Answer to Anonymous Referee (R1) in the Interactive comment on "Local and remote moisture sources for extreme precipitation: a study of the two famous 1982 Western Mediterranean episodes" by **Damián Insua-Costa et al.**

This paper put the interest in one of the topics within the last times: the link between the origin of moisture and the occurrence of precipitation. Although this reviewer has many important general comments, the paper seems interesting to me (and for the scientific community), and after being improved I will recommend its publication.

Thank you very much for your review. We believe that the modifications you suggest will improve the manuscript. Please, find below the responses to your comments.

In general:

The authors need to change the title because it is possible that these two events are "famous" in Spain, or in the Iberian Peninsula, but not in the international community.

Please change "famous", or delete it.

We agree with the reviewer, so the word "famous" is going to be replaced by "catastrophic".

Both selected case occurred during the same year, 1982, why the authors select the events only this year? It is impossible that there is no other case in another year. Please see the work by Ramos et al (2017; DOI: 10.1002/joc.4726) where a ranking of events where done; or the important heavy rains in Lisbon during 26 October 2006 [https://earthobservatory.nasa.gov/images/17545/floods-in-portugal] with associated floods, and there are other examples.

So, the authors need to clarify this fact, and justify comparing with other extreme events the selection of these particular cases, because the event during October 1982 does not appears in the 10 first ranked events of high precipitation in Ramos et al (2017) and the November one appears in 3rd and 5th position for events with 3 days in duration.

Several factors support the choice of these two events. Both events appear, for example, in the list of major flood disasters in Europe between 1950 and 2005 (Barredo, 2007). As discussed in the article, both events exceeded the death toll of 40, making them two of the most catastrophic events in the Mediterranean region in the second half of the 20th century. The amounts of rain recorded were sensational; in addition to those cited in the paper, some researchers have gone so far as to ensure that in the October event more than 1000 mm could have fallen in 15 hours in the observatory located in La Muela de Cortes de Pallás (Valencia), which would be a historical record in Spain. Finally, the fact that the two events occurred in such a short time period and triggered by such different weather conditions (but both very common in this type of episodes) makes them more interesting.

As for the Ramos et al. (2017) method, it takes into account the accumulated precipitation in periods of 3, 5, 7 or 10 days and in the entire Iberian Peninsula (added area of all points with precipitation anomalies greater than two standard deviations), so that events with very high amounts of rainfall in a short time and in more localized regions tend to lose importance in this ranking, despite being the ones that usually cause more damage (such as the October 1982 event).Following the referee's recommendation, we will add a clarification on the reason for the choice of these episodes in the fifth paragraph of the introduction (L14-L27 P3).

Barredo, J. I.: Major flood disasters in Europe: 1950-2005, Natural Hazards, 42, 125–148, https://doi.org/10.1007/s11069-006-9065-2, 2007.

The methodology about the moisture attribution is based on the WVT method and the WRF-WVT tool. Nowadays it seems to be a great tool and corroborated in different paper and applications, but the experiments are impossible to check or prove, as the model is nor freely available for the scientific community. The developer, one of the authors, needs to think in this option as many journals requires accessibility to the software and capability of others future authors to repeat the experiments. This is only a comment.

Thank you for your suggestion. We are currently considering making the code open access.

Another comment about the references cited in the paper. There is a copious quantity of self-references (1/5), and in two cases there are in Spanish. That is the case for those related with "gota fria" and a 1987 Ph.D. thesis. Both references are used to cite the synoptic meteorological system known as cut-off-lows (COLs). Checking the literature about them, there is a special issue published in Meteorological and Atmospheric Physics (MAP) journal in 2007, and no one of the papers included in this compendium were referenced. See in https://link.springer.com/journal/703/96/1/page/1. It would be excellent that the authors take a look at those papers concerning, at least, the Iberian Peninsula. The papers cited they have already been sufficiently amortized.

On the other hand, there are two main papers related to the characteristic of the COLs published after the both cited (one in 1987 and the thesis 1991, and in Spanish): Climatological features of Cut-off low systems in the Northern Hemisphere in Journal of Climate (2005) [https://doi.org/10.1175/JCLI3386.1] and Identification and Climatology of COLs near the Tropopause in Annals of the New York Academy of Sciences in 2008 [doi: 10.1196/annals.1446.016].

Although the paper is focused in the western Mediterranean region, the role of the COLs systems is necessary to put in a global context, showing that these systems occur over other regions around the world causing similar amounts of precipitation or if the effects are also important as in the Mediterranean area.

We disagree with the reviewer in that there is a one to one relationship between the presence of cut off lows and extreme precipitation in the Mediterranean and much less so in other parts of the world. It is indeed true that the cold air aloft associated with COL systems enhances instability and favors convection and precipitation. But this does not mean that this configuration will always result in extreme rains, nor all extreme precipitation events with flooding are necessarily produced by a COL. The main point of the paper is to provide support to the hypothesis that the common feature in all extreme precipitation and catastrophic flooding cases in the Mediterranean is not the synoptic setting (cut off low or not) but a high amount of precipitable water. Of course, some lifting mechanism is also needed, but this does not always have to be the same (the most common ones are nicely summarized in the review paper by Dayan et al., 2015, suggested by the reviewer in the next comment). Instability and convection can result from the presence of low level warm and moist air and not only from an upper level cold air mass, and air parcels can also ascend forced by some dynamical mechanism, such as a frontal circulation or upper level divergence. We illustrate this idea very clearly with the two examples we chose for the study, which are very different in terms of synoptic forcing, as it is discussed in the text.

The equivalence between the presence of a cut off low and extreme precipitation and flooding in the Mediterranean is a common misconception, that in places like Spain has even been embraced by the general public and permeated to everyday language, making cut-off low ("gota fría") and extreme rain and flooding synonymous. This is the main reason why we purposely avoided discussing cut off lows in the text. We also provided only brief information on any other specific synoptic setting that can produce HPEs in the Mediterranean, shifting the focus entirely to moisture, which is the main topic of the article. However, given the frequent involvement of COLs in these extreme events, we will add the two suggested references (Nieto et al., 2005, 2008) when COLs are mentioned in the introduction (P2 L4), as per the reviewer's request.

The references to Llasat (1987, 1991) are justified by the fact that there is scarce literature directly dealing with these particular cases. We do not refer to these articles in allusion to cut-off-lows (COLs) specifically, but to allude to a more in depth general meteorological analysis of the cases in our study.

In the second page, the authors raised a number of questions and they listed five papers using different methodologies. Again, checking the newest literature there are other methods (and I will not go into isotopes methodology) not included here. Lagrangian approaches using backward techniques to follow changes in moisture were used to identify moisture transport from a global point of view and at regional scale during the last year, and it is highlighted the papers by Gimeno et al. (2010, 2011, 2012, 2013). The review paper about the "Oceanic and Terrestrial Sources of Continental Precipitation" is nowadays a seminal reference in this topic. The author should also not forget some papers using other models that justify the contribution of moisture to extreme events, like those by:

Sodemann, H. & Zubler, E. Seasonal and inter-annual variability of the moisture sources for Alpine precipitation during 1995–2002. Int. J. Clim. 2010, 30, 947–961

Schicker, I. et al. Origin and transport of Mediterranean moisture and air. Atmos. Chem. Phys. 2010, 10, 5089–5105.

Ciric, D. et al. Wet Spells and Associated Moisture Sources Anomalies across Danube River Basin. Water 2017, 9, 615. Liberato et al. (2013) Moisture Sources and LargeâA˘ RScale Dynamics Associated With a Flash Flood Event. In Lagrangian Modeling of the Atmosphere, Volume 200. Book Series: Geophysical Monograph Series

Or those related to synoptic conditions, for instance:

Pfahl, S. Characterising the relationship between weather extremes in Europe and synoptic circulation features. Nat. Hazards Earth Syst. Sci. 2014, 14, 1461–1475.

Dayan et al (2015). Review Article: Atmospheric conditions inducing extreme precipitation over the eastern and western Mediterranean. NHESS. doi:10.5194/nhess-15- 2525-2015

And this review assumes that there are many lacks in the references included in this review. So, the authors of the paper, need to improve the list reference as it is evident that in the present manuscript important references are still lacking to put in context the problematic.

In the third paragraph of the introduction (L13 P2- L2 P3), we provide the reader with a general view of the state of the art in the research on moisture sources for extreme precipitation in the Mediterranean. With this purpose, we referenced six authors who used Lagrangian methods, the most commonly employed, and one author (the only one we know of) who uses the tracer's method, just like us. We believe that these references are sufficient to introduce the reader to the numerical study of moisture sources for extreme precipitation in the Mediterranean. Obviously, these methods have also been used for the study of extreme precipitation events in other regions of the planet, as well as for the study of moisture sources, both in the Mediterranean and in other regions in the climatic sense. But we do not believe that it is necessary in this paper to provide the reader with such a global vision of the field of moisture tracking. In a previous article (Insua-Costa and Miguez-Macho, 2018), which is cited in the text, we did a more general review of the state of the art of numerical methods for the study of moisture sources, but we do not think it is pertinent to repeat it here. Notwithstanding, a reference to Gimeno et al. (2012) on line 13 of page 2 does seem appropriate because, as the referee mentions, it is nowadays a seminal reference in this topic. We are going to add it.

Likewise, in our brief synoptic analysis of the events, we believe that it is enough to reference those publications analyzing the weather conditions of the case studies chosen for this paper and not others that deal with the problem of extreme rainfall in general. However, the review paper by Dayan et al. (2015) is very suitable as a reference in the first part of the introduction, when the most common settings for extreme precipitation in the western Mediterranean are mentioned. We will now include it and we thank the reviewer for the suggestion.

Insua-Costa, D. and Miguez-Macho, G.: A new moisture tagging capability in the Weather Research and Forecasting model: Formulation, validation and application to the 2014 Great Lake-effect snowstorm, Earth System Dynamics, 9, 167–185, https://doi.org/10.5194/esd-9-167-2018, 2018.

Gimeno, L., Stohl, A., Trigo, R. M., Dominguez, F., Yoshimura, K., Yu, L., Drumond, A., Durn-Quesada, A. M., and Nieto, R.: Oceanic and terrestrial sources of continental precipitation, Rev. Geophys., 50, 1–41, https://doi.org/10.1029/2012RG000389, 2012.

About the definition of the "predefined" source of moisture: this is from my point of view the major point to check in the paper. It has no sense define all the Northern Atlantic or all the Tropical Atlantic areas. There tools to detect the specific sources of moisture for both events, and then use the WRF-WVT tool. Recently in a discussion paper in ESD https://www.earth-syst-dynam-discuss.net/esd-2018-76/, one of the authors use a Lagrangian methodology to define it. So, why not in this paper? If the definition is more properly the results will be more justifiable. If the authors do not redefine the limits of the sources, they need to justify better this fact in the actual manuscript. On the other hand, there are some papers that analyze the moisture transport for the Iberian Peninsula: "Where Does the Iberian Peninsula Moisture Come from? An Answer Based on a Lagrangian Approach". J. Hydrometeorol. 2010, 11, 421–436 in which a regionalization was done.

We fully agree with the reviewer in that this is a controversial point of the article. In fact, at first we ourselves also thought that the best way to select the sources was the one proposed by the reviewer (like in https://www.earth-syst-dynam-discuss.net/esd-2018-76). However, bearing in mind that our long-term goal is to apply the method to a much larger number of events (as commented in the paper L14-L15 P18), in order to construct a climatology of moisture sources for extreme events, the targeting of originating regions cannot be done following the aforementioned strategy. This is because, with the proposed method, different sources would be chosen for each event, making it difficult to calculate a final average. The selected sources have to always be the same. For instance, to map the spatial distribution of the average moisture input of the tropics to precipitation in these episodes, one would have to divide the general tropical region into smaller subareas down to the desired resolution, and then run the model for each of them and for all cases to finally obtain the average contribution in such detail. For 1x1 degree squares, this means hundreds of simulations just for one case. The selection proposed here is based on the choice of quite extensive sources, which does not mean they are not enlightening: a distinction is made between local (Mediterranean) and remote (Atlantic) humidity; within the remote we distinguish between tropical and non-tropical and within the local between Western and Central Mediterranean. Furthermore, the main point of the paper is precisely to find out whether moisture is of remote or local origin, and not the detailed geographic location of the source.

For each selected moisture source a simulation must be carried out, with the corresponding increase in computational cost, so it would not be feasible to increase the number of selected sources much more if a large number of cases (in the hundreds) is to be analysed in the future. This is why we chose sources as extensive as the entire North Atlantic or the entire Tropical and Subtropical Atlantic.

We agree with the reviewer in that the reasoning behind our source selection should be made clearer, so we will add further discussion in section "2.2 Experimental design".

Specific comments:

Page 2, line 5 and line 30: the authors say that the "moisture as a key factor is often undervalued or not considered in depth" in line 5, and then in line 30 affirm that the cited papers "have provided quite a detail knowledge about the origin of the moisture feeding extreme rainfall ...". This does not make sense, or yes or not. They should consider that the sentence in line 5 is to hard. Please, rewrite it. There many works about the role of the moisture for extreme precipitation.

We are aware that there is research focused on moisture in these events in the literature (see the citations in the introduction section), but we think that other aspects related to Mediterranean extreme rainfall have been much more studied. It is not uncommon to find articles on the causes of some event of these characteristics in which the role of humidity is considered totally secondary. In addition, we also believe that moisture as a key factor is often not sufficiently taken into account in the warning systems and forecasts of meteorological agencies.

However, in order to make this statement less controversial, we are going to change "is often" to "is sometimes".

Page 3, line 3: the application of this tool is not a "novelty". The same authors have many papers using this technique, including researches about extreme precipitation related to Atmospheric Rivers. Of course, in this paper the meteorological systems analyzed are not over the same regions (Atlantic and Pacific). But they have at least five or six papers (or more) using this tool.

The novelty lies in the fact that almost no other research (only one author) has used the Eulerian tracer method for the study of extreme precipitation events in the Mediterranean. All other authors used Lagrangian methods, as it is clearly discussed in the Introduction section. The application of the WRF-WVT tool in itself is of course no longer a novelty.

Page 3 line 11: add a reference about the validation of the tool.

Following the reviewer's suggestion, the reference from line 10 will be moved to line 11.

Page 3 line 25: which are the common types of situation associated with HPEs in the region? Clarify in this part of the text.

We agree so we are going to replace:

"A notable feature of these two episodes is that they represent two of the most common types of situation associated with HPEs in the NWMR, so the conclusions obtained in this work could be extrapolated to many other cases."

With:

"A notable feature of these two episodes is that they represent the two most common atmospheric circulation patterns associated with HPEs in the NWMR (see AP3 and AP13 weather types in the Romero et al., 1999b classification), so the conclusions obtained in this work could be extrapolated to many other cases."

Romero, R., Sumner, G., Ramis, C., & Genovés, A. (1999). A classification of the atmospheric circulation patterns producing significant daily rainfall in the Spanish Mediterranean area. International Journal of Climatology: A Journal of the Royal Meteorological Society, 19(7), 765-785.

Figure 1: the resolution is not good in this version.

The figure resolution will be improved.

Page 5, line 6-11: the 2d or 3D definition needs more explanation. Why the Arabian Sea could influence the ST source? This needs also justification. This review assumes that the Gulf of Mexico affect the Iberian Peninsula, as many works affirm (and they need to be cited here, of course).

Here, we were referring to the work of Krichak et al. (2015), discussed in the introduction section (page 3, L26), who found that tropical moisture exports from the Atlantic and the Arabian sea are involved in more than 50 intense heavy precipitation events in the Mediterranean region that they analyzed using reanalysis data.

We are aware that there are several studies showing the important role of the Gulf of Mexico as a moisture source for precipitation in the Iberian Peninsula. We did not reference those because our focus is specifically on the most intense heavy precipitation events only, and not on the sources for total annual or seasonal precipitation in general. However, we agree with the reviewer in that this general connection with the Gulf of Mexico should be mentioned, since heavy precipitation events account for a sizeable fraction of annual precipitation in several Mediterranean coastal areas, especially in Spain. We will now reference to Nieto et al. (2010) and Gimeno et al. (2012) in the introduction section.

Krichak, S. O., Barkan, J., Breitgand, J. S., Gualdi, S., and Feldstein, S. B.: The role of the export of tropical moisture into midlatitudes for extreme precipitation events in the Mediterranean region, Theoretical and Applied Climatology, 121, 499–515, https://doi.org/10.1007/s00704-014-1244-6, 2015.

R. Nieto, L. Gimeno, A. Drumond, E. Hernández. 2010. A Lagrangian identification of the main moisture sources and sinks affecting the Mediterranean area. WSEAS Trans. Environ. Dev. 6 (5), 365-374.

Gimeno, L., Stohl, A., Trigo, R. M., Dominguez, F., Yoshimura, K., Yu, L., Drumond, A., Durn-Quesada, A. M., and Nieto, R.: Oceanic and terrestrial sources of continental precipitation, Rev. Geophys., 50, 1–41, https://doi.org/10.1029/2012RG000389, 2012.

Page 5 line 7: why this division of the Mediterranean Sea? Please add a reference. It seems an usually division used in previous studies of the Mediterranean Seas as sources of moisture: e.g. Nieto et al., 2010 or Schicker et al., 2010 based in works of Millan et al 1997 and 2002

R. Nieto, L. Gimeno, A. Drumond, E. Hernández. 2010. A Lagrangian identification of the main moisture sources and sinks affecting the Mediterranean area. WSEAS Trans. Environ. Dev. 6 (5), 365-374

I. Schicker, S. Radanovics, P. Seibert. 2010. Origin and transport of Mediterranean moisture and air. Atmos. Chem. Phys., 10, 5089-5105, 10.5194/acp-10-5089-2010.

M. Millan, M.J. Sanz, R. Salvador, E. Mantilla. 2002. Atmospheric dynamics and ozone cycles related to nitrogen deposition in the western Mediterranean. Environ. Pollut., 118, 167-186, 10.1016/S0269-7491(01)00311-6

The division of the Mediterranean into Western and Central basins is based on common geographical criteria. There are many other authors that use the same or a very similar division in all fields of study and we do not think it is necessary to add any citation here.

Page 5, line 14: why the authors ignore the continental areas as sources of moisture? They assume, but they need to justify this based on other paper(s).

Evapotranspiration in continental Europe and Northwestern North America in late October and early November is rather little due to the cold temperatures and the natural cycle of vegetation. The contribution of the mostly desertic Northern Africa is safe to assume that is even smaller. Other possible continental sources in our domain in sub-Saharan Africa are included in the 3D tropical moisture source. However, as per the reviewer's request, we will better justify our assumption by adding a reference to Sodemann and Zubler (2010) and Drumond et al. (2011) at the end of the sentence "We assume that in autumn it is very diminished and hence it does not have a potentially important contribution". These moisture source studies explicitly find that autumn continental ET is not relevant for precipitation in regions around the Mediterranean.

Sodemann, H. and Zubler, E.: Seasonal and inter-annual variability of the moisture sources for Alpine precipitation during 1995– 2002, Int. J. Climatol., 30, 947–961, 2010.

Drumond, A., Nieto, R., Hernandez, E., and Gimeno, L.: A Lagrangian analysis of the variation in moisture sources related to drier and wetter conditions in regions around the Mediterranean Basin, Nat. Hazards Earth Syst. Sci., 11, 2307-2320, https://doi.org/10.5194/nhess-11-2307-2011, 2011.

Page 5 line 16: I assume that these 10 days are used because this time is the typical definition of the mean time-averaged lifetime of water vapor in the atmosphere. Many many papers using this time cited Numaguti et al (1999): Origin and recycling processes of precipitating water over the Eurasian continent: Experiments using an atmospheric general circulation model. J. Geophys. Res., 104 (D2), 1957-1972, 10.1029/1998JD200026.

How sensitive are the results to this time used? In a recent paper by Läderach and Sodemann (2016) they obtained times as short as 4 - 5 days. Did the authors check it?

Läderach & Sodemann, 2016 GRL 43(2), 924-933, doi:10.1002/2015GL067449

As stated in the paper "this 10-day period roughly coincides with the average residence time of water vapor in the atmosphere" and we refer to Trenberth (1998), which is the major reference in this subject, and a more recent study (Van Der Ent and Tuinenburg, 2017).

This later study confirms the traditional estimate of the average residence time of water vapor in the atmosphere (8-10 days), and explicitly rejects the conclusions of studies that suggest an average residence time of 4-5 days. In any case, our results would only be affected if the residence time were longer, not shorter, since the sooner we start the simulation, the lower the contribution of water vapor already present at initial time over the 2D sources to precipitation in the events. This initial water vapor does not have a known origin and we do not want it to interfere with our results.

Trenberth, K. E.: Atmospheric moisture residence times and cycling: Implications for rainfall rates and climate change, Climatic Change, 39, 667-694,https://doi.org/10.1023/A:1005319109110, 1998.

Van Der Ent, R. J. and Tuinenburg, O. A.: The residence time of water in the atmosphere revisited, Hydrology and Earth System Sciences, 21, 779–790, https://doi.org/10.5194/hess-21-779-2017, 2017

Figure 2: the vertical scale in b): is it the elevation. Put this in the caption, please.

The caption will be corrected as suggested.

Page 6, line 2: why the authors span the experiment to 12 days?

Please, see response to the previous comment on page 5. We start the simulations 10 days before the events invoking that this is the average time of water vapor in the atmosphere, precisely to assume that the contribution of initial moisture to precipitation is negligible on days 10, 11 and 12, which are the main day of the extreme precipitation event (day 11) and the days before and after. We analyze those 3 days in total.

Page 6, line 14: which is MESCAN? It is not defined previously.

We are going to replace the paragraph:

"Finally, for model validation we use the MESCAN precipitation analysis dataset (Soci et al., 2016), recently available in the ECMWF MARS (Meteorological Archival and Retrieval System) archive at 5.5 km resolution and covering our entire area of study."

With the following:

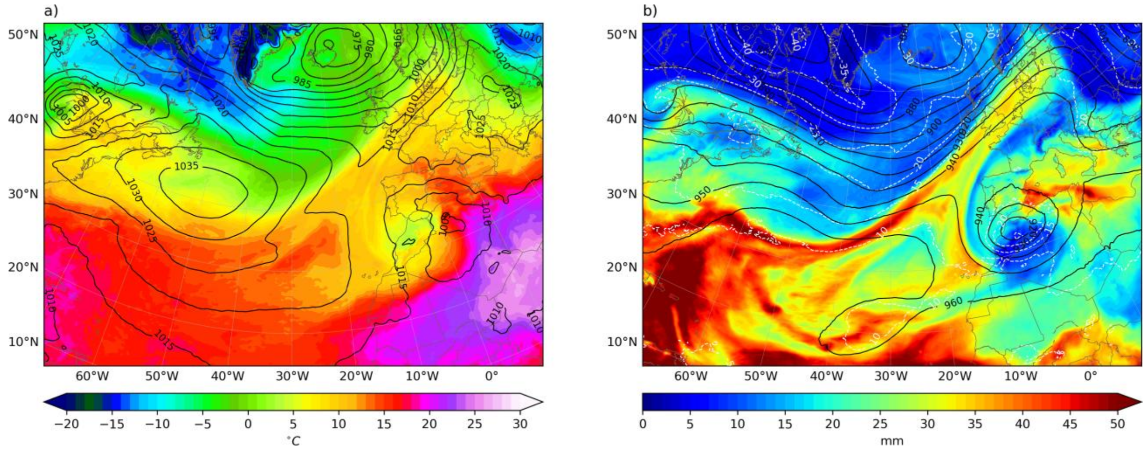
"Finally, for model precipitation validation we use the MESCAN (from Mesoscale Analysis; Soci et al., 2016) system, which combines a downscaled reanalysis and interpolated rain gauge measurements to get a high resolution (5.5 km) daily precipitation dataset. This product is recently available in the ECMWF MARS (Meteorological Archival and Retrieval System) and covers our entire area of study."

In general for the synoptic configuration. It is needed plots with the field using not only WRF outputs.

The use of the WRF model outputs to display the synoptic configuration is based on the use of spectral nudging in the simulations. Model results, except for moisture, are relaxed to ERA-Interim on the large-scale throughout the simulations and thus do not deviate substantially from reanalysis fields. It is practically equivalent to show one or the other.

Page 6, line 18-20: if this day occurs a COL, please add the geopotential field at 200 hPa, or at least, 300 hPa, to show the low in high levels. To show the instability add a field of convergence.

The figure below is the same as Figure 3 in the paper but with the geopotential height at 300 hPa instead of 500 hPa. The fields are very similar (disregarding their values). Therefore, the geopotential height at 500 hPa is sufficient to correctly show the COL.



As already discussed, the aim of this paper is not to describe in detail the synoptic or mesoscale configuration of the event. Thus, we do not think it is appropriate to go as far into this matter as to show the convergence field, because this would only distract the reader from the real goal of the article, which is to evidence that high amounts of moisture of mostly remote origin are involved in this kind of episodes. In addition, we believe that the article has already enough figures to enable readers to easily follow discussions and we do not want to overload it by adding more.

Page 6, line 6: this low referred here is the Cut-off low. And perhaps is not this low the system that stopped the flow, but rather the anticyclone itself and the low pressure system over Iceland that pick the moisture to the north, as it is also evident in Fig5c, where an Atmospheric river associated with it is clear.

Here we are referring to the low pressure system at low levels. As far as we know, a COL is only defined in the upper levels. We understand that this low at low levels appears as a result of the COL formation, but we wouldn't call it a COL.

When we say "The low pressure system situated over North Africa blocks the direct advance of evaporated moisture from the North Atlantic toward the Spanish Levant area" we are referring to the fact that this low organizes a flow that prevents North Atlantic humidity from directly reaching the affected area, and instead , it needs to go around the cyclone (traversing Africa) to do so.

Figure 5 (and fig. 10): it could be useful a VIMF field to see the prevalence of the flux.

We thank the reviewer for the suggestion. We have now added the VIMF in Fig. 5 and Fig. 10:

Figure 5:

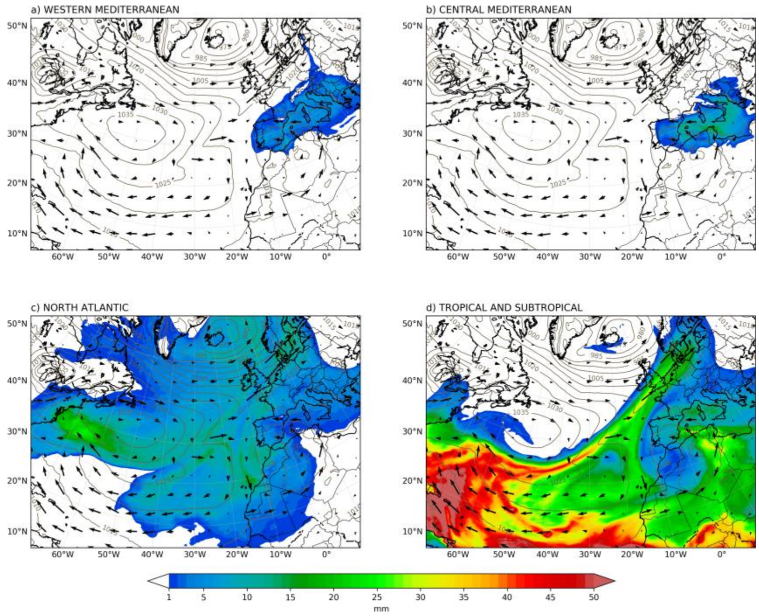
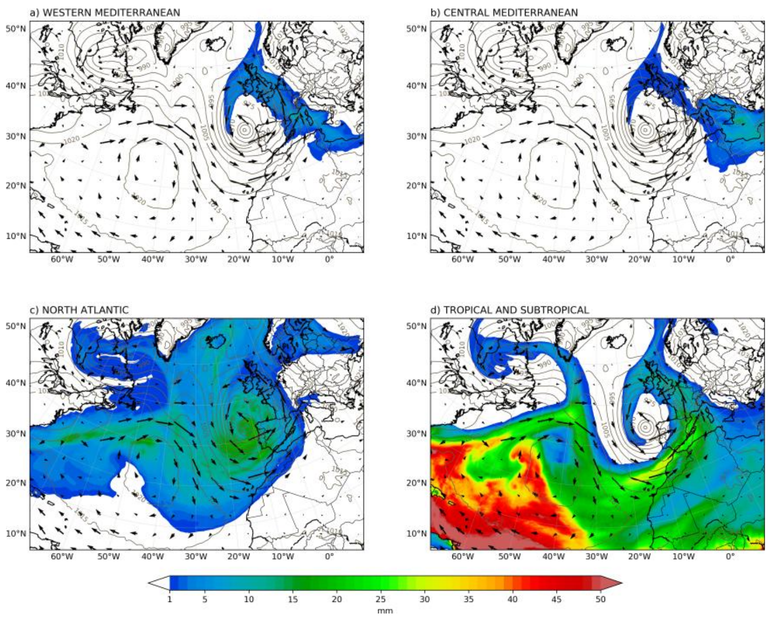


Figure 10:



Page 10, line 5: the 20% moisture mispricе has a similar contribution than those from Central Mediterranean or more. . . Why consider CM and no other sources, for instance the continental ones? Or why the authors do not consider to join CM and WM?

We hypothesize that the Central Mediterranean basin could be in some cases a very important moisture source, especially when a long-distance easterly flow is established. This is quite common, as in the case of October, and anticipating a more relevant role in other events, we explicitly decided to include the Central Mediterranean as an area to consider. In a response to a previous comment we have justified why we have not analyzed other sources, such as the continental ones.

Although we considered both the western and the central Mediterranean as local sources, we found it of great interest to know whether humidity came from the waters closest to the coast or from a more distant area. Thus, we decided to explicitly separate the Mediterranean according to geographical criteria into a western and a central basin.

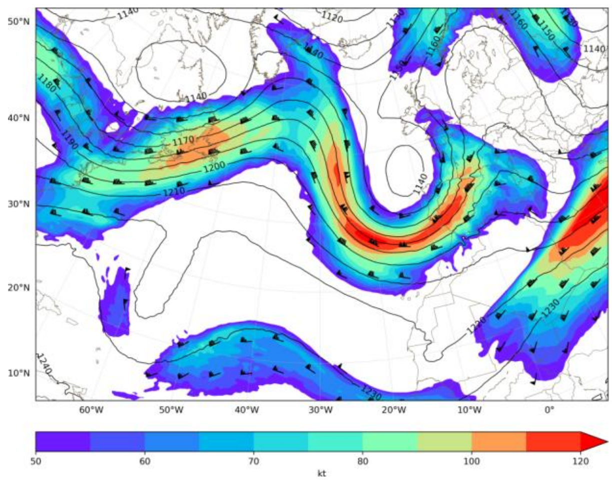
Page 11. How the authors could difference from which part of the ST source the final moisture for precipitation comes from? Because the ST contains also moisture that is advected by the AR to northern latitudes. So it seems that the moisture comes only from the eastern part of the Atlantic Ocean of the ST, and over the Sahel region, that it is not completely taken into account (the plot only show a box from 7.5◦N. Could be the source of moisture even further south?. That is the problem if the sources were previously predefined.

The only way to know which part of the tropical and subtropical source area moisture originates from would be to subdivide this region into several ones. We could generate source areas as small as the resolution of the model (20 km) allows. However, the more sources there are the higher the computational cost, and as we already argued in another response to a reviewer´s comment, the point of the article is not really to go into such geographic detail, but rather to be able to say whether moisture is from local or remote origin.

The ST source is three-dimensional, so all moisture entering it at any level will be tagged, except for the moisture originating in the other three sources, which are two-dimensional. For this reason, it does not make sense to extend this 3D source further south, since all moisture coming from regions below the south-boundary of the domain, will be tagged upon entering it according to the specified boundary conditions from reanalysis. Therefore, the moisture coming from the part of the Sahel that is not included in the domain, is also being taken into account when advected through the ST source.

Page 11, line20: the omega pattern is typical in a cut-off low formation. The October case appears as a pure cut-off low, but it needs to come from an elongated trough, that develops to a phase of tear-off (when an omega configuration is normal. So the big difference between this November case and the October one is that the COL, in this case, is bigger in size.

In our opinion, there was no COL in the November event, since as shown in the image below (geopotential height and wind at 200 hPa), at the key time of the episode (12 UTC on November 7), the jet stream was not yet completely broken. Therefore, as the upper-level low is not completely uncoupled from the westerlies, we would not call it COL. Perhaps the best term to refer to it would be closed low.



Page 12: the affected areas in relation to the cut-off low position were analyzed in a paper included in the special issue in MAP journal commented previously.

Thank you for the comment. We have already cited that paper in a previous section.

Page 14: after these results I recommend the authors to joint CM and WM.

We disagree. For the reasons stated in responses to previous comments, it seems to us more appropriate to maintain the division.

Answer to Oreste Reale (R2) in the Interactive comment on "Local and remote moisture sources for extreme precipitation: a study of the two famous 1982 Western Mediterranean episodes" by **Damián Insua-Costa et al.**

This is an excellent piece of research that brings a substantial advance to the complex issue of moisture sources related to flood-producing precipitation events over the Mediterranean region. While the writing could be improved, the results are very convincing. I find the methodology particularly praiseworthy. As such, I recommend the article to be accepted after some minor revision.

We would like to thank very much the referee for his kind remarks and positive review. Please, find below the responses to your comments.

General comment: expand the focus.

I agree with the other reviewer that the Authors should consider changing the title. Aside from defining as 'famous' events that may not be known outside the hydrology, engineering, and meteorology communities in Spain, I would rather use the term 'infamous' to describe catastrophic events that have caused death and destruction. Even better, I would avoid 'fame' entirely and perhaps refer to the events as 'catastrophic'. The term 'famous' also appears in page 17, second par.

We agree with the reviewer so the word "famous" is going to be replaced by "catastrophic" in the title. "Famous" will be replaced by "infamous" in the text.

Most important, I suggest to modify the introduction, in order to provide a broader motivation that can make the article relevant to a much larger community. The description of general mechanisms as it is cannot provide objective, generic, absolute 'causes'. Furthermore, the Authors themselves acknowledge that the 2 events are very different one from the other. Therefore, I suggest to broaden the focus of this article, by connecting this work with other research. Conditions for the development of these events surely are strong instability, presence of some circulation that organizes the flow, exploiting orographic contribution. However, the puzzling aspect is that most of these conditions, for example Mediterranean baroclinic cyclones, are often present but are rarely associated with extreme precipitation.

It is only a very small subset of Mediterranean cyclones that cause catastrophic events. Furthermore, in some instance the Mediterranean cyclone could be less relevant than the large-scale southerly flow associated with larger cyclonic circulations outside the Mediterranean. So, the Authors may consider starting with the statement that the presence (or absence) of intense moisture transport anomalies on a very large scale could be the critical, discriminating factor between many situations apparently similar but in which only one produces an extreme precipitation event.

Another suggestion is to think in a more 'global' scale. The Authors' experiments, unlike previous work, are both at very high resolution and encompass a very large domain. As such, they have the possibility of linking Mediterranean floods with the global scale. If this is done, the article will attract a much larger set of readers interested in the subject of tropical-extratropical connections.

As a starting work, consider the final part of Wu et al. (2013). In that work, we linked 2 cases of flood-producing precipitation over Europe with the so-called 6-9 day African Easterly Waves (for the part of the article relevant to your work, please see Section 3d, from page 6765 onwards). The 6-9 waves are different from the well-known 3-6 day waves, because they form to the north of the African Easterly Jet, at the jet level (about 600 hPa) and they travel northward. They can be conceived as a 'relaxation' in the subtropical high pressure that bridges mid latitude low pressure systems with the Inter Tropical Convergence Zone (ITCZ).

From this article's perspective, 6-9 day waves are relevant because they represent a way of connecting tropical moisture generated within the ITCZ with midlatitude systems. If one of such waves acts in phase with a deep midlatitude cyclone, a stream of moisture can leave the ITCZ, travel in a relatively stable area associated with the relaxed subtropical high (and thus without loosing moisture) and 'connect' with the warm advection ahead of a frontal system in the midlatitudes. Then, any mechanism able to concentrate and release this enormous amount of moisture over a small area, can cause a flood-producing precipitation event. Figures 14, 15, and 16 from Wu et al. (2013) illustrate this aspect for extreme precipitation events occurred in 2000 and 2002, respectively. It seems that the plume of moisture associated with Fig.3b, Fig. 5d, in this work, bears remarkable similarities.

Most relevant for this work are also the papers by Knippertz (2003), Knippertz et al. (2003) which connect episodes of extreme precipitation over northwest Africa with anomalous advection from the tropics, and place these into the context of a tropical-extratropical interaction.

Schepanksi and Knippertz (2011) further expand in this direction and finds in the Soudano-Saharan depression a key element connecting tropics with midlatides. We think that all these results are very consistent with each other, and simply focus on different aspects of the moisture transport.

It is important to notice that anomalous moisture advection from the tropical Atlantic has been noted also outside the Mediterranean region: the study of Stohl et al. (2008) identifies a very similar moisture path for precipitation events in Norway, connecting these with the tropical Atlantic.

We fully agree with the general comments provided by the reviewer, and we think it very appropriate to include his recommendations in the text. In order to address these suggestions, we are going to rewrite and expand paragraph one and two of the introduction as follows:

"The Western Mediterranean Region (WMR) is characterized by a high frequency in the occurrence of torrential rainfall episodes and floods that cause severe damages, with a very high social and economic impact (Llasat et al., 2010). The main mechanism generating these heavy precipitation events (HPEs) is the strong instability induced by the warm and moist air that for most of the year sits over the mild Mediterranean waters, along with the presence of a low pressure system (usually produced by a Mediterranean cyclogenesis event) that can trigger convection and organize the flow (Llasat, 2009). Other factors such as the complex orography of the region, often take also a very important role (e.g. Buzzi et al., 1998; Rotunno and Ferretti, 2003). Most cases occur in autumn, when the combination of a still warm sea surface temperature (after a peak in late summer), and a southward displacement of the jet stream, which usually favours the appearance of Atlantic lows or cut-off-lows (COLs; e.g. Nieto et al., 2005, 2008) affecting the WMR, make this season the most favourable for the development of these extreme events (see Dayan et al., 2015, for a detailed review of the most frequent atmospheric conditions resulting in Mediterranean HPEs).

While factors such as strong instability or the presence of a Mediterranean low in the vicinity are commonly associated with HPEs (Jansa et al., 2001, 2014), the concurrence of these weather features does not ensure the development of extreme precipitation. For example, in autumn, and other seasons too, the presence of Mediterranean cyclones is certainly much more frequent (Campins et al.,2011) than the occurrence of catastrophic flooding episodes (Llasat et al., 2013). Thus, an important question arises: what is the discriminating factor among many apparently similar weather situations where only one produces an HPE? The starting hypothesis of this work is that the factor setting extreme precipitation situations apart is the existence of a very large moisture supply from remote regions outside the Mediterranean. This very humid external influx, when added to local moisture, would yield the enormous amounts of total precipitable water (TPW) needed to produce the rain accumulations commonly recorded in these episodes, which often remind of the values associated with tropical systems. Once sufficient TPW is present, any mechanism able to concentrate and release this moisture over a small area can cause a flood-producing precipitation event. Under this hypothesis, the configuration of the large-scale circulation would therefore be also critical, since it determines whether an intense moisture transport from remote regions can be established or not.

Different studies support the aforementioned idea, especially those that point to the interaction with tropical regions as being key in the development of mid-latitude HPEs. The argument is that when extra-tropical baroclinic low pressure systems descend enough in latitude, they have the chance to capture large amounts of moisture generated in the tropics and advect them into the mid-latitudes and beyond. Thus, a high risk of severe rainfall would be induced if that high moisture content is forced upward by some mechanism, such as orographic lift. The phase of the baroclinic wave should be such allowing this moisture to enter the circulation on the eastern side of the cyclone, often funneled along the cold front, and then be transported poleward resulting in well-known structures such as tropical plumes or atmospheric rivers. Tropical moisture exports have been shown to be important contributors to precipitation in mid-latitude regions in both hemispheres, especially relevant for extreme precipitation (Knippertz and Wernli, 2010; Knippertz et al., 2013). Case studies of HPEs in different parts of the planet, such as the west coast of the United States and Europe, conclude that moisture from tropical and subtropical regions can be essential, comprising most of the TPW feeding these severe episodes (e.g. Stohl et al., 2005; Eiras-Barca et al., 2017). The tropical-extratropical connection in the aforementioned cases occurred through an atmospheric river, advecting highly humid air from lower latitudes to the affected areas. In the WMR, studies for different events also evidence the important role that tropical moisture exports can play in the development of HPEs (e.g. Winschall et al., 2014; Krichak et al., 2015). Some even go further and claim that tropical systems, such as Atlantic hurricanes and their extratropical remnants, can be instrumental, by injecting large amounts of moisture into the Mediterranean Basin (e.g. Pinto et al., 2001; Reale et al., 2001). In the Eastern Mediterranean, different research have also shown the importance for heavy precipitation of moisture transport from the tropics, sometimes reflected in the formation of tropical plumes (e.g. Ziv, 2001; Rubin et al., 2007). Another example of how tropical-extratropical interactions can trigger Mediterranean severe rains come from Wu et al. (2013), who found that the interaction of the (6-9 days) African easterly wave with mid-latitude low pressure systems resulted in large moisture exports from the tropics that were fundamental in producing the precipitation inducing floods in 2000 and 2002. All these studies reinforce the need to look at the problem of extreme precipitation in the Mediterranean region from a more global perspective and discard a local or regional view, particularly in the case of moisture origin.

However, in the ample literature analyzing the different contributors to the genesis of HPEs in the Western Mediterranean, moisture as a key factor is sometimes undervalued or not considered in depth, often assuming that the high values of TPW involved in these events originate locally at low levels from sea evaporation. But, where does such large amount of water vapour really come from? Is it evaporation in the Mediterranean the main source or, on the contrary, does most of the moisture in precipitation originate remotely?"

Nieto, R., Gimeno, L., de La Torre, L., Ribera, P., Gallego, D., García-Herrera, R., ... & Lorente, J. (2005). Climatological features of cutoff low systems in the Northern Hemisphere. Journal of Climate, 18(16), 3085-3103.

Nieto, R., Sprenger, M., Wernli, H., Trigo, R. M., & Gimeno, L. (2008). Identification and Climatology of Cut-off Lows near the Tropopause. Annals of the New York Academy of Sciences, 1146(1), 256-290.

Dayan, U., Nissen, K., & Ulbrich, U. (2015). Atmospheric conditions inducing extreme precipitation over the eastern and western Mediterranean. Natural Hazards & Earth System Sciences Discussions, 3(11).

Jansa, A., Genoves, A., Picornell, M. A., Campins, J., Riosalido, R., & Carretero, O. (2001). Western Mediterranean cyclones and heavy rain. Part 2: Statistical approach. Meteorological Applications, 8(1), 43-56.

Jansa, A., Alpert, P., Arbogast, P., Buzzi, A., Ivancan-Picek, B., Kotroni, V., ... & Speranza, A. (2014). MEDEX: a general overview. Natural Hazards and Earth System Sciences, 14(8), 1965-1984.

Campins, J., Genovés, A., Picornell, M. A., & Jansà, A. (2011). Climatology of Mediterranean cyclones using the ERA-40 dataset. International Journal of Climatology, 31(11), 1596-1614.

Llasat, M. C., Llasat-Botija, M., Petrucci, O., Pasqua, A. A., Rosselló, J., Vinet, F., & Boissier, L. (2013). Towards a database on societal impact of Mediterranean floods within the framework of the HYMEX project. Natural Hazards and Earth System Sciences, 13(5), 1337-1350.

Knippertz, P., & Wernli, H. (2010). A Lagrangian climatology of tropical moisture exports to the Northern Hemispheric extratropics. Journal of Climate, 23(4), 987-1003.

Knippertz, P., Wernli, H., & Gläser, G. (2013). A global climatology of tropical moisture exports. Journal of Climate, 26(10), 3031-3045.

Stohl, A., Forster, C., & Sodemann, H. (2008). Remote sources of water vapor forming precipitation on the Norwegian west coast at 60 N–a tale of hurricanes and an atmospheric river. Journal of Geophysical Research: Atmospheres, 113(D5).

Eiras-Barca, J., Dominguez, F., Hu, H., Garaboa-Paz, D., & Miguez-Macho, G. (2017). Evaluation of the moisture sources in two extreme landfalling atmospheric river events using an Eulerian WRF tracers tool. Earth System Dynamics, 8(4), 1247.

Winschall, A., Sodemann, H., Pfahl, S., & Wernli, H. (2014). How important is intensified evaporation for Mediterranean precipitation extremes?. Journal of Geophysical Research: Atmospheres, 119(9), 5240-5256.

Krichak, S. O., Barkan, J., Breitgand, J. S., Gualdi, S., & Feldstein, S. B. (2015). The role of the export of tropical moisture into midlatitudes for extreme precipitation events in the Mediterranean region. Theoretical and applied climatology, 121(3-4), 499-515.

Pinto, J. G., Klawa, M., Ulbrich, U., Rudari, R., & Speth, P. (2001, October). Extreme precipitation events over northwest Italy and their relationship with tropical–extratropical interactions over the Atlantic. In Proceedings of the third EGS Plinius Conf. on Mediterranean Storms, Baja Sardinia, Italy, GNDCI Publication (No. 2560, pp. 321-332).

Reale, O., Feudale, L., & Turato, B. (2001). Evaporative moisture sources during a sequence of floods in the Mediterranean region. Geophysical research letters, 28(10), 2085-2088.

Ziv, B. (2001). A subtropical rainstorm associated with a tropical plume overAfrica and the Middle-East. Theoretical and Applied Climatology, 69(1-2), 91-102.

Rubin, S., Ziv, B., & Paldor, N. (2007). Tropical plumes over eastern North Africa as a source of rain in the Middle East. Monthly Weather Review, 135(12), 4135-4148.

Wu, M. L. C., Reale, O., & Schubert, S. D. (2013). A characterization of African easterly waves on 2.5–6-day and 6–9-day time scales. Journal of Climate, 26(18), 6750-6774.

Minor comments:

The WVT could become a formidable tool, particularly because is coupled with the WRF, which is very well known and used worldwide. The Authors should consider distributing it, either through their own portal, or in collaboration with an WRF development team. It would gather widespread attention if it became an easily accessible methodology. I find particularly important, compared to earlier studies, the ability of investigating sources on a 3D scale.

Thank you for your suggestion. As we have also commented to the other reviewer, we are currently considering making the code open access.

Figures. The clarity of the figures illustrating the synoptic situation could be improved. Even coastlines and geographic features are barely detectable. In Figure 3a, I suggest blanking out the temperatures around 0C (such as -2 2) so as to have a white strip between cold and warmer air, and use less intense colors. If done in GrADS, the Authors could consider the use of transparencies which is now an option and allows more readable plots. Otherwise, just use lighter colors.

In figure 3b, I suggest to blank out completely the values of tpw less than 10mm. These are not relevant to this work, indicate simply drier air, and by eliminating them the emphasis would be given to the huge moisture plume stretching from the subtropical Atlantic towards the Iberian peninusula.

Similar suggestions for Figure 8.

We have modified Figure 3 and Figure 8 following the reviewer's suggestions:

Figure 3

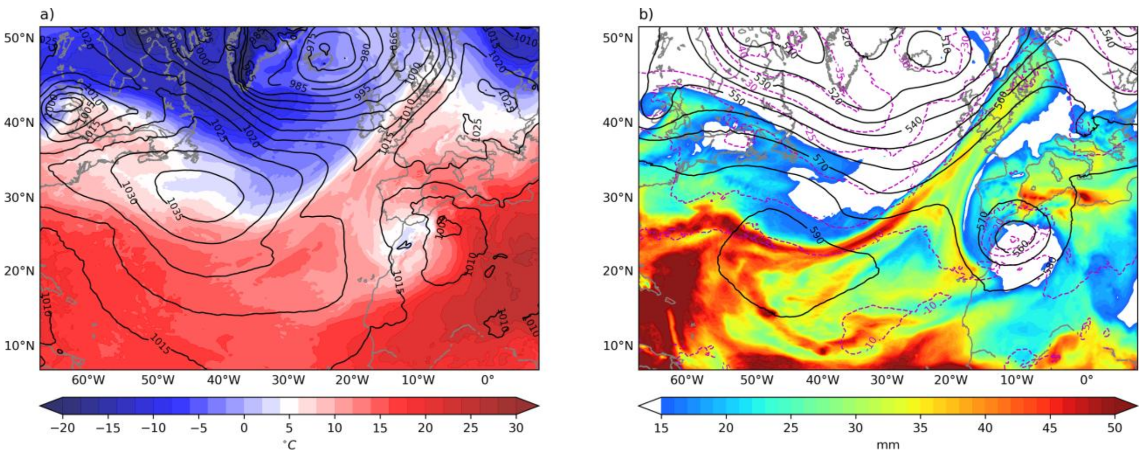
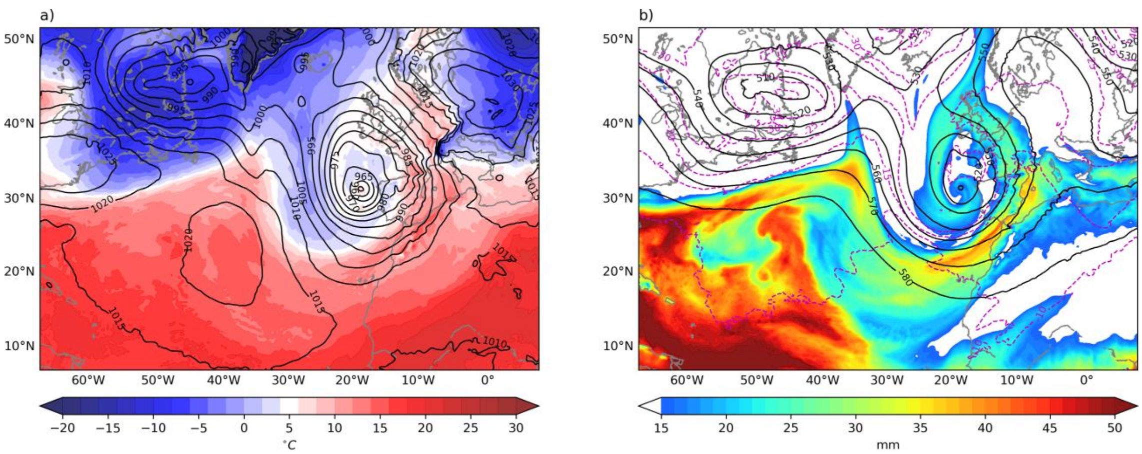


Figure 8



In the text, there are some sentences whose clarity could be improved. See for example page 4, lines 7-8, d

The sentence will be clarified.

Page 18, line 14.. a semantic issue.. Instead of 'verify the hypothesis' .. . Consider something like 'corroborate the idea that remote sources of moisture from the tropics contribute to an important fraction of extreme precipitaiton events in the midlatitudes..'

The sentence will be corrected as suggested.

In summary, aside from these relatively minor suggestions, I believe that the article is a great contribution to precipitation research, and I recommend acceptance after minor revision. However, I believe that the article would benefit by placing the results into the broader context of tropical-extratropical interactions and large scale advection of tropical moisture.

Thank you again for your positive comments.

Correction of the answer to Oreste Reale (R2) in the Interactive comment on "Local and remote moisture sources for extreme precipitation: a study of the two famous 1982 Western Mediterranean episodes" by **Damián Insua-Costa et al.**

In the previous comment, we proposed to modify and extend the first part of the introduction following the reviewer's suggestions. After those changes, the third paragraph of the introduction dealt with the importance of tropical-extratropical interactions for mid-latitudes extreme precipitation:

"Different studies support the aforementioned idea, especially those that point to the interaction with tropical regions as being key in the development of mid-latitude HPEs. The argument is that when extra-tropical baroclinic low pressure systems descend enough in latitude, they have the chance to capture large amounts of moisture generated in the tropics and advect them into the mid-latitudes and beyond. Thus, a high risk of severe rainfall would be induced if that high moisture content is forced upward by some mechanism, such as orographic lift. The phase of the baroclinic wave should be such allowing this moisture to enter the circulation on the eastern side of the cyclone, often funneled along the cold front, and then be transported poleward resulting in well-known structures such as tropical plumes or atmospheric rivers. Tropical moisture exports have been shown to be important contributors to precipitation in mid-latitude regions in both hemispheres, especially relevant for extreme precipitation (Knippertz and Wernli, 2010; Knippertz et al., 2013). Case studies of HPEs in different parts of the planet, such as the west coast of the United States and Europe, conclude that moisture from tropical and subtropical regions can be essential, comprising most of the TPW feeding these severe episodes (e.g. Stohl et al., 2005; Eiras-Barca et al., 2017). The tropical-extratropical connection in the aforementioned cases occurred through an atmospheric river, advecting highly humid air from lower latitudes to the affected areas. In the WMR, studies for different events also evidence the important role that tropical moisture exports can play in the development of HPEs (e.g. Winschall et al., 2014; Krichak et al., 2015). Some even go further and claim that tropical systems, such as Atlantic hurricanes and their extratropical remnants, can be instrumental, by injecting large amounts of moisture into the Mediterranean Basin (e.g. Pinto et al., 2001; Reale et al., 2001). In the Eastern Mediterranean, different research have also shown the importance for heavy precipitation of moisture transport from the tropics, sometimes reflected in the formation of tropical plumes (e.g. Ziv, 2001; Rubin et al., 2007). Another example of how tropical-extratropical interactions can trigger Mediterranean severe rains come from Wu et al. (2013), who found that the interaction of the (6-9 days) African easterly wave with mid-latitude low pressure systems resulted in large moisture exports from the tropics that were fundamental in producing the precipitation inducing floods in 2000 and 2002. All these studies reinforce the need to look at the problem of extreme precipitation in the Mediterranean region from a more global perspective and discard a local or regional view, particularly in the case of moisture origin."

We think it is too early to talk about this now and we prefer to postpone this topic for another article we are working on. In the later article, which we are about to finish, we deal with a much larger number of cases (all major flooding events in the last 35 years), so we hope to draw much more general conclusions. It is at that point that we will attempt to link Mediterranean heavy precipitation events with tropical-extratropical connections, and we will compare the results obtained with those obtained by other authors. In short, we prefer to leave this topic for the closing of our project (my PhD thesis) rather than for the opening. For this reason, we now propose deleting the aforementioned third paragraph.

With this last correction and some other minor modification, the first part of the introduction would read as follows:

"The Western Mediterranean Region (WMR) is characterized by a high frequency in the occurrence of torrential rainfall episodes and floods that cause severe damages, with a very high social and economic impact (Llasat et al., 2010; Jansà et al., 2014). An analysis carried out in the framework of the HYMEX program (Drobinski et al., 2013) showed that 385 flood events (including flash-floods and urban floods) occurred between 1981 and 2010 in north-east Spain, south-east France and south-west Italy (Llasat et al., 2013). The main mechanism generating these heavy precipitation events (HPEs) is the strong instability induced by the warm and moist air at low levels that for most of the year sits over the mild Mediterranean waters and the ensuing vigourous convection is usually triggered by the surrounding mountains or convergence lines (Buzzi et al., 1998; Rotunno and Ferretti, 2003; Llasat, 2009). Jansà et al. (2014) and Reale and Lionello (2013) showed that heavy precipitation in the Mediterranean is usually directly or indirectly related to intense, weak or moderate cyclones. Particularly, they found that in more than 80% of heavy rain cases produced in the Western Mediterranean, a cyclone was situated nearby, in a proper location for organising a warm and moist inflow into the affected area (Jansà et al., 2001; Campins et al., 2011). Most cases occur in autumn, when the combination of a still warm sea surface temperature (after a peak in late summer), and a southward displacement of the jet stream, which usually favours the appearance of Atlantic lows or cut-off-lows (COL's; e.g. Nieto et al., 2005, 2008) affecting the WMR, make this season the most favourable for the development of these extreme events (see Dayan et al., 2015, for a detailed review of the most frequent atmospheric conditions resulting in Mediterranean HPEs).

While factors such as strong instability or the presence of a Mediterranean low in the vicinity are commonly associated with HPEs, as stated in the previous paragraph, the concurrence of these weather features does not ensure the development of extreme precipitation. For example, in autumn, and other seasons too, the presence of Mediterranean cyclones is certainly much more frequent than the occurrence of catastrophic flooding episodes. Similarly, COL's affecting the Iberian Peninsula are more frequent in spring than summer and located west rather than east of Iberia, but heavy rainfall and floods are mainly recorded on the eastern Iberian Mediterranean shore and in autumn. Thus, an important question arises: what is the discriminating factor among many apparently similar weather situations where only one produces an HPE? The starting hypothesis of this work is that the factor setting extreme precipitation situations apart is the existence of a very large moisture supply from remote regions outside the Mediterranean. This very humid external influx, when added to local Mediterranean moisture, would yield the enormous amounts of total precipitable water (TPW) needed to produce the rain accumulations commonly recorded in these episodes, which often remind of the values associated with tropical systems. Once sufficient TPW is present, any mechanism able to concentrate and release this moisture over a small area can cause a flood-producing precipitation event. Under this hypothesis, the configuration of the large-scale circulation would therefore be also critical, since it determines whether an intense moisture transport from remote regions can be established or not.

However, in the ample literature analyzing the different contributors to the genesis of HPEs in the Western Mediterranean, moisture as a key factor is sometimes undervalued or not considered in depth, often assuming that the high values of TPW involved in these events originate locally at low levels from sea evaporation. But, where does such large amount of water vapour really come from? Is it evaporation in the Mediterranean the main source or, on the contrary, does most of the moisture in precipitation originate remotely?

There are, nevertheless, several authors that in the last two decades have used different numerical techniques to answer these fundamental questions. Reale et al. (2001), employing the quasi-isentropic water vapour back-trajectory method (Dirmeyer and Brubaker, 1999), showed that moisture transported by three (westward moving) Atlantic tropical systems and their extra-tropical remnants contributed significantly to the series of floods that affected the north-western and north-central Mediterranean in September and October of 1998. Turato et al. (2004) with the same tool demonstrated that remote moisture sources, mainly the Atlantic Ocean, were crucial in the October 2000 Piedmont flood, and concluded that the contribution of evaporated moisture in the Mediterranean was lower than presumed, at around 20% of the total. Duffourg and Ducrocq (2011) studied the moisture origin and pathways in ten HPEs that took place during the autumn of years 2008 and 2009 in the French Mediterranean region. They also used a water vapour back-trajectory technique, in this case couppled to the Meso-NH atmospheric model (i.e., on-line), concluding that when anticyclonic conditions are dominant during the 3 or 4 days prior to the HPE, the contribution of the moisture from the Mediterranean Sea is clearly dominant, whereas when cyclonic conditions prevail, remote moisture sources have a major role. Pinto et al. (2013), combining a qualitative with a backward trajectory analysis, studied a large number of events (classified in six clusters) ocurred in Northwestern Italy betwen 1938 and 2002, and found that the North Atlantic is a relevant moisture source for precipitation, particularly important in the extraordinary cases. More recently, Krichak et al. (2015) applied a similar method for more than 50 intense cool season HPEs recorded in different parts of the Mediterranean region from 1962 to 2007. Their results highlighted the outstanding role played by tropical moisture reaching the Mediterranean from the Atlantic Ocean and the Arabian Sea. All these studies agree on the importance of the moisture contribution from remote sources, thus supporting our starting hypothesis that a very large moisture supply from regions outside the Mediterranean is often the key factor in these types of episodes. However, practically all of these studies were carried out with Lagrangian models, based on the spatiotemporal tracking of individual fluid particles. This method, despite being very useful for its low computational cost and easy handling, presents a series of simplifications that can introduce important inaccuracies in the calculations, such as errors in particle trajectories (Stohl, 1998) or limitations in the separation between evaporation and precipitation (Stohl and James, 2004). Therefore, further work is needed in this line of research in order to obtain a more complete knowledge about the moisture sources for these extreme rains.”

Local and remote moisture sources for extreme precipitation: a study of the two ~~famous~~ catastrophic 1982 Western Mediterranean episodes

Damián Insua-Costa[1], Gonzalo Miguez-Macho[1], and María Carmen Llasat[2]

[1]Non-Linear Physics Group, Universidade de Santiago de Compostela, Galicia, Spain
[2]Department of Applied Physics, Universitat de Barcelona, Barcelona, Spain

Correspondence: Damián Insua Costa (damian.insua@usc.es)

Abstract. Floods and flash floods are frequent in the South of Europe resulting from heavy rainfall events that often produce more than 200 mm in less than 24 h. Even though the meteorological conditions favorable for these situations have been widely studied, there is a lingering question that still arises: which are the sources of humidity that could explain so much precipitation? To answer this question, the regional atmospheric Weather Research and Forecasting (WRF) Model with a recently implemented moisture tagging capability has been used to analyze the main moisture sources in two ~~famous~~ catastrophic flood events occurred during the autumn of 1982 (October and November) in the Western Mediterranean area, which is regularly affected by this type of adverse weather episodes. The procedure consists in selecting a priori potential moisture source regions for the considered extreme event, and then performing simulations with the tagging technique to quantify the relative contribution of each selected source to total precipitation. For these events we study the influence of four possible potential sources: 1) evaporation in the Western Mediterranean; 2) evaporation in the Central Mediterranean; 3) evaporation in the North Atlantic; 4) advection from the tropical and subtropical Atlantic and Africa. Results show that these four moisture sources explain most of the accumulated precipitation, with the tropical and subtropical input being the most relevant in both cases. In the October event, evaporation in the Western and Central Mediterranean and in the North Atlantic also had an important contribution. In the November episode, however, tropical and subtropical moisture accounted for more than half of the total accumulated rainfall, while evaporation in the Western Mediterranean and North Atlantic played a secondary role and the contribution of the Central Mediterranean was almost negligible. Remote sources were therefore crucial: in the October event they played a similar role to local sources while in the November case they were clearly dominant. In both episodes, long distance moisture transport from the tropics and subtropics occurred mostly in mid tropospheric layers, through well-defined moisture plumes with maximum mixing ratios at medium levels.

1 Introduction

The Western Mediterranean Region (WMR) is characterized by a high frequency in the occurrence of torrential rainfall episodes and floods that cause severe damages, with a very high social and economic impact (Llasat et al., 2010). An analysis carried out in the framework of the HYMEX program (Drobinski et al., 2014) showed that 385 flood events (including flash-floods and urban floods) occurred between 1981 and 2010 in north-east Spain, south-east France and south-west Italy (Llasat et al., 2013). The main mechanism generating these heavy precipitation events (HPEs) is the strong instability induced by the warm and moist air at low levels that for most of the year sits over the mild Mediterranean waters , along with the presence of a low pressure system (usually produced by a Mediterranean cyclogenesis event) that can trigger convection and organize the flow (Llasat, 2009). Other factors such as the complex orography of and the ensuing vigourous convection is usually triggered by the region, often take also a very important role (e.g. Buzzi et al., 1998; Rotunno and Ferretti, 2003)surrounding mountains or convergence lines (e.g. Buzzi et al., 1998; Rotunno and Ferretti, 2003; Llasat, 2009). Jansa et al. (2014) and Reale and Lionello (2013) showed that heavy precipitation in the Mediterranean is usually directly or indirectly related to intense, weak or moderate cyclones. Particularly, they found that in more than 80% of heavy rain cases produced in the Western Mediterranean, a cyclone was situated nearby, in a proper location for organising a warm and moist inflow into the affected area (Jansa et al., 2001; Campins et al., 2011). Most cases occur in autumn, when the combination of a still warm sea surface temperature (after a peak in late summer), and a southward displacement of the jet stream(which usually favors , which usually favours the appearance of Atlantic lows or cut-off-lows cut-off lows (COLs; e.g. Nieto et al., 2005) affecting the WMR), make this season the most favourable for the development of these extreme events(Llasat et al., 2013). For a detailed review of the most frequent atmospheric conditions resulting in Mediterranean HPEs, please refer to Dayan et al. (2015).

In While factors such as strong instability or the presence of a Mediterranean low in the vicinity are commonly associated with HPEs, the concurrence of these weather features does not ensure the development of extreme precipitation. For example, in autumn, and other seasons too, the presence of Mediterranean cyclones is certainly much more frequent than the occurrence of catastrophic flooding episodes. Similarly, COLs affecting the Iberian Peninsula are more frequent in summer and located west rather than east of Iberia (Nieto et al., 2008), but heavy rainfall and floods are mainly recorded on the eastern Iberian Mediterranean shore and in autumn. Thus, an important question arises: what is the discriminating factor among many apparently similar weather situations where only one produces an HPE? The starting hypothesis of this work is that the factor setting extreme precipitation situations apart is the existence of a very large moisture supply from remote regions outside the Mediterranean. This very humid external influx, when added to local Mediterranean moisture, would yield the enormous amounts of total precipitable water (TPW) needed to produce the rain accumulations commonly recorded in these episodes, which often remind of the values associated with tropical systems. Once sufficient TPW is present, any mechanism able to concentrate and release this moisture over a small area can cause a flood-producing precipitation event. Under this hypothesis, the configuration of the large-scale circulation would therefore be also critical, since it determines whether an intense moisture transport from remote regions can be established or not.

However, in the ample literature analyzing the different contributors to the genesis of HPEs in the Western Mediterranean, moisture as a key factor is often sometimes undervalued or not considered in depth, assuming that it originates often assuming that the high values of TPW involved in these events originate locally at low levels from sea evaporation. To result in the water accumulations that are commonly recorded in these episodes, which sometimes remind of the values produced by tropical systems, it is necessary, however, that the situation of strong instability is accompanied by a large amount of total precipitable water (TPW) in the atmospheric column. But, where does such large amount of water vapor vapour really come from? Is it evaporation in the Mediterranean the main source or, on the contrary, does most of the moisture in precipitation originate remotely?

~~In~~ There are, nevertheless, several authors that in the last two decades ~~, several authors~~ have used different numerical techniques to answer these fundamental questions (see Gimeno et al., 2012, for a detailed review of numerical methods used in moisture source studies). Reale et al. (2001), employing the quasi-isentropic water vapour back-trajectory method (Dirmeyer and Brubaker, 1999), showed that moisture transported by three (westward moving) Atlantic tropical systems and their extra-tropical remnants contributed significantly to the series of floods that affected the north-western and north-central Mediterranean in September and October of 1998. Turato et al. (2004) with the same tool demonstrated that remote moisture sources, mainly the Atlantic Ocean, were crucial in the October 2000 Piedmont flood, and concluded that the contribution of evaporated moisture in the Mediterranean was lower than presumed, at around 20% of the total. Duffourg and Ducrocq (2011) studied the moisture origin and pathways in ten HPEs that took place during the autumn of years 2008 and 2009 in the French Mediterranean region. They also used a water vapour back-trajectory technique, in this case couppled to the Meso-NH atmospheric model (i.e., on-line), concluding that when anticyclonic conditions are dominant during the 3 or 4 days prior to the HPE, the contribution of the moisture from the Mediterranean Sea is clearly dominant, whereas when cyclonic conditions prevail, remote moisture sources have a major role. Pinto et al. (2013), combining a qualitative with a backward trajectory analysis, studied a large number of events (classified in six clusters) ocurred in Northwestern Italy betwen 1938 and 2002, and found that the North Atlantic is a relevant moisture source for precipitation, particularly important in the extraordinary cases. More recently, Krichak et al. (2015) applied a similar method for more than 50 intense cool season HPEs recorded in different parts of the Mediterranean region from 1962 to 2007. Their results highlighted the outstanding role played by tropical moisture reaching the Mediterranean from the Atlantic Ocean and the Arabian Sea. All these studies ~~, and some others not discussed here, have provided quite a detailed knowledge about the origin of the moisture feeding extreme rainfall in the Mediterranean region. They all~~ agree on the importance of ~~evaporation from the Mediterranean Sea, but also on the necessary~~ the moisture contribution from remote sources, ~~without which such large accumulations of precipitation would not be possible~~thus supporting our starting hypothesis that a very large moisture supply from regions outside the Mediterranean is often a key factor in these types of episodes. However, practically all of these studies were carried out with Lagrangian models, based on the spatiotemporal tracking of individual fluid particles. This method, despite being very useful for its low computational cost and easy handling, presents a series of simplifications that can introduce important inaccuracies in the calculations, such as errors in particle trajectories (Stohl, 1998) or limitations in the separation between evaporation and precipitation (Stohl and James, 2004). Therefore, further work is needed in this line of research in order to obtain a more complete knowledge about the moisture sources for these extreme rains.

The novelty of this article is the application of a non-Lagrangian technique for the study of moisture origin in WMR HPEs. We use an online Eulerian method, generally known as water vapor tracers (WVTs) method, which is based on coupling a moisture tagging technique with a global or regional meteorological model. This tool is currently regarded as the most accurate in moisture source studies, and has only been applied to Mediterranean events by Winschall et al. (2012). These authors analyzed the origin of moisture feeding the extreme precipitations in Piedmont in November 2002, and found that the three main sources were land evapotranspiration, evaporation from the Mediterranean and North Atlantic moisture. In the present study, we aim at applying a new WVT moisture tagging capability recently implemented into the Weather Research and Forecasting (WRF) regional meteorological model(Insua-Costa and Miguez-Macho, 2018), the so-called WRF-WVT tool. This implementation has been thoroughly validated (Insua-Costa and Miguez-Macho, 2018), showing that the method presents a high accuracy, and thus it will allow us to quantify the contribution of different moisture sources and to perform a detailed three dimensional separation of water vapor from different origins in the development of HPEs in the Mediterranean.

Precisely, we will apply the method to two famous infamous HPEs occurred in the NWMR (North Western Mediterranean Region) during the autumn of 1982. The selection of these two cases is mainly based on the enourmous socioeconomic impact they had, which is why even today they are well remembered by the population. Both events appear, for example, in the list of major flood disasters in Europe between 1950 and 2005 (Barredo, 2007) and are still present in the scientific community and the media. The first of these episodes occurred in October and particularly affected the Spanish Levant area. The highest precipitation amounts were observed on days 19, 20 and 21, especially on day 20, with a maximum of 426 mm fallen in Cofrentes (Valencia, Spain). Particularly dramatic was the situation in the vicinity of the Tous dam, since the exceptionally intense precipitation recorded in the river Júcar basin (where the dam is situated) caused its rupture, seriously aggravating flooding downstream. The consequences were catastrophic; there were 40 fatal victims and about 630M$ (uninflated) in economic-losses (Barredo, 2007). The second event took place only a few days later, between November 6 and 8, with special intensity on the 7th. In this occasion, precipitation affected especially the northeast of Spain (Catalonia), Andorra and the south-east of France, with remarkable amounts such as the 408 mm recorded in Valcebollère (French Pyrenees) and 342 mm in La Molina (Catalan Pyrenees), both in 24 hours. The consequences of the event were also catastrophic; 42 casualties, adding the victims of Spain, Andorra and France (Trapero et al., 2013), and about 300M$ (uninflated) in damages in Catalonia alone (Llasat et al., 2013). A notable feature of these two episodes is that they represent two of the most common types of situation the two most common atmospheric circulation patterns associated with HPEs in the NWMR (see AP3 and AP13 weather types in the classification of Romero et al., 1999), so the conclusions obtained in this work could be extrapolated to many other cases.

The study is structured as follows: Section 2 describes the methodology and the data used, where in addition it will be presented in a more detailed way the WVT method and the WRF-WVT tool. Section 3 and 4 show the results obtained by applying the method to the cases of October and November 1982, respectively, and finally, Section 5 contains a summary and conclusions of the work.

2 Methods

2.1 The WVT method and the WRF-WVT tool

From a physical point of view, the WVT method can be conceptualized as the release of a dye within the hydrological cycle representation of a meteorological model. Moisture originating from a particular source is traced until it leaves the simulation

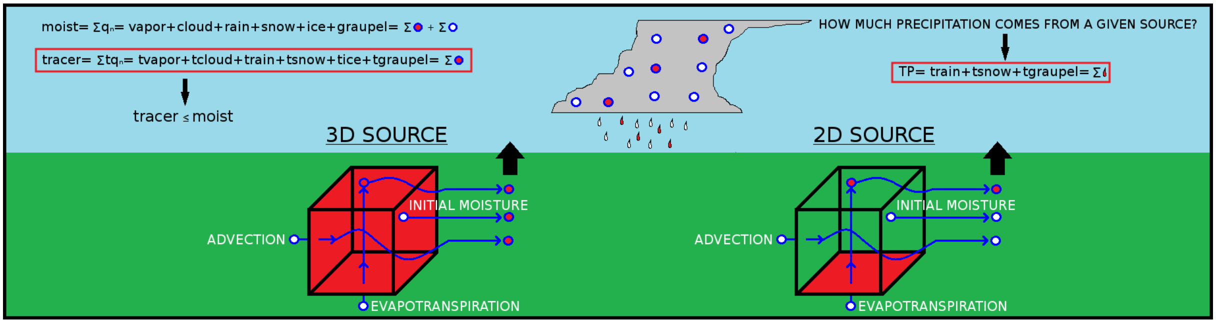


Figure 1. Sketch representing the fundamentals of the moisture tracer method, including the tagging of 3D and 2D moisture sources ~~(from Insua-Costa and Miguez-Macho (2018)~~(from Insua-Costa and Miguez-Macho, 2018).

domain or precipitates, thus making it possible to know in detail the contribution of the considered source to total precipitation at any point in a given model grid (Fig. 1).

From a mathematical point of view, the WVT method consists in replicating for moisture tracers the prognostic equations for total moisture. The equations for tracers are thus in Eulerian form, fully coupled to the full moisture equations, and must be solved simultaneously with them, i.e. "online". The reason for the latter is that in tracer calculations, eddy diffusivities in turbulent mixing are the same as those for full moisture, and in convection and microphysics processes, phase changes among the different tracer species occur as for their full moisture counterparts, but in amounts proportional to the tracer fraction in the species undergoing the change. The WVT method is therefore an online Eulerian moisture tracking strategy, highly accurate and distinct from the most commonly used Lagrangian particle tracking methods, which are integrated offline. For specific details of the implementation of the WVT method in WRF that we use here (WRF-WVTs) and its validation, please refer to Insua-Costa and Miguez-Macho (2018).

Among the different scheme options available in WRF, moisture tracking is currently implemented in the Yonsei University (YSU; Hong et al., 2006) PBL scheme, the WRF-Single-Moment 6-class (WSM6; Hong and Lim, 2006) microphysics scheme and the Kain-Fritsch (Kain, 2004) convective parameterization. Therefore, it is mandatory to choose these three parameterizations when working with WRF-WVTs, although in a convective-resolving scale, tracers can also be used without the Kain-Fritsch parameterization. In accordance with these parameterization choices, six tracer species are considered, namely tracer water vapor, cloud water, rain, snow, ice and graupel. In addition, there are also four new variables corresponding to the different types of tracer precipitation (tracer convective rainfall, tracer stratiform or grid-resolved rainfall, tracer snowfall and tracer graupel).

WRF-WVTs allows moisture tracking from two-dimensional (2D) and three-dimensional (3D) sources (Fig. 1). A 2D source refers to tagging moisture from surface evapotranspiration over a certain area. For its part, a 3D source encompasses the entire atmosphere over a region of interest, or only a part of it (for example the stratosphere), from which all exiting moisture is tagged.

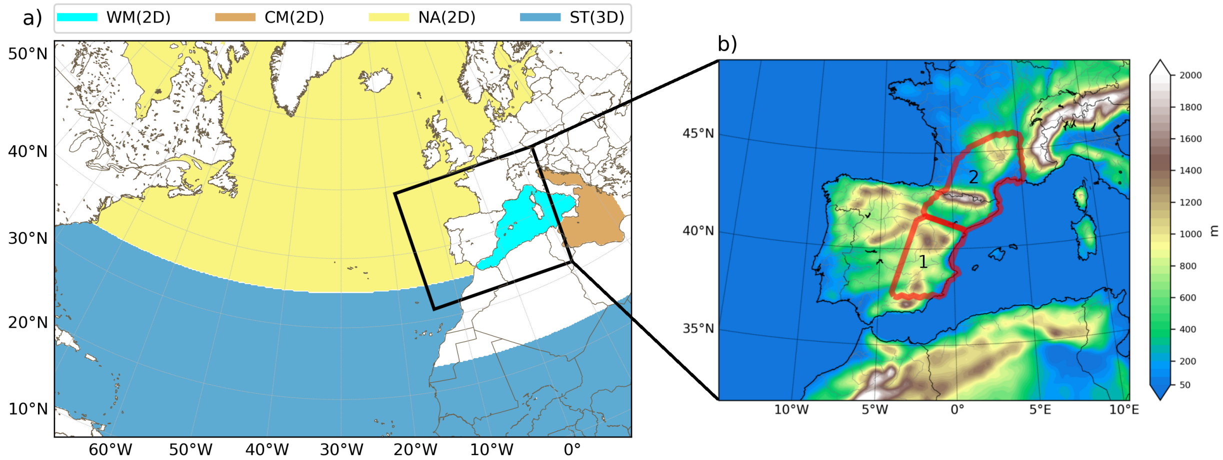


Figure 2. (a) Simulation domain and moisture sources considered: Western Mediterranean (light blue), Central Mediterranean (brown) and North Atlantic (yellow) two-dimensional sources and tropical and subtropical three-dimensional source (dark blue). (b) Domain for precipitation analysis with topography (m) in shades. The areas highlighted in red are the most affected by the October (1) and the November event (2).

2.2 Experimental design

We consider four source regions, three two-dimensional and one three-dimensional. The three 2D source regions cover the Western Mediterranean, the Central Mediterranean and the North Atlantic evaporative sources respectively, whereas the 3D source region tags moisture advected from the tropical and subtropical Atlantic and from tropical Africa (Fig. 2a). The 2D sources target sea evaporation; however, the tropical and subtropical regions are taken as a 3D source in order to include both evaporation and atmospheric water transport from further possibly relevant tropical or subtropical areas outside the model grid, such as the Gulf of Mexico~~or the Arabian Sea~~, which is a relevant moisture source for precipitation in the WMR according to different climatic studies (Gimeno et al., 2009; Nieto et al., 2010). Special care has been taken not to tag humidity from any source twice. For example, moisture evaporated in the North Atlantic is only considered once, even when it reaches the Iberian Peninsula after traversing the 3D subtropical source region. Finally, we note that we do not contemplate all possible moisture sources, such as land evapotranspiration from different continental regions. We assume that in autumn it is very diminished and hence it does not have a potentially important contribution (e.g. Sodemann and Zubler, 2010; Drumond et al., 2011).

With this sources' selection, we will be able to clarify the origin of moisture on the large scale only. In other words, we can determine whether moisture is of local or remote origin, but we will not be able to ensure, for example, where exactly in the Atlantic or tropics this humidty mostly comes from. We could subdivide the four selected sources into many more and then achieve much more detail, but for each selected moisture source a separate simulation must be carried out, with the corresponding increse in comutational cost. For example, for 1 × 1 degree source regions, this means hundreds of simulations just for one case. The selection proposed here is based on the choice of quite extensive sources, which does not mean they are not enlightening: a distinction is made between local (Mediterranean) and remote (Atlantic) humidity; within the remote we distinguish between tropical and non-tropical and within the local between Western and Central Mediterranean.

Simulations for both events start 10 days before their respective main date (October 20 and November 7), thereby allowing moisture sufficient time to evaporate and travel to the area affected by extreme rainfall (highlighted in red in Fig. 2b). Furthermore, this 10-day period roughly coincides with the average residence time of water vapor in the atmosphere (e.g. Trenberth, 1998; Van Der Ent and Tuinenburg, 2017); thus we can neglect the contribution of the moisture present at initial time in the atmospheric volume of the considered domain. The total time span of the experiments is 12 days.

2.3 Model configuration and data used

The simulations for the two 1982 HPEs are performed with the WRF model version 3.8.1 (Skamarock et al., 2008) using a single domain of 20km horizontal resolution and 35 vertical levels. Initial and boundary conditions were obtained from ERA-Interim reanalysis (Dee et al., 2011) with spatial resolution of 0.7º and updated every six hours. In addition to the YSU boundary layer parameterization, WSM6 microphysics scheme and Kain-Fritsch convective parameterization (required when the WRF-WVT tool in its current version is activated), we have also used the Rapid Radiative Transfer Model (RRTM; Mlawer et al., 1997) and Dudhia (Dudhia, 1989) schemes for long and shortwave radiation, respectively, and the Noah Land Surface Model (Noah LSM; Chen and Dudhia, 2001). Spectral nudging of the synoptic circulation in the grid (about 1000km wavelength and longer) towards reanalysis has been applied to avoid distortions due to the interaction between the model's solution and the lateral boundary conditions (Miguez-Macho et al., 2004). Moisture and tracer advection are calculated with the 5th order Weighted Essentially Non-Oscillatory (WENO; Liu, 1994) scheme with positive definite limiter. Finally, for model rainfall validation we use the MESCAN ~~precipitation analysis dataset(Soci et al., 2016),~~ (from Mesoscale Analysis; Soci et al., 2016) system, which combines a downscaled reanalysis and interpolated rain gauge mesurements to get a high resolution (5.5 km) daily precipitation dataset. This product is recently available in the ECMWF MARS (Meteorological Archival and Retrieval System) ~~archive at 5.5 km resolution and covering~~ and covers our entire area of study.

3 The October event

3.1 Synoptic situation and precipitation

The October 1982 case, also known as the Tous event, was associated with a cold-core ~~cut-off low~~COL, which had originated from an Atlantic trough and was centered aloft over Morocco on the 20th, the main day of the episode (Fig. 3b). This configuration caused a marked increase in instability and the emergence of dynamic forcings favouring the appearance of upward air motions in the Spanish Levant area, the one most affected by the torrential rains. At lower levels, the cyclone consisted of an extensive low-pressure system with center over Algeria, which organized a relatively warm (Fig. 3a) and very humid (Fig. 3b) easterly flow almost perpendicular to the coast, increasing the chances of heavy precipitation. In Fig. 3b, the high amount

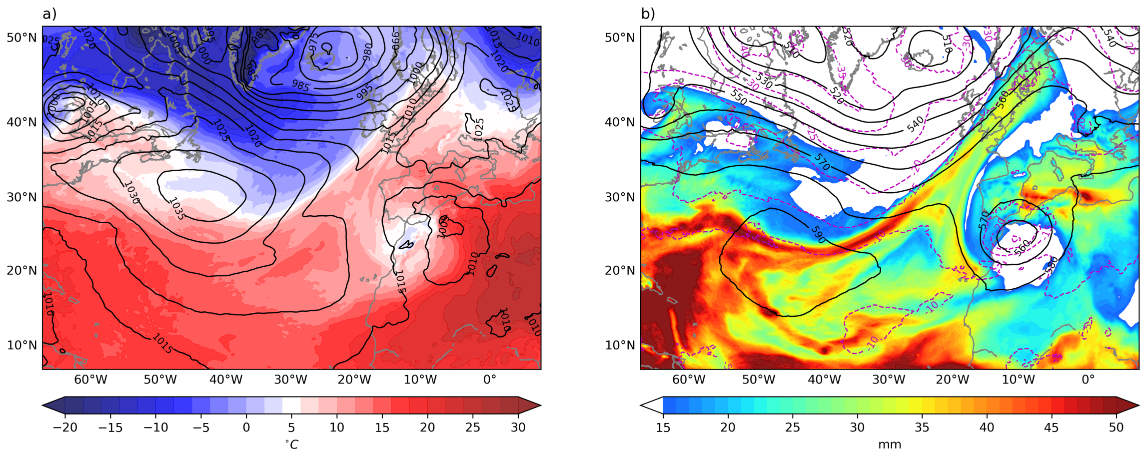


Figure 3. Synoptic situation (from WRF simulation) on October 20, 1982, at 12:00 UTC. (a) Mean sea level pressure (contours, hPa) and 850 hPa temperature (shades, ○C). (b) Geopotential height (solid black contours, dam) and temperature (~~white~~ magenta dashed contours, ○C) at 500 hPa and total precipitable water (shades, mm).

of TPW on the east coast of Spain is particularly noteworthy, with values well above 30 mm. All these elements provided a quasi-ideal scenario for the occurrence of deep moist convection. In fact, during October 20, a mesoscale convective complex (Maddox, 1980), the first identified in Europe, developed east-southeast of the Iberian Peninsula, ultimately causing the HPE (although it was finally defined as a mesoscale convective system, MCS, due to its minor dimensions, Rivera and Riosalido, 1986). For a more in-depth analysis of the factors contributing to this event, please refer to Romero et al. (2000).

Figure 4 shows the observational analysis (Fig. 4a) and simulated (Fig. 4b) precipitation during the days of the event (October 19, 20 and 21). As mentioned earlier, the most affected region by the HPE was the Spanish Levant area and especially the Valencian Community, with maximum precipitation accumulations above 250 mm towards the interior of this region. Note that the recorded amounts in some stations were actually much higher; however, localized peak values are smoothed out in the analyzed precipitation field, since it has a resolution of 5.5 km. Precipitation was well organized around this maximum, which is consistent with the fact that the rains were produced by an almost stationary MCS. The simulated precipitation shows a very good agreement with the observational analysis, both in amounts and spatial distribution. Therefore, despite some discrepancies, we conclude that the model reproduces the episode realistically.

3.2 Moisture origin

Figure 5 shows at 12:00 UTC on October 20, the TPW originating from the different moisture sources considered during the previous 10.5 days, i.e. from the beginning of the simulation (00:00 UTC, October 10). Moisture from evaporation in the Western (Fig. 5a) and Central Mediterranean (Fig. 5b), with total content values in the 5-10 mm range in both cases, remains stagnant in the Mediterranean area, suggesting that throughout the period before the event, the flow was weak in the region as a result of the prevailing anticyclonic situation. The low pressure system situated over North Africa blocks the direct advance of

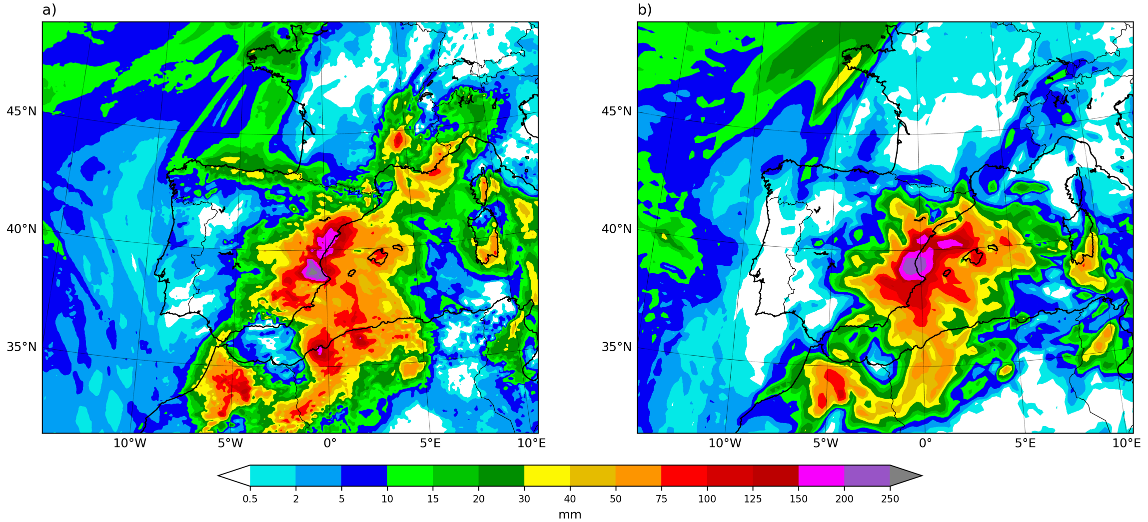


Figure 4. (a) Observed (from MESCAN analysis) and (b) simulated total precipitation (mm) from October 19 at 06:00 UTC to October 22 at 06:00 UTC.

evaporated moisture from the North Atlantic toward the Spanish Levant area (Fig. 5c). Notwithstanding, some of this humidity reaches the region by making its way around the cyclone, and the attained values of TPW from this source are still significant, of around 5 mm. The most important contribution from any source corresponds, however, to that of moisture advected from the tropics and subtropics (Fig. 5d). Following the circulation around the low in North Africa, a well-defined moisture plume rising across the Sahara reaches the east coast of Spain, yielding values of TPW of around 15 mm; locally even exceeding 25 mm.

Figure 6 depicts the source-separated vertical distribution of water vapour 12h before (00:00 UTC, October 20) and 12h after (00:00 UTC, October 21) the time in Fig. 5. Both absolute and relative contribution from each source are reflected. The values shown are spatial averages over the area most affected by the event, highlighted in red and labelled as 1 in Fig. 2b. At the early stages of the episode (Fig. 6a and 6c), the atmospheric moisture content is dominated by evaporative input from the Western Mediterranean and the North Atlantic, and by advection from the tropics and subtropics, with the role played by moisture from the Central Mediterranean being negligible. At the lowest levels of the atmosphere, evaporation from the Western Mediterranean and the North Atlantic in conjunction represent more than 60% of the existing total water vapour. Above 800 hPa, however, moisture becomes increasingly of tropical and subtropical origin, and above 500 hPa these remote sources account for more than 50% of total humidity. As the dynamics of the event progresses, one day later (Fig. 6b and 6d) the vertical distribution of moisture source contribution changes substantially. With the settling in of easterly flow induced by the wide low pressure system over North Africa, moisture content from the North Atlantic becomes almost negligible and it's replaced by Central Mediterranean evaporation. In addition, the injection of tropical and subtropical water vapor is reinforced, clearly becoming the most relevant source in this phase of the event; its presence is very significant in the entire atmospheric column, accounting for more than 60% of the total moisture above 800 hPa. At this stage, the large amount of water present

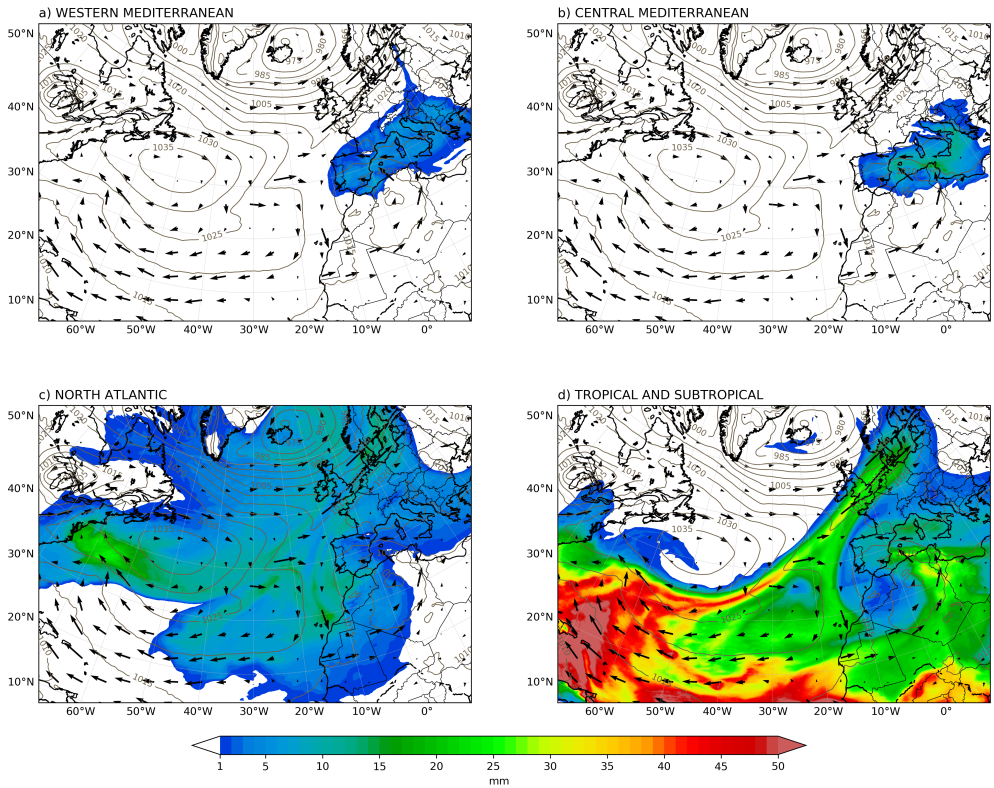


Figure 5. Total precipitable water (mm) coming from the Western Mediterranean (a), the Central Mediterranean (b), the North Atlantic (c) and from the tropical and subtropical Atlantic along with tropical Africa, on October 20 at 12:00 UTC. Contours show mean sea level pressure (hPa) and arrows show the vertically integrated moisture flux (kg m^{-1} s^{-1}).

in the atmosphere at all levels is striking, with a mixing ratio of about 12 g/kg at 950 hPa. Finally, we note that the relative combined contribution of the four sources considered is always higher than 80% throughout the entire column, which agrees with our original hypothesis that other possible moisture sources are of minor importance.

3.3 Precipitation origin

From the previous analysis, it is apparent that moisture at low levels is dominated by evaporative sources, either local (Western Mediterranean) or more distant (first from the North Atlantic, later from the Central Mediterranean), while in mid and upper layers it is mostly of remote tropical and subtropical origin, more so as the event develops. Furthermore, the contribution of this advected moisture from lower latitudes increases significantly the water vapor content throughout the column. We examine next how TPW from each origin translates into precipitation, to address the main question that we posed in this study: how much of the accumulated rainfall in the event is coming from the different analyzed sources. Figure 7 shows a decomposition of the total precipitation field in Fig. 4b according to moisture origin. The contribution from the Western (Fig. 7a) and Central

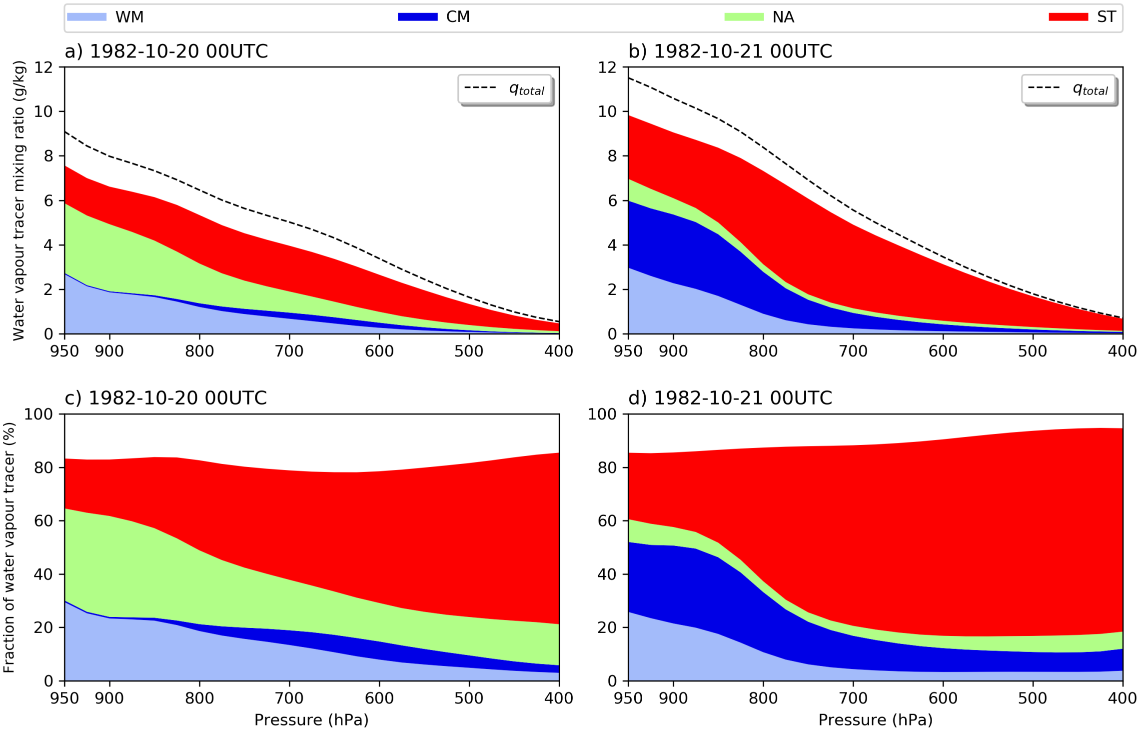


Figure 6. Vertical distribution of water vapour coming from the Western Mediterranean (light blue), the Central Mediterranean (dark blue), the North Atlantic (light green) and from the tropical and subtropical Atlantic along with tropical Africa (red). First-row shows absolute values (g/kg) on October 20 (a) and 21 (b) at 00:00 UTC. Second row depicts relative values (%) on October 20 (c) and 21 (d) at 00:00 UTC. Black dashed lines indicate the total water vapour mixing ratio, from considered and not considered sources (g/kg). Values are area averages over the region highlighted in red and labelled 1 in Fig. 2b.

(Fig. 7b) Mediterranean is approximately equal, with maximum accumulations from October, 19 to 21 exceeding 50 mm in the Spanish Levant area. Here, the amounts coming from North Atlantic evaporation (Fig. 7c), albeit significant, barely reach 30 mm. In North Morocco, another of the impacted regions, the contribution of this source is, however, somewhat higher. Rainfall from tropical and subtropical origin (Fig. 7d) represents the largest share of the total in virtually the entire area affected by the event, with values well above 50 mm over a wide swath around the location of maximum precipitation in Spain.

The relative contribution of the different sources to total precipitation during the main days of the event are quantified in Table 1. Values are calculated over the Spanish Levant area -outlined in red and labelled 1 in Fig. 2b- and shown as percentage of total rainfall. Local moisture from evaporation in the Western Mediterranean basin accounts for only about 20% of precipitation. If we expand the concept of “local” to include the Central Mediterranean, then the contribution from local sources practically doubles, to represent around 40% of the total. In contrast, at least 46% of precipitation originates from water evaporated in remote regions, with tropical and subtropical moisture being the most relevant (31% of the total). The four considered sources

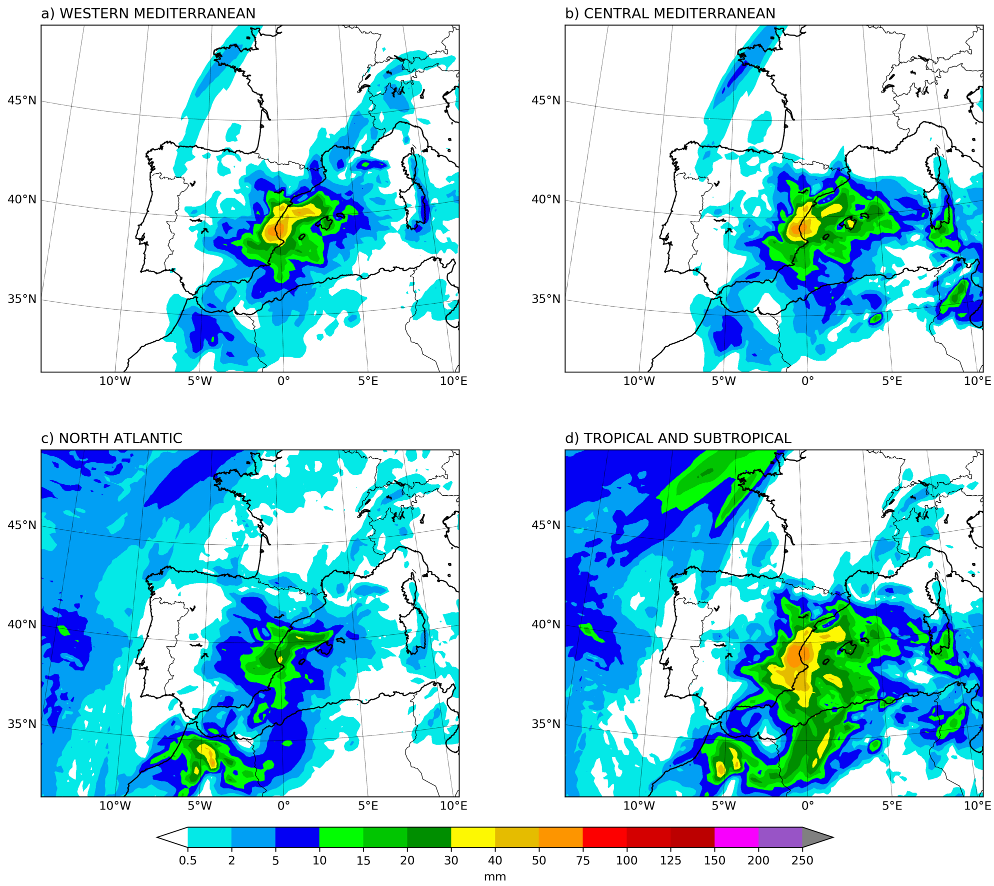


Figure 7. Simulated precipitation (mm) coming from the Western Mediterranean (a), the Central Mediterranean (b), the North Atlantic (c) and the Tropics and Subtropics (d) from October 19 of at 06:00 UTC to October 22 at 06:00 UTC.

account for most of the collected rainfall, around 83%, consistently with the values seen in the previous section for water vapour throughout the atmospheric column.

Table 1. Relative contribution (%) of the considered moisture sources to the accumulated precipitation from October 19 at 06:00 UTC to October 21 at 06:00 UTC in the most affected area (region 1 in Fig. 2b).

	Western Mediterranean	**Central Mediterranean**	**North Atlantic**	**Tropical and Subtropical**
Relative Contribution (%)	19,14	18,28	14,89	31,02

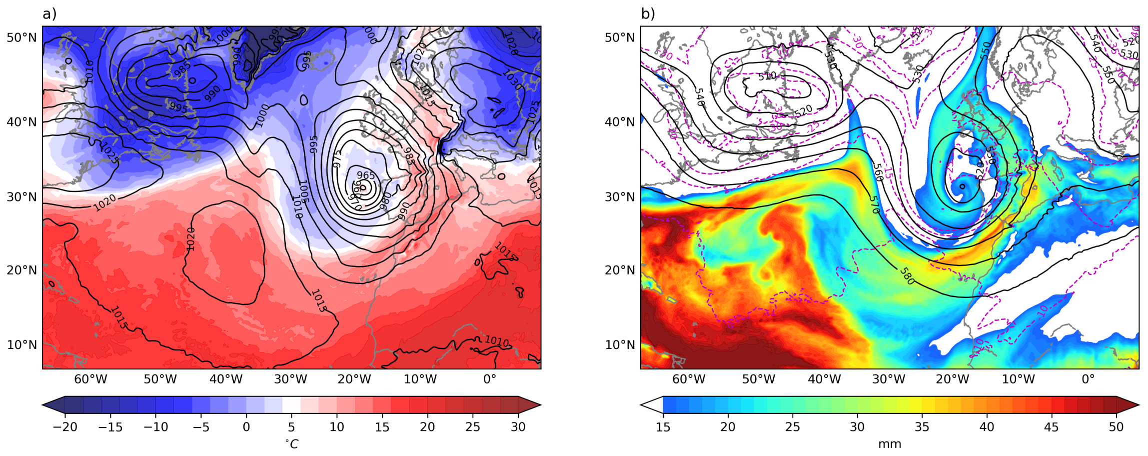


Figure 8. Similar to Fig. 3 but for November 7, 1982, at 12:00 UTC.

4 The November event

4.1 Synoptic situation and precipitation

As the October episode, the case of November had a very high social and economic impact, but the weather conditions leading to it were very different. There was neither ~~cut-off low~~ COL nor cold air aloft in the most affected regions by extreme precipitation (northeast Spain and southeast France); instead, the HPE was connected with a strong omega block pattern (Fig. 8b). At 12 UTC November 7, the main day of the event, an extensive upper-level ridge associated with a strong surface anticyclone covered a large part of Europe, while a deep trough was located west of the Iberian Peninsula, thus leaving northeastern Spain and southwestern France in the frontal zone on its leading side. At the surface (Fig. 8a), a very deep low-pressure system located off the coast of Galicia organized a very intense, persistent (due to the block pattern) and relatively warm low-level south-southwesterly flow into the most affected regions. Another crucial feature drawing attention in Fig. 8b is the very high values of TPW in much of the eastern half of the Iberian Peninsula, seemingly transported to the region by an atmospheric river, which favoured the high accumulations of rainfall. All these elements indicate that dynamic rather than thermal factors were the most relevant in this case. For a more in-depth analysis of the development of this event, please refer to ~~Llasat (1987) and~~ Trapero et al. (2013).

Figure 9 shows the observational analysis (Fig. 9a) and simulated (Fig. 9b) precipitation during the main days of the event (November 6, 7 and 8). The spatial pattern in Fig. 9a indicates that orography played a very important role, since the maximum precipitation occurs in mountainous areas. This is especially evident in the Pyrenees and the southern section of the French Massif Central, where the highest rainfall accumulations were recorded. Precipitation peaks in the latter mountain ranges are well above 250 mm, although, as in the October case, there were much higher amounts measured at specific locations (exceeding 400 mm in just 24 h) that are smoothed out in the analysis. In this November event, extreme precipitation affected, nevertheless, a very large region, including the Iberian Peninsula, Morocco and Southern France, and was not so local as in the

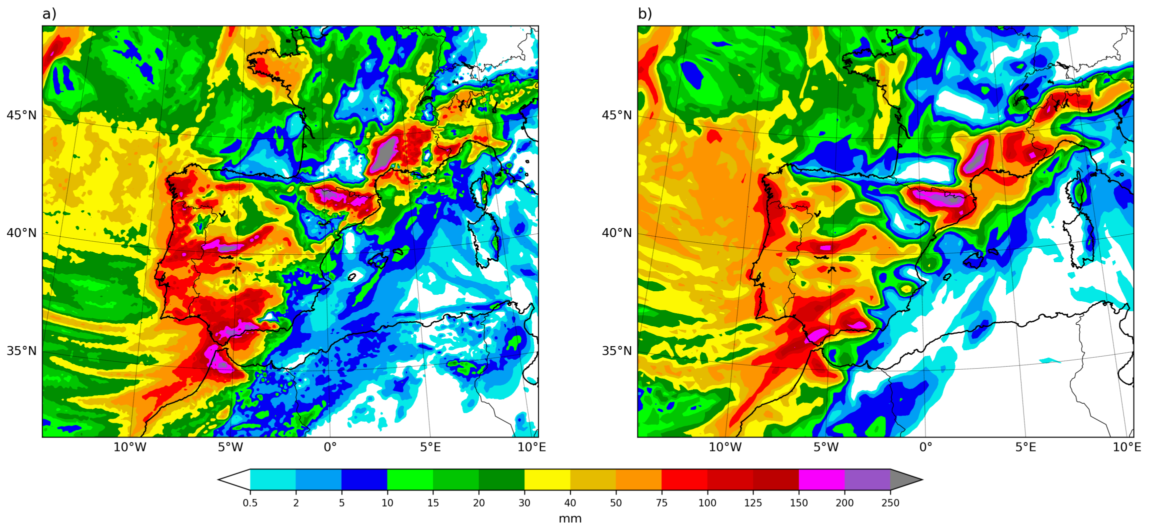


Figure 9. Similar to Fig. 4 but from November 6 at 06:00 UTC to November 9 at 06:00 UTC.

episode from the previous month. This suggests that the nature of precipitation was very different in both cases; in October, it was associated with deep convection whereas in November, precipitation was mainly stratiform, with strong embedded convective cells triggered by the terrain in mountain areas. Therefore, the persistence (forced by the block pattern) and orographic lift enhancement of precipitation, together with a good supply of moisture, were the key factors in this episode. The model simulates realistically these processes and captures the actual spatial distribution and total accumulations of rainfall closely (Fig. 9b).

4.2 Moisture origin

Figure 10 shows at 12:00 UTC, November 7, the TPW generated from each considered origin from the beginning of the simulation, 10.5 days before (October 28, 00:00 UTC). The deep low-pressure system located off the coast of Galicia picks up moisture from all the sources and redistributes it in different ways. TPW from evaporation in the Western (Fig. 10a) and Central Mediterranean (Fig. 10b) is advected due northwest, across France and the British Isles and finally transported into the Atlantic following the cyclonic circulation around the low. The Iberian Peninsula lies only marginally within this path, and as a result, the amount of TPW from the Western Mediterranean is small there, less than 5 mm in Catalonia, and negligible for moisture from the Central Mediterranean. However, in southeast France, the other region most affected by the rains, the contributions from these two sources are substantially more relevant, with values of more than 10 mm of western Mediterranean TPW in the vicinity of the Gulf of Lion. Meanwhile, North Atlantic moisture is transported in large amounts toward the Iberian Peninsula by the intense south-westerly flow associated with the low (Fig. 10c), and TPW from this origin attains values of around 15 mm in the western Iberian margin. Some of this Atlantic water vapor extends to the Mediterranean and France with diminished amounts of TPW, below 10 mm. Finally, as in the October case, the most important contribution to TPW corresponds to that

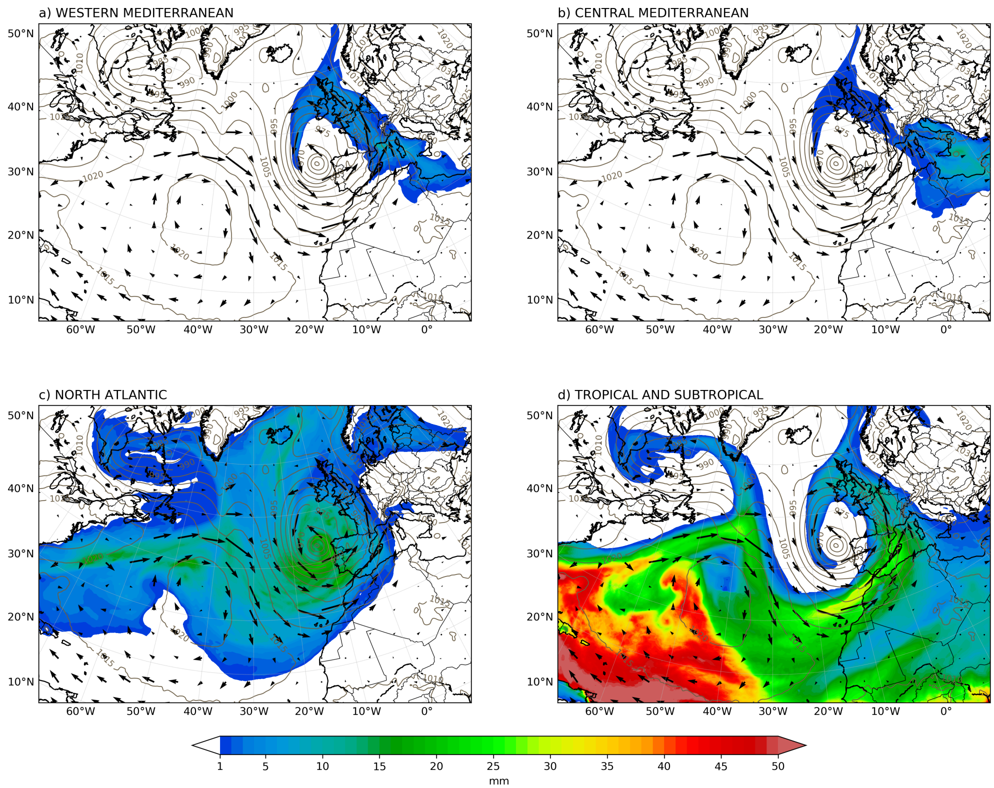


Figure 10. Similar to Fig. 5 but for November 7 at 12:00 UTC.

of moisture advected from the tropics and subtropics (Fig. 10d). A well-defined moisture plume or atmospheric river enters the Mediterranean through the Strait of Gibraltar, stretches along the east coast of Spain and reaches the south of France, leaving values well in excess of 20 mm of TPW in some of these areas.

The vertical distribution of water vapour from the different sources is shown in Fig. 11, which is analogous to Fig. 6 for the October case. The analysis is now performed over the region labelled 2 in Fig. 2b, the one most affected by the torrential rains. At the beginning of the episode (November 7 at 00:00 UTC, Fig. 11a and 11c) , there is mainly moisture from only two origins: Western Mediterranean evaporation, dominating at low layers below 800 hPa, and advected water vapor from the tropics and subtropics, becoming predominant in mid and upper layers above that level. At a more advanced stage of the event, on November 8 at 00:00 UTC (Fig. 11b and 11d), Western Mediterranean evaporation remains in the boundary layer and loses importance while North Atlantic water vapor gains relevance throughout the column. For its part, tropical and subtropical advection becomes clearly the most abundant type of moisture at all levels. At this late stage of the event, these three sources alone account for about 90% of TPW. Central Mediterranean evaporation and other sources not considered are irrelevant. The important contribution of remote moisture transport from the Atlantic (including the tropics and subtropics) at mid and upper levels corroborates the hypothesis made from qualitative observations in the first in depth investigation of this event (Llasat,

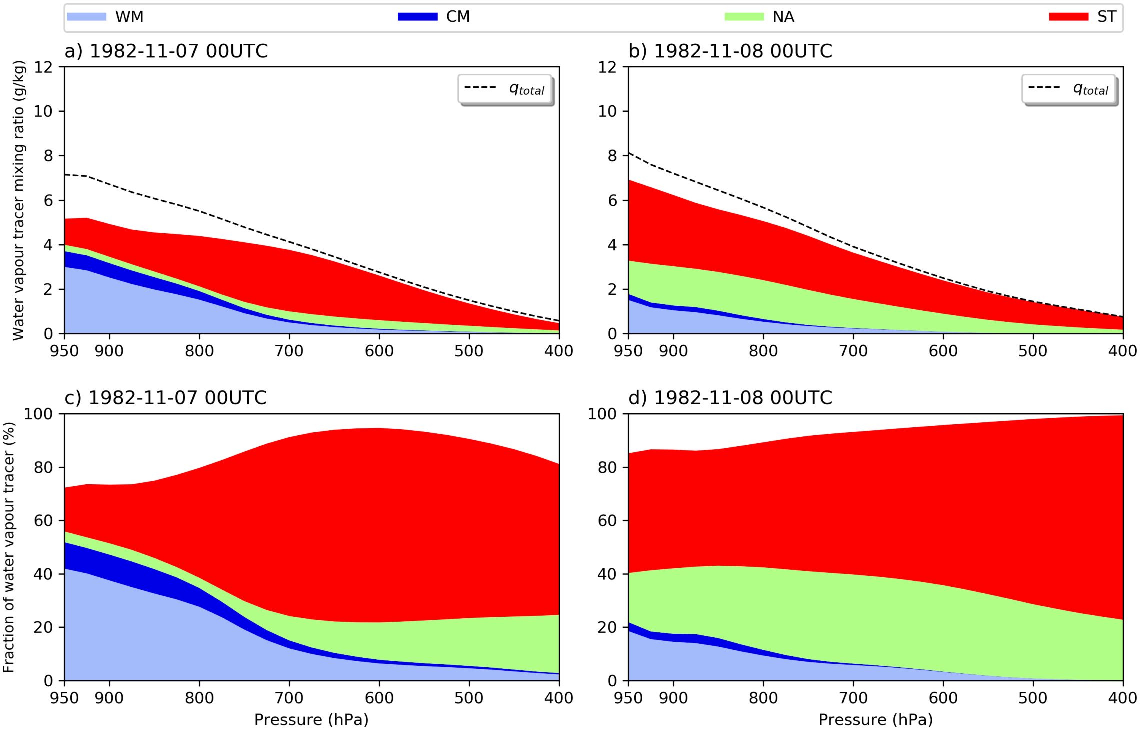


Figure 11. Similar to Fig. 6 but on November 7 (a, c) and 8 (b, d) at 00:00 UTC. The analysis is now over region 2 in Fig. 2b.

1987, 1991). Finally, we note that mixing ratios are high throughout the entire atmospheric column, reaching 8 g/kg at 950 hPa; a significantly lower value, nonetheless, than in the October case.

4.3 Precipitation origin

With regards to the origin of precipitation, Figure 12 shows the share corresponding to each considered source. The largest contributions are clearly from North Atlantic (Fig. 12c) and tropical and subtropical moisture (Fig. 12d). North Atlantic water vapor is found in significant amounts in rainfall in all the affected areas, and it's by far the dominant source in the western half of the Iberian Peninsula, the most exposed to the west-southwesterly flow of the storm off shore. Precipitation of tropical and subtropical origin extends along the path of the atmospheric river discussed in the previous section, in a band stretching from the strait of Gibraltar all the way to the Alps, covering most of the eastern half of the Iberian Peninsula and southeast France. In all these regions, moisture from the North Atlantic is also a significant source, but tropical and subtropical water vapor is clearly the most important contribution. In the north-eastern tip of the Iberian Peninsula and southeast France there is a relevant additional input from Western Mediterranean humidity (Fig. 12a), and in the French Massif Central, even modest precipitation amounts from Central Mediterranean evaporation (Fig. 12b). These areas where all major source contributions overlap are precisely the most impacted by the event and where the highest rainfall accumulations were recorded.

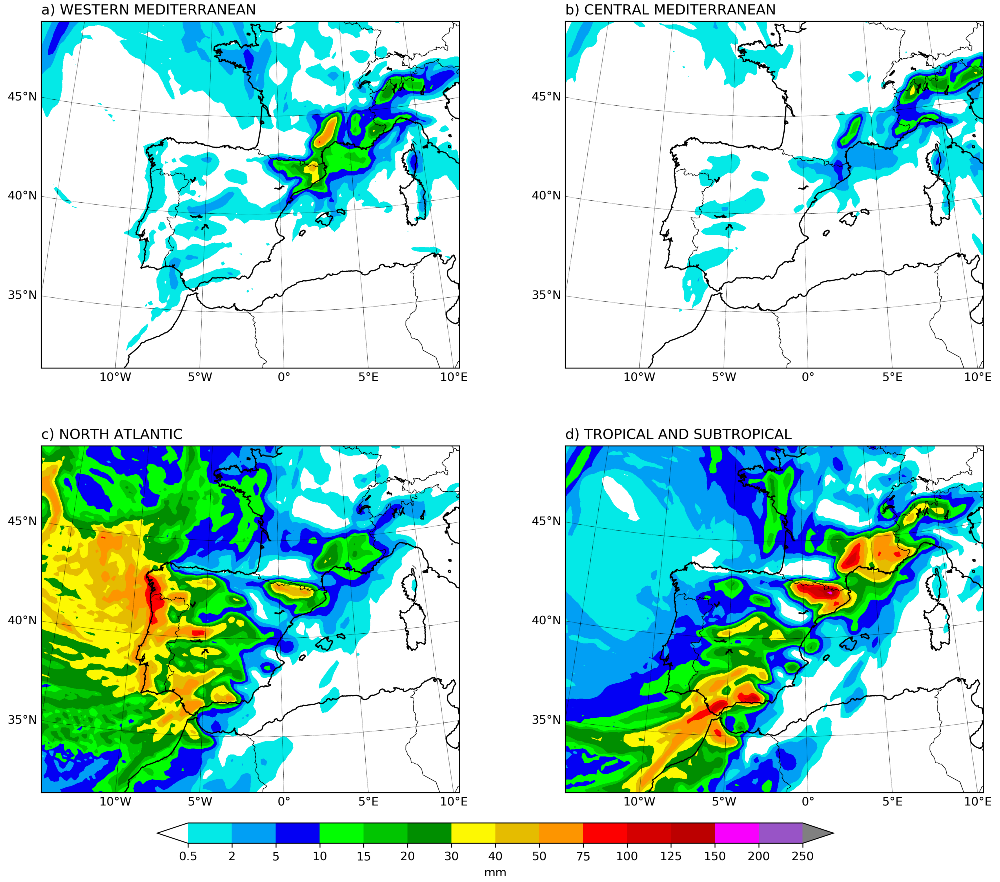


Figure 12. Similar to Fig. 7 but from 06th of November at 06:00 UTC to 09th of November at 06:00 UTC.

Table 2 shows the area averaged relative contribution of each source over northeast Spain and southeast France (region number 2, outlined in red in Fig. 2b, the same used for the vertical distribution of moisture analysis in Fig. 11). In this region, which includes the Pyrenees and the French Massif Central mountains where the most intense downpours occurred, tropical and subtropical sources are clearly dominant, with a contribution surpassing 50%. Western Mediterranean and North Atlantic moisture play an intermediate role, contributing each between 15 and 20%. Of the latter two sources, North Atlantic water vapor is more relevant in the Pyrenees whereas that of the Western Mediterranean is so in the Massif Central. The input of the Central Mediterranean is on average negligible, of only around 3%. These results indicate that in the most affected areas, the contribution to precipitation from remote sources (about 70%) is much more important than that from local sources (less than 20%). The residual amount (11.8%) is, as in the October event, a sum of small contributions from other various sources. We note, however, that although the share of Western Mediterranean moisture is somewhat modest, its relevance is particularly noteworthy; Fig. 12 suggests that without a contribution from the Mediterranean, rainfall accumulations in northeast Spain and southeast France would be comparable to those in many other regions of the Iberian Peninsula, and it is likely that the damage caused would have been much less.

Table 2. Same as Table 1 but from November 6 at 06:00 UTC to November 9 at 06:00 UTC and over region 2 in Fig. 2b.

	Western Mediterranean	**Central Mediterranean**	**North Atlantic**	**Tropical and Subtropical**
Relative Contribution (%)	15,60	2,96	18,20	51,39

5 Summary and conclusions

Torrential rain episodes causing flooding are recurrent features of climate on the shores of the Western Mediterranean. The meteorological drivers for such events can be quite different and nevertheless result in similar outcomes, with catastrophic consequences in terms of damages. We investigate here this type of episodes on the basis of a common hypothesis; for the most extreme events occur, one of the necessary ingredients is a large amount of precipitable water, which is to a great extent advected from remote regions.

We selected two ~~famous~~ infamous Western Mediterranean high precipitation events occurred during the same season, autumn of 1982 (October and November). Both evolved from very different synoptic situations. The case of October was more thermally driven, with the presence of cold air aloft associated with an upper level cut-off low, and deep convection developing and organizing in the form of a mesoscale convective system. In contrast, the November case was more dynamically forced, since it unfolded in the prefrontal and frontal zone of a strong Atlantic baroclinic storm. In this event, orography played a very relevant role, by enhancing the ascent producing precipitation and, in some mountain ranges such as the Pyrenees, also by triggering deep convection. The configurations of the selected cases represent two of the most frequently found during these episodes.

To assess the relevance of locally generated and remote precipitable water, we analyzed four potential moisture sources: evaporation in the Western or Central Mediterranean, evaporation in the North Atlantic and advection from the tropics and subtropics. Mediterranean sources were regarded as local while tropical, subtropical and Atlantic sources were considered as remote sources. Simulations were carried out with the WRF atmospheric model coupled with a moisture tagging technique, the so-called WRF-WVT tool. Lateral boundary forcing came from ERA-Interim reanalysis and a single domain at 20 km resolution was used for calculations. In addition to estimating the contribution of the different sources to the large rainfall accumulations recorded during the episodes, we analyzed the vertical distribution of moisture transport toward the affected areas, in order to obtain a three dimensional diagnosis of the involvement of water vapor from each source in the dynamics of the events. As a result of our findings, we state the following conclusions.

- In both episodes, the largest moisture contribution to the torrential rains was from tropical and subtropical sources. In the case of November, more than half of the rainfall recorded in the most affected area came from this origin, while in the case of October its predominance was somewhat less pronounced, representing around 31% of the total rainfall.

- In the October event, evaporated moisture in the Western and Central Mediterranean, i.e. local moisture, played a very important role, with these sources contributing nearly 20% of total precipitation each. Evaporated moisture in the North Atlantic was also a significant contributor, accounting for around 15% of total precipitation, although it was the least important of the four sources.

- In the November event, the North Atlantic and the Western Mediterranean acted as secondary sources, while the contribution of the Central Mediterranean was almost negligible. Even so, the Mediterranean's contribution is particularly noteworthy: many regions in the Iberian Peninsula received large amounts of rain, coming from Atlantic and tropical and subtropical moisture sources; however, the extra input from the Mediterranean in northeast Spain and southeast France caused the rainfall in these areas to be even higher, so they ultimately were the most damaged areas.

- As for the distinction between remote and local sources, in the October event the contribution of both was similar whereas in the November case the largest share was clearly from remote sources.

- Moisture transport at medium and high levels played a key role in producing the observed large amounts of rainfall. Most water vapor at these layers resulted from long distance advection from the tropics and subtropics, which, as mentioned above, was the main source for the extreme precipitation. There were also high mixing ratios from this remote origin at lower layers, but the maximum values were at medium levels of the atmosphere.

- In the lower layers of the atmosphere, moisture was generally mostly from local evaporative sources in the Western and Central Mediterranean, while water vapour from evaporation in the North Atlantic was distributed at different levels.

- In both cases, moisture from the tropics and subtropics was transported through very defined moisture plumes or atmospheric rivers.

- The combination of high water vapor content at low levels from local sources and at middle and upper levels from remote sources yielded very large values of total precipitable vapor in the column in both events, but more so in the October case.

Our results suggest that the role played by remote sources is fundamental in producing the extraordinary rain accumulations observed in this type of extreme events and that the contribution of local Mediterranean sources is not sufficient to reach such high values. To ~~verify this hypothesis~~corroborate the idea that remote sources of moisture from the tropics contribute to an important fraction of extreme precipitaiton events in the midlatitudes, many more episodes should be analysed. In this sense, this work is intended as a first step in applying the water vapor tracer method to many other cases in order to obtain more robust conclusions.

Competing interests. Authors declare that no competing interests are present.

Acknowledgements. Funding comes from the Spanish Ministerio de Economia y Competitividad OPERMO (CGL2017-89859-R to GMM and DIC) and M-CostAdapt (CTM2017-83655-C2-2-R to MCLL) projects, the European Union Interreg V POCTEFA project (EFA210/16 PIRAGUA to MCLL) and the CRETUS strategic partnership (AGRUP2015/02 to GMM and DIC). All these programs are co-funded by the European Union ERDF. ERA-Interim data was provided by ECMWF. Computation took place at CESGA (Centro de Supercomputacion de Galicia), Santiago de Compostela, Galicia, Spain. This research is part of the HyMeX international programme.

References

Barredo, J. I.: Major flood disasters in Europe: 1950-2005, Natural Hazards, 42, 125–148, https://doi.org/10.1007/s11069-006-9065-2, 2007.

Buzzi, A., Tartaglione, N., and Malguzzi, P.: Numerical Simulations of the 1994 Piedmont Flood: Role of Orography and Moist Processes, Monthly Weather Review, 126, 2369–2383, https://doi.org/10.1175/1520-0493(1998)126<2369:NSOTPF>2.0.CO;2, 1998.

Campins, J., Genovés, A., Picornell, M. A., and Jansà, A.: Climatology of Mediterranean cyclones using the ERA-40 dataset, International Journal of Climatology, 31, 1596–1614, https://doi.org/10.1002/joc.2183, 2011.

Chen, F. and Dudhia, J.: Coupling an Advanced Land Surface–Hydrology Model with the Penn State–NCAR MM5 Modeling System. Part II: Preliminary Model Validation, Monthly Weather Review, 129, 587–604, https://doi.org/10.1175/1520-0493(2001)129<0587:CAALSH>2.0.CO;2, 2001.

Dayan, U., Nissen, K., and Ulbrich, U.: Review Article: Atmospheric conditions inducing extreme precipitation over the eastern and western Mediterranean, https://doi.org/10.5194/nhess-15-2525-2015, 2015.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., Mcnally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J. N., and Vitart, F.: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, https://doi.org/10.1002/qj.828, 2011.

Dirmeyer, P. A. and Brubaker, K. L.: Contrasting evaporative moisture sources during the drought of 1988 and the flood of 1993, Journal of Geophysical Research Atmospheres, 104, 19 383–19 397, https://doi.org/10.1029/1999JD900222, 1999.

Drobinski, P., Ducrocq, V., Alpert, P., Anagnostou, E., Béranger, K., Borga, M., Braud, I., Chanzy, A., Davolio, S., Delrieu, G., Estournel, C., Filali Boubrahmi, N., Font, J., Grubišić, V., Gualdi, S., Homar, V., Ivančan-Picek, B., Kottmeier, C., Kotroni, V., Lagouvardos, K., Lionello, P., Llasat, M. C., Ludwig, W., Lutoff, C., Mariotti, A., Richard, E., Romero, R., Rotunno, R., Roussot, O., Ruin, I., Somot, S., Taupier-Letage, I., Tintor, J., Uijlenhoet, R., and Wernli, H.: HYMEX: A 10-year multidisciplinary program on the mediterranean water cycle, Bulletin of the American Meteorological Society, 95, 1063–1082, https://doi.org/10.1175/BAMS-D-12-00242.1, 2014.

Drumond, A., Nieto, R., Hernandez, E., and Gimeno, L.: A Lagrangian analysis of the variation in moisture sources related to drier and wetter conditions in regions around the Mediterranean Basin, Natural Hazards and Earth System Sciences, 11, 2307–2320, https://doi.org/10.5194/nhess-11-2307-2011, 2011.

Dudhia, J.: Numerical Study of Convection Observed during the Winter Monsoon Experiment Using a Mesoscale Two-Dimensional Model, https://doi.org/10.1175/1520-0469(1989)046<3077:NSOCOD>2.0.CO;2, 1989.

Duffourg, F. and Ducrocq, V.: Origin of the moisture feeding the heavy precipitating systems over southeastern France, Natural Hazards and Earth System Science, 11, 1163–1178, https://doi.org/10.5194/nhess-11-1163-2011, 2011.

Gimeno, L., Nieto, R., Trigo, R. M., Vicente-Serrano, S. M., and López-Moreno, J. I.: Where Does the Iberian Peninsula Moisture Come From? An Answer Based on a Lagrangian Approach, Journal of Hydrometeorology, 11, 421–436, https://doi.org/10.1175/2009jhm1182.1, 2009.

Gimeno, L., Stohl, A., Trigo, R. M., Dominguez, F., Yoshimura, K., Yu, L., Drumond, A., Durn-Quesada, A. M., and Nieto, R.: Oceanic and terrestrial sources of continental precipitation, Reviews of Geophysics, 50, https://doi.org/10.1029/2012RG000389, 2012.

Hong, S. and Lim, J.: The WRF single-moment 6-class microphysics scheme (WSM6), 2006.

Hong, S.-Y., Noh, Y., and Dudhia, J.: A New Vertical Diffusion Package with an Explicit Treatment of Entrainment Processes, Monthly Weather Review, 134, 2318–2341, https://doi.org/10.1175/MWR3199.1, 2006.

Insua-Costa, D. and Miguez-Macho, G.: A new moisture tagging capability in the Weather Research and Forecasting model: Formulation, validation and application to the 2014 Great Lake-effect snowstorm, Earth System Dynamics, 9, 167–185, https://doi.org/10.5194/esd-9-167-2018, 2018.

Jansa, A., Genoves, A., Picornell, M. A., Campins, J., Riosalido, R., and Carretero, O.: Western Mediterranean cyclones and heavy rain. Part 2: Statistical approach, Meteorological Applications, 8, 43–56, 2001.

Jansa, A., Alpert, P., Arbogast, P., Buzzi, A., Ivancan-Picek, B., Kotroni, V., Llasat, M. C., Ramis, C., Richard, E., Romero, R., and Speranza, A.: MEDEX: A general overview, https://doi.org/10.5194/nhess-14-1965-2014, 2014.

Kain, J. S.: The Kain–Fritsch Convective Parameterization: An Update, Journal of Applied Meteorology, 43, 170–181, https://doi.org/10.1175/1520-0450(2004)043<0170:TKCPAU>2.0.CO;2, 2004.

Krichak, S. O., Barkan, J., Breitgand, J. S., Gualdi, S., and Feldstein, S. B.: The role of the export of tropical moisture into midlatitudes for extreme precipitation events in the Mediterranean region, Theoretical and Applied Climatology, 121, 499–515, https://doi.org/10.1007/s00704-014-1244-6, 2015.

Liu, X. D.: Weighted essentially non-oscillatory schemes, Journal of Computational Physics, 115, 200–212, https://doi.org/10.1006/jcph.1994.1187, 1994.

Llasat, M. C.: Episodios de lluvias copiosas en Catalunya: génesis, evolución y factores coadyuvantes, Doctoral Thesis, University of Barcelona, no. 40, Barcelona, Spain, 543, 1987.

Llasat, M. C.: Gota fría, Editorial Boixareu Universitaria, 139–150 pp., ISBN: 84-267-0829-3, 1991.

Llasat, M. C.: High magnitude storms and floods, in: The Physical Geography of the Mediterranean, J.C. Woodward, Oxford University Press, Oxford, 513–540, 2009.

Llasat, M. C., Llasat-Botija, M., Prat, M. A., Porcú, F., Price, C., Mugnai, A., Lagouvardos, K., Kotroni, V., Katsanos, D., Michaelides, S., Yair, Y., Savvidou, K., and Nicolaides, K.: High-impact floods and flash floods in Mediterranean countries: The FLASH preliminary database, Advances in Geosciences, 23, 47–55, https://doi.org/10.5194/adgeo-23-47-2010, 2010.

Llasat, M. C., Llasat-Botija, M., Petrucci, O., Pasqua, A. A., Rosselló, J., Vinet, F., and Boissier, L.: Towards a database on societal impact of Mediterranean floods within the framework of the HYMEX project, Natural Hazards and Earth System Science, 13, 1337–1350, https://doi.org/10.5194/nhess-13-1337-2013, 2013.

Maddox, R. A.: Meoscale Convective Complexes, Bulletin of the American Meteorological Society, 61, 1374–1387, https://doi.org/10.1175/1520-0477(1980)061<1374:MCC>2.0.CO;2, 1980.

Miguez-Macho, G., Stenchikov, G. L., and Robock, A.: Spectral nudging to eliminate the effects of domain position and geometry in regional climate model simulations, Journal of Geophysical Research D: Atmospheres, 109, 1–15, https://doi.org/10.1029/2003JD004495, 2004.

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., and Clough, S. A.: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave, Journal of Geophysical Research: Atmospheres, 102, 16 663–16 682, https://doi.org/10.1029/97JD00237, 1997.

Nieto, R., Gimeno, L., de la Torre, L., Ribera, P., Gallego, D., García-Herrera, R., García, J. A., Nuñez, M., Redaño, A., and Lorente, J.: Climatological features of cutoff low systems in the Northern Hemisphere, Journal of Climate, 18, 3085–3103, https://doi.org/10.1175/JCLI3386.1, 2005.

Nieto, R., Sprenger, M., Wernli, H., Trigo, R. M., and Gimeno, L.: Identification and climatology of cut-off lows near the tropopause, in: Annals of the New York Academy of Sciences, vol. 1146, pp. 256–290, https://doi.org/10.1196/annals.1446.016, 2008.

Nieto, R., Gimeno, L., Drumond, A., and Hernandez, E.: A Lagrangian identification of the main moisture sources and sinks affecting the Mediterranean area, WSEAS Transactions on Environment and Development, 6, 365–374, 2010.

Pinto, J. G., Ulbrich, S., Parodi, A., Rudari, R., Boni, G., and Ulbrich, U.: Identification and ranking of extraordinary rainfall events over Northwest Italy: The role of Atlantic moisture, Journal of Geophysical Research Atmospheres, 118, 2085–2097, https://doi.org/10.1002/jgrd.50179, 2013.

Reale, M. and Lionello, P.: Synoptic climatology of winter intense precipitation events along the Mediterranean coasts, Natural Hazards and Earth System Sciences, 13, 1707–1722, https://doi.org/10.5194/nhess-13-1707-2013, 2013.

Reale, O., Feudale, L., and Turato, B.: Evaporative moisture sources during a sequence of floods in the Mediterranean region, Geophysical Research Letters, 28, 2085–2088, https://doi.org/10.1029/2000GL012379, 2001.

Rivera, A. and Riosalido, R.: Mediterranean convective systems as viewed by Meteosat. A case study, in: Proc. 6th Meteosat Scientific Users Meeting, Amsterdam, pp. 101–104, 1986.

Romero, R., Sumner, G., Ramis, C., and Genovés, A.: A classification of the atmospheric circulation patterns producing significant daily rainfall in the Spanish Mediterranean area, International Journal of Climatology, 19, 765–785, https://doi.org/10.1002/(SICI)1097-0088(19990615)19:7<765::AID-JOC388>3.0.CO;2-T, 1999.

Romero, R., Doswell, C. A., Ramis, C., Romero, R., III, C. A. D., and Ramis, C.: Mesoscale Numerical Study of Two Cases of Long-Lived Quasi-Stationary Convective Systems over Eastern Spain, Monthly Weather Review, 128, 3731–3751, https://doi.org/10.1175/1520-0493(2001)129<3731:MNSOTC>2.0.CO;2, 2000.

Rotunno, R. and Ferretti, R.: Orographic effects on rainfall in MAP cases IOP 2b and IOP 8, Quarterly Journal of the Royal Meteorological Society, 129, https://doi.org/10.1256/qj.02.20, 2003.

Skamarock, W., Klemp, J., Dudhi, J., Gill, D., Barker, D., Duda, M., Huang, X.-Y., Wang, W., and Powers, J.: A Description of the Advanced Research WRF Version 3, Technical Report, p. 113, https://doi.org/10.5065/D6DZ069T, 2008.

Soci, C., Bazile, E., Besson, F. O., and Landelius, T.: High-resolution precipitation re-analysis system for climatological purposes, Tellus, Series A: Dynamic Meteorology and Oceanography, 68, https://doi.org/10.3402/tellusa.v68.29879, 2016.

Sodemann, H. and Zubler, E.: Seasonal and inter-annual variability of the moisture sources for alpine precipitation during 1995-2002, International Journal of Climatology, 30, 947–961, https://doi.org/10.1002/joc.1932, 2010.

Stohl, A.: Computation, accuracy and applications of trajectories—a review and bibliography, Atmospheric Environment, 1998.

Stohl, A. and James, P.: A Lagrangian Analysis of the Atmospheric Branch of the Global Water Cycle. Part I: Method Description, Validation, and Demonstration for the August 2002 Flooding in Central Europe, Journal of Hydrometeorology, 5, 656–678, https://doi.org/10.1175/1525-7541(2004)005<0656:ALAOTA>2.0.CO;2, 2004.

Trapero, L., Bech, J., Duffourg, F., Esteban, P., and Lorente, J.: Mesoscale numerical analysis of the historical November 1982 heavy precipitation event over Andorra (Eastern Pyrenees), Natural Hazards and Earth System Sciences, 13, 2969–2990, https://doi.org/10.5194/nhess-13-2969-2013, 2013.

Trenberth, K. E.: Atmospheric moisture residence times and cycling: Implications for rainfall rates and climate change, Climatic Change, 39, 667–694, https://doi.org/10.1023/A:1005319109110, 1998.

Turato, B., Reale, O., and Siccardi, F.: Water Vapor Sources of the October 2000 Piedmont Flood, Journal of Hydrometeorology, 5, 693–712, https://doi.org/10.1175/1525-7541(2004)005<0693:WVSOTO>2.0.CO;2, 2004.

Van Der Ent, R. J. and Tuinenburg, O. A.: The residence time of water in the atmosphere revisited, Hydrology and Earth System Sciences, 21, 779–790, https://doi.org/10.5194/hess-21-779-2017, 2017.

Winschall, A., Pfahl, S., Sodemann, H., and Wernli, H.: Impact of North Atlantic evaporation hot spots on southern Alpine heavy precipitation events, Quarterly Journal of the Royal Meteorological Society, 138, 1245–1258, https://doi.org/10.1002/qj.987, 2012.