2014

Estimate of Tropical Cyclone Parameters Based on Microwave Humidity Sounders

Qi Shi
ESTIMATE OF TROPICAL CYCLONE PARAMETERS BASED ON MICROWAVE HUMIDITY SOUNDERS

By

QI SHI

A Thesis submitted to the
Department of Earth, Oceanic and Atmospheric Sciences
in partial fulfillment of the
requirements for the degree of
Master of Science

Degree Awarded:
Spring Semester, 2014
Qi Shi defended this thesis on March 4, 2014.
The members of the supervisory committee were:

Xiaolei Zou
Professor Directing Thesis

Ming Cai
Committee Member

Zhaohua Wu
Committee Member

The Graduate School has verified and approved the above-named committee members, and certifies that the thesis has been approved in accordance with university requirements.
I humbly dedicate this manuscript to my parents, Weizhou Shi and Yuchuan Zhang.
ACKNOWLEDGEMENTS

First and foremost, I want to thank Dr. Xiaolei Zou for her guidance, advice and help. I also want to thank Dr. Ming Cai and Dr. Zhaohua Wu for serving as my committee members.

I would like to thank everyone in Dr. Zou’s lab for their help and support.

Last but not least important, I thank my family and friends for their ongoing encouragement during my studies.

This research is supported by NSF project AGS-1037936.
# TABLE OF CONTENTS

List of Tables ........................................................................................................................................ vi
List of Figures ......................................................................................................................................... vii
List of Acronyms ................................................................................................................................... viii
Abstract ................................................................................................................................................ ix

1. INTRODUCTION ............................................................................................................................. 1
   1.1 Dvorak Technique for Estimation of TC Location and Intensity .................................................... 1
   1.2 Uncertainty in Dvorak-based Intensity Guidance ............................................................................. 3
   1.3 TC Wind Structure Estimation ..................................................................................................... 5
   1.4 Application of Microwave Data for TC Monitoring ..................................................................... 6
   1.5 Thesis Organization ..................................................................................................................... 7

2. CASE AND DATA DESCRIPTION ................................................................................................. 9
   2.1 Case Description .......................................................................................................................... 9
   2.2 Data Description .......................................................................................................................... 12

3. TC CENTER AND RADIUS OF MAXIMUM WIND DRIVED FROM MHS .............................. 14
   3.1 Hurricane Structures Observed by MHS ..................................................................................... 14
   3.2 TC Center and Radius of Maximum Wind Estimated by MHS .................................................... 18
   3.3 Comparison with AVHRR ......................................................................................................... 25

4. CONCLUSIONS ............................................................................................................................... 29
   4.1 Conclusions ............................................................................................................................... 29
   4.2 Future Work ............................................................................................................................... 30

REFERENCES ....................................................................................................................................... 31

BIOGRAPHICAL SKETCH .................................................................................................................. 35
LIST OF TABLES

1.1 The relationship between Current Intensity Number (CI), with maximum sustained wind (MSW) and minimum sea level pressure (MSLP) in both Atlantic and West Pacific basins. ........3

1.2 Progression of Dvorak Technique algorithms. .................................................................5

2.1 List of dates, maximum wind speed and minimum sea level pressure for the hurricanes investigated in current study ........................................................................................................10

2.2 MHS instrument characteristics ......................................................................................13

3.1 AVHRR/3 Channel Characteristics ...................................................................................26
LIST OF FIGURES

1.1 (a)-(b) Infrared satellite image from GOES-EAST, and (c)-(d) brightness temperature observed from channel 2 (157.0 GHz) of MHS on board NOAA-18 at 0600 UTC (left panels) and 1800 UTC (right panels) August 30 2010, respectively. ..........................................................8

2.1 (a) Best Track observed track of Hurricane Earl from 0000 UTC August 29 to 0000 UTC September 03, 2010, sea level pressure at 1200 UTC August 31 from NCEP FNL (Final) Operational Global Analysis data is also plotted; and (b) illustration of polar-orbit satellites (color lines) observations available in the hurricane region of Earl from 0000 UTC August 29 to 0000 UTC September 03, 2010. The minimum sea level pressure (hPa, solid) and maximum wind speed (kt, dash) are also plotted. .........................................................................................11

3.1 Evolution of brightness temperature observed from channel 2 (157.0 GHz) of Microwave Humidity Sensor (MHS) on board MetOp-A, NOAA-15, 16, 18, 19 and channel2 (150.0 GHz) of MicroWave Humidity Sounder (MWHS) on board FY-3A. ........................................................15

3.2 NOAA-18 MHS (a) channel 2 $T_b$ horizontal distribution, (b) radial profile of channel 1-5 along line AB in (a). IWP (solid) and CLW (dotted, divided by 3) are plotted in (b). ..................17

3.3 (a) MHS observed $T_b$ (channel2) near Hurricane Earl center at 1724 UTC September 1, 2010; (b) profiles of $T_b$ along fixed scan angles. ...........................................................................20

3.4 (a) Radial distance against the azimuthal angle for the first minimum $T_b$ points from the hurricane center (colored dots); (b) Radial profile of $T_b$ from azimuthal angles shaded in (a), the first minimum $T_b$ points are highlighted as dots and the radial profile is color coded by azimuthal angle. .............................................................................................................................................21

3.5 Best track for 12 TCs listed in Table 2.1..............................................................................................................22

3.6 (a) PDF distribution of distance between hurricane center determined by MHS $T_b$s and Best Track (b) PDF distribution of difference between radius of maximum wind determined by MHS $T_b$s and Best Track for 12 Hurricanes.................................................................................................................................................23

3.7 Scattering plots of the radius of maximum wind estimated from MHS data compared with best track data. The distance between hurricane centers determined from MHS data compared with best track data is indicated in color..........................................................................................................................24

3.8 Spatial distributions of AVHRR channel4 $T_b$ (infrared, 10.8 um, left panels) and MHS Channel2 $T_b$ (157 GHz, right panels) on board NOAA18 and MetOp-A. The Best Track observed and modified hurricane center are indicated as black and red dots respectively. The radius of maximum wind from Best Track and $T_b$ are indicated as black dashed circle and red star respectively.................................................................................................................................................27
LIST OF ACRONYMS

AMSU-A/B – Advanced Microwave Sounding Unit A/B
AVHRR – Advanced Very High Resolution Radiometer
BF – Outer Banding Features
CDO – Center Dense Overcast
CF – Center Features
CI – Current Intensity
CLW – Cloud Liquid Water Content
FOV – Field of View
IWP – Ice Water Path
MHS – Microwave Humidity Sounder
MSW – Maximum Surface Wind
MSLP – Minimum Sea-Level Pressure
MWHS – MicroWave Humidity Sounder
NHC – National Hurricane Center
RMS – Root Mean Square
TC – Tropical Cyclone
TD – Tropical Depression
T-number – Tropical Number
ABSTRACT

TC structures consisting of eye, eyewall and rainband can be clearly resolved by Microwave Humidity Sounder (MHS) window channels. High brightness temperatures are found in cloud-free hurricane eye and cloud streaks, and low brightness temperatures are found in cloud rainbands. In this study, MHS is used to estimate TC center and radius of maximum wind. The TC center location is determined by the warmest brightness temperature of MHS channel 2 within TC eyewall region. The radius of maximum wind is estimated based on the radial profiles brightness temperatures calculating at six-degree azimuthal angles. The shortest distance between the hurricane center and the minimum point of brightness temperature with some minimum points on its neighboring radial profiles is taken as the estimate of the radius of maximum wind. This method for estimating the TC center location and the radius of maximum wind was applied to twelve arbitrarily selected TCs that occurred in 2010, 2011 or 2012 over Atlantic basin. More than 78% of cases have the differences of TC center location and radius of maximum wind between MHS and NHC being less than 15 km and 10 km, respectively. The infrared observations from Advanced Very High Resolution Radiometer (AVHRR) on board the same satellite as MHS are also used for further comparison. It was found that the large differences between MHS estimate and Best Track analysis seem to occur for TCs with asymmetric structure or high-latitude locations.
CHAPTER ONE

INTRODUCTION

1.1 Dvorak Technique for Estimation of TC Location and Intensity

Tropical cyclone (TC) track and intensity are two major factors of TC forecasting. At present, the airborne Doppler radar can observe the hurricane circulation center and wind structure (Mark and Houze 1984) with a high accuracy. However, sampling of tropical cyclone by low-altitude aircraft is performed routinely only in the Atlantic basin. In all other ocean basins, in situ information about inner-core winds is based entirely on occasionally source such as ships, buoys, and island-based metrological measurements. Furthermore, because of the range limitation of the aircraft, hurricanes in the Atlantic are not investigated until they are close enough to aircraft bases required for taking off and landing.

The primary method of monitoring TCs, especially when aircraft reconnaissance data is not available, is the Dvorak TC intensity estimation technique (Dvorak 1975, 1984). The Dvorak technique uses cloud features from satellite visible and infrared observations to estimate the TC intensity and its future change of intensity. Although the satellite pictures of TCs appear in a great variety of patterns, they are classified by Dvorak Technique into a few sets of typical TC patterns, such as a comma or a rotated comma configuration. The pattern of the comma usually consists of a combination of convective cloud lines that cluster and merge together, and cirrus clouds. As the cyclone intensifies, the comma configuration is usually observed to become more circular with its central core clouds increasing in amount and density. In Dvorak technique, two cloud features are considered to be related to cyclone intensity, which are center features (CF) and outer banding features (BF). The central features are those which appear within the broad curve of the comma band and either surround or cover the cloud system center. The outer banding features refer to the part of the comma cloud band that is overcast and curves evenly
around the central features. Those two parameters and an implied cloud depth parameter comprise the Tropical number (T-number) description of cyclone. The basic steps in the Dvorak technique can be summarized as follows: First, determine the TC center location; second, assign a pattern (e.g., eye, banded) to the TC; third, measure the satellite imagery; fourth, assign a Tropical number (T-number); lastly, estimate the current intensity (CI). When the CI number is obtained, the forecasters can convert it to maximum wind speed or minimum sea level pressure based on empirical relationships showed in Table 1.1.

The Tropical Cyclone center is determined by analyzing the satellite observed cloud pattern. If the cloud system has an eye, the cyclone center is located at the center of eye. If partial eye wall is presented, the TC center is located at the center of a partial eye wall. Otherwise, the TC center is determined by fitting circle to the inner curve of the comma band and the curbed lines that appear within its band curve.

After TC center is analyzed, a T-number will be assigned to the TC by the Dvorak technique analyst. The T-number, which ranging from one to eight, is related to TC intensity. The T-number is determined by both central features and outer banding features. The CF estimate depends on the size, shape, and definition of the central cloud features as well as on the amount of central dense overcast (CDO) associated with them. The CDO is a large region of thunderstorms surrounding the center of tropical cyclones. Its shape can be round, oval, angular or irregular. The value of the CF increases when there is an increase in the amount of dense overcast surrounding the eye, and decreases for ragged, large or cirrus-covered eyes. For BF, a larger T-number will be assigned for TCs with more wider and apparent outer rain bands.

The T-number is then converted to CI Number following the rules and constraints specified by the technique. CI number is related to maximum sustained wind (MSW) first, and then minimum sea-level pressure (MSLP) is obtained by wind-pressure relationships. A wide variety of relationships has been proposed for relating the minimum center pressure and maximum surface winds in tropical cyclones (Harper 2002).
Table 1.1: The relationship between Current Intensity Number (CI), with maximum sustained wind (MSW) and minimum sea level pressure (MSLP) in both Atlantic and West Pacific basins. (http://www.ssd.noaa.gov/PS/TROP/CI-chart.html)

<table>
<thead>
<tr>
<th>CI</th>
<th>MSW (kt)</th>
<th>Atlantic MSLP (hPa)</th>
<th>West Pacific MSLP (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>30</td>
<td>1009</td>
<td>1000</td>
</tr>
<tr>
<td>2.5</td>
<td>35</td>
<td>1005</td>
<td>997</td>
</tr>
<tr>
<td>3.0</td>
<td>45</td>
<td>1000</td>
<td>991</td>
</tr>
<tr>
<td>3.5</td>
<td>55</td>
<td>994</td>
<td>984</td>
</tr>
<tr>
<td>4.0</td>
<td>65</td>
<td>987</td>
<td>976</td>
</tr>
<tr>
<td>4.5</td>
<td>77</td>
<td>979</td>
<td>966</td>
</tr>
<tr>
<td>5.0</td>
<td>90</td>
<td>970</td>
<td>954</td>
</tr>
<tr>
<td>5.5</td>
<td>102</td>
<td>960</td>
<td>941</td>
</tr>
<tr>
<td>6.0</td>
<td>115</td>
<td>948</td>
<td>927</td>
</tr>
<tr>
<td>6.5</td>
<td>127</td>
<td>935</td>
<td>914</td>
</tr>
<tr>
<td>7.0</td>
<td>140</td>
<td>921</td>
<td>898</td>
</tr>
<tr>
<td>7.5</td>
<td>155</td>
<td>906</td>
<td>879</td>
</tr>
<tr>
<td>8.0</td>
<td>170</td>
<td>890</td>
<td>858</td>
</tr>
</tbody>
</table>

1.2 Uncertainty in Dvorak-based Intensity Guidance

Since 1980s, the Dvorak technique has been used operationally at TC forecast centers worldwide. The main shortcoming of the Dvorak technique is its subjectivity and widely varying expertise levels of the TC forecasters who utilize it. In the late 1980s, Zehr (1989) developed an initial computer-based objective routine based on the analysis technique outlined by Dvorak (1984) using enhanced infrared satellite data. The Objective Dvorak technique significantly expanded the original technique and for the first time implemented many of the rules and
methods outlined in the Dvorak technique into an objective algorithm (Velden et al. 1998). However, a major shortcoming of the Objective Dvorak technique was its inability to estimate storm intensities below hurricane strength. In addition, the Objective Dvorak technique required a storm center location to be manually selected by an analyst prior to algorithm execution. The deficiency was addressed in the Advanced Objective Dvorak technique, which operates on all TC intensity levels and also incorporates additional Dvorak technique rules and constraints (Olander et al. 2002).

Various studies have been taken to evaluate the Dvorak-based TC guidance with aircraft reconnaissance data (e.g., Sheets and McAdie 1988). Kossin and Velden (2004) documented a pronounced latitude-dependent bias in Dvorak minimum SLP estimates. The results show that the uncertainty of TC center and intensity is a function of intensity (Sheets and McAdie, 1998; Torn and Snyder, 2012), latitude (Kossin and Velden, 2004) and intensification trend (Koba et al, 1991; Brown and Franklin 2002, 2004). Knaff et al. (2010) performed a comprehensive evaluation of Dvorak maximum wind speed estimates in the Atlantic basin from 1989 to 2008. Their results indicate that the Dvorak maximum wind speed estimates are a function of intensity, latitude, translation speed, size, and 12-h intensity trend, while the RMS error is primarily a function of intensity.

Recently, Torn and Snyder (2012) investigated the uncertainty of TC position in NHC advisory information for both Atlantic and eastern Pacific Basin TCs from 2000 to 2009. It is found that the position uncertainty decreases with increasing intensity in both Atlantic and eastern Pacific Basin. It is found that the RMS uncertainty of TC position decreases almost linearly from 43 n mi for tropical depressions (TDs) to 16 n min for category 4 and 5 TCs. The larger uncertainty for weaker systems is likely due to difficulties in identifying a low-level circulation center under cirrus canopies. In contrast, more intense TCs often contain a well-defined eye in both visible and satellite imagery, which simplifies the identification of the TC center. Similar to the TC position, the uncertainty in satellite-based TC intensity estimates are a function of the intensity itself (knaff et al., 2010, Torn and Synder, 2012). Larger root mean
square (RMS) errors were found in minimum sea level pressure and maximum wind speed for more intense TCs. Lacking of resolution in Dvorak CI values for more intense TCs may contributed to the larger root mean square errors in more intense TCs.

Table 1.2: Progression of Dvorak Technique algorithms.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Algorithm Name</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980s</td>
<td>Dvorak Technique</td>
<td>Dvorak, 1984</td>
</tr>
<tr>
<td>Late 1980s-1990s</td>
<td>Digital Dvorak Technique</td>
<td>Zehr, 1989</td>
</tr>
<tr>
<td>1995-2001</td>
<td>Objective Dvorak Technique</td>
<td>Velden et al., 1998</td>
</tr>
<tr>
<td>2001-2004</td>
<td>Advanced Objective Dvorak Technique</td>
<td>Olander et al., 2002</td>
</tr>
<tr>
<td>2004-present</td>
<td>Advanced Dvorak Technique</td>
<td>Olander and Velden, 2007</td>
</tr>
</tbody>
</table>

1.3 TC Wind Structure Estimation

Besides the TC location and intensity, surface maximum wind and the distribution of the wind field are also significant components of TC destructive potential (Powell and Reinhold 2007). Operational forecast centers, such as the National Hurricane Center, are required to provide information of the 34-, 50-, and 64-kt surface winds at 6-h intervals. Nowadays, various methods for measuring or estimating TC surface wind field are available, each with its own strengths and shortcomings. The cloud-track wind deduced from geostationary satellite (e.g., Velden et al. 2005) is available in the outer core region of the TCs. The underlying surface winds can then be estimated by reducing the cloud-track winds to the surface (Dunion et al. 2002; Dunion and Velden 2002). The Special Sensor Microwave Imager (SSM/I) are applied to the
estimation of surface wind over open water but are also limited to the outer core when estimating TC winds (Goodberlet et al. 1989).

Although there are a variety of sources for TC outer core wind data, the inner-core wind data that are routinely available at present are collected by low-altitude aircraft reconnaissance. In the absence of aircraft reconnaissance observation, the uncertainty of wind radii estimation increases, especially when large asymmetry exists. Recently, with the increasing wind observations from satellite-borne scatterometers (Zeng and Brown 1998; Weissman et al. 2002; Yueh et al. 2003), the wind radii estimation becomes less subjective when aircraft reconnaissance is not available. However, Jones et al. (1999) noted many effects that degrade the wind retrieval accuracy from scatterometers, especially near the region of peak winds. Because of the limitations of current TC center and wind radii estimation, alternate methods are desired.

1.4 Application of Microwave Data for TC Monitoring

Satellite-borne passive microwave radiometers, such as the Advanced Microwave Sounding Unit (AMSU) on the NOAA polar-orbiting series, can be a suitable tool to monitor tropical cyclones. AMSU contains two modules: A and B. Since the launch of NOAA-18 on 20 May 2005, the AMSU-B has been replaced by the Microwave Humidity Sounder (MHS). The AMSU-A has 15 channels and is mainly designed to provide information on atmospheric temperature profiles. The AMSU-B/MHS has five channels and is designed for providing the atmospheric moisture profile. Moreover, AMSU-A/MHS observation can be used to derive the parameters related to TC, such as cloud liquid water, cloud ice path, and rain rate. Spencer and Braswell (2001) statistically related six AMSU-derived parameters to the maximum winds of Atlantic TCs. Brueske and Velden (2003) developed a TC estimation algorithm that uses 55-GHz AMSU data to estimate minimum sea level pressure. In their algorithm, AMSU-A observation is used to assess the upper-tropospheric warm anomalies, and AMSU-B data is used to estimate eye size. Demuth et al. (2004) use the AMSU-A data to provide objective estimates of 1-min maximum sustained surface winds, minimum sea level pressure, and the radii of 34-, 50- and 64-kt winds for tropical cyclones. The results are compared to the aircraft reconnaissance observations. The mean errors for
maximum winds and minimum sea level pressure are 11.0 kt and 6.7 hPa respectively. The mean error for 34-, 50-, and 64-kt radii are 30, 24, and 14 n mi, respectively.

In this study, the Microwave Humidity Sounder (MHS) will be used for TC center and radius of maximum wind estimation. Below are several reasons that the MHS observation can be used to monitoring TCs. First, the intense convection associated with tropical cyclone rainbands and eyewall can be easily detected by MHS due to the decreased brightness temperatures by cloud ice particles. Secondly, microwave radiation can penetrate most clouds beyond the top layers, a beneficial feature when a central dense overcast exits. Figure 1.1(a) and (c) can be used as a good example. Thirdly, microwave sensing is available both at daytime and nighttime. The eye diameters of Atlantic tropical cyclones range from 8 to over 200 km, but the majority fall between 30 and 60 km (Weatherford and Gray 1988). The MHS has a resolution of 15 km at nadir, so if a TC falls near the nadir position, the 15-km resolution is sufficient to resolve hurricane eye. Despite its advantages, one limitation of using MHS data for TC analysis is the temporal resolution. The MHS instrument passes over the same location a maximum of two times daily. However, AMSU-B/MHS instrument onboard multi-satellites, such as NOAA-15, -16, -18, -19, MetOp-A, and FY-3A, can help to alleviate this problem.

1.5 Thesis Organization

This thesis is organized as follows: Section 2 will present a description of hurricane cases investigated in this study. The description of MHS, AVHRR and Best Track data is provided in Section 2 as well. Hurricane features observed by MHS are discussed in Section 3.1. The proposed technique for TC center and radius of maximum wind estimation from MHS surface sensitive channel is presented in section 3.2. Section 3.3 will provide a comparison between MHS and AVHRR observations. The thesis concludes in section 4.
Fig. 1.1: (a)-(b) Infrared satellite image from GOES-EAST, and (c)-(d) brightness temperature observed from channel 2 (157.0 GHz) of MHS on board NOAA-18 at 0600 UTC (left panels) and 1800 UTC (right panels) August 30 2010 respectively.
CHAPTER TWO

CASE AND DATA DESCRIPTION

2.1 Case Description

Twelve hurricane cases happened during 2010 to 2012 at the Atlantic Basin were investigated in this study (Table 2.1). The sample included 283 cases, with 13 cases at tropical depression and 124 cases at tropical storm intensities, and the remaining cases are hurricane strength (146 cases). Of the hurricane strength cases, 100 are category-1 or -2 storms and 46 are category -3 or -4 storms. The radius of maximum wind from Best Track for all the 283 cases range from 20 km to 275 km. The Hurricane Earl (2010) and Isaac (2012) are used as examples for the TC center and radius of maximum wind estimation procedure. And the synoptic description for those two hurricanes is provided below.

From August 29 to September 2, Hurricane Earl (2010) experienced two rapid intensification processes and one concentric eyewall replacement process (Fig. 2.1). From 1800 UTC August 29 to 1800 UTC August 30, Earl intensified by 40-kt over 24 h and became a Category 4 hurricane by 1800 UTC 30 August. Shortly after reaching that status, Earl began a concentric eyewall replacement cycle. This cycle halted the intensification process and Earl remained a 115-kt hurricane for the next 24 h. Southwesterly shear increased late on 31 August, which resulted in Earl weakening back to a category 3 hurricane by 0000 UTC 1 September. Earl re-intensified to category 4 strength by 1800 UTC 1 September and reached its peak intensity of 125 kt at 0600 UTC 2 September. Earl then rapidly weakened as it turned northward and fell below major hurricane status by 0000 UTC 3 September.

Hurricane Isaac (2012) was a slow-moving and relatively larger tropical cyclone that caused extensive storm surge and inland flooding over southern Mississippi and southeastern Louisiana. Issac is estimated to be directly responsible for 34 deaths in the United States, Haiti, and the Dominican Republic. It developed from a tropical wave located east on August 21, strengthening into a tropical storm later that day. Issac entered the southeastern Gulf of Mexico early on August
and it moved slowly toward northwest. Issac gradually strengthened while moving across the Gulf of Mexico and reached hurricane strength at the morning of August 28. The storm made its land fall at 2354 UTC August 28, near the mouth of Mississippi River. The center then went westward back over water and made a second landfall west of Port Fourchon, Louisiana, around 0800 UTC August 29. Isaac gradually weakened once it moved inland, and it became a tropical storm at 1800 UTC August 29. A mid-level anticyclone over the southeastern United States steered Isaac northwestward across Louisiana on 30 August, and the cyclone weakened to a tropical depression around 0000 UTC 31 August. The depression turned northward and moved into extreme southwestern Missouri later on August 31. The center of circulation then lost its definition over western Missouri early on 1 September, and Isaac dissipated just after 0600 UTC.

Table 2.1: List of dates, maximum wind speed and minimum sea level pressure for the hurricanes investigated in current study.

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>Dates</th>
<th>Max Wind (kt)</th>
<th>Min Pressure (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earl</td>
<td>2010</td>
<td>29 August–3 September</td>
<td>125</td>
<td>928</td>
</tr>
<tr>
<td>Danielle</td>
<td>2010</td>
<td>29–30 August</td>
<td>115</td>
<td>942</td>
</tr>
<tr>
<td>Igor</td>
<td></td>
<td>4–21 September</td>
<td>135</td>
<td>924</td>
</tr>
<tr>
<td>Julia</td>
<td></td>
<td>12–20 September</td>
<td>115</td>
<td>950</td>
</tr>
<tr>
<td>Irene</td>
<td></td>
<td>21–28 August</td>
<td>105</td>
<td>942</td>
</tr>
<tr>
<td>Katia</td>
<td>2011</td>
<td>29 August–10 September</td>
<td>115</td>
<td>942</td>
</tr>
<tr>
<td>Ophelia</td>
<td>2011</td>
<td>20 September–3 October</td>
<td>120</td>
<td>940</td>
</tr>
<tr>
<td>Rina</td>
<td></td>
<td>23–28 October</td>
<td>95</td>
<td>966</td>
</tr>
<tr>
<td>Isaac</td>
<td>2012</td>
<td>22–30 August</td>
<td>70</td>
<td>968</td>
</tr>
<tr>
<td>Michael</td>
<td>2012</td>
<td>4–11 September</td>
<td>100</td>
<td>964</td>
</tr>
<tr>
<td>Nadine</td>
<td></td>
<td>11 September–4 October</td>
<td>80</td>
<td>978</td>
</tr>
<tr>
<td>Sandy</td>
<td></td>
<td>19–30 October</td>
<td>95</td>
<td>940</td>
</tr>
</tbody>
</table>
Fig. 2.1: (a) Best Track observed track of Hurricane Earl from 0000 UTC August 29 to 0000 UTC September 03, 2010, sea level pressure at 1200 UTC August 31 from NCEP FNL (Final) Operational Global Analysis data is also plotted; and (b) illustration of polar-orbit satellites (color lines) observations available in the hurricane region of Earl from 0000 UTC August 29 to 0000 UTC September 03, 2010. The minimum sea level pressure (hPa, solid) and maximum wind speed (kt, dash) are also plotted.
2.2 Data Description

Microwave Humidity Sounder (MHS) onboard NOAA-18 and MetOp-A polar orbiting satellites is a cross-track scanning microwave radiometer for atmospheric water vapor sounding. The antenna provides a cross-track scan, with a swath width of 2250 km and a total of 90 FOVs on each scan line. Although MHS swaths are 2250 km in width, the sample was limited to those cases in which the storm center fell within 600 km of the swath center. The spatial resolution of MHS is 15 km at nadir and approximately 26 km at 600 km from the swath center. In general, polar-orbit satellites can observe the same geolocation twice a day. However, due to orbital gaps, the samples could be less than twice daily, especially for tropics and low latitudinal zones. Using MHS on board multi-satellite helps to improve the temporal resolution. Figure 2.1b gives an illustration of observations available from MHS on board MetOp-A, NOAA-15, 16, 18, 19 and FY-3A during Earl’s rapid intensification process. The six polar-orbiting satellites provide an evolution of surface-sensitive channel observation for hurricane Earl in every 3 hours.

MHS measures microwave radiation at five channels 89 GHz (surface), 157 GHz (surface), 183.31 ± 1 GHz, 183.31 ± 3 GHz, and 190.31 GHz. Those five-channel high frequency microwave observations are sensitive to ice cloud due to scattering effect. Previous studies have shown that brightness temperature ($T_b$) from high frequency microwave observations can be strongly depressed due to the presence of precipitation-sized ice particles (Wilheit et al. 1982; Adler et al. 1990; Weng and Gordy 2000).

For comparison, TC intensity and wind radii estimations from National Hurricane Center (NHC) best track\(^1\) data is linearly interpolated to the time of the swath. Best track data is NHC post-storm analyses of the intensity, central pressure, position, and size of tropical and subtropical cyclones. Best Track intensity and position estimates have been provided for every synoptic time (0000, 0600, 1200 and 1800 UTC) for the tropical storms, hurricanes, and subtropical storms. The data used in the analyses are satellite observations, scatterometer observations, aircraft reconnaissance data and in situ observations such as ships, buoys etc.

Advanced Very High Resolution Radiometer (AVHRR) is also used for comparison. AVHRR is a six-channel cross-track radiometer. It is currently on board NOAA-15, -16, -17, -18, -19 and MetOp-A, which provides information about cloud, ice cover and sea surface temperature, etc. AVHRR has three visible channels (channel 1, 2, 3a) and three thermal infrared channels (channel 3b, 4, 5). The AVHRR Channel 4 (10.8 µm) observation on board the same satellite as MHS is used in current study.

Table 2.2: MHS instrument characteristics.

<table>
<thead>
<tr>
<th>Channel number</th>
<th>Frequency (GHz)</th>
<th>Nadir Res. (km)</th>
<th>WF (hPa)</th>
<th>Swath width (km)</th>
<th>NE ΔT(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>89</td>
<td>15</td>
<td>Surface</td>
<td>2250</td>
<td>0.23</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>15</td>
<td>Surface</td>
<td>2250</td>
<td>0.37</td>
</tr>
<tr>
<td>3</td>
<td>183.31 ± 1</td>
<td>15</td>
<td>400</td>
<td>2250</td>
<td>0.55</td>
</tr>
<tr>
<td>4</td>
<td>183.31 ± 3</td>
<td>15</td>
<td>600</td>
<td>2250</td>
<td>0.42</td>
</tr>
<tr>
<td>5</td>
<td>190.31</td>
<td>15</td>
<td>800</td>
<td>2250</td>
<td>0.35</td>
</tr>
</tbody>
</table>
CHAPTER THREE

TC CENTER AND RADIUS OF MAXIMUM WIND DRIVED FROM MHS

3.1 Hurricane Structures Observed By MHS

At frequencies higher than 80 GHz, scattering by cloud ice and snow particles becomes strong enough to be detected by spaceborne microwave radiometers. Thus, the sensor can easily detected intense convection associate with tropical cyclone rainbands and eyewall due to the depressed brightness temperatures. Figure 3.1 provides the MHS channel 2 (157 GHz) brightness temperature observation from 1009 pm August 29 to 0655 pm August 3 on board European MetOp-A, United States NOAA-15, 16, 18, 19 and Chinese FY-3A MicroWave Humidity Sounder (MWHS) during Earl’s rapid intensification process. The hurricane eye, eyewall and rainband features are clearly resolved by MHS. The time series of 157 GHz data reveal the evolution of convective structure during Earl’s rapid intensification process.

Figure 3.2a shows the MHS Channel 2 brightness temperature centered at Hurricane Earl at 1739 UTC August 30, 2010. The eyewall and rainband region is corresponding to relatively low brightness temperature, and the hurricane eye is corresponding to high brightness temperature. Large ice particles in the eyewall and rainband region caused a strong scattering effect of microwave radiation and a sharp depression of the brightness temperature. The microwave observation, which can penetrate the cloud, provides a vertical hydrometer distribution in atmosphere. The radial profile of channel 1-5 brightness temperature from MHS located at their weighting function peaks shows the vertical structure of Hurricane (Fig. 3.2b). In the hurricane center, the brightness temperature is relatively high, which related to clear sky in hurricane eye. Surrounding the eye, there is a core of low brightness temperature values. The minimum value is located near 700 hPa, with a horizontal scale of 100 km and a vertical scale of the entire
troposphere. The IWP and CLW profiles along line AB are also showed in the Figure 3.2b. A negative correlation of IWP and brightness temperature at the low level of atmosphere is apparent.

Fig. 3.1: Evolution of brightness temperature observed from channel 2 (157.0 GHz) of Microwave Humidity Sensor (MHS) on board MetOp-A, NOAA-15, 16, 18, 19 and channel2 (150.0 GHz) of MicroWave Humidity Sounder (MWHS) on board FY-3A.
Fig. 3.1 – continued.
Fig. 3.2: NOAA-18 MHS (a) channel 2 $T_b$ horizontal distribution, (b) radial profile of channel 1-5 along line AB in (a). IWP (solid) and CLW (dotted, divided by 3) are plotted in (b).
3.2 TC Center and Radius of Maximum Wind Estimated by MHS

Finding the accurate location of the TC center is a critical first step in the tropical cyclone analysis process. Visible/Infrared Satellite data have been traditionally used to estimate the low level circulation center positions. This has known inadequacies when a true center is obscured by cirrus debris, and/or the true low level circulation center is not aligned with the circulation center provided by clouds above. The microwave radiation can penetrate most clouds beyond the top layers. Therefore, MHS observation can be an alternative method for TC center location. In current study, MHS surface sensitive channel (channel 2, 157 GHz) is used to determine the TC center. The hurricane eye is featured as warming by downdraft and a convection free region surrounded by a ring of strong convection in eyewall. In the MHS brightness temperature distribution, the hurricane eye is featured as a local brightness temperature maximum circled within the extreme low brightness temperature in the eyewall. Figure 3.3 gives an example of determining hurricane center using MHS observed brightness temperature. Brightness temperature profiles at the fixed scan position are plotted to avoid the limb effect. The hurricane center in this case is located at the highest brightness temperature FOV center inside the eyewall, which corresponds to the clear sky in hurricane eye region.

The maximum sustained wind associated with a TC is a common indicator of the intensity of the storm. Within a mature tropical cyclone, it is found within the eyewall at a distance defined as the radius of maximum wind ($R_{\text{max}}$). It is known that the eyewall is a ring of thunderstorms where the most damaging winds and intense rainfall is found. In this study, the $R_{\text{max}}$ is determined by analyzing the brightness temperature radial profiles from the hurricane center. It is seen that brightness temperature has an asymmetric distribution. To consider this asymmetric feature, the brightness temperature radial profiles from the hurricane center in every 6 degree are calculated. It is seen that most of the first minimum brightness temperature points are located near the radius of maximum wind (Fig. 3.4a). Some of the first minimum points are continuous with their neighboring points, such as those shaded points from 60°-120° azimuthal angle in Figure 3.4a. However, some of the first minimum points are just isolated with others.
The local minimum brightness temperature related to the strongest convection located in hurricane eyewall should have certain spatial continuity. Therefore a continuous condition is set for finding the radius of maximum wind. The radial profiles in the range of 60º-120º azimuthal angle are showed in Figure 3.4b. And the radius of maximum wind is finally determined as the radial distance for the first minimum point of brightness temperature with lowest value indicated as pink dot (Figure 3.4b).

The technique of finding TC center location and radius of maximum wind mentioned above was applied to the 12 TCs listed in Table 2.1. The probability density function (PDF) distribution of difference between TC center from NHC and MHS for 12 hurricanes is showed in Figure 3.6. It is showed that 78.52% of the center difference between MHS and Best Track fall within 15 km and only 10.9% of the difference are more than 30 km. The PDF distribution of difference between radius of maximum wind determined by MHS and Best Track also shows a consistency between those two estimations. It can be seen that 78.45% of the radius of maximum wind difference are within 10 km and only 9.4% of the difference are larger than 30 km. These results suggest that MHS can provide TC location and radius of maximum wind estimation that are comparable to NHC Best Track estimation. Because NHC Best Track is independent of MHS data, including MHS to Best Track estimation would likely lead to even more accurate estimates.

The scattering plots of Best Track radius of maximum wind against MHS estimation are showed in Figure 3.7. In TD and TS strength, some cases of large difference between MHS and Best Track estimation occurred. For hurricane intensities, the Best Track and MHS estimation are generally consistent with each other. The differences between Best Track and MHS estimated TC center are also indicated in color in Figure 3.7. Four cases indicated with numbers are chose for further analysis by comparing with infrared images.
Fig. 3.3: (a) MHS observed $T_b$ (channel 2) near Hurricane Earl center at 1724 UTC September 1, 2010; (b) profiles of $T_b$ along fixed scan angles.
Fig. 3.4: (a) Radial distance against the azimuthal angle for the first minimum $T_b$ points from the hurricane center (colored dots); (b) Radial profile of $T_b$ from azimuthal angles shaded in (a), the first minimum $T_b$ points are highlighted as dots and the radial profile is color coded by azimuthal angle.
Fig. 3.5: Best track for 12 TCs listed in Table 2.1.

Earl Danielle Igor Nadine Irene Rina Michael Sandy Ophelia Isaac Katia Julia

TD TS Cat 1 Cat 2 Cat 3 Cat 4
Fig. 3.6: (a) PDF distribution of distance between hurricane center determined by MHS TbS and Best Track and (b) PDF distribution of difference between radius of maximum wind determined by MHS TbS and Best Track for 12 Hurricanes.
Fig. 3.7: Scattering plots of the radius of maximum wind estimated from MHS data compared with best track data. The distance between hurricane centers determined from MHS data compared with best track data is indicated in color.
3.3 Comparison with AVHRR

Infrared images from AVHRR channel 4 (10.8 µm) on board NOAA-18 and MetOp-A are used for comparison. AVHRR is a cross track scanner that provides global imagery twice a day at 1 km resolution (at nadir). The channel characteristics for AVHRR are listed in Table 3.1. Various algorithms for cloud detection and classification using AVHRR data have been developed for use in a wide range of meteorological, climatological, and oceanic applications (Dybbroe et. al. 2005). Inoue (1985), Rozekrans and Prangsma (1986) shows that the temperature difference between AVHRR five-channel data can be used to detect most type of cloud. Atmospheric is relatively transparent to radiation upwelling from the Earth’s surface in the 10-12.5 µm window. According to the temperature dependence of the Planck function, lower brightness temperature is related to colder cloud top radiation. In this study, AVHRR channel 4 infrared images are used directly for the cloud detection purpose.

The infrared image on the left panel of Figure 3.8 shows the hurricane eye region with warm brightness temperature and is generally consistent with the MHS brightness temperature distribution on the right panel. The TC center and radius of maximum wind from Best Track (black) and MHS (red) are indicated as dot and circle respectively in Figure 3.8. In case 1, it is seen that the MHS estimated TC center is also located at the center of hurricane eye from the infrared image. In case 2, the hurricane eye in infrared image is partly covered by cloud. From the MHS brightness temperature distribution, the hurricane eye region is clearer. There might be some thin cloud over the hurricane eye and the microwave observation from MHS can penetrate it. In case 3, the MHS and Best Track estimation is generally consistent with each other with a small deviation. In case 4, there is a large difference between MHS and Best Track determined radius of maximum wind. From infrared image, the radius of maximum wind determined by MHS is located in the cloud region where there is extreme cold brightness temperature. However, this case has some uncertainty to be addressed because the hurricane does not have a complete eye structure. Moreover, the hurricane is located at high latitude. The large scale weather systems, such as trough, can influence the hurricane structure.
<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Resolution at Nadir</th>
<th>Wavelength (um)</th>
<th>Typical Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.09 km</td>
<td>0.58-0.68</td>
<td>Daytime cloud and surface mapping</td>
</tr>
<tr>
<td>2</td>
<td>1.09 km</td>
<td>0.725-1.00</td>
<td>Land-water boundaries</td>
</tr>
<tr>
<td>3A</td>
<td>1.09 km</td>
<td>1.58-1.64</td>
<td>Snow and ice detection</td>
</tr>
<tr>
<td>3B</td>
<td>1.09 km</td>
<td>3.55-3.93</td>
<td>Night cloud mapping, sea surface temperature</td>
</tr>
<tr>
<td>4</td>
<td>1.09 km</td>
<td>10.30-11.30</td>
<td>Night cloud mapping, sea surface temperature</td>
</tr>
<tr>
<td>5</td>
<td>1.09 km</td>
<td>11.50-12.50</td>
<td>Sea surface temperature</td>
</tr>
</tbody>
</table>
Fig. 3.8: Spatial distributions of AVHRR channel4 T_b (infrared, 10.8 um, left panels) and MHS Channel2 T_b (157 GHz, right panels) on board NOAA18 and MetOp-A. The Best Track observed and modified hurricane center are indicated as black and red dots respectively. The radius of maximum wind from Best Track and T_b are indicated as black dashed circle and red star respectively.

1325UTC September 5, 2011 (Cat 2, Δcenter=13.19 km, ΔR_{max}=0.5 km)

0043UTC September 6, 2011 (Cat 3, Δcenter=19.3 km, ΔR_{max}=6.7 km)
Fig. 3.8- continued.
CHAPTER FOUR

CONCLUSIONS

4.1 Conclusions

This study used MHS observation to estimate TC center position and radius of maximum wind. The physical part of this study is that brightness temperature decreased sharply in hurricane eyewall and rainband regions by the scattering effect from cloud ice particles, and is relatively high in the cloud free region. When hurricane eye exits, the hurricane center located at the center of a high brightness temperature region surrounded by a ring of low brightness temperature. In this study, the TC center is determined as the warmest brightness temperature observation point within TC eyewall region.

A relationship between radius of maximum wind and the first minimum point along the brightness temperature profile is observed. The radius of maximum wind is estimated by calculating brightness temperature radial profiles at six-degree interval. The first minimum point with lowest value and continuity with its neighbor points is chosen as the radius of maximum wind.

The method of determining TC center and radius of maximum wind is applied to 12 selected hurricanes. The result shows that MHS can provide TC location and radius of maximum wind estimation that are comparable to NHC Best Track estimation. Since MHS observation onboard polar-orbiting satellite, the method mentioned above can provide estimations for hurricane center and radius of maximum wind globally, especially useful when other types of observation are not available.
4.2 Future Work

Future work may include extend the TC center and radius of maximum wind estimation method globally to all other tropical basins. The potential information of 34-, 50-, and 64-kt wind radii within MHS observation will be investigated. The probability of real time TC center and wind radii estimation by MHS will be studied. The TC center and wind radii information determined by MHS will be assimilated to Hurricane Weather Research and Forecasting (HWRF) model to improve the track and intensity forecast.
REFERENCES


BIOGRAPHICAL SKETCH

Education
M.S. Meteorology, May 2014, The Florida State University, Tallahassee, FL.
M.S. Meteorology, June 2010, Nanjing University, Nanjing, China.
B.S. Atmospheric Sciences, June 2008, Nanjing University, Nanjing, China.

Experience
2010-present: Graduate Research Assistant / Department of Meteorology, FSU
2008-2010: Teaching Assistant / Nanjing, China