Relationship of tropical cyclone wind-field and cloud-band metrics with extreme rainfall events over Mexico

Relación de las métricas de viento y bandas de nubes de los ciclones tropicales con la precipitación extrema en México

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Abstract

Tropical cyclones (TCs) are the costliest hydrometeorological phenomena in Mexico, accounting for approximately 86.5% of the total disasters, where extreme rainfall is the main TC-associated hazard. This study analyzes two TC size metrics during the 2000–2024 period: R34, defined as the mean radius of 34-kt winds, and ROCLOUD, a satellite-derived metric that represents the spatial extent of TC cloud bands. These two TC size metrics are evaluated to determine their skill in detecting extreme precipitation events and identifying TC-associated disaster records from CENAPRED. We use diverse databases for this study: IBTrACS, MSWEP (used to define the 95th percentile of daily precipitation from May to November and identify extreme rainfall events), and official disaster declarations from CENAPRED. Municipalities are affected by TCs when they fall within the spatial domain of

R34 (ROCLOUD). In addition, the SIAT-CT (Early Warning System for Tropical Cyclones by its acronym in Spanish) hazard index is computed during the study period to evaluate its performance in identifying extreme precipitation events induced by TCs. Our results show that at least 70% of TC-related disaster records are associated with tropical storms and tropical depressions. Extreme rainfall events frequently occur at distances greater than 300 km from the TC center, and ROCLOUD detects them better than R34. Radial curves indicate that ROCLOUD adequately covers the extreme events up to 500 km from the TC center, whereas the R34 skill to cover these events decays rapidly beyond 300 km. The SIAT-CT index, mainly based on R34, classifies the most extreme precipitation events into low-hazard categories, revealing important limitations for issuing TC rainfall-related warnings. Therefore, we conclude that SIAT-CT requires both TC wind-based metrics and TC cloud-band extension metrics in order to provide accurate warnings of TC-induced hazards and thus strengthen disaster risk reduction strategies prior to TC landfall.

Keywords: Tropical cyclones; Extreme rainfall; Hazard assessment; Tropical Cyclone Size; Disaster management

Resumen

Los ciclones tropicales (CTs) son los fenómenos hidrometeorológicos más costosos para México, ya que representan el 86.5% de los desastres, en los que la precipitación extrema es la principal amenaza hidrometeorológica. Este estudio analiza dos métricas del tamaño de CTs durante el periodo 2000-2024: el R34, que es el radio medio en el que se extiende la velocidad de 34 nudos y ROCLOUD, una métrica que mide la extensión de las bandas nubosas del CT. Ambas métricas se evalúan para determinar su capacidad de detectar la ocurrencia de eventos de lluvia extrema e identificar las declaratorias oficiales asociadas.

Los datos utilizados son IBTrACS, precipitación de MSWEP, que sirvieron para obtener el percentil 95, y declaratorias de desastre de CENAPRED. Los municipios son afectados por CTs cuando están dentro del dominio espacial definido por R34 (ROCLOUD). También, se calculó el índice de peligro del SIAT-CT para evaluar su capacidad en identificar eventos extremos de precipitación inducidos por CTs. Los resultados muestran que el 70% de las declaratorias asociadas con CTs son debidas a tormentas y depresiones tropicales. Los eventos extremos de precipitación ocurren a más de 300 km del centro del CT, siendo ROCLOUD una mejor métrica para captar estos eventos en comparación con R34. Las curvas radiales confirman que ROCLOUD mantiene cobertura hasta 500 km desde el centro del CT, mientras que R34 decae rápidamente a partir de 300 km. El SIAT-CT, basado en R34, clasifica la mayoría de estos eventos extremos de precipitación en categorías de peligro bajas, lo que evidencia su limitación para emitir alertas relacionadas con la lluvia de los CTs. Por lo tanto, se concluye que el SIAT-CT requiere implementar tanto métricas de viento, como de la extensión de las bandas nubosas, para proporcionar alertamientos precisos de la amenaza que un CT induce y así fortalecer las medidas de prevención antes de que un CT toque tierra.

Palabras clave: Ciclones tropicales; Precipitación extrema; Evaluación de peligro; Tamaño de los ciclones; Manejo del desastre

1. Introduction

Hydrometeorological hazards (e.g., intense rainfall, floods, coastal storm surges, strong winds, droughts, and storms) account for approximately 46% of disasters recorded in Mexico during the 1900–2018 period (Alcántara-Ayala, 2019). Among these, Tropical Cyclones (TCs) are the most impactful hydrometeorological phenomena. TCs are responsible for 86.5% of the annual economic losses associated with disasters in Mexico, with extreme rainfall representing their most hazardous component (CENAPRED, 2019). In this context, extreme precipitation (or extreme rainfall) events are typically defined as accumulated daily rainfall exceeding the 95th or 99th percentile of rainy days over a baseline period of at least 20 years of daily data (Myhre et al., 2019).

Although wind damage near the cyclone core can be severe, TC-related impacts often extend far beyond the storm center. In particular, intense rainfall in peripheral regions frequently triggers floods and landslides (Mandal et al., 2020; Nolasco-Javier & Kumar, 2018). In recent years, multiple TCs made landfall or exerted significant influence over Mexican territory, highlighting the importance of studying key hazardous TC features, such as TC size, extreme rainfall, and associated flooding (Breña-Naranjo et al., 2015; Dominguez et al., 2021; Khouakhi et al., 2017). In this sense, several studies divide the TC effects into two types: (i) direct effects within the TC center (e.g., extreme rainfall associated with the TC center and strong surface winds); and (ii) indirect effects that are far from the TC center, but are relevant for risk management actions (e.g. extreme rainfall located far from the TC center, but can cause floods and landslides). Hence, two complementary definitions of TC size have emerged: the TC inner size (confined to enclosing regions near the TC center) and the TC outer size (a region that extend far from the TC center, but the TC circulation can still be found) (Hidalgo et al., 2020; Knaff et al., 2014; Lu et al., 2017; Pérez-Alarcón et al., 2021).

Conventional approaches to characterizing direct TC effects have relied mainly on intensity-based indicators such as maximum sustained winds (MWS), as defined by the Saffir–Simpson scale (Kelman, 2013; Matyas, 2010). While these parameters provide an adequate metric for the destructive capacity of TC surface winds, they often fail to identify the broader and more complex hazard associated with rainfall extremes (i.e., indirect effects). Pérez-Estrada and Domínguez (2024) show that the spatial extent of TC rainbands, rather than peak TC intensity alone, plays a major role in modulating precipitation distribution and extreme rainfall events. This finding is consistent with previous studies highlighting the importance of rainband structure in shaping rainfall extremes (Domínguez & Magaña, 2018; Lavender & McBride, 2021; Morin et al., 2024). Extreme precipitation events are usually the main natural causes of disasters. In Mexico, complex topography raises rainfall-induced hazards and magnifies the resulting disaster impacts (see CENAPRED, 2019).

The operational Early Warning System for Tropical Cyclones (SIAT-CT, by its acronym in Spanish) in Mexico has four components: 1) scientific knowledge about TCs that affect Mexico (natural hazard component), 2) real-time monitoring of TCs (natural hazard component), 3) communication of public warnings that activate safety protocols (social component), and 4) local planning for well-organized social responses (social component) (CENAPRED, 2026). The SIAT-CT uses the radius of gale-force winds (R34) to determine the extent of damaging winds, which is considered a measure of the TC destructive potential (CENAPRED, 2019). R34 (which is a metric confined in the TC inner core) only provides a partial view of hazards that are confined near the TC center. This metric assumes that heavy precipitation occurs only near the TC center (Emanuel, 2005). Although this is partially true, R34 does not take into account this TC-induced hazard when computing its extent. Perez-Estrada and Domínguez (2024) show that TC rainfall can extend hundreds of kilometers from the TC center, indicating that outer size can detect intense TC rainfall, which can be important for risk management. ROCLOUD was derived from satellite data (Global Precipitation Measurement; Skofronick-Jackson, 2020) and designed to identify convective structures far from the TC center that remain dynamically linked to the TC circulation.

Until now, a significant gap remains in combining wind metrics (such as R34), extreme precipitation events, coastal surges, and landslides with the SIAT-CT hazard level (Dominguez et al., 2019). The creation of an integrated measure of TC hazardous impacts can benefit inhabitants by providing more accurate information for national and local risk management. The first step to achieving this integrated measure is to assess R34 skill in detecting extreme precipitation events and pointing out municipalities that are affected by TCs and therefore at risk of an emergency or disaster. Historical disaster declarations are obtained from the National Center for Disaster Risk Prevention (CENAPRED, by its acronym in Spanish). The SIAT-CT considers the value and spatial extent of R34 when assigning a TC hazard level. Specifically, the TC hazard-levels 4 and 5 require the most critical civil actions to be prepared for an emergency or a disaster. It is therefore important to evaluate whether the information previously provided by R34 corresponds to the disaster declarations issued by CENAPRED.

The main objective of this study is to assess the skill of R34 and ROCLOUD to detect the occurrence of extreme rainfall events and to identify disaster records in Mexico for municipalities that fall within their spatial domain. We use TC tracks, TC size metrics (i.e., R34 and ROCLOUD), a gridded precipitation dataset, and municipal-level disaster declarations from CENAPRED during the 2000–2024 period. Our main scientific question is to determine the extent to which TC size metrics are associated with extreme rainfall events and local impacts for adequately representing TC hazards. The following section describes the datasets and methodology used for defining TC sizes, extreme rainfall, and hazard indices. Section 3 presents results about the analysis of TC size metrics with disaster records and evaluates the performance of the SIAT-CT hazard index in the context of extreme rainfall events. Section 4 mainly discusses the limitations of R34 and ROCLOUD. Finally, Section 5 summarizes the main conclusions and discusses the future directions for improving early warning systems in Mexico.

2. Data and Methods

2.1 TC databases: IBTrACS and ROCLOUD

The International Best Track Archive for Climate Stewardship (IBTrACS) integrates synoptic and operational information on TCs, ensuring consistency across basins and temporal continuity (Kenneth et al., 2019; Knapp et al., 2018). For this study, we selected TC tracks that occurred over the Eastern Pacific (EP) and North Atlantic (NA) basins during the 2000-2024 period.

Additionally, we used two TC size metrics: R34 and ROCLOUD. R34 is defined as the mean radius of gale-force winds (34 kt, ~63 km h^{-1}) averaged across quadrants and expressed in kilometers. It has been used for operational purposes as a robust proxy for TC size and the spatial extent of hazardous winds within the TC inner core, and it is publicly available in the IBTrACS dataset (Bian et al., 2021; Carrasco et al., 2014; Lu et al., 2017). The second metric is ROCLOUD, a recently developed satellite-based index that quantifies the outer radius of TC cloud bands (Perez-Estrada & Dominguez, 2024). The ROCLOUD algorithm combines TC wind fields with convective cluster locations. This technique uses GPM brightness temperature below 233 K (-40°C; i.e., clouds at least 10 km above the surface) (Perez-Estrada & Dominguez, 2024). In this way, ROCLOUD tracks storm clouds that can produce extreme precipitation events (Cotton et al., 2011). This brightness temperature is commonly used to define TC deep convection and intense rainfall (Zhou and Matyas, 2021). Unlike R34, which belongs to the inner structure, ROCLOUD determines the extent of outer convective bands where heavy rainfall may occur and where extreme precipitation events are most likely. In this way, ROCLOUD can provide more information on rainfall-induced hazards (e.g., floods and landslides) occurring far from the TC center. The dataset is publicly available at https://data.mendeley.com/datasets/5bpzbwhynd/2

2.2 Disaster declarations from CENAPRED

The disaster record database was compiled from CENAPRED from the period from 2000 to the present. It constitutes a repository of official municipal-level declarations of emergency, disaster, or climatological contingencies issued by the Mexican federal government in response to a wide range of natural and non-natural hazards (CENAPRED, 2019). This database represents the only official and legally binding record of disaster impacts in the country.

For this study, the declaration records were filtered to retain those explicitly and officially associated with TCs and their induced hazards. However, we found that some declarations from municipalities affected by TCs were not labeled properly, indicating an underestimation of TC-related declarations in CENAPRED records. So, we also included declarations from municipalities affected by TCs (although not labeled as TC-impacted in the CENAPRED database), whose locations fell within the TC spatial extent defined by TC size metrics (i.e., R34 or ROCLOUD) in this study. It is important to note that the number of TC-related declarations varies with the TC size metric. Records unrelated to hydrometeorological hazards (i.e., floods, landslides, extreme rainfall, and strong winds) were excluded.

2.3 Gridded Rainfall dataset

Historical rainfall was obtained from the Multi-Source Weighted-Ensemble Precipitation (MSWEP, v2.8) dataset, which merges in-situ gauges, satellite-based retrievals, and reanalysis products to provide spatially consistent estimates (Beck et al., 2019). MSWEP offers a global record at 0.1° resolution and 3-hourly intervals, spanning 1979 to near-present. Its blended nature improves accuracy in regions with sparse gauge coverage, such as the Mexican Pacific and Atlantic coasts, which makes it particularly suitable for TC studies. Previous research has demonstrated that MSWEP captures localized convective rainfall structures associated with TCs (Morin et al., 2024). We build on this research by using MSWEP as the primary dataset to characterize TC extreme rainfall events over Mexico during 2000-2024 period.

2.4. Method for comparing disasters records according to TC size metrics

The method workflow involves five stages: integrating rainfall data, TC size metrics, disaster records, hazard indices, and impact validation (Figure 1). The method is described as follows:

1. **Detection of extreme rainfall**. Daily accumulated precipitation (rainy days) is computed from MSWEP 3-hourly data during the 2000-2024 period. Only daily precipitation that occurs from May 1st to November 30th (the months when TCs are active) is considered for this study (hereafter, seasonal precipitation). Following Dominguez et al. (2021), we estimate a unique climatological threshold, defined as the 95th percentile of all daily rainy days for each 0.1° MSWEP grid cell during the 2000-2024 period, using only seasonal precipitation. This threshold varies regionally across Mexico and poses a hazard to local infrastructure, rivers, and dams. In this way, extreme precipitation events are defined as days with precipitation at or above the 95th percentile and represent a hazard. Their quantity provides a better estimation of TC-impacts rather than only considering 3-hourly rainfall (Dominguez et al., 2021). It is important to note that this percentile does not account for any maximum monthly or annual rainfall amount in its calculation.

2. **Identification of TC-induced rainfall events**. For each 6-hourly TC position reported by IBTrACS, the R34 and ROCLOUD metrics (TC size metrics) are used to define the TC radial domain of influence. TCs usually move and change their latitude and longitude every 6 hours, but TC positions and size metrics are not averaged daily, as their radial domain of influence can affect different grid cells on the same day. If TC positions remain nearly unchanged for 24 hours, this does not affect the identification of extreme precipitation events, as locations remain invariant. TC-induced extreme rainfall events are attributed to each TC position. These events are flagged when precipitation within this domain exceeds the local 95th percentile. This procedure generated an event-based catalog of extreme rainfall associated with TC positions, thereby linking TC structure with hydrometeorological extremes.

3. **Linking TC disaster declarations with extreme rainfall events.** To establish a connection between extreme rainfall events and disaster records, a spatiotemporal matching routine was applied. First, only CENAPRED disaster declarations that explicitly identified TCs as the triggering cause were retained. These TC-related declarations were used to define the set of affected municipalities and candidate impact locations. Extreme rainfall events were then identified when rainfall equaled or exceeded the climatological 95th percentile threshold during the TC lifetime. For each TC-related declaration, extreme rainfall points occurring within the corresponding municipality and temporally associated with the TC were retained as TC-related extreme rainfall impacts.

4. **SIAT-CT hazard index**. The SIAT-CT was historically reproduced using IBTrACS data. The SIAT-CT defines hazard levels by combining: (a) intensity, derived from the MWS according to the Saffir–Simpson Hurricane Scale (SSHS), and (b) circulation, which is computed as the average of four R34 radii (i.e., northeast, northwest,

southwest, and southeast), multiplied by 0.0337, with a maximum of five (CENAPRED, 2019). The hazard index is the mean of both scales, yielding a color-coded warning ranging from minimal to maximum hazard (i.e. from 0 to 5).

5. **Impact validation.** Municipal-level declarations of emergency and disaster were considered as the impacts. These declarations provided an operational benchmark against which the physical hazard descriptors (ROCLOUD, R34, extreme rainfall, and SIAT-CT) could be evaluated. This comparison allowed assessing not only the ability of size and rainfall metrics to explain hazard, but also their consistency with institutional disaster recognition in Mexico.

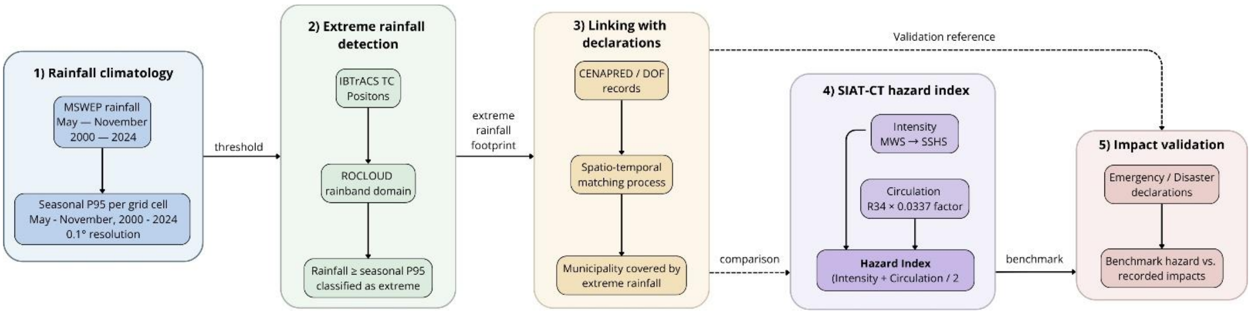

Figure 1. *Method workflow. Steps include: (1) rainfall climatology from MSWEP database to define local P95 thresholds; (2) detection of extremes within the ROCLOUD domain; (3) spatio-temporal linking with CENAPRED disaster declarations; (4) calculation of the SIAT-CT hazard index from intensity and circulation; and (5) validation of hazard indicators against official impact records. MWS and SSHS mean Maximum Wind Speed and Saffir-Simpson Hurricane Scale, respectively.*

3. Results

3.1. Official disaster declarations linked to TCs

Official disaster records in Mexico provide unique information about the social impacts of hydrometeorological hazards. During the 2001–2024 period, TCs accounted for 52% of all official hydrometeorological declarations. In other words, declarations that are only officially labeled as TC-associated by CENAPRED are presented in this section. Emergencies were the dominant category (56%), followed by disasters, while climatic contingencies represented only a minor share (approximately 3%; Figure 2a). Although other hazards, such as floods, droughts, and cold fronts, also triggered numerous declarations, the relative weight of TCs underscores their central role in shaping Mexico's disasters. Out of 34,453 accumulated declarations associated with all types of phenomena during our study period, 90.3% corresponded to hydrometeorological hazards, of which at least 10,543 (30.6%) were directly or indirectly linked to TCs. It is worth noting that the disaster declaration database does not, in many cases, explicitly specify the phenomenon linked to the declaration. The latter leads to an underestimation of the true contribution of TCs.

The geographical distribution of official declarations records reveals regional contrasts (Figure 2b). The state with the most declarations is Baja California Sur. Along the southern Pacific and Gulf of Mexico coasts, municipalities issued more than 30 declarations during the study period. These regions are frequently affected by TCs that made landfall mainly as tropical storms or tropical depressions. The high number of declarations indicates that these regions have a combination of high exposure with high social vulnerability, which enlarges impacts (Dominguez et al., 2021). On the other hand, in sparsely populated regions, such as northern states, the number of declarations is markedly lower. This result is partly due to a minor hazard incident, but it could also point to institutional bias or underreporting, as prior evaluations of the Mexican disaster management system have suggested.

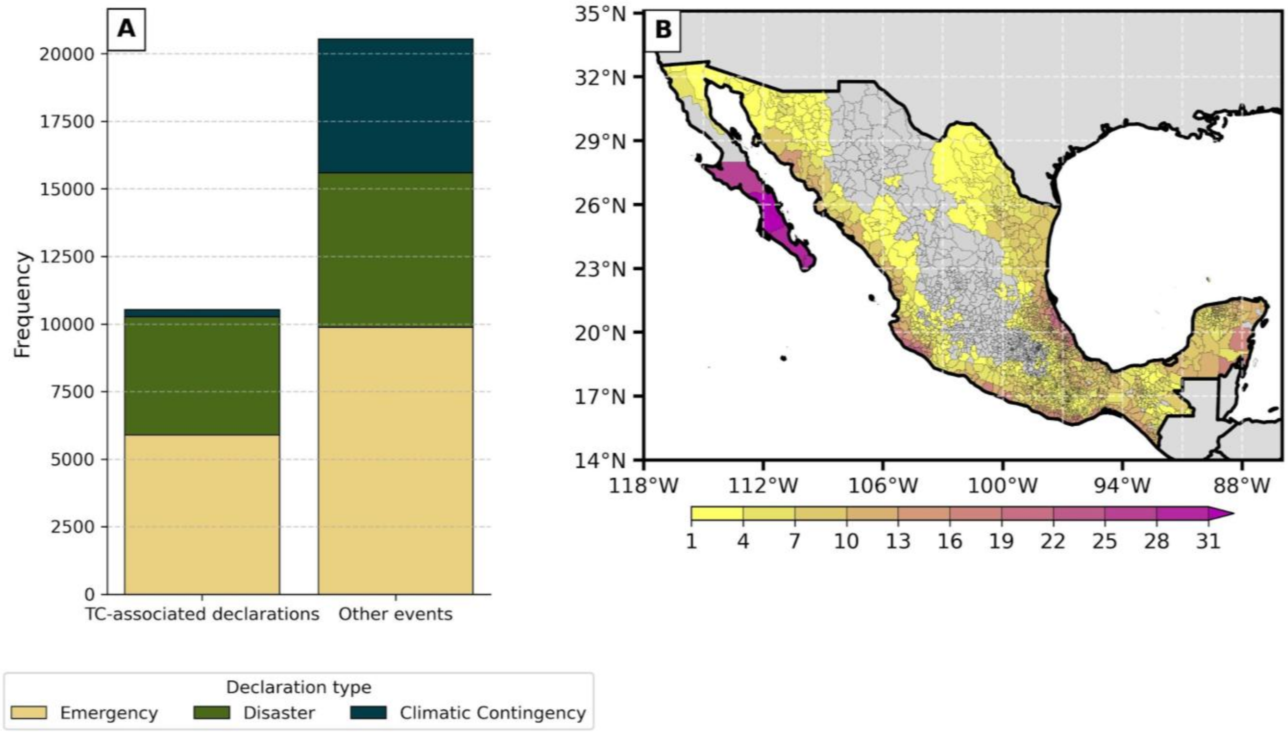

Figure 2. *Disaster declarations from the National Center of Disaster Prevention (CENAPRED in Spanish) over Mexico during the 2001–2024 period. (A) Distribution of emergency, disaster, and climatic contingency declarations, separating those associated with TCs from other hydrometeorological hazards. (B) Spatial distribution of the total number of official declarations associated with TCs at the municipality level. Shaded areas represent the number of declarations.*

Declarations related to tropical storms and tropical depressions are more common than those for hurricanes (i.e., categories 1 and 2) and major hurricanes (i.e., categories 3, 4, and 5), with tropical depressions and tropical storms jointly accounting for approximately 70–83% of all TC-associated declarations, depending on the basin that the TC originates, during the study period (Figure 3a). Despite their weak surface winds, these systems are highly effective at producing widespread rainfall and flooding while interacting with complex topography (Breña-Naranjo et al., 2015; Dominguez et al., 2022; Hidalgo et al., 2020; Touma et al., 2019). The latter results in a high number of emergency and disaster declarations, mainly over coastal municipalities adjacent to mountain ranges, such as the central-southwestern coasts of Mexico (Figure 2b). By contrast, major hurricanes account for less than 10% of all TC-driven declarations, which is associated with their lower frequency of landfall in Mexico (Dominguez & Magaña, 2018). It points out that weak TCs (e.g., tropical depressions and tropical storms) represent a frequently severe hazard to Mexico, although they belong to the lower categories of the Saffir-Simpson scale.

Apart from the Saffir-Simpson scale, the outer TC size can also be relevant for determining the rainfall-induced hazards. However, these outer sizes vary spatially and are not fully correlated with the Saffir-Simpson scale (i.e., its size metric, R34). To illustrate this point, we explore the values of R34 and ROCLOUD during Hurricane Alex in 2010 at 00:00 UTC on 1 July 2010 (Figure 3b). The gale-force wind radius, represented by R34, adequately captures the TC inner core. However, the four ROCLOUD quadrants (i.e., northeast, northwest, southwest, and southeast), which are based on the extent of TC circulation and its cloud bands (Perez-Estrada & Dominguez, 2024), are not close to the TC center, indicating a wider domain of TC affectation. This example underscores the limitations of wind-only metrics (as in R34) in representing all TC-affected areas and, consequently, hydrometeorological hazards associated with TC passages. In this sense, ROCLOUD is a more realistic proxy for rainfall-induced impacts. This result suggests that R34 could underestimate TC indirect effects (i.e., flooding and landslides), which arise from outer TC convective bands that extend beyond the TC inner wind field. This finding is consistent with the results reported by Hidalgo et al. (2020).

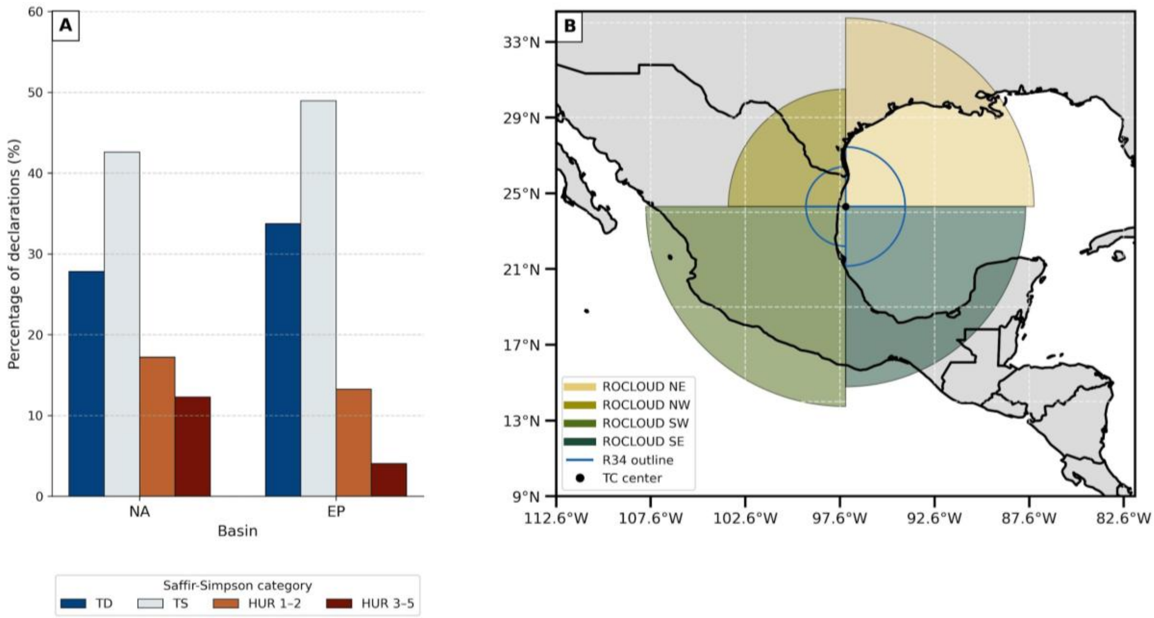

Figure 3. (A) *Saffir-Simpson scale (TD: tropical depression, TS: tropical storms, HUR 1-2: hurricanes category 1 and 2, HUR 3-5: hurricanes category 3, 4 and 5 and its percentage of official TC-associated declarations according to the North Atlantic Ocean (NA) and Eastern Pacific Ocean (EP), (B) R34 and four quadrants of ROCLOUD radii (NE: northeast, NW: northwest, SW: southwest, SE: southeast) during Hurricane Alex in 2010* at 00:00 UTC on 1 July 2010*. A black dot represents the TC center.*

3.2 Relationship of TC sizes with extreme precipitation events

The 95th percentile of daily precipitation from May 1st to November 30th was computed as a first step to obtain the mean annual extreme rainfall produced by TCs (Figure 4a). Mean annual extreme rainfall associated with TC passages varies spatially across Mexico. It is interesting to mention that mean annual extreme rainfall is constrained to the location of mountain ranges, where landslides commonly occur (Breña-Naranjo et al., 2015; Dominguez & Magaña, 2018). For example, mean annual extreme precipitation produced by TCs can reach up to 100 mm/day, mainly southwards 24°N over mountain ranges. Central Mexico that is located inland is not affected by TC extreme precipitation.

We estimate the mean distance from TC centers at which extreme rainfall events are produced by TC circulation (Figure 4b). In general, extreme rainfall events over the Gulf of Mexico and Caribbean Sea coast are induced by TCs whose centers are at least 200 km from landmass. It is worth noting that these events can be induced by TC centers located 350-500 km from landmass along the Mexican Pacific coast, mainly in Oaxaca, Michoacan, Colima, Jalisco, and Sinaloa states (Figure 4b). These results show that extreme rainfall events are not confined to the TC inner core but are present in regions that are distant from the TC center, which suggests that ROCLOUD provides broader coverage of extreme precipitation than R34 (see extension of R34 in Figure 3b).

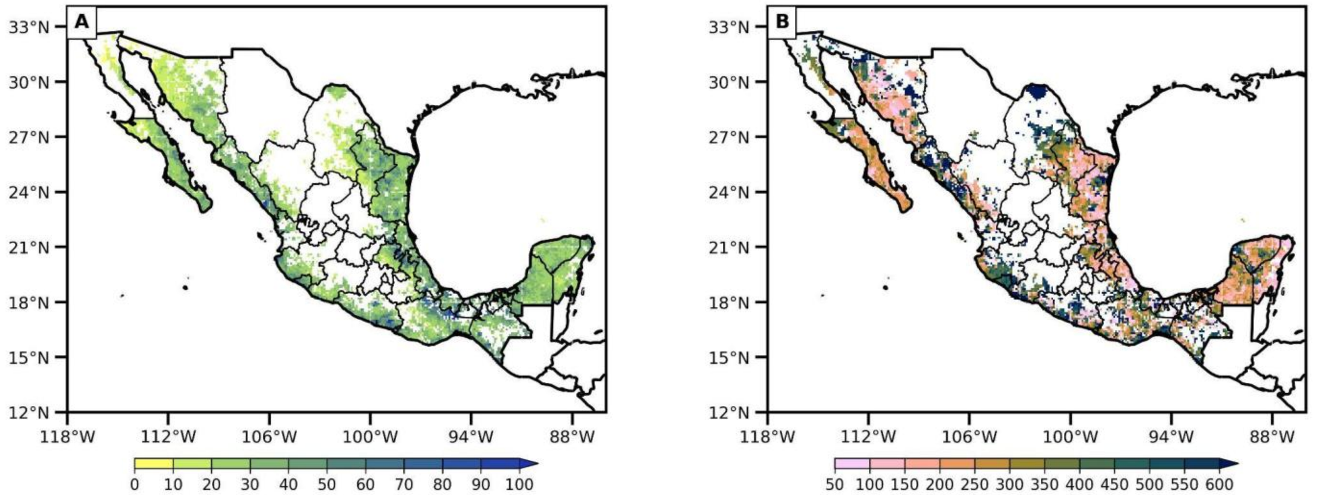

Figure 4. (A) *Mean annual extreme precipitation (mm/day) associated with TCs in Mexico during the 2000–2024 period. Extreme precipitation is defined as daily rainfall equal to or exceeding the climatological 95th percentile, which is based on rainy days from May 1st to November 30th during the study period. (B) Mean radial distance (km) from the TC center to the location of extreme precipitation.*

We compute the percentage of extreme precipitation events identified by ROCLOUD (R34) (Figure 5) as a division between the number of TC extreme precipitation events identified by ROCLOUD (R34) and the total number of TC extreme precipitation events, as shown in

Figure 4a. ROCLOUD by itself captures between 52.5% and 45.9% of extreme precipitation events induced by TCs that originate over the NA and EP, respectively (Figure 5a). What is interesting to mention is that around 40% of all extreme rainfall events over both basins (at a national level) are captured by ROCLOUD and R34. By contrast, R34 only captures less than 1% of all events on both basins at a state level. This indicates that ROCLOUD encompasses nearly all events identified by R34, while additionally capturing a substantial number of extreme rainfall events not detected by R34. It is important to bring out that 7-14% of all events are not detected by any TC size metrics. When analyzing the percentage of both metrics at the state level, most regional TC extreme events are identified by ROCLOUD or by its combination with R34. This result underlines that R34 lacks the skill to include hazards induced by TC extreme rainfall (e.g., landslides, floods, and extreme precipitation that extends beyond the TC inner core) at a state level.

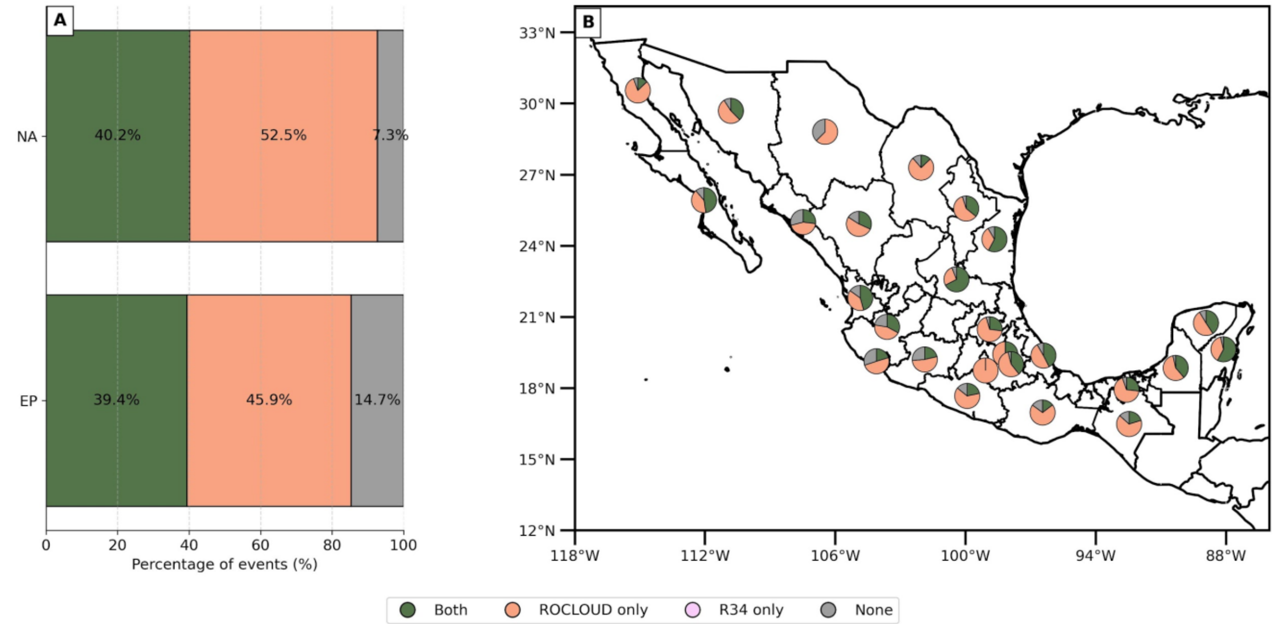

Figure 5. *(A) Percentage (%) of extreme rainfall events per basin and (B) percentage (%) at the state level of extreme rainfall events captured by ROCLOUD, R34, both, or none TC size metrics during the 2000-2024 period.*

We also analyzed the percentage of precipitation extreme events per grid (0.1° of spatial resolution) covered by ROCLOUD and R34, according to the Saffir-Simpson scale intensity during the 2000-2024 period (Figure 6). These results demonstrate that ROCLOUD identifies more than 80% of all extreme events near the Gulf of Mexico and Caribbean Region in all TC intensities. However, the percentage decreases near the Mexican Pacific coast, mainly in the tropical depressions and tropical storms that affect the Baja California Peninsula and Sinaloa. This behavior is likely linked to small TC radii affecting this region and their typically offshore trajectories of tropical depressions over cold EP waters. This small TC radius affects a minor fraction of the Mexican landmass, consistent with previous TC size statistics (Perez-Estrada & Dominguez, 2024). By contrast, R34 covers only around 40% of all extremes across coastal and inland regions, revealing that this TC wind-based metric does not present the same spatial pattern as the TC extreme rainfall distribution. R34 adequately captures the extreme events in more than 60% for specific locations and intensities. For instance, ~60% of extreme precipitation events induced by tropical storms are covered by R34 in Baja California Sur. In addition, ~65% of extreme precipitation events induced by hurricanes (category 1 and 2) and major hurricanes (category 3, 4, and 5) are captured by R34 over the Yucatan Peninsula, Tamaulipas, and the south of Baja California Sur, regions that are commonly affected by intense TCs (Dominguez Sarmiento, 2022). It is worth noting that states located inland (e.g., Aguascalientes, Zacatecas, Guanajuato, and EdoMex) are not affected by TC extreme rainfall events, as shown in Figures 4 and 6.

While making differences between RCLOUD and R34 percentages of coverage, the differences show that ROCLOUD detects more than 30%-40% of extreme rainfall events when compared to R34, depending on the region and TC intensity. The lowest difference is found in the major hurricanes, where percentages can be up to 20%. This result suggests that R34 properly detects extreme precipitation induced by major hurricanes rather than by weak TCs (e.g., tropical depressions, tropical storms). In this sense, ROCLOUD performance is relatively consistent across TC intensity categories, although slight reductions in coverage are observed for extreme precipitation induced by tropical depressions over Baja California Sur, likely reflecting regional storm characteristics rather than methodological limitations.

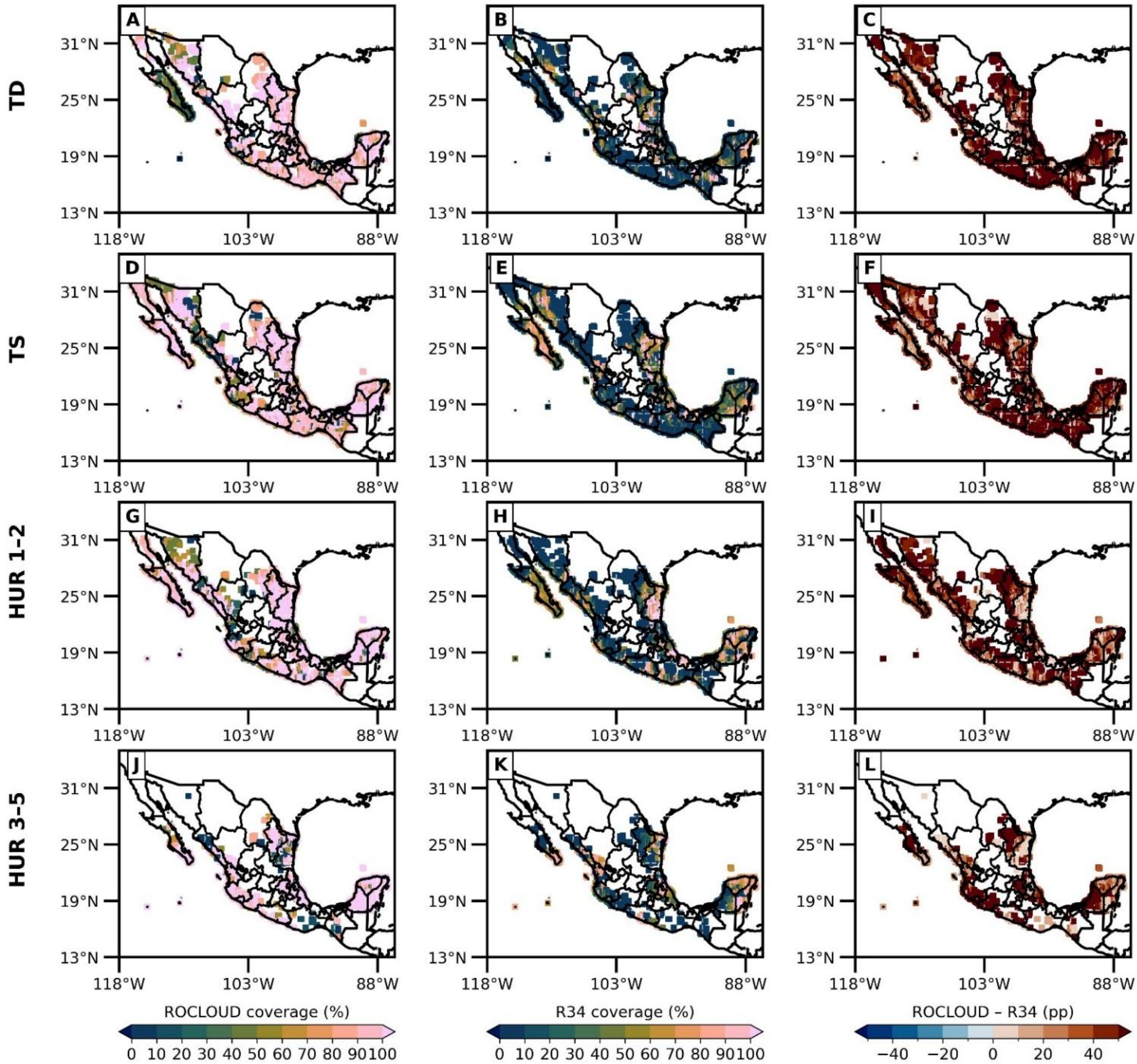

Figure 6. *Percentage (%) of TC extreme precipitation events covered by ROCLOUD and R34. The left column represents the percentage of events covered by ROCLOUD, the middle column represents the percentage covered by R34, and the right column represents their difference (ROCLOUD – R34 in percentage), according to the Saffir-Simpson scale intensity*

during the 2000-2024 period. TD: tropical depressions, TS: tropical storms, HUR 1-2: hurricanes category 1 and 2, HUR 3-5: hurricanes category 3 and 5.

The conditional probability of coverage is estimated for ROCLOUD and R34 using diverse radial distances from the TC center and Saffir-Simpson scale intensities (Figure 7). For quantifying uncertainty, a nonparametric bootstrap resampling was applied at the 95% confidence level for all TC intensities. Confidence bands are narrower at short distances for all TC intensities, using both R34 and ROCLOUD, due to the sample size. However, these bands widen beyond ~700 km, where fewer extreme precipitation events were observed, mainly for ROCLOUD. These results point out important different features between the two TC size metrics. The curves for R34 nearly drop rapidly and approach zero within 300–350 km from the TC center, showing no significant differences in TC intensity or basin. On the other hand, ROCLOUD covers around 90–100% of all extreme rainfall events at 550–650 km from the TC center, depending on the basin. TC intensity bands are noticeably different beyond 700 km in both basins. Hurricanes and major hurricanes show slightly higher persistence than tropical depressions and storms, particularly over EP. However, the 95% bootstrap confidence bands widen in this radial range, indicating that such differences are not statistically distinguishable from the aggregated curve.

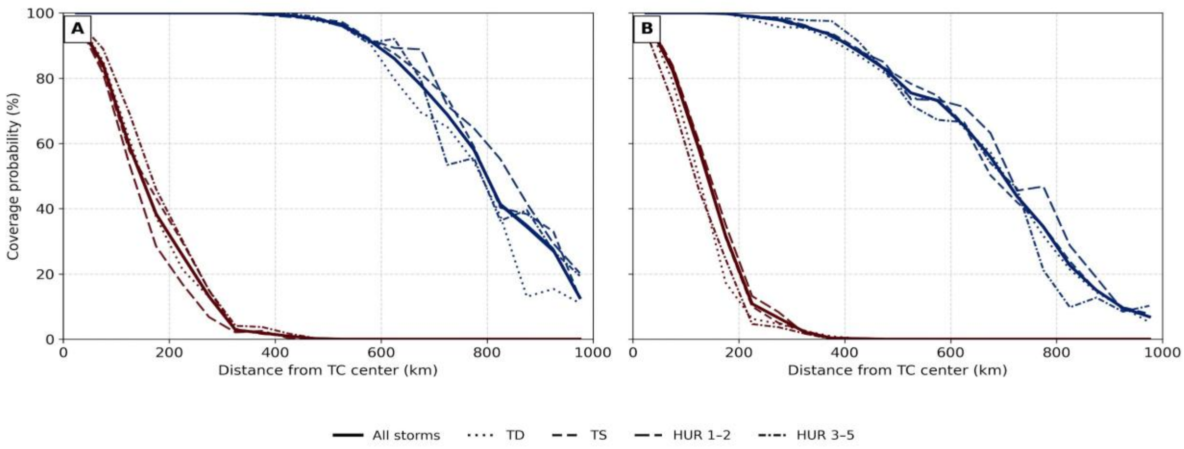

Figure 7. *Radial coverage probability of extreme precipitation events by distance from the*

TC center. Curves show empirical coverage for ROCLOUD (in blue) and R34 (in brown) for TCs that originate in (A) the NA and (B) the EP, with bootstrap confidence intervals and separation by Saffir-Simpson scale intensity during the 2000-2024 period.

Figures 6 and 7 reveal that ROCLOUD consistently detects a more accurate extreme rainfall distribution induced by all TC intensities than R34. Therefore, the TC size metric R34 systematically underestimates rainfall-induced hazards in regions located more than 300 km from the TC center, and remains strongly dependent on TC intensity. These findings suggest that the operational SIAT-CT, by relying exclusively on a TC wind-based metric, systematically underrepresents rainfall-induced hazards. Consequently, this structural limitation constrains early warnings for rainfall-related impacts, particularly in regions of complex topography such as the Mexican mountain ranges. Incorporating TC cloud-based size metrics into SIAT-CT would substantially improve the robustness and reliability of its early warning protocols.

3.3 Assessment of the SIAT-CT hazard index

The SIAT-CT requires both surface wind intensity and TC circulation (defined by R34) to compute its hazard levels from 0 (no hazard) to 5 (maximum hazard) (i.e, SIAT-CT hazard index). This index is operationally relevant for Mexico, thus its performance in representing precipitation-driven impacts requires careful assessment. The relationship between SIAT-CT hazard level and TC extreme rainfall distribution shows no considerable differences (Figure 8a). Median values of extreme rainfall events (i.e., around 30 mm/day) remain invariant from hazard levels 0 to 5, with a large overlap in the interquartile ranges. This finding shows that extreme rainfall events can occur at any hazard level, undermining the SIAT-CT skill to properly warn rainfall-induced hazards. What is more, Figure 8b demonstrates that ~70% of extreme rainfall events fall within TC-hazard levels 1 and 2, with very few events indicated in TC-hazard levels 4 and 5, levels that indicate that actions to face emergency and disaster should be prepared. This bias suggests that the SIAT-CT systematically underestimates the rainfall-induced hazard associated with TC passages, and it can assign a minor hazard level to TCs that can be extremely dangerous due to their extreme precipitation.

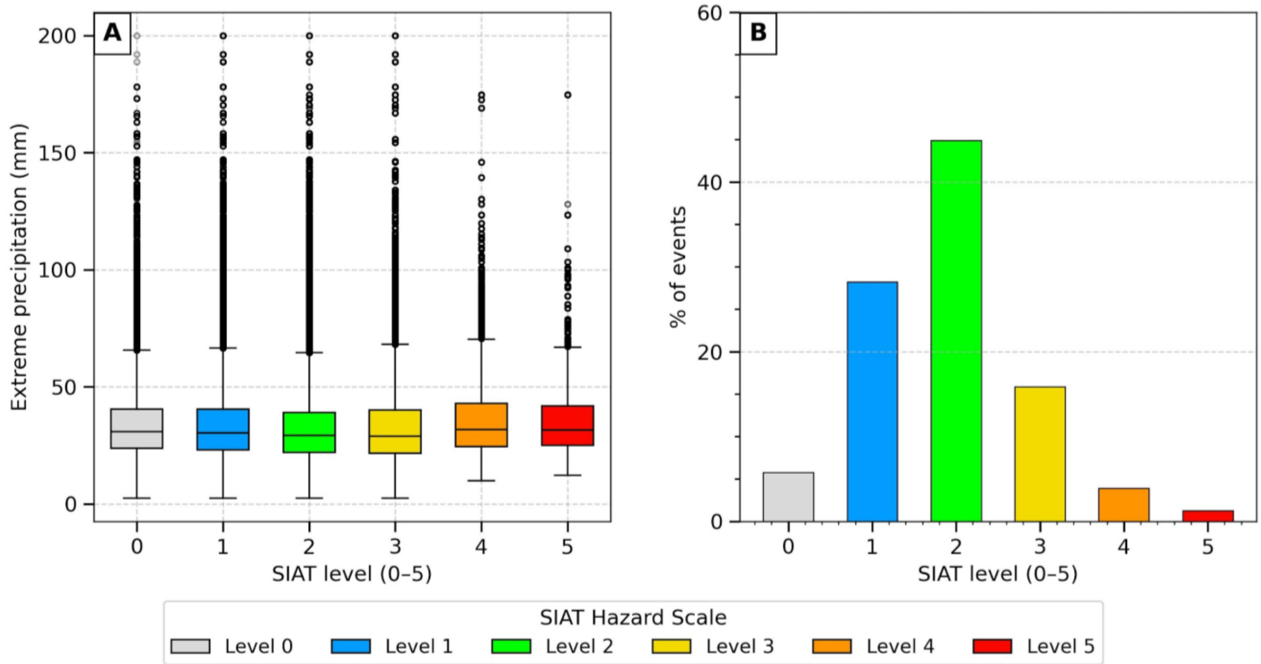

Figure 8. *Distribution of TC extreme precipitation events by SIAT-CT hazard levels. (A) Boxplots of TC extreme precipitation (mm/day) across hazard level 0–5. (B) Relative frequency (%) of extreme precipitation events assigned to each hazard level during the 2000-2024 period.*

Considering all historical SIAT-CT hazard-level warnings during the 2000-2024 period, we find that the mean SIAT-CT hazard level, as defined by R34, ranges from 0 to 2 in most of the country (Figure 9a), even in regions with recurrent landslides (e.g., Michoacan, Guerrero, Oaxaca, Chiapas, Veracruz, and Puebla) (Domínguez-Morales et al., 2016; Mendoza-López et al., 2002). It is remarkably important to mention that each hazard level corresponds to safety protocols that society implements before TCs impact Mexico. So, low-level hazards indicate low impact and suggest that emergency or disaster declarations will not occur (Perez Estrada et al., 2024). In addition, the percentage of extreme rainfall events classified as low-level hazards (i.e., from 0 to 2) varies from 50 to 80% in most of the country (Figure 9b), revealing a consistent spatial underestimation of the TC rainfall-induced hazard. This serious underestimation is particularly evident over mountain regions, where orographic TC convection is enhanced.

These findings exhibit that the SIAT-CT hazard index based on R34 is a valuable tool for warning hazards associated with winds from TCs whose Saffir-Simpson intensity is hurricane categories 3, 4, or 5. However, this index critically fails to warn hazards associated with weak TCs (i.e., tropical depressions and tropical storms), despite at least 70% of TC-related disaster declarations being associated with these hydrometeorological phenomena (Figure 3a).

By contrast, ROCLOUD can identify extreme rainfall events produced by TCs from both basins, demonstrating to be a better metric that considers TC circulation and cloud bands in its computing (Perez-Estrada and Dominguez, 2024), when compared to R34. Incorporating wind and rainfall metrics, such as ROCLOUD, into the operational SIAT-CT framework would enhance the system's capacity to adequately assign hazard levels and properly implement safety protocols in advance of TC landfall. The latter will help reduce TC-driven disasters and accurately communicate TC hazards.

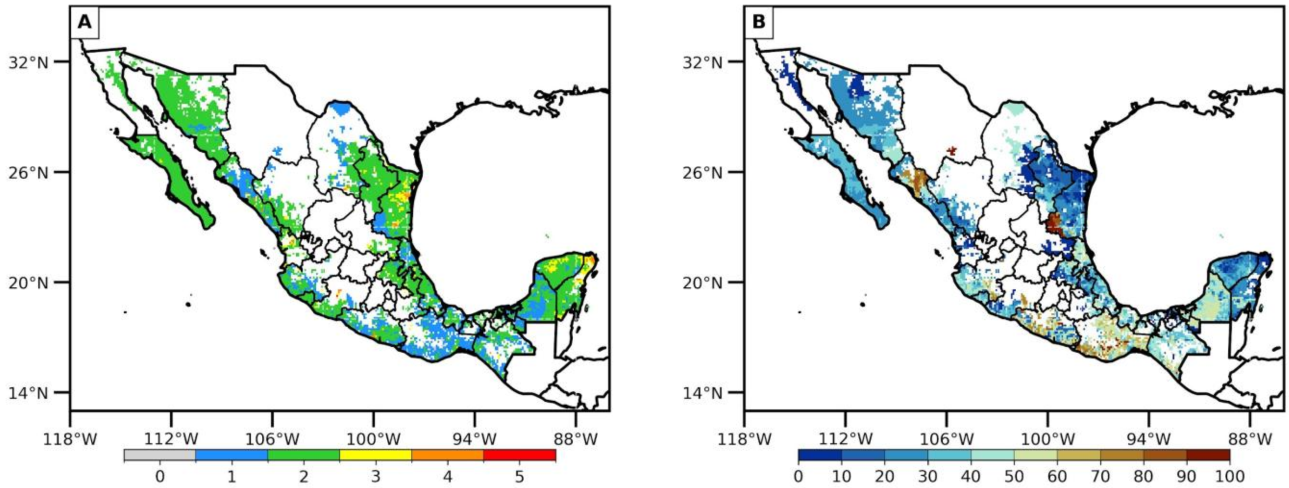

Figure 9. *(A) Historical mean of SIAT-CT hazard level (B) percentage (%) of extreme rainfall events assigned to SIAT-CT low-level hazards (0–2) during the 2000-2024 period.*

4. Discussion

R34 is used for describing the radial extent of gale-force winds near the TC inner core and the main metric for issuing the TC-hazard level for the SIAT-CT. However, this radial extent does not encompass most TC rainfall-induced hazards. This limitation is particularly relevant for Mexico, where tropical depressions and tropical storms are the most common TCs affecting the country (Figure 3a). Their TC-related impacts are associated with extreme rainfall, flooding, and landslides rather than destructive winds alone. Extreme rainfall events produced by TCs frequently occur beyond the inner-core wind field at distances greater than 300 km from the TC center (far from distances defined by R34, Figure 7). This mismatch between wind radii and extreme precipitation events limits SIAT-CT's operational capability to warn of TC-level hazards, especially in coastal and mountainous regions exposed to outer rainbands.

ROCLOUD is a metric that represents the outer cloud-band structure with rainfall-producing convection. We demonstrated that this TC metric detects 52.5% and 45.9% of extreme precipitation events induced by TCs originating over the NA and EP, respectively (Figure 5a), compared with less than 5% detected by R34. ROCLOUD is used here as a physical proxy for the spatial domain where extreme precipitation events induced by TC circulation can occur. One limitation of the ROCLOUD algorithm is that it considers only convection with brightness temperatures below 233 K. Although most extreme precipitation can occur in the cloud-cover area detected by ROCLOUD, some extreme precipitation events produced by clouds lower than 10 km above the surface (e.g., cumulus congestus and nimbostratus) might be neglected. These lower clouds can only produce extreme precipitation events in the presence of local cloud microphysical processes (Khadke et al., 2024), which are outside the scope of this study. Furthermore, ROCLOUD is affected by satellite cloud-top detection, temporal sampling, quadrant-based radial simplification, and displacement between cold cloud shields and surface precipitation (Sun et al. 2017).

Declarations from CENAPRED (i.e., emergency and disaster declarations) are institutional governmental records, so their issuance is influenced by reporting capacity, administrative criteria, emergency management practices, and governmental decisions regarding financial support (CENAPRED, 2022). The latter shows uncertainty about the annual number of official TC-associated declarations, which is likely underestimated by the Mexican government. Our results show that no official TC-associated declarations are reported inside the country (Figure 2b), although TC extreme precipitation occurs (Figure 4a), demonstrating this underestimation. SIAT-CT commonly assigns TC-hazard levels 1 and 2 for TC extreme precipitation (Figure 8b). These levels indicate a minimum and low hazard, respectively, and do not correspond to actions to be taken in response to an emergency or disaster (CENAPRED, 2019). The SIAT-CT has been operational since 2000, and the formula for computing TC-level hazards has not been modified since then. Here, we show that TC-level hazards associated with extreme precipitation events have been underestimated by SIAT-CT (e.g. Tropical Storm Cristobal 2020 as shown in Perez-Estrada et al., 2024). Thus, the current SIAT-CT wind-centered formula is insufficient to characterize the full spatial extent of rainfall-related impacts.

Our findings demonstrate that ROCLOUD can be used as an important input variable for classifying TC hazard levels. The future approach should consider forecasting TC size (i.e., ROCLOUD), TC wind speed, and daily accumulated precipitation to incorporate this information into SIAT-CT. This study can also be useful to other countries affected by TCs, whose topography is complex.

5. Conclusions

This study demonstrates that TC wind-based metrics, such as R34, partially include TC rainfall-induced hazards, which are responsible for at least 70% of the TC-associated disaster declarations in Mexico. The latter represents a critical limitation for the performance of SIAT-CT, which assigns low-level hazards to TC extreme rainfall events. Consequently, the implementation of proper safety protocols is constrained by a bias in SIAT-CT. On the other hand, TC size metrics that consider both TC circulation and cloud band extension, such as ROCLOUD, are robust proxies for capturing the extreme rainfall events occurring beyond 300 km from the TC center. The use of this TC size metric could help warn of flooding and landslides, hazards arising from TC extreme rainfall rather than TC surface winds. These findings underline the need to improve the SIAT-CT by incorporating TC precipitation-driven metrics alongside traditional wind-based metrics into its operational framework.

A future modern SIAT-CT should integrate multiple components of the TC structure (i.e., inner-core wind fields and outer-size rainfall) to properly warn direct and indirect hazards to society. The latter will enhance alignment between TC hazard levels and disaster declarations, an advance urgently needed, and help Mexican media properly communicate the TC hazard level. Accurate TC early warnings can provide a reliable basis for local decision-makers to reduce disaster risk, particularly in municipalities with high-vulnerability populations (Dominguez et al., 2021).

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