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COLLEGE OF ARTS AND SCIENCES

ON DETERMINING THE HURRICANE BOUNDARY LAYER

By

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This thesis is dedicated to my family

who will always stand by me.

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– A.C.P

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LIST OF SYMBOLS AND ACRONYMS

BOMEX – Barbados Oceanographic and Meteorological Experiment

FSU – Florida State University

GPS – global positioning system

HEXOS – Humidity Exchange over the Sea

hPa – hectopascal

HPC – Hydrometeorological Prediction Center

ISU – Iowa State University

JASIN – Joint Air-Sea Interaction Experiment

km – kilometer

LAT – latitude

LON – longitude

m – meter

MM5 - PSU/NCAR mesoscale model

NCEP – National Centers for Environmental Prediction

NOAA - National Oceanic and Atmospheric Administration

NOAH - National Centers for Environmental Prediction [NCEP]-Oregon State University-Air Force Geophysical Laboratory-Hydrometeorological Prediction Center [HPC] model

OSU – Oregon State University

PBL – Planetary Boundary Layer

Ri - Richardson number

Ri_{cr} - critical Richardson number

sst – sea surface temperature

TKE – turbulent kinetic energy

TOGA COARE - The Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment

u_* – friction velocity

U_{10} – wind speed at 10 m

USAF – United States Air Force

UTC – Coordinated Universal Time

Theta_v – Virtual Potential Temperature

WRF - Weather Research and Forecasting Model

θ - potential temperature

θ_s – potential temperature at surface

θ_{sv} – virtual potential temperature at surface

θ_o - air potential temperature at the first model level.

θ_{ov}* - reference virtual potential temperature at the first model level above the surface

θ_s - surface temperature.

θ_v(h)- virtual potential temperature at the model level h (currently 50 meters for the unstable case and first model level, or 10 m, above the surface for the stable case)

ABSTRACT

The hurricane boundary layer thickness as determined through the uniform slab model and varying depth slab model presented by Smith and Vogl (2008) is compared to the Troen and Mahrt (1986) method. Smith and Vogl presented the uniform slab approach from Emanual (1986) and a spatially varying boundary layer thickness based on inertial stability from the gradient wind. The Troen and Mahrt method of diagnosing the boundary layer thickness using the Richardson number is a basis for the Hong and Pan or MRF boundary layer schemes available in many hurricane models including WRF and MM5. .Hurricane Isabel (2003) is analyzed from dropwindsondes and GFDL model output. An additional hurricane, developed in the CM1 without a specified boundary layer formulation, is analyzed for comparing methods in determining the boundary layer thickness. The *in situ* observations did not lead to any conclusive results, however the modeled environments did show patterns in the boundary layer depth which support a spatially varying depth. The inertial stability method and the Troen and Mahrt method of determining the boundary layer thickness differed with depths increasing with increasing radius away from the eyewall for the inertial stability method and depths decreasing with increasing radius away from the eyewall with the Troen and Mahrt method.

CHAPTER 1

INTRODUCTION

The planetary boundary layer (PBL) is the part of the atmosphere in which most direct human interaction occurs. This being the case, the PBL and the associated interactions with the surface and free atmosphere provides a fuzzy or unclear understanding of all the processes which occur for this ever changing layer. Gupta and Ramachandran (1998) stressed the importance of gaining a full picture of the PBL before the PBL can be fully understood. The atmospheric PBL extends from the surface to the beginning of the free atmosphere at a height where turbulent transfers of heat, mass, and momentum become insignificant (Arya 1981). Heat and moisture fluxes and frictional drag directly influence this layer of the atmosphere. The resulting turbulence generates eddies of various sizes. The thickness, depth, or height of the top of the PBL (used interchangeably), as Arya (1981) defines it, also determines the dimensions of the largest eddies. Above the planetary boundary layer, shear stress and heat fluxes are negligible. The BL depth, though it may be defined by multiple methods, is an essential parameter for modeling and predicting atmospheric dispersion. It is also applied to similarity theory due to its influence on mean flow and turbulence structure in the atmosphere. The principles behind the PBL processes over land are often taken to represent the PBL processes over water, in a marine environment, but the theory is modified slightly to take into account the different surface properties. While observations over land are seemingly plentiful compared to those in the marine environment, the characteristics of land and sea are quite different. As a result, great effort has gone into developing theory appropriate for the PBL in a marine environment. This study looks specifically at the height of the top of the BL in a hurricane and hurricane environment (both will be referred to as hurricane environment unless specifically stated otherwise).

1.1 Defining the Boundary Layer Processes

The height of the lowest inversion in the atmosphere often indicates the BL depth. Similarly, a region where the thermodynamic properties of atmospheric sinking and turbulent mixing are in balance defines the BL depth (Augstein et al. 1973). Augstein et al. also noted this was about the level of maximum winds, if one occurs near the surface as opposed to jet stream level winds. While the BL depth varies locally and regionally, efforts have been made to understand this transforming layer both in storm-free and storm environments. Realistic parameterization of the attributes and processes in the boundary layer allow for a broader approach for understanding the structure and changes of the PBL. These efforts have spanned theoretical, *in situ* data sources, modeling, and remote sensing. The Barbados Oceanographic and Meteorological Experiment (BOMEX) studied the properties of the tropical boundary layer. The BOMEX mission found the BL depth was near the top of the friction layer to be about 130 hPa above a 500 km^2 surface of a tropical ocean in a storm-free environment (Holland and Rasmusson 1973). Nicholls (1985) described MABL characteristics from observations during the joint air-sea interaction experiment (JASIN). The Humidity Exchange over the sea (HEXOS) studied air-sea fluxes, water vapor, momentum, and latent and sensible heat fluxes important to the boundary layer (Katsaros et at. 1987). The Tropical Oceans-Global Atmosphere (TOGA) program studied the atmospheric circulation and sea surface temperature (SST) variations in the ocean (Halpern 1996). TOGA COARE (the Coupled Ocean—Atmosphere Response Experiment) studies sst and air-sea interactions. (Webster and Lukas 1992). Additional research continues to add understanding of the BL processes in a marine environment (Hendon and Glick 1997, Folkins and Braun 2003). Samelson et al. (2006) tried to understand the effect the intensification changes of turbulent mixing on near-surface winds by using satellite observations of SST and modeling.

A more complete understanding of the BL attributes in a hurricane environment is no less pursued. Continuing efforts explore many of the parameters in hurricanes such as the drag coefficient for higher wind speeds where observations are few (Powell et al 2003, French et al. 2007). Drennan et al. (2007) extended the latent heat flux associated with wind speed range and the humidity fluxes to over 50% greater than the previously thought values due to the effects of sea-spray. Moisture fluxes of the boundary layer potentially cause variations in symmetry especially in the inner core region of tropical cyclones (Van Sang et al. 2008). Newly available instrumentation such as GPS dropsondes suggest values of the drag coefficient and roughness lengths may make potential changes to u_* and U_{10}, where u_* is the frictional velocity and U_{10} is the 10 m wind (Kepert 2008). Foster (2005) suggested the hurricane boundary layer has structure and will support rolls implying a further need to develop parameterizations for roll modification of turbulent fluxes. A basis for comparison seems to require a basic understanding and definition of the boundary layer structure.

Comparisons and understandings of the hurricane BL provide grounds for disputations, especially since until recently observations of the BL structure have been less frequent in tropical storms. The hurricane BL interfaces with the ocean surface but as ocean roughness lengths increase and the air sea boundary becomes difficult to distinguish. Between the ocean surface and the top of the BL surface interactions are not negligible; fluxes and turbulence matter. The top of the BL interfaces with the free-atmosphere where the BL these processes are no longer the dominant forcings. The properties at this interface represent the resultant effects of the BL processes. This interface represents the area of exchange of fluxes (including, for example, entrainment) from the boundary layer to the free-atmosphere and back. By establishing the interface, the dominant processes both above and below may be better understood. After extensive model testing, Braun and Tao (2000) described the PBL structure of a hurricane as being important in models and significant to hurricane sensitivity.

1.2 Characterizing and Defining the Boundary Layer Thickness in a Hurricane Environment

With the extension of BL research into the hurricane environment, efforts have been made to distinguish and characterize this layer. Early in hurricane research, Smith (1968) used eddy diffusivity and the Monin-Obukov length as a basis for the BL thickness formulations. Smith noted that the thickness of the BL decreases with decreasing radius from about 300 km then farther out varies little with radius for three of his modeled conditions. In the other case, the BL thickness increased with decreasing radius over the inner 300 km by increasing eddy viscosity inward by a factor of two between 1000 km and 40 km. Smith also noted the top of the inflow layer was used at the top of the BL. The thermodynamic approach by Augstein et al. (1973) looked for the lowest inversion or maximum winds. The lifting condensation level (LCL) was also used as a proxy (Powell 1980). Powell also described the level of maximum radial winds as the top of the boundary layer. The Ekman layer was proposed an acceptable proxy as diurnal effects are weak in the hurricane environment (Blackadar 1979, Nichols 1985, Kepert 2001). The BL has also been represented by turbulent kinetic energy (TKE) and is used in other hurricane modeling (Krishnamurti et al. 2008). The BL thickness is typically found in these models as the level where TKE vanishes with height or as the level the tangential wind equals the gradient wind.

Some assumptions were made to simplify the research in modeling. A slab or constant boundary layer height was assumed to represent the top of the BL (Shapiro 1983, Emanuel 1986; hereafter E86, Smith 2003; hereafter S03). E86's hurricane theory based on the Carnot cycle and gradient wind balance suggested that the boundary layer height is constant (spatially) for steady state developed hurricanes. He also proposed that air follows constant angular momentum lines through the hurricane environment giving a situation of lifting air in the BL to the top of the BL where it is neutrally buoyant following the path of constant angular momentum. The approach offered an elegantly simple method of describing and modeling a hurricane and closed the system.

Some of the assumptions made in E86 were violated over portions of the domain such as the regions near the eye (Kepert 2001, S03). S03 developed a linearized steady-state hurricane model to address some of these violations such as supergradient wind. This model included mixing by shallow convection. The same basic uniform slab was used for the BL thickness. Later Smith and Vogl (2008; hereafter SV08) made some corrections to the model which presented cause to reanalyze the previously assumed BL thickness. The uniform slab thickness was changed to note changing characteristics of the BL processes; thickness values of 550 m to 850 m presented as samples. They noted a sensitivity in the solution to the BL thickness chosen. The values of the tangential or gradient wind fields changed with these changing levels as well as the radius of maximum radial and tangential winds. These values depended on the thickness prescribed. Additionally, a step was taken to provide an analysis of a radially varying BL thickness. By replacing the uniform BL thickness with varying surface (in space not time), further insight was gained on boundary layer processes. The BL depth was given to decrease with decreasing radius. Following Eliassen and Lystad (1977) and Kepert (2001) the depth decreased at a rate inversely proportional to the square root of the inertial stability (see SV08 figure 6). As a result of this new varying slab, they noted the maximum vertical velocity was reduced at the top of the BL which agreed better with previous research. The model was also compared with the work done by Montgomery et al. (2006) and Bell and Montgomery (2008) on the observational data from hurricane Isabel (2003). They noted an agreement in the radial pattern of equivalent potential temperature (θ_e). The 550 m and 850 m surfaces showed increasing θ_e with decreasing radius as similar wind intensities to that of Isabel.

Using the improved model described by SV08, Smith et al. (2008; hereafter S08) formally offered a rebuttal against Emanuel's constant boundary layer height assumption for regions near the center of the storm arguing that gradient wind balance assumption required for constant BL thickness is violated and does not apply. Vogl and Smith (2009; hereafter VS09) later noted the BL thickness increased with increasing radius until about 300 km away from the center of rotation, then the BL depth decreased further away finding the BL typically less than 1 km deep.

Some of the conclusions reached by SV08 included that the BL depth decreases as inertial stability increases and that at larger radius the turbulence and subsidence aloft determine the BL depth. The latter of these two conclusions is similar to one method of diagnosing the BL thickness as presented by Troen and Mahrt (1986; hereafter TM86). The method described by TM86 uses a Richardson number (Ri) criterion to determine the top of the BL. This method is used in a variety of models including the WRF (Wang et al. 2008) and the MM5 (Grell et al. 1995) available as the MRF boundary layer scheme developed by Hong and Pan (1996). The scheme is a nonlocal diffusion concept which was eventually was a basis for the NOAH model (Mitchell 2005). The TM86 model allows for a simple diagnosis of BL thickness analyzing the ratio of shear to stability in order to establish the level of the BL. This allows an independent analysis of BL depth from *in situ* and from model data which do not implement the Ri criterion. The advantage of this diagnosis of the BL thickness over the prescribed BL thickness is the top of the BL is allowed to vary with changes in the storm environment, based upon changes in buoyancy and/or shear.

The question then becomes, is the SV08 description of the radially varying BL height for use in their linear model supported or confirmed by TM86's calculation of the boundary layer height based on the Richardson number formulation criteria over the entire domain? It is hypothesized that the diagnosed BL thickness varies radially with distance but the TM86 Richardson number criteria dependence on shear and inertial stability will change the varying structure of the radial BL depth in a more realistic way, and one that is easy to diagnose from existing model parameters or variables.

This study will use both *in situ* and model data to analyze the depth of the BL. First, details of the Ri criterion are given, followed by data sources in Chapter 2. Then the diagnosed results are presented and discussed in Chapter 3. Finally, a summary and conclusions are discussed in Chapter 4.

Chapter 2

UTILIZING THE OSU/FSU 1D PBL MODEL

The OSU/FSU 1D PBL model is a diagnostic model that evaluates, as opposed to predicting, the height of the PBL based on an evolution of temperature, humidity and momentum. The model is based on the TM86 scheme. The relatively simple diagnosis of h makes for an easy interpretation of the BL thickness. The basic equations and uses for diagnosing h in the model are first discussed in this chapter. This will be followed by the required data source for initializing the model in this study including quality control (QC) procedures for both *in situ* and model sources.

2.1 The OSU/FSU 1D PBL Model

The OSU/FSU 1D PBL model uses the TM86 method of calculating the PBL based on the bulk Richardson number, a dimensionless quantity that expresses the ratio of buoyancy and shear. Linear models generally assume a stable (unstable) layer exists if the value is greater (less) than 0.25. Non-linear models assumes a stable (unstable) layer if the value is greater (less) than 1, with a transitional approach used when $0.25 \leq Ri \leq 1$. The version of the model used here assumes a critical value of 0.25.

For the original optimization, the model input requirements include weak synoptic/mesoscale forcing, input of the surface lower boundary, and the initial boundary layer cloud cover. The model diagnoses the height of the BL. The model requires a vertical profile including pressure levels, height, temperature, mixing ratio, and wind speed and direction to the initialization of the model. This allows for the calculation of specific humidity and the virtual potential temperature.

The profile is interpolated onto a sigma grid from the input sounding. The height of the BL is then calculated using

$$h = Ri_{cr} \frac{\theta_{ov} |V(h)|^2}{g(\theta_v(h) - \theta_{ov}^*)},$$

Where Ri_{cr} is the critical Richardson number, θ_{ov} is the reference virtual potential temperature at the first model level above the surface, θ_v(h)is the virtual potential temperature at the model level h (currently 50 meters for the unstable case and first model level, or 10 m, above the surface for the stable case), and horizontal wind velocity is represented by V_h (figure 2.1).

The model defines the boundary layer once layer stability becomes supercritical ($Ri>Ri_c$). The model ignores a secondary or possibly more prominent boundary layer above a lower layer which meets the criteria. Occasionally the criteria fail to be met and the boundary layer remains unresolved. This BL diagnostic tool was originally developed to be used over land with weak synoptic/mesoscale forcings (TM86). Since the BL scheme has been extended and used by others over water, the simple use of the diagnosed height of the BL lends credibility for exploring this parameter within the context of the hurricane environment.

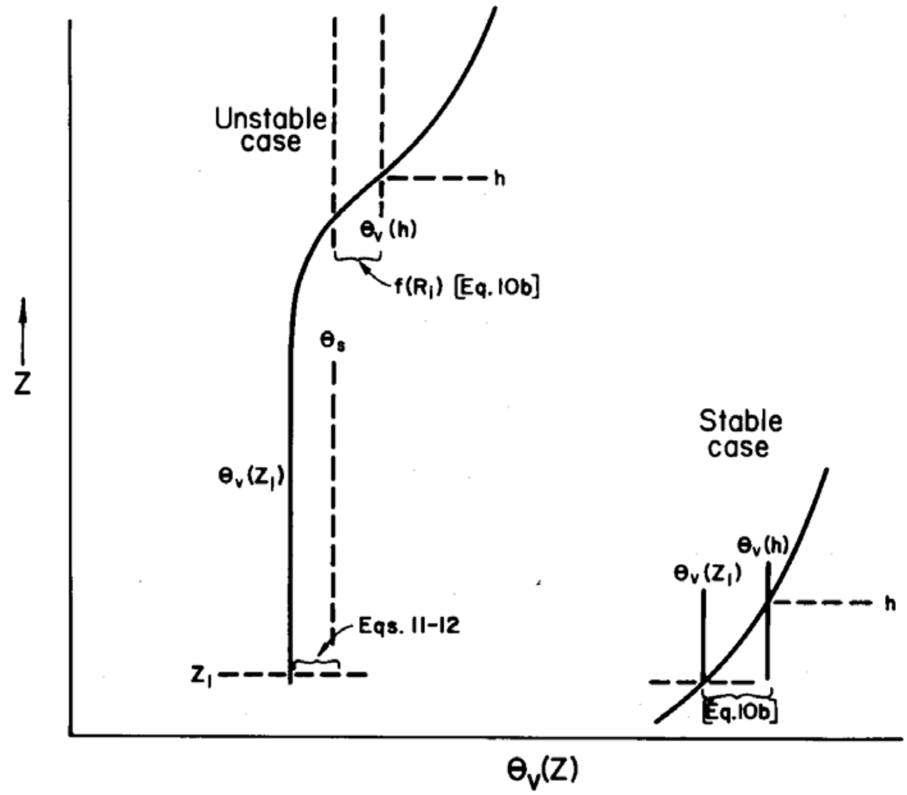

Figure 2.1 from TM86. Geometric sketch of the boundary layer depth relationship to the profile of potential temperature above the surface layer (solid profile). For the unstable case, the first vertical broken line to the right of the profile indicates the potential temperature after enhancement due to the temperature excess associated with surface heating. The vertical broken line on the right indicates the potential temperature at the boundary layer top after deepening due to shear-generated mixing as formulated in terms of modified bulk Richardson number. The latter mechanism completely determines the depth of the stable boundary layer.

2.2 Smith and Vogl Boundary Layer Depth Scale

The formulation Smith and Vogl (2008) use to calculate the BL depth scale, δ, is based on constant eddy diffusivity, the gradient wind (v_g), and the Coreolis force. The depth scale is a function of the inertial stability parameter defined by I^2 (VS09). With an eddy diffusivity constant of $K=10\ m^2s^{-1}$ and a Coreolis force of $f=5x10^{-5}\ s^{-1}$ the BL depth is found with the following equations:

$$I^2 = \xi_g \varsigma_{ag} \, ,$$

$$\xi_g = \frac{2v_g}{r} + f \, ,$$

$$\varsigma_{ag} = \frac{dv_g}{dr} + \frac{v_g}{r} + f \, , \text{ and}$$

$$\delta = \sqrt{\frac{2K}{I}} \, .$$

The gradient wind is taken at three different uniform levels in a modeled hurricane environment for comparison.

2.3 Data Sources and Model Initialization

This analysis uses Hurricane Isabel from 2003 because of the highly axisymmetric nature, it maintained a category 3 or stronger status for approximately 6 days, and did not make landfall during the period of interest. Hurricane Isabel was sampled with GPS dropwindsondes and 6 hour GFDL model archives were available for the period of interest. Data sources are taken for *in situ* measurements from the dropwindsondes and for model from the GFDL initialized and 60 hour model runs. Additionally the CM1 was used as an independent model with a hurricane of similar strength as a model data source.

2.3.1 *In Situ* Data

Dropwindsondes are a common way of obtaining sample profiles from hurricanes. In more recent years, the GPS dropwindsonde has been used in obtaining these profiles. The profiles vary in range due to the flight level at the time of release. These soundings provide a higher resolution of up to 2 Hz and improved tracking which allows for more accurate height levels and wind speeds based on translation (Hock and Franklin 1999). The use of this *in situ* data source allows for understanding of actual processes in the hurricanes and improvements on parameterization given the context of actual sampled profile (Powell et al. 2003). These soundings are reported in various ways including through the WMO as recorded into the HRD Spline Analysis (HSA) format.

HSA

The HSA, real-time processed data, is also comprised of mandatory and significant levels. Missing data are flagged. The soundings are reported with the initial time stamp to the minute. Some QC checks may have been performed before transmission. Only reported soundings with at least 6 reported levels that did not contain flagged data were used. For the QC, only reported soundings with at least 6 reported levels that did not contain flagged data were used. Additionally an approximate hydrostatic check was made before the diagnosis to verify levels. The processed HSA soundings are available through HRD data archives (available online at http://www.aoml.noaa.gov/hrd/data_sub/dropsonde.html).

2.3.2 Model data

In order to get a basis for comparison, GFDL model vertical profiles of the simulated Hurricane Isabel are used for analysis. By diagnosing the analyzed model in addition to the in situ data, the hurricane boundary layer thickness as described by the models used in E86 and VS09 can be compared to the diagnosed values from the OSU/FSU 1D PBL model. The GFDL model is used at the initialized time and the 60 hour forecast in order to observe patterns in both of the BL thicknesses. In addition, a hurricane developed in the CM1 is analyzed to provide an independent look into the BL thickness of a hurricane.

GFDL – initialized

The GFDL model is initialized with a GFS data grid with the hurricane vortex replaced by a separate vortex made to match the last reported conditions. The data from the vortex is extracted on the 1/3 degree grid resolution from the center of rotation and as appropriate in the vertical.

The only QC performed on the data is the same QC procedure which was used for level verification with the HSA data. Four radial slices were taken from the center of the model by increasing and decreasing latitude and longitude while holding the other fixed. Soundings were taken in the vertical with no tilting for each radial data point out to 550 km.

GFDL – 60 hour

The GFDL model which was initialized as previously described is allowed to run for 60 hours. The BL scheme is the level 2.5 Mellor-Yamada turbulence closure, based in TKE. The data from the vortex is extracted on the 1/3 degree grid resolution from the center of rotation and as appropriate in the vertical. This vortex differs from the initialized as it has had an opportunity to interact with the environment. The only QC performed on the data is the same QC procedure which was used for level verification with the HSA data. Four radial slices were taken from the center of the model by increasing and decreasing latitude and longitude while holding the other fixed. Soundings were taken in the vertical with no tilting for each radial data point out to 550 km.

CM1

The CM1 model (Bryan and Fritsch 2002) was initialized with a baroclinic vortex (Rotunno and Emanuel 1987) on an f-plane. The background state is the Jordan mean hurricane season sounding (Jordan 1958) with no additional background mean flow. The grid spacing was a stretched grid with horizontal resolution varying from 2 km to 12 km in the horizontal and from 25 m to 500 m in the vertical with the 25 m resolution in the lowest 2 km. The model domain is 558 by 558 by 100 grid points (2376 km by 2376 km by 23.9 km), with the inner 306 grid points (612 km) in both directions at the highest resolution. Rayleigh damping layers occupy the outer 100 km on each side of the domain and the top 2 km of the domain to absorb gravity waves. The external horizontal boundaries beyond that are periodic in nature. The sea surface temperatures are held at a constant of 29 deg C with no turbulent ocean features.

The model was run using the Bryan and Fritsch (2002) conservative equation set and using the

NASA-Goddard LFO microphysics scheme (Tao and Simpson 1993). A fifth-order advection scheme was used; therefore, no additional diffusion was required. Of the multiple pressure solvers available in the CM1, the vertically-implicit compressible pressure solver was used since $dz \ll \{dx,dy\}$. Since the model was uses an Arakawa E-grid, the wind output was interpolated to the half-grid points of scalars for easier data manipulation.

The CM1 has no specified BL scheme but does include some eddy diffusivity profile parameterization. Simple moisture and heat fluxes off the surface are handled explicitly by the TKE scheme. The surface heat and momentum flux coefficients used are those given by Donelan et al. (2004) and Drennan et al (2007). The only QC performed on the data is the same QC procedure which was used for level verification with the HSA data. Four radial slices were taken for model the analysis by increasing and decreasing latitude and longitude while holding the other fixed. Soundings were taken in the vertical with no tilting for each radial data point out to 900 km.

CHAPTER 3

DIAGNOSING BOUNDARY LAYER THICKNESS

By using the OSU/FSU 1D PBL model to diagnose the BL depth based on the TM86 scheme, a framework can be established to determine if the Ri criterion for determining BL thickness supports the BL thickness as presented by SV08 which presented both uniform slab and prescribed spatially varying depth surfaces. In many forecast models, and in the GFDL model and CM1 models in particular used here – BL height is not an output diagnostic variable – so it must be calculated somehow. Since formulations based on the TM86 scheme are so widely used in mesoscale, operational NWP, and climate models, we are assessing its utility here for the tropical storm environment.

In order to provide an adequate BL thickness comparison, both *in situ* observations and GDFL model are used for hurricane Isabel, the hurricane discussed in section 5.2 of SV08. Additionally, a strong category 3 hurricane developed in the CM1 model is used for an independent comparison. The quality control criteria mentioned in chapter 2 are applied. The processed *in situ* observations are first analyzed for dropwindsondes from the HSA format. Then, the GFDL model initialization and 60 hour forecast are analyzed. The CM1 hurricane is presented using the Ri criterion followed by an analysis using the gradient wind as a BL thickness proxy as used in SV08.

3.1 *In Situ* Diagnosed Boundary Layer Thickness

The observations taken from Hurricane Isabel include 230 usable dropwindsondes from the HSA format. The time for the study starts 12 Sept 2003 at 17 UTC and ends at 18 Sept 2003 at 12

UTC before landfall (Figure 3.1). Hurricane Isabel remained at least a category 2 hurricane during this time period and displayed an axisymmetric nature. The annular nature of the storm is used to help describe the radial profile with the *in situ* observations. The assumption is made that the vertical profiles of the storm are similar at constant radius. While this is not necessarily a valid assumption, for the purposes of this research it is sufficient. Soundings and boundary layer diagnoses were made from each of the four storm quadrants but did not show notable changes in patterns (not shown here). The storm center is taken from the official 6-hourly best track dataset and linearly interpolated by position and maximum sustained wind to the nearest hour. The effective radial resolution of the distance from the storm center to observed sounding is 11 km (0.1° lat). The potential radial translation of a dropwindsonde is smaller than the radial resolution; the tangential translation is ignored due to the axisymmetric assumption.

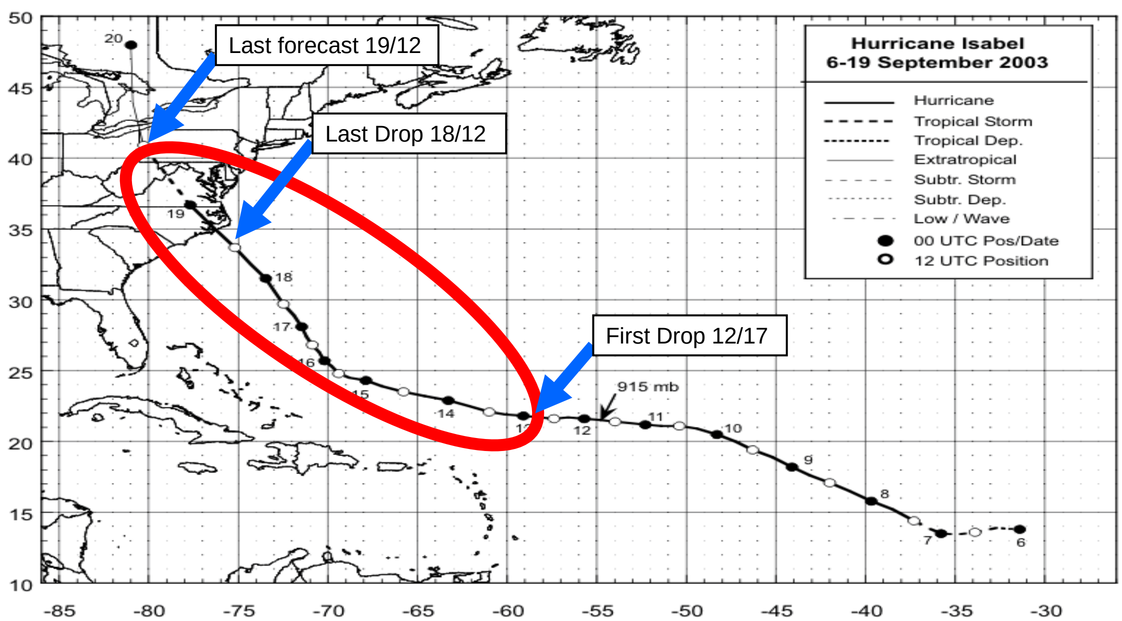

Figure 3.1 Track of Hurricane Isabel and time range of interest (Beven and Cobb 2009). The ellipse shows the region of intense scrutiny during which numerous dropwindsondes were available for examination of the boundary layer structure in the near-hurricane environment.

There are 230 independent dropwindsondes available from the HSA data for incorporation into this study during this time period varying radially from 8 km to 1500 km from the storm center.

All but 6 of the soundings are within 1000 km of the center of rotation. BL thicknesses varied from 35 m to over 2500 m (Figure 3.2). The BL thickness did not appear to have a specific radial structure. Cloud coverage extended radially from about 300 km to 500 km for hurricane Isabel. The BL thicknesses in the nearest 500 km range did not indicate a pattern or constant level as SV08 might indicate. The soundings close to the eyewall varied in BL thickness from 300 m to 1800 m. Under the area of cloud coverage, about 300 km from the center, the median BL thickness is about 1000 km. The vertical resolution of the usable levels from the sampling which passed quality control indicates an additional possible reason for the large range of BL depths. The varying nature of the vertical wind profile and the θ_v profile over time, especially in a hurricane, in the BL based on profile measurements, the distributions of the calculated BL thicknesses are reasonable for *in situ* measurements.

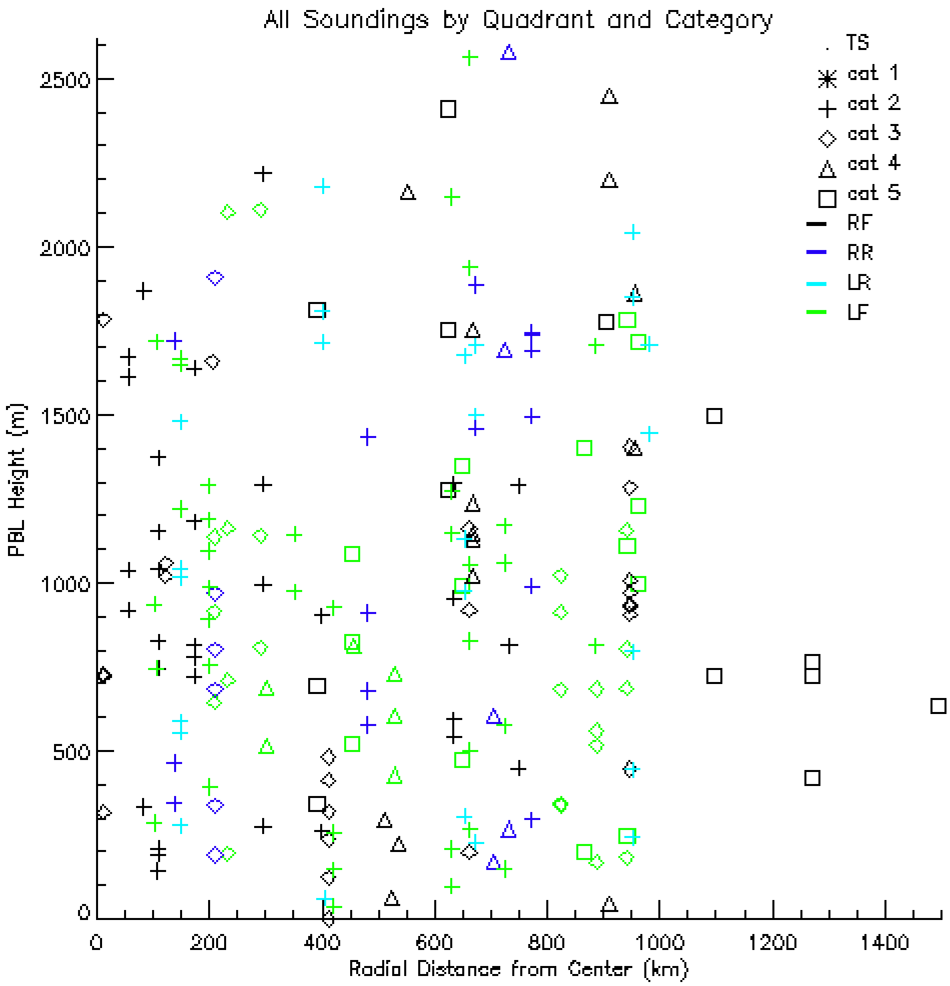

Figure 3.2 BL thicknesses as diagnosed using the Ri criterion for Hurricane Isabel using HSA dropwindsondes. The radial distance from the center of the hurricane in km is on the x axis and the BL thickness in meters (m) is on the vertical. Different symbols represent different storm intensities according to the Saffir-Simpson scale and are as noted in the legend. Color coding is used to indicated the quadrant from which the initial sounding was taken (RF=right front; RR = right rear; LR = left rear; LF = left front).

3.2 GFDL Model Diagnosed Boundary Layer

To further understand the hurricane BL, the BL thickness of the GFDL modeled hurricane Isabel was analyzed. This is done in two parts with initialized data and 60 hour forecasted data providing instantaneous looks into the hurricane structure. The hurricane is tracked and analyzed for the same time as for the *in situ* observations. This provides additional information into the hurricane BL structure in the modeled environment. SV08 prescribed either constant or radially varying surfaces for their model. The diagnosed BL thickness from the GFDL model data provides an intermodal comparison for the structure of the top of the BL.

3.2.1 GFDL Model – Initialized

The GFDL initialized used vertical profiles from the center and at 15 different radial distances in each of the four storm quadrants making up to 61 possible samples out to about 555 km radially from the storm center. These 61 different sounding locations were processed for every 6 hour model runs from 13 September 2003 at 18 UTC through 15 September 2003 at 12 UTC, the time period for Hurricane Isabel. Nearly all of the profiles met the Ri criterion for diagnosing the BL thickness.

A distinct pattern showed up in each of the radial directions. The BL thickness increased with decreasing radius from 555 km to about 74 km where the thickness then decreased rapidly to the center of the hurricane (Figures 3.3 and 3.4). This pattern was repeated through the entire time period of interest. Thickness varied from 500 m to 2500 m over the entire domain. Maximum thicknesses remained near the radius of 100 km and only varied between 2000 m and 2500 m. Different patterns were noted from 300 km to the outer limit suggesting possible hurricane or environment influences in the regions with values ranging from 500 m to 1000 m. Since the initialization vortex is inserted and matched to the environment around the edges in the GFDL model, the patterns noticed beyond 300 km from the storm center likely represent the background model environment instead of the initialized vortex. This is contrary to SV08's varying BL thickness profile in that after the first 100 km the thickness decreases. Only out to about 70 km is the thickness consistently increasing.

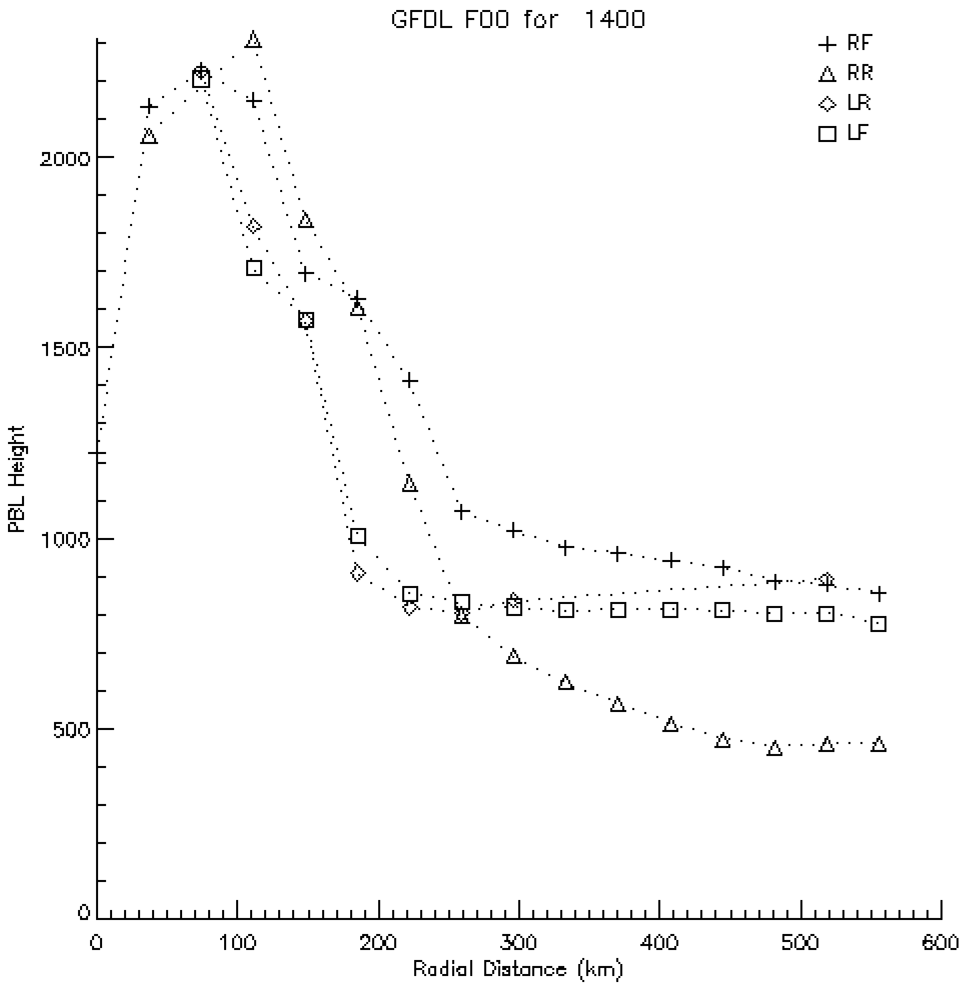

Figure 3.3 BL thicknesses as diagnosed using the Ri criterion for Hurricane Isabel on 14 September 2003 at 00 UTC from the GFDL Model initialization. The radial distance from the center of the hurricane in km is on the x axis and the BL thickness in meters (m) is on the vertical. Different symbols represent the quadrant from which the radial slice was taken (RF=right front; RR = right rear; LR = left rear; LF = left front).

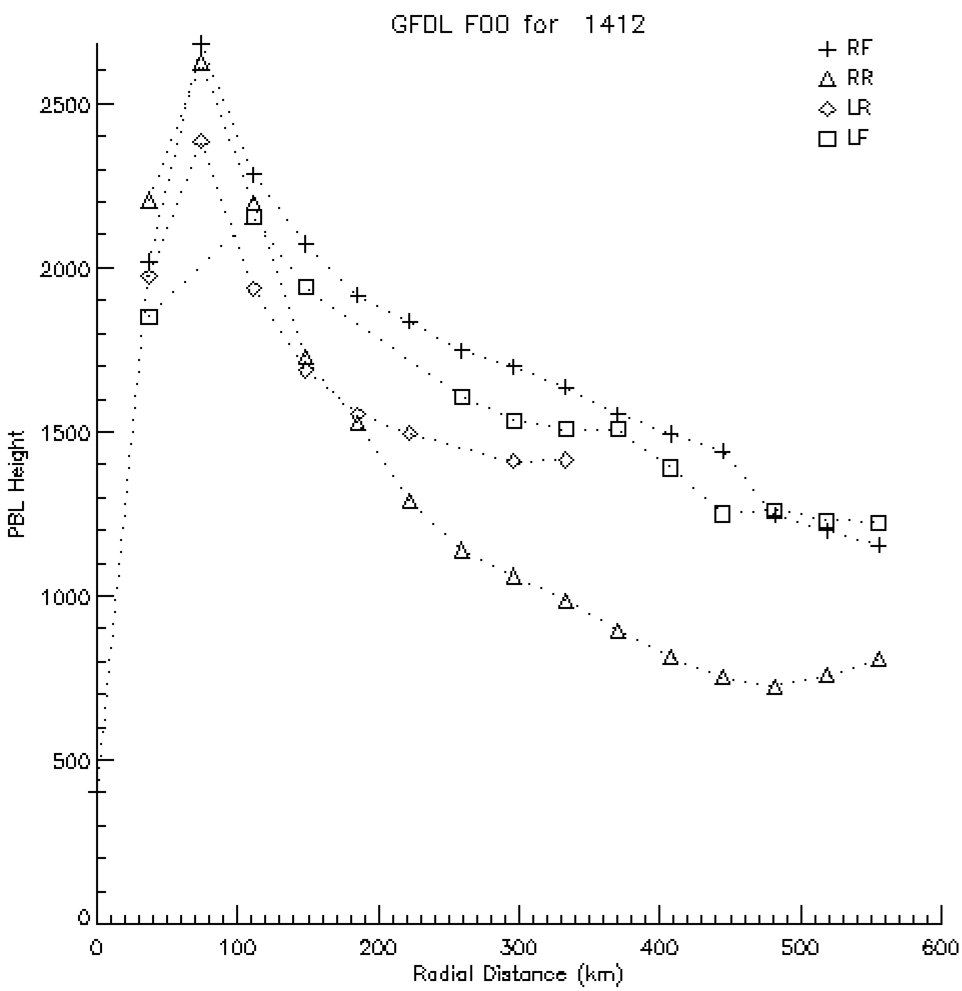

Figure 3.4 As in Figure 3.3, but for 14 September 2003 at 12 UTC.

3.2.2 GFDL Model – 60 hours

The same storm centered radially define grid as was used for the GFDL initialized was used for the 60 hour forecast. These 61 different sounding locations were processed for every 6 hour model runs from 11 September 2003 at 12 UTC, the same corresponding forecast time as the initialized time. Over half of the profiles did not meet the Ri criterion for diagnosing h. This is likely on account of the thermodynamic structure not having a stable layer to overcome the shear. The 12 September 2003 at 00 UTC 60 hour forecast (Figure 3.5), the same time as the initialized 14 September 2003 at 12 UTC, shows the comparative difference in the model's forecasted BL thickness. The forecasted storm had relatively little variation in the thickness with most values at or below 600 m. No strong patterns or trends as shown with the initialized model data are present with the 60 hour forecast. Though a hurricane was still present in the 60 hour forecast, the vortex perturbation of h as seen in the initialized model data was not visible. The GFDL model is assumed to have assimilated this vortex into the background environment which lowered the BL thickness from the 500 m to 1000 m range from the initialized to the 50 m to 600 m range for the 60 hour forecast. This is much more consistent with a slab model uniform thickness. The 60 hour forecasted hurricane did not match the intensity or θ_v profile of the initialized vortex for the same time making the 60 hour forecasted storm much different than the initialized vortex and environment in terms of diagnosed BL thicknesses.

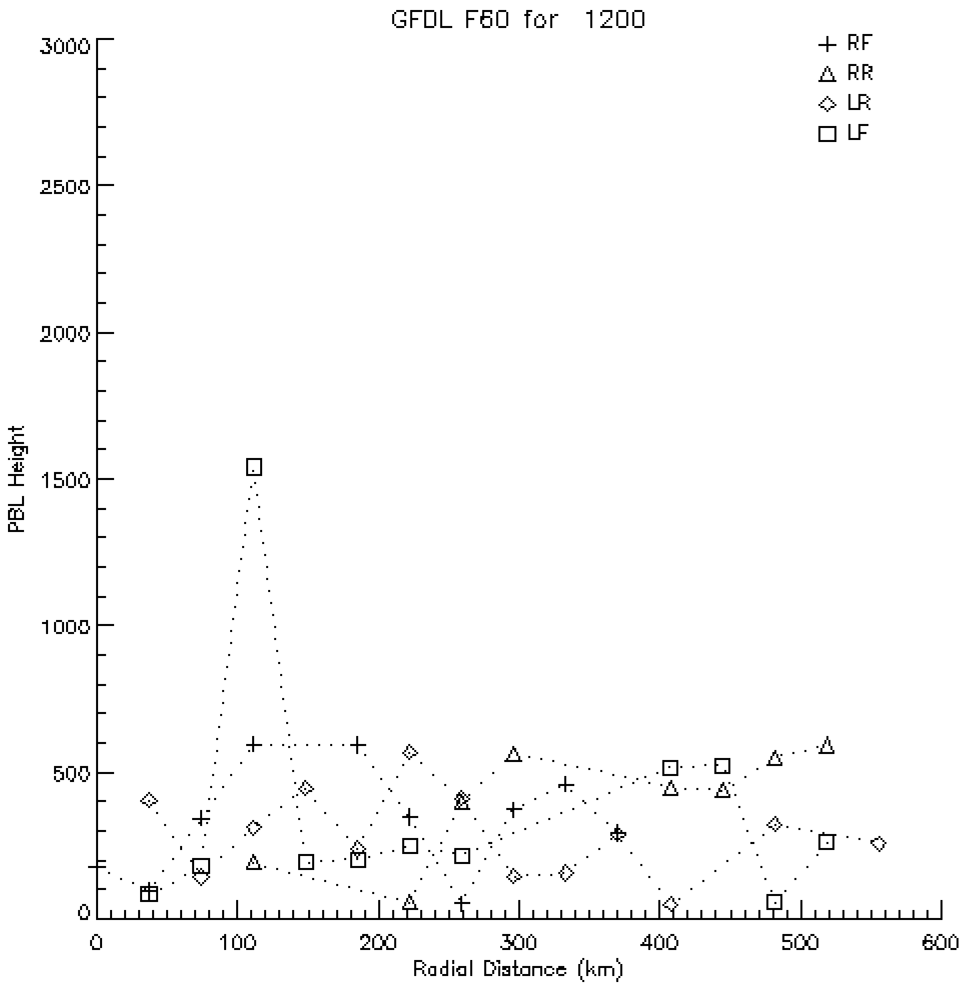

Figure 3.5 As in Figure 3.3, but for the 12 September 2003 at 00 UTC from the GFDL Model 60 hour forecast (14 September 2003 at 12 UTC).

3.3 CM1 Diagnosed Boundary Layer

An independent storm was developed in the CM1 as described in section 2.2.2. Since the CM1 does not a have a specifically prescribed BL formulation, this was meant to be an independent examination of the Ri criterion in diagnosing the BL thickness. The simulated hurricane is not matched at a specified radius to a separate background environment like in the GFDL model. This allows for an independent analysis of the BL thickness of just the hurricane and possible environmental modifications. The stretched grid allowed for much finer horizontal and vertical resolution than the GFDL model provided. When the hurricane was fully developed, the vertical profiles were taken at radial distances for 250 grid points in each of the four storm quadrants making up to 1001 possible samples out to about 900 km radially from the storm center.

The sloping BL thickness pattern which was available in the GFDL initialized data set was seen again in the CM1 hurricane (Figure 3.6, only one quadrant shown). In general, the BL thickness increased with decreasing radius until about 15-20 km from the center of rotation which corresponded to the region near the eyewall. The BL thickness then sharply declined in the eye. From 700 km to the outer limit, the variations in h were limited indicating the hurricane is not affecting this part of the background environment. Other smaller features are not examined in this study but could be attributed to rain bands and motes or other rain-free areas, for example.

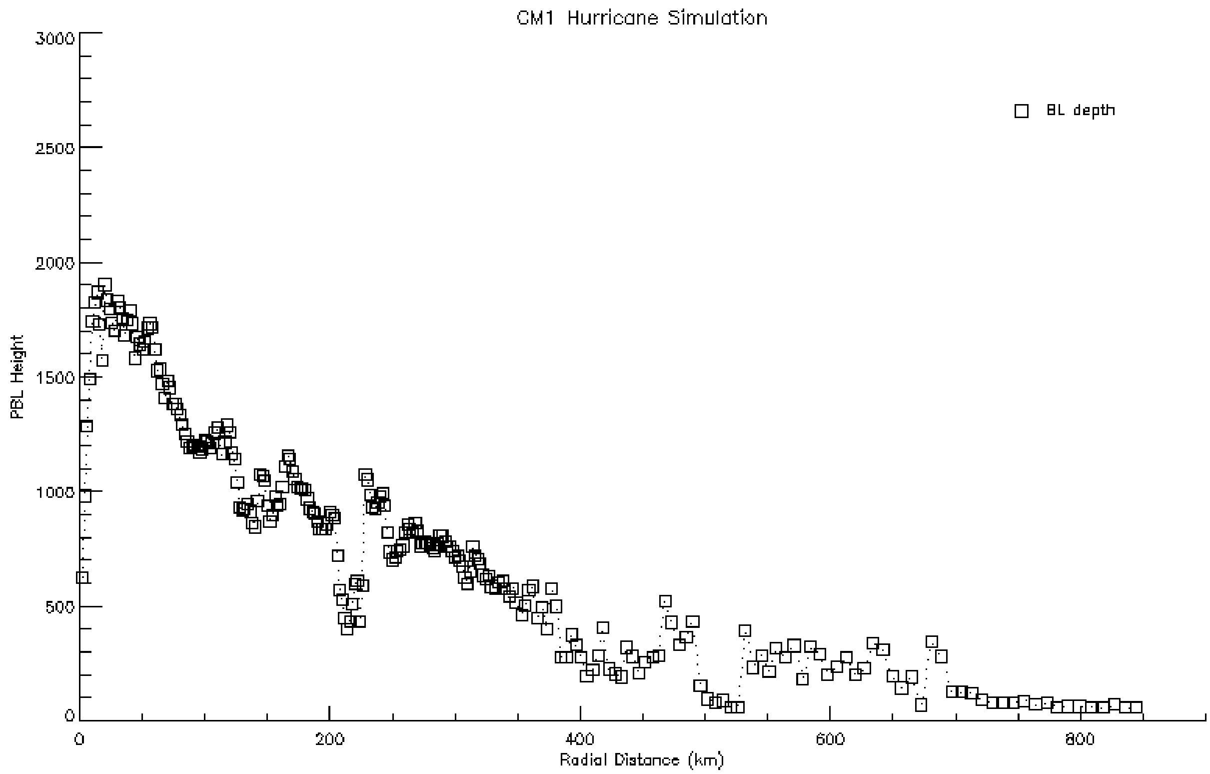

Figure 3.6 BL thicknesses as diagnosed using the Ri criterion for a hurricane developed in the CM1. The radial distance from the center of the hurricane in km is on the x axis and the BL thickness in meters (m) is on the vertical. Radius taken through the left front quadrant.

3.3.1 The Relationship Between Diagnosed Boundary Layer and the LCL

Returning to Powell's (Powell 1980) reference to the LCL being a proxy for BL thickness, a calculation of the LCL was performed on the CM1 profiles to look for consistencies. Using Barnes's (1968) formulation for the LCL, the CM1 hurricane shows a fairly consistent LCL height of near 500 m from 100 km to the outer limit radially (Figure 3.7). The LCL starts to decrease with decreasing radius inside of the 100 km range. This pattern of 500 m or nearly constant BL thickness is consistent with E86 which is the model S03 was trying to improve upon as noted in S08.

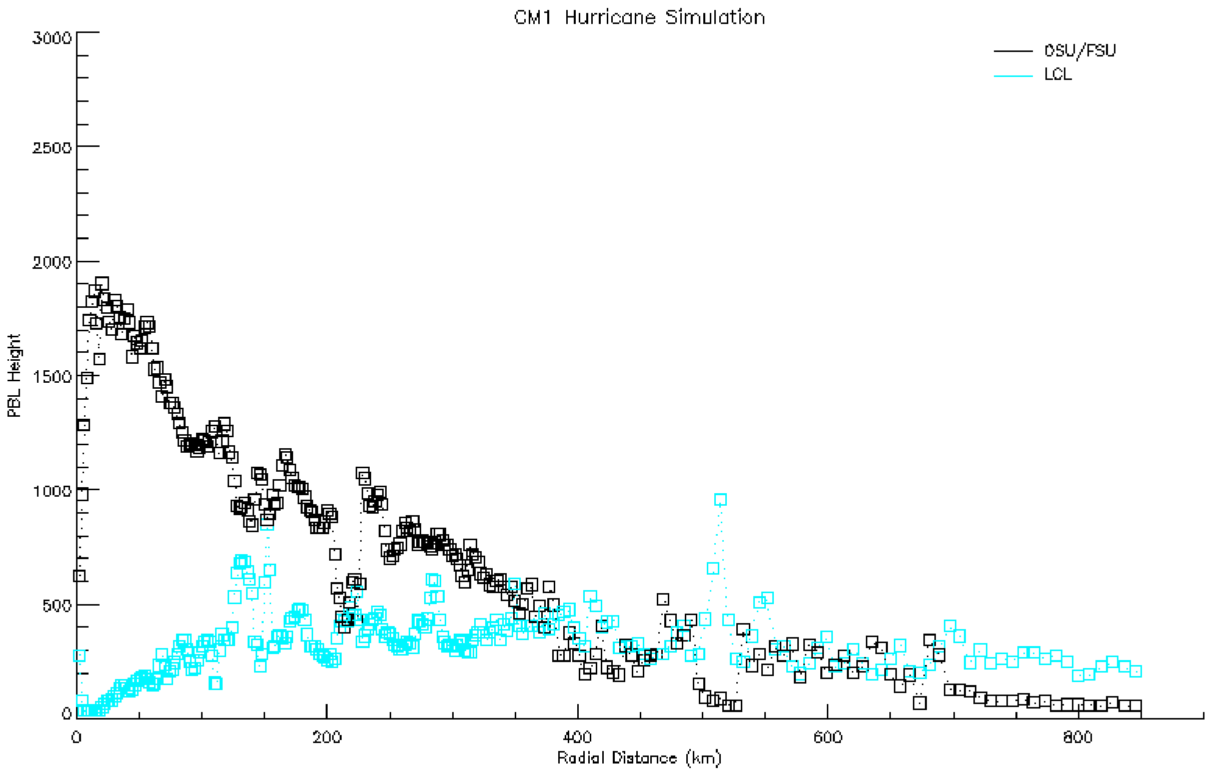

Figure 3.7 BL thicknesses as diagnosed using the Richardson criteria and the LCL for a hurricane developed in the CM1. The radial distance from the center of the hurricane in km is on the x axis and the BL thickness in meters (m) is on the vertical. Radius taken through the left front quadrant.

Part of the background theory of E86's hurricane is that air parcels will follow constant lines of angular momentum. In the boundary layer, this would take an air parcel and lift it dynamically.

This lifting would be consistent with the lifting associated with condensation beginning at the LCL. Using the LCL is then an appropriate proxy for E86's boundary layer as values are near 400 m – 500 m outside the radius of 100 km from the storm center. S08 indicated a failure in E86's approach to correctly function inside and outside of the radius of maximum tangential wind speed. A Ri-based criterion would require an evaluation of wind shear and buoyancy through the use of virtual potential temperature. This takes into account both the thermodynamic aspects which E86 appeared to get correct and the varying wind speed which S08 deemed important. Additionally, the Ri criterion is applied over the entire region which may simplify theory. The overlay of the LCL-derived surrogate BL thickness and the Ri-diagnosed BL thickness illustrates a substantial difference between the E86 and the TM86 methods of establishing BL thickness.

3.3.2 Gradient Wind and the Diagnosed Boundary Layer

Taking the approach of using a single layer (uniform slab) and analyzing the tangential and gradient wind to determine the inertial stability, the gradient wind is calculated from the CM1 model output. Following Elsberry (1995), the tangential wind and gradient wind are taken at 650 m in height (Figure 3.8). Both the tangential wind and the gradient wind follow a similar structure to that presented in SV08 and VS09. The peak intensity appears around 25 km away from the center of rotation. The tangential wind is much smoother in transition. The gradient wind field is dependent on the pressure gradient. Some of the variations in the local pressure gradient showed changes in vorticity consistent with roll vorticies as well as the propagation of Rossby waves.

With the tangential and gradient wind speeds from the CM1, the BL scaling method suggested by SV08 and VS09 for indentifying an appropriate BL depth based on the inertial stability is shown to be consistent in part for both the CM1 and SV08 models in general (Figure 3.9). Indeed the overall depth decreases with decreasing radius from the storm center to 400 km. The calculated BL depth is not as smooth as the surface presented in SV08, however, the previously noted perturbations in the radial wind field could attribute to these irregularities. Outside of about 400 km, the BL depth remains fairly consistent at about 650 m. Interestingly, this level of 650 m is same level used for the calculations of the tangential and gradient winds; the mean values are around or less than 10 m/s. This may indicate a region where the inertial stability method is not an appropriate method of calculating the BL thickness. SV08 alluded to this fact as a limitation to a one-layer model.

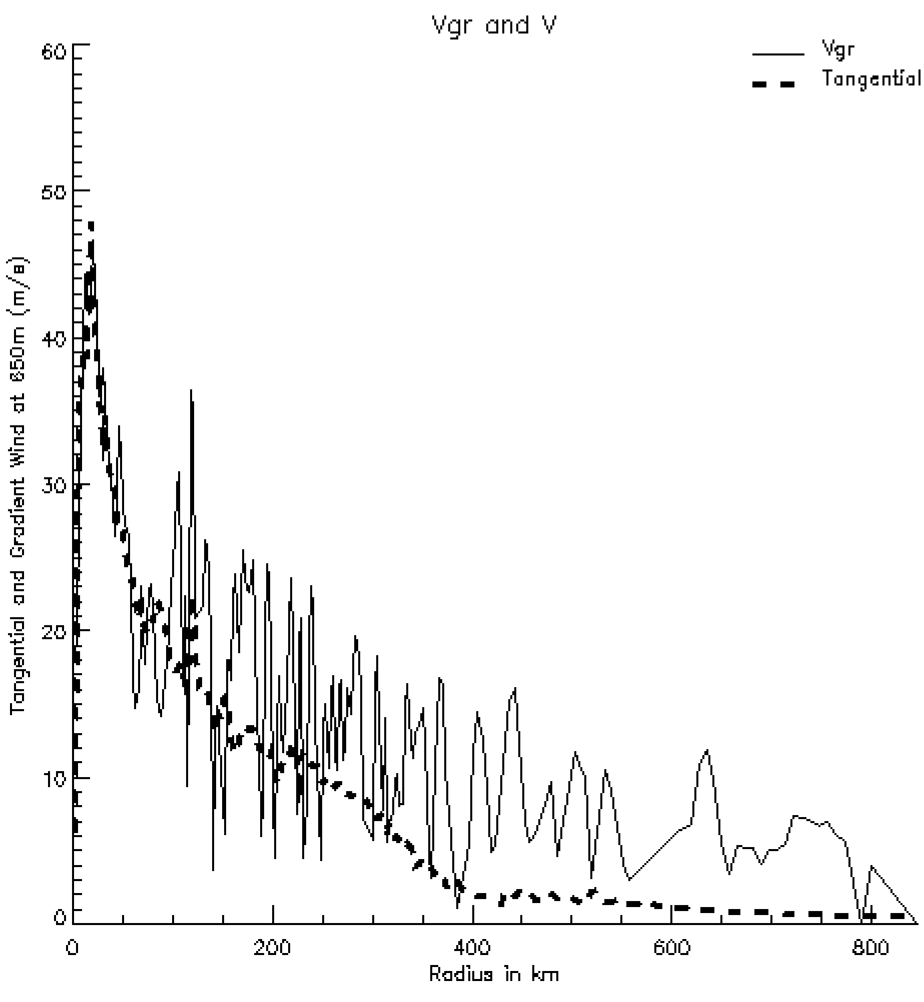

Figure 3.8 Tangential and gradient wind speeds (m/s) at 650 m for a hurricane developed in the CM1. The radial distance from the center of the hurricane in km is on the x axis and 650 m tangential and gradient wind speeds are on the vertical. Radius taken through the left front quadrant.

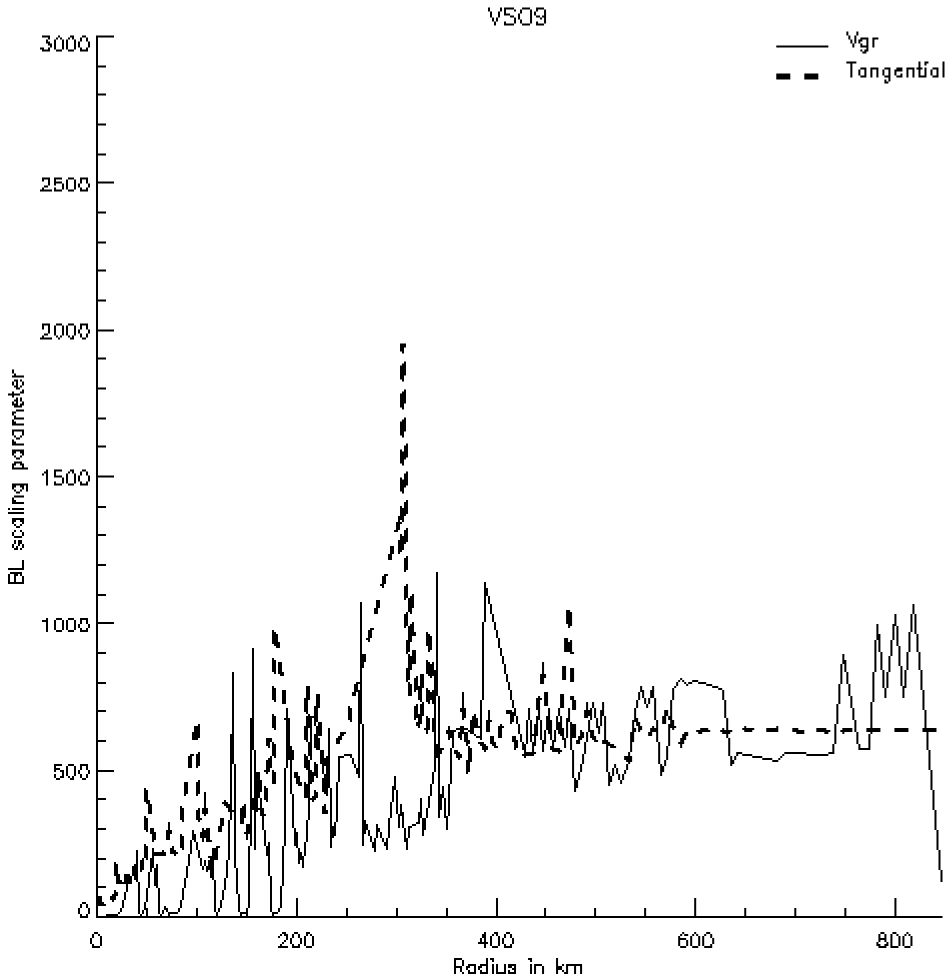

Figure 3.9 BL scaling parameter used in SV08 and VS09 as calculated by the tangential and gradient wind speeds (m/s) at 650 m for a hurricane developed in the CM1. The radial distance from the center of the hurricane in km is on the x axis and the BL thickness in meters (m) is on the vertical. Radius taken through the left front quadrant.

3.3.3 Vertical Profiles and the Diagnosed Boundary Layer

The BL depth according to the SV08 is based on a inertial stability parameter which uses the gradient wind in the calculations. While SV08 explored the possibility of using different heights for the gradient wind, the challenge comes in defining the actual level of the gradient wind. By looking at the vertical profiles of the radial and tangential wind, u and v respectively, and the total wind then comparing the gradient wind calculated at all levels, the areas where the wind is gradient, sub-gradient and super-gradient can be visually determined. Since the TM86 scheme uses the vertical profile of both the wind and the virtual potential temperature in the calculation of the BL depth, a comparison to the two different methods at one radial profile. The vertical profile just outside of the eyewall, at 32 km, the gradient wind from 550 m, 650 m and 800 m provides range of BL depths of 104 m – 106 m for the SV08 calculation and the TM86 provides a value closer to 1800 m (Figure 3.10). The vertical, displayed up to 5000 m, demonstrates the tangential and total wind to be approximately the gradient wind except from the surface to about 200 m. Farther away from the center of the storm, at 122 km, the values of the tangential total winds are near the gradient wind (Figure 3.11). The SV08 calculation provides for a range of BL depth of 140 m – 150 m, and the TM86 method gives a value about 1775 m. This confirms the rising BL depth with increasing distance from the SV08 method and the decreasing BL depth with increasing distance from the TM86 method. While there is a difference in the wind velocity at the levels used in calculating the SV08 values and the level where the TM86 method diagnosed the BL depth, this does not entirely account for the large difference in BL depth values between the two methods. The thermodynamic profile must play a strong role in determining the BL depth for the TM86 method. It is not as simple as looking for an inversion for a layer of stability, but the delicate balance between the buoyancy and shear.

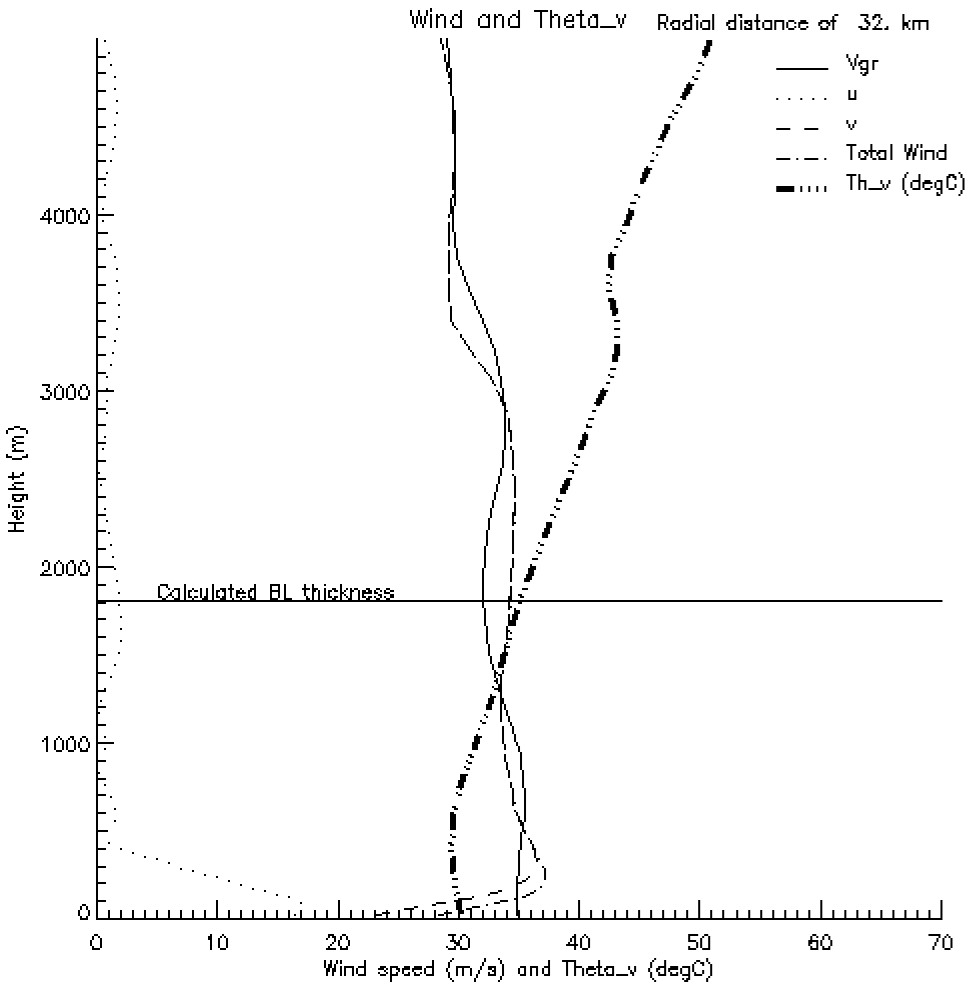

Figure 3.10 Vertical profile of the radial and tangential winds, u and v respectively, along with the total wind (m/s) and the virtual potential temperature (Th_v in °C) from the surface to 5,000 m at 33 km from the center of rotation for a hurricane developed in the CM1. Additionally the TM86 calculated BL thickness is shown. Values of the BL depth from SV08 method from the 550 m, 650 m, and 800 m levels ranged from 104 m – 106 m. The wind speed and virtual potential temperature are shown on the x axis and height above the surface in meters (m) is on the vertical. The profile is taken through the left front quadrant.

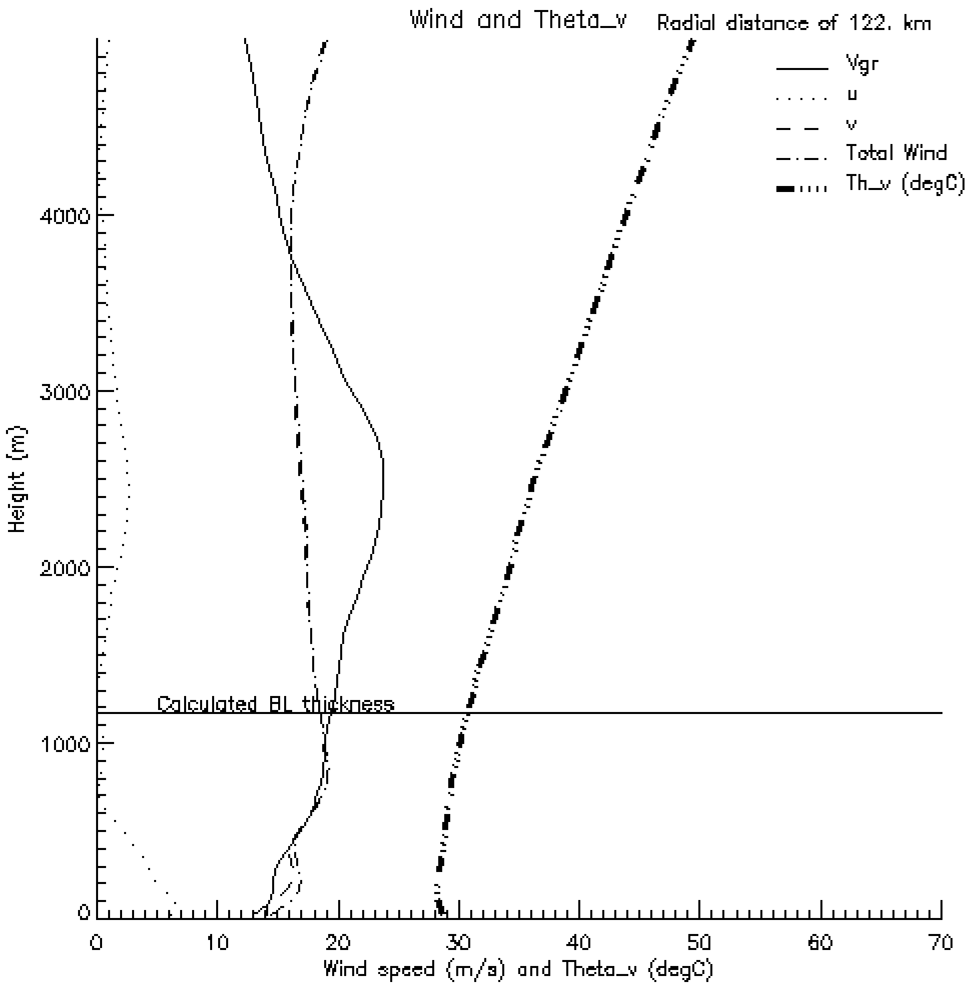

Figure 3.11 As in Figure 3.11 but at 122 km from the center of rotation. Values of the BL depth from SV08 method from the 550 m, 650 m, and 800 m levels ranged from 140 m – 150 m.

3.3.4 Richardson Criterion at Slab Levels

As the inertial method may not be appropriate for all regimes in a hurricane environment, the Ri criterion is applied to the slab method demonstrate regions of agreement and disagreement in the techniques. Areas of similar values would indicate regions of appropriate use for both methods. Ri is calculated at levels 550 m and 850 m as presented by SV08 and by the 650 m level used by Elsberry (1995). Unity is added to the Ri values for display purposes; the Ri threshold, 0.25, used for determining the BL thickness in the TM86 model is also displayed (Figure 3.12). The regions where the calculated Ri and the Ri criterion value are similar values appear to be from about 50 km to 200 km in radius. Beyond 200 km, Ri quickly increases and continues to increase with increasing radius. These slab layers indicate only a small regime over which the slab method and the Ri criterion tentatively agree. Even then, this region cannot equally be applied to all hurricanes since the wind speed and θ_v can be different though a region likely exists in hurricanes where the methods agree.

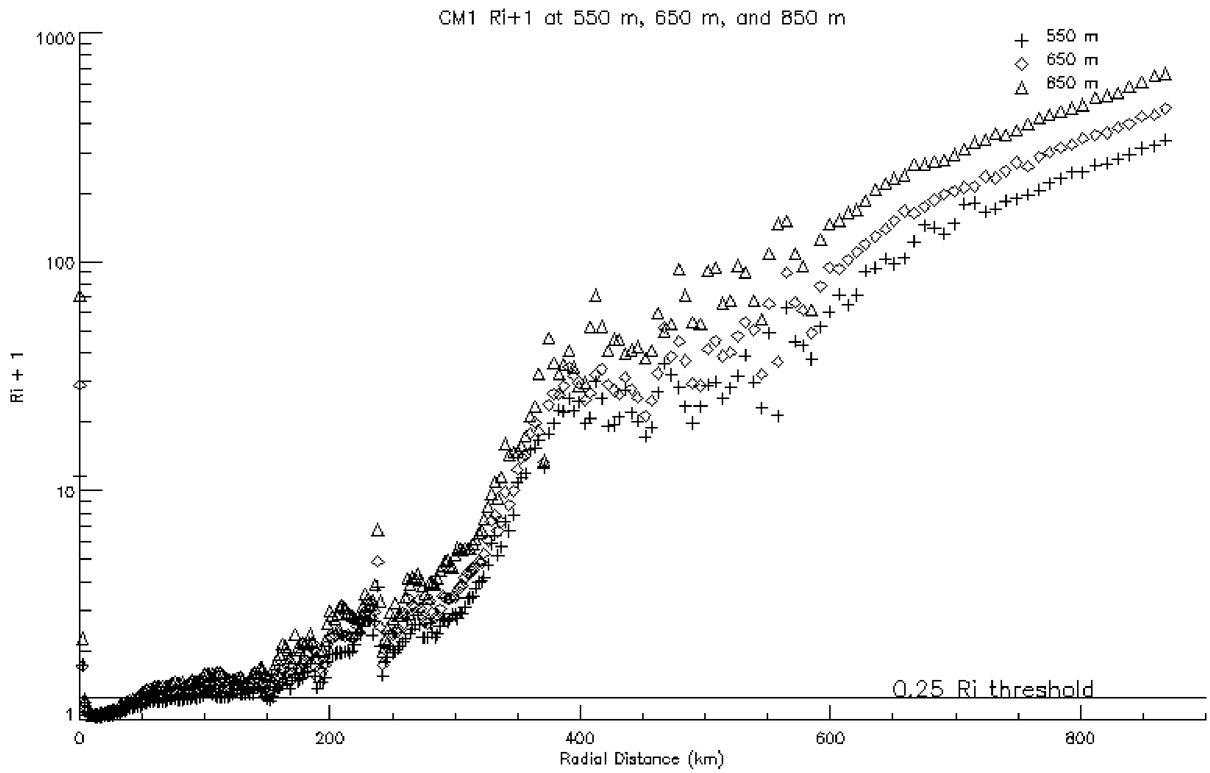

Figure 3.12 Ri + 1 at 550 m, 650 m, and 850 m heights for a hurricane developed in the CM1. The radial distance from the center of the hurricane in km is on the x axis and Ri + 1 is on the vertical. Radius taken through the left front quadrant.

By taking a closer look at the domain where the slab method and the Ri criterion may agree, the variation from the critical value is better identified (Figure 3.13). Each of the three levels presented are near the Ri criterion of 0.25, but heights of 550 m and 650 m are closer to the value for a longer period of time. This would indicate the value of 850 m to be less reasonable for use in a slab model. The pattern of each of the three thicknesses from 50 km to about 200 km radially would indicate there is a reasonable agreement in this region and may justify continued use of slab based modeling in this regime. Interestingly, within and just outside of the eyewall, where the Ri values are less than the Ri criterion used, this is also the region over which S08 argued gradient wind balance did not apply according to E86's hurricane theory which used a slab model.

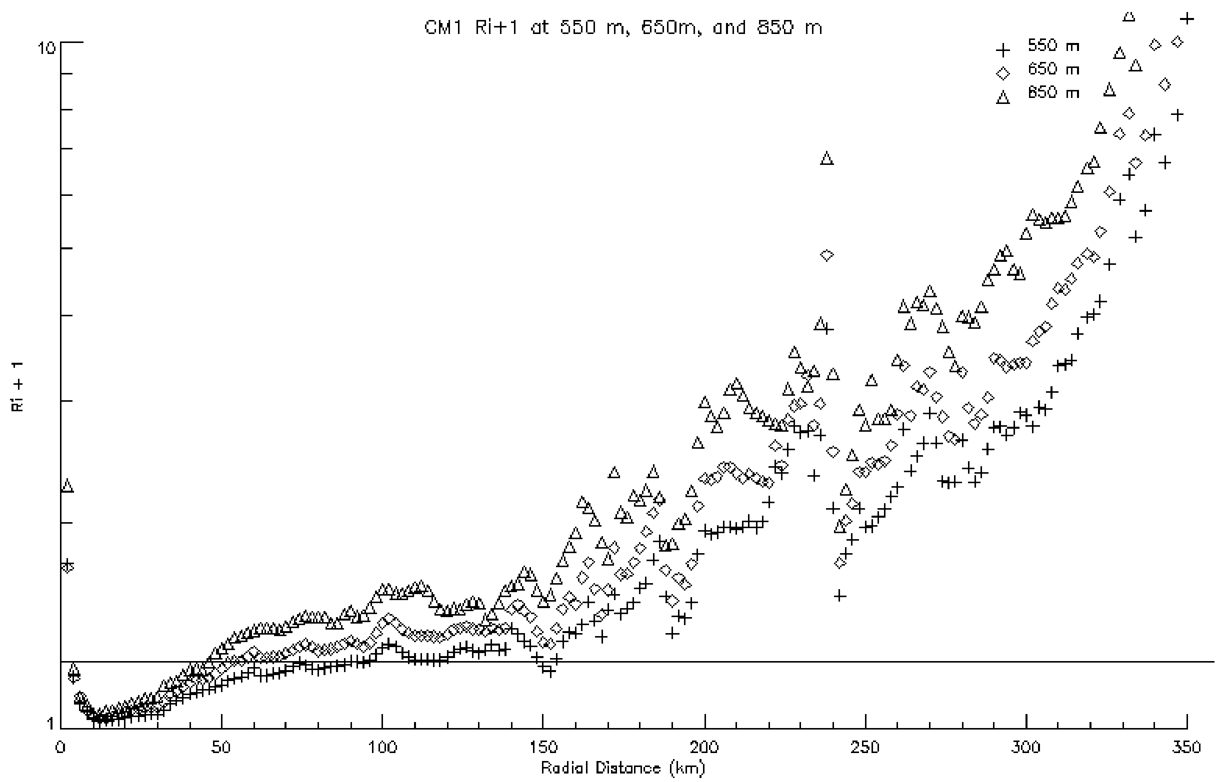

Figure 3.13 As in Figure 3.12, but with a smaller radial domain.

The 650 m surface, as represented in figures 3.8 and 3.9, was similar to the varying surface used by SV08. Assuming similar features in the gradient and tangential wind fields and applying the thermodynamic profile from the CM1 hurricane, the calculated Ri from the 650 m θ_v values represents similar values as though this calculation were performed on profiles from SV08. While the Ri criterion value in other applications of the TM86 scheme are known to vary from .25 to unity, the regions where the constant thickness and the Ri criterion agree continue to be similar. Therefore there are regions where the SV08 and Ri criterion agree, however the thermodynamic structure appears to play a role outside of these regions, namely about where S08 would also disagree with the uniform slab model.

While the CM1 model and the improved linearized model presented by SV08 had seemingly similar hurricanes as identified by the wind field and similar results were realized for each model using the BL scaling parameter presented by VS09, the scaling parameter and the Ri criterion were not in agreement though as for the scaling parameter thickness decreased with decreasing radius and as for the Ri criterion increased with decreasing radius from about 300 km radius. The slab method potentially agreed with the Ri criterion in some regions of the hurricane.

CHAPTER 4

SUMMARY AND CONCLUSIONS

4.1 Discussion

The TM86 and SV08 methods for determining the BL thickness differ but still result in similar values over some regimes. Their differences occur largely owing to the extent to which wind and/or buoyancy which determine the thicknesses. SV08 presented two methods for determining the BL thickness, first a uniform slab thickness was introduced with a heritage involving observational and modeling methods for determining thickness (E86, Elsberry 1995). While these uniform slab methods have helped to improve the fundamental understanding of hurricanes, observations, both *in situ* and remote sensing, and computing power have surpassed this legacy of uniform slab modeling. The times at which these methods were required due to limited availability in observational and computational resources may be past, allowing, today, for continued improvement in the understanding of BL processes and interactions in hurricanes. The second method SV08 presented was a variation on the slab modeling for a steady state hurricane allowing for a top surface of the BL thickness to change spatially. Following other research done by Kepert (2001), the varying BL surface was described based on gradient wind, typically taken at a single level. The TM86 method using the Ri criterion, developed and well-used and validated over land environments in particular, takes advantage of both the wind field and the thermodynamic profile to determine the BL thickness. By using the thermodynamic profile as well, buoyancy and can be taken into account giving a potentially better representation of the BL depth. This comparison of methods will hopefully aide in the understanding of determining BL depths. The dominant features are reviewed and discussed below.

- The investigation into the dropwindsondes from Hurricane Isabel yielded no conclusive results except for differing BL thickness with a median value near 1,000 m as determined by the Ri criterion. The profiles do not resolve the structure of the entire storm, but rather they indicate conditions at only one vertical profile in the storm. The inertial stability method used by SV08 does have an advantage in this area in that a BL could be determined based on the gradient wind, however, the nature of the profiles causes a failure in resolving the local radial pressure gradient field which is required for calculating the gradient wind.

- Applying the Ri criterion to the GFDL model for both initialized and 60 hour forecast for hurricane Isabel, yielded two different results. The initialized model appeared to have a BL which decreased with increasing distance away from the eye wall, but 60 hours of model time removed the sloping BL thickness leaving a more uniform thickness. Using the gradient wind would have given a result as used in SV08, but the difference in the BL surfaces as determined by the Ri criterion indicated a model tendency to remove or reduce these changes in BL thickness. If the wind fields are similar, the thermodynamic profile has changed, primarily modifying the buoyancy, though the shear profile is expected to be modified as well.

- In the CM1 hurricane simulation, from the center of rotation out to about 50 km, a completely different pattern in the BL thickness emerges (Figure 4.1). A uniform slab model continues the constant BL thickness through this whole field. S08 determined the gradient wind field assumptions are violated in this region where super-gradient winds are possible. This issue was addressed by SV08 using a varying BL depth using the gradient wind as part of an inertial stability parameter to determine the BL depth. Thickness decreased with decreasing radius. It was shown by the TM86 method that when the thermodynamic profile is also applied to an inertial stability calculation, the BL depth increases with decreasing radius until the eye where the depth quickly decreases.

The eye in both the varying depth and the TM86 method agree. Approaching the eyewall from the outside, the thermodynamics seems to drive the BL thickness to be greater, dominating the inertial stability. This indicates that while super-gradient winds may violate E86's hurricane model in this region, buoyancy may violate the SV08 method of determining the BL thickness.

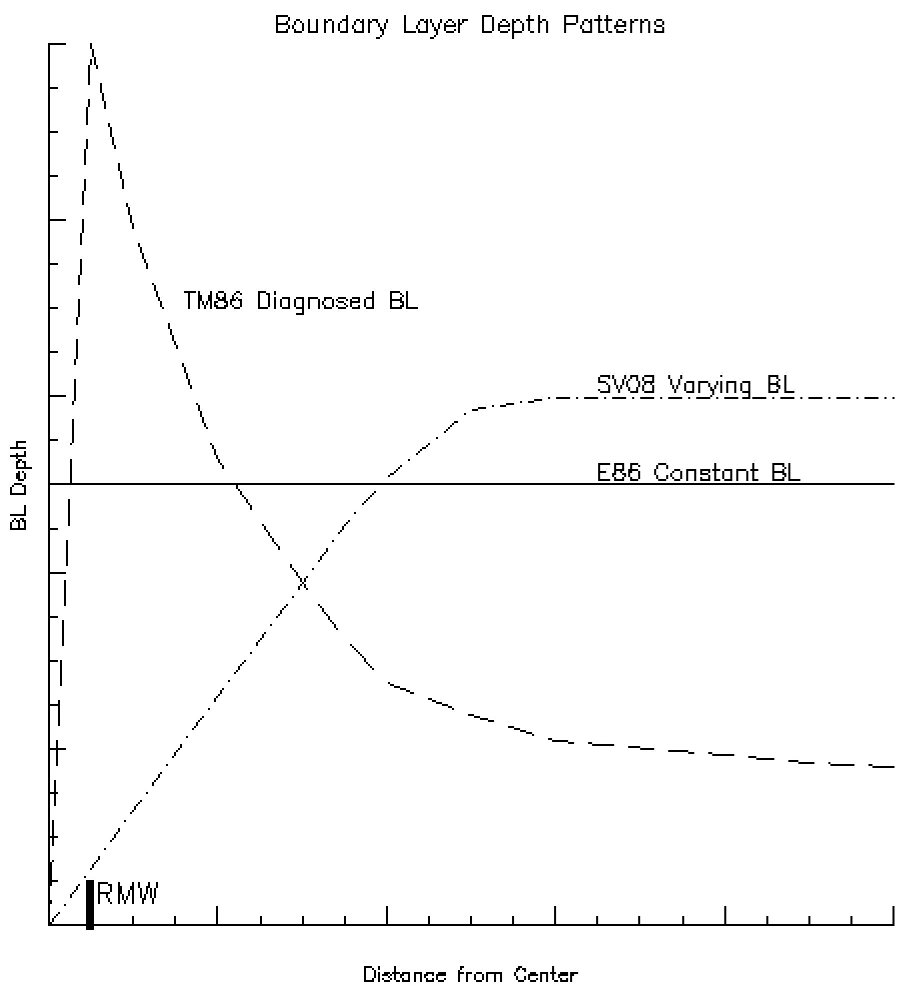

Figure 4.1 The patterns of the BL depths discussed of the E86 constant BL depth, the SV08 varying BL depth, and the TM86 diagnosed BL depth.

- From about 50 km - 150 km radially in the CM1 hurricane simulation both methods showed a similar pattern in the BL thickness. There was a leveling out of the calculated Ri with values from about 0.20 to unity for the 550 m, 650 m, and 850 m levels. These values for Ri are within the range used in the community to indicate the top of the BL. The threshold for a critical Ri of 0.25 is a value commonly used and extensively tested in land environments for the OSU/FSU 1D PBL model that was used to determine the BL thickness (Kara 1996, Kara et at. 1998), and used in current formulations such as in NOAH NCEP and other one-dimensional treatments (Mitchell 2005). While this is a modification to the TM86 approach in this assessment and the bulk Ri number is calculated for the specified levels instead of calculating the bulk Ri number for each model level until Ri > Ri criterion, this method of allows for an analysis of the structure at the previously indicated levels. The relatively close agreement of these values would indicate an area over which the methods of calculating the BL from TM86 and SV08 in both uniform and varying slab methods produce similar results. S08 indicated a region over which the gradient wind assumption from E86 is not violated that corresponds well to this region as well. Assuming the thermodynamic profile does not vary greatly in this region, the changes in the gradient or tangential wind, as seen in both SV08 and the CM1 model, could be considered the feature dominating BL thickness.

- From 150 km – 400 km in the CM1 hurricane simulation, the BL thickness continued the patterns of increasing with increasing radius for the SV08 varying slab method and decreasing with increasing radius for the Ri criterion.

- From 400 km – 900 km in the CM1 hurricane simulation, the BL thickness leveled off for both the SV08 varying slab method and the Ri criterion. The values for SV08 were near 650 m. SV08 did not present values out to 900 km from the center of rotation, but did note that a more appropriate method for determining the BL depth would involve a balance between turbulence and subsidence aloft. According to the Ri criterion, the BL depth continued to decline with increasing radial distance, but values were already less than the 650 m SV08 suggested. This region was not under the extent of the cloud coverage for the CM1 hurricane, but this tailing off of values indicated a region of hurricane influence far beyond the area of cloud cover.

4.2 Conclusions

This study analyzed the methods presented by SV08 and TM86 used to determine the BL thickness in the observed and modeled Hurricane Isabel which varied in intensity from a category 5 to a category 2 hurricane over the time period of interest and in a hurricane modeled with the CM1 rated as a strong category 3 hurricane according to the Saffir-Simpson scale. By focusing on the hurricane BL thickness, patterns and features unique to the methods described by SV08 and TM86 were compared and discussed. Each of the three methods involving a uniform slab model, a spatially varying slab model, and a diagnosed BL thickness from vertical profiles present unique characteristics of the BL thickness. The uniform slab model allows for a simpler conceptual understanding. The varying slab model provides the ability to adjust and modify the BL depth to accommodate for the radially varying gradient wind. As presented by SV08 and VS09, the BL depth in the varying slab model depends on the inertial stability from the wind and increases with increasing distance from the center of rotation until a region where the depth remains nearly constant. The TM86 method requires both the wind field and the thermodynamic vertical profile in order to diagnose the BL depth based on a balance between buoyancy and shear. Differing from the inertial stability determined depth, from the eyewall outward in the TM86 method the BL thickness decreases with increasing distance. Further conclusions are presented below.

- The TM86 scheme for determining the BL thickness does work in hurricane for *in situ* observations and for some models, but the use of this method for determining the BL thickness in the potential modification of the complete hurricane structure needs to be analyzed further.

- A dynamical approach for determining the BL thickness reveals a more realistic hurricane structure than a uniform slab parameterization. The different resulting patterns in the BL thickness from Ri criterion and SV08 varying slab methods for determining requires further investigation. The linearized hurricane model might provide a platform for determining the consequences of using these methods for determining the BL depth as the BL depth may be independently prescribed without the use of the presented inertial stability parameterization.

- Since both the varying slab method and TM86 use the wind field in calculating the BL depth, the additional parameter involving buoyancy used by TM86 may be an important contributor to the different patterns in the BL depth, particularly for any diagnostics that require estimates of turbulence intensity in the PBL. This could be related to estimates of maximum wind speed or gustiness, and damage effects, for example.

- Additionally, assuming this top of the BL acts as an interface between the BL and the free atmosphere or the rest of the hurricane, understanding the variations in thickness of the BL as it pertains to hurricane modeling could affect the regions over which potential vorticity conservation may change or modify local changes in vorticity including structures like rolls.

4.3 Future work

The models presented here were assumed to provide and analyze steady-state hurricanes. One advantage of the TM86 method would be the potential application of the method for non-steady-state hurricanes. While the Ri criterion requires new diagnostic calculation is modified, the simple calculation should not be overly cumbersome for current computing power and capabilities of most models. An important shortcoming to the present research was the need to calculate the BL depth since this variable, among other important boundary layer variables, is often not available in standard diagnostic output grids of NWP, climate and mesoscale models, making routine diagnosis of detailed boundary layer structure difficult in post-analysis. In the future an investigation should be done to determine the applicability of TM86 method for determining the BL depth of a developing or decaying hurricane.

Additionally, using a vertical profile for determining the BL thickness by the Ri criterion may be more appropriately calculated following a profile of constant angular momentum instead of a simple profile in the vertical. As dropwindsondes do not follow purely vertical profiles and are translated in the hurricane, using a profile of constant angular momentum may be a better indication of the BL depth as a parcel from within the BL would find it.

4.3 Concluding Remarks

In conclusion, the varying slab method as presented by SV08 presents a way to hybridize the uniform slab method with features not normally captured in a uniform slab model by prescribing a varying BL thickness. The inertial stability parameterization was compared to a Ri criterion presented by TM86 for determining the BL depth. Differences and similarities were presented for hurricane Isabel from *in situ* and GFDL modeled data and for a hurricane developed in the CM1. BL depth increased with increasing radius for the inertial stability parameterization and decreased with increasing radius for the Ri criterion. Possible reasons were discussed for the different patterns noted. Finally, the results of this study indicate a need to further understand the roll of the BL thickness on modifying hurricanes, their structure, development, and decay.

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