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The contribution of tropical cyclones to rainfall in Mexico

J. Agustín Breña-Naranjo *, Adrián Pedrozo-Acuña, Oscar Pozos-Estrada, Salma A. Jiménez-López, Marco R. López-López

Instituto de Ingeniería, Universidad Nacional Autónoma de México, Cd. Universitaria, 04510 Coyoacán, D.F., Mexico

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A B S T R A C T

Investigating the contribution of tropical cyclones to the terrestrial water cycle can help quantify the benefits and hazards caused by the rainfall generated from this type of hydro-meteorological event. Rainfall induced by tropical cyclones can enhance both flood risk and groundwater recharge, and it is therefore important to characterise its minimum, mean and maximum contributions to a region or country's water balance. This work evaluates the rainfall contribution of tropical depressions, storms and hurricanes across Mexico from 1998 to 2013 using the satellite-derived precipitation dataset TMPA 3B42. Additionally, the sensitivity of rainfall to other datasets was assessed: the national rain gauge observation network, real-time satellite rainfall and a merged product that combines rain gauges with non-calibrated space-borne rainfall measurements. The lower Baja California peninsula had the highest contribution from cyclonic rainfall in relative terms (~40% of its total annual rainfall), whereas the contributions in the rest of the country showed a low-to-medium dependence on tropical cyclones, with mean values ranging from 0% to 20%. In quantitative terms, southern regions of Mexico can receive more than 2400 mm of cyclonic rainfall during years with significant TC activity. Moreover, (a) the number of tropical cyclones impacting Mexico has been significantly increasing since 1998, but cyclonic contributions in relative and quantitative terms have not been increasing, and (b) wind speed and rainfall intensity during cyclones are not highly correlated. Future work should evaluate the impacts of such contributions on surface and groundwater hydrological processes and connect the knowledge gaps between the magnitude of tropical cyclones, flood hazards, and economic losses.

1. Introduction

Tropical cyclones (TCs) are major natural disasters, ranking as the second leading cause of fatalities related to natural hazards, and are expected to cause more damage and economic losses in the future (Peduzzi et al., 2012). The Atlantic TC season begins on approximately June 1st and ends on November 30th, whereas the season in the Northeast Pacific Basin typically begins in late May or early June and often continues through late October or early November. Observed impacts of TCs are typically associated with wind speed as defined by the Saffir-Simpson scale (Simpson, 1974) and the induced storm surges that may produce severe coastal flooding. For example, large-scale coastal floods have been registered in the United States, with combined economic losses on the order of hundreds of billions of dollars (Michel-Kerjan, 2012). Several studies have noted that in addition to strong winds and high water levels, TCs may also bring torrential rains when they make landfall (Gao et al., 2009; Dong et al., 2010; Nogueira and Keim, 2010). Such amounts of rainfall have the potential to generate significant floods, which contribute to a large percentage of the registered damages caused by TCs (Larson et al., 2005; Chen et al., 2014). On the other hand, TCs can make important contributions to subsurface hydrological processes (Descroix et al., 2007) and to recharge and storage in lakes and reservoirs, and they can therefore relieve water stress in regions experiencing drought and/or facing persistent water scarcity (Kam et al., 2013). For instance, Maxwell et al. (2012) found that approximately 40% of the droughts that occurred in the southeastern U.S. during the second half of the 20th century were abruptly ended by TCs.

Due to its geographical location (Fig. 1), Mexico is prone to strikes by landfalling tropical cyclones along both its Pacific and Atlantic coasts. Thus, it is not surprising that flooding is the major and costliest natural hazard in Mexico. This has been recently observed during the incidence of TCs such as Manuel in 2013 and Odile in 2014 on the Pacific coast and Arlene in 2011 and Ingrid in 2013 in the Gulf of Mexico, which produced severe flooding that caused large social disruption and economic losses

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* Corresponding author at: Instituto de Ingeniería, UNAM, Mexico City, Mexico.
E-mail address: jbrenan@ii.unam.mx (J. Agustín Breña-Naranjo).

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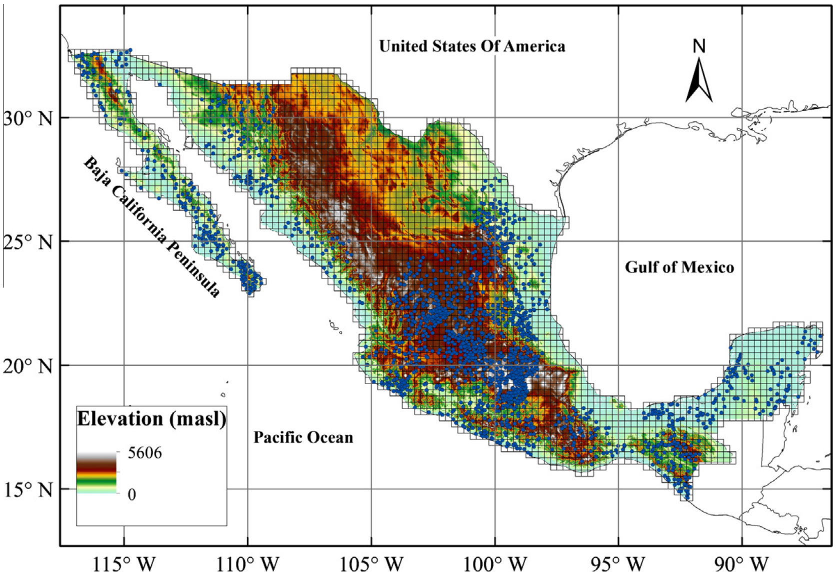

Fig. 1. Location of rain gauges (blue dots) and distribution of the TMPA grid across Mexico's terrestrial surface. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Pedrozo-Acuña et al., 2014). Such events also provided moderate rainfall in regions located out of the main hurricane path and hence replenished aquifers and reservoirs, but the total contribution of cyclonic precipitation to the total annual rainfall in Mexico remains unknown. Hence, studying the amount of rainfall attributed to tropical depressions, storms and hurricanes can improve our understanding of the different sources of precipitation (cyclonic, convective, orographic) and the control they exert on the terrestrial water balance. Additionally, quantifying the sources and fates of precipitation could be used to establish a modelling framework to quantify the sensitivity of the water balance to future changes in precipitation.

Previous studies have investigated the TC rainfall contribution worldwide (Jiang and Zipser, 2010; Prat and Nelson, 2013a), as well as in different countries such as the United States (Atallah et al., 2007; Knight and Davis, 2009; Kam et al., 2013; Brun and Barros, 2014), Australia (Dare et al., 2012; Chen et al., 2013; Ng et al., 2014) and China (Cheng et al., 2008). These studies have largely benefited from the advent of satellite-based remote sensing, specifically that used to monitor the Earth's climatic variables. For instance, satellites can assess the distribution of hurricane-induced rainfall (Lonfat et al., 2004) and detect the contribution of cyclones to the world's greatest rainfall events (Breña-Naranjo et al., 2014), among others. Moreover, satellite-derived datasets of precipitation have increased the ability to evaluate the hydrological response of catchments to cyclonic rainfall (Villarini et al., 2011; Chen et al., 2014).

The observational joint mission between the National Aeronautics and Space Administration (NASA) of the United States and the National Space Development Agency (NASDA) of Japan, known as the Tropical Rainfall Measuring Mission (TRMM) (Kummerow et al., 1998), demonstrated the ability to quantify rainfall rates in tropical and temperate regions of the world. The primary rainfall instruments on the TRMM are the TRMM Microwave Imager (TMI), precipitation radar (PR), and a Visible and Infrared Radiometer System (VIRS). This dataset has been used to estimate the rainfall contribution of TCs to total annual rainfall between 35°N and 35°S (Yokoyama and Takayabu, 2008). However, the TRMM Multisatellite Precipitation Analysis (TMPA, also referred to as TRMM 3B42; Huffman et al., 2007) provides quasi-global (50°S–50°N) coverage of rainfall estimates at 3 h and daily temporal resolutions and a $0.25^\circ \times 0.25^\circ$ spatial resolution. The TRMM 3B42 product was previously used to assess the global contribution of tropical cyclones over six regions of the world that are constantly hit by cyclonic events (Jiang and Zipser, 2010; Jiang et al., 2011; Prat and Nelson, 2013a). TC studies based on TRMM data have been carried out for different purposes as well, such as investigating the roles of storm asymmetry (Lonfat et al., 2004), areal extents (Matyas, 2014) and convection in the inner core of TCs (Chang et al., 2014) on the magnitude of rainfall rates and cumulative totals.

Mexico is a country that is highly vulnerable to TCs on both coasts, and thus it is desirable to understand their contribution to the total rainfall observed in the country. The identification of geographical, seasonal and interannual patterns of rainfall associated with these events is particularly important because there is a large spatial variability in both the rainfall contribution of each storm and the geographical location of its landfall (Jiang and Zipser, 2010).

The purpose of this investigation is to estimate the contribution of TCs in relative and absolute terms, i.e., the ratio to the total annual rainfall and the cumulative annual values, respectively, that occurred in the country between 1998 and 2013, using the TMPA 3B42 dataset. This product identifies the regions in Mexico with the greatest contributions from TC rainfall. Previous estimates of the contribution of cyclonic rainfall relative to the rainfall climatology in Mexico can be found in Rodgers et al. (2001), Larson et al. (2005), Jiang and Zipser (2010) and Prat and Nelson (2013a). These studies showed that the Baja California Peninsula (Fig. 1, northwesternmost region) is the region in Mexico (and of the world's terrestrial surface) that receives the largest amount of cyclonic rainfall relative to the total mean annual precipitation, with percentages ranging between 55% and 60% (Jiang and Zipser, 2010; Prat and Nelson, 2013a). Other regions receiving an important rainfall contribution from cyclonic events are the central-northern Pacific coasts and the Yucatan Peninsula with total contributions of up to 20% (Prat and Nelson, 2013a). The contribution of cyclonic rainfall during the peak hurricane season within these three regions is significantly higher, with values up to 90% of the total monthly rainfall (Larson et al., 2005).

This paper is organised as follows: The dataset and methodology for classifying the rainfall associated with TCs are presented in Section 2. The satellite-derived annual precipitation in Mexico,