Atmospheric Research 214 (2018) 375–385

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Conditions associated with rain field size for tropical cyclones landfalling over the Eastern United States

Yao Zhou[a,*], Corene Matyas[b], Han Li[c], Jingyin Tang[d]

[a] School of Public Administration, National Center for Integrated Coastal Research, University of Central Florida, Orlando, FL 32816, USA
[b] Department of Geography, University of Florida, 3141 Turlington Hall, Gainesville, FL 32611, USA.
[c] Department of Geography and Regional Studies, University of Miami, Coral Gables, FL 33124, USA
[d] IBM, 1001 Summit Blvd, Brookhaven, GA 30319, USA

ARTICLE INFO

Keywords:
Tropical cyclones
Rain field size
Geographic Information System
Statistical models

ABSTRACT

This study analyzes the relationships between the size of tropical cyclone (TC) rainfall fields and storm attributes and surrounding environmental conditions. A Geographic Information System analysis is employed to measure the area and averaged-quadrant extent of rain fields associated with 70 U.S. landfalling TCs as detected by satellites at a three-hour resolution during 1998–2015. Statistical models are developed to predict the area and extent of TC rainfall fields before and after landfall. The conditions examined include storm intensity, motion, storm location, total precipitable water (TPW), upper-tropospheric divergence, and deep-layer wind shear. The spatial pattern of the area and the quadrant-averaged extent exhibits large variability. The total area and rear extents are much larger over the southeastern Gulf, especially for the right-rear extent, which is approximately 300 km away from the center. As the area and rear extents quickly decay, rainfall in the forward quadrants can still extend farther than 200–300 km from the storm center during and after landfall. The average rainfall duration is 30 (22) hours on the right (left) side of the storm track. The statistical models reveal that TPW within 400 km of the storm center and upper-tropospheric divergence are the strongest predictors of both overall coverage and extent in all quadrants. A deep-layer vertical wind shear with a strong westerly component correlates well with a larger extent in the forward quadrants of the storm. Storm intensity has more influence on rainfall over the ocean, while the distance to the coastline has more influence over land.

1. Introduction

When a tropical cyclone (TC) makes landfall and moves inland, storm surge, strong wind, intense rainfall, and tornadoes can cause tremendous damage and numerous fatalities in both coastal and inland regions. Among these TC-associated hazards, tropical cyclone precipitation (TCP) and the induced inland freshwater flooding (or mudslides in mountains induced by flash flooding) are one of the most deadly and destructive hazards to society and the environment (Aryal et al., 2018; Rappaport, 2000, 2014; Villarini et al., 2014). Correctly predicting the specific areas that will experience moderate to high rain rates that can result in flooding is extremely important in disaster mitigation. When TCs approach the coastline and move over land, their rain fields exhibit high variability in size and distribution, which presents operational challenges to the prediction of TCP (Atallah et al., 2007; Lonfat et al., 2007; Zick and Matyas, 2016). Predicting how far ahead of the storm center rain fields extend is key to forecasting when rainfall will begin ahead of landfall. Thus, presenting the climatology of the size of TC rain fields and identifying the factors contributing to the organization of rainfall while these systems are over the ocean prior to making landfall, and after they make landfall, is needed to improve the prediction of the spatial pattern of TCP (Lonfat et al., 2004, 2007; Matyas, 2013; Rappaport, 2014).

Traditionally, the size of a TC is measured as the radius of a particular wind speed (e.g., the radius of gale-force winds) or the radius of the outermost closed isobar (ROCI) (Kimball and Mulekar, 2004; Knapp et al., 2010). In addition to these intensively investigated TC attributes, the size of TCP has drawn attention from scholars in recent years due to its importance in hazard mitigation and the forecasting challenge it presents (Lin et al., 2015; Matyas, 2010b; Rezapour and Baldock, 2014). The size of TCP is identified as the area or extent of TC rainfall over a certain rain rate threshold. Matyas (2010b) measured the extent of rainfall in each quadrant from ground-based radar as hurricanes crossed the U.S. coastline. Other researchers have measured the size of

---

[*] Corresponding author.
E-mail addresses: Yao.Zhou@ucf.edu (Y. Zhou), matyas@ufl.edu (C. Matyas), han.li@miami.edu (H. Li), Jingyin.Tang@ibm.com (J. Tang).

https://doi.org/10.1016/j.atmosres.2018.08.019
Received 24 March 2018; Received in revised form 19 August 2018; Accepted 21 August 2018

TCP from gridded precipitation datasets with various spatial-temporal resolutions (Jiang et al., 2011; Lin et al., 2015; Matyas, 2014; Nogueira and Keim, 2010). However, we are not aware of a study employing satellite-based estimations of rain rates to measure and predict the size of TC rain fields prior to, during, and after landfall.

Previous numerical and observational research has examined a variety of TC attributes and environmental conditions that contribute to the rainfall structures of TCs, including storm intensity, storm size, storm motion, moisture availability, vertical wind shear, and interactions with midlatitude systems (Jiang et al., 2008a; 2008b; Konrad and Perry, 2010; Lonfat et al., 2007; Matyas, 2010b; Zick and Matyas, 2016). A stronger storm intensity and higher environmental moisture contributes to a higher convective rainfall magnitude and larger rainfall coverage with a more cohesive pattern (Cerveny and Newman, 2000; Hernández Ayala and Matyas, 2016; Hill and Lackmann, 2009; Jiang et al., 2008b; Kimball, 2008; Konrad and Perry, 2010; Lonfat et al., 2007; Zick and Matyas, 2016). Moreover, stronger divergence in the upper-level troposphere is also related to larger TC size and higher rainfall potential (Jiang et al., 2008a; Konrad and Perry, 2010). TCP asymmetries are mostly related to the vertical wind shear and storm motion. When storm forward velocity increases, rainfall shifts to a location ahead of the storm due to the enhanced low-level convergence in the front quadrants (Corbosiero and Molinari, 2002; Rodgers and Pierce, 1995; Shapiro, 1983). However, more recent research shows that the wind shear effect is more dominant than the motion effect. Strong vertical wind shear causes rainfall to occur in the downshear direction, especially to the downshear left side in the inner portion of the storm (< 100 km) (Cecil, 2007; Chen et al., 2006; Wingo and Cecil, 2010) and downshear/downshear right in the outer rain bands (100–300 km) (Corbosiero and Molinari, 2002; Matyas, 2010a). Moreover, moisture distribution also influences the asymmetry of TC rainfall. When relatively dry air is drawn into a TC's circulation from one side, it reduces rainfall on that side (Kimball, 2006, 2008; Matyas and Cartaya, 2009).

As TCs move into the midlatitudes, as they do when approaching the U.S. mainland, they may experience changes in environmental conditions including increased baroclinicity, enhanced horizontal moisture gradients, strong vertical wind shear, and interaction with frontal systems or troughs, and they may undergo an extra-tropical transition (ET) (Atallah and Bosart, 2003; Evans et al., 2017; Jones et al., 2003). During the ET process, the structure of the TCs changes dramatically as it loses symmetric structure and gradually takes on the appearance of an extratropical cyclone. At the beginning of the ET process, the rainfall area ahead of the storm center begins to expand due to warm and moist tropical air being lifted over the poleward region (north or northwest) as the TC's circulation intersects with an upstream trough and/or with a low-level baroclinic zone (Harr and Elsberry, 2000). Meanwhile, the rain fields decrease behind the storm center, forming a “dry slot”, because of the advection of relatively drier and cooler air to the rear of the storm center (south or southwest) (Jones et al., 2003). As ET proceeds, a right-to-left cross-track shift in the rainfall distribution might be observed, and high-rain rate regions can extend a few hundred kilometers from the storm center (Atallah et al., 2007; Matyas et al., 2018; Evans et al., 2017). The entire ET process can vary in length from as few as 12 h to 72 h and beyond (Hart et al., 2006).

Although many studies have investigated TCP over land or ocean and its contributing factors using both dynamical modeling and empirical methods, a need exists to investigate combinations of these factors and build statistical models that determine which variables make the strongest contributions to rainfall area and extent in each quadrant before and after landfall. This study utilizes Geographic Information System (GIS) analysis to measure the area and extent of rain fields associated with TCs making landfall over the eastern U.S. from 1998 to 2015 from a satellite-derived precipitation dataset. The research questions are: first, what is the spatial variation in the size of TC rain fields in each quadrant of the storm before and after landfall? Second, which TC attributes and environmental conditions, including TC intensity and motion, environmental moisture, upper tropospheric divergence and vertical wind shear, have the highest correlations with the size of TC rain fields and at which time lags over the ocean and land? Last, what is the order of importance of storm attributes and environmental conditions for the prediction of TC rain field size as revealed using statistical models? Identifying these conditions could help improve the accuracy of the spatial distribution of TCP in forecasts so that people located various distances from either side of the forecasted TC track can better know whether or not they will receive TCP and the start time of the rainfall.

2. Data and methodology

2.1. Data

The precipitation data used in this study are taken from the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) 3B42 precipitation product version 7 (Huffman, 2007). The TMPA 3B42 product contains rain rates derived from satellite-based passive microwave and infrared sensors and applies a correction using data from rain gauges. The TMPA 3B42 data are available every 3 h from 1998 to 2015, with a spatial resolution of a 0.25° latitude-longitude grid over a global latitude belt from 50°S to 50°N (Huffman, 2007). The TMPA 3B42 dataset has been widely used to explore TC rainfall regionally and globally (Jiang et al., 2011; Lau and Wu, 2011; Lau and Zhou, 2012; Luitel et al., 2018; Matyas, 2014; Prat and Nelson, 2013, 2016; Xu et al., 2014; Villarini et al., 2011). Although the TMPA dataset is subject to uncertainties over land, especially in regions of complex orography (Zhou et al., 2015), TRMM 3B42 data still offer good quality when exploring TC rain fields over ocean and land due to their high spatial and temporal resolutions, semi-global coverage over ocean and land, and relatively low bias compared to other satellite products, such as the CPC morphing technique (CMORPH) and Global Satellite Mapping of Precipitation (GSMaP) (Blacutt et al., 2015; Chen et al., 2013; Maggioni et al., 2016; Zagrodnik and Jiang, 2013; Zhu and Quiring, 2017).

The TC position data are obtained from the IBTrACS database (Knapp et al., 2010). After excluding TCs that dissipated < 12 h after landfall and short-lived TCs that formed near the coastline, 70 TCs are included in this study (Fig. 1). Thirty-four TCs became extra-tropical cyclones. The 6-hourly positions are interpolated to every 3 h using a cubic spline method to match the timestamps of the TRMM observations (Jagger and Elsner, 2006). To match the spatial coverage of TMPA data which extends to 50°N, and since the rain fields of TCs may extend outward to > 500 km from storm center as suggested by previous studies (Jiang et al., 2011; Khouakhi et al., 2017), we limit observations to those wherein the circulation center is located south of 45°N. As our goal is to examine rain fields near and over land, each TC is examined at a 3-h interval beginning from when it was first within 600 km of the U.S. coastline and ending at the time when it dissipated over land, moved north of 45°N, or crossed back over the ocean. The storm intensity, motion speed, and direction are also calculated from the interpolated center positions. A higher storm intensity should be positively correlated with larger rainfall coverage and higher rain rates. Moreover, if TCs gain a faster speed to the north or northeast direction, this implies that TCs are interacting with the westerlies, which should result in expansion of the TC rainfall area, especially on the left side (Jones et al., 2003).

Several environmental conditions, including moisture, upper troposphere divergence, and deep-layer wind shear, are employed to explore their associations with TC rain field size. These variables that characterize the environmental conditions around the storms are obtained from the Statistical Hurricane Intensity Scheme (SHIPS) database (DeMaria and Kaplan, 1999; DeMaria et al., 2005). The SHIPS variables are derived from the National Centers for Environmental Prediction