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Tropical cyclone - induced heavy rainfall and flow in Colima, Western Mexico

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Abstract

Tropical cyclone (TC) landfall is often accompanied by storm surges, strong winds, and heavy rain that cause destructive flash floods, especially in mountainous regions. However, there is limited understanding of the contribution of TCs to major flood events, especially in western Mexico. In this study we assess the contribution of TCs to the annual rainfall, extreme rainfall and stream flow in the mountainous region of Colima, one of the most TC-exposed areas in western Mexico. The top 1% of daily rainfall and stream flow, annual maximum rainfall and the highest 20 stream flow events from 1970 to 2015 are examined for their association to TCs. Results indicate that the relative contribution of TCs to the average annual rainfall can exceed 25 % in the coastal area of Colima. Over 25% to 35% of heavy daily rainfall (top 1% rainfall) recorded in the coastal rain gauges is found to be associated with TCs. In terms of high flow, approximately 20% to 24% of the top 1% flow events and 28% to 35% (~7 events) of the top 20 flow events are driven by TCs. The heaviest precipitation and high flow events occur typically in the late TC season (September and October). Our results provide insights on the role of TCs in inducing rainfall and stream flow relevant for water and flood risk management.

1. Introduction

Tropical cyclones (TCs) are one of the natural hazards that cause the greatest harm to populations and damage to infrastructure around the globe. In Mexico, landfalling TCs are generated in two different TC basins; the Atlantic and the Northeast Pacific. The TC season in both basins starts generally from June 1st and finishes by the end of November for the Atlantic TCs and October for the Northeast Pacific TCs.

Flooding is one of the main consequences of TCs; according to CONAGUA (2011), during the period of 2002-2010, floods and severe rainfall events (all sources included) in Mexico caused 812 deaths and affected 14 million inhabitants, 970,000 homes, 18,400 schools, 2.8 million hectares of crops and damage of 64 000 km of primary roads. In terms of TC related damage, hurricane Kenna, in 2002, for example resulted in extensive damage, with economical losses estimated to be US$5 million, mostly caused by storm surge hitting Puerto Vallarta. Extensive surge damage also occurred in San Blas, where 80 to 90% of the homes were damaged or destroyed (Franklin *et al.*, 2003). On the east coast, hurricane Isidore hit the Yucatan Peninsula in September 2002 and affected approximately 500,000 people and caused economic losses estimated at US$ 870 million (Salas and Jimenez, 2014).

Although TC-induced storm surges are the most hazardous effect of TCs at the global scale, the influence of TC-induced rainfall is also considerable. Many of the fatalities are TC rain-induced disasters especially on steep terrain such as flash flooding and landslides. This is particularly true in Western Mexico where flash flooding from torrential rains can cause major disruptions and fatalities. These hazards also cause most of the economic damage from TCs (SMN 2013).

In the state of Colima, flooding from torrential rain is one of the most critical issues, especially in the urban area of Colima city. In 2011, TC Jova caused significant damages and most roads were flooded and bridges damaged. In 2015, TC Patricia caused heavy rainfall and severe damage to infrastructures and agriculture, with economic losses estimated at US$102.6 million. Patricia made landfall not far from Colima and is considered the most intense Pacific TC on record to strike Mexico as well as one of the most intense TCs on record globally (Rogers *et al.*, 2017). Although Patricia weakened rapidly as it hit the high terrains of the Sierra Madre, its remnants induced heavy rainfall that extended far inland across central Mexico. During the 24 hours following landfall, Patricia caused an accumulated rainfall ranging from 200 to 300 mm in the coastal area and 100 to 200 mm in the uplands near Colima (Figure 1).

The contribution of TCs to rainfall in Mexico has been demonstrated on a broad scale (e.g. (Agustín Breña-Naranjo *et al.*, 2015; Dominguez and Magaña, 2018; Englehart and Douglas, 2001; Khouakhi *et al.*, 2017). Agustin et al. (2015) found that TCs in Mexico may contribute between 20 and 60% of the observed seasonal rainfall for some coastal regions. At the seasonal scale Khouakhi et al. (2017) reported that between 30 and 50 % of rain was linked to TCs in western Mexico. Englehart and Douglas, (2001) broadly analysed rainfall associated with tropical storms along Mexico's Pacific coast using rainfall records from 1949 to 1997, but from only 18 rain gauges and found 20 to 60% of rainfall contributions from TCs, and in more extreme cases, as much as 25 to 30% of seasonal rainfall totals in western interior locations. Correlations have also been found between TC and atmospheric teleconnections: for example, Pérez-Morga et al., (2013) showed that extreme TC rainfall in Oaxaca area are associated with La Niña and the neutral condition of El Niño–Southern Oscillation (ENSO).

Despite this broad understanding of TC-induced rainfall in Mexico at large scales, there remains little understanding of the relationship between TC-rainfall and flood regime, especially in regions with steep terrain where flash floods are common and life-threatening. Additionally, few studies in the literature have quantified the TC contribution to stream flow (e.g. Barth *et al.*, 2018). In this study we focus on assessing the TC-induced extreme rainfall in Colima and develop a new method to evaluate the TC contribution to stream flow peaks in the main rivers in the state of Colima, which is one of the most flash flood-prone areas in western Mexico. We consider rainfall and stream flow in the hydrological region of Armeria - Coahuayana which is one of the 37 hydrological regions of Mexico and covers an area of 17,685 km^2. The two main rivers of the region are the Armeria and Coahuayana rivers. The Armeria river is the largest river in the state of Colima: it originates in the state of Jalisco and crosses the state of Colima before flowing into the Pacific. Its main tributaries are the Comala, Colima and the Ayuquila rivers. The Coahuayana River starts in the Cerro del Tigre, within the State of Jalisco, under the name of Tejocote, and serves as the boundary between the States of Jalisco and Colima. Its main tributaries are the Ahuijullo, Barreras and Salado rivers. The Coahuayana river flowing into the Pacific Ocean in Boca de Apiza (Figure 2).

The structure of this paper is as follows: Section 2 presents the data and the methodology. Section 3 describes the results of Colima TC statistics, TC contributions to annual and to extreme rainfall and stream flow, and section 4 summarizes and concludes the paper.

2. Data and methods

Tropical cyclone data are obtained from the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al., 2010). The data provide information on the storm location and the maximum sustained wind (MSW) every 6 hours in addition to other information such as basin and nature of the TC. We selected TCs that have been developed in the East Pacific and in the North Atlantic basins. We used TC records starting from 1970 as pre-satellite records are less certain (Pielke *et al.*, 2005; Vecchi and Knutson, 2008).

For the rainfall and stream flow, we used daily rainfall and stream flow data from 40 rain gauges and 3 stream gauges with varying record lengths from 1970 to 2015 with at least 25 years of data. We only consider yearly records that have more than 90% (~330 days/year) of data completeness (Figure 2). Rainfall records are obtained from the national meteorological database (CLICOM system). The hydrometric time series are obtained from the BANDAS database (Banco Nacional de Aguas Superficiales) managed by the Mexican Institute of Water Technology.

In order to analyse TC contribution to rainfall at the annual and monthly temporal scales and estimate the relative contribution of TCs to extreme rainfall and high flow events, we first separate rainfall caused by tropical cyclones from that induced by other mechanisms. We consider daily rainfall to be TC-associated if the centre of circulation of the TC storm is located within a 300 km radius from the rain gauge during a time window of ±1 day of the rainfall event. In most of the literature, the 500 km radius is used (e.g., Dare *et al.*, 2012; Jiang and Zipser, 2010; Scoccimarro *et al.*, 2014), but in the present study we choose to be more conservative by using a smaller radius (a) to focus on TCs that passed near the Colima area, and (b) because recent work (Rios Gaona *et al.,* 2018) has shown that the highest rainfall intensities over land are recorded with TC radii of less than 300 km. Additionally, we conducted a sensitivity analysis using a 500 km radius to examine how the results change depending on the chosen radius (Supplemental materials Figures S2 -S4).

To estimate the TC contribution to heavy rainfall, we first selected heavy rain days using two methods: 1) identifying the top 1% of the rainfall at each rain gauge, by selecting rainfall values exceeding the 99^{th} percentile of each gauge data distribution and 2) focusing on the annual maximum rainfall days. We then calculate the proportion of those heavy rainfall events associated with TCs at each rain gauge and for each method.

In terms of high stream flow associated with TCs, similar to heavy rainfall, we identified high flow events at each stream gauge by selecting the top 1% of flow events. As a second approach, for comparison, we also identified the top 20 flow events by ranking daily stream flow amounts from the highest to the lowest and selecting the first 20 high flow events. To identify independent flow events we follow Lang *et al.* (1999), and we retain the highest flow value within a time window that lasts 3 times the average time to peak; additionally the minimum discharge between two consecutive peaks must be less than two thirds of the discharge of the first of the two peaks. The rising limb at our stream gauges is generally steep, with an average of 3 days between the start of the rising limb and the peak. Hence, we select 9 days as the minimum time window to define independent flood peaks.

Next, we define stream flow associated with TCs by examining if the high flow event occurred within a certain time window after the TC rainfall event day (defined in the first step) at rain gauges located upstream of a given stream gauge. We used cross correlation between stream flow and TC rainfall to estimate the time window (Figure S1 in the supplemental materials). We found 1 to 5 days was an adequate time window, and additionally, we performed a sensitivity analysis by varying this time window from 1-3 to 1-8 days to test how the TC high flow fractions change.

3. Results

3.1 TC activity over Mexico

To provide an overview of Mexican TC activity, we considered TCs that passed within 300 km from the Mexican shoreline, i.e. the distance within which TC centres can generate observable rainfall on coastal areas. Descriptive statistics of these TCs over 48 years (1970 to 2018) indicate that 174 tracks were generated in the North Atlantic basin (referred to as MexNA) with 71 and 75 tracks that developed in the Caribbean Sea and in the Gulf of Mexico respectively. The vast number of Mexican TCs develop in the Eastern Pacific basin with 316 tracks (denoted hereafter MexEP, Figure 3a), i.e. 64.5% of all Mexican TCs.

Analysis of the TC tracks that reached or approached the coastline (where the centre of the storm is close to the coast, excluding islands) indicate that 45% of the MexEP tracks (143 out of 316) and 63 % (109 out of 174) of the MexNA made landfall or passed close the coast. We classified the intensity of those TC storms that reached the coast into 4 main categories based on the MSW following the Saffir-Simpson Hurricane Scale (i.e. MSW $\leq$ 33 kt for tropical depression (TD), 34 kt $\leq$ MSW $\leq$ 63 kt for tropical storm (TS), 64 kt $\leq$ MSW $\leq$ 95 kt for hurricanes categories 1&2; CAT12, MSW $\geqslant$ 96 kt for hurricanes categories 3 to 5; CAT35) and found most TCs reached the coast as categories TD and TS from both TC basins with a higher number of MexEP CAT12 storms compared to the MexNA CAT12 storms (Figure 3a).

In terms of the annual frequency of storms that passed within 300 km from the Mexican shoreline, the locally weighted scatterplot smoothing (LOESS) of the TC counts in both basins (Figure 3b) indicates (1) a tendency towards increased MexEP TC frequency in the last 2 decades, but (2) for MexNA TCs, a period of decrease in TC frequency from the 1970s to the late 1980s followed by a period of increase from 1990 to 2005 and another period of decline over the last decade. Overall, the average annual number of TCs generated in the EP basin that passed within 300 km from the coast is estimated at 6 TCs/year. In contrast, only 3 MexNA TCs/year reach the nearby eastern Mexico coasts.

In terms of intensity, we calculated the average MSW for each track in both TC basins and estimated the temporal linear trends. Figure 3c indicates a positive (negative) and significant trend in the strength of the MexNA (MexEP) at the 5% significance level. The evolution of TC lifetime indicates a small increase in the duration of Mexican TCs from both basins of TC origin, however trends are not significant at the 5% significance level (Figure 3d), whereas the average translation speed of TCs shows a significant slowdown of the MexEP TCs and a slight increase (but not significant) in the translation speed for MexNA TCs (Figure 3e).

3.2 TC rainfall and stream flow in Colima

3.2.1 Total rainfall associated with TCs

Among all the TC tracks that passed within 300 km from the Colima area, most TCs were generated in the EP basin. However, there are also some TCs generated in the North Atlantic basin that crossed the land to reach the area of Colima. Of all the MexEP TC tracks for the period 1970 to 2018, about 50 % passed within a radius of 300 km from the Colima area. In total, 160 TC tracks (in addition to 6 tracks generated in the MexNA basin) passed near Colima and most of them occurred in August, September and October.

The average annual rainfall across the Armeria - Coahuayana catchment gauges varies significantly. Between 800 to ~ 900 mm/year is recorded along the coastal area gauges and 700 to ~ 1200 mm/year is recorded as one moves inland towards the city of Colima and to the highlands. At the individual catchment scale, the Coahuayana catchment receives more rain on average with ~ 1000 mm/ year compared to Armeria, at ~790 mm/year.

In terms of TC rainfall, we separated the rainfall associated with TCs and rainfall driven by phenomena other than TCs denoted hereafter as non-TC (NTC) rainfall. Figure 4a summarises the average annual rainfall associated with TC versus NTC. As we would expect, the highest TC rainfall are generally recorded in rain gauges located nearby the coast with annual average rainfall ranging from 190 to ~ 244 mm/year; these values decrease to a minimum of 50 mm/year at the gauges furthest inland from the coastline. Similar to the total rainfall, slightly higher amounts of TC rainfall fall in the Coahuayana catchment (~130 mm/yr) compared to the Armeria catchment (~110 mm/yr).

Proportionally (i.e. the ratio of TC rain over the total annual rainfall at any given rain gauge), the highest percentages are 25 to 30 % of the average annual rainfall found in the coastal region. These proportions decrease to 16-20 % around the city of Colima and to 12% or less as one moves towards the uplands of the Armeria - Coahuayana catchment (Figure 4b).

3.2.2 Extreme rainfall associated with TCs

To evaluate how TCs affect heavy rainfall in Colima, we selected rainfall values exceeding the 99th percentile of the daily rainfall distribution at each rain gauge and examined the proportion of these exceedance values associated with TCs. As one would expect, most of the intense rainfall associated with TCs is recorded in coastal areas with more than 35% of the top 1% rainfall (Figure 5a). These proportions remain high and exceed 30% near the city of Colima. The TC fractional contribution drops from 25% to less than 10% as we move inland from the shoreline. We also examined the association of the rainfall annual maxima to TCs and found higher proportions (i.e. > 40% at coastal gauges) in comparison with the top 1% rainfall (Figure 5b), indicating that TCs play a considerable role in driving the most extreme rainfall events in the coastal area of Colima.

We have analysed how TC extreme rainfall are distributed at a monthly time scale. Figure 5c shows the TC contribution to heavy rain for each month of the TC season, where September and October are the months that witness most of the TC rainfall extremes. Note that high percentages are also recorded in May; this is because there are very few high rainfall events recorded in May which are predominantly caused by TCs.

3.2.3 High flows associated with TCs

In addition to rainfall, we analysed the fractional contribution of TCs to high flow events in both the Armeria and Coahuayana catchments. In the Armeria catchment, we found over 20 % of the top 1% flow events were driven by TCs, with 23% at the Coliman gauging station (gauge #1) and 20% recorded in the Peñitas gauge (gauge #2, Figure 6a). In the Coahuayana catchment, results indicate that TCs contribute to 21% to the high flows at the outlet gauge (gauge #3).

The above results are obtained using a time window of 1 to 5 days between the TC rainfall event and the peak flow event as estimated from the cross-correlation functions between rainfall and stream flow (Figure S1). The sensitivity of the results has been explored by using larger and smaller time window from 3 days to 8 days; results are summarised in Figure 6c, which shows the change in fractional contribution of TCs at each stream gauge with a varying time window. Results indicate that the fractions do not change significantly with different window sizes (~1 to 3%), and that the 5-day window allowed us to capture the peak flow events associated with TCs.

To examine how TCs affect the most extreme of the top 1% of flow events, we have selected the top 20 peak flows at each stream gauge and analysed their attribution to TCs. Results in

Figure 6b indicate higher percentage contributions compared to the results found using the entire top 1% of the distribution. We found 35% and approximately 30% of the top 20 flow peaks at Armeria and Coahuayana catchments respectively are associated TCs (Figure 6b).

Table 1 shows the names and characteristics of TCs that contributed to highest 20 flow events at each of the three stream gauges. Most of the TC storms had the strength of hurricanes (i.e. CAT12 and CAT35) when they reached the closest location to the Colima area. We also found high flow events that could be associated to multiple TCs events: for example, in August 1993, three separate TCs passed close to Colima between 15 to 22 August and contributed to the peak flow of 595m^3/s recorded at the gauge number 1 on 22 August 1993. Tropical cyclones Jova in October 2011 and Manuel in September 2013 also caused the highest flow peaks of 2632 m^3/s and 3220 m^3/s respectively.

4. Summary and Conclusion

The main aim of this study was to evaluate the contribution of tropical cyclones to heavy rainfall and stream flow in one of the most TC-exposed areas of western Mexico. We used rain gauge and stream gauge data alongside TC tracks from 1970 to 2015 and developed a new approach to quantify the effects of TC rainfall on high stream flow. Analyses of patterns of tropical cyclone activity of Mexico from 1970 to 2018 (note that for TC activity analyses over Mexico, we used TC records ending in 2018 and considered TC tracks that passed within 300 km from the Mexican shoreline) show an increase in the frequency of MexEP TCs after the year 2000. In contrast, MexNA TC frequency exhibits a decadal to multidecadal pattern, with a period of decrease from 1970 to 1990, a clear shift towards higher frequency from 1990 to 2005, and another period of decrease in the last decade. These patterns are possibly related to the Atlantic Multidecadal Oscillation climate mode since previous studies highlighted an increase in the frequency of landfalling TCs along the United States east coast during the positive phase of the AMO (e.g. Gray et al., 1997; Klotzbach and Gray, 2008). We also showed that there has been a tendency towards an increase in the average TC lifetime in both TC basins and a slowdown in the average TC translation speed of the MexEP TCs, which might have effects on the amount of local rainfall associated with TCs.

In terms of the TC contribution to rainfall, an estimated ~25 to 30 % of the average annual rainfall is generated by TCs in areas up to 40 km from the shoreline. These proportions decrease as one moves towards the uplands of the Armeria - Coahuayana catchment, reaching 16 to 20% in the vicinity of Colima city. The contribution of TCs to extreme rainfall (top 1% heavy rainfall days at each gauging station) is much higher, with approximately 30 to 35 % of TC-induced rainfall recorded within the strip of 0 to 60 km from the shoreline, which includes the city of Colima. When using the annual rainfall maxima, the TC effects are even higher, with 40 to 55 % of rainfall associated with TCs at the coastal area. At the monthly scale we found that most of the extremes occurred in the late TC season during September and October. Similarly, we found approximately 20 to 25% of the peak flow events (top 1% flow) are associated with TCs. When focussing on the top 20 flow peaks, we found much higher proportions ranging from 28 to 34 % of peaks caused by TCs in both the Armeria and Coahuayana catchment outlets.

This study highlights the role of TCs in generating heavy rainfall and some of the largest flow events on record in the area of Colima. The Armeria - Coahuayana catchment topography has a strong gradient which generates rapid runoff inducing overbank inundation and damage to infrastructure in the city of Colima in the event of heavy TC rainfall. For example, the most recent major TCs, Jova in 2011 and Patricia 2015, have left serious damage to infrastructure in the state of Colima, and in the city of Colima, such as road networks, communication systems and domestic services.

In summary, this paper presents insights into the occurrence of TCs in the Colima area and provides evidence of the role of TCs in driving heavy rainfall and high flows in Colima, Mexico. Our findings are relevant for water and flood risk management. Further work should examine other mechanisms that produce heavy rainfall events in Colima that contribute to the flooding in the region.

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Figure captions

Figure 1: **Tropical cyclone Patricia** (October 2015) and its associated total rainfall during the 24 hours following landfall. Rainfall is estimated using high spatiotemporal resolution data (0.1°×0.1° every 30 min) from the Integrated Multi-satellitE Retrievals for GPM (IMERG) (Huffman *et al.*, 2018). Left panel: the circles on the TC track indicate the TC storm centre location every 6 hours; with colour referring to the strength of the storm following the Saffir-Simpson Hurricane Scale. Right panel: zoom-in on the hydrological region of Armeria and Coahuayana including the Colima area, with circles indicating rain gauges.

Figure 2: Rainfall and Stream flow data, and their record length. (a): Spatial distribution of rainfall gauges (blue circles) and stream gauges (red circles); (b) rainfall (upper panel) and stream flow (lower panel) record length and completeness. Gauge numbers on the map match those of right panels. We considered 2 stream gauges on the Armeria river (i.e. 1 = Coliman, 2 = Peñitas) and one on the Coahuayana catchment (i.e. 3 = Callejones).

Figure 3: TC activity over Mexico from 1970 to 2018. a) TC storm categories at landfall and within 50 km from the Mexican coasts. The dots represent the centre of the storm and the embedded bar plot on the map indicates the TC counts by category (colours indicate the different categories using the Saffir-Simpson Hurricane Scale). b) Frequency of Mexican TCs generated in both the North Atlantic and Eastern Pacific basins (number of storms). The colour lines represent the LOESS regression smoothing to highlight patterns (blue: MexEP, red: MexNA). Time series and linear trends are shown in panels c-e for: c) average MSW of each track, d) TC lifetime in hours and e) average translation time. Grey shading indicates the two-sided 95% confidence bounds of the trends.

Figure 4: **Spatial distribution of the TC rainfall across the Armeria - Coahuayana catchment.** Each circle indicates the location of a rain gauge. a) represents TC annual rainfall amounts and b) the annual TC and NTC rainfall. The circle outline colours in b indicate TC (white) and NTC (black) rainfall amounts and the fill colour represents the fractions of TC annual rainfall relative to the total TC and NTC rainfall.

Figure 5: Percentage of the extreme rainfall associated with TCs at each rain gauge based on (a) the top 1 % of rainfall distributions and b) the annual rainfall maxima. c) represents the TC contribution to the top 1% rainfall at the monthly scale. Gauges in (c) are ordered by their distance to the shoreline (i.e. gauge number 1 is the closest to the shore and 40 is the farthest).

Figure 6: percentage of peak flow events associated with TCs at the Armeria – Coahuayana catchment. a) using top 1% flow events and b) using only the highest 20 flow events. c) represents sensitivity analysis of TC-high flow driven using various time windows from the TC rainfall day.

References

Agustín Breña-Naranjo J, Pedrozo-Acuña A, Pozos-Estrada O, Jiménez-López S a., López-López MR. 2015. The contribution of tropical cyclones to rainfall in Mexico. *Physics and Chemistry of the Earth, Parts A/B/C* (JUNE). DOI: 10.1016/j.pce.2015.05.011.

Barth NA, Villarini G, White K. 2018. Contribution of eastern North Pacific tropical cyclones and their remnants on flooding in the western United States. *International Journal of Climatology* **38**(14): 5441–5446. DOI: 10.1002/joc.5735.

CONAGUA, 2011. Manual para el control de inundaciones. National Water Comission (CONAGUA), Mexico, available at https://cenca.imta.mx/pdf/manual-para-el-control-de-inundaciones.pdf

Dare RA, Davidson NE, McBride JL. 2012. Tropical Cyclone Contribution to Rainfall over Australia. *Monthly Weather Review* **140**(11): 3606–3619. DOI: 10.1175/MWR-D-11-00340.1.

Dominguez C, Magaña V. 2018. The Role of Tropical Cyclones in Precipitation Over the Tropical and Subtropical North America. *Frontiers in Earth Science* **6**(March): 1–14. DOI: 10.3389/feart.2018.00019.

Englehart PJ, Douglas A V. 2001. The role of Eastern North Pacific tropical storms in the rainfall climatology of Western Mexico. *International Journal of Climatology* **21**(11): 1357–1370. DOI: 10.1002/joc.637.

Franklin JL, Avila LA, Beven II JL, Lawrence MB, Pasch RJ, Stewart SR. 2003. Eastern North Pacific hurricane season of 2002. *Monthly Weather Review*.

Gray WM, Sheaffer JD, Landsea CW. 1997. Climate Trends Associated with Multidecadal Variability of Atlantic Hurricane Activity. *Hurricanes*. DOI: 10.1007/978-3-642-60672-4_2.

Huffman GJ, Bolvin DT, Braithwaite D, Hsu K, Joyce R, Kidd C, Nelkin EJ, Sorooshian S, Tan T, Xie P. 2018. NASA Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM (IMERG) - Algorithm Theoretical Basis Document (ATBD) Version 5.2. *IMERG Algorithm Theoretical Basis Document (ATBD)*. DOI: https://pmm.nasa.gov/resources/documents/gpm-integrated-multi-satellite-retrievals-gpm-imerg-algorithm-theoretical-basis-.

Jiang H, Zipser EJ. 2010. Contribution of Tropical Cyclones to the Global Precipitation from

Eight Seasons of TRMM Data: Regional, Seasonal, and Interannual Variations. *Journal of Climate* **23**(6): 1526–1543. DOI: 10.1175/2009JCLI3303.1.

Khouakhi A, Villarini G, Vecchi GA. 2017. Contribution of Tropical Cyclones to Rainfall at the Global Scale. *Journal of Climate* **30**(1): 359–372. DOI: 10.1175/JCLI-D-16-0298.1.

Klotzbach PJ, Gray WM. 2008. Multidecadal variability in North Atlantic tropical cyclone activity. *Journal of Climate*. DOI: 10.1175/2008JCLI2162.1.

Pérez-Morga N, Kretzschmar T, Cavazos T, Smith S V., Munoz-Arriola F. 2013. Variability of extreme precipitation in coastal river basins of the southern Mexican Pacific region. *Geofisica Internacional* **52**(3): 277–291. DOI: 10.1016/S0016-7169(13)71477-6.

Pielke RA, Landsea C, Mayfield M, Laver J, Pasch R. 2005. Hurricanes and global warming. *Bulletin of the American Meteorological Society*. DOI: 10.1175/BAMS-86-11-1571.

Rios Gaona MF, Villarini G, Zhang W, Vecchi GA. 2018. The added value of IMERG in characterizing rainfall in tropical cyclones. *Atmospheric Research*. Elsevier **209**(March): 95–102. DOI: 10.1016/j.atmosres.2018.03.008.

Rogers RF, Aberson S, Bell MM, Cecil DJ, Doyle JD, Kimberlain TB, Morgerman J, Shay LK, Velden C. 2017. Rewriting the Tropical Record Books: The Extraordinary Intensification of Hurricane Patricia (2015). *Bulletin of the American Meteorological Society* **98**(10): 2091–2112. DOI: 10.1175/BAMS-D-16-0039.1.

Salas MA and Jiménez, P. 2014. Inundaciones. Serie Fascículos Available at Centro Nacional de Prevenciòn de Desastres, Secretaría de Gobernación, Mexico. http://www.cenapred.gob.mx/es/Publicaciones/archivos/3-FASCCULOINUNDACIONES.PDF

Scoccimarro E, Gualdi S, Villarini G, Vecchi G a., Zhao M, Walsh K, Navarra A. 2014. Intense Precipitation Events Associated with Landfalling Tropical Cyclones in Response to a Warmer Climate and Increased CO 2. *Journal of Climate* **27**(12): 4642–4654. DOI: 10.1175/JCLI-D-14-00065.1.

SMN (Servicio Meteorológico Nacional), 2013. Reporte del clima en México. Annual Report 2013, National Water Comission (CONAGUA). Available at http://smn1.conagua.gob.mx/climatologia/analisis/reporte/Anual2013.pdf

Vecchi GA, Knutson TR. 2008. On estimates of historical North Atlantic tropical cyclone activity. *Journal of Climate*. DOI: 10.1175/2008JCLI2178.1.