Responses to Dr. Adams (Short Comments)

I commend the authors, several of whom are my colleagues, efforts to attack this important problem, a problem that goes way beyond the scope of the North American Monsoon region. However, there are some fundamental problems with this paper that need to be addressed before publication. It is clear the study is fundamentally flawed by the conclusion that the Pacific Ocean off the coast of California is a moisture source for the monsoon. This is patently absurd given the water temperatures (10 to 20C) of the Pacific Ocean (see typical sounding Figure 2 below), no need to even consider the stable Subtropical Pacific High and nearly impassable mountains of California. So, just for this reason alone, all other results from this study should be called into question. However, the indication that the Sonoran and Mojave Desert could be a major moisture source through also stretches the limits of credibility– one of the driest, warmest regions on Earth that receives scares, very localized rainfall during the Monsoon becoming an important local source. These results are surely a result of the FLEXPART modeling employed which is apparently inadequate for the task at hand.

We thank Dr. Adams for his valuable time. Please find the response to your comments:

The Pacific Ocean off the coast of California together with the Gulf of California (GoC) is a moisture source region for the NAM. We have joined the two regions for simplicity, although the contributions from the latter region are higher. It is well known that the moisture transport from the GoC can be an important source for the North American Monsoon (NAM) precipitation. Please, find the references in our introduction section.

Previous works also highlight the importance of water vapour of NAM region itself in which the Sonoran desert is mostly included. Vegetation greening starts around two weeks after the rainfall and causes evapotranspiration to increase. Pleased find some references in our introduction. In fact, it is noteworthy that one of the reviewers of this manuscript (Dr. Vivoni) has recommended more insightful literature about this topic (Vivoni et al, 2008; Mendez-Barroso et al., 2010; Xiang et al., 2018).

The Mojave Desert in the southwest U.S. is a region of mean positive divergence of water vapour during summer at climatological scale, and constitutes a moisture source. To explain divergence of water vapour over land prevailing under a large subtropical anticyclone is difficult. In this case, surface and underground flows from less arid regions must supply the water required to counterbalance the observed excess of evaporation over precipitation (Peixoto and Oort, 1992).

These radical, game-changing conclusions that the authors arrive at, contradicting nearly 4 decades of the vast majority of studies (both observational and modeling), need to provide extraordinary evidence (particularly direct observational support, not modeled products of water vapor or precipitation products over Mexico) for their conclusions. Below I outline basic points that should be addressed in order to validate their conclusions.

Our introduction condenses a vast amount of previous studies on the NAM at **climatological scale** where it becomes clear that the conclusions of this study are no ‘game-changing conclusions’.

(1) From simple thermodynamic arguments (the water vapor scale height is only about 2km), mid-level cannot be responsible for for the in the NAM region west of the elevated terrain (SMO, Continental Divide, etc). This is shown by Adams and Souza (2009), Maddox et al. 1995, Mazon et al. 2016, Rogers et al. 2017 and many, many others. Low-level water vapor (below 800mb) is required for generating convective instability over the valleys and low deserts. Elevated water vapor sources (above ~ 700mb) can help with initiation over elevated regions (e.g. SMO or Four-Corners region) but this convection cannot migrate towards lower regions without the support of low-level moisture. Entrainment of dry air is too detrimental. Gulf of Mexico can certainly contribute to NAM convective precipitation, but can not “cause” or be “responsible” for a sizeable portion of it, west of the SMO/Continental Divide regions. No low-level moisture, no deep convective precipitation in low-lying zones. Likewise, no strong surface heating, no deep convection (higher level moisture can actually be detrimental to the later, soundings can be too moist (see Adams and Souza 2009)).

We don´t suggest that water vapor above 800 mb generates convective instability over NAM region west of the SMO. We don´t affirm that moisture transport form the GOM "cause" or is directly "responsible" of the convective precipitation over the NAM.

We state that the water vapor from the Gulf of Mexico (GOM), Caribbean Sea and the terrestrial region over northeastern Mexico can play an important role days before of the synoptic-scale heavy precipitation events during the monsoon peak. In fact, we accept that low-level water vapor transport from the GOC can supply moisture at day 0 to provide convective instability, as Schiffer and Nesbitt (2012) proposed (lines 25-27).

In summary, moisture from large-scale patterns could influence (1) pre-surge air masses and thus surge generation (what is important to address surge predictability), or (2) precipitation production during surges.
We will revise the manuscript to be sure that there isn't any possible misunderstanding.

(2) The Model. The authors will have to provide more evidence as to how their extremely simplistic model (FLEXPART) which can not account for vertical transport inconvective updrafts, (scale 100s of meters to kms on the high end of organized convection, and order minutes to an hour), nor for entrainment/mixing in a realistic manner, and no need to mention the proper formation of hydrometeors and precipitation processes. Even assuming FLEXPART is a valid model for doing the impossible, consider also the arguments of Ana Maria Quesada. The evaporation/precipitation relationship is entirely space/time resolution dependent (See our figure 3 below, local surface fluxes have little relationship with total column, precipitable water vapor).

It is important to emphasize that we are working from a climatological perspective. We are providing a climatology of the long-range water vapor transport aimed toward the NAM.

Since the last decade, an increasing number of studies have taken advantage of the use of FLEXPART to analyze the water transport towards different regions. The accuracy and robustness of this approach have facilitated the assessment of the averaged values of moisture sources in various climatic regions as the Iberian Peninsula (Gimeno et al., 2010) or the Danube River Basin (Stojanovic et al., 2017; Ciric et al., 2017). But FLEXPART model have also provided insightful information about the moisture transport toward tropical regions as Centro America (Durán-Quesada et al., 2010; Durán-Quesada et al., 2017), Colombia (Hoyos et al., 2018), Sahel (Nieto et al., 2006), India (Ordonez et al., 2012) or the Amazon region (Drumond et al., 2014; Sorí et al., 2018) where convective precipitation dominates.

We are not studying local processes related to the evaporation/precipitation relationship. Regarding the arguments of the reviewer #2 Dra. Duran-Quesada, please find our response to her comments.

(3) Data. ERA-Interim data is not adequate. Reanalysis data, in general, is inadequate because model-generated values depend on convective and microphysical parameterizations. Pressure, geopotential heights and winds, can be dynamically constrained, the water vapor distribution cannot. This poorly measured quantity is extremely difficult to replicate in the NAM region (see Radhakrishna et al. 2016 and many others) (Also, See attached figure 3 for ERA-Interim vs GPS Precipitable water vapor data below). ERA-5 is still bad, but much better than ERA-Interim or NARR. Given the radically different nature of surface evaporation of the oceanic (e.g., different surface wind speeds and temperatures) zones and more critically over the complex topography of Mexico and the Southwest U.S., how is the evaporation determined at the necessary spatial/temporal resolution.

In this work, the atmospheric water arriving to the NAM region at climatological scale is studied by using the Lagrangian particle model FLEXPART. Therefore:

(1) A gridded product to run FLEXPART is necessary. ERA-Interim reanalysis is used as this dataset has been found to provide a reliable representation of the atmospheric branch of the hydrological cycle (Lorenz and Kunstmann 2012; Trenberth et al. 2011).

(2) Typically, in climatology a 30 years period is considered as an appropriate period of time to average variations in weather and evaluate climatic effects. GPS precipitable water vapor (PWV) data over the Mexican NAM region starts around 2012. It is then obvious that the available temporal span is still too short for estimating a reasonably proper climatology.

PWV values observed in the GPS sites could reflect diurnal variations related to mesoscale processes or the complex terrain, which obviously could not be analysed in a 1ºx1º daily reanalysis product. However, this is not the topic of our work.

(4) Moisture recycling. Just a point of logic, if local moisture recycling is important then (1) how does the monsoon precipitation begin? Vegetation green up occurs at the end of July into August (2) Why does precipitation decrease, become for more variable around the second week of August (see for example Kursinski et al. 2008) in Northwestern Mexico and Arizona even though vegetation is green and surface moister, in general? Also, wet surfaces can actually be detrimental to deep convection, as convective temperatures cannot be reached for this region (see Kirsten Findell's 2011 article among others). Our results from the GPS Hydromet Network show that at the sub- diurnal scale, local water vapor fluxes and precipitable water vapor have small correlations, lagged or not. So at least locally, it is not apparent that moisture recycling (see figure 3 below) plays any important role in column water vapor. Boundary layers are extremely deep and well-mixed over much of the region, so very local surface evaporation would be mixed out quickly, not providing sufficient "density" to either contribute to increasing convective instability, nor precipitation efficiency. Only large-scale advection could account for generating the necessary water vapor fluxes to produce the instability necessary to generate convective activity.

(E-P)>0 values over the NAM itself have been roughly approximated to the recycling ratio but it is not strictly correct. We will delete the term "recycling" overall the manuscript and instead of that, we will use "inland evaporative sources".
Please note that this work is not about subdiurnal and local scales but climatological and monsoonal scales.

(5) And probably most important and what makes this a very difficult problem to separate sources easily is the mixing over the SMO due to deep convective activity. Moist air to the east of Arizona and the SMO, in general, may result from deep convective mixing further south and then transported northward along the high terrain with or without precipitation.

We don't find an allusion to our study in this comment.

Minor Comments

"Later studies claimed" is not the correct word, better "indicated" or something of the like. The vast majority of studies over the last several decades have shown that the time mean as well as transient flow are dominated by the EPac and GoC.

The context of "later studies" is after the 50s and 60s decades.

"While compelling, these results are based on observations from a limited field campaign". These are a least real-world data and not model dependent as are ERA-Interim.

Fortunately, for large-scale climatologists, there exist global PWV products as NVAPM (Vonder Haar et al., 2012) that incorporates observations from a variety of surface and space borne sensors including GPS, supporting a more reliable climate analysis.

ERA-Interim dataset has given a reasonable estimate of PWV when compared against GPS data at daily, monthly, and seasonal scales in several regions as Gana (Acheampong et al., 2015), United States (Bordi et al., 2016) or the Tibetan Plateau (Wang et al., 2017) among others. The agreement is better at monthly (figure R1), and seasonal scales, but in general, the intraseasonal variability, which is important for the present work, is captured properly.

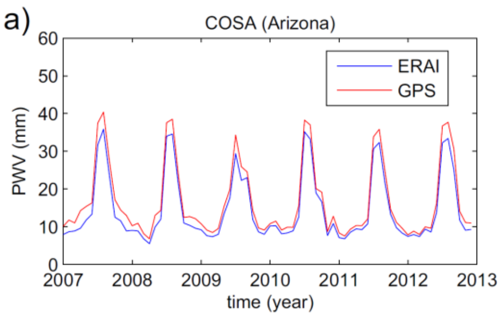

Figure R1. Comparison between monthly PWV measured by Arizona GPS station (red line) and that by ERAI reanalysis (blue line). Source: Fig 6 from Bordi et al. (2016).

“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.” This is sort of a throwaway statement. Our understanding of IV is fairly good and there dynamic effects (increased shear) appears to be responsible for convective organization. Water vapor transport plays no role, nor its advection, as these features are found at 300 or 200mb. (See Finch and Johnson2010).

Finch and Johnson (2010) analyzed one significant IV that passed over northwestern Mexico from 10 to 13 July 2004. One case of study, in which limited data from NAME were examined (Newman and Johnson, 2012).

We find surprising that Dr. Adams declares to understand the processes related to the role of IVs in supporting convective outbreaks being coauthor of Lahmers et al. (2016) where the following statement can been literally found: “the exact roles of synoptic and mesoscale processes associated with IVs and convective organization are not entirely understood”.
Maybe more exploration is needed for a better understanding.

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. You need to back this claim up. As shown by Finch and Johnson (2010). windshear in organizing convection is important, adiabatic lifting is weak. From our examination of Marty Ralph and Tom Galarneau’s results (using lightning data as a proxy) Invited Manuscript for Atmospheric Research there is little evidence of low-level water vapor transport from the Gulf of Mexico on strong convective days. Strong shear can certainly be important in the easterly winds, but we should not convolve dynamics and water vapor transport. “This wind reversal is not of sufficient magnitude and scale to meet the criteria of Ramage (1971) for a monsoon (Hoell et al. 2016).” You need more the two citations to make the claim that it is not a monsoon circulation. “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 GOMand Caribbean Sea).” As Bosilovich et al. (2003) note in their study “It is also worth while to reiterate that the model does not resolve the Gulf of California, which should influence the sources of water”. Always critical to consider space/time resolution of large-scale models.

Finch and Johnson (2010) analysed only one case of study….

Regarding the affirmation, “*This wind reversal is not of sufficient magnitude and scale to meet the criteria of Ramage (1971) for a monsoon (Hoell et al. 2016)*.”

This is simple. Ramage (1971) defined a global monsoon domain based on the seasonal reversal of large-scale lower tropospheric wind. Such monsoon domain is found over the Eastern Hemisphere as shows the figure R2:

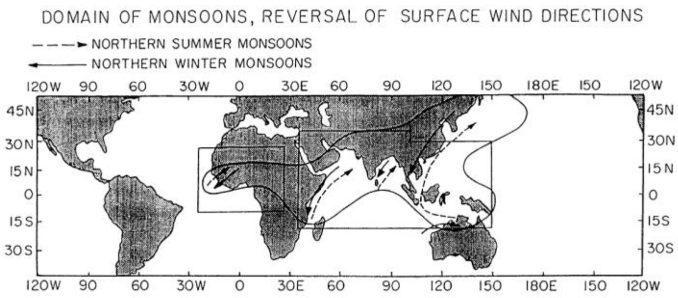

Figure R2. Domain of monsoons of Ramage (1971). Source: Krishnamurti et al. (2013).

The seasonal wind reversal along the Pacific coast of the NAM do not satisfy this global definition because occurs below the boundary layer. That is to say, the scale of the onshore circulation is not enough to meet the criteria of Ramage (1971).

Moreover, the monsoonal behaviour of this region is not being discussed in this work, but its name. Please see the comment # 1 of the reviewer Dra. Duran-Quesada.

Our work with Chris Castro and others demonstrates the need for Convective Resolving Models in order to capture mesoscale convective systems (order kms resolution), which are responsible for a large portion of precipitation particularly in NW Mexico. Results from low resolution models 1degree x 1 degree should be critically assessed given their inability to produce these systems correctly. (see Lamhers et al. 2016,Luong et al. 2017, Moker et al in press JAMC)

Taking into account the objective of this study, to resolve mesoscale convective systems is not necessary. In this work, the origin of the atmospheric water arriving to the NAM during a 34-yr period is investigated by using a Lagrangian diagnosis method. Rainfall events over the NAM are identified at synoptic scale, being representative of a large area of the studied region. We explore if the identified moisture sources play a (direct or indirect) role on such scale rainfall development.

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