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Contribution of tropical cyclones to seasonal precipitation over the tropical Americas

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Abstract: Tropical cyclones (TCs) are an important element of the climate dynamics in the tropical Americas. They produce intense precipitation during a few days of the rainy season. The contribution of tropical cyclone precipitation to seasonal accumulated rainfall may be as large as fifty per cent, particularly in the arid and semi-arid regions of northern Mexico. A positive trend in the number of tropical cyclones over the eastern Pacific, has resulted in more of these systems approaching the Baja peninsula and a positive trend in annual precipitation. However, the contribution of TCs to regional accumulated may be positive or negative depending on the trajectory followed by the system. If the TC is not close enough to the coastal region, it may induce atmospheric moisture divergence over land, reducing the chances of tropical convective activity and rainfall. Years of large but "distant to continent" TC activity result in negative anomalies in precipitation for some regions of the tropical Americas. Seasonal regional climate predictions or regional climate change scenarios provide information on TC activity but not on preferred trajectories. By means of TC cluster analysis, the preferred trajectories of TCs around the tropical Americas are explored in relation to quasi-stationary circulations at the steering level. Some ideas on how to estimate preferred TCs trajectories for a season are given.

Keywords: tropical cyclones; extreme precipitation; moisture divergence

1. Introduction

Tropical Cyclones (TCs) are key atmospheric phenomena in the hydrological cycle of several tropical regions around the world [1]. They are frequently associated with natural disasters given the negative impacts that intense winds, storm surges and heavy rainfall produce on vulnerable regions [2]. In some places though, they are key meteorological phenomena to produce precipitation that results in water availability. The TC rainfall depends on the evolution of its wind field, regional geographical elements such as topography, and their closeness to shorelines [3,4], i.e., their track, as well as their radius (size), and the environmental conditions related to relative humidity and large scale dominant circulations [5, 6]. The Saffir-Simpson scale was created to categorize tropical cyclones based on their sustained winds, which is important to quantify damage produced by storm surges and wind speed on buildings over coastal areas. However, a scale based on the size of TC, translational speed and rainfall intensity would be ideal to estimate their impacts on surface hydrology processes, reservoir storage and runoff. This scale could provide information about the expected water storage caused by TCs during summer seasons.

The contribution of TCs to monthly rainfall may be as important as natural variations from other factors. For instance, Shephard et al. [7] found that TCs accounted from 8 to 17% of cumulative rainfall during hurricane seasons at different locations along the coastal southeastern United States. Wu et al. [8] pointed out that TCs produce more than one third of the total precipitation between June and November at Hainan Island in China. A TC that is close to the Pacific coast of Mexico may contribute from 20 to 60% of seasonal rainfall along coastal regions of Mexico, and up to 30% in landmass of western Mexico [9,10,11]. Hence, TCs are essential climatic elements of summer rainy seasons in Mexico [12,13]. The regional Mexican climate varies from dry conditions in the north to wet tropical conditions in the south, so the TC footprint in regional precipitation is higher in places where the annual summer rainfall (from May to November) may reach >400 mm, since they carry moisture from the Caribbean Sea and Gulf of Mexico to the semi-arid regions, as the north of Mexico. While summer rainfall in the north is > 500 mm yr-1, the southern precipitation regime is up to 1700 mm yr-1. Most recent studies of TCs that made landfall [10-14], quantify amounts of precipitation in a general way and define their contribution without considering whether it depends on their type of track or size.

TCs are supplying mechanisms of water that recharge aquifers, rivers, lakes and stratus of groundwater [15]. In this way, TCs can buffer the water crisis in the northeastern Mexico by providing enough water to fill reservoir inflows up [16].

Summer rainfall over Mexico has a natural variability due to the association of TC activity with ENSO phase. While this relationship is well known over the North Atlantic Ocean (NAT), there is not a clear signal in the Eastern North Pacific Ocean (ENP) [17-19]. For example, the inactive tropical cyclone seasons over the Gulf of Mexico and Caribbean region (henceforth IAS) during El Niño years have resulted in negative precipitation anomalies in the northeastern Mexico and prolongated meteorological droughts that later become hydrological and agricultural droughts [20]. ENSO has been used as the main predictor to carry out seasonal outlooks, including TC activity forecasts. Kossin et al. [18] linked certain types of TC tracks to the ENSO phase over the NAT.

One the main goals of seasonal forecast services is to provide climate information for water resource planning and adaption strategies in the agricultural sector due to water availability. Decision makers located in semi-arid regions, which greatly depend on water storage levels, need reliable seasonal precipitation forecast. However, the likely types of tracks and the probably affected regions are not issued in any seasonal outlooks of TC activity. This is still a big challenge but urgently needed.

The impacts of TCs in water balances and management should be incorporated in seasonal precipitation forecast when semiarid regions of northern Mexico are considered. Nevertheless, this is not a simple task since seasonal forecasts of TC activity [17] do not provide any information of likely future tracks or even changes in regional precipitation due to TC passages. For instance, negative anomalies of monthly precipitation may still appear at the regional level if most TC trajectories are not close enough to Mexico, although TC activity is normal or above-normal over the IAS or ENP. Thus, if such types of meteorological systems are distant enough from the shoreline, they may not contribute to the total amounts of precipitation over continental regions.

The controversy about distance threshold for TC-related rainfall has prevailed over years. Whereas Englehart and Douglas [9] suggested that the precipitation produced by TCs is the rainfall confined within a diameter of 5º (~550 km) from the TC center, Breña-Naranjo et al. [11] indicated that the distance from the TC center at distances larger than 500 km but less than 1000 km has little impact in TC rainfall. Futhermore, Kouakhi et al. [14] showed that the TC contribution to the rainfall in coasts of North America and Central America tended to decline after 400-km distance because of large mountain ranges. Rain events associated with remnants or deep moisture convergence associated with TC circulations that are remote from the TC center (i.e. Predecessor Rain Events, as detailed in [21]) are beyond the scope of this paper.

The TC circulation essentially consists in a region where the flow converges at low levels of the atmosphere where tropical convection is enhanced, the wet air ascends within cloud towers that tend to concentrate in the narrow outward eyewall. The radial outflow is confined near the tropopause and a gentle subsidence at a larger radius that the storm center is created by the induced circulation. Other mechanisms are needed to compensate upward air movements in the eyewall, including: divergence at high levels that originates a downward air movement [22] called as subsidence (Fig. 1).

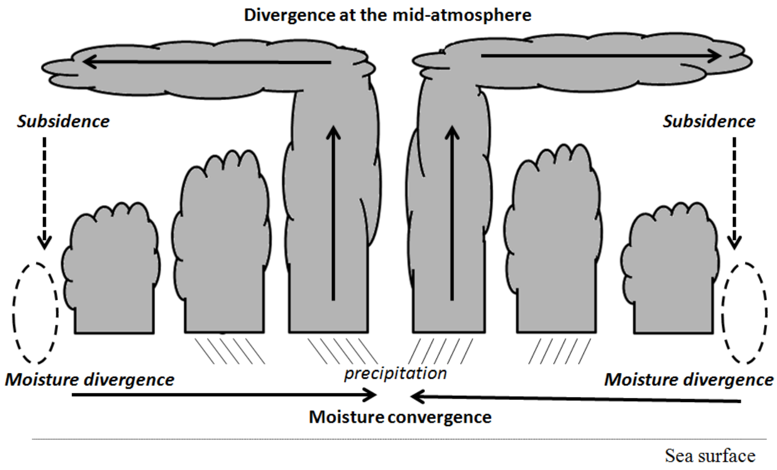

Figure 1. Idealized schematic cross section of secondary meridional circulation in a tropical cylone.

Therefore, TCs may imply both, a "moistening effect" – which is associated with extreme precipitation- and a "drying effect" - which is supported by divergence in high levels and weak subsidence over distant regions from the center. This effect could be relevant for seasonal climate forecasts or climate change scenarios.

2. Data and methods

TCs tracks for the IAS and ENP were obtained from the best-track database (HURDAT) of the NHC for the 1979-2009 period. These datasets contain 6-hourly records of the pressure center, location, intensity and 34 kt wind radii maximum extent in the northeastern, southeastern, northwestern and southwestern quadrants that are used to define size. Only TCs whose intensity is a tropical storm or higher and location are in the domain between 10º-35ºN and 120º- 70ºW, were taken into account for the present analysis.

Meteorological data from the European Centre for Medium-Range Weather Forecasts (ERA-Interim) were used to analyze TC rainfall by means of composite patterns. Divergence fields were used to examine the circulations induced by TCs that may result in a drying effect. The ERA-Interim reanalysis have a T255 spectral resolution (~80 km) on 60 vertical model levels [23]. This spatial resolution is adequate to describe circulations associated with TCs and their impact in rainfall over continental areas.

A probabilistic clustering technique, called Curve Clustering Toolbox (CCT) was used to group TC tracks considering their length, location and geographical shape. Four dominant clusters of tracks were obtained to characterize TC activity over IAS. Although these clusters are similar to those ones proposed by Kossin et al. [18] for the North Atlantic Ocean (NAT), our study was carried out in a smaller domain. Four clusters were also defined over ENP and they are different from those ones proposed by Camargo et al. [17]. Clusters were thought to examine the closeness of systems to the continental region of Mexico. Following Englehart and Douglas [9] and Larson et al. [13], the diameter of 5º (~550 km) from the TC center was used as threshold. This size was used as a reference to define regions where a TC from a cluster produces rainfall, and surrounding regions as those where precipitation is inhibited.

The Storm Relative 16 km Geostationary Water Vapor Imagery archive (referred to as GWV imagery) from the Cooperative Institute for Research in the Atmosphere (CIRA) [24] was used to look for deep convection and atmospheric subsidence at the day and hour that the two TCs (case studies). The GWV imagery is available online for TCs from 2006 to 2013 and continuously updated.

3. Results

The purpose of this study is to investigate the TC contribution to summer rainfall over Mexico - considering not only the number of systems, but their preferred tracks during the 1979-2009 period, which may affect seasonal precipitation by increasing accumulated precipitation- and their effect in reservoir storage. This section is organized as follows: subheading 1 outlines the climatic contribution of TC clusters to accumulated seasonal precipitation over the Intra Americas Seas (IAS) and Eastern North Pacific (ENP) regions. Subheading 2 shows the “drying effect of TCs”, which causes a negative effect in precipitation by means of an induce subsidence.

3.1. Contribution of TCs to seasonal precipitation

In arid or semi-aried regions of Mexico, the effect of a land-falling or close TCs to shorelines, leads to wet years. In this way, changes in TC activity impact regional precipitation. For instance, the annual precipitation in the southern part of the Baja California peninsula is around 200 mm when TCs does not affect this region. If deep convection from the TC affects the southern part of the Baja peninsula, precipitation varies from 500 to 800 mm/year, which highlights the role that TCs play over this region. In recent decades, the number of TCs over the TEP, in particular around southern Baja California peninsula, has risen (Fig. 2), inducing a positive trend in rainfall. The increase in extreme rainfall could be only explained based on the rise of TCs that affect the Baja California Peninsula, since they are the only atmospheric systems that produce extreme precipitation during summer.

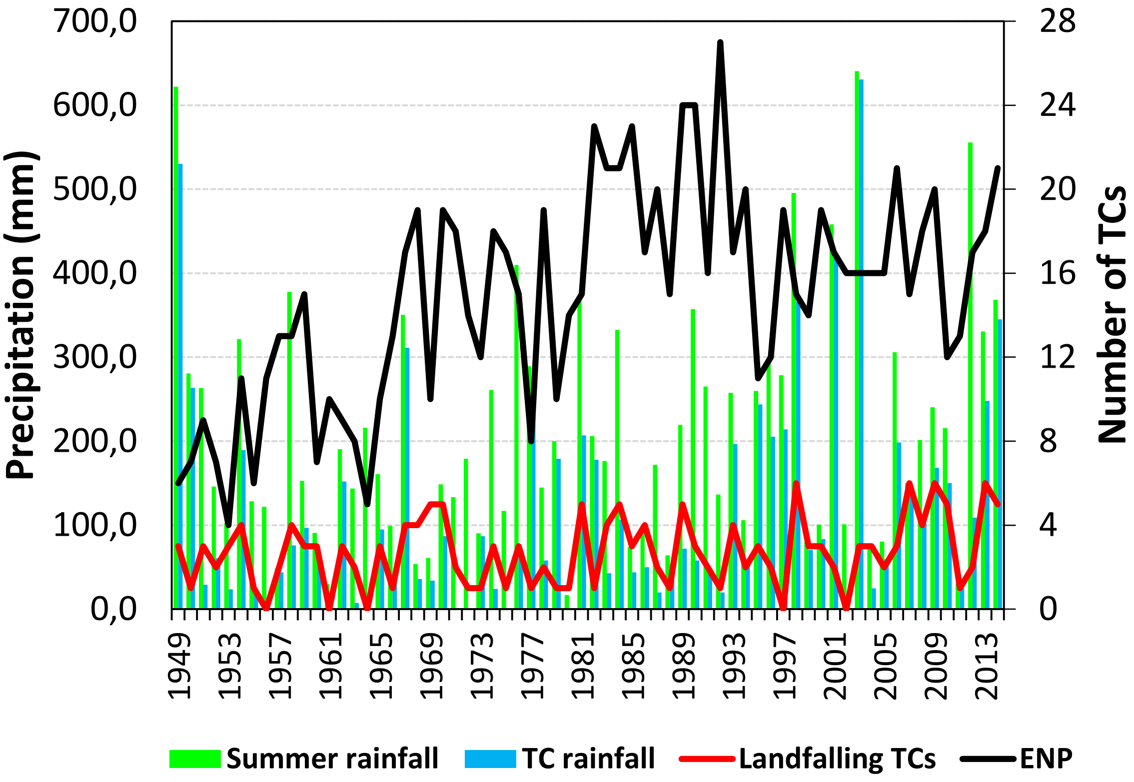

Figure 2. Annual summer precipitation (mm) in the south of the Baja California peninsula (green bars) and the contribution of tropical cyclones (TCs) to precipitation in the region (blue bar). Number of TCs in the eastern Pacific (black line) and number of TCs that affected the southern part of the Baja peninsula (red line) between 1949 and 2013.

Over the IAS, the four principal tracks describe straight (IAS-A), curved (IAS-B), short-term lifetime, as well as erratic (IAS-C) and straight-curved combined moving (IAS-D). Over ENP, the four defined clusters are: tracks that affect the Baja California Peninsula (ENP-A), TCs that have long tracks and form over the southwest of Mexico (ENP-B), tracks that run parallel to the western Mexican coast (ENP-C) and TCs that do not make landfall in Mexico and have a northwestward movement (ENP-D).

The importance of TCs in seasonal precipitation over Mexico may be examined by considering mean daily precipitation calculated from days when TCs are present or absent in the surrounding oceans (Fig. 3). There is a substantial difference of their contribution in several parts of the country, particularly in the northern semiarid regions. However, determining the importance of TCs in summer precipitation over Mexico may be related not only to their frequency but to their tracks indeed. The TC impact was determined according to the different types of tracks grouped into clusters. The percentage of TC contribution to summer rainfall is obtained by aggregating the precipitation that was produced by TCs during their lifetime. The cluster IAS-A and ENP-A significantly contributed to summer precipitation over Mexico (Fig. 3), these types of tracks are likely to make landfall in northeastern and northwestern Mexico. On average, their contribution may be up to 50 percent of mean annual precipitation, particularly in semiarid regions where annual rainfall is around 400 mm. In spite of damages on these regions due to extreme rainfall, the clusters IAS-A and ENP-A supply substantial amounts of water to the north of Mexico and this is why water resource managers and decision makers have expressed interest in predicting this kind of track on seasonal time scales.

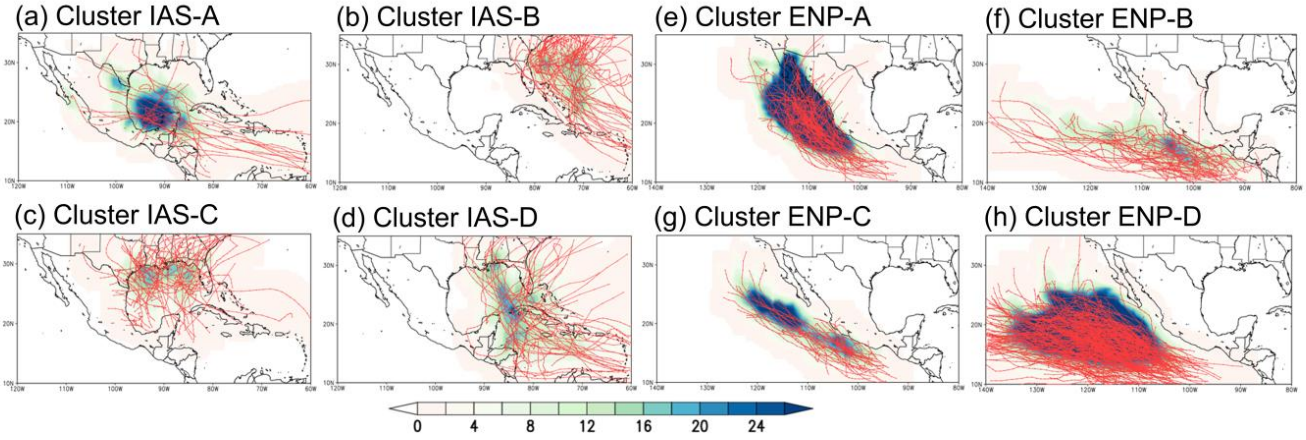

Figure 3. Clusters contribution (%) to summer rainfall over the Intra Americas Seas and the Eastern North Pacific Ocean for the 1979-2009 period

The contribution of TCs to the summer precipitation is not present every year though. It strongly depends on whether a TC is close enough to the Mexican continental regions. For instance, years of El Niño conditions are characterized by a weak TC activity over NAT and this reduces the chances of TCs to make landfall over the eastern Mexican coast [25]. El Niño summers are usually featured by negative precipitation anomalies near the northern Gulf of Mexico coast [25]. Positive precipitation anomalies could increase if at least two TCs approached the northwestern Mexico.

The percentage of TC contribution to seasonal precipitation is also linked to the type of track. On average, the cluster IAS-C contributes 10% of the summer rainfall over the northeastern Mexico, but the cluster IAS-A produces 35% of the precipitation over the same region. It seems that the type of track is also determinant for producing extreme rainfall on a climatological sense (Fig. 4).

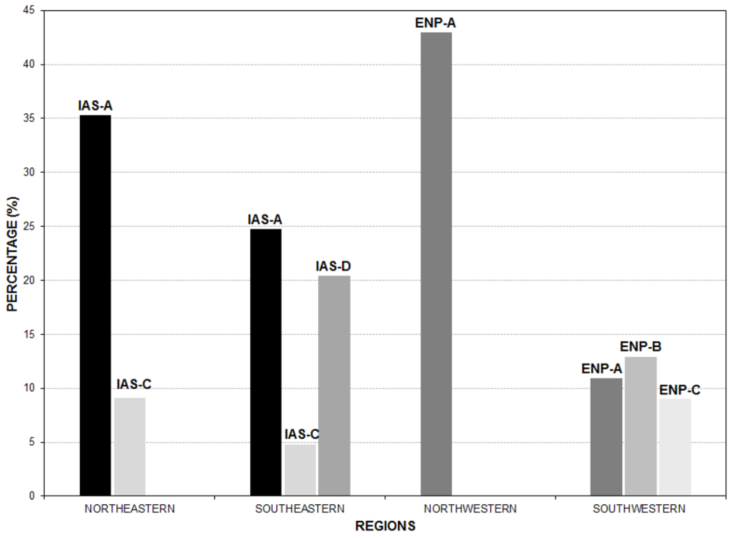

Figure 4. Average contribution of clusters to the summer precipitation in the Mexican regions for the 1979-2009 period.

3.2. The Drying Effect: subsidence and divergence induced by TCs

TCs can induce monthly negative anomalies in precipitation if their "synoptic effect" frequently affects continental regions in Mexico. This "drying effect" is the result of low level moisture divergence induced by subsidence at high levels as a compensating motion of the cyclonic system. TCs produce intense moisture convergence towards the eyewall, but this horizontal motion removes moisture from surrounding regions. It is known that when a TC is passing over ENP or IAS at a 200-300 km distance from the coastal regions, the Mexican central plateau can experience clear skies.

Figure 5 presents snapshots of (1) precipitation, streamlines and divergence fields at 850 mb, (2) cross sections of vertical motion and (3) GWV imagery of (a) the Hurricane Gustav, which was category 3 at the selected location in 2008 and it belonged to cluster IAS-B, and (b) the Tropical Storm Blanca in 2009 that belonged to cluster ENP-D. Gustav exhibited an intense subsidence (Fig. 5.1.a; 5.2.a), that is supported by the well defined divergence around a radius of 10º (1100 km) from the center. Gustav presented the drier environment ahead of its circulation, where a weaker subsidence is produced (Fig. 5.3.a). The strong subsidence is also supported by divergence and it inhibited convection on the right side of Gustav. However, the downward motion did not have the same magnitude in both sides. Blanca caused a forceless subsidence on the western coast of Mexico but it still was sufficient to prevent convection on that region (Fig. 5.1.b; 5.2.b) what implies clear skies.

The subsidence was found to increase across the TC intensity (not shown) but it did not happen symmetrically around the TC circulation. Even more, the translational movement and the extent of the spiral rain bands appear to diminish the induced subsidence.

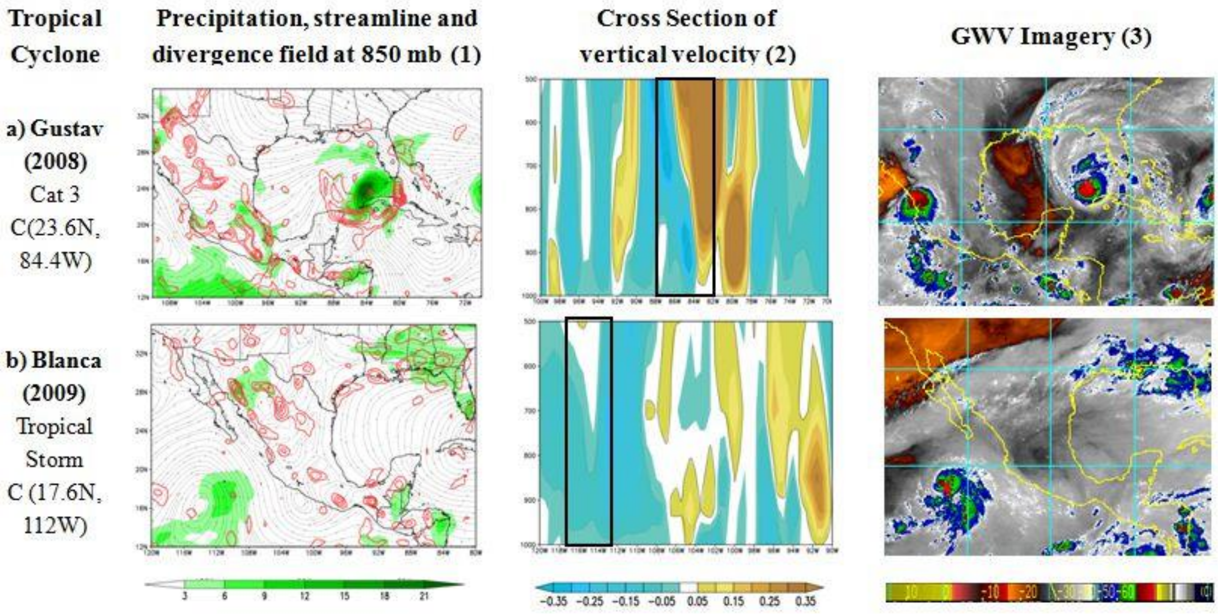

Figure 5. Precipitation (shaded), streamlines and divergence field (dotted line) at 850 mb, cross section of vertical velocity at the center's latitude (positive values are in solid line) from 1000 to 500 mb and GWV imagery for: a) Gustav in 2008 b) Blanca in 2009. The letter C refers to 'center' as issued by NHC and the rectangle marks the TC size.

The drying effect is less important when compared to heavy rainfall produced by TCs but they also act to produce day-to-day weak subsidence and negative precipitation anomalies (not shown) from inhibited convective activity. On average, the drying effect over the northeastern and northwestern part of Mexico mainly due to clusters IAS-B, IAS-D, ENP-B and ENP-D, whose lifetime is around 10 days, should be considered in the total accumulated rainfall.

The previous analysis indicates that the radius of TC influence, defined as 500 km by Englehart and Douglas [9], should be extended when the potential drying effect is considered. The radius of TC influence should be in the range between 1100-1800 km away from the center of the system, in a sort of synoptic scale influence by means of low-level moisture divergence and induced subsidence. The intensity of the TC may modulate the induced effects and has relevance in the hydrological cycle at the regional level.

5. Conclusions

The moistening and drying effects of Tropical Cyclones (TCs) have been analyzed considering clusters (types of tracks) for the Intra Americas Seas Region and the Eastern North Pacific Ocean during the 1979-2009 period. TC tracks near the shoreline may result in substantial increases in regional precipitation over northern Mexico. However, in some years these tropical systems are absent and negative anomalies in the monthly or seasonal accumulated precipitation appear in some regions. Even more, years of above-normal TC activity, either over the Gulf of Mexico or Eastern North Pacific Ocean, may result in relatively dry years in northeastern or northwestern Mexico, if TC tracks are sufficiently distant from the Mexican shoreline.

The "moistening effect" shows that contribution of TCs to seasonal precipitation in Mexico varies largely depending on the cluster. The climatic contribution of TCs to summer rainfall in Mexico may be up to 50% in some regions, particularly in locations where annual precipitation does not exceed 400 mm. TCs also play a "drying effect" which depends on the track and characteristics of the system. Although this effect is not as large as the absence of TCs near the Mexican shoreline, it acts for a few days during the summer season by means of subsidence and low-level moisture divergence to inhibit precipitation over continental regions. This can be explained in terms of a decrease in water vapor column because of the subsidence, which is induced at higher levels and at a radius of 1100 km away from the center of the system.

The effect of TCs in the hydrological cycle of northern Mexico is missing in most global or regional climate models even when they play a relevant role. Even though TC activity and characteristics should be included in the water management planning process in Mexico, there are no predictive schemes aimed at meeting such goal. Given that the moistening and drying effect are not well represented in climate models, water management in several northern semiarid regions is based only on the amount of water availability in dams.

Seasonal or even monthly outlooks of TC activity over Intra Americas Seas may not be enough to estimate the TC impact in the hydrological cycle since subtle elements, such as the track and size, are not forecast at least one month in advance. Statistical and dynamical approaches [17, 19] to predict seasonal TC activity, which are based mainly on the ENSO phase, have not shown to be good enough in forecasting frequency; TC track still remains as a challenge in monthly outlooks. As a result, it can lead wrong outlooks in some regions, for instance over northern Mexico. The problem is even more complicated when regional climate change scenarios for the water sector are used to make projections of the potential impacts of such extreme phenomenon. Therefore, a "bottom-up" approach to define adaptation is more appropriate [26].

Future work should consider the role of large scale forcing in determining preferred TC tracks and ensembles of projections on what their effect could be at regional scale. One possible approach to this problem is to seed TC-like vortices in predicted cyclogenesis regions and explore their development and tracks in high resolution climate models.

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