1990s, dropsondes were collected without GPS system. Hawkins (1976) studied the general typical tropical cyclone structures with these non-GPS based dropsondes and found the inflow layer appeared to extend no higher than 750 hPa level. Later, Jorgensen (1983) depicted the mesoscale motion and thermodynamic fields that associated with the eyewall for Hurricane Allen. Accompanied with convergence, an organized ascent was noticed inward several kilometers from the radius of maximum wind (RMW). Weatherford (1987) analyzed the varying relationship between cyclone inner-core intensity and outer-core wind strength in relation to latitude, season, and time of day. Franklin (1988) analyzed two soundings in the eye of Hurricane Gloria which showed dramatic thermodynamic changes as the hurricane deepened. The substantial warming was caused by above descent motions, while the beneath saturated conditions was separated by a well-defined inversion. Franklin (2003) analyzed the characteristics of the averaged wind profiles both from eyewall and outside region using dropsondes covering a few TCs. An estimation of surface maximum wind from the flight level (700 hPa) was given. Barnes (2008) identified three unusual thermodynamic structures in the lower-cloud and sub-cloud layers. Positive lapse rate of equivalent potential temperature was found near the top of the inflow, which promoted energy increases rapidly by insulating the inflow from the negative impacts of entrainment mixing.

Furthermore, since the dropsonde observations provide unprecedented accuracy measurements in the lower troposphere with high vertical resolution, they also have been widely used to study the hurricane features and air-sea interaction in the boundary. Coine (2000) showed
the temperature differences between the sea surface and air significantly increased at the outer region, which is primarily due to a reduction in surface air temperature. The greatest increase in surface sensible heat flux was associated with the strong surface winds and large sea-air temperature contrasts. Zhang et al. (2011) used 794 dropsondes to analyze the characteristic height scales of the hurricane boundary layer and found that the dynamical boundary layer height was much deeper than the thermodynamic one. Later, Zhang (2013) also investigated the asymmetric structure of the hurricane boundary layer in relation to the environmental vertical wind shear. The cycling process associated with triggered active convection and released energy in the following quadrant was found might be directly tied to shear-induced asymmetry of convection in hurricanes.

Besides the direct use of observations from dropsonde profiles to study hurricane characteristics, dropsonde data are also applied in TC predictions. So far, many attempts have been made to improve hurricane forecasts through satellite data assimilation. Dropsonde data are also used to modify the initial boundary conditions for numerical TC forecast models by assimilation, aimed to improve TC diagnosis, analyses, and forecasts. Particularly, the study of targeted observations, through detecting the most important region in the initial field by sensitivity guidance, has contributed greatly to the improvements of TC track forecasts (Torn, 2010; Aberson, 2011; Wu et al., 2007; Chou et al., 2011).

Furthermore, these dropsondes supply a unique dataset for the validation and verification of vortex fields which obtained from remotely sensed data and model simulation in the study of TC. Satellite retrieved temperature and wind fields for hurricane initialization compared favorably to the dropsonde observations at certain pressure level, taken in the vicinity of the storm Bonnie and Katrina (Zhu et al., 2002; Weng et al., 2007). The large variations of hurricane
eye and eyewall soundings from the results of mode simulation for Hurricane Andrew resemble well those dropsonde observations (Liu et al., 1997).

1.3 Objectives and Main Tasks

One of the two main objectives of this study is to construct for the first time the intensity-based composite TCs using 3769 GPS dropsonde data within and round 35 TCs from 1996 to 2010. According to the intensity of storms, these data are grouped into 6 different categories. Then, composite analysis will be applied to generate the radial-vertical profiles of axisymmetric low-level wind and thermal structures of TCs for different categories. The dynamical and thermodynamic characteristic and consistency among these fields, as well as the variability between weak and strong storms are examined.

The other main objective is to identify the main deficiencies of Mathur vortices, which are used by the NCEP’s QLM as initial vortices for TC forecasts by comparing the dropsonde-based TC composites of the same intensity. The Mathur vortices representing different intensities will be constructed in each TC category using the same specifications given from NCEP’s QLM. The averaged Mathur vortices for 6 categories will be compared with the dropsonde composite results accordingly.

The thesis is organized as follows. Chapter 2 describes the dropsonde dataset and definitions for TC intensity categories and key steps in constructing Mathur vortices. Chapter 3 presents statistical evaluation of dropsonde data and the composite analysis. Chapter 4 presents the radial-vertical wind and thermal structures of different TC categories. Chapter 5 compares the dropsonde derived structures with the Mathur constructed vortices. Chapter 6 gives out the main conclusions of this study.
CHAPTER TWO

DATA AND BASIC INFORMATION

2.1 Data

2.1.1 Dropsonde Data

Dropsondes are deployed from an aircraft at the height of about 700 hPa, descending at
rates of 10-25 m/s, with a vertical sampling resolution about 6-7 m. During the process of
descending, the atmospheric profiles of pressure, temperature, relative humidity, and horizontal
wind are collected. The accuracies of pressure, temperature, humidity and horizontal wind are
±1.0 hPa, ±0.2 °C, ±5 % and ±0.5 m/s, respectively. The detailed operating ranges and
resolutions of these measurements could reference to Hock and Franklin (1999).

The data used in this study is from the National Hurricane Center (NHC) Hurricane
Research Division’s (HRD) Full-Resolution Data (FRD) file, which passed the post-flight quality
control steps using HRD’s Editsonde program. The main body of data contains the observation
sequential number, elapsed time, the meteorological observations (pressure, temperature, relative
humidity, and wind), as well as the latitude, longitude and altitude determined by the dropsonde's
GPS navigation chip.

In this study, 3769 GPS dropsonde profiles collected by National Oceanic and
Atmospheric Administration (NOAA) research aircraft in the vicinity of 35 named TCs from
1996 to 2010 will be analyzed to study the dynamic and thermodynamic structures of storms
with different intensities.
2.1.2 Tropical Cyclone Parameters

The Automated Tropical Cyclone Forecast (ATCF) best-track data provided by NHC contains the characterized parameters for each tropical cyclone (TC) four times a day from 1996 to 2010. The parameters used in study include latitude and longitude of storm center, minimum sea level pressure ($p_{cent}$), pressure of the last closed isobar ($p_{out}$), radius of last closed isobar ($r_{out}$), and radius of maximum wind ($r_{max}$). The radial distance of maximum wind ($r_{max}$) is defined as distance between the center of a cyclone where $p_{cent}$ is located and its band of strongest winds, with the highest average wind over one-minute at the height of 10 meters above the surface. The $r_{max}$ as well as the information of latitude and longitude will be used in the composite analysis of dropsonde profiles for TC of different intensities. These four TC parameters are needed to construct Mathur vortex which is used as initial conditions for operational TC forecasts by the NCEP’s Quasi-Lagrangian Model (QLM).

2.2 Basic Information

2.2.1 Intensity Classification

The TC intensity classification is based on the Saffir-Simpson scale, which gives the threshold value for each category based on the ranges of minimum center pressure ($p_{cent}$) and the maximum wind ($v_{max}$). There are 6 categories of TC intensity based on the Saffir-Simpson scale: tropical storm (TS), hurricane category 1 (H1), hurricane category 2 (H2), hurricane category 3 (H3), hurricane category 4 (H4), and hurricane category 5 (H5). The ranges of pressure ($p_{cent}$) and the maximum wind ($v_{max}$) for each of the 6 categories of TC intensity are provided in the first three columns of Table 2.1.
2.2.2 Mathur Vortex Construction

Mathur (1990) formulated a semi-empirical algorithm for constructing radial profile of surface pressure and radial-vertical profiles of tangential wind, temperature, and humidity using the information of the TC parameters (i.e., $p_{cent}$, $p_{out}$, and $r_{out}$) as the initial condition for the NCEP’s operational TC forecasts using the QLM model. We here refer to such a constructed vortex as a Mathur vortex. In order to compare the radial-vertical profiles of Mathur vortex with the radial-vertical profiles of TC derived from dropsonde profiles, we have used the Mathur’s method to construct Mathur vortex. Below, we provide a brief summary of the key procedures to construct Mathur vortex based on the information of the TC parameters. Readers may consult with Mathur (1990) for more details on the construction of Mathur vortex using the TC parameters.

The Mathur’s method first uses the TC parameters to construct the radial profile of surface pressure of as a function of radius. From the constructed surface pressure profile, one obtains the radial profile of geopotential height 1000 hPa. The radial profile of tangential wind is then derived from the radial profile of geopotential height 1000 hPa based on the gradient wind relation. Then, an empirical vertical function is used to extend the constructed tangential wind at 1000 hPa to the vertical. From the radial-vertical profiles of tangential wind, the radial-vertical profiles of geopotential and temperature are separately derived from the gradient wind relation and hydrostatic balance. The radial-vertical profile of relative humidity is constructed by assuming the relative humidity to be 100% at the vortex center and linearly decreases to the environmental value at the distance of outermost closed isobar. The radial-vertical profile of atmospheric water vapor can be determined using the Clausius-Clapeyron relation from the radial-vertical profiles of temperature and relative humidity.
Table 2.1: Storm Classification Criteria from Saffir-Simpson Scale

<table>
<thead>
<tr>
<th>Category</th>
<th>$p_c$ (hPa)</th>
<th>$v_{\text{max}}$ (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS</td>
<td></td>
<td>34-63</td>
</tr>
<tr>
<td>H1</td>
<td>$&gt;980$</td>
<td>64-82</td>
</tr>
<tr>
<td>H2</td>
<td>965-980</td>
<td>83-95</td>
</tr>
<tr>
<td>H3</td>
<td>945–964</td>
<td>96-112</td>
</tr>
<tr>
<td>H4</td>
<td>920–944</td>
<td>113-136</td>
</tr>
<tr>
<td>H5</td>
<td>$&lt;920$</td>
<td>$\geq137$</td>
</tr>
</tbody>
</table>
CHAPTER THREE

DROPSONDE DATA PROCESSING AND COMPOSITE

Dropsondes have high resolution in the vertical, but relatively sporadic horizontal distribution for a given storm. The composite method is usually applied to analyze dropsonde data for TC inner-core structure, boundary layer structure and surface layer air-sea thermal structure studies (Jorgensen 1984; Frank 1977a, b, 1984; Franklin et al. 2003; Cione et al. 2000). In this study, we use the composite method to construct the radial-vertical profiles of thermal, tangential wind, and humidity of TC of different intensities. It is of importance to point out that the composite method helps not only to reduce the “noise” or “observational errors” of dropsonde profiles by averaging over TCs of the same category, but also to increase horizontal resolution by combining sporadically distributed dropsonde observations at various distance from the TC center of the same category. As to be reported shortly, it turns out that the usage of compositing mainly helps to increase the horizontal resolution of the composite TCs and the conventional averaging effect of composite is only secondary.

The first step to obtain a composite TC is to pair the deployment time of each dropsonde profile with the timing of the TC parameters derived from the ATCF best-track data. Because the TC parameter data is available only 4 times a day, we interpolate linearly the values of two adjacent TC parameter observations to the deployment time of the dropsonde profile that lies in between. We only consider those dropsonde profiles that meet the following four conditions: (i) they have continuous measurements of wind speed, temperature, and humidity from the fight level to surface; (ii) they are paired with the original TC parameters (before temporal interpolation) observed within ±3 hours from the dropsonde deployment time, (iii) their paired TC parameters falling into one of the 6 categories of TC intensity (i.e., TS or H1-H5), and (iv)
they are deployed within 300 kilometers from the paired TC center recorded in the TC parameter data. After all of these, we only have 1149 dropsonde profiles (out of 3769) that meet the 4 conditions aforementioned.

Next we group these 1149 dropsonde profiles into the 6 categories of TC intensity based on the information of their corresponding TC parameters. We then use the 1149 dropsonde profiles to construct six composite radial-vertical profiles of TCs for each of the 6 categories. Table 3.1 provides the usage information of the 1149 dropsonde profiles for the 6 categories of TC intensity. The second row is the distribution information of the total number of dropsonde profiles for each TC category. It is seen that the TS and H1 categories have relatively small counts of dropsonde profiles (about 110) while the H4 has the most data samples (344 dropsonde profiles). Note that the number of the targeted TC in each category (the 3rd row) corresponds to the maximum possible number of independent TC cases for composite averaging at a given radius from the center of the composite TC. The average number of dropsonde profiles per targeted TC case (the 4th row) is the lower bound of the horizontal resolution of the composite TC. It is seen that the average number of dropsonde profiles per targeted TC case tends to be larger for a stronger TC than for a weaker TC, ranging from 6.6 (for TS), to 11 for H4 and 17.5 (for H5). Therefore, the composite helps to increase horizontal resolution more for stronger TC, such as H4 and H5, than weaker TC (i.e. TS). The effect of increasing the horizontal resolution by compositing will become clear after we show the spatial distribution of these dropsonde profiles for each category.

Fig. 3.1 shows the geographic locations of these 1149 dropsonde profiles with TC category information color-coded. As indicated in the footnote #2 of Table 3.1, these dropsonde observations were taken for 13 named storms at different locations along their tracks and at
different stages (i.e., different categories). The category change of these 13 named storms during the period covered by the 1149 dropsondes explains why the sum of the named storms list in the bottom row of Table 3.1 is 44, three times more than the number of distinctly named storms. In other words, these 13 named storms changed their categories, on average, three times during the period covered by the 1149 dropsondes. The total number of targeted TC is 117, 9 times more than 13. This indicates that on average, these 1149 dropsondes were taken at 9 different locations of each of these 13 named storms along their tracks. Another important feature shown in Fig. 3.1 is that these non-black colored circles tend to be around the black circles, indicating that dropsondes are also distributed in the azimuth direction in addition to the radial direction. Therefore the radial-vertical profiles of the composite TCs are obtained also as the averaging along the azimuth direction in addition to the averaging over different targeted TC cases of the same category.

Table 3.2 summarizes the mean values and their standard deviations of the TC parameters of these 6 composite TCs. The standard deviations measure the case-to-case differences of TC parameters of the same category TC. It is seen that as the intensity category changes from TS to H5, the composite mean maximum wind (\( v_{\text{max}} \)) increases but the central pressure (\( p_c \)) decreases, in accordance with the definition of the hurricane intensity. The case-to-case differences of maximum wind (\( v_{\text{max}} \)), central pressure (\( p_c \)), and pressure of the last close isobar (\( p_{\text{out}} \)) of the same category TC are relatively small. Even adding the standard deviation of \( p_c \) and \( v_{\text{max}} \) to their corresponding mean values, different TC categories can still be distinguished clearly. However, the mean radius of maximum and the mean radius of last close isobar appear not to be related to the TC intensity. Furthermore, the standard deviations of the RMW and the
radius of last closed isobar are relatively large. In particular, there are large case-to-case
differences in $r_{\text{max}}$ for TS and H2 categories.

The fact that the RMW of TCs in the same intensity category may vary greatly as
indicated in Table 3.2 prompts us to consider how to take the information of RMW into the
consideration in our constructing the radial-vertical profile of the composite TC of a given
intensity category. Obviously one choice is to ignore the information of RMW by just averaging
the dropsonde profiles at the same radial distance from the center of TCs of the same intensity.
Another choice is to consider a “normalized” radial distance, which is defined as the ratio of the
actual radial distance from the center to the radius of maximum wind (i.e., $r = r / r_{\text{max}}$). Then the
radial-vertical profile of the composite TC of a given intensity can be made by averaging the
dropsonde profiles at the same normalized radial distance from the center of TCs of the same
intensity. We have done the composite radial-vertical profiles in both ways.

In the remaining portion of this Chapter, we will show the spatial distributions of the
dropsonde profiles used to construct the radial-vertical profiles of the composite TC of each of
the 6 categories in both actual radial coordinate and the normalized radial coordinate. These
diagrams would help us to illustrate what would be the differences between the composites made
using the actual radial distance and the normalized distance. Fig. 3.2 shows the dropsonde
distribution in both azimuth and radial directions relative to the center of TC of different
intensities whereas Fig. 3.3 shows the counterpart distribution using the normalized radial
distance. It is seen that the distribution pattern along the radial distance is similar to that along
the normalized radial distance, namely much more dropsonde observations are near the center of
TC. Nevertheless, there are still more dropsonde observations in the region far away from the
center when the distance is measured in terms of the normalized radial distance than in real radial
distance. Since the normalized radial distance is measured in reference to the RMW, the composite with the normalized radial distance should capture the dynamical signature of TC of the same intensity but with different RMW more objectively.

The impact of the case-to-case differences on the RMW on the composite TC profiles can be further illustrated in Fig. 3.4, which shows the number of dropsonde profiles as a function of the actual radial distance (ordinate) and the normalized radial distance (abscissa). One would expect a straight (or linear) line in such a plot if the RMW of TC of the same intensity were the same. A casual inspection of these plots immediately indicates that the relation between the actual radial distance and the normalized radial distance for all TCs in H5 is very close to a linear line. This implies that the RMW of all H5 TCs (at least during these dropsonde observation periods) is very close to a constant, which is consistent with the Table 3.2 showing the standard deviation of the RMW is only 18% of the mean RMW of all H5 TCs, smallest in terms of both absolute value and percentage among all of the 6 categories. According to Table 3.2, the largest case-to-case differences in RMW, in terms of both absolute value and percentage, are found for TS and H2 categories. Indeed those results shown in Figs. 3.4a and 3.4c show largest spreads from a linear line. It is of interest to point out that the large spreads from a linear line for categories TS and H2 are mainly due to the existence of two linear lines with distinct slopes. This implies that there are mainly two distinct RMW values for categories TS and H2. Another noteworthy feature shown in Fig. 3.4 is that a stronger TC tends to have a smaller RMW, consistent with the mean RMW value for each category shown in Table 3.2.

Shown in Fig. 3.5 are the radial-vertical distributions of data counts for different TC categories when dropsonde profiles are composited directly using the radial distance in the horizontal. For all TC categories, dropsondes have continuous measurements ranging from 700
to 950 hPa in the vertical and most data counts are gathered near TC center with the radial
distance less than 50 km. Since reconnaissance aircrafts fly across the TC, most measurements
are taken near the center. As a TC becomes stronger, the inner core pressure drops and there are
less data samples of pressure greater than 950 hPa within the range of $r = 50$ km. This kind of
dropsonde count recording distribution is favorable for the study of TC boundary layer and inner
core structure, due to the high vertical resolution and relative reliable eye observations. Fig. 3.6
shows the counterpart results of Fig. 3.5 by using the normalized radial distance. It is seen that in
terms of the normalized radial distance, these dropsonde profiles do have a very good
representation of the vertical profile both inside inner core (inside $r_{\text{max}}$ ) and outside. For the
categories H1- H5, the best coverage of dropsonde observations is placed near the RMW. Have a
look at the situations of TS and H2 which are with the largest case-to-case spreads of RMW
values. For TS the coverage of dropsonde observations spreads at various locations in terms of
the normalized radial distance, while for H2 we still see that the composite made using the
normalized radial distance still captures the information of RMW.

Note that the difference between composites made using the normalized radial distance
and those using the actual distance can be vividly illustrated in Fig. 3.4. In essence, the
composites made using the actual radial distance are achieved by summing up all points in the x-
axis for each value in the y-axis of Fig. 3.4. The composites made using the normalized radial
distance, on the other hand, are done by summing up all points in the y-axis for each value in the
x-axis. It is seen that the composites made using the normalized radial distance would help to
increase the resolution along the radial direction more whereas the composites made using the
actual radial distance helps to increases the number of the observations at the same radial
distance instead of increasing the resolution. The feature of favoring resolution increase by doing
the composite according to the normalized radial distance can be further illustrated in the plots shown in Figs. 3.5-3.6. For example, most dropsonde observations for TS are located at 50 km in the radial direction. Therefore, the TS composite made in actual radial coordinate is mainly to take average of different dropsondes collected for different TS at the same distance from the center of each storm. The TS composite made in normalized radial coordinate, however, has a better radial coverage spanning a wider range of the (normalized) radial distance near the RMW. A better radial coverage is also found at outer region when doing the composite according to the normalized radial distance, particularly for stronger cases (i.e. H4 and H5). As we will demonstrate in the next Chapter, the quality of the selected dropsondes is very reliable because the independent measured dynamical and thermodynamic variables satisfy the gradient and hydrostatic dynamics constraints. Therefore, gaining resolution is a more beneficial factor for using dropsondes observed for different TCs of the same intensity. Combined the information from Figs. 3.2-3.6, we conclude that the composite made using the normalized radial distance would have good coverage both inside and outside the inner core with the best coverage around the core region. Furthermore, the composite made using the actual radial distance may be affected by the case-to-case differences in $r_{\text{max}}$ of the same intensity and therefore it may end up with double “eye” walls in terms of the maximum tangential wind. Therefore, we will only present the composite radial-vertical profiles using the normalized radial distance, although we have also made the composite using the actual radial distance which indeed shows the unrealistic feature of double “eye” walls in terms of the maximum tangential wind.
Table 3.1: Usage Information of Dropsonde Profiles for Different TC Categories

<table>
<thead>
<tr>
<th>Category</th>
<th>TS</th>
<th>H1</th>
<th>H2</th>
<th>H3</th>
<th>H4</th>
<th>H5</th>
<th>Total</th>
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<tr>
<td>Number of Dropsondes</td>
<td>112</td>
<td>109</td>
<td>211</td>
<td>198</td>
<td>344</td>
<td>175</td>
<td>1149</td>
</tr>
<tr>
<td>Number of Targeted TC*</td>
<td>17</td>
<td>12</td>
<td>24</td>
<td>23</td>
<td>31</td>
<td>10</td>
<td>117</td>
</tr>
<tr>
<td>Averaged Number of Dropsondes</td>
<td>6.6</td>
<td>9.1</td>
<td>8.8</td>
<td>8.6</td>
<td>11.1</td>
<td>17.5</td>
<td>9.8</td>
</tr>
<tr>
<td>Number of Named Storms*</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>9</td>
<td>9</td>
<td>4</td>
<td>44</td>
</tr>
</tbody>
</table>

* The difference between the number of targeted TC and that of named TC reflects the fact that the same named TC were observed multiple times along its track. We also note that there were only 13 distinct named storms covered by these 1149 dropsondes. The total of named storms listed in the table is 44. This implies that each of these 13 named storms, on average, had changed their categories more than three times during the deployment of these 1149 dropsondes.

Table 3.2: The Statistic Features of TC Parameters for Different TC Categories
(The number of dropsondes is in the parentheses)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TS (112)</td>
<td>H1 (109)</td>
</tr>
<tr>
<td>$r_{\text{max}}$ (km)</td>
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<td>29.88</td>
</tr>
<tr>
<td>$v_{\text{max}}$ (m s$^{-1}$)</td>
<td>25.49</td>
<td>39.33</td>
</tr>
<tr>
<td>$p_c$ (hPa)</td>
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<td>972.43</td>
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<tr>
<td>$P_{\text{out}}$ (hPa)</td>
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<td>1010.27</td>
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<td>$r_{\text{out}}$ (km)</td>
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<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

17
Figure 3.1: The distribution of the dropsonde geographic locations (circles are color-coded by different TC categories), and the storm centers (black dots).
Figure 3.2: The dropsonde distribution in azimuth and radial directions relative to storm center for different TC categories, using real radial distance to do composite.
Figure 3.3: Same as Figure 3.2, but using normalized radial distance to do composite.
Figure 3.4: The number of dropsonde profiles as a function of the actual radial distance (ordinate) and the normalized radial distance (abscissa) for different TC categories.
Figure 3.5: The radial-vertical distribution of data counts for different TC categories, using the actual radial distance in the horizontal to do composite.
Figure 3.6: Same as Figure 3.5, but using the normalized distance in the horizontal to do composite.
CHAPTER FOUR

SYMMETRIC STRUCTURES OF DIFFERENT INTENSITIES

4.1 Hurricane Category 5

Shown in Figs. 4.1 are the radial-vertical profiles of these six parameters of the composite TC of category H5 made using the normalized radial distance. Since the core of a hurricane (or the axis of maximum tangential wind) typically tilts slightly outward toward larger radial distance with height, the maximum tangential wind at a given elevation above the ground is found between $\kappa = 1$ and $\kappa = 2$, where $\kappa = r / r_{\text{max}}$ is the normalized radial distance, instead of exactly at $\kappa = 1$ as at the surface (Fig. 4.1a). It is seen that the tangential wind first increases with height from the surface to the layer just above boundary layer and then decrease with height till 700 hPa before increasing with height in the layer above. For the composite hurricane of category H5, the maximum tangential wind is as large as 65 m s$^{-1}$ and is located at about 850-900 hPa. The vertically decreasing profile of maximum wind at the core above the boundary layer is indicative of a warm core of a hurricane by the thermal wind relation. One reason for the vertically increasing profile of maximum wind at the core within the boundary layer is due to the frictional effect. A close examination of the temperature profile (Fig. 4.1c) indicates that below 800 hPa, there is a ring of cold temperature between $\kappa = 1$ and $\kappa = 2$ surrounding the warm core (inside $\kappa = 1$), which is surrounded by another ring of warm air outside before the temperature drops off towards the environment air temperature at large radial distance from the center of the storm. Such an alternation of warm, cold, warm, and cold air in the radial profile from the center to the outer radius of the storm can be seen much clearly from Fig 4.1d which shows the difference between the radial-vertical profile of temperature and the vertical profile of
its horizontal average. The reverse of the temperature gradient along the radial increasing direction from negative inside \( r_c = 1 \) to positive between \( r_c = 1 \) and \( r_c = 2 \) explains both why the axis of maximum tangential wind tilts outward below 850 hPa and why the maximum tangential wind is found in the layer 850-900 hPa, rather than at the ground. This kind of distribution of temperature anomaly plays much more important role than frictional effect for the above discussed features shown in the tangential wind (Fig. 4.1a). At further upper layers, the single warm core expands outwards with height and the cold ring surrounding the warm core gradually becomes diminished. As a result, the axis of the maximum tangential wind starts to tilt inward above 850 hPa whereas the maximum tangential wind (in the radial direction) starts to decrease with height.

In the layer below 800 hPa, the radial-vertical profile of mixing ratio field (Fig. 4.1e) follows the temperature profile (Fig. 4.1c) closely, namely that more water vapor is found in the region where temperature is warmer. This suggests that relative humidity is relatively uniform in both radial and vertical directions, as shown in Fig. 4.1b. The lower center is nearly saturated, with the relative humidity nearly reaches 95%. Above 800 hPa, the mixing ratio tends to be more uniform in the radial direction but still decrease with height. Since the warm core gets stronger at upper level center, implying a more rapid decreasing in temperature outwards along the radial direction, the relative humidity would have to be minimum in the core region above 800 hPa, as indicated in Fig. 4.1b. In terms of mixing ratio anomalies (i.e., the departures from the horizontal mean of the mixing ratio field), the maximum moisture anomalies are found only in the lower layer inside the warm core (Fig. 4.1e), despite that the warm core itself gets stronger and stronger till the middle troposphere (Fig. 4.1d).
4.2 Hurricane Category 4

Overall, the features from the radial-vertical profiles of the composite TC of category H4 (Figs. 4.2) are similar to those for category H5 cases (Figs. 4.1). For example, the tilting of the isotach along the out edge of the maximum wind region changes direction after passing the 900 hPa. Below 900 hPa, the isotach tilts outward with height from surface due to the alternative change of warm and cold ring in the boundary layer shown in the Fig. 4.7b. This explains why the maximum tangential wind is not located at $r_c = 1$. Above 900 hPa, the isotach tilts inward with height due to the upper level single warm core. As in the category H5 case, the profile of mixing ratio (Fig. 4.2e) follows the temperature field (Fig. 4.2c) very closely, explanatory of very weak variation in the relative humidity in both radial and vertical directions below 750 hPa (Fig. 4.2b). However, above 750 hPa, relative humidity decreases rapidly, mainly due to a rapid lager decreasing of mixing ratio profile both outward and upward in comparison with the temperature profile.

Compared with the radial-vertical profiles of category H5, besides the magnitude of tangential wind is obviously weaker for category H4 case (about 57 ms$^{-1}$), the perturbations on both temperature and mixing ratio fields are small in the boundary layer. In the upper layers, a relative weaker warm core of 3.5 K (Fig. 4.2d) is still presented at near 700 hPa. A moisture core (Fig. 4.2f) locates in the lowest layers, with a stronger magnitude of water vapor maximum compared with that of category H5.

4.3 Hurricane Category 3

The radial-vertical profiles of the composite TC of category H3 are shown in Figs. 4.3. Generally speaking, the main features shown in Figs. 4.1 for the composite of category H5 are
also found in the composite of category H3. Specifically, the axis of maximum tangential wind also first tilts outward with height between the surface and 900 hPa, and then tilts inward with height in the layer above. However, besides the weaker maximum tangential wind since, it is for category H3, the inward tilting of the axes of maximum tangential wind is more noticeable than that for category H5. Such difference is also reflected in the difference in the radial profile of temperature. The comparison of Fig. 4.7c and Fig. 4.7a (or Fig. 4.3d versus Fig. 4.1d) reveals that the magnitude of cold ring outside the warm core is rather weak. This, per the thermal wind relation, explains why the speed of tangential wind decreases with height rapidly between \( r_1 = 1 \) and \( r_2 = 2 \), responsible for a more pronounced inward tilting of the maximum wind. In addition, the location for the tilting axis seems move little outward than that for category H5 case. Such position shift is also associated to the difference in the radial profile of temperature. The comparison of Fig. 4.7c and Fig. 4.7a reveals that the positive temperature gradient is relative far away from storm center, located near \( r_2 = 2 \). This explains the outward moving of the tilted axis of maximum tangential wind. Similar to the category H5 case, the consistent change of profile of mixing ratio (Fig. 4.3e) with the temperature field (Fig. 4.3c) contribute to uniform distribution in both radial and vertical directions below 800 hPa (Fig. 4.3b). It is nearly saturated, with the magnitude larger than 95%. While above 800 hPa, relative humidity may drop below 80% in the eye, which is associated with the presence of warm core (Fig. 4.3d). Regard to the mixing ratio anomalies (Fig. 4.3f), the maximum moisture core is mainly found in the lower troposphere, even though the warm core itself prevailingly exits in the middle troposphere.

Compared with the radial-vertical profiles of category H5, the magnitude of tangential wind is obviously weaker for category H3 case (about 49 ms\(^{-1}\)). The profiles of temperature anomaly and mixing ratio anomaly are more expanded, due to the outward movement of the
tilting axis. Again, a relative weaker warm core of about 3.5 K is still presented near 700 hPa. A weaker moisture core of about 3 g kg\(^{-1}\) locates in the lower layers.

### 4.4 Hurricane Category 2

The radial-vertical profiles of the composite TC of category H2 are shown in Figs. 4.4. On the whole, the typical features found in the composite of category H2 are comparable with that for category H5 cases. Concretely, the maximum tangential wind is located 900 hPa. The wind and temperature fields satisfy the thermal wind relationship. Below 900 hPa, the outward tilted axis of maximum tangential wind (Fig. 4.4a) increases with height from the surface is accompanied with the alternation of warm and cold anomaly ring (Fig. 4.4d) along the radial direction in the boundary layer. This kind of change of negative and positive radial gradient of temperature is seen much clearly from Fig. 4.7d. This explains why the location of maximum tangential wind is not at ground, but at about 900 hPa. Above 900 hPa, the inward tilted axis of maximum tangential wind (Fig. 4.4a) decreases with height is associated with a single warm core in the upper layers (Fig. 4.4d). In addition, the profile of mixing ratio (Fig. 4.4e) closely follows the temperature field (Fig. 4.4c). According to the Clausius-Clapeyron relation, it explains the uniform distribution of relative humidity below 800 hPa shown in Fig. 4.4b. The hurricane center is almost saturated below 800 hPa, with the magnitude of relative humidity of about 95%. While it shows a dry feature in the upper layer, mainly due to the dominate role of the rapid decreasing of mixing ratio profile both outward and upward. The maximum mixing ratio anomaly is mainly found in the lower troposphere, in spite of the warm core prevails in the middle troposphere, which is similar to category H5 case.
Compared with the radial-vertical profiles of category H5, besides the magnitude of tangential wind is obviously weaker for category H2 case (about 45 m s\(^{-1}\)). Again, perturbations on temperature and mixing ratio fields are small (Fig. 4.4d). In the upper layers, a relative weaker warm core of 3.5 K (Fig. 4.4d) is presented near 750 hPa. A moisture core (Fig. 4.4f) locates in the lower layers, and the magnitude of maximum water vapor is about 3 g kg\(^{-1}\), due to the high protuberance in the storm center.

4.5 Hurricane Category 1

The radial-vertical profiles of the composite TC of category H1 are shown in Figs. 4.5. In short, the main features found in Figs. 4.5 differ in some way from that shown in Figs. 4.1. Illustrate it in detail is that the axis of maximum tangential wind first tilts outward with height between the surface and 900 hPa and then almost straight in above layers. Such difference is also reflected in the difference in radial profile of temperature. The comparison of Fig. 4.7e and Fig. 4.7a reveals that the magnitudes of cold ring and the outside warm ring are relative small. This suggests that the radial temperature gradient is small, and the alternation of warm and cold anomaly along the radial direction in the boundary layer is not distinctive. Meanwhile the upper level temperature anomaly is also relative weak. As a result, the influences of the temperature anomaly from upper level and boundary layer countervail each other above 900 hPa, which attributes to the straight axis above. Nevertheless, the tangential wind still decreases with height below 900 hPa and increases till upper level. Similar to category H5 case, the profile of mixing ratio (Fig. 4.5e) follows the temperature field (Fig. 4.5c) very closely, increasing toward the storm center, with highest value in the eye near surface. The consistent distribution causes the very weak variation in the relative humidity in both radial and vertical directions below 700 hPa.
(Fig. 4.5b). Since the mixing ratio decreases more quickly than the temperature both outward and upward, relative humidity reduces to 83% above 700 hPa accordingly. In addition, regarding to profile of the mixing ratio anomalies (Fig. 4.5f), the moisture core moves to the middle troposphere, instead of locating near the surface. A weaker adiabatic descending motion for weaker storm can explain the change of the vertical extension of the moisture core.

Compared with the radial-vertical profiles of category H5, the magnitude of maximum tangential wind is obviously weaker for category H1 case (about 33 ms\(^{-1}\)) located at about 900 hPa. The warm core and moisture core are still obvious in the storm center, with the strength of 2 K and 2.5 g kg\(^{-1}\), respectively (Fig. 4.5d, Fig. 4.5f).

### 4.6 Tropical Storm

In general, the major features from the radial-vertical profiles of the composite TC of category TS (Figs. 4.6) are similar to those for category H5 cases (Figs. 4.1), even though some disparate still exist. For example, below 950 hPa, the vertically increased tangential wind, as well as the outwards tilted isotach along the out edge of the maximum wind region, is associated with the alternative change of warm and cold ring in the boundary layer (Fig. 4.7f). Above 950 hPa, the vertically decreased tangential wind and inwards tilted isotach are related to the single expanded upper warm core (Fig. 4.6d). However, the tilted axis seems move little outward (Fig. 4.6a) in the comparison with the category H5 case, which is also found in category H3 case (Fig. 4.3a). Such position shift of the tilted axis corresponds to the more outward location of the positive temperature gradient in the radial direction as compared to category H5 case (Fig. 4.7f and Fig. 4.7a). That is why the maximum tangential wind is located about \( r_c = 2 \). In addition, the profiles of mixing ratio (Fig. 4.6e) follow the temperature field (Fig. 4.6c), which contributes a
relatively uniform relative humidity distribution below 750 hPa, with the magnitude of above 92% (Fig. 4.6b). The dry feature above 750 hPa, with relative humidity of 83% in the eye, is mainly due to the presence of warm core (Fig. 4.6d). In addition, moisture core is found in the middle troposphere instead of near the surface (Fig. 4.6f), which is similar to the profile of mixing ratio anomaly for category H1 case (Fig. 4.5f).

Compared with the radial-vertical profiles of category H5, besides the magnitude of tangential wind is obviously weaker for category TS case (about 21 m s$$^{-1}$$), the location of the axis of maximum tangential wind is outwards moved in the radial direction, at about $$r = 2$$ (similar to H3 cases). A weak warm core of 3.5 K is located at about 700 hPa, and moisture core of 2.5 g kg$$^{-1}$$ is located at about 750 hPa.

4.7 Discussions for Specific Features

More observational evidence and the plausible explanation about the tilting of axis of the maximum tangential wind are discussed here. Shea and Gray (1973) firstly documented the tilting feature of RMW based on the wind observations. The outward tilting of RMW was also noticed in the reflectivity surfaces of the eyewall from airborne Doppler radar observations (Jorgensen, 1984; Marks and Houze, 1987). They found that RMW tended to slope outward more in weaker storms and was more upright in the stronger storms. In addition, such outward tilting contributes to the pressure depression and warm core enhancement in the storm center (Malkus and Riehl, 1960). Several plausible factors have been considered to explain the outward tilting of RMW, such as the angular momentum conservation, frictional processes, outflow in the upper levels, convection in the inner-core region, and wind shear (Black et al, 1994; Kepert,
2006; Malkus, 1958; Shea and Gray, 1973; Aberson et al., 2006), which is connected to changes
in both the horizontal and vertical structure of vortex and warm core.

Table 4.1 shows the magnitude and radial location of the maximum tangential wind of
the composites TC of different categories from dropsonde observations. Note that the magnitude
and location of mean maximum tangential wind at surface for each category are composited
using the paired parameters provided by Best Track Data (the 3rd and 4th rows). Therefore, by
definition, the radial location of the maximum tangential surface wind of these composite TCs is
at RMW. It is clearly seen that the maximum tangential wind at lower troposphere for each
category (the 9th and 10th rows) is stronger than that at the surface and is located further outward
than RMW. As we explained in the previous sections of this Chapter, such vertically increasing
profile and outward tilting of tangential wind of TC in all categories are related to the presence
of a cold ring surrounding the warm core in the lower troposphere via the thermal wind relation
beside the frictional effects. The radial location of the cold ring explains why the maximum
tangential wind in the lower troposphere tends to lie between 1-2 units in terms of RMW from
the center of the storm.

In terms of the vertical elevation, the maximum tangential wind is located at about 900-
950 hPa and between \( r = 1 \sim 2 \) (the 11th and 12th rows). Both the standard deviations of \( v_{\text{max}} \) at
the surface (the 5th row) and that at in the lower troposphere (the 13th rows) are relatively small,
even though they are obtained from two different sets data. In addition, the radial distance
between the RMW at the lower troposphere and the RMW at the surface (i.e., the 10th row minus
the 4th row) tends to decrease for stronger storms. This confirms the early finding that RMW tend
to tilt outward more in weaker storms and is more upright in the stronger storms (e.g., Shea and
As discussed above, we have related the outward tilting of maximum tangential wind of a TC in the lower troposphere to the presence of the cold ring surrounding the warm core. As far as we can tell, the existence of such cold ring in the lower layers between \( r_c = 1 \sim 2 \) surrounding the warm core of TC has not been discussed in the literature extensively. Perhaps, Cione et al. (2000) is among these studies that have reported the existence of dry and cold ring outside the warm core using the surface observations. Both observations (Barnes et al., 1983; Powell, 1990) and numerical simulations (Brown, 1979; Leary, 1980) have indicated that the convective downdrafts associated with hurricane rainbands (tropical squall line convection) transport relatively dry and cold air to the surface, resulting in cold air ring outside the warm core at the center (Cione et al., 2000). In addition, the cooling of surface temperature could be caused by the adiabatic cooling experienced by surface air parcels as they flow inward lower pressure or due to the evaporation of sea spray, which is more related to the magnitude of surface winds (Pudov, 1992).
Table 4.1: The Magnitudes and Locations of Maximum Wind at Surface and Lower Layers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Surface</th>
<th></th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>TS</td>
<td>H1</td>
<td>H2</td>
<td>H3</td>
<td>H4</td>
<td>H5</td>
</tr>
<tr>
<td>$\vec{v}_{\text{max}_\text{surface}}$ (m s$^{-1}$)</td>
<td>25.49</td>
<td>39.33</td>
<td>45.91</td>
<td>55.23</td>
<td>61.76</td>
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<td>$r_{\text{max}_\text{surface}}$ (km)</td>
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<td>64.67</td>
<td>32.79</td>
<td>29.99</td>
<td>37.48</td>
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<tr>
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<td>2.03</td>
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<td>12.05</td>
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<td>H2</td>
<td>H3</td>
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<td>H5</td>
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<td>925</td>
<td>915</td>
<td>908</td>
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<td>Std of $v_{\text{max}_\text{lower}}$ (m s$^{-1}$)</td>
<td>2.19</td>
<td>3.54</td>
<td>5.95</td>
<td>4.55</td>
<td>3.30</td>
<td>1.49</td>
</tr>
</tbody>
</table>
Figure 4.1: The radial-vertical profiles of (a) tangential wind (m s\(^{-1}\)), (b) relative humidity (%), (c) temperature (K), (d) temperature anomaly (K), (e) mixing ratio (g kg\(^{-1}\)), and (f) mixing ratio anomaly (g kg\(^{-1}\)) for category H5.
Figure 4.2: Same as Figure 4.1, but for hurricane category 4.
Figure 4.3: Same as Figure 4.1, but for hurricane category 3.
Figure 4.4: Same as Figure 4.1, but for hurricane category 2.
Figure 4.5: Same as Figure 4.1, but for hurricane category 1.
Figure 4.6: Same as Figure 4.1, but for tropical storm.
Figure 4.7: The radial profiles of temperature anomaly (K) at 875 hPa, 900 hPa, and 925 hPa of different TC categories.
CHAPTER FIVE

MAJOR DEFICIENCY OF MATHUR VORTEX IN REFERENCE OF DROPSONDE COMPOSITE

In the section, we compare the radial-vertical profiles of wind and thermal structures of dropsonde composite with those of constructed Mathur vortices for different TC categories. The major deficiencies of Mathur vortices against the dropsonde composite of TCs are examined.

5.1 Tangential Wind

The radial-vertical profiles of observed and constructed tangential wind of different TC categories are presented in Fig. 5.1. Generally, the most notably different feature among tangential wind radial-vertical profiles between dropsonde composites and Mathur vortices is the vertical location of maximum. For the observed one, it roughly locates at about 850-950 hPa; while for constructed one, it only exists at surface. That means the empirical vertical structure function which extends the constructed surface wind at 1000 hPa to two-dimensional wind could not well capture the actual distribution of wind in the boundary layer. Mathur vortices also do not have the calm wind inside the storm core as in the dropsonde observations. In addition, the horizontal location of maximum tangential wind seems more located at \( r_e = 1 \), indicative of a smaller eye size for Mathur vortices. The small deviation from RMW is mainly due to the error exist in the construction of surface wind profile.

After examining the respective differences between the radial-vertical profiles of observed and constructed tangential wind for each TC category in detail, some discrepancies are illustrated in the following. First, the tangential winds from Mathur vortices only have one
maximum, while there exist two wind maxima in the vertical with the magnitudes decrease sharply upward from dropsonde composite of category H2-H5. The upper-level maximum is generated partly by vertical advection of angular momentum and partly by latent-heat-induced acceleration in the eyewall (Liu, 1997). Second, the axis of maximum tangential wind of a Mathur vortices do not tilt, while it slopes outward with height for dropsonde composites. Third, Mathur vortices have a weaker vertically decreasing profile in the lower troposphere, which is particularly true for a stronger hurricane (i.e. H3-H5).

5.2 Temperature

The radial-vertical profiles of observed and constructed temperature of different TC categories are presented in Fig. 5.2. None of Mathur vortices have a cold ring outside the warm core near the boundary layer. Also Mathur vortices do not have a reasonable radial gradient of the temperature profile within RMW. For stronger storms (i.e. H3-H5), the relative magnitude of horizontal gradient of temperature inside the RMW is much larger for Mathur vortices in comparison with those from dropsonde composites. That means the Mathur vortices overestimate the temperature of inner core region, manifesting a higher and narrower protuberance. Such distributions of temperature of Mathur vortices will cause the error in the magnitude of upper warm core. For weaker storms (i.e. TS, and H1-H2), the situation is opposite.

5.3 Temperature Anomaly

The radial-vertical profiles of observed and constructed temperature anomaly of different TC categories are presented in Fig. 5.3. Generally, the pattern, location, and intensity of warm core are consistent with the rapid decreasing of tangential wind in the vertical which is shown in
The main deficiency of Mathur vortices is that the horizontal extension of the whole warm anomaly region seems constant in diameter with height, even though the radial size of the maximum magnitude of warm anomaly increases with height. This constant horizontal extension of positive temperature anomaly with height is consistent with the non-tilting axis of maximum tangential wind in Mathur vortices (Fig. 5.1). In addition, we find the intensity of warm cores near RMW in the lower troposphere from Mathur vortices is stronger than those from dropsonde observation for all categories. It is indicated that Mathur vortices cannot represent the net cooling (~2 K) below the melting level outside the eyewall. In the upper level (near 700 hPa), the radial temperature gradient of Mathur vortices is larger than that of dropsonde observations, with 1-2 K warmer for category H1-H5 cases (because of lacking of the observations above 700 hPa, here we only discuss the pattern below 700 hPa). While the warm anomaly for category TS case is underestimated.

### 5.4 Mixing Ratio

The radial-vertical profiles of observed and constructed mixing ratio of different TC categories are presented in Fig. 5.4. The distribution of mixing ratio has the pattern that is similar to temperature fields (Fig. 5.2). Compared with dropsonde observations, two noticeable differences could be found in the Mathur vortices. One is the dramatic large increasing rate of mixing ratio in storm center. Another is the smoothly increasing profile of water vapor content toward the center. These two discrepancies are obvious due to the constructed error in the vortex initialization.

Taking a further look of profiles of observed and constructed mixing ratio, the respective differences for each TC category are distinct. The Mathur vortices overestimate the mixing ratio
both in the upper center and the boundary layer. These regions are too moisture compared to the real situation. The constructed mixing ratio field intensifies too fast as the storms become stronger. In particularly, for stronger storms (i.e. H2-H5), this sharp moisture protuberance is more apparent in the center, and the overestimation nearly covers the whole lower troposphere.

5.5 Mixing Ratio Anomaly

Regard to the moisture core at the center, Fig. 5.5 presents the radial-vertical profiles of observed and constructed mixing ratio anomaly of different TC categories. The most significant difference of mixing ratio anomaly fields between dropsonde composites and Mathur vortices is the vertical location of the water vapor core. The pattern, intensity and location of water vapor core from Mathur vortices are always correspond to that of warm core. The moisture core of Mathur vortices clearly moves upward as the storm intensifies from TS to H5, without encompassing the effects of adiabatic descending in the center. Furthermore, the horizontal extension of the whole region of positive water vapor anomaly seems constant in diameter with height for Mathur vortices due to the non-tilting axis of maximum tangential wind, while it tends to increase with height for dropsonde observation. Mathur vortices neither can represent the net dry (2-3 g kg$^{-1}$) related to the downward motion outside the eyewall.

Examining the case-to-case differences between radial-vertical profiles of observed and constructed mixing ratio anomaly for each TC category. Mathur vortices overestimate the mixing ratio anomaly in upper center for category H1-H5 cases, while it underestimates the moisture anomaly for TS case.
5.6 Relative Humidity

The radial-vertical profiles of observed and constructed relative humidity of different TC categories are presented in Figure 5.6. The main deficiencies of the moisture content provided by the Mathur vortices appears is systematically wetter than dropsonde observations at upper levels, with high relative humidity extends to mid-troposphere. However, for dropsonde observations, the relative moist troposphere is restricted below about 800 hPa with maximum located in the lower center. It is evidently that the error assumption of saturation, with relative humidity of 100% in the storm center, attributes to the false larger vertical extension of high relative humidity in Mathur vortices. Due to above difference, the Mathur vortices could not characterize the inversion in the core region, which is located at 700 hPa in the eye.

It is of interest to examine the differences of relative humidity between dropsonde observations and Mathur vortices for different TC categories, since they are have dramatic differences in the temperature and mixing ratio fields. Mathur vortices significantly overestimates the moisture in the upper core for category H4 and H5 cases, since there is an obvious decreasing of relative humidity in the dropsonde observations for stronger storms. The dry feature in the mid-troposphere from dropsonde observations is related to the intense subsidence in the core, indicative of the presence of warm core.
Figure 5.1: The radial-vertical profiles of tangential wind (m s\(^{-1}\)) of TCs of different categories for (a1-a6) dropsonde observations, (b1-b6) Mathur vortices, and (c1-c6) the differences (middle panels minus left panels).
Figure 5.1: - continued.
Figure 5.2: The radial-vertical profiles of temperature (K) of TCs of different categories for (a1-a6) dropsonde observations, (b1-b6) Mathur vortices, and (c1-c6) the differences (middle panels minus left panels).
Figure 5.2 - continued.
Figure 5.3: The radial-vertical profiles of temperature anomaly (K) of TCs of different categories for (a1-a6) dropsonde observations, (b1-b6) Mathur vortices, and (c1-c6) the differences (middle panels minus left panels).
Figure 5.3 - continued.
Figure 5.4: The radial-vertical profiles of mixing ratio (g kg$^{-1}$) of TCs of different categories for (a1-a6) dropsonde observations, (b1-b6) Mathur vortices, and (c1-c6) the differences (middle panels minus left panels).
Figure 5.4 - continued.
Figure 5.5: The radial-vertical profiles of mixing ratio anomaly (g kg\(^{-1}\)) of TCs of different categories for (a1-a6) dropsonde observations, (b1-b6) Mathur vortices, and (c1-c6) the differences (middle panels minus left panels).
Figure 5.5 - continued.
Figure 5.6: The radial-vertical profiles of relative humidity (%) of TCs of different categories for (a1-a6) dropsonde observations, (b1-b6) Mathur vortices, and (c1-c6) the differences (middle panels minus left panels).
Figure 5.6 - continued.
CHAPTER SIX

SUMMARY AND CONCLUSIONS

All operational numerical forecasts for TCs require an accurate representation of the initial vortex. However, the key problem that remains for TC initialization is the lack of observation, especially in the core region and boundary layer. Since 1997, GPS-based dropsonde has begun in operation, measuring vertical profiles of wind, temperature, and humidity between flight level and sea surface with a high vertical resolution. This study mainly focuses on applying dropsonde observations to understand hurricane core structure both in the boundary and lower troposphere, as well as its potential role for TC forecasts initialization.

First part of this study considers 3769 GPS dropsonde data within and round 35 named TCs over the tropical Atlantic basin from 1996 to 2010 to study the dynamical and thermodynamic structure of TCs of different categories. After pairing these dropsonde with available TC parameters from NHC, only 1149 dropsonde profiles are considered (the remaining dropsonde profiles are not considered mainly because the lack of a complete set of hurricane parameter records at the dropsonde deploying time or the location of dropsonde is far away from the storm center, or the lack of observations of all variables in a dropsonde). The radial-vertical profiles of axisymmetric low-level wind and thermal structures of TCs for different categories are obtained in both actual radial distance and the normalized radial distance (by the RMW). The radial distribution of these dropsonde profiles along the normalized radial distance has a more uniform spread than that along the actual radial distance. Also the composite made using the normalized radial distance would automatically ensure there is only one maximum wind core in the composite radial-vertical profile. Therefore, we choose to present the results obtained using the normalized radial distance only. The dynamical and thermodynamic characteristics and
consistency among these fields, as well as the variability between weak and strong storms are examined.

We examine the radial-vertical profiles of low-level tangential wind, temperature, temperature anomaly, mixing ratio, mixing ratio anomaly, and relative humidity of TCs of different categories. We find the dynamical and thermodynamic variables are consistent with each other. The key findings of common features of the dropsonde composites for all categories are: (i) all TCs have the maximum tangential wind within 1 km above the ground and a distance of 1-2 times of the RMW at the surface; (ii) all TCs have a cold ring surrounding the warm core near the boundary layer at a distance of 1-2 times of the RMW and the cold ring structure gradually diminishes at a higher elevation where the warm core structure prevails along the radial direction; (iii) the existence of such shallow cold ring outside the RMW explains why the maximum tangential wind is within 1 km above the ground and is outside the RMW, as required by the hydrostatic and gradient wind balance relations. (iv) the temperature fields closely follow the mixing ratio fields, which contributes to the uniform distribution of relative humidity in both radial and vertical directions and the nearly saturation in the lower troposphere; (v) the middle troposphere center dry is associated with the rapid decreasing of mixing ratio with height and the presence of warm core.

The followings summarize the main differences of dropsonde composites between categories, besides the speed of the maximum tangential wind and central pressure, (i) The vertical extent of near-saturated moisture air layer inside the core: a weaker TC tends to have a deep layer of the near-saturated moisture air layer whereas a stronger TC has a shallow one; (ii) The intensity and vertical extent of the warm core extending from the upper layer to the lower layer: in general, a stronger TC has a stronger warm core extending downward further into lower
layer and vice versa; (iii) The tilting of the isotach along the out edge of the maximum wind region: The axes of maximum tangential wind tilts outwards below the height of about 1km and tilts inwards above for category TS, H2-H5 cases. The axes of maximum tangential wind are almost straight above 900 hPa for H1 and the magnitude of cold ring at about \( r_c = 1 \) is small for H1. In short, the features of (i) and (ii) are consistent with the fact that a stronger TC tends to have stronger descending motion inside the core. The features of (iii) are related to combined effects of the relative magnitude of both the temperature gradients in the boundary layer and upper layer.

The second part of this study is to identify the main deficiencies of Mathur vortices used in the NCEP’s QLM as initial vortices for TC forecasts by comparing them with the dropsonde-based TC composites of the same intensity. We first constructed Mathur vortices using the NHC’s hurricane parameters that are paired to the dropsonde profiles under the consideration. Secondly, we made the same composites of these Mathur vortices for each category using the normalized radial distance. Finally, we compared the radial-vertical profiles of tangential wind, temperature, mixing ratio, and relative humidity from Mathur vortices and dropsonde composite.

Although the radial-vertical profiles the constructed Mathur vortices of different hurricane intensities “look like” to those from dropsonde observations, there exist many salient deficiencies of Mathur vortices in representing the radial-vertical profiles of TCs of different intensities: (i) Mathur vortices of all categories have the maximum wind at the surface with a much straight axis in the vertical; (ii) none of Mathur vortices have a cold ring outside the warm core near the boundary layer; (iii) Mathur vortices tend to overestimate warm core structure in reference to the horizontal mean temperature profile; (iv) Mathur vortices tend to overestimate the vertical depth of the near-saturated air layer near the boundary layer.
The intensity-based dropsonde composites of TCs advance our understanding of the dynamic and thermal structures of TCs of different intensities along the radial direction in and above the boundary layer. They have several important applications for TC forecasts and research. For example, one could use them to identify the deficiencies in the existing algorithms to construct initial bogus vortices for TC forecasts, such as Mathur vortices as we did in this study. One could also use numerical models to study the transition from one category to another category and to understand what are the dynamical and physical processes that determine the radial-vertical structure of TCs and what cause the changes in the radial-vertical structure of TCs from one category to another.
REFERENCES


BIOGRAPHICAL SKETCH

Yifang Ren grew up in Suzhou, Jiangsu Province, China. Fascinated with weather forecasting, Yifang attended School of Atmospheric Science in the Nanjing University of Information Science and Technology (NUIST) and completed her Bachelor’s degree in June 2008. Then, she transferred to Chinese Academy of Meteorological Sciences (CAMS) to study agrometeorological risk assessment and completed her Master’s degree in 2011.

Yifang started graduate study at Florida State University (FSU) in August 2011 and worked in Dr. Zou’s lab. Under the supervision of Dr. Zou and Dr. Cai, she was focused on her master thesis about the intensity based tropical cyclones structures derived from dropsonde observations. Her research interests include tropical cyclone structures study and numerical model initialization.