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On the origin of moisture related to synoptic-scale rainfall events for the North American Monsoon System.

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Abstract. This work examines the origin of atmospheric water vapor arriving to the North American Monsoon (NAM) region over a 34-yr period (1981-2014) by using a Lagrangian diagnosis method. This methodology computes budgets of evaporation minus precipitation by calculating changes in the specific humidity of thousands of air particles advected into the study area by the observed winds.

During the NAM wet season, on average the recycling process is the main water vapor source, followed by the supply of moisture from the Gulf of California. However, the water vapor transport that generates synoptic-scale rainfall comes primarily from the Caribbean Sea, the Gulf of Mexico and terrestrial eastern Mexico. An additional moisture source over the southwestern U.S. is also identified in association with synoptic rainfall events over the NAM region.

A high (low) moisture supply from the Caribbean Sea and the Gulf of Mexico from 4 to 6 days before precipitation events is responsible for high (low) rainfall intensity on synoptic scales during the monsoon peak. Westward propagating mid to upper level inverted troughs (IVs) seem to favor these water vapor fluxes. A 200% increase in the moisture flux from the Caribbean Sea is related to the occurrence of heavy precipitation in the NAM area, accompanied by a decrease in water vapor advection from the Gulf of California.

1 Introduction

Historical studies used the reversal in wind direction to identify a monsoon domain (Ramage, 1971). Such monsoon domains are found mainly over tropical areas of the Eastern Hemisphere because the seasonal wind reversal is much better defined there than over the Americas (Hsu, 2016). Besides the wind field, precipitation is another fundamental variable used to delineate a monsoon climate. In a monsoon region the majority of the annual rainfall occurs in summer while winters are quite dry. This classification includes the North American and South American Monsoon Systems (Wang and Ding, 2006; 2008; Liu et al. 2009; Wang et al. 2011; Zhou et al. 2008; Hsu et al. 2016). The tropical area of North America, north of roughly 10ºN, is considered a major regional monsoon within the global monsoon system (Wang and Ding, 2008; IPCC, 2013; Hoell et al. 2016).

The term "North American monsoon (NAM) system" is used to denote the monsoon-like summer rainfall centered over northwest Mexico and extending into the southwestern United States (U.S.) (e.g., Douglas et al. 1993; Adams and Comrie 1997; Higgins et al. 1997; Barlow et al. 1998; Higgins et al. 1999; Higgins and Gochis, 2007). The NAM system is part of the regional monsoon system located over tropical North America, which is part of the global monsoon system (Vera et al., 2006). This summer feature has also been referred to as the Mexican Monsoon, the Arizona Monsoon, and the Southwest United States Monsoon in early studies.

The arrival of strong convection in northwestern Mexico during mid to late June marks the onset of the NAM system (Adams and Comrie 1997; Higgins et al. 1997). Increases in precipitation over the southwestern U.S. occur abruptly around the beginning of July, at the same time as the development of a thermally induced trough, northward displacements of the Pacific and Bermuda highs, and the formation of southerly low-level winds over the Gulf of California (GOC). This wind reversal is not of sufficient magnitude and scale to meet the criteria of Ramage (1971) for a monsoon (Hoell et al. 2016). The NAM system is fully developed during July-August-early September (Vera et al., 2006) and supplies about 70%, 45% and 35% of the annual precipitation for northwestern Mexico, New Mexico, and Arizona, respectively (Erfani and Mitchell, 2014).

The identification of the origin of the water available for precipitation in a region constitutes a very complex problem. Over the years, it was accepted that moist air moves into the NAM system on a broad band of middle troposphere southeast winds from the Gulf of Mexico (GOM) (Bryson and Lowry, 1955; Green and Sellers, 1964; Jurwitz, 1953). Later studies claimed that the eastern tropical Pacific and boundary layer flow from the GOC is the major source of moisture for the NAM system (Douglas, 1995; Stensrud et al. 1995; Berbery, 2001; Mitchell et al., 2002), while the middle tropospheric flow also remained important (Schmitz and Mullen, 1996). As this mean flow is typically not sufficient to bring deep moisture flow into the NAM region, some mechanism must enable a deeper penetration of moisture into the core monsoon region. One important feature is the moisture intrusion known as a "gulf surge", a coastally trapped disturbance (Rogers and Johnson, 2007; Newman and Johnson, 2013) that is typically initiated by a tropical easterly wave or tropical storm that crosses near the GOC entrance and is then propagated north-westward along the GOC axis. This phenomenon can be wet or dry depending on if the surge is followed by positive or negative spatially averaged mean precipitation anomalies over Arizona and western New Mexico (Hales et al. 1972; Stensrud et al. 1997; Higgins et al. 2004; Pascale and Bordoni, 2016). Wet surges occur between seven and ten times during the monsoon season (Pascale et al., 2016). There are other synoptic circulation controls of deep convection and precipitation in the region. These include transient upper-level inverted troughs (IVs), cold-core cut off lows, open troughs in the westerlies and surface fronts (Douglas and Engelhardt, 2007; Seastrand et al., 2015). Gulf surges typically occur in conjunction with such disturbances, particularly IVs, to produce rainfall over the northern NAM region (Stensrud et al. 1997; Fuller and Stensrud 2000; Higgins et al. 2004; Bieda et al. 2009; Finch and Johnson 2010; Newman and Johnson, 2012; Seastrand et al. 2015).

Today it is widely accepted that both the middle level easterly moisture coming from the GOM and the southwesterly low-level moisture from the GOC contribute to monsoonal precipitation. However, a recent study suggests that low level moisture from the GOM may also be important to monsoonal rainfall as it passes through the Chiricahua Gap in the northern Sierra Madre Occidental mountains (Ralph and Galarneau, 2017). In addition, other studies have highlighted the role of surface soil moisture and vegetation dynamics in the NAM region (e.g., Dominguez et al., 2008; Méndez-Barroso et al., 2009; Bohn and Vivoni, 2016). Specifically, Hu and Dominguez (2015) by using the extended dynamic recycling model (DRM, Dominguez et al., 2006) have found that terrestrial sources contribute approximately 40% of monsoonal moisture. Bosilovich et al. (2003) used water vapor tracer diagnostics in global numerical simulations to quantify the effect of local continental evaporation on the monsoon precipitation, finding that it is the second most important source of precipitation after the GOM. Dominguez et al. (2016) have used water vapor tracer diagnostics in a regional climate model to quantify the water vapor from four different oceanic and terrestrial regions that contribute to precipitation during the NAM season. They have documented that local recycling is the second source after the lower-level moisture coming from the GOC. Therefore, despite the large number of studies, the major moisture sources to the NAM system and their relative importance are still actively debated.

In this work, we use the Lagrangian particle dispersion model FLEXPART to analyze the water vapor transport towards the NAM. Evaporation minus precipitation (E – P) is tracked from the NAM region along the trajectories of appropriately selected particles, thereby facilitating the determination of water source-receptor relationships. This work addresses two main objectives: (1) define the main moisture sources for the NAM region, and (2) determine the moisture transport that effectively contributes to the synoptic-scale rainfall development over the NAM area. In section 2 the data and methods used are presented. Section 3 includes the results and we dedicate section 4 to present the main conclusions of the study.

2. Data and Methods

2.1 Lagrangian Diagnostic of E-P

The Lagrangian particle dispersion model FLEXPART version 9.0 (Stohl et al., 1998; Stohl and Thomson, 1999) is employed in this study to quantify the atmospheric water vapor transport towards the NAM region. At the model start, the atmosphere is homogeneously divided into a large number of air parcels (particles), each representing a fraction of the total atmospheric mass. Then, the particles are allowed to move freely with the observed wind, overlapping stochastic turbulent and convective motions (Stohl et al., 2005) while maintaining their mass constant. Following the method of Stohl and James (2004), for each particle the net rate of change in water vapor content $[\frac{dq}{dt} = \frac{(e-p)}{m}]$ is computed along its trajectory, where q is the specific humidity, and e and p are the rates of moisture increases and decreases along the trajectory, respectively. To diagnose the net surface freshwater flux in an area A, the moisture changes of all particles in the atmospheric column over A are aggregated, giving the field (E - P), where E is the evaporation rate and P is the precipitation rate per unit of area.

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FLEXPART is driven at 1ºx1º resolution by ERA-Interim reanalysis (Dee et al., 2011) available on 60 model levels from 0.1 to 1000 hPa. There are approximately 14 model levels below 1500 m and 23 below 5000 m. We use analyses every 6 h (at 0000, 0600, 1200, and 1800 UTC), and 3-h forecasts at intermediate times (at 0300, 0900, 1500, and 2100 UTC). The 3-h forecasts are used here to supplement the analyses because the time resolution is critical for the accuracy of Lagrangian trajectories (Stohl et al. 1995). FLEXPART was run for a 34-yr period from 1981 to 2014 over the domain shown in Figure 1 (which is the NAM domain used by Hu and Dominguez, 2015). We calculated the water vapor transport up to 6 days before its arrival to the target area using the backward mode for tracking the particles that reside each 6 h over the NAM region. The transport time was limited to 6 days, as that is the optimal lifetime of vapor in the atmosphere calculated over our study area. This lifetime was defined after several calculations of the precipitation simulated by FLEXPART out to 10 days (Miralles et al., 2016). The selected lifetime represents the minimum absolute difference between the simulated precipitation by FLEXPART and CHIRPS data (Funk et al., 2015) over the NAM. CHIRPS merges both satellite infrared observations and surface station data using a novel "smart interpolation" algorithm. The ability of CHIRPS to represent the precipitation over Mexico with high temporal and spatial resolution has recently been shown by Perdigón-Morales et al. (2017).

2.2 Tracking E-P for different precipitation events

The methodology described in the previous section determines the average net changes of q for air particles aimed to the study area, but the moisture transported towards the NAM region does not always generate effective precipitation. Therefore, the air particles that arrive to the NAM during wet and dry days must be tracked separately. This requires a definition of wet and dry days over the NAM region. For this purpose, daily CHIRPS data are used with a spatial resolution of 0.25° x 0.25°. The assessment of long-term statistics is performed on a 34-year (1981-2014) period. A "common wet day" over the region was obtained using the methodology described by Ordoñez et al. (2012). In this method, the target region is assumed to present an approximately homogeneous precipitation regime. For each grid point, the values above 10% of its corresponding standard deviation are considered an individual precipitation event. To define a wet day at synoptic scales (i.e., affecting the entire NAM region), we compute the percentage of grid points inside the region that must have simultaneous precipitation events in order to obtain the observed annual average precipitation over the region. This percentage resulted in 41.3% with a total of 2513 days classified as wet days for the study period. Figure 2 shows the precipitation distribution throughout the year according to this methodology.

The wet days have also been classified as a function of intensity following the methodology of Ordoñez et al. (2012). To define moderate and extreme precipitation events, the 50^{th} (P50) and 90^{th} (P90) percentiles of the precipitation series at each grid point have been computed, respectively. These percentiles must be exceeded in at least 41.3% of the grid points inside the NAM area. In this way, the method assures that a moderate or extreme rainfall event is characterized by a well-determined precipitation value in a significant portion of the NAM region. Weak precipitation days are the remaining wet days. Figure 3 shows the yearly precipitation composites for the different precipitation categories. The general increase of the synoptic-scale precipitation of the entire NAM area is clearly appreciated in Figures 3b to 3d.

In order to extract information about synoptic patterns associated with different rainfall intensities over the NAM region, we use different climatic fields (heopotential height, especific humidity and horizontal winds components) from the ERA-Interim reanalysis.

3. Results

3.1 Moisture sources for the NAM region

Figure 4 shows the 6-day aggregated monthly average values of surface fresh water flux (E - P) before air masses aimed towards the NAM reach the region for the period 1981-2014. $(E-P)_n$ designates the freshwater moisture flux value for day "n" before arrival to the target area. The sum of the net freshwater flux from day 1 to day 6 (sum of $(E-P)_1$, $(E-P)_2$, …, $(E-P)_6$) is denoted using $(E-P)_{1-6}$. Although the NAM season is usually defined from July to September, we found several synoptic-scale precipitation events during June (see Figure 2), so the results for the 4 months from June to September are presented in this figure. Reddish/bluish colors are used to show regions of water vapor gain/loss according to the sign of dq/dt of particles across their trajectories. The North Eastern Pacific off the coast of the United States and the GOC are found to be net moisture sources during the summer. The monthly analysis shows that while the terrestrial region east of the NAM area is an active source throughout the summer, there is a source region over the GOM and the Caribbean Sea that seems to be significant mainly during July and August. The southwestern U.S. also appears as an active source region from June to September. This arid subtropical region is known to be a region of mean positive divergence of water vapor during summer where evaporation is larger than precipitation (Peixoto and Oort, 1992). Finally, recycling processes seem to be a moisture source for the whole region in June and September, whereas during July and August the recycling contributes over the northern NAM region, and the southern NAM shows negative values of $(E-P)_{1-6}$, which means that this area is a net sink of moisture during the peak monsoon.

According to these results, five main moisture sources for the NAM region have been defined: (1) the NAM region itself (NAM), (2) the terrestrial region east of the NAM (EAST), (3) the Atlantic (ATL) which includes a part of the GOM and the Caribbean Sea, (4) the southwestern U.S., toward the north of the NAM (NORTH), and (5) the Pacific (PAC) which includes the Eastern Pacific and the GOC. Figure 5 shows their boundaries. These source regions were defined using the values greater than P90 of $(E-P)_{1-6} > 0$ for the period from June to September. The summer monthly evolution of $(E-P)_{1-6}$ integrated for these fixed areas is shown in Figure 6. During June, the recycling process and the water vapor from PAC are the main moisture sources for the NAM System. In July, NORTH also provides almost a similar amount of moisture as these other regions. The situation is slightly different for August, when the recycling process is the main source and the EAST region shows its peak values of $(E-P)_{1-6}$. September is characterized by the peak contribution from recycling, while the relative contribution from the remaining sources decrease with respect to their August values.

Following the monsoon onset (from July to September), FLEXPART describes a recycling contribution of moisture of 38% on average, with an incoming freshwater flux from the NAM itself of 26%, 34% and 55% during July, August and

September, respectively. FLEXPART reports a larger contribution from recycling than other previous studies that also found the local recycling to be a very important contributor. Bosilovich et al (2003) considered the entire Mexican continental region and found this terrestrial source to be the dominant contributor, at roughly 30%, 25% and 20% during July, August and September, respectively. Hu and Dominguez (2015) estimated the contribution from recycling to be about 10% during the monsoon peak. However, the model they used has proven to be imprecise at tracking the moisture transport in the monsoon region because of the model's assumption of a well-mixed atmosphere, when in fact the monsoon region has a relatively strong shear causing an underestimation of local recycling (Dominguez et al., 2016). However, aside from model performance, it must be pointed out that Hu and Dominguez (2015) estimated the precipitable water contributions and Bosilovich et al. (2003) the fraction of precipitation that originates as evaporation from the region, while FLEXPART estimates the net moisture gain, (E – P) > 0, since precipitation and evaporation are not directly separable in this model. Therefore, FLEXPART also counts recycling during days when precipitation does not occur. This may result in an overestimation of the recycling contribution to NAM rainfall by FLEXPART.

3.2. Role of moisture source regions during synoptic scale precipitation events

As stated, FLEXPART diagnoses (E - P), but the advected moisture may or may not produce effective precipitation. Figure 7 depicts the differences in the advected moisture from the different source areas between days with or without precipitation during the wet season (JAS). The integrated series of (E - P) for the fixed areas in Figure 5 are shown for the sixth to the first day before the air masses aimed at the NAM reach this region (days -1, -2, -3, -4, -5, and -6 hereafter). All the source regions contribute with higher recharges before the synoptic-scale rainfall events, indicating the importance of extra-water uptake in these areas to generate effective precipitation. The greatest difference in the total amount of moisture transported before dry and wet days is obtained for the EAST area. In fact, over EAST the particles are already losing moisture during day -1 before a synoptic rainfall event over the NAM, so this region is a net sink of moisture likely due to its proximity to the target region. The monthly analysis for July, August and September separately yields similar results (not shown).

Bosilovich et al. (2003) found the dominant sources of monsoon precipitation to be the local evaporation and transport from the tropical Atlantic Ocean (including the GOM and Caribbean Sea). In contrast, Dominguez et al. (2016) reported that the GOC contributes a higher moisture amount to the NAM precipitation than the GOM and the local evapotranspiration (ET). This latter study used water vapor tracers embedded into a regional climate model using lateral boundary conditions derived from the North American Regional Reanalysis (NARR; Mesinger et al. 2006). However, the ET fields from NARR might have significant deficiencies in the primary moisture source areas (Bohn and Vivoni, 2016). Our results are in better agreement with those of Bosilovich et al (2003) and suggest that the ATL and EAST could be a major contributor to the monsoonal rainfall. However, we cannot conclude that this is the only decisive source for rainfall development, because as we have mentioned, the other sources also exhibit important changes for precipitation versus no precipitation days.

Our next objective is to examine which source regions are the most relevant for the modulation of rainfall intensity. We have found only 32 extreme precipitation events occurring in September from 1981 to 2014. Therefore, in order to obtain statistically meaningful results, only water vapor transport that generated heavy rainfall during the monsoon peak (July and August) is studied. Figure 8 shows the anomalies of (E - P) for the extreme precipitation events with respect to weak intensity rainfall events during days -1, -2 and -5. For day -1 the northern/southern NAM presents negative/positive anomalies of (E - P), suggesting a rainfall intensification mainly in the northern NAM with respect to the low rainfall days, which is consistent with Figure 3. On day -2, larger contributions are identified over the NAM region as a whole. On day -5, larger supplies of (E - P) are found along a pathway that crosses the EAST and reaches the ATL region. A high (low) moisture supply from the ALT for 4 to 6 days back in time appears to be one of the most important factors affecting the precipitation intensity over the northern part of the NAM during the monsoon peak.

The above-mentioned differences can be clearly observed in Figure 9, which presents the integrated water vapor flux time series for extreme, moderate and weak rainfall days. Over ATL and EAST, the water intake is related to the intensity of the precipitation from day -6 to -4 (Figures 9c and 9b) with an increase of more than 200% in the case of ATL and 44% for EAST from weak to extreme rainfall days. The integrated time series of (E - P) for NAM itself and NORTH does not show a systematic change related to the intensification of the rainfall (Figures 9a and 9d). In the case of the PAC, it is noteworthy that the changes in the moisture transport amount are inversely related to the rainfall intensity (Figure 9e). Therefore, these results show clearly that southeasterly vapor fluxes from the Caribbean Sea, overtaking the Sierra Madre into higher latitudes, are related to the monsoonal rainfall intensity, particularly over the northern NAM region (Arizona and New Mexico).

Figure 10 depicts geopotential height and moisture transport anomalies at 700 and 200 hPa for weak, moderate and strong precipitation days with respect to dry days. For the low to mid-troposphere (Figures 10a, 10b, and 10c) positive geopotential height anomalies show a center over the western United States and transient lows (easterly waves or tropical cyclones) off the west coast of Mexico are also observed. Both features are better defined as the precipitation becomes more intense over the NAM. At 200 hPa a positive height anomaly is located over the desert Southwest as an extension of the monsoon anticyclone (Figures 10d, 10e and 10f). A negative height anomaly develops roughly over the GOM that is also more intense as the precipitation intensifies over the NAM and may indicate inverted troughs (IVs). This result has been previously described, low-level troughs interacting with an upper-level IVs enhancing precipitation into the southwestern United States and northwest Mexico (Stensrud et al. 1997; Fuller and Stensrud 2000; Higgins et al. 2004; Seastrand et al., 2015). IVs have been associated with heavy rainfall events in the border region of U.S. and Mexico. (Bieda et al. 2009; Finch and Johnson, 2010; Newman and Johnson 2012). How exactly mesoscale and synoptic circulations related to IVs help organize deep convection over the NAM region is not entirely known (Lahmers et al., 2016). Newman and Johnson (2012) find that these transient features increase surface-to-mid level wind shear, with midlevel flow from the northeast perpendicular to the topography. The enhanced vertical wind shear across the topography supports the upscale growth and westward propagation of diurnal convection initiated over the Sierra Madre Occidental, resulting in wide spread convection over the western slopes and coastal low lands of the NAM region noted by the previous studies. While compelling, these results are based on observations from a limited field campaign. More observations of the dynamic and thermodynamic environment during the

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passage of IVs, as well as improved models of the flow over complex terrain like that of the NAM region are both needed to better understand the role of IVs in supporting convective outbreaks across the monsoon region.

4. Summary and concluding remarks

Despite the large body of literature on the transport of water vapor and precipitation patterns associated to the NAM System, there are still important knowledge gaps regarding the sources of water vapor involved, their relative importance, and the pathways through which the water vapor can reach the NAM region. In this article, a 3D Lagrangian method of diagnostic has been used to assess the location of the major moisture sources of the NAM System for a 34-yr period from 1981 to 2014. Five main moisture sources for the NAM region have been identified, three terrestrial and two oceanic sources: the evapotranspiration from the region itself, the Mexican terrestrial area east of the NAM region, the southern part of the Gulf of Mexico and the adjacent Caribbean Sea, the southwestern U.S, and the Gulf of California together with the most eastern part of the Northern Pacific. The moisture sources identified by FLEXPART concur with the existent literature, in which traditionally the debate has been centered in the relative importance of the Gulf of California versus the Gulf of Mexico and more recently, the role of the recycling process. However, to best of our knowledge, this is the first time that the southwestern U.S has been specifically identified as an active source for the NAM region.

Our results show that during the wet monsoon season (from July to September), the local recycling is the main moisture source and the water vapor coming from the Gulf of California and the Northeastern Pacific is the second-most important source. However, when the moisture transport for the days leading to synoptic-scale rainfall events and dry days are compared, the influence of the water vapor from the Caribbean Sea and the Gulf of Mexico on days -4 to -6 is seen, in agreement with Bosilovich et al. (2003). The remaining moisture sources also show major contributions during the days before precipitation events, suggesting that the precipitation events over the NAM have different origins.

Moisture transport from the Gulf of Mexico, the tropical Atlantic Ocean and the terrestrial area east of the NAM region plays a fundamental role for synoptic-scale heavy precipitation development over the northern NAM region during the monsoon peak. In contrast, the relevance of the water vapor transport from the Gulf of California and Eastern Pacific diminish the days before as the intensity of synoptic-scale precipitation events increases. In the case of heavy precipitation events, both low level troughs and upper-level inverted troughs are observed. This result is in agreement with Schiffer and Nesbitt (2012) which suggest the moisture from the GOM to be important for providing pre-surge moisture to the northern NAM, whereas local recycling and GOC moisture would be important after the surge arrives at the northern end of the GOC. In fact, Schiffer and Nesbitt (2012) described deep easterly flow anomalies along the southern edge of the monsoon high over the NAM core, as obtained in this study, prior to an initiation of a wet surge. Other authors also reported gulf surges occurring if an easterly wave trough passes east to the GOC following the passage of an upper-level mid-latitude trough (Stensrud et al., 1997; Fuller and Stensrud, 2000). Particularly for the occurrence of rainfall over the northern part of the NAM (region of Arizona and New Mexico) there have been recently produced different results. Ralph and Galarneau (2017) document the role of easterly transport of water vapor in modulating the most extreme precipitation events over southeastern Arizona. This particular apportionment of water vapor to the region is hypothesized to flow through a gap in the mountain range that connects the Continental Divide and the Sierra Madre in southern Arizona-New Mexico and Northern Mexico, named the Chiricahua Gap by the authors. In contrast, Jana et al. (2018) find the Gulf of California to be probably the leading moisture source for precipitation development at two locations selected over Arizona (Laveen) and New Mexico (Redrock), although these authors also find moisture contribution from the Gulf of Mexico at low levels (below 2000 m) for the western New Mexico location.

We assume that rainfall over the NAM could have different origins, even in cases of extreme precipitation events, since our work is based on composites. However, we clearly show that, on average, the intensity of synoptic-scale rainfall events is related to the moisture amount transported from the Caribbean Sea and south of the GOM from 4 to six 6 days before. The intensity of synoptic-scale extreme rainfall events is also associated with westward propagating IVs south of the monsoon ridge. IVs seem to help the moist air to bypass the Sierra Madre westward accompanied by organized convection and upward vertical velocity over the NAM region. The implications of these results for predictability in the NAM region will be explored in a future work since the monsoon rainfall variability presents a profound socio-economic impact over the region and the production of reliable seasonal climate forecasts remains a challenge.

Competing interests

The authors declare that they have no conflict of interest.

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Figures

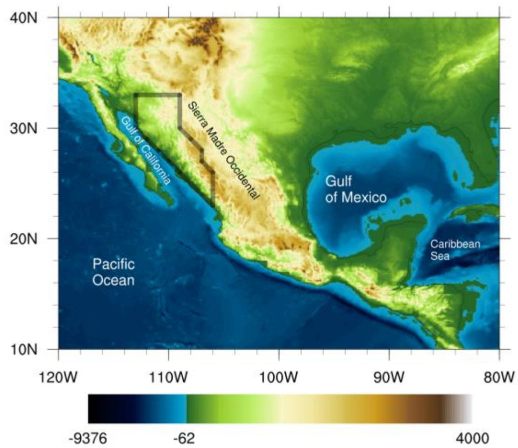

Figure 1: Study region (black solid line) and its topography (m).

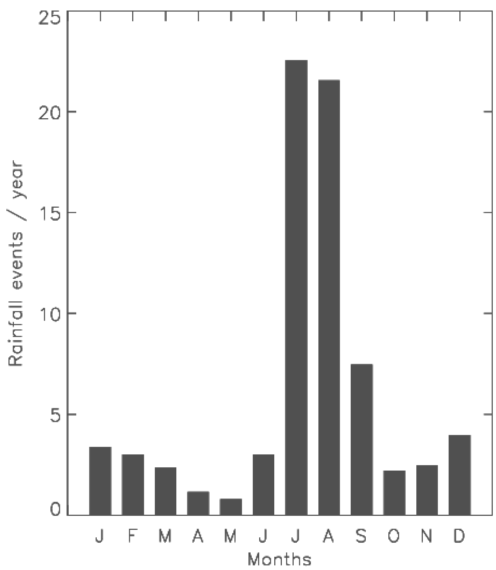

Figure 2. Number of precipitation events per month.

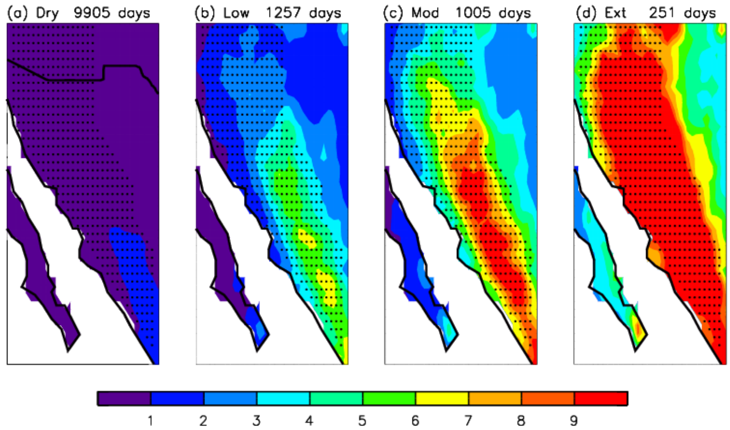

Figure 3. Mean daily rainfall (mm/day) (1981-2014) for the (a) dry days, (b) weak precipitation days, (c) moderate precipitation days, and (d) extreme precipitation days. Dotted area represents the study region. Precipitation intensity composites are based on percentiles; see section 2 for further details.

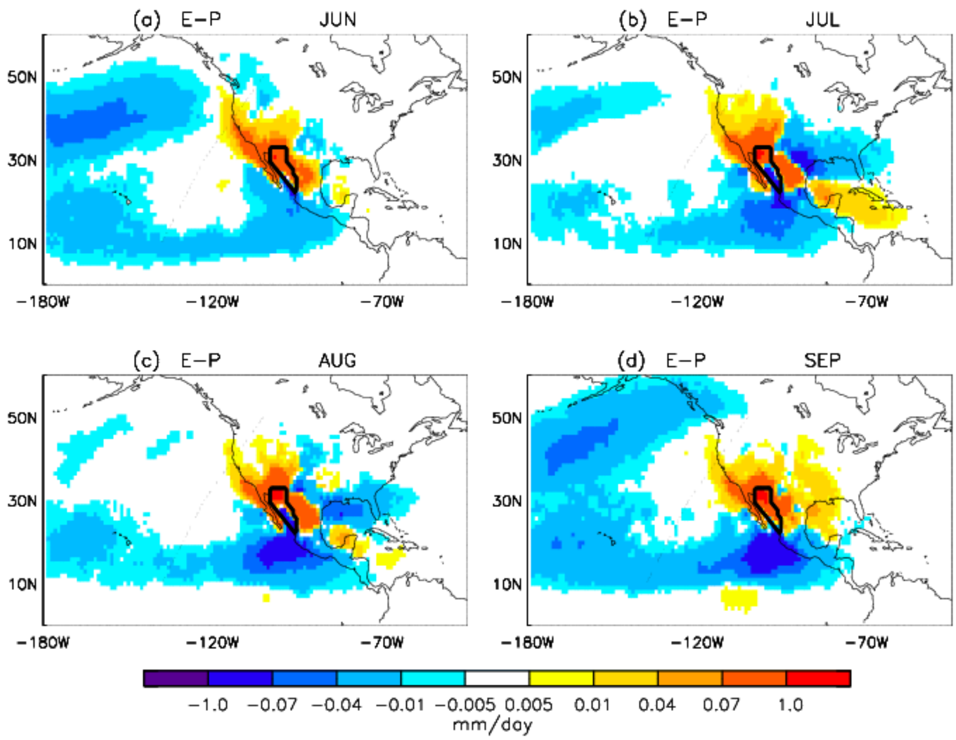

Figure 4. Monthly averaged values of $(E-P)_{1-6}$ (mm/day) for all the particles aimed toward the NAM region during (a) June, (b) July (c) August and (d) September (period of study: 1981 – 2014). Black line delineates the study region.

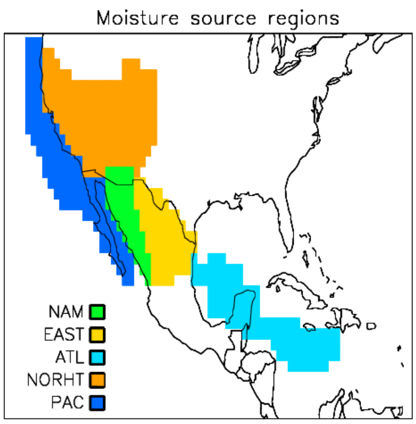

Figure 5. Name and geographic limits of the moisture sources defined for the NAM region.

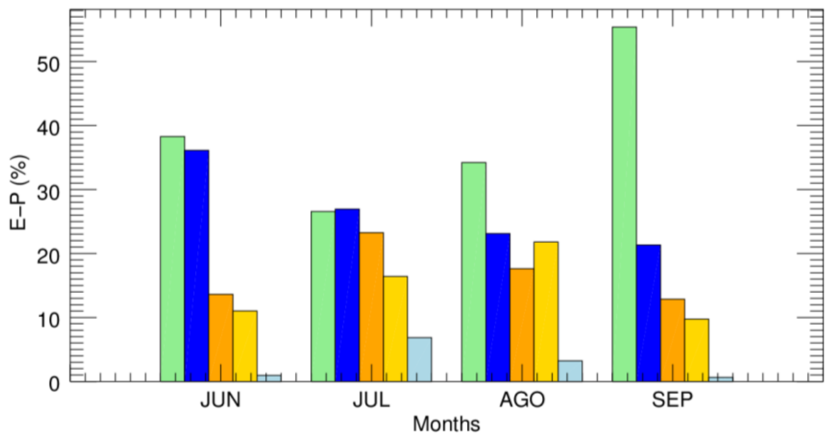

Figure 6. Monthly $(E - P)_{1-6}$ percentages for the five areas defined as moisture sources.

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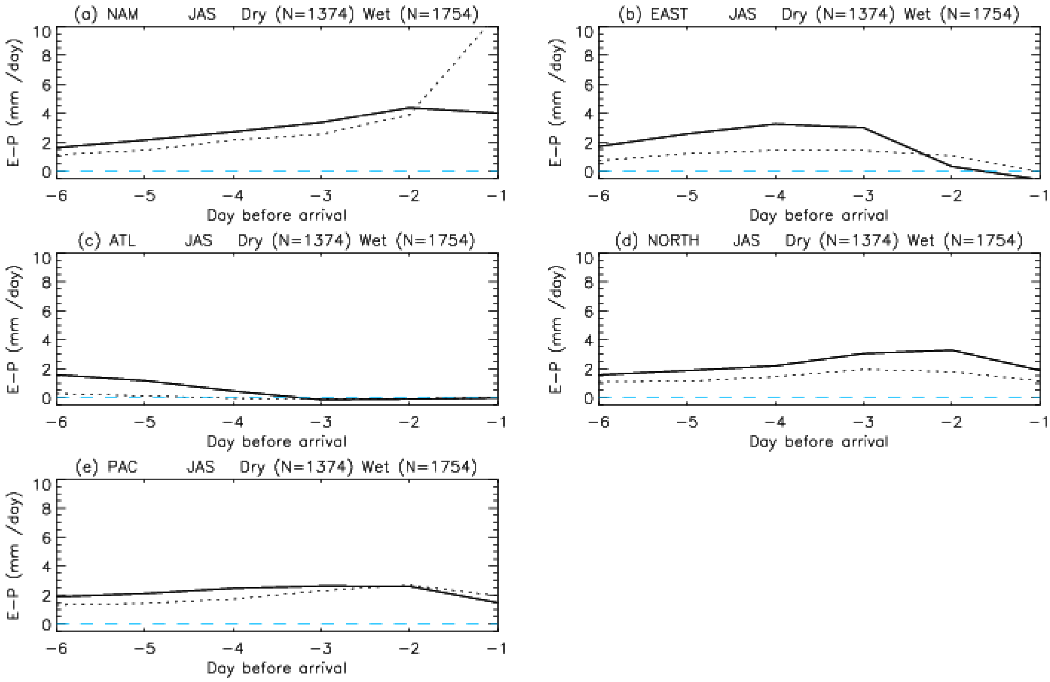

Figure 7. JAS time series of (E – P)$_n$ (n =1 to 6) integrated over (a) NAM, (b) EAST, (c) ATL, (d) NORTH and (e) PAC. Solid line: wet days. Dotted line: dry days.

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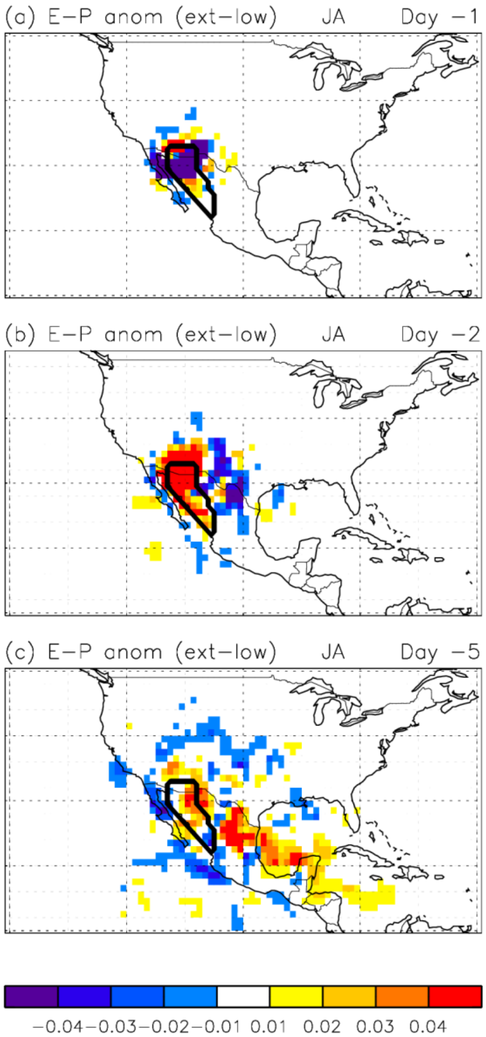

Figure 8. Anomalies of $(E-P)_1$, $(E-P)_2$, and $(E-P)_5$ during JA (1981–2014) for extreme rainfall days minus low rainfall days. Unit: mm/day. Black line delineates the study region.

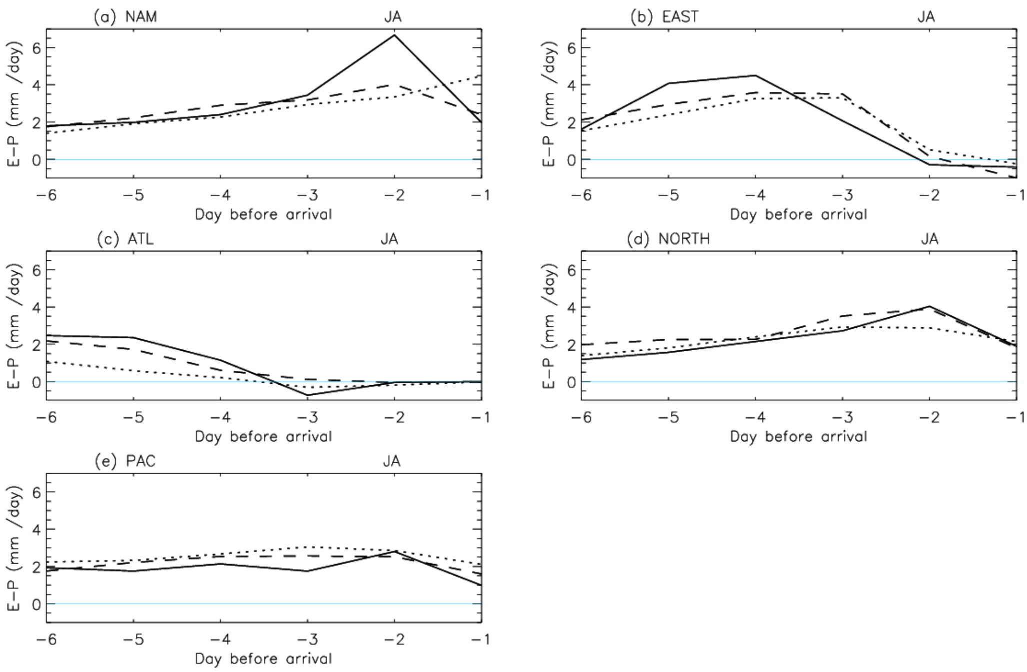

Figure 9. JA time series of $(E - P)_n$ (n=1 to 6) integrated over (a) NAM, (b) EAST, (c) ATL, (d) NORTH and (e) PAC. Black solid line: extreme, dashed line: moderate and dotted line: weak rainfall events.

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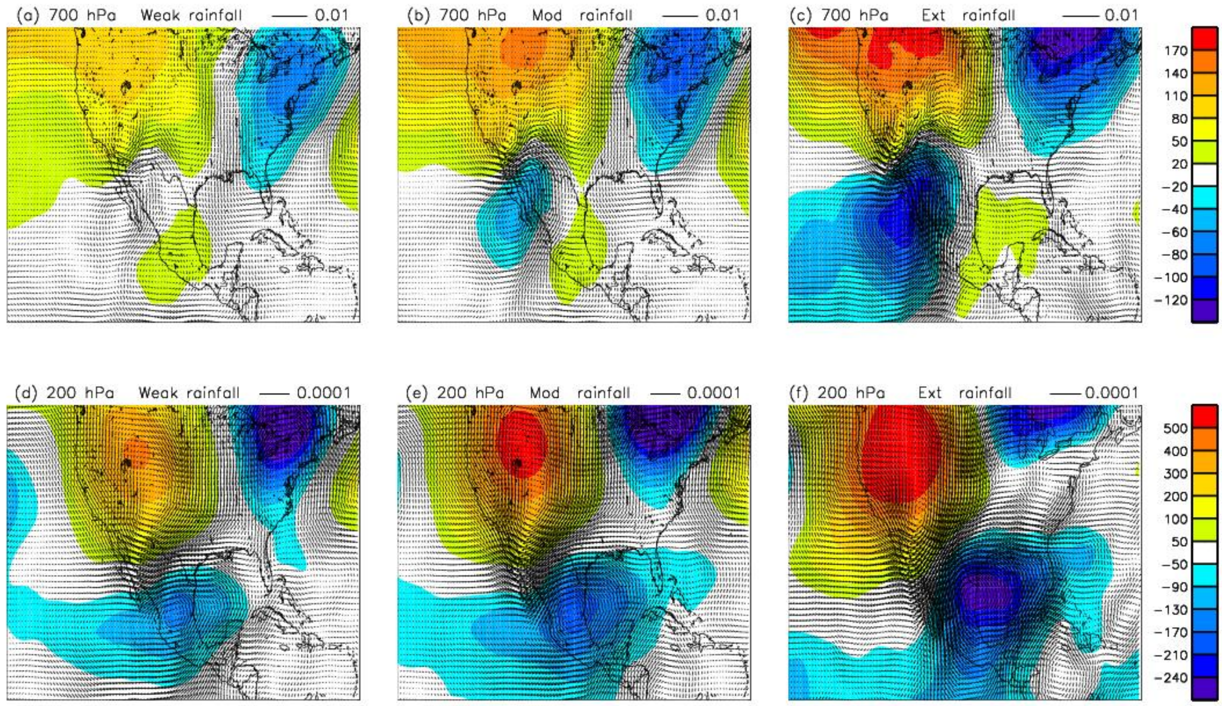

Figure 10. Composites at of geopotential height anomalies (colors, m) and moisture transport anomalies (arrows, kg kg^{-1} m s^{-1}) with respect to synoptic-scale dry events over the NAM region during the monsoon peak (July and August) for synoptic-scale (a) weak, (b) moderate and (c) extreme precipitation events at 200 hPa and (d) weak, (e) moderate and (f) extreme precipitation events at 700 hPa.