REVIEWER #1

We would like to thank the reviewer for his/her insightful comments on our manuscript. We acknowledge that these comments have helped us make some important clarifications related to specific sections of the text and have led to an improvement of the work as a whole. In addition, we are now confident that we have provided sufficient information to explain the major role of ARs in the occurrence of intense precipitation events. We fully understand the criticism that some of the key points in the manuscript were not as clear as they could have been and the suggestions and comments made by the different reviewers have therefore been taken into account in order to improve the clarity and readability of the article.
Detailed responses to each reviewer are set out below. For clarity all comments have been numbered.
In addition, the title of the manuscript was changed to "Atmospheric rivers moisture sources from a Lagrangian perspective" in order to represent better the main purpose of the manuscript.

1) This paper analyses atmospheric rivers (AR) across the North Atlantic and Europe (from NCEP 2 reanalysis from 1979 to 2012, 6-hourly time scale) using a Lagrangian perspective using the FLEXPART tool. I understand the interest of AR to explain some extreme events as flood or heavy snow, but I do not see what is the real added value of the approach and analyses in this paper.
We would like to stress that we used ERA-Interim to detect ARs (and as the input to the FLEXPART model), rather than the NCEP 2 reanalysis suggested by the reviewer. This information was (and still is) clearly stated in the methodology section.
Regarding the added value of the manuscript, this is mainly twofold:

a) **first,** to the best of our knowledge, the current study is the first to identify those regions characterized by the Anomalous Uptake of Moisture (AUM in the new version of the paper) for ARs based on E-P from a climatological perspective. The sole previous study in which moisture sources along AR trajectories were analysed was undertaken for a simple case study in Norway (Stohl et al., 2008).
It is important to note that an AR transports a large amount of moisture that reaches a continental area. This moisture is necessarily available in the atmosphere and it therefore needs to be evaporated or accumulated in certain areas during the days prior to the intense tracking of the AR. The anomalous moisture needs to be available for the AR, because an intense wind flux is possible, but if the moisture is not anomalous the AR does not exist *per se*. Therefore, in this work we consider the 10 days prior to the AR reaching landfall, during which the anomalous moisture uptake to the atmosphere is available to supply the AR. This explanation will be included in the new version of the methodology.

b) **secondly** we have made refinements to the AR tracking method introduced by Lavers et al. (2012). In the present version we use 3 reference meridians instead of one fixed one for the whole of Western Europe, in order to give a high accuracy of the landfall times and locations. This is of the utmost importance for analysing the anomalous AR moisture uptake using the E-P method because a few degrees of difference in the reference meridian longitude may cause significant errors in the AUM.
In our opinion this clearly shows the added value of this approach and analyses presented in this paper because, as discussed in the introduction, there is an ongoing open debate regarding the objective characterization of the moisture uptake associated with ARs. We nevertheless understand the criticism that some of the key points made in the original version were not as clear as they could have been, and therefore the suggestions and

comments of the different reviewers to improve the manuscript have been taken into account in the revised version, improving the quality and readability of the manuscript.

2) The introduction is not well organized (see minor points below) and the novelty of the analyses does not appear clear to me. My main concern is also that some of the conclusions are indeed very well known, for example, that moisture in western Europe comes primarily from subtropical North Atlantic through the westerlies. It could be seen simply with the integrated flux of moisture or even the surface latent heat flux (which peaks over the Gulf Stream off the North America coast in winter) combined with westerlies (WSW flow in winter) across the North Atlantic make it easy to infer. My point here is : what is the new information provided by AR in that context ?

The introduction has been rewritten according to the reviewer's suggestion to put the novelty of the results discussed in the present work into a wider context, as well as giving more precise insights into the relationships between ARs and extreme precipitation events in Europe. Again we acknowledge that all the reviewers are correct in stating that the objectives of the manuscript were not as clearly drafted as they could have been, and these have been improved in the new version. In a nutshell, the aim of this work is to find those (Atlantic) oceanic areas where abnormal quantities of moisture are available during the 10 days prior to the formation of an AR, i.e., where it is possible to observe points related to the anomalous uptake of moisture (AUM).

We do not agree that the main conclusions are well known. In fact, the reviewer is referring to the generalized mechanism of moisture transport and heat towards Europe that occurs in the north Atlantic; this was also the subject of other studies by the authors (Gimeno et al., 2011; Gimeno et al., 2010). We wish to quantify, from a climatological point of view, that transport related to changes in the intensity and position of the main areas in which the ARs uptake moisture abnormally (in an AUM), which then become embedded in the most intense ARs. These ARs do not occur that frequently (as stressed by the reviewer below in major comment #4), but are nevertheless responsible for a large proportion of the intense precipitation events occurring in Europe, as stated by the authors in a number of different studies (Lavers and Villarini, 2013; Ramos et al., 2015) and explained in our answer to the major comment #3.

In addition, the concept of integrated horizontal flux transport (IVT) from an Eulerian point of view is useful when studying the temporal variability of moisture flows for specific locations around the globe, and is therefore widely used in the identification of ARs. However, this Eulerian perspective is not suitable for finding the sources of moisture, and cannot therefore be used to find AUM regions [our objective], because Eulerian methodologies do not follow specific "particles" (or atmospheric air masses) transported by ARs. This can be accomplished using Lagrangian models instead, such as FLEXPART (used in this paper). FLEXPART allows us to follow atmospheric air parcels through space and time, from which we can generate trajectories and characterize with some accuracy the history of the air streams reaching a specific site by considering the humidity or temperature, among other meteorological variables. The use of Lagrangian models has proven a useful and important tool for analysing the moisture sources of ARs, as advanced by Stoll et al. (2008) for the particular case study of an AR that occurred in Norway.

In an attempt to answer the last part of the reviewer's comment, we compare the IVT field with the results obtained from FLEXPART for one particular AR. In Figure R1a) we show the moisture sources (E-P>0) computed for 10 days for an AR that made landfall in the Iberian Peninsula on 14 December 1981 at 00UTC. Three source areas clearly emerge, one more local one to the west of the Iberian Peninsula and two more distant sources located in sub-tropical and tropical regions. In Figure R1b) we show the IVT field for the same day together with the locations of the IVT maximum (black line) used to find the AR, following our methodology. In addition, the moisture sources detected in Figure R1a are also shown, plotted using red contours. It can clearly be seen that the moisture sources and the IVT maximum are different. When we analyse either the IVT or the IVT maximum, we are considering only a snapshot of the integrated horizontal flux transport for that specific time step (like a photograph) rather than the paths of the air masses; neither parameter indicates where the moisture comes from. This can only be achieved using the FLEXPART model.

We believe that Figure R1 is a clear example of the differences between the two methods used. Therefore, we have included this figure in the new version of the manuscript in order to provide readers with a clear illustration of the differences between the two methods.

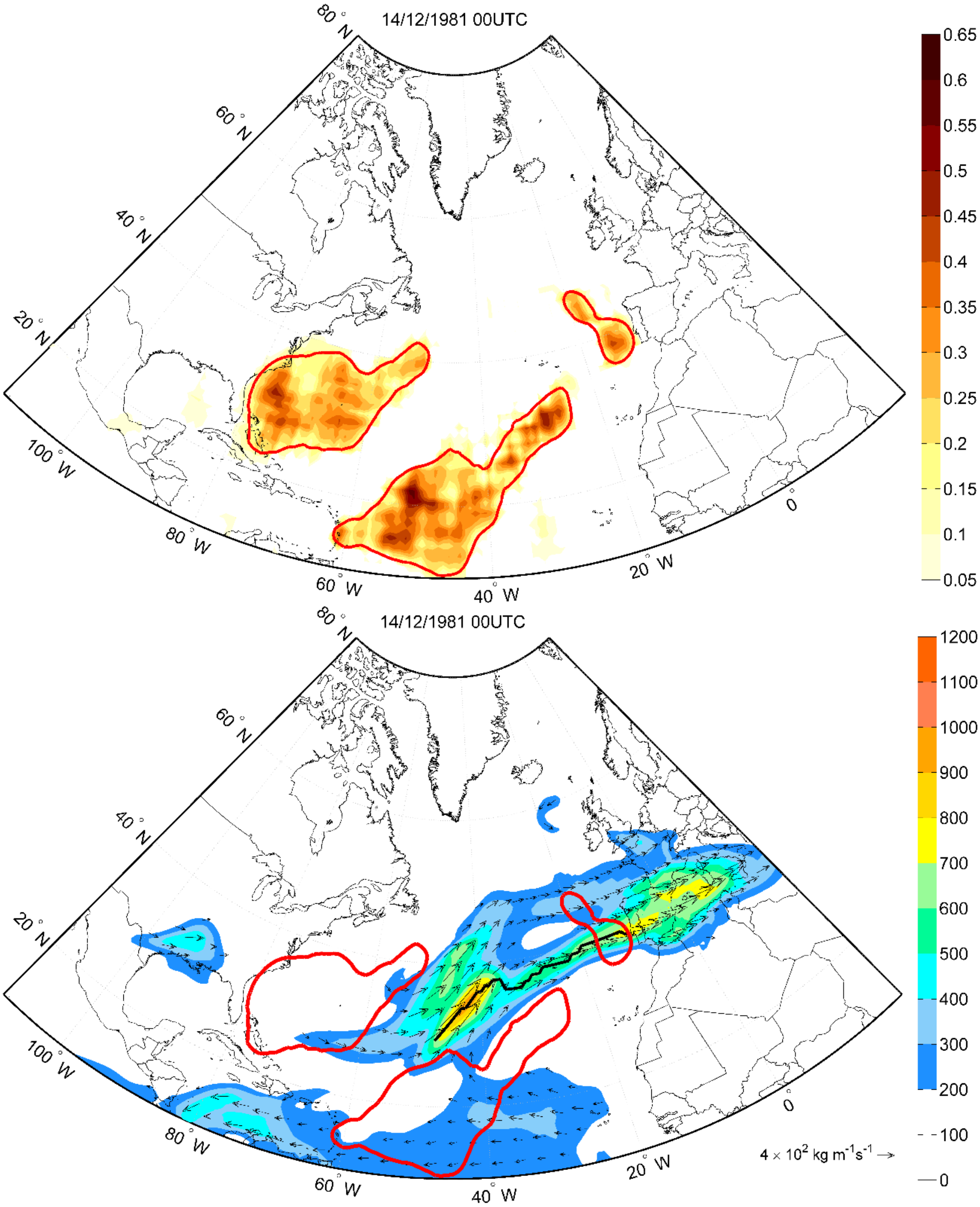


Figure R1. a) The moisture sources (E-P>0) computed for 10 days for an AR that made landfall on the Iberian Peninsula on 14 December 1981 at 00UTC. b) The vertically integrated horizontal water vapour transport (IVT) field for 14 December 1981 at 00UTC and the location of the IVT maxima (black line) are also shown. The moisture sources detected in a) are also plotted using red contours.

Taking these results into account, we are confident that compared with Eulerian methods the use of Lagrangian models can help us identify more precisely and in greater detail those areas where the moisture uptake is anomalous for the ARs and is then transported by them, and can therefore help in the ongoing understanding and debate around this topic.

3) I add that the successive steps used to define AR days lead to a major reduction of the total number of cases. At the end, from 33 winters x 182 days (or 183 for leap winters) x 4 (6-hourly time steps) = 24024 (or 24156), only 21-140 cases remain so 0.1 to 0.7% (table 2). I understand that thresholds should be crossed to define AR by definition, but then, what is the reliability of the "climatology" based on such a reduced set? If you can demonstrate that AR days are related (or relevant) to some extreme events as flooding downstream in Europe, that would be fine but it is not shown in the current version. At least, such precise information could better justify your analyses.
This point is extremely important and we hope to be able to provide clarification here. Firstly, we stress that the comparison made by the reviewer is not entirely accurate. It is correct that we have 33 winters x 182 days (or 183 for leap winters) x 4 (6-hourly time steps), giving a total of 24024 (or 24156) time steps. As shown in Table 2, the number of AR time steps ranges from 117 in the Iberian Peninsula and 665 in France, corresponding to ~0.5% to 2.8% of the total possible time steps.
We nevertheless agree that the overall numbers are rather low, but this is no reason not to undertake the analysis. In fact, we are particularly interested in analysing the anomalous uptake of moisture of the most intense ARs, i.e., those often associated with extreme precipitation events. As queried by the reviewer in the second part of this comment, we stress that there is currently no doubt that a large proportion of the most intense precipitation events (and their associated floods) in Western Europe are objectively associated with the occurrence of ARs, particularly in the UK (Lavers et al., 2013) and the Iberian Peninsula (Ramos et al., 2015). As an example, we reproduce here the illustrative result of Lavers and Villarini 2013 (their Figure 3, reproduced below), that shows the number of the Top 10 annual maximum precipitation events related to ARs. It is immediately striking that there are some parts of the Iberian Peninsula, France, UK, and Norway where up to 6 out of the top 10 annual maxima are associated with ARs. In addition, for the Iberian Peninsula, Ramos et al. (2015) showed that ARs play a central role in most extreme precipitation days but their importance is reduced for less extreme precipitation days. This information has been included more explicitly in the new version of the manuscript.
Moreover, according to the suggestion made by reviewer #1, we have included data on the number of top 10 annual maxima precipitation events (for the extended winter months) that are related to ARs. Please see our answer to reviewer #2's major comment regarding AR detection.

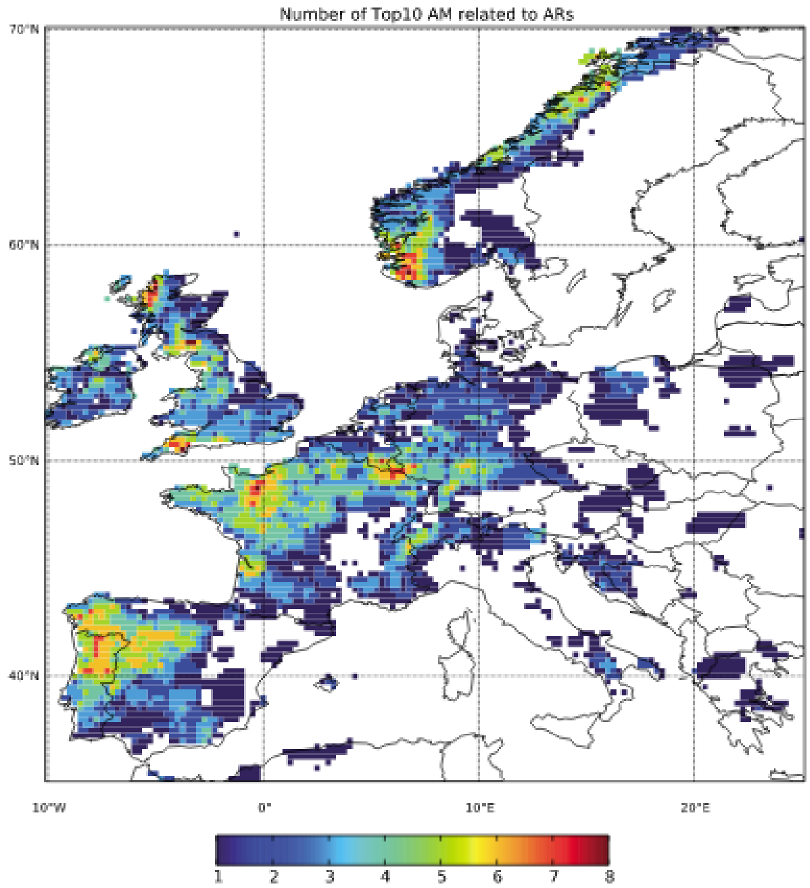


Figure R2. The number of top 10 annual maxima precipitation events related to ARs (Lavers and Villarini, 2013).

4) Then, I do not understand how exactly is computed the climatology on page 10, and subsequently, how to interpret the anomaly from this climatology. The authors indicate that and "(E-P) climatology is computed for each Julian day where an AR occurs". If I understand well, for example, there are 21 cases for the Iberian Penisula, right? Even if we consider that AR are followed over few days (max = 10 days), each Julian day should be related to a very few number of AR cases, and probably some of them does not correspond to any AR day? This climatology is then compared with the "composite of all AR days". Here I am lost, or probably, I miss something in the methods, but it is, at least, confusing and it should be clarified so that your physical interpretation is rightly understood.

We acknowledge that the method applied in this part of the paper is not sufficiently well described, and some parts are confusing. We have rewritten this part, and we think that it is clearer now. We present the case for the Iberian Peninsula in the belief that in so doing the method will become clear.

For the Iberian Peninsula (IP) we have 117 AR time steps. For each time step we compute the uptake of moisture and for each we follow all the particles that leave the IP domain, computing changes in specific humidity (q) and retaining changes in q (e-p) every 6 hours for 10 days (thus yielding 40 points of trajectory). For each grid point (1°x1° in latitude and longitude) we add those changes in q for all those particles residing over an area of 1°x1°. At this point, we have the balance of E-P for all 40 time steps for the AR. We retain only positive values (E-P>0), representing the uptake of moisture destined for the AR. We repeat this for all the ARs, 117 times in the case of the IP.

During the 10 days of analysis the atmosphere gains moisture over the areas detected, although for some days the AR does not exist; however, as we explain in point 1 above, the atmosphere needs to have moisture available in high quantities to allow moisture uptake before the AR occur.
To check whether these areas differ from the climatology we compute the anomaly between '(E-P)>0 for the AR-day' and the climatology ('(E-P)Clim>0'), understanding 'climatology' in this study to correspond to the same Julian day but for all 33 years of the study (again retaining only the positive values of E-P for each 6-h time step). For, instance, if an AR occurs on 14 Dec 1981 00UTC, we calculate the mean moisture uptake for every 14 December 00UTC over this 33-year period. We then compute the difference to obtain the anomaly for this day, (E-P)An>0.
The final plot in the new version of Figure 4 shows the mean accumulated values for all AR time steps, i.e., the climatology and the anomaly.

In the current version, I do not really understand what is shown by the maps on figure 3, especially the anomalies: does it reveal mostly the seasonal cycle of AR days during the 6 months ? Or the interannual anomalies ? Or both ? Not understanding what is revealed by this figure limits the "portée" of this paper.
We have rewritten our description of how Figure 3 is computed and we believe that in its present form the interpretation of the maps is now clearer.

5) If these figures are retained, you need also to add a level of significance for the anomalies and say, at least, few words about the robustness of the results taking into account more cases by changing slightly the rules used to define AR days.
We agree with the reviewer that the level of significance should be present in the anomaly figures in order to support the robustness of the results obtained. Therefore, we have applied T-Student statistics at grid point level comparing the series of the values of (E-P)Clim>0 with the series of the values for ARs: (E-P)AR>0. In the new versions of the figures, only those anomalies that are statically significant at the 90% level are shown. In addition, this explanation has also been included in the new version of the manuscript.

More minor concerns
6) I do not understand the last sentence of the abstract
The last sentence of the abstract has been rewritten in order to make it clearer.

7) I found the introduction not well organized and it is hard to grab the novelty of the current analyses. It would be interesting to give some precise insights of the relationships between AR and extreme events in Europe (a sentence line 23-24 page 3 "... studied its relationship with extreme precipitation" is for example not precise enough; what is the form and intensity of the relationship exactly? The same comment applies to the following sentence too. Then, page 4, it is difficult to trust you when you say that "works dealing. . . are scarce (typo on this word", since you cite a large bunch of paper just one page before ; these papers deals with AR, so we can assume that they deal with moisture transport and source ?
As mentioned in our answer to point 2 above, the introduction has been rewritten according to the reviewer's suggestion to provide a context for the novelty of the results of the present work together with some precise insights into the relationships between ARs and extreme events in Europe (as stated in detail in our answer to point 4). In addition, as explained in our answer to point 2, papers dealing with IVT and ARs rarely consider moisture sources.

8) The methodology needs clarification: line 4 (p. 6) why stating latitude "threshold"? It is simply the latitude of the highest IVT over a longitude, isn't it?
The method used is very similar to that developed by Lavers and Villarini (2013) and Lavers et al. (2013) and uses the classical definition of ARs. The method has been described at length in those previous papers, so here we have tried to simplify the text in order not to repeat all the steps of a method that has already been published and used successfully. However, on reflection we agree that the AR definition is fairly novel and many readers will not have seen it. We have therefore introduced some additional information to clarify the methodology.
We used 3 reference meridians as shown in Fig 1. For each meridian, we extracted the maximum IVT between 35ºN and 75ºN (for the 9.75ºW and 4.50°W meridians) and between 50ºN and 70ºN (for the 5.25ºE meridian) and sorted it into 10º latitude bins. Following the approach adopted in Lavers et al. (2013) the threshold chosen for each bin corresponds to the 85th percentile of the maximum IVT values included in that bin. This information has been clarified in the new version of the manuscript.

9) It is also confusing to use the term "domain" (as in lines 2 and 4, p. 6) when you deal with a single longitude (even if we understand that moisture passing across a longitude is important for the downstream area). The "maxima IVT at each longitude" (line 18) means upstream?
We agree that the use of the term 'domain' is probably not the best option in this context given that we using the same term for the different AR target regions. In this case we are referring to the different bins as explained in our answer to point 8. This paragraph has been rewritten in order to accommodate this clarification and the term 'reference meridians' has been used instead of 'domain' in this context.

10) I do not understand the term "an AR time step" in alinea b.
All the stages mentioned on page 2623 between lines 5 to 23 are applied at each time step. Therefore we use the term "AR time step" to a reanalysed time step that meets all the aforementioned criteria. Ramos et al. (2015) provide a good example of the identification of a persistent AR (i.e., an AR that lasts at least 18 hours) in their Figure 6 (reproduced below). It was shown that for this particular AR, its detection began on 4 November 1997 at 1800UTC and lasted for 5 consecutive time steps ending on 5 November 1800UTC, Figure 6d. In this case the AR was detected for more than 3 consecutive time steps and it is therefore considered a persistent AR. We have clarified the use of the term 'time step' in the new version of the manuscript.

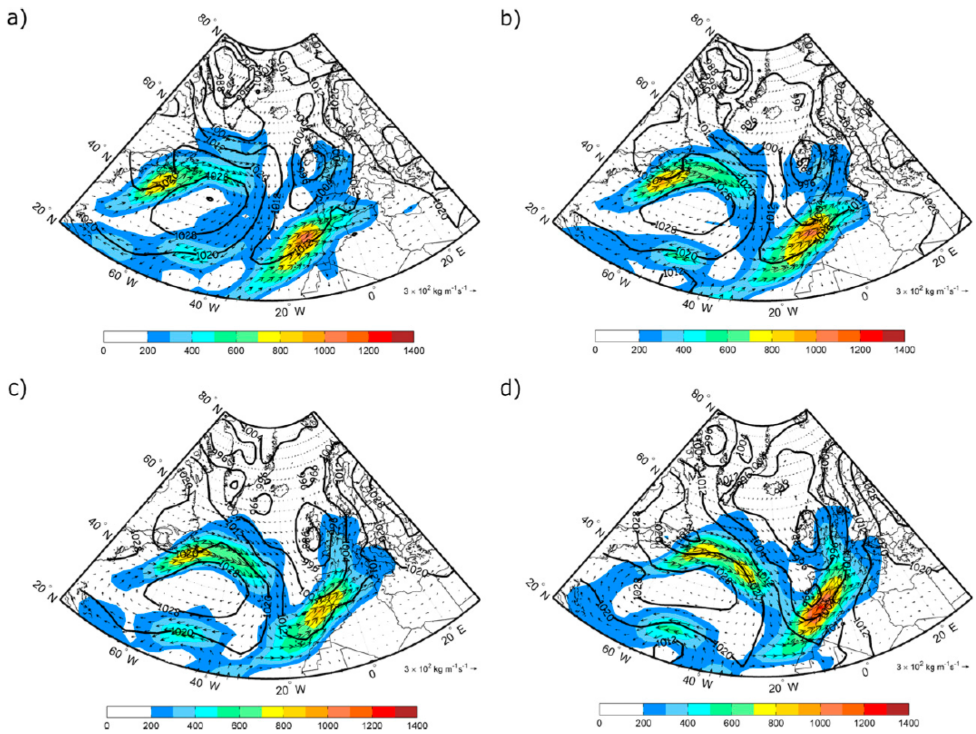


Figure R3. IVT direction (vectors) and intensity (kgm21 s21; colour shading) and SLP (hPa; contours) fields at (a) 0000, (b) 0600, (c) 1200, and (d) 1800 UTC, 5 Nov 1997.

11) The length and duration criteria do not overlap? I ask that because I imagine that a track covering at least 1500 km lasts at least 18 hours, but perhaps I am wrong? If both criteria overlap, are they both really useful? In each step, it would be interesting to quote also the number of cases to see where the reduction from the full sample to AR days is concentrated.

The length and duration criteria do not overlap. For example, it is possible to have a track covering at least 1500 km but with a duration of no more than two (12h) time steps. In this case we do not consider the event to be a persistent AR and it is therefore discarded. It is also possible to have 4 consecutive time steps with the IVT above the minimum threshold where the minimum length criteria is not met. We also discarded these cases.

12) The statement lines 11-12 p. 8 seems rather trivial to me, since I do not any see any physical reason why AR should be restricted to UK.

We agree with the reviewer that the text of this description was unclear. The use of country names to identify specific meridians (e.g., Iberian Peninsula-Ireland) is misleading. We have decided to label differently the 3 meridians chosen using a simple numerical code rather than country names.

13) Page 9: on figure 2, it is hard to see any NW component on figure 9a. I see a WSW component. Perhaps the conic projection does not help and it is perhaps better to use a flat projection with horizontal latitudes to see the meridional component of AR? Same comment applies to “a more zonal path” below (hard to see if it is “more” or “less” zonal)

The reviewer has correctly identified that the NW component is not correct. It was a typo and we intended to show a WSW component on Figure 9a while showing a more SW component for the other domains. This has been corrected in the new version of the manuscript.

14) What are the connections between AR and 4-5 well-known weather types across the North Atlantic? I imagine that AR days are concentrated in one (or 2) WT.
As an example, to respond this question, we use the circulation weather types (WTs) computed by the authors via the methodology of Ramos et al. (2010) but centred in the Iberian Peninsula. The period in common with the AR database is 1979-2012, and the reanalysis used to calculate the WTs is Era-Interim. During winter, ARs are concentrated in 2 WTs: SW and W (~ 80% frequency for AR days vs. ~18.5% climatological extended winter).
The reviewer could additionally be referring to weather types as modes of low frequency variability. The authors have shown in other studies that the Scandinavian pattern is negatively correlated with the occurrence of ARs in Britain (Lavers et al., 2012), while for the rest of Europe the North Atlantic Oscillation also has an influence on the occurrence of ARs (Lavers and Villarini, 2013). In addition, Ramos et al. (2015) showed that for the particular case of the Iberian Peninsula, the East Atlantic pattern also plays a major role in explaining the annual variability of ARs.
Despite these comments, we believe that the association between ARs and the different modes of low frequency variability is beyond the scope of this work, therefore we have only included a small paragraph in the introduction on this matter.

Ramos, A. M., M. N. Lorenzo, and L. Gimeno (2010), Compatibility between modes of low-frequency variability and circulation types: A case study of the northwest Iberian Peninsula, J. Geophys. Res., 115, D02113, doi:10.1029/2009JD012194.

15) Page 11, lines 13-16: another time, these differences could be inferred simply from the mean flow (WSW in mean decreasing the latitude on the west of the basin relatively to the east): what is new here?
The novelty here is related to the detection and quantification of the main areas where the moisture uptake is anomalous for the ARs (see also comment 1) and to investigate whether this moisture originates in faraway sources or instead mostly from the local advection of moisture. Such an assessment has not previously been performed from a Lagrangian point of view.

16) Line 32, page 11: southern mid-latitudes sound weird (perhaps southern edges of the mid latitudes?)
The text has been corrected accordingly.

17) As said in my main comment, what is the real added value of this approach vs a study of the IVT only?
Please see our answer to points 1 and 2 above.

REVIEWER #2

1. Overall evaluation

The manuscript presents an analysis of the evaporation-minus-precipitation (E-P) signature along atmospheric river (AR) trajectories of hydrological relevance to various sectors of west Europe. The detection of AR is based on an existing method introduced in Lavers et al. (2012) with refinements to facilitate applications to different geographical sectors. Analysis of AR trajectories is based on a Lagrangian dataset produced by a global simulation of the FLEXPART model widely used in the community. The ERA-Interim reanalysis is used for the detection of ARs, and for forcing the FLEXPART model. The methods used are reasonable, and the results represent a useful contribution to the ongoing understanding (sometimes debate) of the moisture sources and transport associated with ARs.

I would like to recommend publication of the article in Earth Syst. Dynam. subject to major revisions suggested below.

We would like to thank the reviewer for his/her insightful comments and positive feedback on the manuscript, which have helped us to improve our work.

2. Major comments

2.1 AR detection

The detection of ARs is based on refinements to the method introduced in Lavers et al. (2012). Specifically, multiple (i.e., three) reference meridians are used instead of a fixed one for the entire west Europe. Landfall time and locations based on the three reference meridians are then pooled and regrouped into five sub-domains based on geographical relevance.

Part of the overarching difficulties involved in AR detection over large domains is the challenge to establish a universal threshold for the AR intensity, and the above is a potentially useful effort toward improved AR detection over large domains based on the Lavers et al. method, and may represent one of the novel aspects of the study.

However, it is not clear whether the refinements actually improved AR detection. For example, do ARs in the final five sub-domains better correlate with heavy precipitation in each sub-domain than does the original set of ARs based on a single reference meridian at 10W? I wish the authors would take the opportunity to show that the refined method indeed works better.

The reviewer is justified in stressing that the use of different reference meridians is an improvement for AR detection over large domains. We also agree that it represents a clear novel methodological advance, despite not being clearly stated in the original version of the manuscript. This has been explained more clearly in the new version.

We also understand the reviewer's question of whether these refinements actually improved AR detection. In developing the refinements of the AR detection scheme our main intention was to identify the most accurate landfall area for the ARs, which is mainly achieved via the use of the different reference meridians and also via the reorganisation of the detected ARs to include only those reaching land.

According to the reviewer's suggestion, we have computed for each calendar year (only for the extended winter months) the annual maxima from 1979 to 2012 at each grid point (E-OBS, at 0.25º resolution, Haylock et al., 2008). The numbers of top 10 annual maxima precipitation events related to our AR database (Section 2.1) were computed for Europe between 10ºW and 30ºE and between 35ºN and 70ºN. The results are shown in Figure R1.

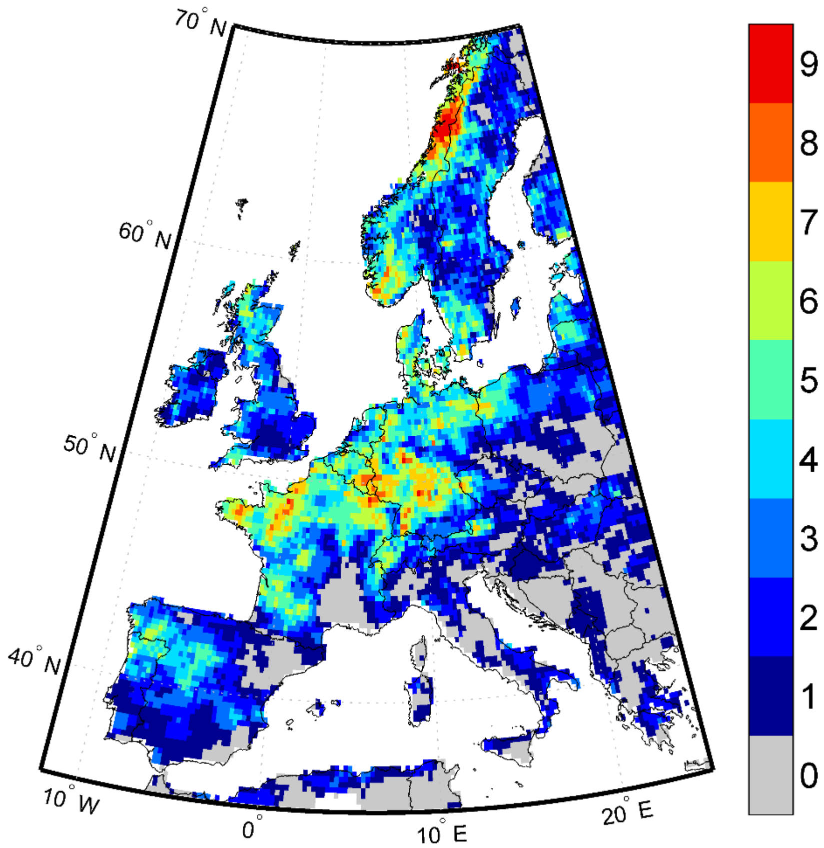


Figure R1. The number of the top 10 annual maxima precipitation events (extended winter) that are related to ARs.

Our results are presented only for the extended winter months, in contrast with the results presented by Lavers and Villarini (2013, their Figure 3), therefore a direct comparison between the two cases is not possible. We nevertheless believe that there is an improvement in the relationship between the incidence of ARs and the annual maxima specifically for France, Belgium, Germany, and the Scandinavian countries. Regarding the Iberian Peninsula and the British Isles it seems that the relationship between our AR database and the annual maxima is weaker than that contained in Figure 3 of Lavers and Villarini (2013). The reasons for this apparent deterioration are twofold: 1) our AR database has fewer ARs than that presented by Lavers and Villarini (2013) due to the constraints on our domains, and 2) we only analyse the annual maxima precipitation occurring during the winter months while Lavers and Villarini (2013) analyse the entire year.

2.2 Trajectory analysis

To my knowledge the current study is one of the two studies that analyzed the E-P (or dq/dt) signature along AR trajectories, the other study being the case study in Stohl et al. (2008). In this regard, the current study is the first to present the E-P signature from a climatological perspective, a novel aspect not articulated in the paper currently.

What would make the paper more interesting and insightful would be to additionally analyze the E and/or P components of E-P to show the relative importance of E vs. P over different moisture source regions. The analysis, if done, would have important implications to observing and simulating ARs as precipitation is among the least well represented processes in GCMs which may limit our capability to realistically simulate the AR moisture balance along its trajectory.

As the reviewer is aware, FLEXPART allows us to obtain the balance of E-P, which yields the contribution of moisture sources (in this case the anomalous source of moisture) to precipitation (computed as E-P<0, see the new explanation given in the methodology) over a particular continental region (Gimeno et al., 2012). To do this, we used the forward FLEXPART mode to identify where particles that leave the regions where the moisture uptake is anomalous (AUM) lose this moisture in the form of precipitation (measured as E-P<0).

To obtain further details of the effect of ARs over the analysed domains in Europe (land areas) we ran FLEXPART in its forward mode for particles located inside those areas of AUM (i.e., those in Figure 3) and compute the precipitation (as E-P<0) over each continental domain (Figure 1).

We did this for both climatological and AR days, and the following table shows the results of the climatological precipitation (E-P<0 Clim) as well as those only for those cases when ARs occurred in each domain (E-P<0 AR), together with the ratio between the two.

Domain	(E-P<0)Clim (mm/day)	(E-P<0)AR (mm/day)	Prec(AR)/Prec(Clim)
1) Iberian Peninsula	255.85	788.14	3.07
2) France	360.94	779.01	2.16
3) UK	561.61	709.86	1.26
4) Southern Scandinavia and The Netherlands	616.42	829.89	1.34
5) Northern Scandinavia	601.35	871.06	1.44

If we eliminate from the climatological values those days with ARs, the results are as follows:

Domain	(E-P<0)Clim (mm/day)	(E-P<0)AR (mm/day)	Prec(AR)/Prec(Clim)
1) Iberian Peninsula	245.31	788.14	3.21
2) France	308.30	779.01	2.53
3) UK	552.52	709.86	1.28
4) Southern Scandinavia and The Netherlands	600.05	829.89	1.38
5) Northern Scandinavia	586.15	871.06	1.49

These results show that ARs bring a high amount of precipitation, on average much higher than the mean precipitation. In this context it is appropriate to state that ARs are extreme events that bring exceptional amounts of precipitation. For the Iberian Peninsula, for instance, during an AR day it might be expected to triple the amount of rainfall. These new results have been included in Section 4.

What would usefully complement the E-P analysis would be the distribution of track densities, i.e., the count of parcels that contributed to the E-P calculations at each location, for example, see Figs. 3d-f of Rutz et al. (2015). With this information on track density the inference of AR moisture source regions would be more complete and compelling.
According to the reviewer's suggestion, we computed the distribution of the track density of the anomalous moisture uptake (using a 5º by 5º grid cell) for each European domain, by counting the parcels that contributed to the (E-P)>0 calculation at each grid point of the anomalous source areas.
An example for the Iberian Peninsula is presented below where the percentage of parcels in each grid box (5º by 5º) is shown.

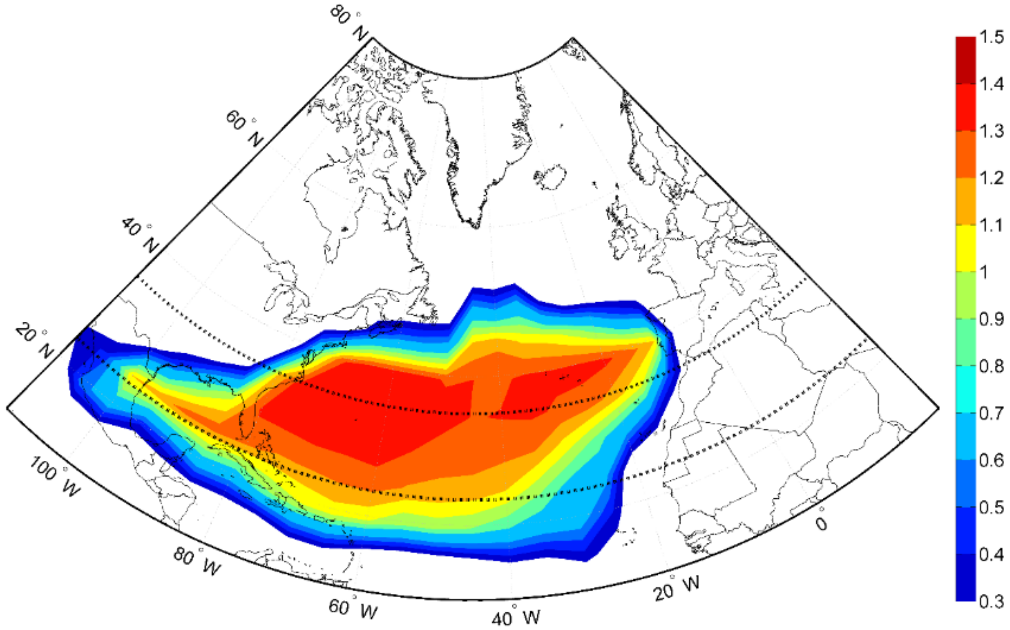


Figure R2. Track density (%) of the air parcels used to compute the anomalous moisture uptake (using a 5º by 5º grid cell) for the Iberian Peninsula domain.

In addition, it must be borne in mind that the areas of maximum parcel density may or may not correspond to areas of maximum anomalies and *vice versa*, because we can have a high concentration of air parcels in a certain region but their contribution to the E-P anomaly may be rather small.
This new figure has been mentioned in the new version of the manuscript and included as supplementary material.

While I do not expect the authors to conduct all of the new analysis suggested in my major comments, I encourage the authors to take the opportunity to make the paper a more insightful and potentially more influential contribution to the science of ARs.
We believe that we have answered all the major comments and that all the changes made have resulted in an improved and potentially more influential contribution to the science of ARs.

3. Minor comments and corrections

P2618L12: it would make more sense to give the parcel size; the total number of parcels is less relevant.

The size of the parcel is a function of the altitude. The FLEXPART model imposes a condition on the mass, which must be constant. The mass takes into account the volume and density of the air. We used 61 levels in the atmosphere, from 1000 to 0.1 hPa, so the volume of the "air parcel" (the particles) varies in concordance with the levels: the typical volume unit is smaller near the surface and greater as it ascends because the air density is greater near the surface and less at high altitudes.

In view of this we have removed all reference to the total number of parcels in the abstract and have included this information in Section 2 of the new version of the manuscript.

P2618L19: remove "is" before "found".

The abstract has been corrected.

P2618L22-23: change "further the analysed longitude along the North Atlantic is located eastward" to "at locations closer to AR landfalls".

The abstract has been corrected.

P2619L2: "~500 km" is not accurate, "on average ~500 km" will be better.

We have changed this accordingly.

P2619L7: Neiman et al. (2008) could be cited.

The Neiman et al. 2008 reference has been included in the new version of the manuscript.

P2619L18: remove "the use of".

This part of the sentence has been removed.

P2619L20: it feels the paragraph is not naturally ended, i.e., you mentioned there are two approaches, and so what does that entail?

We have included a new sentence as suggested.

P2619L23: Ralph et al. (2004) could be cited.

Ralph et al. 2004 has been included in the new version.

P2620L4: what exactly does "analyses" mean here?

The word "analyses" has been replaced by the word "studies".

P2620L7: change "proposes" to "proposed".

We have changed this.

P2620L11: change "has" to "have".

We have changed this.

P2620L13: fix the grammar in "It is discussed the possibility that".

We have changed this.

P2620L18: could a reconciling remark be made here regarding the two different views?

A new sentence has been included.

P2620L20: change “scares” to “scarce”.
This typo has been corrected.

P2620L20: one or more of the following latest studies could be cited and briefly discussed: Garaboa-Paz et al. (2015), Rutz et al. (2015), Ryoo et al. (2015).
We have added both Rutz et al. (2015) and Ryoo et al. (2015) to the introduction section, while Garaboa-Paz et al. (2015) has been added to the end of section 4.

P2620L23: change “on the Norwegian” to “in Norway”.
We have changed this.

P2621L6: change “specific moisture” to “specific humidity”.
We have changed this.

P2622L6: change “humidity” to “specific humidity”.
We have changed this.

P2622L16-17: do you mean a meridian (a line) or an area (a box)? If a line why “centered”?
The reviewer is absolutely right. We intended to mention a line and not an area. The text has been changed accordingly.

P2623L1: “. . . since . . .”: this is not really an explanation which I suggest be removed.
We have included a new reference in support of our affirmation and have therefore changed the sentence accordingly.

P2623L13: “local IVT threshold”: does “local” mean the threshold is dependent on both longitude and latitude?
The reviewer is correct. The “local” IVT thresholds used are shown in Table 1. In any case we have changed the text to make this clear.

P2623L16: change “20.25” to “22.5”.
This typo has been corrected.

P2623L17: as far as I know one degree of longitude at 55N is ~64 km.
The reviewer is once again absolutely right. The reference distance to one degree of longitude was assumed to be 50º and not 55º, we have corrected this.

P2623L20: to define persistent ARs do you limit how far the AR can move along the north-south direction over the 18 h period? In principal two independent ARs separated by certain distance can each make landfall at the same reference meridian at two adjacent time steps – how is this scenario handled?
We used the same methodology as Lavers and Villarini (2013). Therefore we only allowed a 4.5º latitude movement to the north or south of the initial IVT maximum in an 18h period. Because the method has been described at length in previous papers, here we have tried to simplify the text to avoid repeating all the steps of a method that has already been published and used successfully. However, we agree that this information is important and have included it in Section 2.

P2624L6: see comment above to P2618L12.
See answer to comment P2618L12

P2624L10: remove “mentioned”.
We have removed this.

P2625L1: K is the total number of parcels in the column above area A, and therefore must be a function of A, not a constant like 2 million. Please fix the explanation.
The reviewer is right. In the new version of the manuscript we have deleted the part of the sentence inside the parenthesis relating to the number of particles involved in the E-P computation.

P2625L19: change “9.75” to “9.75◦W”.
This typo has been corrected.

P2625L25: the re-organization needs more detailed explanation: how does it go from a line-based landfall to a box-based landfall?
Regarding the reorganisation, we did not change from a line-based to a box-based landfall. Instead we reordered the ARs into a narrow landfall line (coloured lines in Figure 1b). The boxes in Figure 1b only show those target regions where the particles inside the box on AR days are analysed from a Lagrangian point of view. In any case, we agree with the reviewer that this information was not clear in the manuscript and have changed it accordingly.

P2627L21: “(a)” does not a corresponding “(b)”.
We have changed a) and b) to 1) and 2).

P2628L29 and P2640 2nd from bottom line: as far as I understand the Tropic of Cancer is currently located at 23◦26’N or 23.43◦N, NOT 23.26◦N.
The reviewer is right. The typo has been corrected accordingly.

P2630L9: the word “confirms” sounds weird as in the previous sentence you just described something inconsistent with your result.
We have changed this.

P2630L25: add “divided” before “into”.
We have changed this.

P2631L7: change “4.5” to “4.5◦W”, and change “45-55” to “45-55◦N”.
The typo has been corrected.

P2632L6: change “longitudes are located westward” to “for longitudes away from the landfall locations”.
We have changed the text accordingly.

Figure 1: I think the readability of the figure can be considerably improved if the two panels are combined into one single plot over one single domain. That way the reader can visually understand how the five boxes are defined relative to the three reference medians.
Figure 1 has been changed according to the reviewer’s suggestion. We have combined panel a) and b) into one single plot. The 3 reference meridians have been marked from 1

to 3. Because we present a reduced domain, the Tropic of Cancer parallel (23.43ºN) and the 35ºN parallel are now shown on Figure 3.

Figure 3: either increase the font size for the axis labels, or remove them entirely. Currently they are way too small to be read.
We have almost doubled the font size in the axis labels and in the colour bar. In addition, the Tropic of Cancer parallel (23.43ºN) and the 35ºN parallel are also shown in the new version of Figure 3.

References
http://dx.doi.org/10.1063/1.4919768
http://dx.doi.org/10.1175/MWR-D-14-00288.1
http://dx.doi.org/10.1002/2014JD022023
All three references have been included in the new version.

In addition, the title of the manuscript was changed to "Atmospheric rivers moisture sources from a Lagrangian perspective" in order to represent better the main purpose of the manuscript.

REVIEWER #3

Synopsis:
Ramos et al. consider the origin of moisture for atmospheric rivers (AR) making landfall at the western coast of Europe. The topic itself is interesting and there are still open questions to be addressed, as outlined in the introduction of the study. However, the study would benefit from a more in-depth analysis of the moisture sources. Furthermore, some details of the method remain unclear and need to be discussed in greater detail to make the study publishable. Finally, I felt also a little 'upset' by the rather large number of really avoidable little language issues! In short, a more careful proof-reading before paper submission would have been appropriate! Given this, I only recommend publication of the study if major revisions are provided. They are listed in the following in detail.
The manuscript have been sent to a proof-reading editor in order to correct the language issues.

Major Concerns:
1. The introduction could be clearer! For instance, warm conveyor belts (WCB), tropical moisture exports (TME) and atmospheric rivers (AR) are all introduced, but their relationship is not clearly worked out although a recent discussion is referred to (Dettinger et al., 2015). In particular, the authors should make clearer in which sense AR differ from WCB and TME. As a characteristic feature of AR a pre-cold frontal low level jet is mentioned, which is also characteristic for WCBs. But this low-level jet and the front are not further discussed later in the manuscript.
We agree with the reviewer that the interplay between some of these topics is not particularly well explained in the introduction. The introduction has now been rewritten according to a number of suggestions raised by several reviewers, particularly in terms of placing in a wider context the novelty of the results attained in the present work. In addition, the 2nd paragraph has been completely rewritten in the new version of the manuscript. Our intention in the manuscript was never to analyse the dynamical characteristics of the AR, and this is why there is no mention of the pre-cold frontal low level jet later on. In any case, we believe that the AR properties should be included in the introduction, and these have therefore been retained in the revised version.
In addition, the title of the manuscript was changed to “Atmospheric rivers moisture sources from a Lagrangian perspective” in order to represent better the main purpose of the manuscript.

Furthermore, the introduction at several places lacks a little coherence, e.g., at P2619,L16-20 two different methods how to identify AR are presented, but this more 'technical aspect' is a little out of place: it would fit in more nicely towards the end of the introduction or in the methodology section.
We agree with the reviewer. The new version of the manuscript contains this particular paragraph in Section 2.1.

Finally, at P2620,L7-18 a scientific 'debate' about the origin of moisture in AR is presented: local moisture convergence along fronts, direct poleward transport from the subtropics and sweeping-up of water vapour in cyclones' warm sector. As a reader I would now expect that the climatological analysis of the present study tries to quantify the relative contributions of these mechanisms. But this is not the case! I think that the study would gain a lot if such a quantification is set as the ultimate goal. Otherwise, several of the results 'only' confirm, or slightly improve, well-known results of, e.g. Lavers and Villarini (2013). Note that a 'comprehensive analysis of AR moisture sources and transport' (P2621,L20) is actually listed as a main goal of the study.

As stated in our introduction, we are well aware that ARs are linked with the mechanism suggested by the reviewer, but the aim of this paper is not to quantify the transport of moisture in ARs, and we accept that this could be misunderstood from the introduction. Our goal in this work is twofold:

a) first, to the best of our knowledge, the current study is the first to present those regions where Anomalous Uptake of Moisture (AUM in the new version) can be identified for ARs using E-P from a climatological perspective. The sole previous study of moisture sources along AR trajectories was undertaken for a simple case study in Norway (Stohl et al., 2008). Locating and quantifying those areas where the moisture uptake to the atmosphere is abnormal during the days prior to the occurrence of an AR is important, because an excess of moisture is a prerequisite for an AR to exist.

b) secondly, we have made refinements to the AR tracking method introduced by Lavers et al. (2012). In the present version we use 3 reference meridians in preference to a fixed one for the whole of western Europe given the high accuracy of the landfall times and locations. This is of the utmost importance for analysing the anomalous AR moisture uptake based on the E-P method because just a few degrees of change in the reference meridian longitude may translate into large errors in AUM.

We recognise that the objective and methods were not as clear as they could have been in the first version of the paper. We have modified the text to make it clear that we wish to study the anomalous uptake of moisture (AUM) for AR events; we have also changed the title of Section 2.2 because in this paper we do not analyse the transport of moisture as is normal in papers of this type.

Moreover, we do not agree that our “results 'only' confirm, or slightly improve, well-known results of, e.g. Lavers and Villarini (2013)”. Most AR studies use the integrated horizontal flux transport (IVT) from an Eulerian point of view (e.g., Lavers and Villarini (2013)). This is useful when studying the temporal variability of moisture flows for specific locations around the globe and is therefore widely used in the identification of ARs. However, this Eulerian perspective is not suitable for finding the sources of moisture, and therefore not appropriate for identifying AUM regions [our objective], because Eulerian methodologies do not follow any specific “particle” (or atmospheric air mass) transported by an AR. This can only be accomplished using Lagrangian models such as FLEXPART (as used in this paper). FLEXPART allows us to follow atmospheric air parcels through space and time, to generate trajectories, and to characterise with some accuracy the history of the air streams reaching a specific site using humidity or temperature among other meteorological variables. The use of Lagrangian models has been shown to be worthwhile and important as a tool for analysing the moisture sources of ARs, as shown by Stoll et al. (2008) for a particular case study of an AR occurring in Norway.

To illustrate the difference between the two approaches, we compare the IVT field with the results obtained from FLEXPART for one particular AR. In Figure R1a) we show the moisture sources (E-P>0) computed for 10 days for an AR that made landfall in the Iberian Peninsula on 14 December 1981 at 00UTC.

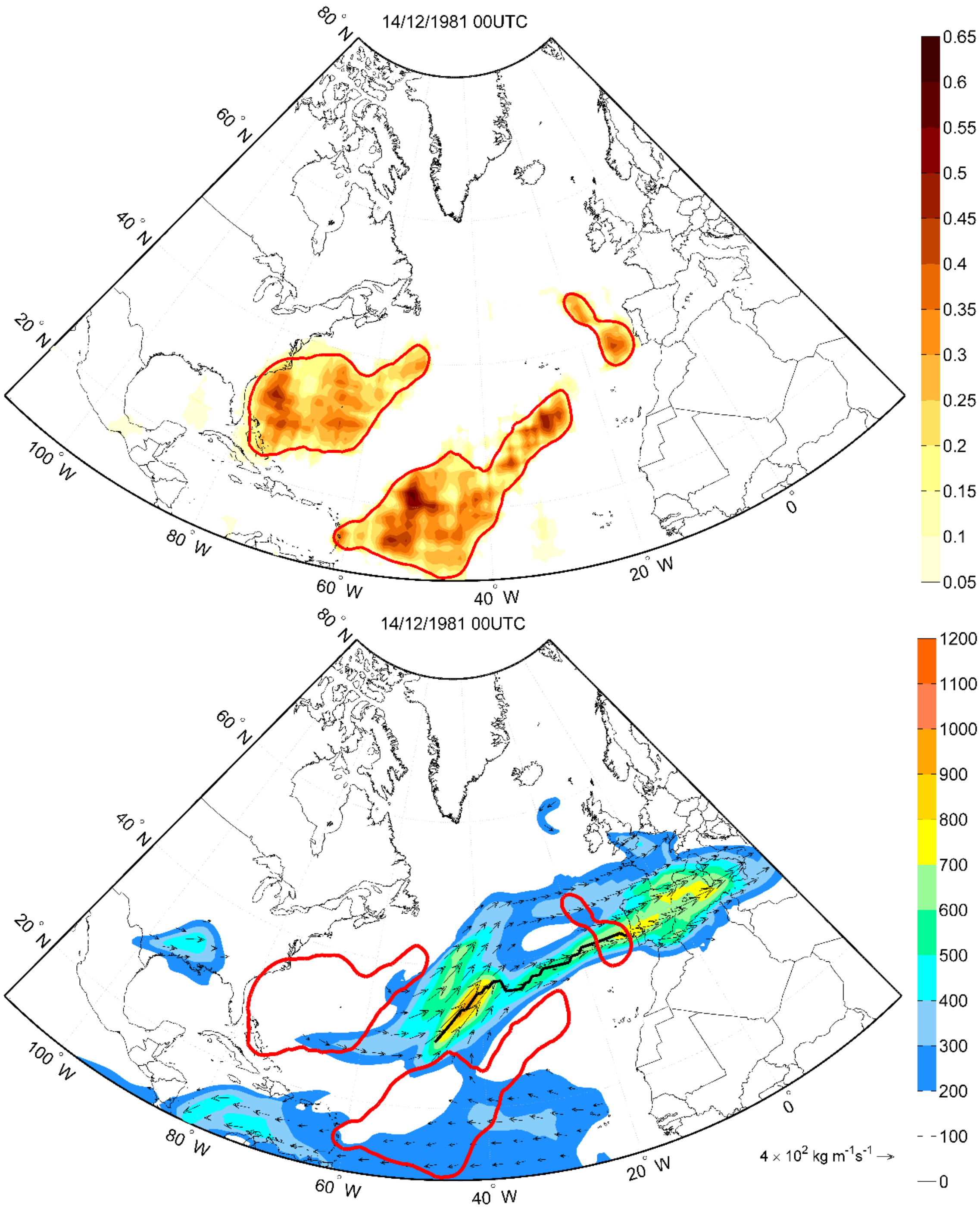


Figure R1. a) The moisture sources (E-P>0) computed for 10 days for an AR making landfall in the Iberian Peninsula on 14 December 1981 at 00UTC. b) The vertically integrated horizontal water vapour transport (IVT) field for 14 December 1981 at 00UTC and the location of the IVT maxima (black line) are also shown. The moisture sources detected in a) are also shown using red contours.

Three source areas clearly emerge from this approach, one located to the west of the Iberian Peninsula and two more distant sources located in sub-tropical and tropical regions. In the Figure R1b) we show the IVT field for the same day and the locations of the IVT maximum (black line) that were used, following our methodology, to find the AR. In addition, the moisture sources detected in R1a is also shown in the same plot using red contours. It can clearly be seen that the moisture sources are in a different location to the IVT maximum. When we consider the IVT or the IVT maximum, we are analysing only a snapshot of the integrated horizontal flux transport for that specific time step (like an photograph) rather than the path of the air masses, and neither indicates when the moisture comes from. This can only be achieved using the FLEXPART model.

We believe that Figure R1 is a clear illustration of the differences between the two methods used in this work. We have therefore included this figure in the new version of the manuscript in order to provide readers with a clear picture of the differences between the two methods.

With this in mind, we are confident that the use of Lagrangian models can help us to identify in detail and more precisely those areas where the moisture uptake is anomalous to ARs and is then transported by them. It is these models rather than Eulerian ones that can help us in developing our understanding and occasional debate of this topic.

2. The whole description of the Lagrangian moisture transport (section 2.2) remains rather unclear to me. Actually, I am a little concerned about the interpretation of the E-P surface freshwater fluxes and their relation to the AR. Let me explain in a hypothetical case: Suppose you follow back an Iberian AR trajectory for 10 days. At day -10 the flux E-P>0 which according to the methodology would mark this position and time as a source of the AR. Let's further assume that the air parcel moves on, conserving its moisture, until time day -7 when there is heavy precipitation and the air parcel basically loses all it moisture. Then it moves on until day -2, when the flux E-P is again >0 and the corresponding position and time is marked as an AR source. The crucial question to be asked now is: Do you really want to attribute the 'day -10' flux as a source to the AR? I would argue that it has nothing to do with the AR moisture finally found at the Iberian west coast. In this sense, the current method might easily overestimate the long-range moisture transport of the AR! The problem, as a far as I can see, comes from neglecting of the precipitation along the AR backward trajectories. Possibly, this difficulty is correctly handled by the method presented in section 2.2. But it is by far not obvious to me? I wonder whether a more refined moisture-source diagnostic is needed? The authors must carefully discuss this issue and possibly convince that their method handles it correctly. Otherwise, I would recommend to apply a more refined moisture source diagnostic, e.g. the one used in

Sodemann and Stohl (2013). Note that this issue affects also Figs. 3 and 4.

The reviewer is justified in making these comments and in his/her doubts about the method. We recognise that the methodology was not well explained in the first version of the paper. However, we wish to explain here (as for the other reviewers) that our intention is not to show the moisture sources for the AR in respect of a particular target domain, since these can be inferred from the normal literature using Lagrangian models. The aim of this study is rather to detect where the moisture uptake to the atmosphere is anomalous and is therefore available for an AR.

It is important to note that an AR transports a large amount of moisture that then reaches a continental area. This moisture must be available in the atmosphere and it therefore needs to be evaporated or accumulated in certain areas during the days prior to the intense tracking of the AR. The anomalous moisture must be available for the AR, because an intense wind-driven flux is possible, and if the moisture is not anomalous the AR cannot exist *per se*. In this study we therefore detected (for the 10 days prior to the AR reaching landfall) those areas where the moisture uptake to the atmosphere is anomalous and available for the AR.

In addition, the reviewer is aware that FLEXPART allows us to obtain the balance of E-P, it is thus possible to assess the contribution of the moisture sources (in this case the anomalous sources of moisture) to the precipitation (computed as E-P<0, see the new explanation in the methodology) over a particular continental region (Gimeno et al., 2012). To do this, we use the forward FLEXPART mode to identify where those particles leaving the regions where the moisture uptake is anomalous (AUM) then lose this moisture in the form of precipitation (measured as E-P<0).

To investigate further the effect of ARs over the analysed domains in Europe (land areas) we ran FLEXPART in its forward mode for the particles located within those areas of anomalous uptake of moisture (in Figure 3) and computed the precipitation (as E-P<0) over each continental domain (Figure 1). We did this for both climatological and AR days, and the following table shows the results both of the climatological precipitation (E-P<0 Clim) and only for those cases where ARs occurred in each domain (E-P<0 AR) together with the ratio between the two.

Domain	(E-P<0)Clim (mm/day)	(E-P<0)AR (mm/day)	Prec(AR)/Prec(Clim)
1) Iberian Peninsula	255.85	788.14	3.07
2) France	360.94	779.01	2.16
3) UK	561.61	709.86	1.26
4) Southern Scandinavia and The Netherlands	616.42	829.89	1.34
5) Northern Scandinavia	601.35	871.06	1.44

If we eliminate from the climatological values those days with ARs, the results are as follows:

Domain	(E-P<0)Clim (mm/day)	(E-P<0)AR (mm/day)	Prec(AR)/Prec(Clim)
1) Iberian Peninsula	245.31	788.14	3.21
2) France	308.30	779.01	2.53
3) UK	552.52	709.86	1.28
4) Southern Scandinavia and The Netherlands	600.05	829.89	1.38
5) Northern Scandinavia	586.15	871.06	1.49

These results show that the ARs bring a high amount of precipitation, on average much higher than the mean precipitation. In this sense it is appropriate to characterise ARs as extreme events bringing exceptional amounts of precipitation. In the Iberian Peninsula, for instance, an AR can be expected to bring triple the normal amount of rainfall. These new results have been included in Section 4.

We believe that this new table illustrates that the limitations of the methods as stated by the reviewer are overcome because we show that the moisture sources found in the new Figure 4 are responsible for an increase in the precipitation over land during AR landfall days.

3. In section 4 and Figure 3 two different E-P calculations are discussed. I am not completely sure whether I understand this analysis! The basis is the days when AR occur, e.g. in Iberia, where the AR days are defined by the criteria listed in section 2. Based on these days the climatological (E-P) is calculated, i.e., the climatological E-P over all AR days. On the other hand, an (E-P) composite over all AR days is computed. To me this sounds exactly the same! Possibly, I do not understand the meaning of 'Julian day', but according to its definition it simply is the number of days since a reference date. I guess that the climatological (E-P) is the mean, in some sense, over the whole ERA-Interim of the E-P flux. This should be clarified. Intuitively, I see that the authors want to show in Fig. 3 how the E-P flux is enhanced during AR compared to a climatology. But it must be discussed more clearly. Furthermore, it is somewhat irritating that E-P fluxes are introduced in the context of the Lagrangian moisture transport (in section 2.2), but it is not immediately clear how the patterns in Figure 3 are related to the trajectories. Let me explain! At first I thought that Figure 3 shows all the position along the back trajectories where (E-P)>0. That's what I take from the first paragraph of section 4 (P2627,L15). But if so, the patterns in Fig. 3 are remarkably smooth. Note, for instance, that the Iberian Pensinsula has in total 21 AR and 117 AR time steps (see Table 2). But I am not sure whether a 'gridding' of all back- tracjectory positions where (E-P)>0 would yield such smooth patterns as shown in Figure 3. In short, I think that I don't fully understand how Figure 3 is built. Some further explanations are necessary.

This comment echoes a criticism made by the other reviewers. We recognise that the method described in this part of the paper was not described well, and was confusing. We have rewritten this part, and we now think that it is clearer. We will now present the case for the Iberian Peninsula with the aim of providing further clarity.

For the Iberian Peninsula (IP) we have 117 AR time steps. We compute the uptake of moisture for each time step, by following all the particles that leave the IP domain computing changes in specific humidity (q) and retaining changes of q (e-p) every 6 hours for 10 days (yielding 40 points of trajectory). Over each grid point (1°x1° in latitude and longitude) we then add these changes in q for all the particles residing over this 1°x1° area. We now have the balance of E-P for all 40 time steps for the AR. We retain only positive values (E-P>0), representing the uptake of moisture, in which the moisture is considered uptake for the AR. We repeat this for all the ARs, for 117 cases in the case of IP.

During these 10 days of analysis the atmosphere is gaining moisture over the areas detected, although for some days the AR does not exist; but, as we explain in point 1 of this reviewer comment, the atmosphere must have moisture available in high quantities and the moisture uptake must take place before the AR can occur.

To check whether these areas differ from the climatology we computed the anomaly between the '(E-P)>0 for the AR-day' and the climatology ('(E-P)Clim>0'), understanding 'climatology' in this study as corresponding to the same Julian day but for all 33 years of the study (retaining again only the positive values of E-P every 6-h time step). For instance, for an AR occurring on 14 Dec 1981 00UTC, we calculated the mean moisture uptake for every 14 December 00UTC throughout the 33 years. We then computed the difference to obtain the anomaly for this day, (E-P)An>0.

The final plot in the new figure 4 shows the mean accumulated values for all AR time steps: the climatology and the anomaly.

Minor Comments:

-P2619,L8-9: "The attribution of the terms atmospheric or tropospheric rivers rose some debate by Wernli (1997) and Bao et al. (2006)" → It sounds as if Wernli and Bao are the sources of the debate, which is not correct.

We agree with the reviewer that this particular sentence was not clear. In the new version of the manuscript this sentence has been revised.

- P2621,L13: Gimeno et al. (2012) is missing. Should it be 2014 instead?!

The reference Gimeno et al., 2012 has been added to the reference list.

- **P2622,L11**: The definition of the IVT has two terms: the IVT in the zonal direction (IVT{W-E}, vertical integral over q u) and the one in the meridional direction (IVT{S-N}, vertical integral over q v). Then the total IVT is taken as the length of the combined vector $IVT = (IVT(W\text{-}E)^2 + IVT(S\text{-}N)^2)^{1/2}$. But at a single level, the moisture flux is essentially $q (u^2 + v^2)^{1/2}$. One could argue that an integral of this single-level flux over all levels gives the resulting overall flux. I know that it is a detail: But why is the IVT defined according to the first version and not the second one?

The IVT was computed for 7 different pressure levels between 1000 and 300 hPa and then vertically integrated in order to ensure a good discretisation of the zonal and meridional IVT. If we use only one single level flux (accumulated vertical specific humidity and averaged the zonal and meridional fields of all levels) we do not obtain a good discretisation of the different fluxes at the different atmospheric levels and the results computed later on will be only a rough estimate of the IVT.

- P2622,L6-7 and L12-13 are essentially repeating the same.

We have removed the abbreviations from the first sentence, but we believe the text is much clearer in its present form, therefore we maintained the explanation of the variables in equation 1 as they were.

- **P2622,L15-16**: Please repeat the key elements of the AR identification according to Lavers and Villarini (2013). Two to three sentences might be sufficient. Otherwise, the description of the identification remains rather unclear. (between P2622,L15-25).

According to the suggestions made in several reviewer comments, parts of Section 2.1 have been rewritten for clarity.

- **P2623,L11**: "We then performed a backward/forward search" → At this place it is not clear what is meant with 'forward/backward' search! Furthermore, in the next sentence a length criterion is introduced. The AR have to be at least 1500 km long. But the length of the AR is only determined based on the contiguous longitudinal points? What if the AR has an essentially south-north orientation, as for instance for the Scandinavian Ars? The length criterion seems to be biased?

The terms 'forward/backward' have been replaced in the new version of the manuscript by 'west/east'. All our published work on ARs in Europe (Lavers and Villarini, 2013; Lavers et al., 2011; Lavers et al., 2012, Ramos et al., 2015) only use contiguous longitudinal points to compute the length of the AR. From our assessment of many previous manuscripts including the analysis of hundreds of IVT fields, it is very difficult if not impossible for an AR to have a pure south-north orientation, therefore the detection method of ARs is not biased. A good example of this is shown below, from Figure 1 of Lavers and Villarini, 2013.

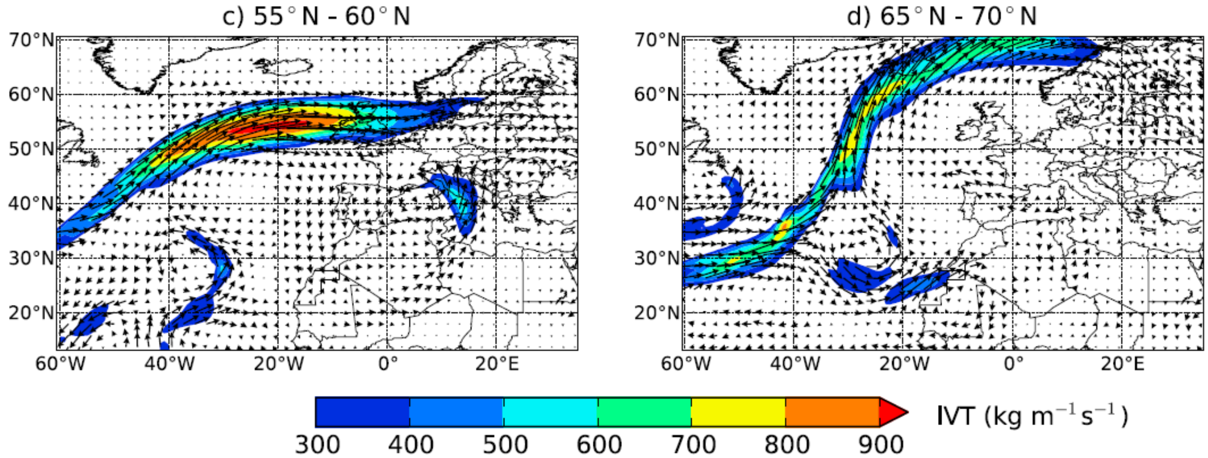


Figure. IVT of ARs detected by the algorithm in the latitude bands (c) 55º 60ºN (at 0000 UTC 6th Mar 2002), and (d) 65° 70°N (1 Dec 1989 1800 UTC).

- P2624,L6-7: "and it was forced by the 1◦ latitude–longitude grid ERA-Interim reanalysis (Dee et al., 2011) available every 3 h." → Be more precise: 1 deg is not the inherent horizontal resolution of ERA- interim, and 3 h is not the time resolution. Intermediate 3-h forecasts are used!

The reviewer is understandably confused. The previous data description is neither adequate nor accurate. We have rewritten this part of the paper.

- P2624,L10-14: Some further details about the FLEXPART model are appropriate? For instance, what does it mean that "the atmosphere is homogeneously divided into a large amount of air parcels"?

It is possible that this explanation is not appropriate. The atmosphere is divided into a large number of particles transported by the model. These particles are positioned in the atmosphere homogeneously to cover the largest volume possible, and always considering the mass distribution in the atmosphere. We have changed this in the revised version of the manuscript.

- **P2624,L14**: "also processed by FLEXPART mode" → What does 'processed' mean?

This sentence has been rewritten in the new version of the manuscript for clarity.

- **P2624,L15-16**: "The changes on the specific moisture (d*q*) of a particle (with mass *m*) along the time (dt) during its trajectory..." → Please rephrase!

The sentence has been rephrased in the new version of the manuscript.

-P2624,L21-22: "Each particle is tracked backwards for a transport time of 10 days because that is the average residence time of water vapour in the atmosphere (Numaguti, 1999)." → The sentence is a little out of place. In the sentence before the topic is (e-p). In the next paragraph it is (E-P). And between is the statement about the time period of the back tracking!

The sentence has now been placed at the end of the 4th paragraph of Section 2.2.

- P2625,L7-9: "Following the application of the various steps of the method explained in the previous Sect. 2, for all the different domains, the IVT threshold and the number of ARs considered for each domain is summarized in Table 1." → Please rephrase. Simply start with "Table".
The sentence has been rephrased in the new version of the manuscript.

- **P2625,L16-P2626,L7**: As a reader I get a little confused. So far, you have introduced in section 2.1 (as also just discussed in the previous paragraph) the AR for the different latitudes (the meridian domains). Now, you tell the reader that new domains will be introduced. Note that in the following paragraph you come back again to the meridian domains. Hence, you are jumping between different domains which distracts the reader. Furthermore, in this section 3 I would expect some results about the landfall of AR, but instead the rather long second paragraph brings a 'technical' aspect, i.e., the definition of new domains. Two suggestions: First, I would present all domains already in section 2, which deals with methodology. Second, because the focus of the study is on the landfall of the AR, why not start (and define) the domains listed here from the beginning? Why do you start with the meridional domain, and only then bring in the new landfall domains? I think the manuscript would benefit if this 'complexity' is avoided.
We agree with the reviewer that the previous version of the manuscript was not clear in this regard and there was some confusion concerning the target domains and the meridian domains (as also stated by reviewer #1). In the new version of the manuscript the term 'reference meridians' has been used instead of 'meridional domain'. In addition, we also agree with the reviewer that in its present form the definition of the new target domains is not straightforward and is somewhat confusing. Therefore the new version of the manuscript has been changed according to the reviewer suggestion.

- P2629,9-11: "The displacement to the south of the anomaly with the longitude is a common feature for all the regions, being the longitudinal slope higher with the latitude of the sink region." → Please rephrase! You can't say "Displacement …. with the longitude". Furthermore, the meaning of "longitudinal slope" might be guessed correctly, but it sounds a little 'bulky'.
The reviewer is absolutely right. The new version of the manuscript has been changed accordingly.

- **P2629,L23-P2630,L3**: In this paragraph, the moisture source study by Sodemann and Stohl (2013) is referred to. In fact, the introductory sentence 'promises' to relate the findings of this study compared to the one by Sodemann and Stohl (2013). However, basically only the key results from the latter study are summarized, and a critical discussion/comparison with the new findings of the study is missing. In short, please use Sodemann's and Stohl's results and critically compare them to your results.
In the new version of the manuscript we have included a couple of sentences in order to discuss/compare our results with those of Sodemann and Stohl.

- P2630,L13-14: "It must be noticed that the method is not able to separate *E* and *P* entirely as it does not represent completely the evaporation field, but provides only an estimation" → I do not understand. Please explain in greater detail.
We have removed this sentence in the new version of the manuscript

- P2632,L4-8: "To conclude, we show that the main sources and advection of moisture linked to ARs that strike western Europe coast have the subtropical areas as the most important ones as the moisture sources longitudes are located westward, but one must be aware also to the appearance of the tropical source, and the extra-tropical moisture sources as we move nearest the European coast." → Please rephrase! Very difficult to understand at first reading!
The last sentence has been rewritten in the new version of the manuscript.

REVIEWER #4

Reviewer #4 makes three rather general comments on our manuscript. These comments are challenging to reply to because it is difficult to determine precisely the opinion of the reviewer. Nevertheless, we will do our best to respond to his/her points and have now improved the clarity of the manuscript, taking into account also the comprehensive review carried out to accommodate all the issues raised by the other 3 reviewers. We believe these comments may be related to some of the more specific criticisms reviewer #4 had in mind.

In addition, the title of the manuscript was changed to "Atmospheric rivers moisture sources from a Lagrangian perspective" in order to represent better the main purpose of the manuscript.

1) My main concern with this study is the attribution of a lot of the moisture sources to atmospheric rivers. Whilst it highlights studies that discuss the connection between atmospheric rivers and extra-tropical cyclones, given this study is focussed on the moisture sources I do not think this is adequately addressed. Looking at the figures it seems to me that all they are highlight are the storm tracks, and thus further raising the question of the interaction of atmospheric rivers to extra-tropical cyclones.

In the introduction we mentioned not only studies of the connection between atmospheric rivers and extra-tropical cyclones but also warm conveyor belts (WCB) and tropical moisture exports (TME). Our focus in the introduction is an overview of this topic, without recourse to any detailed discussions. In any case, as mentioned by reviewers #1 and 3, the introduction was not sufficiently clear and we have therefore made stringent efforts to rewrite parts of it.

Moreover, from our point of view, it does not seem reasonable to state that the figures (we assume that the reviewer is talking about Figures 2 and 3) highlight the storm track. Figure 2 is a first guess of the track of the ARs, while Figure 3 highlights the main areas where the moisture uptake is anomalous and contributing to AR events that reach each of the different European domains. In any case, as we stated in the introduction, "the WCB refers to the zone of dynamically uplifted heat and vapour transport close to a mid-latitude cyclone. This vapour is often transported to the WCB by an AR", one can therefore assume that some connection between ARs and extra-tropical cyclones exists, but we do not agree that "all [the figures] highlight are the storm tracks".

Furthermore, to the best of our knowledge, the current study is the first to present from a climatological perspective the anomalous moisture sources of the ARs based on calculations of E-P. The sole previous attempt made in Europe to analyse moisture sources for ARs that make landfall (this is not the same as our study) was undertaken for a single case study in Norway by Stohl et al. (2008). The relationship and interaction between ARs and extra-tropical cyclones is beyond the scope of the present work. In fact, some of us are currently studying this relationship as can be seen in a recently article by Ferreira et al. (2016).

Ferreira, J.A.., Liberato, M.L.R., Ramos, A.M. (2016) On the relationship between atmospheric water vapour transport and extra-tropical cyclones development. Physics and Chemistry of the Earth. Doi: 10.1016/j.pce.2016.01.001.

2) It also does not discuss, nor are there any plots of, any SST fields. Given the results show that a lot of this moisture is Atlantic in origin I feel this is a significant oversight. It is with little doubt that the SST pattern will have an effect on the moisture source for ARs, and there will be a strong variation between years which also is not addressed.

We agree with the reviewer and we are aware that the SST usually plays an important role in the uptake of moisture from the Atlantic. In a recent work, some of us showed that the winter storm Xynthia was affected by an AR during its explosive development phase (Liberato et al., 2013). In their Figure 4, these authors show a positive SST anomaly located south of the position of the cyclone track (dotted area in the figure below).

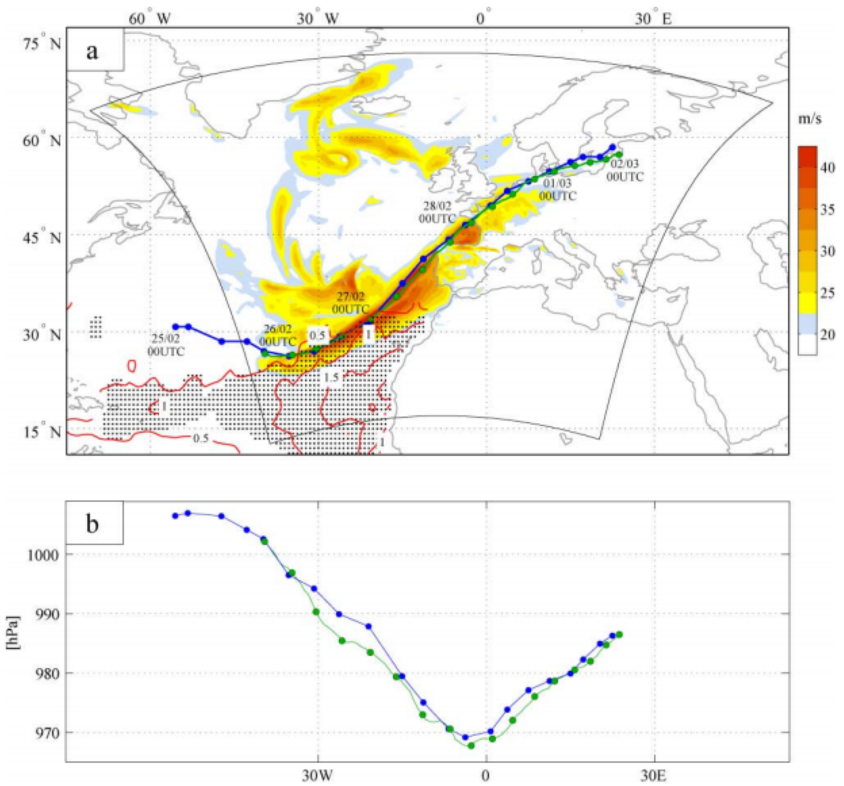


Fig. 4. (a) Surface track of Xynthia as represented in ERA-interim (blue) and in the CCLM simulation (green). Wind gust field corresponds to local maximum wind values (m s^{-1}) during simulation period. The position of the storm at six-hourly intervals is marked with a filled circle. The SST anomaly over the south-eastern North Atlantic for the month February 2010 is depicted as red isolines (each 0.5 K). Areas with an SST anomaly exceeding the climatological standard deviation by a factor of 2 are dotted. **(b)** The corresponding core MSLP data are shown for the period 00:00 UTC 25 February 2010 to 00:00 UTC 2 March 2010.

Moreover, Liberato et al. (2013) also showed some moisture advection from the subtropics mainly from the area of positive SST as shown in their Figure 9 (reproduced below). In addition, according to Gimeno et al. (2012) over the Oceans, apart from the SST the near-surface wind speed and the near-surface atmospheric specific humidity are also bound to play significant roles in the process of moisture uptake.

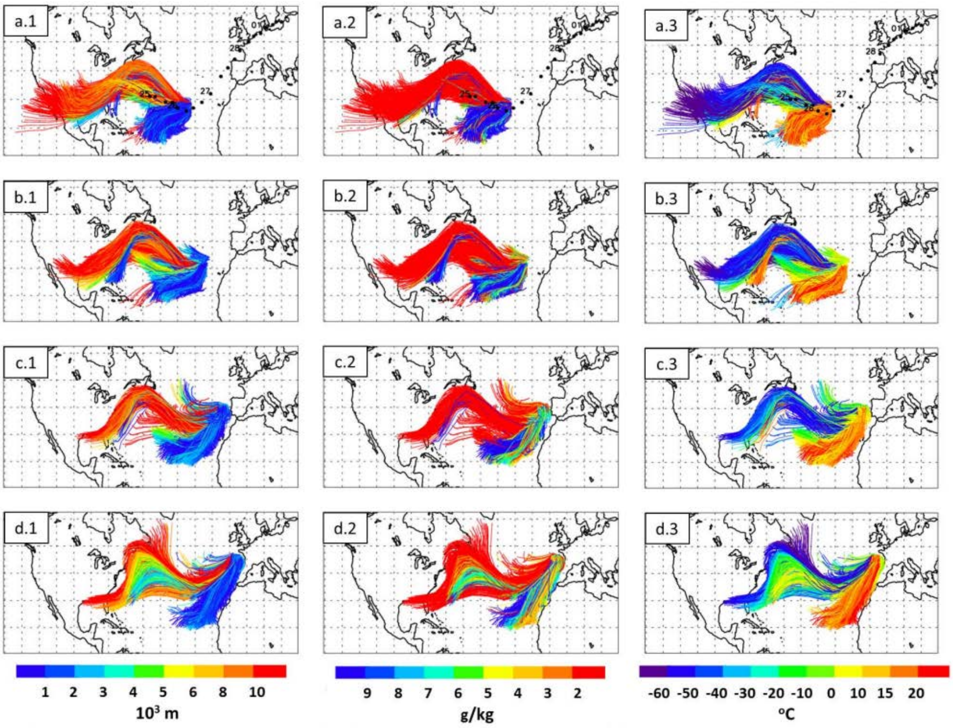


Fig. 9. Two days trajectories diagnosed from back trajectories of the target particles arriving in the box of 5° latitude/longitude SE of the cyclone position as detected by the tracking scheme during explosive development. **(a)** for 06:00 UTC 26 February 2010; **(b)** for 18:00 UTC 26 February 2010; **(c)** for 06:00 UTC 27 February 2010; **(d)** for 18:00 UTC 27 February 2010. For each panel: (1) Height (m); (2) specific humidity ($g\,kg^{-1}$); (3) temperature (°C). The position of the storm at six-hourly intervals is marked with a filled circle on the top panels.

The reviewer also mentioned the possible inter-annual variability of ARs due to changes in the SST field and given what was described before, we agree that this is a topic worthy of more detailed study.
However, taking into account the scope of the manuscript and the questions we are trying to address in the present study, we have chosen not to analyse the inter-annual variability due to the SST but to provide an essential understanding of the main moisture sources of the ARs. Nevertheless, we have decided to include a new paragraph referring to the possible association between the SST fields and the effect on moisture uptake, and of course between the near-surface wind speed and the near-surface atmospheric specific humidity.

Liberato, M. L. R., Pinto, J. G., Trigo, R. M., Ludwig, P., Ordóñez, P., Yuen, D., and Trigo, I. F.: Explosive development of winter storm Xynthia over the subtropical North Atlantic Ocean, Nat. Hazards Earth Syst. Sci., 13, 2239-2251, doi:10.5194/nhess-13-2239-2013, 2013

3) Overall I feel this study does not go into enough detail to reach the conclusions drawn. There are a number of unanswered questions, and some oversights in the analysis that need to be addressed before they can come to the conclusions they have.
The lack of any specific criticism makes this type of comment almost impossible to refute or respond to at all. We do stress that our conclusions are sound, particularly when taking into account the lengthy answers to some of the major issues raised by the other 3 reviewers, including a number of important issues that were not clear in the first version of the manuscript. We would make the following four points A-D in this regard:

A. The novelty of the work was not made sufficiently clear in the first version of the manuscript, as pointed out by reviewers #1 and #2. The added value of the manuscript is mainly twofold: **first,** to the best of our knowledge, the current study is the first to present the moisture sources of ARs using E-P from a climatological perspective. The sole previous attempt to analyse moisture sources along AR trajectories was undertaken for a simple case study in Norway (Stohl et al., 2008); **secondly,** we have made refinements to the AR tracking method proposed by Lavers et al. (2012). In the present version we use 3 reference meridians instead of a fixed one for the whole of western Europe, given the high accuracy of landfall times and locations. This is of the utmost importance for analysing AR moisture sources using the E-P method because just a few degrees of change in the reference meridian longitude may translate into significant E-P source errors;

The capacity to refine the definition of ARs suitable for each longitudinal meridian and latitudinal band is particularly relevant for potential users of our AR database when trying to link extreme precipitation events with the occurrence of ARs. As shown below, a significant percentage of the 10 most extreme precipitation events in the winter half year over western Europe are directly associated with an AR.

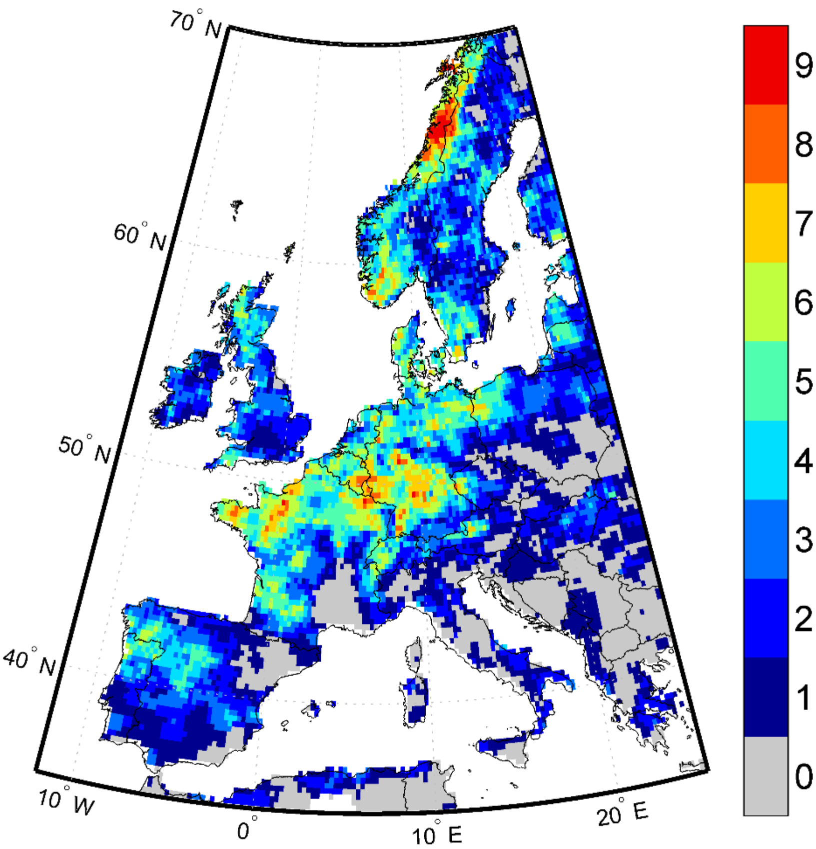


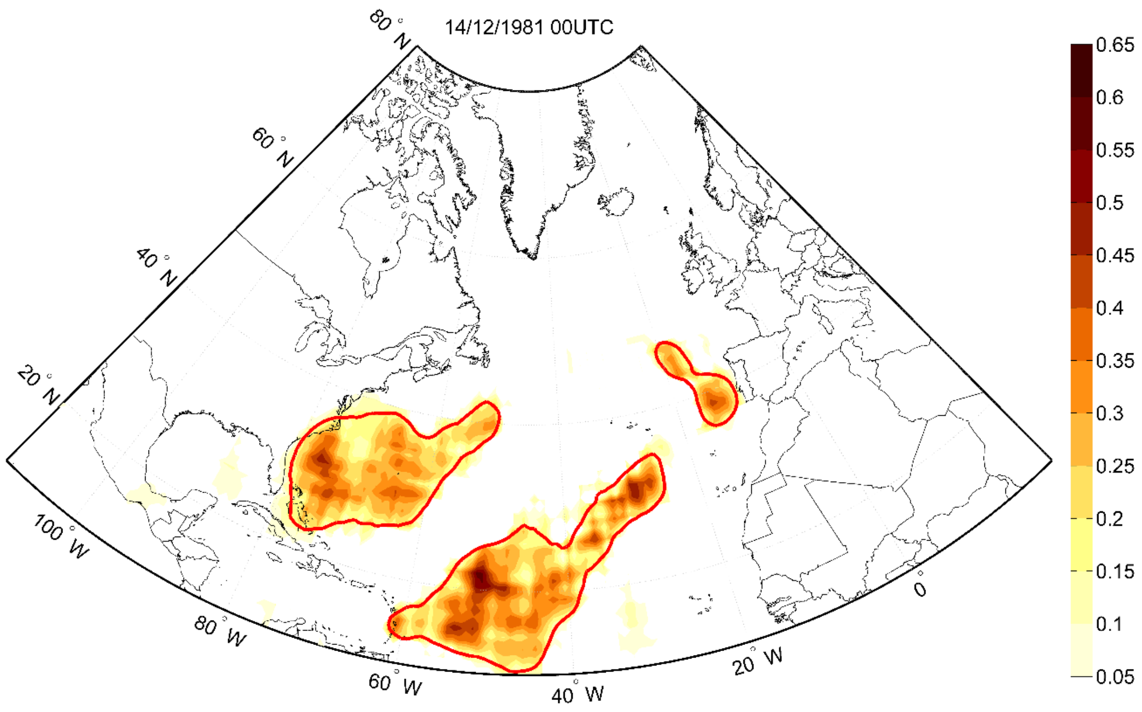
Figure R1. The number of top 10 annual maxima precipitation events (winter half year) that are related to ARs.

Figure R1 was computed as follows: for each calendar year (only for the extended winter months) from 1979 to 2012 at each grid point (E-OBS, at 0.25º resolution, Haylock et al., 2008) we obtained the annual maxima. The number of the top 10 annual maxima precipitation events that are related to our AR database (Section 2.1) were computed for Europe (between 10ºW to 30ºE and 35ºN to 70ºN).

We believe there to be a clear added value in the approach and analyses used in this paper because, as mentioned in the introduction, there is ongoing open debate around the objective characterisation of moisture sources and transport tracks associated with ARs. In any case, we understand the criticism that some of the key messages in the manuscript were not as clear in the manuscript as they could have been, and therefore the suggestions and comments made by the different reviewers have been taken into account in order to improve the message and readability of the manuscript. The new version of the manuscript includes a number of improvements to reflect this.

B. Another major issue raised by the other reviewers relates to the difference between the IVT (Eulerian perspective) and moisture sources (Lagrangian perspective) and the methodology itself, none of which was as clear as it could have been.

In an attempt to answer the last part of the reviewer's comment, we compare the IVT field and the results obtained from FLEXPART for one particular AR. In Figure R1a) we show the moisture sources (E-P>0) computed for 10 days for an AR that made landfall in the Iberian Peninsula on 14 December 1981 at 00UTC. Three source areas clearly emerge, one located to the west of the Iberian Peninsula and two more distant sources located in the sub-tropical and tropical regions. In Figure R1b) we show the IVT field for the same day and the locations of the IVT maximum (black line) that were used, following our methodology, to find the AR. In addition, the moisture sources detected in Figure R1a are also shown on the plot using red contours. It can clearly be seen that the moisture sources and the IVT maximum are different. When we use the IVT or the IVT maximum, we are analysing only a snapshot of the integrated horizontal flux transport for that specific time step (like a photograph) rather than the path of the air masses; neither parameter indicates when the moisture comes from. This can only be achieved using the FLEXPART model. We believe that Figure R1 gives a clear example of the differences between the two methods used in this work. We have therefore included this figure in the new version of the manuscript in order to provide readers with a clear indication of the differences between the two methods.



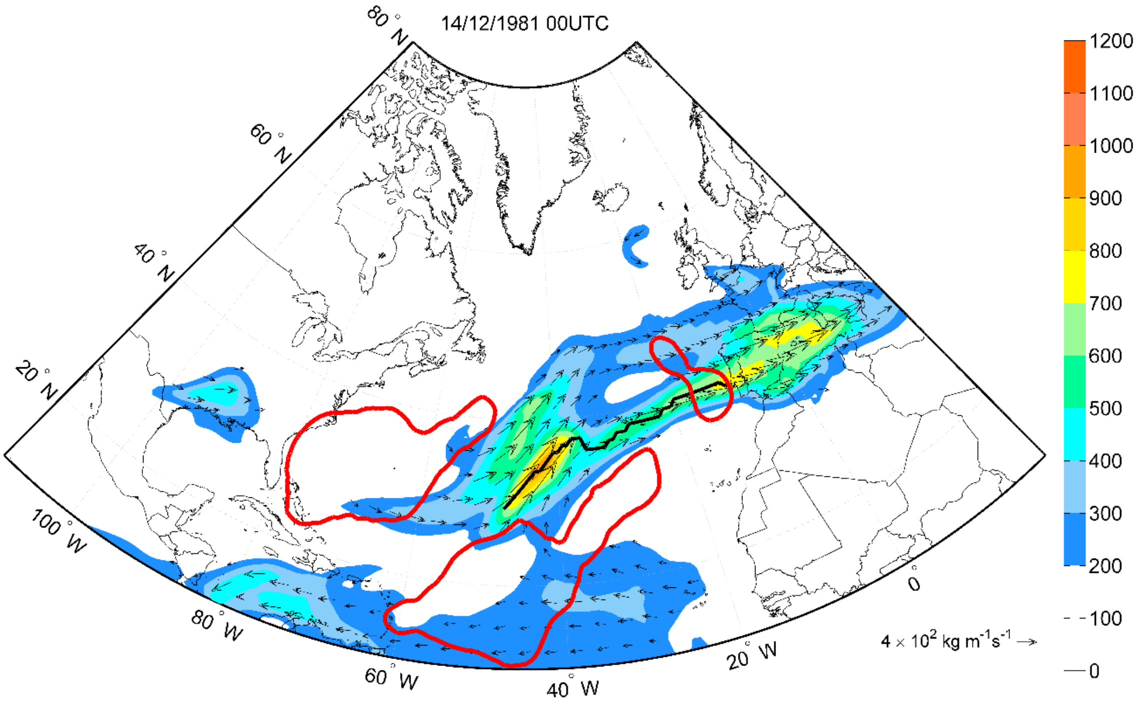


Figure R1. a) The moisture sources (E-P>0) computed for 10 days for an AR making landfall in the Iberian Peninsula on 14 December 1981 at 00UTC. b) The vertically integrated horizontal water vapour transport (IVT) field for 14 December 1981 at 00UTC and the location of the IVT maxima (black line) are also shown. Moreover, the moisture sources detected in a) are also shown using red contours.

Taking these points into account, we are confident that Lagrangian models can help us identify in detail and more precisely than Eulerian methods those areas where the moisture uptake is anomalous and contributes to ARs and is then transported by them. This will help in the ongoing understanding and debates on this topic.

C. The trajectory analysis has been improved in two ways: 1) by analysing the E and/or P components of E-P to show the relative importance of E vs. P over different moisture source regions and 2) by including the distribution of the track densities. Both suggestions have been included in the new version of the manuscript, but we would also like to highlight the new Table 5 shown below. We ran the forward mode of the FLEXPART model for the particles within those areas of anomalous uptake of moisture (those in Figure 3) and compute the precipitation (as E-P<0) for the climatological values and only for the AR days to show the effect on the precipitation of ARs (computed with FLEXPART) over Europe.
We did this for climatological and AR days, and the following table shows the results of the climatological precipitation (E-P<0 Clim) and only for those cases when ARs occur in each domain (E-P<0 AR), and also the ratio between the two.

Domain	(E-P<0)Clim (mm/day)	(E-P<0)AR (mm/day)	Prec(AR)/Prec(Clim)
1) Iberian Peninsula	255.85	788.14	3.07
2) France	360.94	779.01	2.16
3) UK	561.61	709.86	1.26
4) Southern Scandinavia and The Netherlands	616.42	829.89	1.34
5) Northern Scandinavia	601.35	871.06	1.44

If we eliminate from the climatological values those days with ARs, the results are as follows:

Domain	(E-P<0)Clim (mm/day)	(E-P<0)AR (mm/day)	Prec(AR)/Prec(Clim)
1) Iberian Peninsula	245.31	788.14	3.21
2) France	308.30	779.01	2.53
3) UK	552.52	709.86	1.28
4) Southern Scandinavia and The Netherlands	600.05	829.89	1.38
5) Northern Scandinavia	586.15	871.06	1.49

The results show that the ARs bring a large amount of precipitation, on average much higher than the mean precipitation. In fact, it is appropriate to state that ARs are in general extreme events bringing exceptional amounts of precipitation. In the case of the Iberian Peninsula, for instance, when an AR occurs it can be expected to bring triple the normal amount of rainfall. These new results have been included in Section 4.

D. All three reviewers noted that the methodology describing the computation of the previous Figures 3 and 4 was not clear. We present the case for the Iberian Peninsula with the intention of clarifying the method. For the Iberian Peninsula (IP) we have 117 AR time steps. For each time step we computed the uptake of moisture, and for each time step we followed all the particles leaving the IP domain computing changes in specific humidity (q) and retaining changes of q (e-p) every 6 hours for 10 days (yielding 40 points of trajectory). Over each grid point (1°x1° in latitude and longitude) we added those changes in q for all the particles residing over an area of 1°x1°. At this moment, we have the balance of E-P for all 40 time steps for the AR. We then retain only positive values (E-P>0), representing the field of uptake of moisture, where the moisture uptake is for the AR. We repeat this for all ARs, in the case of IP there are 117 cases.

During these 10 days of analysis the atmosphere gains moisture over the areas detected, although some days the AR does not exist; but, as we explain in point 1 of this reviewer comment, the atmosphere must have moisture available in high quantities for it to exist and there must be moisture uptake before the AR can occur.

To check whether these areas are different from the climatology we compute the anomaly between '(E-P)>0 for the AR-day' and the climatology ('(E-P)Clim>0'), understanding 'climatology' in this study to correspond to the same Julian day but for all 33 years of the study (again retaining only the positive values of E-P every 6-h time-step). For instance, if an AR occurs on 14 Dec 1981 00UTC, we calculate the mean moisture uptake for every 14 December 00 throughout the 33 years of the analysis. We then compute the difference to obtain the anomaly for this day, (E-P)An>0.
The final plot in the new Figure 4 shows the mean accumulated values for all AR time-steps: the climatology and the anomaly.

In addition, we would like to stress that an AR transports large amounts of moisture that then reaches a continental area. This moisture must be available in the atmosphere, therefore it needs to evaporate or accumulate in certain areas during the previous days of the intense track of the AR. The anomalous moisture needs to be available for the AR, because an intense wind flux is possible, but if the moisture is not anomalous the AR does not exist *per se*. Therefore, in this work we detect over 10 days (considered prior to the AR reaching landfall) where the moisture uptake to the atmosphere is anomalous and available for the AR. This information has been included in the new version of the methodology.

To conclude, many minor comments and suggestions have been included and discussed in the new version of the manuscript in support of the conclusions drawn. Therefore, we are confident that the new version is an improvement on the original and we also believe that all the questions raised by all four reviewers have been addressed.

Atmospheric rivers moisture sources from a Lagrangian perspectiveAtmospheric rivers moisture transport from a Lagrangian perspective.

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Abstract

An automated atmospheric ~~rivers (ARs~~river (AR) detection algorithm is used for the North Atlantic Ocean Basin, allowing the identification of the major ARs ~~that affected~~affecting Western European coasts between 1979 and ~~2014~~2012 over the winter half-year (October to March). The entire ~~west~~western coast of Europe was divided into five domains, namely~~,~~ the Iberian Peninsula (9.75ºW; 36ºN – 43.75ºN), France (4.5ºW; 43.75ºN – 50ºN), UK (4.5ºW; 50ºN-59ºN), Southern Scandinavia and ~~The~~the Netherlands (5.25ºE; 50ºN-59ºN), and Northern Scandinavia (5.25ºE; 59ºN – 70ºN). Following the identification of the main ARs that made landfall in Western Europe, a Lagrangian analysis was then applied in order to identify the main ~~sources of moisture that reach~~areas where the moisture uptake was anomalous and contributed to the ARs reaching each domain. The Lagrangian dataset used was obtained from the FLEXPART model global simulation from 1979 to 2012~~, where the atmosphere was divided into approximately 2.0 million parcels, and it~~ and was forced by ERA-Interim reanalysis on a 1º latitude-longitude grid.

~~Results~~The results show that, in general, for all regions considered, the major climatological ~~source of~~areas for the anomalous moisture ~~extends~~uptake extend along the subtropical North Atlantic, from the Florida Peninsula (northward of 20ºN~~),~~) to each sink region, with the nearest coast to each sink region always appearing as a local maximum~~ of evaporation.~~. In addition, during ~~the~~ AR events~~,~~ the Atlantic subtropical source is reinforced and displaced, with a slight northward movement of the ~~moisture~~ sources~~ is~~ found when the sink region is positioned at higher latitudes. In conclusion, the results confirm the anomalous advection of moisture linked to ARs from subtropical ocean areas, but also the existence of a tropical ~~one, and the~~source, together with mid-latitude anomaly sources ~~further the analysed longitude along the North Atlantic is located eastward~~at some locations closer to AR landfalls.

1 Introduction

Atmospheric ~~rivers~~Rivers (ARs) are relatively narrow ~~(~500Km~~(on average ~500 Km) pathways of water vapour (WV) transport that can extend for thousands of kilometres~~ and~~, **contain large amounts of WV**, and are often accompanied by strong winds (Zhu and Newell, 1998; Ralph et al., 2004). According to several authors (Ralph et al. ~~(~~2004; 2005), ~~AR~~their properties include a ~~concentred~~concentrated band of enhanced WV in the~~-~~ lower troposphere and a pre-cold frontal low level jet (LLJ) due to the temperature gradient across the cold front~~.~~ (Neiman et al., 2008; Ralph et al. 2004; Ralph et al. 2005).

The attribution of the terms 'atmospheric river' or 'tropospheric ~~rivers rose~~river' and their genesis caused some debate ~~by Wernli (1997) and Bao et al. (2006).~~in the scientific community. Recently, ~~an~~some agreement has ~~moved~~been achieved (Dettinger et al., 2015) regarding the relationships ~~among~~between ARs, warm conveyor belts (WCBs), and tropical moisture exports (TMEs). The term WCB refers to the zone of dynamically uplifted heat and vapour transport close to a mid-latitude cyclone. This vapour is often transported to the WCB by an AR, and the result of the uplift is heavy rainfall that generally marks the downwind end of an AR, provided that the AR has not experienced orographic uplift (upslope flow), accompanied by rainout over mountains earlier on its approach to the WCB. TMEs are zones of intense vapour transport out of the tropics, vapour that is frequently conducted by ARs ~~toward~~towards cyclones and WCBs. TMEs can provide important vapour sources for ARs, but most ARs also incorporate mid-latitude sources and convergences of vapour along their paths (Dettinger et al., ~~2015~~2015; Sodemann and Stohl, 2013). In addition, the role of ARs in explosive cyclogenesis over the North Atlantic Ocean has been shown for three extra-tropical cyclones (Klaus; Gong and Stephanie), all of which had major socio-economic impacts in parts of Europe (Ferreira et al., 2016).

~~The detection of ARs can be achieved adopting two considerably different approaches, namely: a) using integrated column water vapor (IWV) (e.g. Ralph et al., 2004; Ralph and Dettinger, 2011), and b) based on the use of the vertically integrated horizontal water vapor transport (IVT) (e.g. Zhu and Newell, 1998; Lavers et al., 2012; Ramos et al., 2015).~~

The importance of ARs in extreme precipitation events and floods has been analysed in detail for the ~~U.S.~~ west coast of the USA (particularly for ~~the~~ California) over the last decade (e.g~~.~~., Dettinger et al., 2011; Neiman et al., 2008; Ralph et al., 2004; Ralph et al., 2013).~~ In~~

For Europe, Lavers and Villarini (2013) showed that ARs are responsible for many annual maximum precipitation days in Western Europe, ~~ARs have been recently studied from a~~

~~climatological point of view for~~ with the relationship being stronger along the western European seaboard, and with some areas having up to eight of their top 10 annual maxima related to ARs. It was also shown that 40-80% of winter floods in the UK are associated with persistent ARs and that that these ARs are critical in explaining the 10 largest winter flood events in a range of British rivers basins since 1970 (Lavers et al., 2011; Lavers et al., 2012~~) and for~~). For the Iberian Peninsula~~ where~~, Ramos et al. (2015) ~~studied its relationship with~~ showed that ARs play an overwhelming role in most extreme precipitation~~.~~ days, decreasing in importance for less extreme precipitation days. Moreover, over the North Atlantic Ocean and for the island of Madeira, in particular, the association between extreme precipitation and ARs was also established (Couto et al., 2012; Couto et al., 2015).

In addition, the importance of ARs in a few particular cases of extreme precipitation in Europe has also been analysed ~~(Liberato et al., 2012; Stohl et al., 2008) including some important historical cases (e.g. Trigo et al., 2014).~~in some detail. Liberato et al. (2012) discussed an extreme precipitation event associated with an AR occurring in the city of Lisbon, Portugal, in November 1983, which produced flash flooding, urban inundations, and landslides causing considerable damage to infrastructure and human fatalities. On the Norwegian southwest coast, an extreme precipitation event occurred in September 2005 and was also shown to be directly linked with an AR (Stohl et al., 2008). More recently, Trigo et al. (2014) considered the record precipitation and flood event in the Iberia Peninsula of December 1876 and highlighted the importance of ARs in this historical event.

The association between ARs and modes of low frequency variability has already been addressed, with the Scandinavian pattern having a negative correlation with the occurrence of ARs in Britain (Lavers et al., 2012), while it is the North Atlantic Oscillation that controls their occurrence to a certain extent in the rest of Europe (Lavers and Villarini, 2013). In addition, Ramos et al. (2015) showed that for the particular case of the Iberian Peninsula, the East Atlantic pattern also plays a major role in explaining the annual variability of ARs.

The increasing attention to the ~~AR~~ topic of ARs is confirmed by the publication of two recent reviews, with Ralph and Dettinger (2011) ~~putting emphasis on~~emphasising the multiple ~~analyses produced for the~~ studies of ARs striking the western coast of the USA, while Gimeno et al. (2014) ~~have~~ focused on the structure, methods ~~for~~of detection, impacts, and dynamics of ARs.

Bao et al. (2006) ~~proposes~~suggested that the moisture present in ~~the~~ ARs has two main origins~~:~~, namely local moisture convergence along the front of extra-tropical cyclones, and direct poleward transport of tropical moisture, suggesting that ~~the ARs~~they play an important role in the water cycle, especially in transporting moisture from the tropics to the mid and high latitudes. In this context Dacre et al. (2015~~), has~~) analysed selected cases of the transport of water vapour within a climatology of wintertime North Atlantic extra-tropical cyclone. ~~It is discussed~~In this particular study, the possibility was discussed that ARs are formed by the cold front that sweeps up water vapour in the warm sector as it catches up with the warm front. This causes a narrow band of high water vapour content to form ahead of the cold front at the base of the warm conveyor belt airflow. Thus, according to Dacre ~~and colleagues,~~et al. (2015), water vapour in the ~~cyclone's~~ warm sector~~, not~~ of the cyclone, rather than long-distance transport of water vapour from the subtropics, is responsible for the generation of ARs. According to Dettinger et al. (2015) it seems that a combination of the two points of view are valid because TMEs can provide important vapour sources for ARs, but most ARs also incorporate mid-latitude sources and convergences of vapour along their paths.

To the best of our knowledge ~~works~~studies dealing with moisture ~~transport and~~ sources from a Lagrangian point of view along the paths of ARs are ~~scares~~scarce and ~~were~~have only ~~done mainly~~been developed for selected case studies. For instance, Moore et al. (2012) used Lagrangian trajectories associated with heavy flooding rainfall in Nashville (USA) to analyse ~~if they~~whether these were connected with ~~ARs~~AR events~~.~~, while Ryoo et at. (2015) analysed the transport pathways of water vapour associated with AR events that made landfall along the West Coast of the USA between 1997 and 2010. In addition, Rutz et al. (2015) analysed the evolution of ARs over western North America using trajectories released at 950 and 700 hPa within ARs along the Pacific coast. In this case a forward mode was used to study the inland penetration of ARs.

For Europe, Stohl et al. (2008) ~~studied~~investigated the remote sources of water vapour forming precipitation ~~on the Norwegian~~in Norway and their link with ARs ~~on~~over a 5~~-~~-year period. Liberato et al. (2012) showed that the evaporative sources for precipitation falling over Lisbon area, in Portugal, on the heaviest precipitation event occurring there during the twentieth century were distributed over large sectors of the tropical-subtropical North Atlantic Ocean and included a significant contribution from the (sub)tropics. Moreover, Sodemann and Stohl (2013) analysed the origins of moisture ~~origin~~ and meridional transport in ARs and their association with multiple cyclones ~~for~~in December 2006. Finally, Knippertz and Wernli (2010~~), present~~) presented a Lagrangian climatology of tropical moisture exports to the Northern

Hemispheric extra-tropics by analysing forward trajectories leaving a box between 0º and 20ºN ~~spanning from~~for 1979-2001.

These ~~researches base~~researchers based their ~~result~~results on the use of Lagrangian models, which ~~are able~~allow to ~~model~~study the evolution of ~~the~~ moisture in the atmosphere along ~~several~~a number of trajectories. The use of Lagrangian models such as~~,~~ FLEXPART (Stohl et al., 1998~~),~~) can help us to assess the main sources of moisture and its transport within ~~the~~ ARs. This Lagrangian model allows ~~following~~us to follow the moisture that reaches a specific region, more specifically ~~is~~making it possible to ~~know~~track changes in the specific humidity along the trajectories ~~in~~over time. ~~Knowing~~By knowing the specific ~~moisture~~humidity (q) ~~in~~at every time step it is possible identify ~~the~~those particles that ~~loose~~lose moisture through precipitation (p), or receive it through evaporation (e). FLEXPART can "transport" ~~the~~these particles ~~backward~~backwards or ~~forward~~forwards in time using a 3D wind field. The ~~account~~record of evaporation minus precipitation ~~permits knowing~~(e-p) provides information on the sources ~~of moisture~~ (when evaporation ~~is higher than~~exceeds precipitation) and sinks (~~contrary case).~~when precipitation exceeds evaporation) of moisture.

The Lagrangian methodology of identifying moisture ~~source~~sources based on FLEXPART has been extensively used ~~in~~over the ~~last~~past decade ~~for~~ both for regional ~~studies~~ (e.g~~.~~., Nieto et al., 2006) and global ~~ones~~studies (Gimeno et al., 2010a). The comprehensive review by Gimeno et al. (2012) provides details of the uncertainty and significance of this Lagrangian approach, as well as a comparison with other methods of estimating moisture sources, and the original paper by Stohl et al. (2004) provides further information on the FLEXPART model.

Here we are mainly interested in analysing the backward trajectories that arrive in the various regions along the Atlantic coast of Europe where ARs make ~~their~~ landfall. The objectives of this work are~~ twofold~~: 1) to identify the ARs affecting the western European coast between 1979-2012 during the winter half-year (ONDJFM) and, 2) to provide a comprehensive analysis of ~~AR moisture sources and transport in the winter half-year over the different European domains.~~ the areas where the AR moisture uptake is anomalous over the same period for the ARs that reach the different European domains. The added value of the manuscript is mainly twofold: a) firstly the current study is the first to analyse those areas where the moisture uptake is anomalous for the ARs that reach the European coast from a climatological perspective; b) secondly we have made refinements to the AR tracking method introduced by Lavers et al. (2012). In the present version, we use 3 reference meridians rather than a single fixed one for the whole of Western Europe to have a higher accuracy on landfall times and locations (see

Sect. 2.1). This is of the utmost importance for analysing the anomaly for the moisture uptake for the ARs based on the use of (E-P), because just a few degrees of difference in the reference meridian longitude may translate into an erroneous detection for any anomalous moisture sources.

The work is ~~organized~~organised as follows: ~~in Sect. 2~~we present the datasets and the different methodologies ~~are presented~~ in Sect. 2 while in Sect. 3 ~~analyses the~~we analyse ARs that reach landfall in Europe. The ~~ARs~~ detection of those areas where the moisture ~~transport~~uptake is anomalous for ~~the~~ ARs that reach Europe is analysed in Sect. 4. Finally ~~the~~, our conclusions are presented in Sect. 5.

2 Methods and Datasets

2.1 Atmospheric River detection

The detection of ARs can be achieved by adopting two very different approaches, namely a) using integrated column water vapour (IWV) (e.g., Ralph et al., 2004; Ralph and Dettinger, 2011), and b) based on vertically integrated horizontal water vapour transport (IVT) (e.g., Zhu and Newell, 1998; Lavers et al., ~~We~~2012; Ramos et al., 2015). The choice of either of these two approaches is perfectly valid, and will depend on the purpose and location of the study.

In this case we have used the ERA-Interim reanalysis (Dee et al., 2011) with a 0.75º latitude-longitude grid resolution, spanning from 1979-2012 for the winter half-year (October to March ~~(~~, ONDJFM) for the detection of ~~the~~ ARs. The variables used at ~~a~~ 6-h time steps were ~~:~~ the specific humidity ~~(*q*),~~, as well as zonal ~~(u)~~ and meridional ~~(v)~~ winds at the 1000, 925, 850, 700, 600, 500, 400 and ~~300hPa~~300 hPa levels ~~since~~, given that most of the moisture ~~are~~transport is accounted for in these levels.

The ~~ARs~~AR detection scheme employed (Lavers et al., 2012; Ramos et al., 2015) depends entirely on the vertically integrated horizontal water vapour transport (IVT) and was computed between the 1000 and the ~~300hPa~~300 hPa levels (equation 1):

$$IVT = \sqrt{\left(\frac{1}{g}\int_{1000hPa}^{300hPa} qudp\right)^2 + \left(\frac{1}{g}\int_{1000hPa}^{300hPa} qvdp\right)^2}, \qquad (1)$$

where q is the specific humidity, u and v are the zonal and meridional layer averaged wind respectively, while dp is the pressure difference between two adjacent levels. ~~Finally,~~ g ~~is~~denotes the acceleration due to gravity.

The identification of ~~the~~ ARs ~~was~~is similar to that performed ~~as in~~by Lavers and Villarini (2013) for Europe and Ramos et al. (2015~~), but considering~~) for the Iberian Peninsula, and considers only one reference meridian for the computation of the ARs. In this case we have used three distinct ~~meridian~~ reference ~~domains~~meridians (Fig. ~~1a) centred respectively~~ 1) located at~~:~~ 9.75ºW (meridian 1, just west of both the Iberian Peninsula and Ireland), 4.50ºW (meridian 2, located west of the UK and France~~)~~), and 5.25ºE (meridian 3, west of Scandinavia). Each different reference meridian~~-domain~~ (Fig. ~~1a~~1) was further divided into 10º latitudinal sections between 35ºN and 75ºN for the 9.~~75W~~75°W and 4.50ºW reference meridians, and between 50ºN and 70ºN for the ~~Scandinavia domain (~~5.25ºE~~)~~ reference meridian, to allow for ~~different~~ differences in IVT depending on latitude~~-dependent IVT~~.

The value for the highest IVT and its respective latitude (IVT threshold~~,~~) for ~~the 9.75ºW~~each meridian~~-domain,~~ was computed ~~by taking~~as follows: we extracted the ~~daily~~ maximum IVT at 1200UTC each day for the entire period between 35ºN and 75ºN (~~over~~for the 9.~~75W) at 1200UTC on each day~~75ºW and 4.50°W meridians) and between ~~1979-2012 and binned it~~50ºN and 70ºN (for the 5.25ºE meridian) and sorted these into 10º latitude ~~sectors~~bins. Following the approach adopted in Lavers et al. ~~(2012)~~(2013), the threshold chosen for each bin corresponds to the 85th percentile of the ~~IVT in each latitude sector was used as the threshold value of the AR identification, since this percentile was associated with the most intense ARs. For the other meridian domains a similar procedure was adopted with the~~ maximum IVT values included in that bin. The derived thresholds for the different ~~domains~~reference meridians and sectors ~~summarized~~are summarised in Table 1.

~~With~~Having computed the ~~distinct~~different thresholds ~~computed for the different domains~~for each reference meridian the following detection scheme was applied for each sector:

a) at each 6-h time step of the dataset (each day has 4 time steps) between 1979 and 2012 over the winter half-year, we -compared the IVT values at the grid points for each ~~different domain~~reference meridian and extracted the maximum IVT value and its location;

b) ~~if~~where the maximum IVT exceeded the local IVT threshold (which depends on both longitude and latitude and was computed for each meridian reference bin [Table 1~~),~~]), this particular grid point was highlighted. We then performed a ~~backward/forward~~west/east search to identify the maximum IVT at each longitude and tracked the location for the grid points where the local IVT threshold was exceeded. However, ARs ~~must~~have to extend ~~over 1500km~~for at least 1500 km, therefore a minimum length threshold was also imposed. ~~This condition is checked every 6 hours and we considered it an AR time step when it is fulfilled.~~ In this case, it ~~corresponds~~corresponded to 30 contiguous longitude points (30*0.75º=~~20~~22.25º~1600 km, considering that at ~~55~~50°N the length of a degree of longitude is ~71km~~);~~) Provided that this condition was fulfilled for a particular time step we considered it to be an AR time step;

c) ~~with~~because we applied the same procedure to all time steps, we obtained all the AR time steps identified for the different ~~domains,~~reference meridians, but only ~~the~~ persistent AR events ~~will be~~were retained. For a persistent AR event to occur (Lavers and Villarini 2013; Ramos et al., 2015) a ~~minimum~~ temporal ~~criteria must be fulfilled:~~ criterion was applied in that 1) it ~~must have~~ required a persistence of at least 18h ~~persistence~~ (three continuous time steps~~)~~), and 2) to be independent, ~~that is~~ two persistent ARs were considered distinct only ~~if~~when they were separated by more than 1 day (four time steps). A spatial criterion was also applied: a movement of not more than 4.5º latitude to the north or south of the initial IVT maximum in a 18h period.

~~The number of persistent ARs identified for each domain is summarized in Table 1 (last column) and will be discussed in Sect. 3.~~

~~**2.2 Lagrangian moisture transport**~~

The number of persistent ARs identified for each reference meridian is summarised in Table 1 (last column) and will be discussed in Sect. 3. Given that we are particularly interested in those ARs that have impacts over land we reorganised the previously computed ARs (Fig. 1 and Table 1) into the following 5 new domains shown in Fig. 1 using different coloured solid lines and identified as: 1) *Iberian Peninsula* (red, 9.75ºW; 36ºN – 43.75ºN); 2) *France* (blue, 4.5ºW; 43.75ºN – 50ºN); 3) *UK* (green, 4.5ºW; 50ºN-59ºN); 4) *Southern Scandinavia and the Netherlands* (yellow, 5.25ºE; 50ºN-59ºN) and 5) *Northern Scandinavia* (purple, 5.25ºE; 59ºN – 70ºN). This allows us to use contiguous domains from 36ºN to 70ºN, with domains 3) and 4) only differing in terms of the meridional reference while maintaining the same latitudinal division. This new division will be very helpful in Sect. 4 where the study of the anomalous moisture uptake for ARs will be analysed in greater detail, given that the specific location at which the ARs make landfall is of the utmost importance.

2.2 Lagrangian moisture quantification

The method developed by Stohl and James (2004) ~~was used in this work which~~ allows ~~tracking~~us to track the atmospheric moisture along Lagrangian trajectories of air parcels in the atmosphere~~. The Lagrangian dataset used, come from a Lagrangian model~~ using the FLEXPART v9.0 ~~global simulation from 1979 to 2012, in which the atmosphere was divided into~~ Lagrangian model. This model simulates the movement of approximately 2.0 million atmospheric parcels~~, and it~~ every 3 hours. Our global simulation was forced ~~by the 1º latitude-longitude grid~~using data ERA-Interim reanalysis data (Dee et al~~.~~., 2011) ~~available every 3 hours. The output of the FLEXPART simulation, consist in four daily outputs (at times 0000, 0600, 1200 and 1800 UTC).~~

~~The Lagrangian mentioned method divides the atmosphere homogeneously into a large amount of~~from 1979 to 2012. At each initial time this Lagrangian model distributes the air parcels (also namely particles~~), where each one represents a fraction of the total atmospheric~~) homogeneously to cover the largest possible volume, always taking the distribution of mass~~.~~ in the atmosphere into account. The FLEXPART model imposes a condition on the mass, which must be constant. The mass takes into account the volume and the density of the air. We use 61 levels in the atmosphere, from 1000 to 0.1 hPa, so the volume of the air parcel varies in accordance with the level concerned: a volume is thus smaller near the surface and larger higher up because the air density is greater near the surface and lower at high altitudes. These particles are then ~~advected~~moved using the reanalysis wind field~~ while the other~~, and in addition turbulence and convection parametrizations are taken in account, always maintaining the consistency of the atmospheric mass distribution (Stohl et al., 1998; Stohl et al., 2005). The meteorological properties of the air ~~parcel (e.g.~~parcels, such as specific humidity ~~and~~or temperature~~)~~ among many others, are ~~also processed by~~retained in the outputs of the FLEXPART model~~.~~, taking into account the ERA-Interim reanalysis input.

The changes ~~on the~~in specific ~~moisture~~humidity (dq) of a particle (with mass m) ~~along the~~over time (dt) during its trajectory can be expressed as (equation 2):

$$e - p = m\frac{dq}{dt}, \qquad (2)$$

where (e-p) can be inferred as the freshwater flux in the parcel (the difference ~~of~~between evaporation and precipitation). ~~Each particle is tracked backwards for a transport time of 10 days because that is the average residence time of water vapour in the atmosphere (Numaguti, 1999).~~

The moisture changes (e-p) of all ~~of~~ the particles in the atmospheric column over a specified area (A) ~~gives~~yields the surface freshwater flux (E-P), where E is the evaporation rate per unit area, and P is the precipitation rate per unit area (equation 3):

$$E - P \approx \frac{\sum_{k=1}^{K}(e-p)}{A}, \qquad (3)$$

where K is the total number of particles in the atmospheric column ~~(~2 million in our experiment~~. Each particle is tracked backwards for a transport time of 10 days, this being the average residence time of water vapour in the atmosphere (Numaguti, 1999).

The different areas where the ARs make landfall ~~will be~~are discussed in Sect. 3, while the selection of each ~~domains~~European domain where the particles ~~will be~~are selected for the ~~backwards~~backward trajectories (E-P) analyses ~~is going to~~will be discussed in Sect. 4.

3 Landfall of atmospheric rivers in Europe

~~Following the application of the various steps of the method explained in the previous Sect. 2, for all the different domains, the IVT threshold and the~~ The number of ARs ~~considered~~ for each domain is ~~summarized~~summarised in Table 1. There were 271 ARs ~~over the Iberian Peninsula/Ireland domains~~for reference meridian 1, with a maximum of 87 ARs ~~on~~in the ~~45ºN~~45º-55ºN sector; for ~~the UK/France domain~~reference meridian 2 the total number is 351, with ~~the~~a maximum of 98 ARs observed at ~~the~~ latitudes between 55ºN and 65ºN. In the case of ~~Scandinavia,~~reference meridian 3 and ~~since~~given that the ARs come from the Atlantic region, we ~~chose to divide~~divided the ~~domain in~~reference meridian into two sectors (50ºN to 60ºN and 60ºN to 70ºN), with the maximum number of ARs being recorded ~~at~~in the 50ºN-60ºN sectors (100 ARs). The IVT threshold has a maximum around 45ºN and 55ºN for the reference meridians, in good agreement with the results obtained by Lavers and Villarini (2013) near 10ºW. In addition, this maximum is also confirmed by the analysis of the seasonal IVT mean fields, where a maximum is present between 45ºN and 55ºN (not shown).

~~This first~~ The number of ARs and the corresponding AR time steps for each new domain are shown in Table 2 and will be analysed in detail in Sect. 4. This varies from 21 ARs (117 time steps) in the Iberian Peninsula domain up to 140 ARs (665 time steps) in the France domain.

This assessment of ARs for the different ~~domains~~reference meridians confirms the ~~results in~~findings of Lavers and Villarini (2013~~), namely~~) that the ARs also strike ~~other~~ regions of

Europe ~~and not only~~other than the Iberian Peninsula (Ramos et al., 2015) or the UK (Lavers et al., 2011). In ~~any case~~this regard, we are confident that the use of three different meridians of control (9.75ºW, 4.5ºW and 5.25ºE) provides a ~~finer~~more precise and ~~more~~ robust assessment of all the ARs that make landfall in Europe. ~~This will be very helpful in Sect. 4 where the study of the ARs~~

While it can be argued that the overall frequency of ARs is rather low, in fact we are particularly interested in analysing tracking and the anomalous moisture ~~transport will be analysed in detail, since the specific location where the ARs made landfall is of~~ sources for the most intense ARs, i.e., those ARs that are often associated with extreme precipitation events. It has been shown that a large proportion of the most intense precipitation events (and of course their associated floods) in Western Europe are objectively associated with the occurrence of ARs, both in the UK (Lavers et al., 2013) and in the Iberian Peninsula (Ramos et al., 2015). In particular, Lavers and Villarini (2013) showed in their Fig. 3 the number of Top 10 Annual maximum events related to ARs. It is immediately striking that some areas of the Iberian Peninsula, France, UK, and Norway have up to 6 out of 10 top annual maxima associated with ARs. In addition, Ramos et al. (2015) for the Iberian Peninsula showed that ARs play an overwhelming role in the most extreme precipitation days but these decrease in importance~~.~~ ~~Taking this into account, and since the we~~ for less extreme precipitation days.

The refinements made to the detection scheme for ARs (in the use of three reference meridians regrouped into five sub-domains in terms of their geographical relevance) as introduced by Lavers et al. (2012), were ~~particularly interested in the ARs that have impacts over land we havere-orgazined the ARs previously~~intended to improve AR detection and allow us to obtain more precise locations for AR landfalls. To analyse whether these refinements actually improve AR detection, the number of Top 10 annual maxima precipitation events (for the extended winter months, i.e., ONDJFM) related to ARs were computed ~~(Fig. 1a and Table 1) into the following new 5 domains (~~. To this end, the annual maxima were computed for each calendar year (only for the extended winter months) from 1979 to 2012 at each grid point (E-OBS, at 0.25º resolution, Haylock et al., 2008). The results obtained (supplementary material Fig. ~~1b), identified: 1) *Iberian Peninsula* (9.75ºW; 36ºN – 43.75ºN); 2) *France* (4.5ºW; 43.75ºN – 50ºN); 3) *UK* (4.5ºW; 50ºN-59ºN); 4) *Southern Scandinavia and The Netherlands* (5.25ºE; 50ºN-59ºN) and 5) *Northern Scandinavia* (5.25ºE; 59ºN – 70ºN). This allows having contiguous domains from 36ºN to 70ºN, with domains 3) and 4) only changing the meridional reference maintaining the latitudinal division. An analysis in Table 2, shows the number of ARs~~

and the correspondent ARs times steps for each new domain that will be analysed in detailed in Sect. 4. This varies from 21 ARs (117 time steps) in the Iberian Peninsula domain and the 140 ARs (665 time steps) in the France domainS1) show that there is an improvement in the relationship between ARs and annual maxima for France, Belgium, Germany and the Scandinavian countries compared to the results of Lavers and Villarini (2013), in their Fig. 3.

The IVT threshold has a maximum around the 45ºN and 55ºN for all meridian domains which is in good agreement with the results obtain by Lavers and Villarini (2013) near to 10ºW. In addition, this maximum is also confirmed by the analysis of the seasonal IVT mean fields, where a maximum between 45ºN and 55ºN is present (not shown).

In order to have the perception of track the path of the ARs, we have computed the maximum longitudinal IVT for each ARsAR, in order to have a first guessobtain a preliminary estimate of the position of the ARs alongin the North Atlantic Ocean. For everyeach new domain, we have computed the median, 90th percentile, and 10th percentile of the maximum IVT positions of the different ARs along their first--guess trajectories and the results are presented in Fig. 2. The use of the 90th and 10th percentilepercentiles allows oneus to visualizevisualise the spread inof the positions of the vast majority of the ARs alongthroughout the North Atlantic basin associated towith each domain.

Regarding the Iberian Peninsula (Fig. 2a), the median position of the ARs is mainly zonal, with a small NWWSW component, while thetheir spatial dispersion is quite high, especiallyparticularly as we move away from the landfall area. This NWWSW component is in line with the results obtainobtained by Ramos et al. (2015), where a positive anomaly of Sea Level Pressure is found to the south of Portugal when the ARs make landfall in the Iberian Peninsula.

In the cases of France and the UK (Fig. 2b), the paths and dispersions are similar with respect to the median path of the ARs, especially on the EastEastern North Atlantic domain. The main differences are closer to the two domains, namely: 1) a more zonal path associated towith the France domain, while for the UK its path near the reference meridian is clearly more SW-NE oriented, and 2) the dispersion of the ARs path areAR paths is higher infor the UK domain then inthan for the France onedomain, particularly to the west of 40ºW. The results for the UK confirm those obtained by Lavers et al. (2011) but), although here we have used the full climatology whilewhere Lavers et al. (2011) only analysed the ARs path ofAR paths for selected cases. Concerning the last two domains (Fig. 2c), the results are very similar with the onesto those obtained for the France and UK domains, i.e.., most ARs show a strong SW-NE orientation, particularly to the east of 40ºW ~~particularly~~ for ~~the~~those ARs that arrive in the north Scandinavian domain. In addition, the dispersion of the paths in these two domains is relatively ~~higher than for~~high compared with the other three domains.

These five new domains (Fig. ~~1a~~1) are ~~the ones~~those that will be used in the computation of the ~~ARs~~ moisture transport for the ARs that make landfall over the western coasts of the European domains analysed ~~Europe domains~~.

4 Atmospheric rivers and anomalous moisture ~~transport~~uptake

~~The use of the FLEXPART simulations and the computation of the E-P, intends to find the origin of the moisture associated with the ARs reaching the Atlantic European coast. As we are interested in the effective moisture sources the analysis is restricted to areas where evaporation exceeds precipitation, i.e. (E-P)>0 clearly depicted in colour in Figs. 3 and 4.~~

~~The E-P~~The use of the integrated horizontal flux transport (IVT) is an effective Eulerian approach for studying the temporal variability of moisture flows for specific locations around the globe, and is therefore widely used in the identification of ARs. However, this Eulerian perspective is not suitable for finding sources of moisture, and of course it is impossible to use it compute where the uptake of moisture to the AR is, given that the method is not able to follow any specific "particle" transported by the ARs. To illustrate the difference between the use of the IVT and the information that can be extracted from FLEXPART, we provide in Fig.3 an example of a particular AR that occurred on 14 December 1981 at 00UTC, which reached the Iberian Peninsula. Fig. 3a shows the sources of moisture (E-P)>0 computed for 10 days back in time (reddish colours). Three areas clearly emerge as sources: one located to the west of the Iberian Peninsula near the coast, and two larger ones located in the central and western Atlantic. In Fig. 3b we show the IVT field for the same day and the maximum edge of the IVT denoted by a black line and used in this study to detect ARs, together with a red contour delimiting the sources of moisture in Fig 3a. It can clearly be seen that the moisture sources and the IVT maximum are not coincident. When we analyse either the IVT maximum or the IVT field, we only reveal a snapshot of the integrated horizontal flux transport for that specific time-step, and not the path of the air masses. This indicates neither where the moisture comes from, nor where the moisture uptake is anomalous during the previous days of the AR, which is one of the objectives of this analysis.

The use of Lagrangian models such as FLEXPART allows us to study air parcels as they move through space and time, i.e., their trajectory, and also allows us to characterise accurately the history of the air parcels (e.g., their specific humidity) that arrive at a specific site. The use of Lagrangian models was shown to be a worthwhile and important tool for analysing the moisture sources in a case study of ARs in Norway (Stohl et al., 2008) and in Portugal (Liberato et al. 2012). In the latter case the methodology has been applied over different accumulated periods (for 1 to 3, 3 to 5 and 5 to 10 days) allowing also to identify the relative importance of the several moisture sources contribution over time. Our use of FLEXPART simulations and the computation of (E-P) is intended to help us locate the origin of the anomalous moisture uptake associated with ARs reaching the Atlantic European coast for all the systems detected and from a climatological point of view. It is important to note that an AR transports a large amount of moisture that often reaches a continental area. This moisture must necessarily be available for transport in the atmosphere. Therefore, it must be evaporated and accumulated in certain areas during the days prior to the intense track of the AR. The existence of an intense flux is important but not sufficient, in that an intense anomalous quantity of moisture must be available for the AR to occur. Therefore, in this research we detect (for the 10 days prior to the AR reaching landfall) where the moisture uptake to the atmosphere is anomalous.

The backward ~~trajectories analysis~~trajectory analyses were performed for air particles residing over the ~~western~~area 5~~ degrees from~~° to the ~~ARs~~west of the AR detection meridian reference (Table 3): e.g~~.~~., for the Iberian Peninsula region it ~~includes~~included particles located inside a rectangle (~~spreading~~covering an area between 9.75ºW and 4.75ºW and from 36ºN to 43.75ºN) ~~on a 6-hourly basis.~~and tracked backwards for 10 days at 6-hour intervals (a total of 40 time steps).

We computed the uptake of moisture for all individual ARs at all time steps, retaining only positive values of (E-P) every 6 hours during the 10-day back trajectories (40 time steps). For instance, there are 117 cases for the Iberian Peninsula, so we computed 117 fields of (E-P)>0, and the same for the other domains. To check whether these areas (where the ARs take on moisture) differ from the climatology, we computed for each AR the anomaly between (E-P)>0 of the ARs and the 'climatology' for the corresponding AR dates. The 'climatology' at this point corresponded to the same (Julian) time step but for all 33 years of the study (retaining again only the positive values of (E-P) for each 6-h time step). For the example given in Fig. 3, if an AR existed on 14 December 1981 00UTC, we computed the anomaly between a) (E-P>0) on 14 December 1981 00UTC and b) (E-P)>0 for all time steps of 14 December 00UTC, in other words, (E-P)>0 for the corresponding day for the 33 years of the entire period. We then computed the anomaly for this particular case (14 December 1981 00UTC) using the difference between b) and a). The climatology and the anomaly for each domain, ~~two very different E-P computations were performed: a) the E-P climatological~~ denoted by (E-P)$_{Cli}$ ~~computation for each Julian day where an AR occurs, and b) the E-P composite (E-P)$_{AR}$ for all the AR days. In addition, the E-P anomaly~~ >0 and (E-P)$_{An}$ ~~was also computed by simply obtaining the difference between (E-P$_{AR}$) - (E-P$_{Cli}$). A comprehensive~~>0 in Fig.4, corresponds to the mean values for all the respective ARs. A representation of the fields of (E-P)$_{Cli}$>0 and (E-P)$_{An}$~~,~~>0 for all the five ~~studied~~ regions studied is provided in Fig.~~3~~4 (left panel) and Fig.~~3~~4 (right panel), respectively. Moreover, the anomalous moisture of the sources are only shown for the areas that are statistically significant at the 90% level, applying a T-student test to the (E-P)>0 for all the ARs and the climatology (Table 4). In general, for all ~~the~~ regions~~,~~ the major ~~climatological source~~anomalous uptake of moisture (hereafter AUM) extends along the subtropical north Atlantic (from the Tropic of Cancer to ~~35N~~35°N according to the definition of the American Meteorological ~~Society' definition~~Society), from the Gulf Stream Current, just off the Florida Peninsula (~~northward~~to the north of 20ºN), to each sink region, being ~~farther southward~~further to the south (clearly subtropical) on the ~~west~~western basin of the North Atlantic Ocean and reaching extra-tropical latitudes on the ~~east~~eastern basin coast. Moreover, the nearest coast to each sink region ~~is~~ always ~~appearing~~appears as a local maximum of ~~evaporation;~~AUM (e.g~~.~~., see the southern Iberian Peninsula coast or the Bay of Biscay ~~Gulf for~~in France). The Norwegian Sea acts as a more important ~~source as~~AUM because the region analysed is located at higher latitudes, ~~reaching~~and is a maximum for the north Scandinavia region.

The distribution of the particle density used to compute the AUM (using a 5º by 5º grid cell) for each domain was also computed. In the supplementary material Fig. S2 shows how many times a parcel (in percentage terms) contributes to the (E-P)$_{An}$>0 field. In addition, one must be aware that the areas of maximum density of the parcels may (or may not) correspond to areas of maximum anomalies and *vice versa*, because a grid cell can contribute many times but its AUM contribution could be less than that of others with a lower AUM density.

The importance of the North Atlantic Ocean as a source of moisture for some regions of Europe has already been ~~noticed~~noted in previous ~~works~~studies. In a complete moisture source catalogue for important climate regions, Castillo et al. (2014) showed that for Southern Europe (including our Iberian Peninsula and France ~~regions~~domains) and ~~the~~ Northern Europe (UK, Southern Scandinavia and ~~The~~the Netherlands, and Northern Scandinavia~~)~~)), the dominant source of moisture is the Northern Atlantic, with a strong signal over the Norwegian Sea when northern continental areas were ~~analyzed~~analysed. Studies focused on specific regions also found similar results, for instance Gimeno et al. (2010b) and Drumond et al. (2011) for the Iberian Peninsula, or studies ~~done over~~of European regions at higher latitudes (Nieto et al., 2007; Sodemann et al., 2008) revealed the importance of the Atlantic source. Interestingly, in almost all ~~of~~ these studies the authors ~~point~~pointed to the effects of ~~the atmospheric rivers~~ARs as the major moisture transport mechanism from the subtropical Atlantic. In this work, the key novelty is that we show those regions where the moisture uptake is anomalous and significant when an AR occurs.

We are particularly interested in understanding which ~~moisture source~~ regions with higher AUM (depicted in Fig. ~~3~~4 left panel) are reinforced during ARs associated ~~to~~with each of the five different ~~regions. This~~domains. These reinforced sectors are identified in yellowish and reddish ~~colour~~colours in maps of $(E-P)_{An}$ (Fig. ~~3~~4, right panel). Overall, the largest anomalies are detected in the middle of the Northern Atlantic, between 20ºN and 40ºN, with a ~~light~~slight northward movement when the sink region is positioned at higher latitudes. ~~The~~These results confirm that part of the excess of moisture transported by ARs vs the climatology comes from tropical latitudes (~~under~~south of the Tropic of Cancer~~ line~~, 23.~~26ºN~~43ºN), but the bulk of the additional amount provided by the ARs is obtained from subtropical ocean areas (i.e~~.~~., those between the Tropic of Cancer and 35ºN). The most notable anomaly ~~in the evaporation~~ is detected for the Iberian Peninsula, followed by ~~the~~ Southern Scandinavia and ~~The Netherland region~~the Netherlands domain, and the lowest is for the Northern Scandinavia ~~region~~domain. Each ~~region~~domain shows differences in values of $(E-P)_{An}>0$ in both latitude and longitude. To understand ~~better~~ these patterns rather better we ~~quantify~~quantified the anomaly values ~~at different longitudes~~every 10° between 70ºN ~~to~~and 5ºN and ~~from~~between 10ºW ~~to~~and 60ºW ~~every 10 degrees.~~ .

Fig. ~~4~~5 shows the different latitudinal sections for all the studied regions, in which values over the 90th percentile of the anomaly (Table 4) are highlighted ~~as~~using a bold line. We~~ will~~ refer to these values to compare the five ~~areas~~domains of study. ~~The displacement to the south~~In general, there is a longitudinal southern shift of the anomaly~~ with the longitude~~, which is a common feature for all the regions~~, being the longitudinal slope higher with the latitude of the sink region.~~. So~~,~~ for instance, for~~ the~~ Northern Scandinavia (purple line) the anomalous uptake of moisture at 10ºW occurs mostly between 60-48ºN, while at 60ºW it occurs predominantly between 40-30ºN; whereas for the Iberian Peninsula (IP, red line) at 10ºW the anomalous uptake occurs mainly in a band between 43-33ºN, and at 60ºW it is particularly intense between 36-21ºN. The Iberian Peninsula shows the highest values of ~~$(E-P)_{An}$~~AUM for all the latitudes and is the region where the anomalous moisture uptake occurs ~~further~~furthest south, with local maxima partially over tropical areas. ~~As~~Because the region is positioned more to the North, the tropical ~~source of moisture~~AUM tends to be lower, but the subtropical source still dominates, particularly at central and western longitudes. ~~A~~In the supplementary material Fig. ~~S1~~S3 is included to complement the information ~~give~~given in Fig. ~~4~~5, but showing the same results for each ~~individually~~individual domain.

To understand more about the effect of ARs over the European domains we checked whether those areas with significant AUM contribute to a significant increase in precipitation. Because FLEXPART can be run in forward mode we looked for the sinks for those air parcels (particles) that leave a particular area, using the AUM regions (those in Fig. 3 right panel) to compute the precipitation (as E-P<0) over each target domain. We computed (E-P)<0 values for the climatological period ($(E-P<0)_{Clim}$) and only for the AR days ($(E-P<0)_{AR}$). The results show that the AUM areas associated with ARs support sufficient moisture to increase the precipitation (Table 5). The ratio between the climatology and the AR values provides evidence of an increase ranging from 1.26 times as much precipitation in the UK to 3 times more in the Iberian Peninsula.

It is important to ~~put~~place these results in the light of recent works ~~that deal~~dealing with the origin of moisture in ARs. Sodemann and Stohl (2013~~), show~~) showed that ~~for~~in December 2006~~,~~ several ARs~~,~~ reached from the subtropics to high latitudes, inducing precipitation over western Scandinavia. The sources and transport of water vapour in the North Atlantic storm track during that month were examined, and ~~revealed~~they reveal that the ARs were composed of a sequence of meridional excursions of water vapour. Different moisture sources ~~where~~were found: 1) in cyclone cores, ~~fast~~the rapid turnover of water vapour by evaporation and condensation were identified, leading to a rapid assimilation of water from the underlying ocean surface; 2) in the regions of long-range transport, water vapour tracers from the southern ~~mid-latitudes and subtropics dominated over local contributions~~edges of the mid-latitudes and subtropics dominated over local contributions. Our results generalize for all the domains previous findings of Liberato et al. (2012) obtained for a case study for Portugal, confirming the presence of extended source areas that support anomalous moisture uptake (tropical and subtropical) for all the domains, with the highest anomalies being found for the Iberian Peninsula and the UK. Because ARs are always dynamically coupled to cyclones, Sodemann and Stohl (2013) also analyse in their study the change in moisture composition in the vicinity of the cyclone responsible for the intense events over western Scandinavia. This fact may be better corroborated in future work by using the long database of ARs for all European coastal domains. In any case, our results also suggest contributions from nearby sources of anomalous moisture uptake associated with the ARs. According to Sodemann and Stohl (2013), this may be due to the rapid turnover of water vapour by evaporation and condensation, leading to the rapid assimilation of water from the underlying ocean surface near the cyclone cores.

We acknowledge ~~that~~ the scepticism of some authors ~~are sceptical on~~regarding the far~~-~~-reaching origin of moisture considered to contribute to the ARs. ~~Thus,~~ Dacre et al. (2015) ~~have looked into~~considered a selected number of cases of water vapour transport associated ~~to~~with North Atlantic extra-tropical cyclones in winter. The authors inferred that ~~ARs~~AR moisture originates mostly from the water vapour in the cyclone's warm sector, and not ~~so~~that much from the long-distance transport of water vapour from the subtropics. Our long term (E-P)>0 analysis~~, confirms~~ shows that~~,~~ for the ARs that landfall ~~in~~on the western European coast, the ~~advection of~~anomalous moisture linked with the ARs comes mainly from subtropical areas and, to a ~~less extend~~lesser extent, from mid-latitudes. In addition, a small anomalous moisture ~~source was~~uptake has also been found ~~at~~in the tropical zone.

~~It must be noticed~~Garaboa-Paz et al. (2015), using Lagrangian Coherent Structures (LCSs), showed for two AR case studies that the ~~method is not able to separate E and P entirely as it does not represent completely the evaporation (E) field, but provides only an estimation. Even so, the approach is sufficiently robust whether the method is applied at daily scale or at~~passive advection of water vapour in the ~~monthly or ever at longer time-scales (Castillo et al., 2014), providing a useful tool to study the geographical location of moisture sources and to analyse their anomaly and~~ AR from tropical latitudes is possible~~ variability~~.

5 Conclusions

We have ~~undertaken a novel~~described our innovative study ~~regarding~~related to the anomalous uptake of moisture ~~source of the~~for ARs that ~~strike~~reach different western European domains in ~~Europe in~~ the winter half-year (ONDJFM). To achieve this goal, we ~~have~~ used an objective AR detection scheme (Lavers et al., 2012; Ramos et al., 2015) that depends entirely on the vertically integrated horizontal water vapour transport (IVT). In order to ensure ~~a consistent~~that the AR detection ~~scheme~~is performed as close to the coast as possible, this analysis was applied to 3 different reference meridians (9.75ºW, 4.~~50º~~50ºW and 5.25ºE) divided into 10º sectors between 35ºN and 75ºN. The use of 3 different reference meridians represents a refinement ~~over~~to the approach of Lavers and Villarini (2013~~) that~~), who only ~~use~~used the

10ºW meridian reference. ~~Since~~Because we are mostly interested in those ARs that make landfall in western Europe and over land, we ~~have re-grouped~~regrouped the ~~ARs~~ previously computed ARs (Fig. ~~1a~~1 and Table 1) into the following 5 new ~~5~~ domains (Fig. ~~1b):~~1, 1) *Iberian Peninsula* (9.75ºW; 36ºN – 43.75ºN); 2) *France* (4.5ºW; 43.75ºN – 50ºN); 3) *UK* (4.5ºW; 50ºN-59ºN); 4) *Southern Scandinavia* ~~*andThe*~~*and the Netherlands* (5.25ºE; 50ºN-59ºN) and 5) *Northern Scandinavia* (5.25ºE; 59ºN – 70ºN).

The number of ARs found ~~show~~shows a latitunal dependence, with the highest values being recorded for the three merdional references 9.75ºW, 4.~~50º~~50ºW and 5.25ºE are 45ºN - 55ºN, 35ºN - 45ºN and 50ºN - 60ºN respectively. We then considered only ~~the~~those ARs that ~~make~~made landfall in Western Europe ~~and~~ over land into the new domains ~~is considered,~~, where the French (~~140ARs~~140 ARs) and Southern Scandinavia and ~~The~~the Netherlands (~~90ARs~~90 ARs) domains ~~record~~showed the highest values, while the Iberian Peninsula (21) domain ~~record~~recorded the lowest value.

The Lagrangian perspective of this work can help ~~to give~~provide additional input regarding the effective moisture sources associated ~~to~~with most of the ARs that ~~strike~~reach Europe. ~~The~~ To achieve this objective, we detected those areas where the moisture ~~sources analysis~~ uptake to the atmosphere occurs in an anomalous way. The computation of positive values of (E-P) ~~were evaluated~~every 6 hours for each AR for 10 days of transport was undertaken, taking into account the air particles residing over the ~~western~~ 5 degrees ~~from~~west of the ARs detection meridian reference mentioned above and shown in Table 3. This amount was computed for all the ARs that reached a continental domain and was compared with the climatology. We have therefore shown in this paper the anomalous uptake of moisture (here termed the AUM) areas for the ARs.

The near-surface wind speed and the near-surface atmospheric specific humidity, together with the SST, are bound to play a major role in the process of moisture uptake over the Oceans (Gimeno et al., 2012). Therefore, despite not analysing the role of SST in the present study, we can nevertheless speculate the possibility of positive anomalies of sea surface temperature influencing the interannual variably of the ARs. Future studies of the SST variability and its influence over the ARs should be considered in order to understand this relationship better.

The most important results obtained ~~for the ARs moisture sources and transport can be summarized~~can be summarised as follows:

- In general, for all the regions, the major ~~climatological source of moisture extends~~AUM areas extend along the subtropical North Atlantic, from the Florida Peninsula (~~northward~~north of 20ºN) to each sink region. However, the mid-latitude also plays an important role~~ as effective source of moisture~~, with the coastal area nearest to each sink region always appearing as a local maximum of ~~evaporation~~AUM.
- The Atlantic subtropical AUM source is reinforced during ARs where the major uptake anomalies are detected in the middle of the Northern Atlantic, between 20ºN and 40ºN, with a slight northward movement when the sink region is positioned at higher latitudes.
- The most notable anomaly ~~in the evaporation~~of moisture uptake is detected for the Iberian Peninsula, ~~following~~followed by the Southern Scandinavia and ~~The Netherland region, and~~the Netherlands domains, with the lowest for the Northern Scandinavia ~~region~~domain.

To conclude, we ~~show~~have shown that the main ~~sources and advection~~anomalous uptake of moisture ~~linked to~~areas associated with the ARs that strike Western Europe coast ~~have the~~ are located over subtropical ~~areas as~~latitudes. For the ~~most important ones as the moisture sources longitudes are located westward, but~~southern domains one must be also be aware ~~also to the appearance~~ of the presence of a tropical ~~source, and the extra-tropical moisture sources as we move nearest the European coast.~~AUM area. Near the sink continental areas~~ the main source~~, extra-tropical areas with anomalous uptake of moisture are also apparent, confirming the local ~~as~~transport produced by the nearby ocean~~ vicinity~~.

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Tables

Table 1. The vertically integrated horizontal water vapour transport (IVT) threshold and the number of persistent atmospheric rivers detected for each different ~~domain~~reference meridian

	Sector	IVT threshold (kg m^{-1} s^{-1})	Number of AR
~~Iberian Peninsula / Ireland~~ Reference meridian 1 **(9.75°W)**	35°N - 45°N	621.7048	79
	45°N - 55°N	691.5456	87
	55°N - 65°N	614.4121	70
	65°N - 75°N	453.4208	35
~~UK / France~~ Reference meridian 2 **(4.50°W)**	35°N - 45°N	527.9475	113
	45°N - 55°N	637.2342	94
	55°N - 65°N	544.0915	98
	65°N - 75°N	439.4734	46
~~Scandinavia~~ Reference meridian 3 **(5.25°E)**	50°N - 60°N	524.1678	100
	60°N - 70°N	468.0643	80

Table 2. The new defined ~~atmospheric rivers~~ Atmospheric Rivers landfall domains and the ~~correspondent~~corresponding number of Atmospheric Rivers and the respective number of time steps.

ARs domains	Number of ARs	Number of ARs time steps
1) Iberian Peninsula 9.75ºW; 36ºN – 43.75ºN	21	117
2) France 4.5ºW; 43.75ºN – 50ºN	140	665
3) UK 4.5ºW; 50ºN-59ºN	74	343
4) Southern Scandinavia and The Netherlands 5.25ºE; 50ºN-59ºN	90	423
5) Northern Scandinavia 5.25ºE; 59ºN – 70ºN	83	317

Table 3. (E-P) backward trajectories regions where the computation is made for all the air parcels inside it.

ARs domains	**Latitude and Longitude limits**
1) Iberian Peninsula	9.75ºW – 4.75ºW ; 36ºN – 43.75ºN
2) France	4.5ºW – 0.5ºE ; 43.75ºN – 50ºN
3) UK	4.5ºW – 0.5ºE ; 50ºN – 59ºN
4) Southern Scandinavia and The Netherlands	5.25ºE – 10.25ºE ; 50ºN – 59ºN
5) Northern Scandinavia	5.25ºE – 10.25ºE ; 59ºN – 70ºN

Table 4. Percentile 90th for the anomaly values of (E-P) > 0 field [$(E-P)_{An}$] for each studied domain and longitude (in mm/day):

	Iberian Peninsula	**France**	**UK**	**Southern Scandinavia and the Netherlands**	**Northern Scandinavia**
10ºW	0.45	0.40	0.50	0.55	0.41
20ºW	0.77	0.56	0.69	0.73	0.53
30ºW	0.82	0.69	0.90	0.86	0.63
40ºW	0.99	0.85	0.93	0.90	0.62
50ºW	0.98	0.81	0.83	0.80	0.56
60ºW	1.06	0.79	0.64	0.71	0.52

Table 5. The contribution of the different moisture sources to the precipitation derived from FLEXPART, computed as E-P<0 (P_{FLEX}), over the analysed 5 domains for the climatological period (P_{FLEX}Clim) and for the ARs days (P_{FLEX}AR). The ratio between the two is also shown.

Commented [AMR1]: New Table

Domain	P_{FLEX}Clim (mm/day)	P_{FLEX}AR (mm/day)	P_{FLEX}AR/ P_{FLEX}Clim
1) Iberian Peninsula	255.85	788.14	3.07
2) France	360.94	779.01	2.16
3) UK	561.61	709.86	1.26
4) Southern Scandinavia and the Netherlands	616.42	829.89	1.34
5) Northern Scandinavia	601.35	871.06	1.44

Figure Captions

Figure 1. a) Location of the three different reference meridians ~~domains~~ and sectors in Europe used for the computation of the ~~atmospheric rivers.~~Atmospheric Rivers. b) The new defined ~~atmospheric rivers~~Atmospheric River landfall domains: Iberian Peninsula (red), France (blue), UK (green), South Scandinavia and the Netherlands (yellow) and North Scandinavia (purple). ~~The Tropic of Cancer parallel (23.26ºN) and the 35ºN parallel are also shown.~~

Figure 2. The median position (~~colour~~coloured line) and the respective 90th ~~percentile~~and 10th ~~percentile~~percentiles (dashed ~~line~~lines) of the ~~atmospheric rivers~~Atmospheric River path along the North Atlantic Ocean before arriving ~~to~~in each studied domain: a) Iberian Peninsula (red), b) France (blue) and UK (green) and c) Southern Scandinavia and ~~The~~the Netherlands (yellow) and Northern Scandinavia (purple).

Figure 3. a) The moisture sources (E-P>0) computed for 10 days for an AR making landfall in the Iberian Peninsula on 14 December 1981 at 00UTC. b) The vertically integrated horizontal water vapour transport (IVT) field for 14 December 1981 at 00UTC and the location of the IVT maxima (black line). The moisture sources detected in a) are also plotted using red contours.

Figure 4. For each studied sink domain (Iberian Peninsula, France, UK, Southern Scandinavia and ~~The~~the Netherlands, and Northern Scandinavia) for wintertime from 1979 to 2012: **Left:** Mean value of the (E − P) > 0 field [$(E\text{-}P)_{Cli}$], backward integrated over a 10 day period. **Right:** (E − P) > 0 anomaly field for ~~ARs~~AR days [$(E\text{-}P)_{An}$] . Units in mm/day. Regarding the anomaly fields only the results that are statistically significant at the 90% level are shown. The Tropic of Cancer parallel (23.43ºN) and the 35ºN parallel are also shown.

Figure ~~4~~5. Longitudinal cross section of the anomaly values of (E-P) > 0 field [$(E\text{-}P)_{An}$] for each studied domain: Iberian Peninsula (red line), France (blue), UK (green), Southern Scandinavia and ~~The~~the Netherlands (yellow), and Northern Scandinavia (purple). ~~Bold~~The bold line shows those values over the 90th ~~percentil~~percentile of each ~~serie~~series (values shown in ~~table~~Table 4). Units in mm/day. The Tropic of Cancer parallel (23.26ºN) and the 35ºN parallel are also shown.

Supplementary Material Figure Captions

Figure S1. The number of Top 10 annual maxima precipitation events (for the extended winter months) related to Atmospheric Rivers

Figure S2. Track density (%) of the air parcels used to compute the anomalous moisture uptake (at a 5º by 5º grid cell) for a) Iberian Peninsula, b) France, c) UK, d) South Scandinavia and the Netherlands, and e) North Scandinavia.

Figure S3. Longitudinal cross section of the anomaly values of (E-P) > 0 field [$(E\text{-}P)_{An}$] for each studied domain every 10 degrees: ~~10W~~10°W (red line), ~~20W~~20°W (orange), ~~30W~~30°W (green), ~~40W~~40°W (yellow), ~~50W~~50°W (blue), and ~~60W~~60°W (purple). ~~Bold~~The bold line shows those values over the 90^{th} ~~percentil~~percentile of each ~~serie~~series (values shown in ~~table~~Table 4). Units in mm/day.

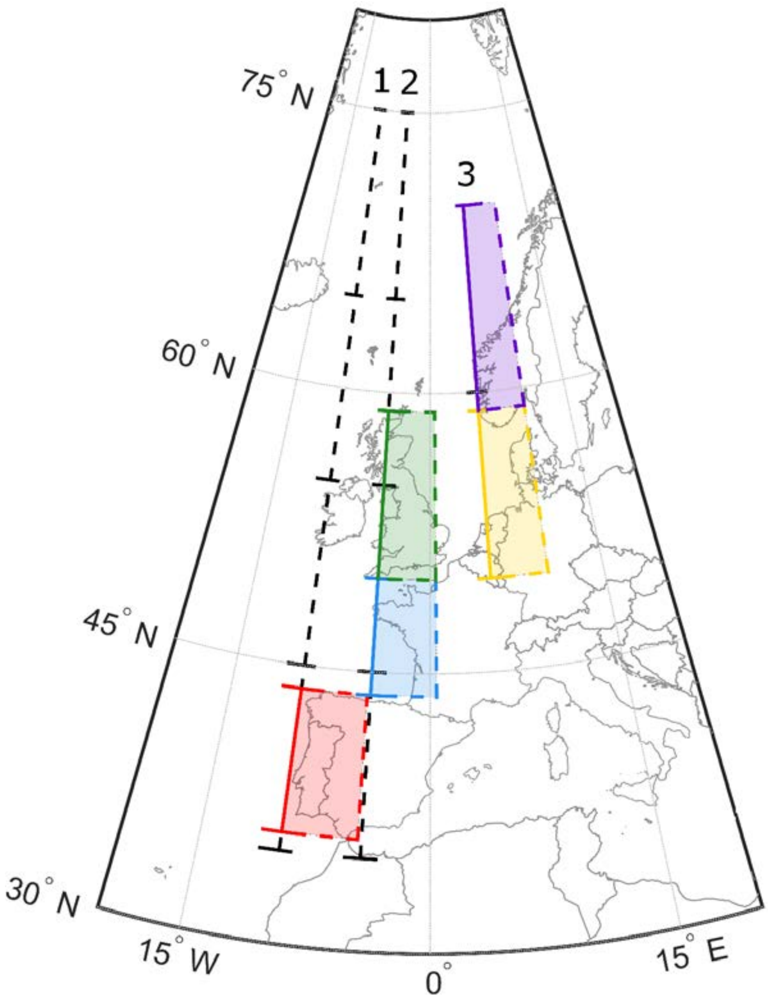
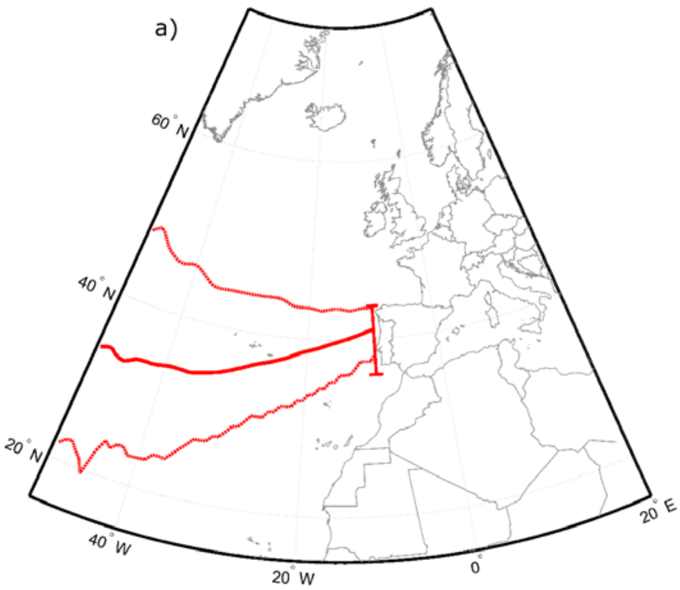


Figure 1.

Commented [AMR2]: Figure 1 reviewed.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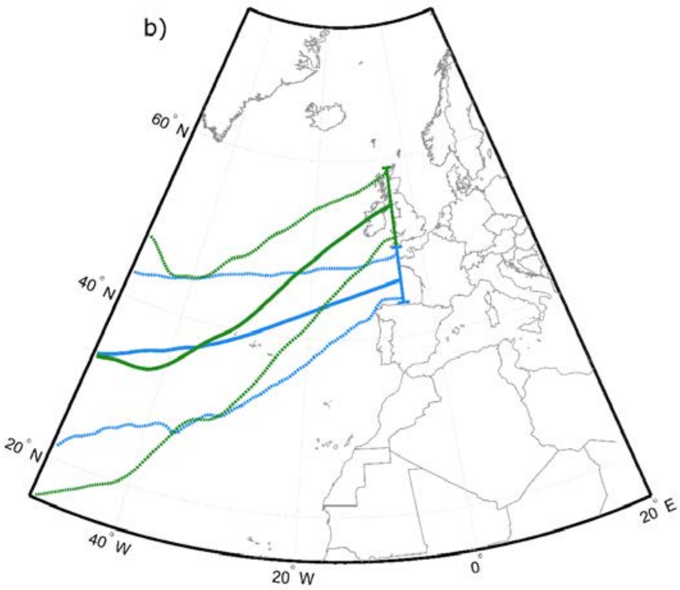
60° N
40° N
20° N
40° W
20° W
0°
20° E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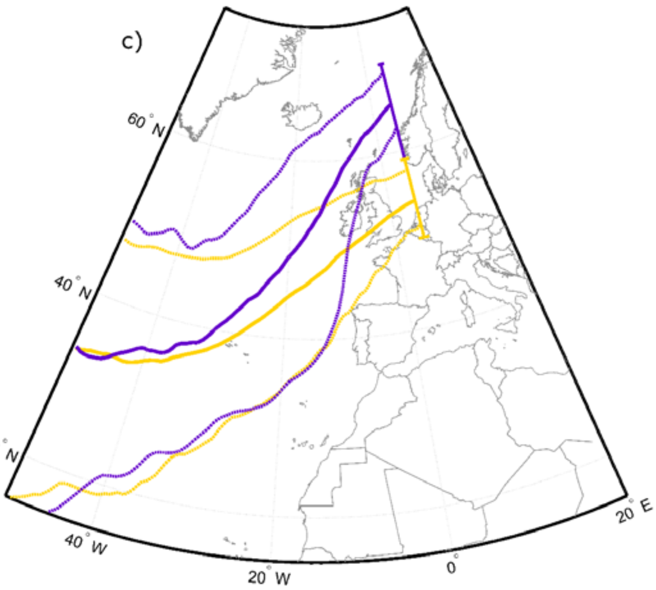

Figure 2.

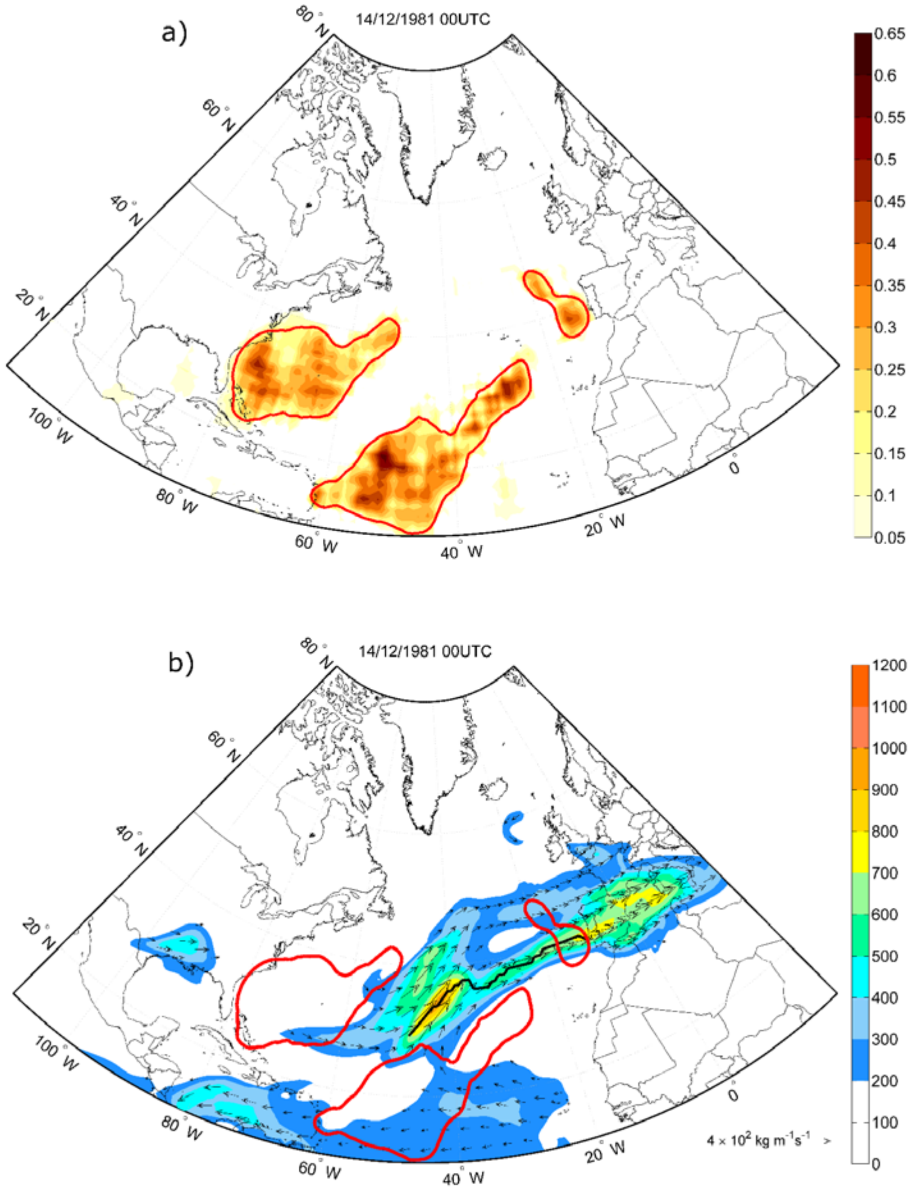

Figure 3.

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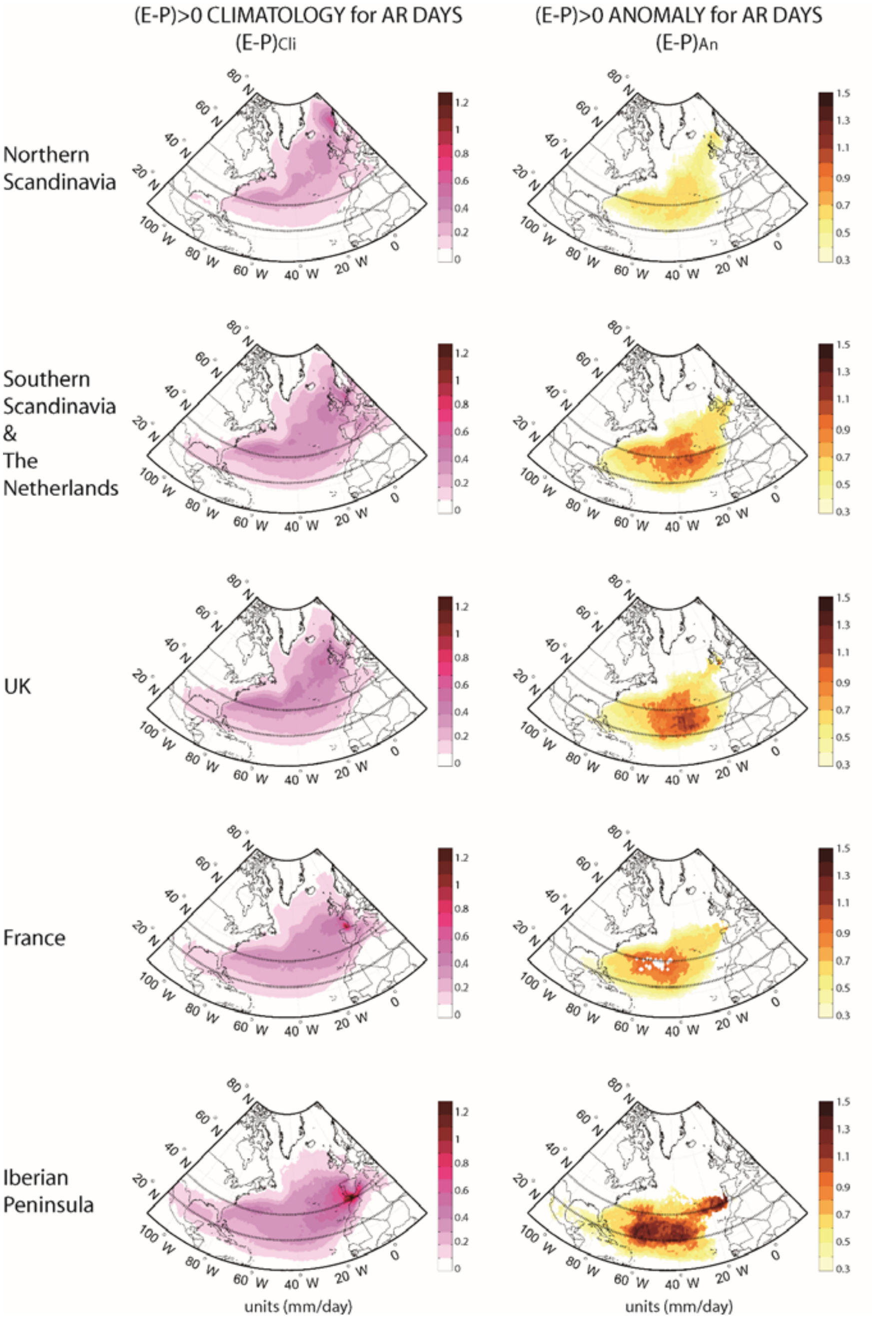
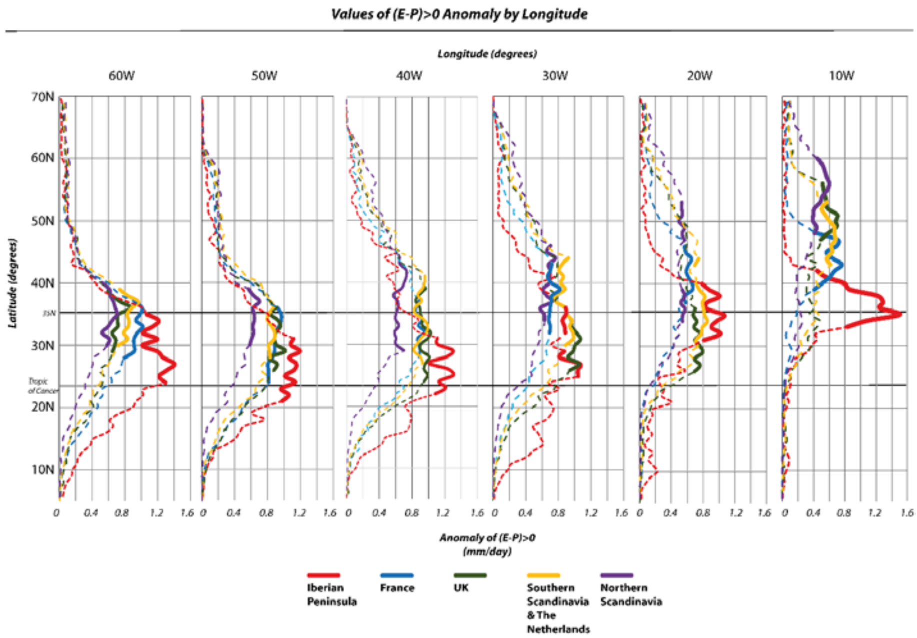


Figure 4

Commented [AMR4]: Figure 4 reviewed.



Values of (E-P)>0 Anomaly by Longitude
Longitude (degrees)
60W
50W
40W
30W
20W
10W
70N
60N
50N
40N
35N
30N
Tropic of Cancer
20N
10N
Latitude (degrees)
0 0.4 0.8 1.2 1.6
Anomaly of (E-P)>0 (mm/day)
Iberian Peninsula
France
UK
Southern Scandinavia & The Netherlands
Northern Scandinavia

Figure 5.