Extreme precipitation events in the Mediterranean area: contrasting two different models for moisture source identification

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Abstract.

Concern about heavy precipitation events has increasingly grown in the last years in Southern Europe, especially in the Mediterranean region. These occasional episodes can result in more than 200 mm of rainfall in less than 24 h, producing flash floods with very high social and economic losses. To better understand these phenomena, a correct identification of the origin of moisture must be found. However, the contribution of the different sources is very difficult to estimate from observational data, thus numerical models are usually employed to this end. Here, we present a comparison between two methodologies for the quantification of the moisture sources in two flooding episodes occurred during October and November 1982 in the Western Mediterranean area. A previous study, using the online Eulerian WRF-WVTs model, determined the contributions to precipitation from moisture evaporated over four different sources: 1) the Western Mediterranean; 2) the Central Mediterranean; 3) the North Atlantic ocean and 4) the tropical and subtropical Atlantic and tropical Africa. In this work we use the offline Lagrangian FLEXPART-WRF model to quantify the role played by these same sources. Considering the results provided by WRF-WVTs as "ground truth", we validated the performance of the FLEXPART-WRF. Results show that this Lagrangian method has an acceptable skill in identifying local (Western Mediterranean) and medium-distance (Central Mediterranean and North Atlantic) sources. However, remote moisture sources, like tropical and subtropical areas, are underestimated by it. Notably, for the October event, the tropical and subtropical area reported a relative contribution six times lower than with the WRF-WVTs. In contrast, FLEXPART-WRF overestimates the contribution of some sources, especially from North Africa. These over- and underestimates should be taken into account by other authors when drawing conclusions from this widely used Lagrangian-offline analysis.

1 Introduction

Extreme rainfall and associated floods are one of the most devastating agents in the weather context. As an example, in 2019 alone, more than 5000 people died as a result of floods and more than 30 million people were affected, resulting in economic losses of more than USD 35 billion (International Disaster Database; dat). Therefore, the study of such catastrophic events is fundamental for prediction and anticipation.

Heavy precipitation events (HPEs) are distributed unevenly across the planet, and there are places that are very prone to receiving large rain accumulations in a short time, as opposed to other areas where the precipitation regime is much more moderate. One of these regions where extreme precipitation and flooding are very recurring is the Western Mediterranean Region (WMR) (Llasat et al., 2010). Several characteristics make this part of the planet so exposed to heavy precipitation; the Mediterranean Sea is a large and mild water body, enclosed by very complex orography and in a relatively northern latitude (e.g., Buzzi et al., 1998; Llasat, 2009; Dayan et al., 2015). In this area, most of the events take place in autumn (Mariotti et al., 2002), when Atlantic lows or cut-off lows (Nieto et al., 2005) often interact with warm Mediterranean Sea waters leading to strong convection.

While HPEs are a regional phenomena, moisture feeding them not only comes from nearby sea evaporation, but can originate in remote regions and be transported by different atmospheric mechanisms. In this sense, it has been shown that long-distance moisture transport through atmospheric rivers (ARs) is a crucial contributor to total precipitation amounts recorded in Europe and the United States (e.g., Lavers and Villarini, 2015; Hu and Dominguez, 2019; Pérez-Muñuzuri et al., 2018) and also to extreme rainfall episodes (e.g., Stohl et al., 2008; Eiras-Barca et al., 2017). As for the WMR, recent studies (e.g., Winschall et al., 2012; Pinto et al., 2013; Krichak et al., 2015; Insua-Costa et al., 2019) suggest that remote sources of moisture such as the North Atlantic or tropical or subtropical areas could contribute significantly to the frequent torrential rains there.

In order to find the origin of the moisture, different methodologies have been used in the past (see Gimeno et al. (2012), for a detailed review of numerical methods used in moisture source studies), with the Lagrangian models being the most widely used technique. It is based on the analysis of the moisture content change of air parcels being tracked backward (or, less commonly, forward) in time. Lagrangian methods are generally offline, and therefore very efficient from a computational point of view. On the other hand, online Eulerian-type methods are much more computationally expensive, and therefore have been less used. However, they are considered to be the most accurate tool for moisture sources studies (see Dominguez et al. (2020), for a classification by complexity of the different models used for moisture tracking). In the western Mediterranean, Lagrangian methods have been used by several authors (e.g., Reale et al., 2001; Turato et al., 2004; Nieto et al., 2010; Duffourg and Ducrocq, 2011), while the online Eulerian approaches have only been used by Winschall et al. (2012) and Insua-Costa et al. (2019).

In this study, we analyzed the moisture sources in two catastrophic flooding episodes occurred in the WMR, using both the Lagrangian and Eulerian approaches. The online Eulerian model for moisture tracking employed was the WRF-WVTs (Insua-Costa and Miguez-Macho (2018)). The results obtained using this tool have already been presented in a previous article (Insua-Costa et al., 2019). Thus, the objective of this study is to repeat the same strategy, but in this case using the offline Lagrangian FLEXPART-WRF model (Brioude et al., 2013), so that we can intercompare the results provided by both methodologies. This type of comparison has already been presented recently by Winschall et al. (2014). However, the present study is especially focused on identifying the possible limitations of the FLEXPART-WRF and their causes, based on the assumption

that WRF-WVTs represent the "ground truth". This was the same strategy followed by van der Ent et al. (2013) and Dominguez et al. (2020) in previous studies. One of the novelties with respect to these articles, is that here the moisture sources will be analyzed from a non-local point of view, that is to say, a large scale domain has been employed to be able to cover sources of remote origin. The aim is to check whether the FLEXPART-WRF has the same capacity to detect short-distance sources as well as long-distance ones. In summary, the present work is intended to contribute to the improvement of a type of Lagrangian analysis widely used for moisture source attribution on the basis of another technique (WRF-WVTs) that is more accurate but much more computationally expensive and therefore less practical.

This study is structured as follows: in Section 2, Lagrangian and Eulerian methodologies are described and the procedure presented. The two case studies are briefly introduced in the first part of Subsections 3.1.1 and 3.1.2 respectively. More detailed description can be found in Insua-Costa et al. (2019). After that, results are structured as follows: Section 3.1 presents the moisture sources analysis obtained from the offline Lagrangian method, Section 3.2 shows the comparison between the results provided by the FLEXPART-WRF and WRF-WVTs techniques and Section 3.3 discusses the limitations of the Lagrangian technique used. Finally, Section 4 summarizes and concludes this work.

2 Methods

This section will describe the techniques used in the study. It is important to highlight that there are different types of Eulerian and Lagrangian tools for moisture tracking, so from now on, when we refer to the Lagrangian or Eulerian approach, we will be referring to the specific methodology explained here. A summary of the characteristics of the models discussed below can be found in Table 1.

	WRF-WVTs	FLEXPART-WRF
Moisture pathways	Eulerian	Lagrangian
Simulation	Online	Offline
Tracking direction	Forward	Backward
Phase changes	Yes	No
Evaporation atribution	Direct	E-P balance
Boundary layer parametrization	Hong et al. (2006)	Hanna (1982)
Convection scheme	Kain and Fritsch (1990)	Emanuel and Živković-Rothman (1999)

Table 1. Some differences between the WRF-WVTs model and the FLEXPART-WRF model.

2.1 Lagrangian approach

In this study we use the offline FLEXPART model (FLEXible PARTicle dispersion model; Pisso et al. (2019)), which has been widely used to study moisture sources from a climatological perspective (e.g. James et al., 2003; Ciric et al., 2018; Drumond et al., 2014; Gimeno et al., 2013) as well as in particular heavy precipitation events (e.g. Stohl et al., 2008; Sun and Wang, 2014) . Specifically, we use a version of FLEXPART that works with the Weather Research and Forecasting (WRF) regional atmospheric model (et al. Skamarock WC (2008)), known as FLEXPART-WRF (Brioude et al. (2013)).

The FLEXPART-WRF model itself is not a model for moisture source analysis, but a Lagrangian particle dispersion model. This means that additional processing of the data provided by the model is necessary for its use in the study of moisture origin. Two hydrological techniques for this purpose based on moisture tracking along the trajectories calculated by FLEXPART-WRF are explained below. Although FLEXPART-WRF only deals with the dynamical part of the calculation (particle trajectories) we will refer with this name to the complete Lagrangian methodology (dynamical and hydrological part) used for the analysis of moisture sources.

2.1.1 E-P balance

According to the distribution of atmospheric mass, the simulation domain (covering from $90°W$ to $60°E$ and from $3°S$ to $65°N$) is homogeneously divided into 4 million air parcels (or particles), which are subsequently advected backward in time during 11 days forced by the atmospheric fields provided by the WRF simulations. To find moisture origin , specific humidity q content change along the trajectory described by each particle is calculated as,

$$e - p = m\frac{dq}{dt} \tag{1}$$

where m is the mass of the particle and the difference between e and p accounts for the increasing or decreasing water vapour ratio along the trajectory. From the previous equation, we can estimate the net water flux over a model grid cell of area A ($1° \times 1°$), summing the variation rate in specific humidity for all the air parcels (K) contained in the atmospheric column over that area:

$$E - P \approx \frac{\sum_{k=1}^{K}(e-p)}{A} \tag{2}$$

To analyze the moisture source regions that fed the 1982 WMR catastrophic precipitations, we calculate the balance $E - P$ only for those air parcels involved in these episodes. Based on the precipitation fields provided by the WRF simulations (Figure 2 (b) and 5 (b)), for the October 1982 case we only consider those particles contained within the affected region (blue in Figure 1 (c)) at some point during the event (from October 19, 06UTC to October 21, 21UTC). Likewise, for the November 1982 event, we consider particles within the red area in Figure 1 (c) from the November 6, 06UTC to November 8, 21UTC . Furthermore, to ensure that we only select the particles contributing to precipitation, we will only select those that lose moisture $\frac{dq}{dt} < -0.06$ g(kg·3hr)$^{-1}$ over an area with outstanding accumulated rainfall rates $E - P < -2$mm(3h)$^{-1}$. Since we are

only considering a subset of the total air parcels, $E-P$ cannot be seen in this case as the net surface water flux, but as an indicator of where the particles contributing to the extreme rains gained or lost moisture. The $E-P$ field is calculated every 3 hours and subsequently accumulated during 1, 4, 7 and 11 days prior to the precipitation events studied.This procedure for the identification of moisture sources based on the E-P field has been widely used since it was described by Stohl and James (2004).

2.1.2 Quantifying the contribution of the moisture sources

An air parcel tracked back in time over a 11-day period can experience different gains and losses of water vapour during that period. Let us suppose for example that one of the air parcels involved in the 1982 Mediterranean rains has positive values of dq/dt eight days before the event, when it was located over the Tropical Atlantic. The fact that the particle gains humidity in that area does not guarantee that this region will end up contributing to the event, because it is likely that this humidity will precipitate before that particle reaches the Mediterranean. Therefore, areas with positive values $E-P$ should not be interpreted as moisture sources but as potential moisture sources. Sodemann et al. (2008) proposes a method to avoid this problem and to quantify the relative contribution of the sources. It is based on tracking, for a given moisture uptake, all subsequent gains and losses to know if that gained moisture reaches the study area or precipitates before it does. Once we know the uptakes that really contribute to the rain event analyzed, we can define the relative contribution (RC) of a particular region of area A_i as,

$$\%RC = 100 \cdot \frac{E|_{A_i}}{E|_{A_T}} \tag{3}$$

where $E|_{A_i}$ is the total water vapor gained over the region of interest in a period of 11 days prior to the event and $E|_{A_T}$ is the equivalent for the total domain area A_T.

Sodemann et al. (2008) also propose to retain only moisture uptakes from particles below 1.5 Boundary Layer Height (BLH), since water vapor uptakes in the free atmosphere cannot be due to a surface flux, but to deficiencies in the methodology. This attempt to reduce the possible errors of the method leads to the reformulation of Eq. 3 as:

$$\%RC_{BLH} = 100 \cdot \frac{E_{BLH}|_{A_i}}{E_{BLH}|_{A_T}} \tag{4}$$

where $E_{BLH}|_{A_i}$ and $E_{BLH}|_{A_T}$ are calculated in the same way as $E|_{A_i}$ and $E|_{A_T}$, but taking into account only the air parcels within the boundary layer.

2.2 Eulerian approach

The Eulerian-online method consists of a moisture tagging tool coupled to a regional or a global atmospheric model. The model code is modified in order to calculate new variables, called moisture tracers, which represent, for example, water vapour or cloud water coming from a desired moisture source region. This allows the detailed estimation of the relative contribution of each considered source to a given precipitation event. As mentioned in the introduction, the Eulerian tool used in this study
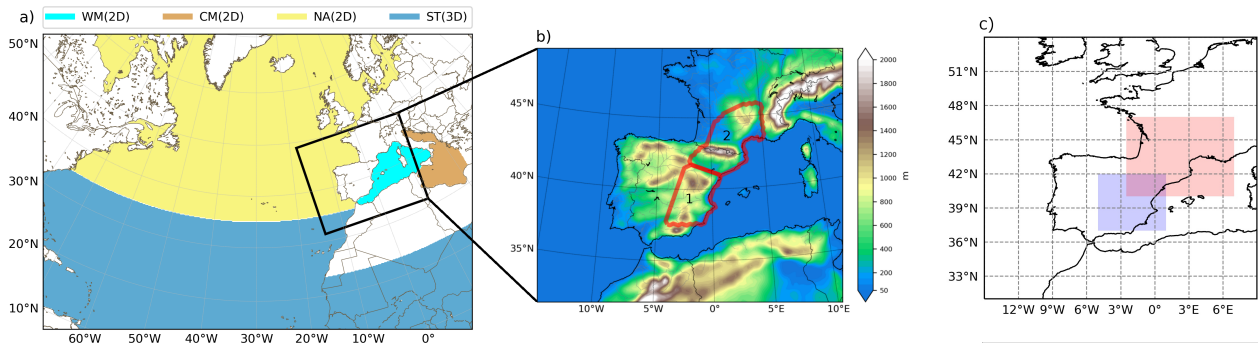
Figure 1. (a) Moisture sources considered: Western Mediterranean (cyan), Central Mediterranean (brown) and North Atlantic (yellow) 2D sources; and tropical and subtropical 3D source(blue). (b) Regions most affected by the October (1) and November (2) events [Original figure from Insua-Costa et al. (2019)]. (c) FLEXPART-WRF particle selection areas for the October (blue) and November (red) events.

is the WRF-WVTs (Insua-Costa and Miguez-Macho, 2018) , a moisture technique recently implemented in the WRF model version 3.8.1 (et al. Skamarock WC, 2008).

The results obtained with the WRF-WVTs for both 1982 precipitation events were already presented in Insua-Costa et al.
145   (2019). For these two case studies, these authors analyzed moisture coming from two-dimensional (2D) and three-dimensional (3D) sources. To take into account moisture coming from sea surface evaporation over the Western Mediterranean, Central Mediterranean and North Atlantic, they used three different 2D sources, while to track moisture from tropical and subtropical regions they considered a 3D source in order to include both evaporation and atmospheric water transport from other neighbouring tropical regions. These source regions and the simulation domain used by Insua-Costa et al. (2019) are shown in Figure
150   1 (a). In addition, Figure 1 (b) shows the regions most affected by the October (1) and November (2) events, respectively, on which Insua-Costa et al. (2019) calculated the precipitation fractions coming from the four source regions studied. For each analyzed source, a 11-day simulation was run with the WRF model over a large domain of 20 km of horizontal resolution and 35 vertical levels. For initial and boundary conditions, they used the ERA-Interim reanalysis (Dee et al., 2011), with spatial resolution of 0.7º and updated every six hours. In the present study, the simulations of Insua-Costa et al. (2019) are used as
155   (1) input fields to run the FLEXPART-WRF model and (2) to compare the results provided by this offline Lagrangian tool. Note that this strategy is especially appropriate for validating the results provided by the Lagrangian model, since both the WRF-WVTs and the FLEXPART-WRF are driven by the same WRF meteorological model.
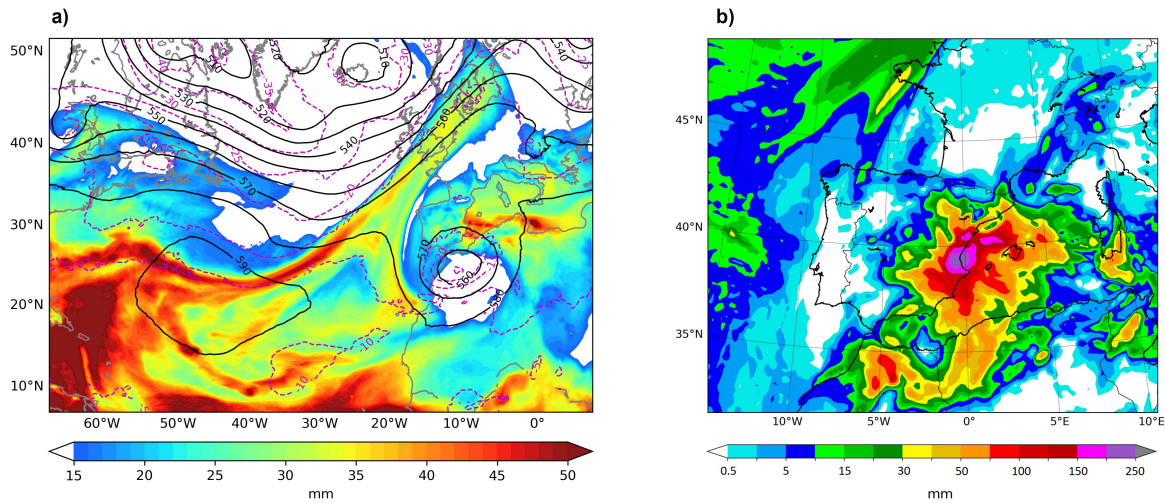
Figure 2. (a) Synoptic situation (from WRF simulation) on October 20, 1982 at 12:00 UTC. Geopotential height (solid black contours, dam) and temperature at 500 hPa and total precipitable water (shades,mm). (b) Simulated total precipitation (mm) from October 19 at 06:00 UT to October 22 at 06:00UTC (Insua-Costa et al. (2019)).

3 Results

3.1 FLEXPART-WRF moisture source diagnosis

160 **3.1.1 October event**

October 20, 1982, also known as "the Tous case", was a catastrophic flooding event caused by the extraordinary rains that fell over the Spanish Levant on that day. Heavy rainfall specially affected the Valencian Community (Fig. 2b), over which a quasi-stationary mesoscale convective complex was formed, the first identified in Europe (see Romero et al. (2000), for a detailed analysis of this episode). The synoptic situation leading to such extraordinary rainfall corresponded to the classic configuration

165 usually affecting that region (Fig. 2a): a cut-off low near the Iberian Peninsula increasing thermal and dynamic instability and, simultaneously, low pressures emerging form north Africa at lower levels organising a warm and humid flow that permanently feeds and sustains convection.

Humidity exchanges along trajectories for a small subset of particles previously selected are shown in Figure 3. Only those

170 particles that experience a significant moisture decrease for October 20, 18-21 UTC , were considered. The high density of trajectories over the Western and Central Mediterranean indicate that much of the moisture could come from evaporation over this area. In fact, the dq/dt values for air parcels crossing the Mediterranean are generally positive, indicating that they gain moisture along their paths over this sea. In addition, part of the trajectories point to a remote origin of the moisture. Some of
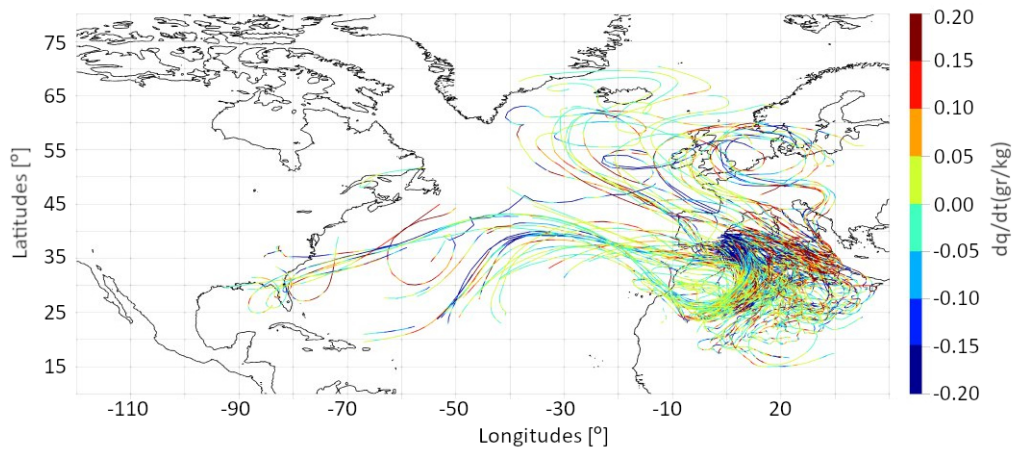
Figure 3. 11 day backtracking for a reduced subset of selected particles precipitating over the target area (blue in Fig. 1c) between 18-21 UTC on October 20. Moisture exchanges are represented along the particle path.

the particles comes from the tropical Atlantic and reach the affected region after crossing the Atlantic and North Africa. The anti-clockwise turn of the trajectories over Morocco reflects the position of the cut-off low that led to the heavy rains (Figure 2). Finally, other air parcels originated over the North Atlantic, indicating that various moisture sources may have contributed to the event.

The $E - P$ balance shown in Figure 4 more clearly points the areas where the air parcels contributing to precipitation in the events gained or lost moisture. Specifically, we show the $E - P$ balance evolution for the time periods of 1, 4, 7 and 11 days prior to the end of the event (October 21, 06UTC) . As expected, the lowest values of $E - P$ are found over the target region during the first 3 days, which reflects the moisture discharge during the extreme precipitation event. Thus, negative values in the first days show the area most affected by the extreme rainfall. In the first 24 hours, the highest positive values of $E - P$ are found in the eastern end of the Atlantic. Backwards in time, up to 4 days before the end of the event, the areas with positive $E - P$ values expand to much of the Western and Central Mediterranean. Therefore, these areas nearby would have fed the air parcels contributing to the event just hours before they reached the target region. In the case of the Mediterranean, $E - P$ values continue to increase up to 7 days before, indicating that not only was the contribution of evaporation in the hours prior to the event significant, but also evaporation in the previous days. In addition, a clear difference between days 4 and 7 is that positive (and also negative) values of $E - P$ appear in remote regions, mainly over the North Atlantic. These positive values extend even into the tropical and subtropical Atlantic when we calculate the accumulated $E - P$ of the previous 11 days. This indicates that the contribution of humidity from the Atlantic may have been significant. Furthermore, this humidity would be older, i.e. it would have had a longer residence time. One last area with positive $E - P$ values is North Africa. Although the values on the northern coast of the continent might be realistic, the values inland are totally inconsistent since evaporation in
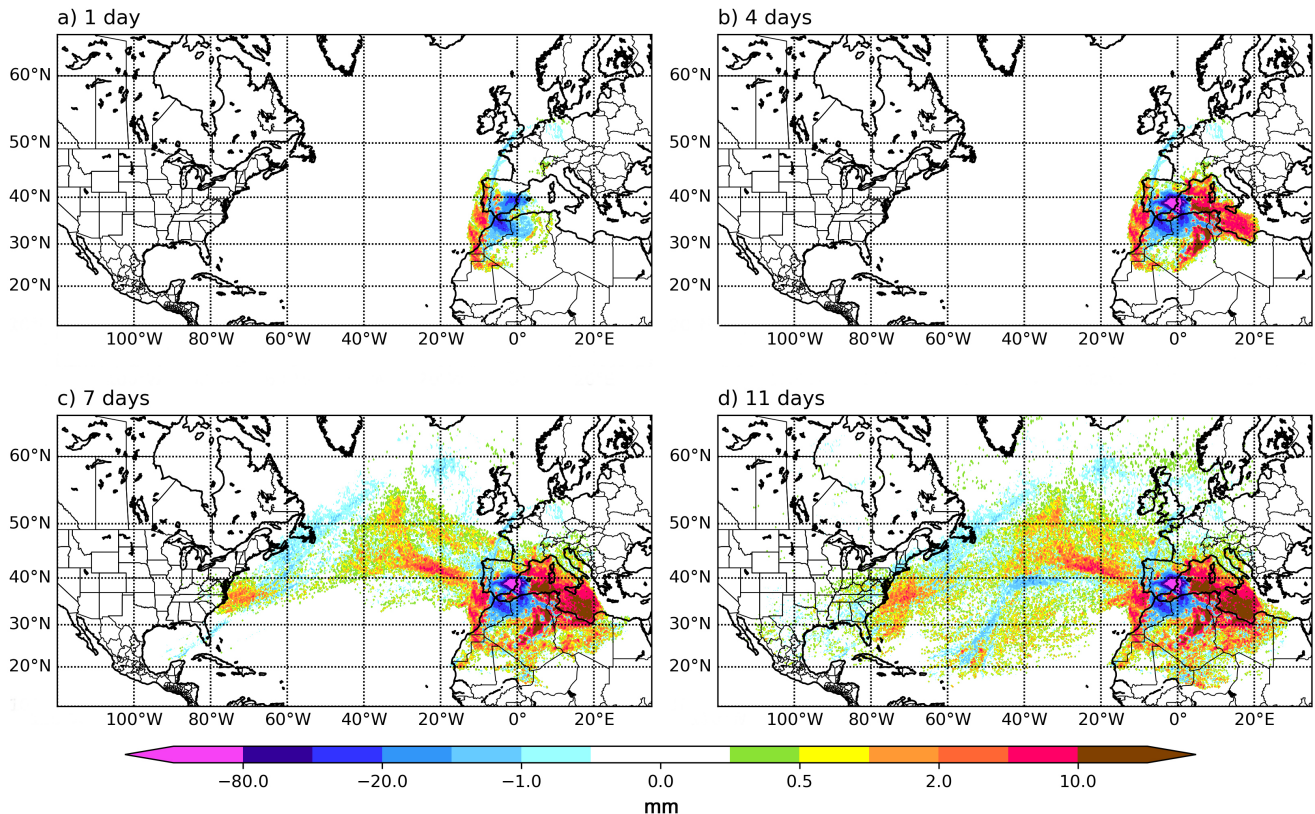
Figure 4. $E - P$ balance evolution back in time for 1 (a), 4 (b), 7 (c) and 11 (d) days. Particles were selected from $5°$W-$1°$E and $37°$-$42°$N for the 19 October 06UTC to 21 October 21UTC.

that area of the Sahara desert is practically zero throughout the year. Therefore, these values must necessarily be due to the limitations of the method. We will return to this subject below.

Finally, we would like to clarify again that while positive $E - P$ values occur in areas with a high probability of having contributed to the event, this is not entirely certain, since part of the moisture gains, especially those more distant in time and space, are likely to have been lost in a previous precipitation discharge. Regions with negative $E - P$ could also have contributed moisture to the event, although this is less likely. For example, the Spanish east coast in Figure 4 has very negative values because there the P values were very high during the event. However, this does not mean that the E values were zero; a preliminary analysis shows that a significant fraction of the total evaporation occurs when E-P<0 (see https://doi.org/10.5194/hess-2020-651-RC2). In fact, it is very likely that evaporation in this area in the previous days contributed significant amounts of moisture. This contribution, which would correspond to local precipitation recycling, would be completely ignored if one considers that only areas with $E - P > 0$ can contribute to the event. It is therefore very important
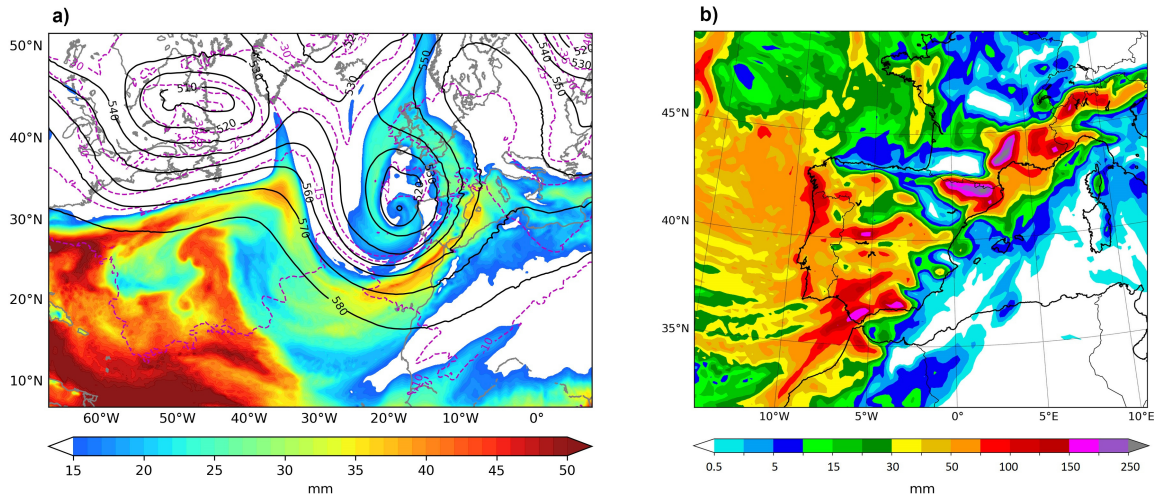
Figure 5. (a) Synoptic situation (from WRF simulation) on November 7, 1982 at 12:00 UTC. Geopotential height (solid black contours, dam) and temperature at 500 hPa and total precipitable water (shades,mm). (b) Simulated total precipitation (mm) from November 6 at 06:00 UTC to November 9 at 06:00 UTC (Insua-Costa et al., 2019).

to take these nuances into account in order to make a proper reading of the $E - P$ field.

3.1.2 November event

Only a few days after the Tous case, on November 7, catastrophic flooding occurred again in the WMR. In this case, heavy
210 rainfall particularly affected northeast Spain, southeast France and Andorra (Fig. 5b). The atmospheric configuration that led
to the excessive rainfall was very different from that occurring in October (Fig. 5a): a deep low-pressure system centred off the
Atlantic coast of Galicia drove a very humid and relatively warm south-westerly flow that impacted perpendicularly against
the Pyrenees and the southern face of the French Massif Central. The orographic lift in these areas triggered convective cores
embedded in a wider area of stratiform rainfall, which in turn gave rise to persistent and occasionally very intense precipitation
215 (see Trapero et al. (2013), for a more detailed discussion about this event).

Figure 6 shows the specific humidity content change for a subset of particles with significant moisture losses between 12-15
UTC November 7. In this case the particle trajectories are not as varied as in the case of October, but a main route distinguishes
itself. Most of the trajectories have their origin in the western tropical Atlantic. From there the parcels are advected towards
220 the north and cross the Atlantic driven by the deep low-pressure system that gave rise to the extreme rainfall event (Figure 5).
In the final phase, a few hours before the particles reached the northeast of the Iberian Peninsula, the air parcels were advected
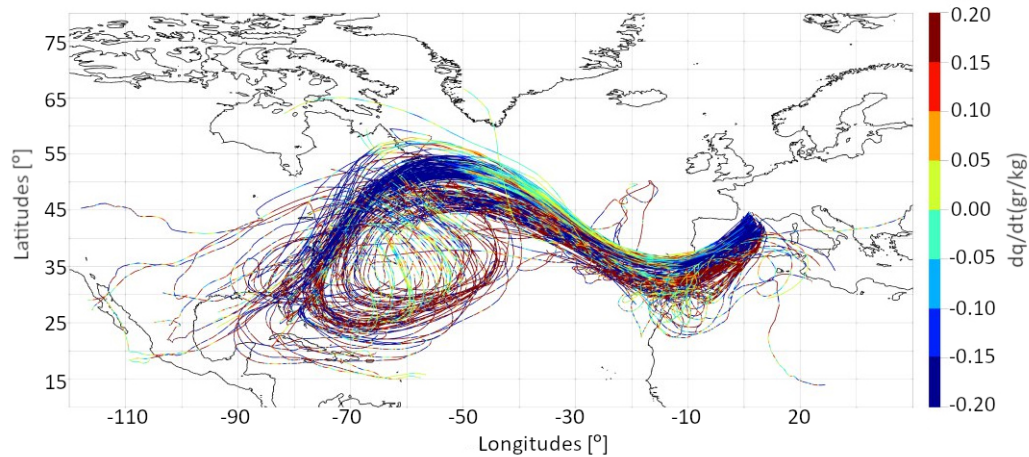
Figure 6. 11 day backtracking for a subset of particles precipitating over the region of interest between 12-15 UTC on November 7. Color corresponds to moisture exchanges along the paths followed by particles.

northward again, entering via North Africa and southern Spain. Some of them crossed the western end of the Mediterranean before their impact on the target area. It follows that in this case the main source of moisture must be the Atlantic, while the contribution of the Mediterranean should be minor because the time that air parcels spend over this potential moisture source
225 is limited.

Figure 7 is analogous to Figure 4 but for the November event. In this case, the negative values of $E - P$ in the first 24 hours cover a vast region, due to the large size of the low-pressure system located off the coast of Galicia (Figure 5). Positive values of $E - P$ in the first 24 hours are only found in the Western Mediterranean. Therefore, the Mediterranean provided a last humidity
230 recharge before the air parcels contributing to the precipitation reached the affected region. The $E - P$ field accumulated in the 4 days prior to the end of the event clearly shows the areas most affected by extreme rainfall (northeast and southwest Spain, south of France and Andorra). The positive values of $E - P$ extend towards the Atlantic and increase in the Mediterranean. Further back in time, between days 7 and 11, the highest values are found in the tropical and subtropical western Atlantic. The way the $E - P$ values are distributed is consistent with the particle trajectories (Figure 6) and also with the precipitable water
235 field (Figure 5 (a)). In summary, the air mass in this event had a tropical/subtropical origin and was recharging its moisture content as it passed through the Atlantic and finally through the Western Mediterranean.

3.2 Comparison of WRF-WVTs vs. FLEXPART-WRF methodologies

The previous analysis of the particles trajectories and the $E - P$ field allows a qualitative diagnostic of the moisture sources, but not a quantitative one. In contrast, the WRF-WVTs method of Insua-Costa et al. (2019) calculates the exact percentage
240 of precipitation coming from the four source regions of Figure 1a for the two infamous events of autumn 1982. In order to
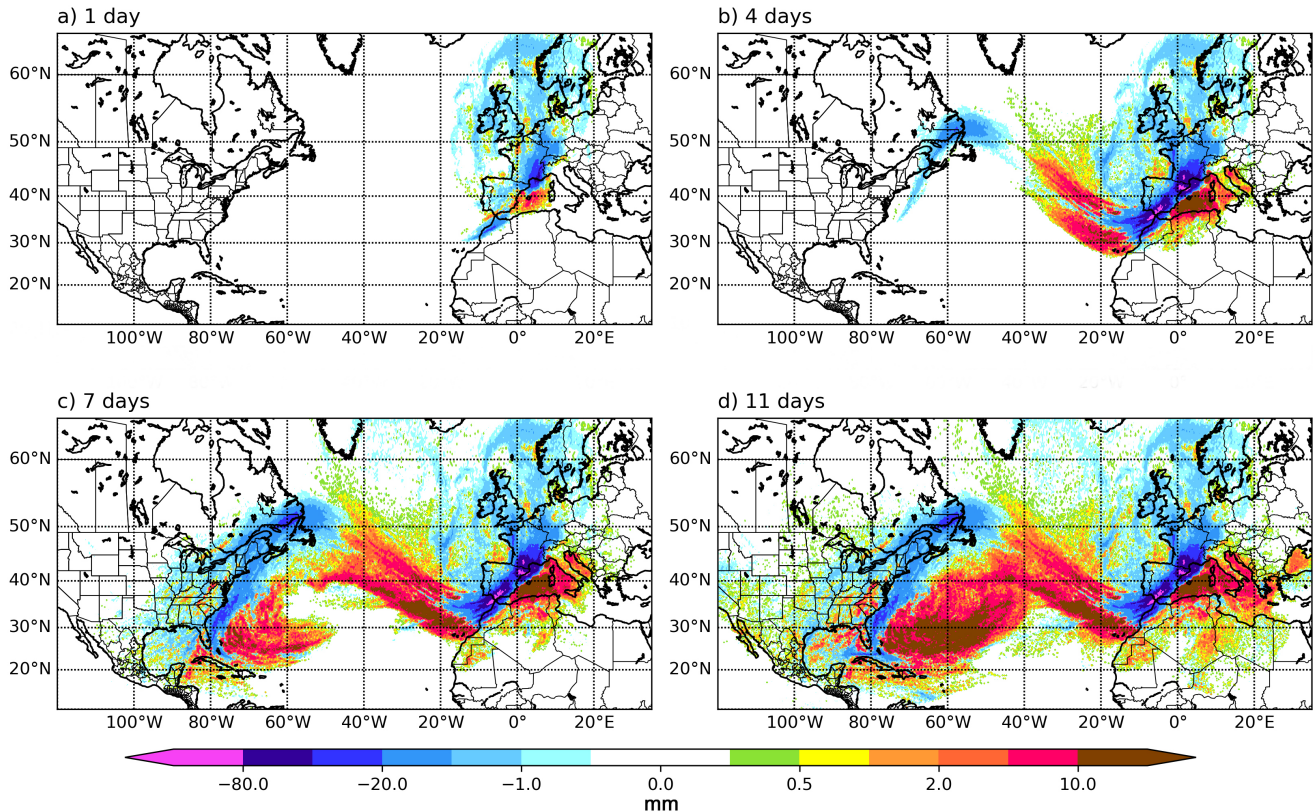
Figure 7. Similar to Figure 4. Balance $E - P$ evolution back in time for 1 (a), 4 (b), 7 (c) and 11 (d) days. Particles were selected from $2.5°W - 7°E$ and $40° - 47°N$ for the 06 November 06UTC to 08 November 21UTC.

compare the results provided by the FLEXPART-WRF technique with those obtained by Insua-Costa et al. (2019) , these same percentages have been computed using the methodology introduced by Sodemann et al. (2008), previously described.

245   Figure 8a shows the fraction (RC, Eq. 3) of the total precipitation accumulated during the case of October 1982 coming from each of the four analyzed sources, calculated with the WRF-WVTs (blue) and the FLEXPART-WRF (purple). Both methods yield similar contributions from the Western Mediterranean Sea (16.81 % versus 19.14 %) and North Atlantic Ocean (13.25 % versus 14.89 %). However, the Central Mediterranean contribution according to the FLEXPART-WRF is half of that calculated with the WRF-WVTs (7.38 % versus 18.28 %). The most surprising difference between the results provided by both methods is found in the tropics and subtropics; while for the WRF-WVTs this is the main source (31.02%), for the FLEXPART-WRF

250   its contribution is only 5.39%. The great difference for this source finally results in that the WRF-WVTs assigns about 83 % of relative contribution to the ensemble of the four considered sources, while the FLEXPART-WRF reports a much smaller contribution for these same areas in conjunction (45.49 %).
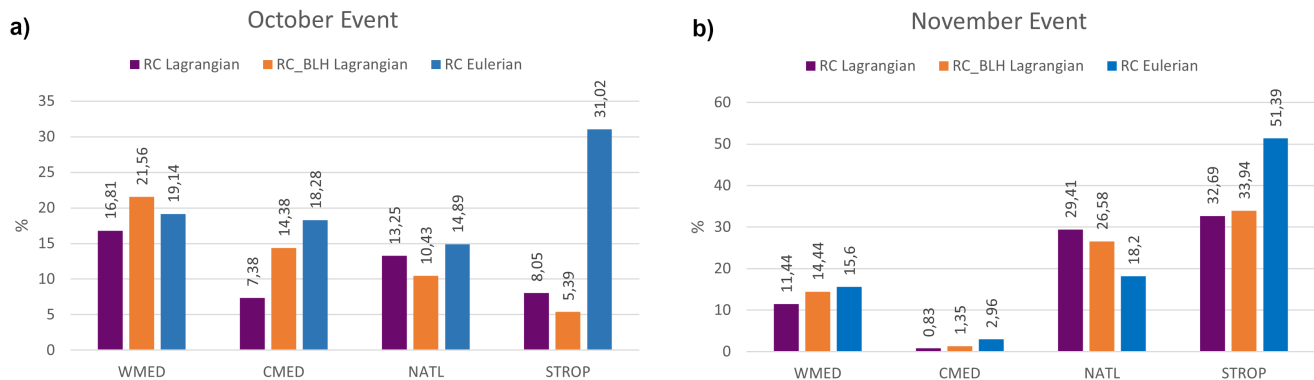
Figure 8. Comparison between the relative contributions provided by the FLEXPART-WRF and the WRF-WVTs models for the October event (a) and the November event (b). WMED, CMED, NATL, and STROP correspond to Western Mediterranean, Central Mediterranean, North Atlantic and tropical/subtropical areas, respectively.

For the November event, the relative contributions are shown in Fig. 8b. In this case, the FLEXPART-WRF estimates 74.37
255   % of joint relative contribution for the four considered sources, a very similar value to that obtained by the WRF-WVTs (88.15 %). A comparison between both approaches shows similar estimations for the Central Mediterranean sea (0.83 % versus 2.96 %) and the Western Mediterranean sea (11.44 % versus 15.60 %), the least important moisture sources for this episode. Nevertheless, for the North Atlantic, the FLEXPART-WRF results in a significant overestimation compared with the WRF-WVTs (29.41 % versus 18.20 %). On the contrary, the FLEXPART-WRF underestimates the contribution of moisture from the tropics
260   and subtropics(32.69 % versus 51.39 %).

3.3   Limitations of the analysis with FLEXPART-WRF and possible causes

The above results show a great difference between the relative contributions obtained with the FLEXPART-WRF and the WRF-WVTs methods. The biggest discrepancy is found in the subtropical and tropical contribution. For the case of October,
265   FLEXPART-WRF underestimates this source by 74% while in the case of November this underestimation is 36%. For local moisture sources, such as the Mediterranean Sea, there is generally a better match, but significant biases remain.

Our experiments suggest that the FLEXPART-WRF is limited for quantitative moisture source analysis in specific case studies. That limitation seems to especially affect estimates of the moisture contribution from remote sources, such as the tropics
270   and subtropics in our case. Notwithstanding, in the November event the underestimation for tropical and subtropical moisture was substantially less than in the October case. The November episode was more "dynamic", with higher winds that would have made air parcels to travel faster along a narrower pathway. In the October event, particles move slower and through diverse paths, so that they disperse more backward in time and spend more time in regions with weak wind. This difference could have

been crucial to make more problematic the calculations in the October case.

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In an attempt to reduce these large biases, we have recalculated the relative contributions of each source considered in Insua-Costa et al. (2019) by considering only the moisture increases of those air parcels within the boundary layer (RC_{BLH}, Eq.4), as proposed in Sodemann et al. (2008). Results are also shown in Fig 8 (orange bars). In general, this new approach improves the results, i.e., they are closer to those provided by the WRF-WVTs. However, the error reduction is small and large biases remain for remote sources. Therefore, we conclude that most of the errors of this analysis are associated with air parcels located within the boundary layer.

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Another important consideration is related to the unrealistic values that the FLEXPART-WRF yields in some parts of the region of study. This problem is especially evident for the October case over the Sahara desert, as stated above. $E - P$ values are highly positive suggesting an important moisture gain. However is not possible for that gain to come from a surface evaporation flux because evaporation over that area is essentially zero. Initially, we had hypothesized that these unrealistic values might be due to phase changes, which are not taken into account by the FLEXPART-WRF. Cloudiness was abundant over most of Northern Africa, so that some of this water could have evaporated into the very dry Saharan lower atmosphere, leading to an increase in the particles' water vapour content. To quantify this effect, we have taken advantage of the fact that the WRF model includes 6 moisture species (vapour, cloud water, rain water, snow, ice and graupel) to incorporate the sum of all these species in the FLEXPART-WRF. That is, we have repeated the calculation shown in Eq. 1, but in this case with q being the sum of all moisture species within an air parcel instead of just water vapour. Results show that the effect of including liquid and solid water in the model is very small. Specifically, the average relative difference in $E - P$ field values is about 4% (Figure 9). These results agree with those of van der Ent et al. (2013), who reached the same conclusion using a totally different methodology.

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Therefore, the errors found must have their causes in other physical or numerical processes that the FLEXPART-WRF is not considering correctly. The increase over time of inaccuracies in the calculations of particle trajectories or in the interpolations of specific moisture content could be some examples. Importantly, one of the problems that could have contributed the most to the errors encountered is the fact that the FLEXPART-WRF neglects the convergence and divergence of moisture (see https://doi.org/10.5194/hess-2020-651-CC1). Figure 10 describes this process. In a "normal" situation, a Lagrangian air parcel moves (dynamic situation) and variations in the specific moisture content along its trajectory are associated with evapotranspiration or precipitation processes. However, when the particle is in a converging air flow, the position of the particle does not change (zero net velocity) if convergence takes place equally from all sides of the particle, but the moisture content increases. The FLEXPART-WRF will associate this increase to a surface evaporation process, when in fact it has nothing to do with it. On the contrary, if a particle is in a diverging flow, its moisture content could be reduced without this being associated with a precipitation process. This could be especially problematic when tracking a small set of parcels (Tuinenburg and Staal, 2020). This issue would require further and more detailed investigation, specifically focused on moisture convergence and divergence
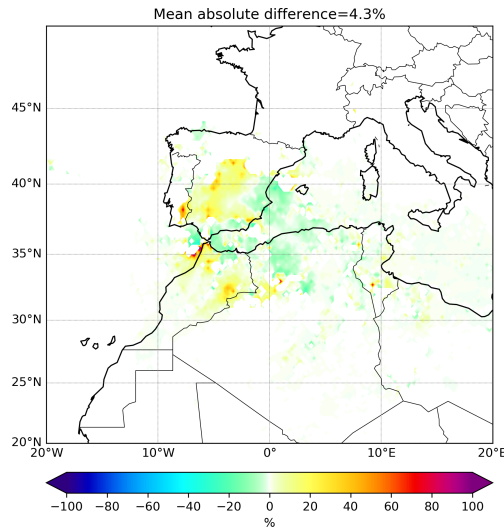
Figure 9. Relative difference (%) between E-P field values calculated considering humidity phase changes and without considering them. The domain has been cropped with respect to Figures 4 and 7 because the values outside the shown area are very small.

situations to establish a more robust and definite conclusion.

4 Summary and conclusion

Two of the most used techniques for the study of moisture origin are the Lagrangian-offline and the Eulerian-online models. The use of one or the other can be a controversial point (van der Ent et al. (2013)), but in general it is clear that Lagrangian models are more computationally efficient, which makes them more practical. For this reason, they have been widely used. However, it is important to take into account the limitations of these methods for a more rigorous analysis.

Here, we have compared the results of the Lagrangian FLEXPART-WRF model with those obtained from the Eulerian WRF-WVTs model for two extreme rainfall events occurred in the Western Mediterranean region in October and November 1982, respectively. The objective was to validate the performance of the FLEXPART-WRF, considering the WRF-WVTs results as the "truth" with which to compare.

The results show that the use of the FLEXPART-WRF is very limited for a quantitative study of moisture sources because large biases were found when compared with the WRF-WVTs. For the nearest sources, as are in our case the Mediterranean Sea and the North Atlantic Ocean, the results obtained with both methods have in general a remarkable coincidence. However, the contribution of tropical and subtropical areas is not adequately captured by FLEXPART-WRF, since it is grossly underestimated. In addition, the model produces unrealistic values in some areas. These unrealistic values become especially evident
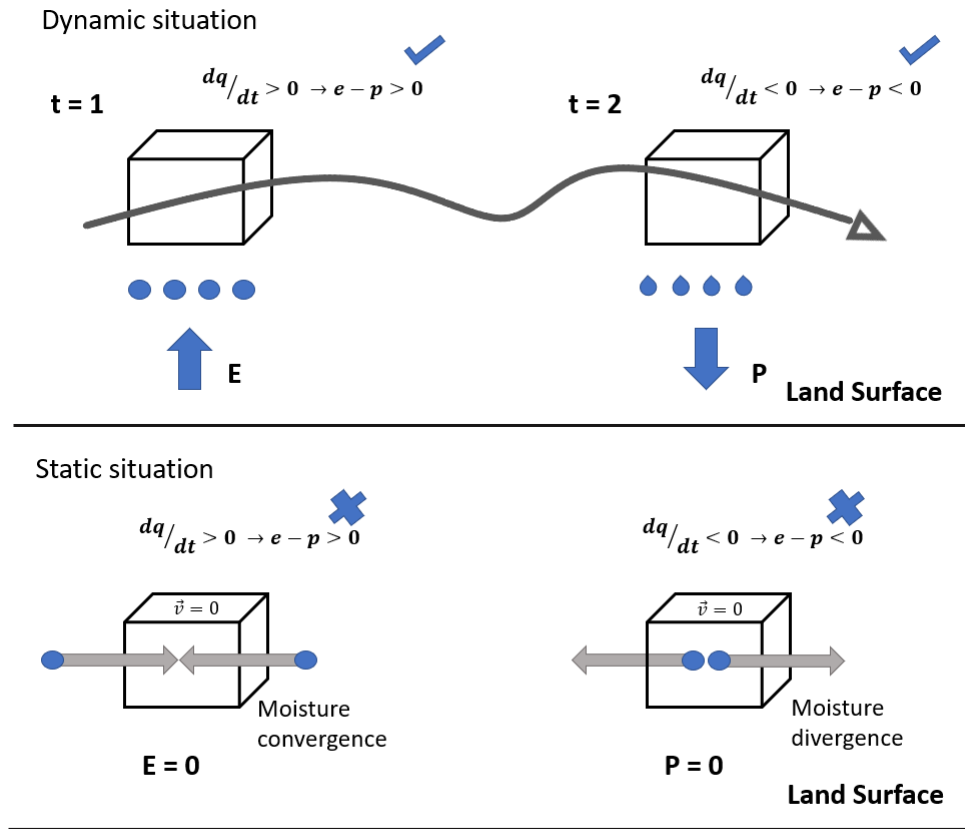
Figure 10. Schematic representation of the problem with convergence and divergence of moisture undergone by the FLEXPART-WRF.

over the Sahara region during the case of October. Due to the low evaporation rate in that zone, it is impossible for it to act as one of the main moisture sources, as the FLEXPART-WRF suggests.

Therefore, we propose that the FLEXPART-WRF is more appropriate for a qualitative description of the origin of moisture rather than to estimate precise source contribution numbers. Finally, we have delved into some of the causes and possible solutions to the errors found. We have shown that phase changes, which had been raised as a potential source of error by other authors (Stohl and James (2004)), actually affect the calculations very little. A simple approach to improve the performance of the Lagrangian method, which had been proposed by Sodemann et al. (2008) and consisted in considering only the air parcels within the boundary layer, has proved insufficient to reduce the errors encountered. Therefore, we conclude that it is necessary to make further progress in the improvement of this type of tools for moisture tracking.

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Competing interests. Authors declare that no competing interest are presented.

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References

EMDAT.database, http://www.emdat.be/database.

345 Brioude, J., Arnold, D., Stohl, A., Cassiani, M., Morton, D., Seibert, P., Angevine, W., Evan, S., Dingwell, A., Fast, J. D., Easter, R. C., Pisso, I., Burkhart, J., and Wotawa, G.: The Lagrangian particle dispersion model FLEXPART-WRF version 3.1, Geoscientific Model Development, https://doi.org/10.5194/gmd-6-1889-2013, 2013.

Buzzi, A., Tartaglione, N., and Malguzzi, P.: Numerical simulations of the 1994 piedmont flood: Role of orography and moist processes, Monthly Weather Review, https://doi.org/10.1175/1520-0493(1998)126<2369:NSOTPF>2.0.CO;2, 1998.

350 Ciric, D., Nieto, R., Losada, L., Drumond, A., and Gimeno, L.: The mediterranean moisture contribution to climatological and extreme monthly continental precipitation, Water (Switzerland), https://doi.org/10.3390/w10040519, 2018.

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.,
355 Bechtold, P., Beljaars, A. C. M., 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, https://doi.org/10.1002/qj.828, 2011.

360 Dominguez, F., Hu, H., and Martinez, J. A.: Two-layer dynamic recycling model (2L-DRM): learning from moisture tracking models of different complexity, Journal of Hydrometeorology, 21, 3–16, 2020.

Drumond, A., Marengo, J., Ambrizzi, T., Nieto, R., Moreira, L., and Gimeno, L.: The role of the Amazon Basin moisture in the atmospheric branch of the hydrological cycle: A Lagrangian analysis, Hydrology and Earth System Sciences, https://doi.org/10.5194/hess-18-2577-2014, 2014.

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

Eiras-Barca, J., Dominguez, F., Hu, H., Garaboa-Paz, D., and Miguez-Macho, G.: Evaluation of the moisture sources in two extreme land-falling atmospheric river events using an Eulerian WRF tracers tool, Earth System Dynamics, https://doi.org/10.5194/esd-8-1247-2017, 2017.

370 Emanuel, K. A. and Živković-Rothman, M.: Development and evaluation of a convection scheme for use in climate models, Journal of the Atmospheric Sciences, https://doi.org/10.1175/1520-0469(1999)056<1766:DAEOAC>2.0.CO;2, 1999.

et al. Skamarock WC: A description of the advanced research WRF version 3, NCAR Tech. Note, NCAR/TN-468+STR, Natl. Cent. for Atmos. Res. Boulder, Colorado, 2008.

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

Gimeno, L., Nieto, R., Drumond, A., Castillo, R., and Trigo, R.: Influence of the intensification of the major oceanic moisture sources on continental precipitation, Geophysical Research Letters, https://doi.org/10.1002/grl.50338, 2013.

Hanna, S. R.: Atmospheric turbulence and air pollution modelling, Atmospheric Turbulence and Air Pollution Modelling, pp. 275–310, 1982.

Hong, S. Y., Noh, Y., and Dudhia, J.: A new vertical diffusion package with an explicit treatment of entrainment processes, Monthly Weather Review, https://doi.org/10.1175/MWR3199.1, 2006.

Hu, H. and Dominguez, F.: Understanding the Role of Tropical Moisture in Atmospheric Rivers, Journal of Geophysical Research: Atmospheres, https://doi.org/10.1029/2019JD030867, 2019.

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, https://doi.org/10.5194/esd-9-167-2018, 2018.

Insua-Costa, D., Miguez-Macho, G., and Llasat, C.: Local and remote moisture sources for extreme precipitation: A study of the two catastrophic 1982 western Mediterranean episodes, Hydrology and Earth System Sciences, 23, 3885–3900, https://doi.org/10.5194/hess-23-3885-2019, 2019.

James, P., Stohl, A., Forster, C., Eckhardt, S., Seibert, P., and Frank, A.: A 15-year climatology of stratosphere-troposphere exchange with a Lagrangian particle dispersion model: 1. Methodology and validation, Journal of Geophysical Research Atmospheres, https://doi.org/10.1029/2002jd002637, 2003.

Kain, J. S. and Fritsch, J. M.: A one-dimensional entraining/detraining plume model and its application in convective parameterization, Journal of the Atmospheric Sciences, https://doi.org/10.1175/1520-0469(1990)047<2784:AODEPM>2.0.CO;2, 1990.

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, https://doi.org/10.1007/s00704-014-1244-6, 2015.

Lavers, D. A. and Villarini, G.: The contribution of atmospheric rivers to precipitation in Europe and the United States, Journal of Hydrology, https://doi.org/10.1016/j.jhydrol.2014.12.010, 2015.

Llasat, M. C.: High magnitude storms and floods, The Physical Geography of the Mediterranean, edited by: Woodward, JC, Oxford University Press, Oxford, pp. 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, https://doi.org/10.5194/adgeo-23-47-2010, 2010.

Mariotti, A., Struglia, M. V., Zeng, N., and Lau, K. M.: The hydrological cycle in the Mediterranean region and implications for the water budget of the Mediterranean sea, Journal of Climate, https://doi.org/10.1175/1520-0442(2002)015<1674:THCITM>2.0.CO;2, 2002.

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, https://doi.org/10.1175/JCLI3386.1, 2005.

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, 2010.

Pérez-Muñuzuri, V., Eiras-Barca, J., and Garaboa-Paz, D.: Tagging moisture sources with Lagrangian and inertial tracers: Application to intense atmospheric river events, Earth System Dynamics, https://doi.org/10.5194/esd-9-785-2018, 2018.

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, https://doi.org/10.1002/jgrd.50179, 2013.

Pisso, I., Sollum, E., Grythe, H., Kristiansen, N., Cassiani, M., Eckhardt, S., Arnold, D., Morton, D., Thompson, R. L., Groot Zwaaftink, C. D., Evangeliou, N., Sodemann, H., Haimberger, L., Henne, S., Brunner, D., Burkhart, J. F., Fouilloux, A., Brioude, J., Philipp, A., Seib-

ert, P., and Stohl, A.: The Lagrangian particle dispersion model FLEXPART version 10.3, Geoscientific Model Development Discussions, https://doi.org/10.5194/gmd-2018-333, 2019.

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

420 Romero, R., Doswell, C. A., and Ramis, C.: Mesoscale numerical study of two cases of long-lived quasi-stationary convective systems over eastern Spain, Monthly Weather Review, https://doi.org/10.1175/1520-0493(2001)129<3731:MNSOTC>2.0.CO;2, 2000.

Sodemann, H., Schwierz, C., and Wernli, H.: Interannual variability of Greenland winter precipitation sources: Lagrangian moisture diagnostic and North Atlantic Oscillation influence, Journal of Geophysical Research Atmospheres, https://doi.org/10.1029/2007JD008503, 2008.

425 Stohl, A. and James, P.: A Lagrangian analysis of the atmospheric branch of the global water cycle: Part 1: Method description, validation, and demonstration for the August 2002 flooding in central Europe, Journal of Hydrometeorology, https://doi.org/10.1175/1525-7541(2004)005<0656:ALAOTA>2.0.CO;2, 2004.

Stohl, A., Forster, C., and Sodemann, H.: 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, https://doi.org/10.1029/2007JD009006, 2008.

430 Sun, B. and Wang, H.: Moisture sources of semiarid grassland in China using the lagrangian particle model FLEXPART, Journal of Climate, https://doi.org/10.1175/JCLI-D-13-00517.1, 2014.

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, https://doi.org/10.5194/nhess-13-2969-2013, 2013.

435 Tuinenburg, O. A. and Staal, A.: Tracking the global flows of atmospheric moisture and associated uncertainties, Hydrology and Earth System Sciences, https://doi.org/10.5194/hess-24-2419-2020, 2020.

Turato, B., Reale, O., and Siccardi, F.: Water vapor sources of the October 2000 Piedmont flood, Journal of Hydrometeorology, https://doi.org/10.1175/1525-7541(2004)005<0693:WVSOTO>2.0.CO;2, 2004.

van der Ent, R. J., Tuinenburg, O. A., Knoche, H.-R., Kunstmann, H., and Savenije, H. H. G.: Should we use a simple or complex model for
440 moisture recycling and atmospheric moisture tracking?, Hydrology and Earth System Sciences Discussions, https://doi.org/10.5194/hessd-10-6723-2013, 2013.

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, https://doi.org/10.1002/qj.987, 2012.

Winschall, A., Pfahl, S., Sodemann, H., and Wernli, H.: Comparison of Eulerian and Lagrangian moisture source diagnostics - The flood
445 event in eastern Europe in May 2010, Atmospheric Chemistry and Physics, https://doi.org/10.5194/acp-14-6605-2014, 2014.