Responses to Dr. E. R. Vivoni (Referee comments)

General Comments:

The study describes the sources of atmospheric water vapor during the North American monsoon and its dependence on the size of synoptic-scale rainfall periods. To achieve this, a particle tracking analysis of air parcels was applied using a reanalysis product in order to estimate fields of evapotranspiration minus precipitation (E - P) taken as the metric to study sources and sinks of water vapor. The authors have done a very nice job in bringing a different tool to a subject matter that is under considerable debate. Their work provides some new insights that will be useful for the community at large to consider. Furthermore, their work is well written and illustrated. The comments below are intended for the authors to improve their work and increase its overall impact by demonstrating the solid nature of their method, results and interpretations.

We thank the reviewer for his kind comments that will help to improve the manuscript. We will revise the paper according to the comments. Responses to the specific comments are given below.

Specific Comments:

1. It is important that the authors have a more in-depth explanation of the FLEXPART algorithm as it pertains to the generation of the E-P field, including the limitations therein, within the introduction and methods section. Some of the limitations are indicated subsequently in the results section, which is considered too late in the manuscript. What type of errors in E-P are expected from its estimation as dq/dt?.
How sensitive is the method to the selection of the ERA-Interim reanalysis fields at 1 degree, 3 hourly resolution?
How realistic are these fields with respect to observations or other reanalysis products that independently estimate P and E, and from which E-P can be obtained? The reader needs to have confidence in the accuracy of E-P before it is used to make inferences on the sources and sinks of water vapor in the monsoon region.

(E - P) diagnosed by FLEXPART has been already compared with (E - P) obtained using other data that individually estimate E and P with similar results (Stohl and James, 2004), so we are quite confident in the methodology. However, we agree with the reviewer and in our paper we do not explain this too convincingly. In this regard, the excellent papers by Gimeno et al. (2010) or Gimeno et al. (2012) contains a detailed explanation of the methodology and its reach, by using the very same kind of data as us (resolution, source of data, etc.). In the revised version, we will refer the reader to these works for a revision in depth of the methods.

Notwithstanding, we will explain the FLEXPART-based method to calculate E-P more in depth including a subsection in the “method section” explaining the limitations of the Lagrangian approach.

In our work, we used the tracks computed using ECMWF available data: operational analyses available every 6 hours (00, 06, 12 and 18 UTC) plus short-term forecasts available at intermediate times (3, 9, 15, 21 UTC). We will obtain (E - P) from a combination of observed E and P datasets (eg. E from GLEAM and P from CHIRPS for terrestrial surfaces, and E from OAFLUX and P from GPCP for oceanic surfaces, although the latter only cover roughly a half of the study period) and by computing the divergent part of the water vapour flux (Eulerian method) from other reanalysis (as CFSR). We will compare these results with the figure 4 of the manuscript.

2. It would be useful for the authors to present a justification and/or further detailed explanation for the following aspects of their methodology:

Modifications will be incorporated following these suggestions. Please, see details below.

a. The coarse resolution (1 degree by 1 degree) of the meteorological fields used in the FLEXPART model, given the scale of land and ocean features in the NAM region.

In this work, we are obtaining average values from a climatological perspective. At this scale, the 1ºx1º resolution is sufficient to capture the moisture origin of a large area. For this kind of analysis, we run FLEXPART (v9 experiment in this case) on a global domain. In our case, the atmosphere was divided into approximately 2 million homogeneous particles. Running global-scale FLEXPART experiments at finer scales would most probably not affect the results (at the scale we deal with in our research) and it would be extraordinarily time consuming, and impossible in terms of computing power for our team.

b. The selection of the time period (1981-2014).

1981 is the first year when CHIRPS data exist. When we started the study, 2014 was the last available complete year of ERA-Interim for running FLEXPART. In this work, we have a 34-yr climatology, we consider that adding two or three more years wouldn't be a significant difference. We will explicitly explain our time period in the revised version.

c. The boundary selected to represent the NAM region and its consistency with the tiered approach advocated by Higgins and co-authors during the North American Monsoon Experiment.

In this work, our objective is to study the NAM as a monsoon, i.e. at a broad scale, to detect long-range atmospheric water vapor transport that could influence the precipitation. Nevertheless, the core of the NAM region is based on the North American Monsoon Experiment and in consequence, it is consistent with it. We will explicitly include this information in the revised paper.

d. The use of the term anomaly when discussing differences between wet and dry days. An anomaly is formally a difference with respect to a long-term average, not a difference between extreme cases.

The referee is right. The term “differences” instead of “anomalies” is more precise in this case. We will change it.

3. The authors should provide explanation for some of their conclusions which are hard to see from the figures, not shown by the figures, or ignored with respect to the figures:

We will revise the text in order to further detail our explanations, in particular in relation to the figures.

a. Page 6, Line 3: There is an opposing behavior in this study and Bosilovich et al. (2003) with respect to the change in the recycling contribution from July to September. In this study, this contribution increases, but in Bosilovich et al. (2003), it decreases in time. Can the authors comment on why there is a discrepancy?.

Strictly, we are not computing the recycling, but E-P over the NAM region itself, and in this sense, as the other reviewer also suggests, the term recycling can be confusing and we will change it.

Additionally, our approach is not strictly comparable to that of Bosilovich et al. First, these authors compute the fraction of precipitation that originates as a result of the evaporation from the region. Unfortunately, we can’t separate E and P with our methodology. Second, in this figure, we are not computing E-P before precipitation events but the general climatology of E-P. We commented it briefly in lines 9-11 of page 6.

However, this is an interesting question. In the revised version we will specifically address this comparison as best as we can with our approach. We will include a new figure for E-P before precipitation events to go deeper into this question.

b. Page 6, Line 17: The description of ’all the source regions contribute with higher recharges before the synoptic-scale rainfall events’ is too vague for a reader to see in the figures. Some regions have higher E-P at different days before the event, with monotonically-increasing, monotonically-decreasing or humped behaviors shown. Perhaps the authors can be more specific as to what days they are comparing?.

In the revised version we will improve (and expand) this explanation.

c. Page 6, Line 31: There is an important difference between wet and dry days for the NAM region on -1 days that is not discussed. A similar difference is noted for EAST on -1 and -2 days. These could potentially be interpreted as evaporation from land surfaces that does not lead to significant rainfall.

It could be interpreted for the NAM region because in the case of NAM during the day -1 before the rainfall events E-P>0, therefore evaporation still dominates.

In the case of the EAST region E-P<0, so the region is a net sink of moisture during days -2 and -1. We interpret that the particles over EAST are already losing moisture during these days because this region is close to the target region (NAM).

We will explicitly address these differences and their implications in the revised version.

d. Page 7, Line 3: The interpretation of difference between wet and dry days of the term E-P is quite difficult for most readers to make. (E-P)wet - (E-P)dry includes four terms, two related to E and two related to P. While the authors cannot separate these terms, it would be useful to explain to the reader why a positive anomaly means rainfall intensification and a negative anomaly means evaporation intensification, if that is the case.

An explanation will be included in the revised version.

e. Page 7, Line 12: The authors indicate that the NAM region has no systematic change during the wet period, but Figure 9a shows a large change in -2 days. The discussion needs to reflect this difference.

It is difficult to interpret, but E-P before the weak precipitation days presents a behaviour similar to dry days. In contrast, moderate and heavy rainfall events show another completely different behaviour that could be related to the strong surface heating that is needed prior to these kind of precipitation events. This will be argued in the text.

f. Page 7, Line 16: It is hard to see from the figures where the authors have conclusively shown that the northern NAM region shows a particularly important relation to the fluxes from the Caribbean Sea.

Figure 3 shows that the main difference between the pattern of moderate and extreme rainfall intensity is found over the northern NAM. In figure 8a we can also see that main differences of E-P at day -1 are over the northern NAM. However, we concur with the referee and it is difficult to appreciate these changes. We will clarify them in the revised version.

g. Page 8, Line 14: Perhaps the authors need to remove this statement. Other studies have looked at terrestrial land sources over the entire continental land mass in North America. They might not have defined a sub-region called 'southwestern U.S.' in the same way as it is done here, but that is a minor point.

We will take into account this comment in the revised version.

4. The authors have not shown a comparison of their E-P estimates to observational data which limits the credibility of the study. There is a mention of the observational dataset CHIRPS as being used to help specify the lifespan of 6 days through a comparison of simulated precipitation from FLEXPART to CHIRPS. It would be useful to show a comparison of FLEXPART P and CHIRPS P or the NAM region, rather than simply relying on a reference to Perdigon-Morales et al. (2017).
Furthermore, the authors are encouraged to compare simulated E or simulated E-P to available observations or other reanalysis products given that the entire validity of this study relies on how well E-P is captured by FLEXPART.

The above-mentioned lifespan was computed both with CHIRPS and ERA-Interim precipitation data with the same result of 6 days.

We use CHIRPS data to classify the precipitation events because we have confidence that CHIRPS data are more realistic than ERA-Interim precipitation database. CHIRPS incorporates 0.05° resolution satellite imagery with in-situ station data, meanwhile ERA-Interim precipitation data comes from the atmospheric model forecast.

Besides that CHIRPS have been proved by Perdigón-Morales (2017) to reproduce properly some of the particular characteristics of the Mexican rainfall as the Mid-Summer Drought, we also performed a test founding that CHIRPS precipitation classification is consistent with the classification from the observed PWV obtained by GPS network over three locations over the NAM (Figure R1).

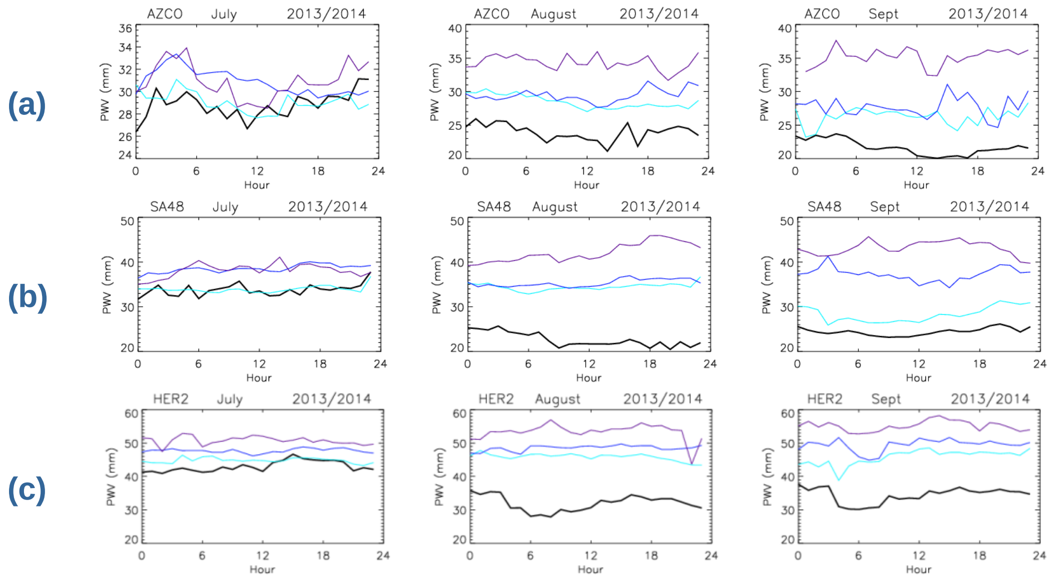
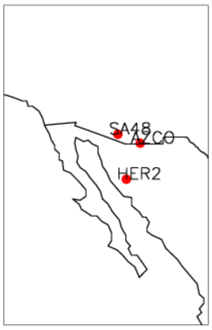


Figure R1. Precipitable water vapor average during dry days (black line), weak rainfall days (light blue line), moderate rainfall days (dark blue) and extreme rainfall days (purple line) at (a) AZCO, (b) SA48, (c) HER2 (locations are indicated in the map below) for the years 2013/2014.



FLEXPART doesn't use precipitation data from ERA-Interim to estimate (E-P) but "q", "u", "v", "w" which comes from the atmospheric model analysis and not from the atmospheric model forecast. We use the ERA-Interim reanalysis because this dataset has been found to provide a reliable representation of the atmospheric component of the hydrological cycle (Lorenz and Kunstmann 2012; Trenberth et al. 2011).

As we mentioned in the comment #1, we will compare the simulated (E - P) with (E - P) from a combination of observed E and P datasets and with (E - P) obtained by the Eulerian method.

If we ignore the presence of liquid water and ice in the atmosphere, the water budget in an atmospheric column can be written as:

$$E - P = \frac{\partial w}{\partial t} + \nabla \frac{1}{g}\int_0^{p_s} qv\, dp$$

Where E-P is the surface freshwater flux, $w = 1/g \int_0^{p_s} q\, dp$ is the precipitable water, "t" is time, "g" is the gravitational acceleration, "q" is the specific humidity, "v" is the wind, and "E" is the evaporation and "P" the precipitation rate per unit area (Trenberth and Gillemot, 1998).

Averaged over time, the rate of change of water storage is small, and E-P is largely balanced by the second term of the right hand. Satellite observations with fine temporal and spatial resolution have shown great promise in improving the estimation of this term (Gimeno et al., 2012).

5. The authors have defined precipitation recycling to be a process of local evaporation from the NAM region exceeding precipitation. It is important that the authors be more careful in this definition for a number of reasons:

a. Terrestrial evaporation from other land masses (EAST, NORTH) should also be considered precipitation recycling when it leads to precipitation in the NAM region.
b. Precipitation recycling still occurs even if evaporation does not exceed precipitation. In other words, the authors have equated E>P to recycling, but this is not necessary the case as recycling is still occurring when E<P.

We have approximated the E-P budget over the NAM by the recycling process. As the referee points out, this is not strictly correct, we will substitute the term "recycling" by an "evaporative source form de NAM region itself".

6. The identification and naming of the regions should be reconsidered and perhaps more strongly justified. The names 'NORTH', 'EAST', 'ATL' and 'PAC' could be misinterpreted as these are specific to this study and not generally accepted terms. ATL is Gulf of Mexico/Caribbean Sea, PAC is Baja California and Eastern Pacific, NORTH is southwestern U.S. and EAST is northeastern Mexico. More insightful and relevant naming would be useful. Most studies in the NAM would also include portions of the NORTH and EAST inside the NAM boundary. Other than justifying their selection by citing Hu and Dominguez (2015), the authors should further explain their choice as it is important for the overall outcomes and interpretation of their work.

The names of the regions will be changed to be consistent to previous studies as follows:

NAM ----->NAM
PAC ----->NEP
PAC ----->GOC
ATL ----->GOM-CAR
NORTH ----->SW-US
EAST ----->NE-MEX

Please note that the region PAC has been divided in two regions, GOC and the North Eastern Pacific coast (NEP) as suggested by the reviewer Dra. Duran-Quesada. Please see her comment # 10.

We chose the same boundaries than Hu and Dominguez (2015) because they used a semi-Lagrangian scheme (DRM) to delineate and quantify the climatological moisture sources of NAM precipitation. In this work, we also determine the climatological moisture sources of NAM with a similar but more sophisticated three-dimensional Lagrangian method. As we are working in the same space and time scales we made the results more directly comparable by choosing the same domain. However, it is important to note that the choice of Hu and Dominguez (2015) was based on both the North American Monsoon Experiment (NAME) Science and Implementation Plan and NAME precipitation zones, as defined by Castro et al. (2012).

Technical Corrections:

Corrections will be incorporate following the suggestions of the reviewer.

References

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