Answer to Referee 3 in the Interactive comment on "Evaluation of the Moisture Sources in two Extreme Landfalling Atmospheric River Events using an Eulerian WRF-Tracers tool" by Jorge Eiras-Barca et al.

Supplemenatary Material : One-to-one answer to technical comments

Comments Regarding the introduction:

We thank the reviewer for the advices. The introduction is going to be rewritten taking into account all the reviewer's comments.

Add models overview

It was not our intent to present the WRF-Tracer tool in this paper. Our goal was to just use it to answer specific questions about the importance of tropical moisture sources in ARs. We will make this point more explicit, as we leave the in-depth details of the method and the discussions of advantanges/disadvanges with respect to other methods for another publication in review in this same ESD special issue:

Insua-Costa, D. and Miguez-Macho, G.: A new moisture tagging capability in the Weather Research and Forecasting Model: formulation, validation and application to the 2014 Great Lake-effect snowstorm, Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-80, in review, 2017

that we will now cite in the text. However, as per the reviewer's suggestion, we will also include a brief discussion stating the main characteristics and the advantages of using our tracer tool.

Add paragraph on AR and LLJ

One of the motivations of the paper was to contribute to the on-going discussion in the community to provide a definition of Atmospheric River for the Glossary of Meteorology. The current draft definition reads as follows:

"A long narrow and transient corridor of anomalously strong horizontal water vapor transport that is typically located in the lowest 3 km of the troposphere and associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in atmospheric rivers is supplied by tropical and/or extratropical moisture sources and atmospheric rivers frequently lead to heavy precipitation where they intersect topographic or other lower-tropospheric boundaries, or enter into the warm-conveyor-belt-related isentropic upward air motion. Atmospheric rivers conduct over 90% of all poleward water vapor transport in the extratropics in less than 10% of the zonal circumference of the globe.

(Please, see https://annual.ametsoc.org/2017/index.cfm/programs/town-hall-meetings/atmospheric-rivers-a-discussion-of-the-definition-under-development-for-the-glossary-of-meteorology/)

The low level jet is mentioned in the first sentence of the proposed definition, implicitly equaling it to the AR itself. Furthermore, in this same sentence, ARs are defined purely in terms of moisture transport, and not in terms of moisture content, hence giving further weight to the low level jet concept. Most detection algorithms in the literature, however, use both water vapor flux and water vapor content to define ARs, to avoid strong jets with average moisture loads to be confused with ARs. We tend to favor a characterization of ARs that includes both moisture transport and moisture content, and thus, with the statement the reviewer is referring to ("It is widely accepted in the literature that the bulk of moisture in ARs is primarily advected within the LLJ.") we were, perhaps not very effectively, transmitting that we do not agree with identifying low level jet and AR.

Our results do not conflict with the existent literature, especially with seminal observationally based studies like Ralph et al. (2004, 2005). We find that most of the moisture content AND transport defining ARs occur in the lower 3km and in a narrow zone along the cold front. This is where the LLJ is located, and this maximum in wind is also a local maximum in moisture transport. Our point is that moisture content (IWV) is also a big part of what defines an AR, and, as we show in the cases we study, the bulk of the moisture load is clearly not associated with the LLJ. Most moisture transport does occur in the lower 3km, as the proposed definition states, but not just within the LLJ.

As per the reviewer's request, a paragraph discussing the relationship between the AR and the LLJ is going to be added to the introduction. In particular we will refer to observational studies like Ralph et al (2004, and 2005), already cited in the paper, that describe the vertical structure of moisture and moisture transport in ARs. We will also rephrase the concluding paragraph to make our point more clear and to avoid confusion

Add selection motivation

The motivation in the selection of the events is going to be expanded (see below)

Comments regarding Methods:

o What is the method used for AR detection? Is it one of the methods described in the introduction?

Both cases are some of the most intense, documented and discussed AR-events over the Atlantic and Pacific basins, although much of these discussions refer to impacts, rather than to the structure of the ARs themselves. These events are very well detected by all methods and algorithms published in the literature (GUAN2015, BRANDS2016 and EIRAS2016). The lack of agreement among different algorithms in the detection of ARs usually occurs in much weaker cases. Following the advice of the reviewer we are going to add this sentence to the final version of the manuscript: *"... both events are very intense in terms of IVT and IWV, and are well detected by different detection methods -GUAN2015, EIRAS2016 and BRANDS2016-."*

o How is the position of LLJ estimated?

The position of the LLJ is estimated as a relative maximum in the module of the wind at lower levels, around 1km elevation, just ahead of the cold frontal boundary..

• Selection of AR events. Why have the authors chosen to only analyse two events for which there are no possibility for comparisons with previous studies? Would it not be useful to also analyse AR event(s) that others have analysed, so that the results can be compared and potential differences discussed? Especially since the authors are introducing a new model, and challenging previous findings (on e.g., how ARs relate to LLJ)? I am not suggesting that it is absolutely necessary to include an analysis of a previously studied AR event, but I miss the discussion and reasoning behind the choice of not doing so.

We selected the events in terms of socio-economic impacts (extreme precipitation, flooding and damages), and because they are very intense paradigmatic Atmospheric River cases, especially the Pacific case. It is true however, that there are no other studies on the thermodynamic structure of these systems, focusing explicitly on the associated Atmospheric River and the origin of moisture within. So, a comparison like the suggested by the reviewer is not possible. Notwithstanding, we think that these two cases illustrate very well the two main points we wanted to make. First, that a high tropical moisture content is likely needed for Atmospheric Rivers to produce extreme precipitation events and second, that the bulk of moisture content that defines the Atmospheric River does not have to coincide with the low level jet. (see discussion above on LLJ and ARs). The latter point is

somewhat more controversial, because in some cases ARs are defined purely on atmospheric moisture transport (like in the proposed definition mentioned previously), whereas in others (such as in detection algorithms) ARs are defined in terms of both atmospheric content and atmospheric transport.
We will add a paragraph discussing the motivations in the selection of the events when reforming the introduccion section, per the reviewer's suggestion.

• Limitations and uncertainties. Could you also discuss limitations and uncertainties in a separate paragraph?

The limitations and uncertainties of the tracers tool are those associated with the WRF simulations, as demonstrated in the Insua-Costa and Miguez-Macho (2017) paper about the method, that we will now cite. If we accept the results of WRF in terms of moisture transport, distribution, etc, as accurate, then the tracer tool running coupled to the model can separate moisture from different sources with a very small error (much less than 1% in traceability). Thus, the tracer tool is very accurate in the "model world", and the uncertainty in the "real word" is due to the WRF model error in simulating the systems. Following the advice of the reviewer, the limitations and uncertainties are going to be discussed in the final version of the manuscript, both in the introduction and the conclusions.

Specific comments

• Figures 1, 6 and 7. Please consider adding corresponding videos in the supplementary information to show the temporal development in addition to the snapshots.

Following the advice of the reviewer, we are going to edit and include the videos in the supplementary information of the manuscript.

• P4.L9 "10 days". How is that motivated? How much can the results be affected by the cutoff at 10 days?

The reason for performing a 10 day simulation is to capture the full complex development of both systems. As shown in Fig 1, for the Pacific case, there is a preexistent plume of tropical moisture in the precursor storm, already 5 days before making landfall. In the Atlantic case, most of the tropical moisture export occurs from the Caribbean area, even before those 5 days. Thus, in order to properly track moisture from its tropical source, the extended 10 day period is needed. Results would be significantly affected if using shorter periods because we would be missing a large portion of the tropical moisture actually involved in the storms. We will clarify this point when stating the length of the simulations.

• P6.L5-6: What difference do you expect between only tracking evaporation from the surface versus the presented approach of volume tracking? Could you discuss that?

A 3D source is needed in our experiments to make sure that the moisture in the tropical air mass intervening in the development of the simulated storms is properly tagged. To obtain similar results with a 2D source, we would have to, first, include the whole tropical region in our domains, and second, perform much longer simulations, to ensure that the moisture in the tropical air mass is entirely made up of water vapor evaporated within our simulated period and domain, and therefore, tagged.
We are not intending to contrast two different approaches, with 3D sources vs 2D sources, as those used in a previous study. We developed tracking from a 3D source specifically to address the question in this paper about the tropical contribution to moisture in ARs. To avoid confusion, we will rephrase the paragraph in P6, eliminating references to previous studies, as follows:

“The Eulerian tracer tool operates as follows: A wide region in the domain covering the tropical latitudes is set up as a three dimensional tracer mask. All the water vapor in this three-dimensional volume (including the water vapor evaporated and advected into the masked region) is tracked in space and time.,

- **P8.L1 “(sub)tropical”: Tropical or subtropical? Which latitudes? Please specify what is considered “tropical moisture”?**

All areas inside the masks depicted in Fig 5 are considered tropical latitudes in the study. These correspond approximately to latitudes below the Tropic of Cancer, with some deviations due to the lambert conformal projection used in the model grid in which the masked regions are defined. We will remove mentions to the sub-tropics to avoid confusion.

- **P8.L4-10: It is not clear how the information described can be interpreted from Figs. 6 and 7. E.g., how can the reader tell the relative tropical moisture content? How can the location of the “local convergence mechanism” be observed? Or how do we see that the tropical moisture contribution is less in Fig 7 than in Fig 6? Please consider providing clearer analyses and plots (e.g., of relative tropical contribution instead).**

Fig 6 and 7 are intended to show the complexity of the 3D structure of the moisture fields from an unconventional perspective, using a snapshot from a 3D viewer. Clearer analyses and plots of the tropical moisture contribution in each case follow suit in Fig8 and 9 (that we will merge into one per some other reviewer’s request). These two figures show 2D plots of the percentage of tracer moisture in total precipitable water in the column. Figure captions will be reworded to clarify this point and a mention in the text to better guide the reader, will also be included.
With regard to the “local convergence” mechanism, we were implicitly referring to the study of Dacre et al (2014) about the formation mechanisms of ARs. They assess whether external advection of moisture or convergence of moisture from local sources (evapotranspiration) are the responsible mechanisms for the high amount of total precipitable water defining ARs. We borrow their terminology here, meaning that if high moisture content values are not from external advection, they have to be generated from local moisture, by means of converging mechanisms linked to the dynamics of the front. We will now clarify this in the text as follows:
“The high moisture values behind the front are not related to tropical advection, thus generated by convergence of moisture from local sources occurring along the frontal region”

- **P8.L33-P9.L8 and Figure 10: As LLJ is a key issue investigated, would it not be more informative to calculate and plot how often and when the maximum moisture actually coincides with the low level jet? Also, is LLJ simply defined as the “maximum in wind speed at lower levels” – or is there a wind speed threshold as well? If this is the definition, Fig 10b also shows maximum wind speeds spots at 1 km height, which coincide more with maximum moisture content – why are these spots not identified as LLJ?**

The LLJ is defined as the local maximum in wind speed at low levels (around 1km elevation from the surface) along the cold frontal boundary. There is no threshold criteria. Sometimes there is more than 1 local maximum at low levels, like in Fig 10b, and we made a mistake by placing the label where it is. The LLL is the maximum at around 1km right next to the cold frontal boundary, which is to the west.
It was not our intent to make the LLJ the focus of the paper. As explained earlier, one of our points is that we do not think that ARs can be identified with LLJs, as it is implicit in the current draft definition for the Glossary of Meteorology. We believe that this is sufficiently evident in the cross sections that we show, where the high tropical moisture content, responsible for most of the precipitation, lies in low levels (below 3km) along a relatively narrow zone in the prefrontal region of the system. Just not only within the LLJ. We will tone done down the discussions on the LLJ to give more relevance to the investigation on the origin of moisture in the studied ARs, which is really our main objective in this paper.

Technical corrections

• Figure 5. What is the area highlighted in blue?

The area highlighted in blue is the domain of simulation. The area highlighted in red is the area of the domain of simulation where moisture is tagged. We will clarify this throughout the text.

• Figure 11. Please label the vertical axes. Also, should the two axes scale really be identical? If not, consider changing the Ratio axis colour to red.

We will add labels to the axis in the next version of the paper. The two axes scale is identical, even though the units for each variable are not. This is now going to better clarified in the caption.

• P7.Eq1: Please define sfc.

Sfc will be define as “surface”