Simultaneous Episodes of Heavy Rainfall in Morocco and Southern Alps: 2. Time Scales and Mapping of Remote and Local Evaporative Sources

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Abstract A mesoscale modeling system, previously used to evaluate the evaporation sources during the August 2002 Central-European Floods (ACEF), is now adapted to analyze the 14–16 November 2002 simultaneous torrential rains in the Alps and Morocco. The meteorology of the selected episode and the climatology and time of recurrence of similar episodes were discussed in the companion article. Contrary to the ACEF estimations, the vapor sources keep almost constant for the 3-day rainfalls, in accordance with a quasi-stationary large-scale forcing. They show a dominance of marine sources (60% and 93% of the total attributed precipitations in the Alps and Morocco, respectively) with a main role of the Western Central Mediterranean for the Alpine targets and the Atlantic Ocean for Morocco. A share of 12%, comparable with the August episode, comes from direct rain-column evaporation in the Alps. Vapor loading rates of the target vapor show an exponential increase during the last 3–4 days before the initiation of the episode, while for the ACEF episode we estimate a longer period of 6–7 days. Three areas of intense marine evaporation are observed, two in the North Atlantic Ocean and one in the Mediterranean Sea, related with the rainfall targets and corresponding with regions of enhanced sea surface temperature decrease. Vapor from the main terrestrial source in North Africa, including the tropical region, is transported inside the prefrontal secondary circulation into the Alpine region. A similar circulation and evaporative source distribution are documented during other simultaneous episodes.

1. Introduction

The capability of discriminating moisture sources with precision is an important requirement for a better understanding of the mechanisms of extreme rainfalls. A high-resolution mesoscale meteorological model and 3-D Lagrangian backward trajectories were integrated in a modeling system (MesoWat_Source) developed to assess moisture sources associated with selected rainfall events (Gangoiti, Sáez de Cámara, et al., 2011, Gangoiti, Gómez-Domenech, et al., 2011). In a more recent contribution (Gangoiti et al., 2015), the capability of the model was enhanced to allow for the discrimination of additional vapor sources such as the direct rainfall evaporation (virga). The model was applied to investigate the vapor sources distribution and their evolution during the 11–13 August 2002 Central-European Floods (ACEF) in the Alpine region, after the intensification of a cyclone over the Gulf of Genoa. The highly changing nature and distribution of the moisture sources contributing to the episode were thoroughly described by the model: marine sources in the Western Mediterranean (WM) were important during the initiation of the episode, whereas the recycling through land evaporation in vast areas of the European continental landmass dominated throughout the remaining days of heavy rain. Virga accounted for 18% of the target rainfall during that summer episode and its main fraction took place over land, close to the specific target region. This percentage showed important variations depending on the location of the target, and its time scale (around 2 days) was at least 3 to 4 times shorter than that of the surface sources, which took place at a larger region and during a longer period of time. The relative importance of recycling over the European landmass during summer extreme rainfall episodes in central Europe has also been shown by Kelemen et al. (2016), using a completely different methodology. Similar results were obtained in other target areas: extreme rainfalls in eastern Europe analyzed by Winschall et al. (2014), using both Eulerian and Lagrangian moisture source diagnostics and extremes in southern Sweden studied by Gustafsson et al. (2010).
On the other hand, autumnal episodes of heavy rainfall in the Alpine region are known to show a complete different vapor source distribution than in summer, at least in reference to the land/sea relative contribution (Sodemann & Zubler, 2010), with a greater fraction from marine sources and a relevant role of the WM. The later source shows the highest intensity during that season, following the conclusions of the referred contribution. Moisture sources of the 14–16 November 2002 severe rainfall episode, which affected the Alpine region, were estimated by Winschall et al. (2011). They used a water-tagging simulation with a limited-area model to evaluate the contribution of different sources and concluded that marine evaporation had the largest share, with 45% of the target precipitation during 15 and 16 November 2002: 19% came from the Atlantic Ocean and 26% from the Mediterranean Sea. Their simulation showed that almost all the Atlantic contribution came from a preselected hot spot region in the eastern North Atlantic (N-Atlantic). They also show that the contribution from land evaporation changed during the 2-day episode (28%–33%) as well as the nonattributed evaporation that entered into the domain, mainly from the west and northwestern “Atlantic” boundaries (21–13%). Direct rainfall evaporation (virga) was not evaluated as a possible source of vapor. However, this component of the water cycle has been shown to play a key role in propagating/removing inland precipitation (Gangoiti et al., 2015). According to the intense föhn and high temperatures documented during the November 2002 episode (Zängl & Hornsteiner, 2007), rain column evaporation might have contributed with a percentage even larger than the 18% estimated with the MesoWat_Source model for the ACEF episode.

With the objective of testing the referred hypothesis of an important contribution of vapor from rain evaporation during this type of intense föhn episodes, we have selected the episode of 14–16 November 2002 to undertake a detailed evaluation of all types of vapor sources, including virga. The distribution of local and remote sources is evaluated as well as the relative contribution from marine and land sources and their intensity changes during the episode. The evaporation time sequence associated with each rainfall event is also explored by using the MesoWat_Source model. On the other hand, this type of Alpine extreme rainfall episodes, which develops after the formation of an elongated upper level trough, used to be concurrent with severe rainfalls and floods in the west facing slopes of the Middle and High Atlas, including the Er-Rif (ER) mountains in Morocco. A detailed analysis of this type of simultaneous episodes and their recurrence is treated in Gangoiti et al. (2019), referred to as G19. In Morocco, the referred rainfall episode lasted for a shorter time (14–15 November 2002) and the evaluation of its sources will help us to elucidate whether they share the same moisture sources than the Alpine rainfalls. The modeling system is episodic (Gangoiti et al., 2015) and requires a detailed setup of the meteorological, vapor emission, and trajectory inputs in order to estimate evaporative sources for a period of 2–3 weeks before the rainfall episode. It would be time-consuming and cost-prohibitive to simulate several years or even a complete year of a target region/precipitation at an hourly resolution. Alternatively, a selection of other similar/different synoptic forcing scenarios has been simulated to search for similarities and differences in the distribution and strength/intensity of the evaporative sources. The results will also help to understand the role of the Atlantic/Mediterranean evaporation, the formation of regions of enhanced evaporation over the sea during the episodes, and their possible impact in the sea surface temperature (SST) distribution in the N-Atlantic and the Mediterranean Sea.

The manuscript is organized as follows: A brief description of the methodology for the search of sources, the selection of the precipitation targets in both regions, and the coverage/resolution of the evaporation domain are described in section 2. Section 3 shows the main modeling results, including mapping of the sources, and comparisons with the ACEF episode and other autumn episodes. A discussion about the vapor losses across the boundaries of the domain and the time scales and intensity changes of the evaporation processes are also included in this section. Section 4 shows the relative importance of local versus remote sources and the main atmospheric processes involved. The SST changes in the N-Atlantic and the Mediterranean, together with sea evaporation and the main moisture sources feeding the episodes during the period 1981–2016, are discussed in section 5. Finally, section 6 provides a summary of the results and the main conclusions. In a previous companion paper G19 we explored the meteorology of this type of episodes of concurrent heavy rainfall in Morocco and southern Alps, performed the mesoscale simulation, and validated the main results of the 14–16 November 2002 torrential rainfall. The time of recurrence of similar episodes was also investigated, as well as the occurrence of concurrent areas of enhanced evaporation in the N-Atlantic.
2. Materials and Methods

The results of the Regional Atmospheric Modeling System (v6.0) (Pielke et al., 1992) applied to the referred episode 14 – 16 November 2002 were described in G19, as part of the necessary steps to estimate evaporation sources within the framework of the *MesoWat_Source* modeling system (Gangoiti, Gómez‐Domenech, et al., 2011, 2015). The rest of the software modules (Figure 1) are devoted to the transport of water vapor parcels from the precipitation sites in back trajectories into their sources. The HYbrid PArticle Concentration and Transport model (HYPACT v1.5) (Tremback et al., 1993) is used for estimating the transport of moisture following full three‐dimensional trajectories, and the rest of the modules inside the red dotted limits in Figure 1 are used for postprocessing and depiction of maps included in this manuscript. The water vapor uptake (surface evapotranspiration) is calculated by the module “Source Attribution Model” following the scheme by Dirmeyer and Brubaker (1999), modified to include the assumption of complete mixing in the planetary boundary layer (PBL) instead of the complete mixing in the whole troposphere (Gangoiti, Gómez‐Domenech, et al., 2011). Following this scheme, moisture is added from surface sources to trajectories only when they are within the PBL, whereas trajectories in the free troposphere do not incorporate it. The vapor ratio added inside the PBL depend on the local \((i,j)\) rate of evapotranspiration \(E_{ij}\) \([\text{MT}^{-1} \text{L}^{-2}]\), its column water vapor in the PBL, \(\text{ColumnPBL}_{ij} \ [\text{ML}^{-2}]\), and the residence time inside the PBL, which depends on each trajectory. Thus, the vapor ratio added to the trajectory in a time step \(\Delta t\) is as follows:

\[
R_{ij} = \frac{E_{ij} \cdot \Delta t}{\text{ColumnPBL}_{ij}}
\]

At any time \(t\) before the precipitation event, the water vapor uptake \(M_{ev}\) from the underlying surface at grid cell \((i,j)\) into the tracked parcel inside the PBL can be estimated:

\[
M_{ev} = R_{ij} M^t_w
\]

where \(M^t_w\) is the total mass of vapor of the tracked parcel, at time \(t\) before the precipitation event.

The evaluation of the remaining vapor in the parcel, at time \(t = t + \Delta t\), is

\[
M^t_{w+\Delta t} = M^t_w + M_{ev}
\]

The modeling system also includes the rain evaporation when a trajectory crosses a rain shaft (Gangoiti et al., 2015). For the later evaluation, the model assumes an average terminal velocity \((V_p)\) value of 6 m/s.
(within a range of 4–8 m/s) for the precipitation occurring below cloud. A sensitivity study of the estimation of sources associated with this assumption for the terminal velocity was presented in Gangoiti et al. (2015). The vapor ratio added in this case is as follows:

$$R_{ijk} = \frac{(pc_1 - pc_2) \cdot V_p \cdot \Delta t}{Z_k \cdot \omega_k}$$

where \((pc_1 - pc_2)\) is the difference of the precipitation mixing ratio at top and bottom of a grid cell \((i,j,k)\) of the domain, which is crossed by the falling precipitation estimated by the mesoscale model; \(\omega_k\) is the vapor mixing ratio inside the grid cell, and \(Z_k\) the height of the grid cell. The time step \(\Delta t\) has to be smaller than the time of residence of the vapor trajectory crossing the grid cell \(\Delta t < X/U\), where \(X\) is the horizontal spacing of the finest meteorological grid cell (8 km) and \(U\) is the wind transporting the tracked parcel of vapor. The vapor uptake from a rainshaft is also estimated at every time step for each tracked parcel, as for the surface evapotranspiration.

One full HYPACT simulation was done for every hour of precipitation in the target domains. Thus, as the precipitation events responsible for the Alpine rainfalls lasted for 3 days (14–16 November 2002), a total number of 72 HYPACT simulations was performed to track the hourly precipitation during the rainfall episode from each grid cell of the target precipitation regions (E-Alps and W-Alps in Figure 2), back in time to the initial time of the simulation. A shorter rainfall period in Morocco (14–15 November) resulted in 48 HYPACT simulations.

Each HYPACT simulation tracked thousands of particles from the center of each of the vapor emitting grid cells located over the target (1 particle released every 60 s, representing a variable mass of vapor for each
hourly precipitation at the grill cell), as described in Gangoiti, Gómez-Domenech, et al. (2011). In this way the methodology allows for tracking the history of the moisture associated with the fallen precipitation at every hour in the target regions. The “source_attribution_model” performs the attribution/mapping though the different grid domains and resolutions. The results are shown in an “evaporation domain” equal to Grid 1 (Figure 2) using a prescribed constant space resolution of 48 km, which are recorded at a time resolution of 1 hr back to the first day of the simulation period (30 October). The selected resolution of the evaporation domain is greater than the one we used for the ACEF simulation (54 km).

3. Source Mapping and Evaporation Sequences

3.1. Maps of Evaporation Totals for the 14–16 November Episode and Differences With Other Episodes

Following the methodology described in section 2 and in Gangoiti, Gómez-Domenech, et al. (2011, 2015), the evaporation attributed to the total target precipitation in W-Alps and E-Alps was calculated. It is mapped in Figure 3. Surface evapotranspiration (left) and virga (right) are represented using the same color scale. The open white/red rectangles in the Alps delimit the target regions. Three areas of intense marine evaporation are observed for both targets (Figures 3a and 3c). The most important one is located in the Western and Central (WC-Mediterranean), while there are two secondary areas over the N-Atlantic: one in the northwest, the region of cyclogenesis mentioned in section 2 in the companion paper G19, and the other in the eastern region, near the coastal fringe of Western Iberia and Morocco. During the period 13–16 November, and concurrent with the development of the episode, this latter region fell under the persistent intense north-to-northwesterly winds blowing at the western flank of the elongated trough which formed the hot spot described in G19. There are some differences between the contributing regions of both alpine targets: a higher contribution of the Ionian and Adriatic Sea in the Central Mediterranean to the E-Alps rainfalls with respect to its contribution to the W-Alps, and a relatively small, but clearly identifiable, contribution from
the African Intertropical Convergence Zone (ITCZ) for the E-Alps (Figure 3c), which was already signaled for the October 2000 Piedmont Floods (Turato et al., 2004). The later episode was also identified as a “simultaneous” episode with a large amplitude wave, as shown in G19. Our estimations for the same October 2000 episode and target precipitation, which includes the Piedmont region, show also a contribution of the African ITCZ for both surface and rain sources (Figure S1 in the supporting information). The evaporation from rain columns represented in Figures 3b and 3d for the same targets shows a completely different area distribution and intensity than from the surface sources. Here, the evaporation is organized in elongated narrow bands covering a smaller area than the surface evaporation. Small but intense areas of evaporation are observed in the remote Western Atlantic (W-Atlantic), at the location of the rain columns in the region of the Atlantic midlatitude cyclones as well as in the WM, following a direction SW-to-NE of the approaching trajectories into the Alps. These bands of rainfall evaporation, parallel to the eastern coast of Iberia, are located at the western edge and over the main surface evaporation spot of the Mediterranean Sea, which occupies a larger surface (Figures 3a and 3c). Buzzi et al. (1998) studied the complex structure and evolution of these rainbands for the 1994 Piedmont Flood over the WM and showed that the rainfall evaporation during these episodes causes the cooling of the air preceding the cold front, which runs parallel to the eastern coast of Iberia and moves slowly to the east. Cooled air can run over the sea ahead of the parent cold front, triggering the formation of multiple fronts and rain/cloud bands, which extend to the east over the sea, as it was the case for the 14–16 November 2002 episode.

Figure 4 shows a similar representation of the vapor sources for the 14–15 November precipitations in Morocco. The target region is again marked with white/red rectangles in the figure. A large and very intense area of surface evaporation is located off the west coast of Morocco (Figure 4a). The area, which is also a source with a smaller intensity for the Alpine rainfalls (Figure 3), occupies the same place of the hot spot identified in the National Centers for Environmental Prediction (NCEP) reanalysis surface latent heat flux map (Figure 5b), also identified in the companion paper G19. Wind data in Figure 5 correspond to the 6-hourly NCEP-Reanalysis II (Kanamitsu et al., 2002), available at https://rda.ucar.edu/datasets/ds091.0/). The latent heat flux is a 6-hourly NCEP/DOE AMIP-II reanalysis at the website (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.gaussian.html). More remote secondary evaporation areas locate on the W-Atlantic, between 30°N and 45°N, which are also associated with regions of enhanced sea evaporation as those shown in Figure 5a. Evaporating rainfall (virga) for the precipitations in Morocco (Figure 4b) follows a similar pattern of narrow bands observed in the N-Atlantic for the Alpine targets.

The total evaporation represented in Figures 3 and 4 has been distributed according to the nature type of the evaporative sources: terrestrial, marine Atlantic or Mediterranean, and virga/rain column. Results are presented in Tables 1 (Alps) and 2 (Morocco). The evaporation totals in the tables average 60% of the precipitation target in the Alps and only 45% of the one in Morocco. Most of the remaining vapor is lost in the back trajectories across the outer boundaries of the domain, represented by the solid black lines in Figures 3 and 4.
The sequence of this vapor leakage across boundaries and its consequences in the correct interpretation of the sources distribution during this episode will be discussed in section 3.3. From the relative contribution of sources observed in Table 1, it follows that the marine sources (averaging 60% of the total share) dominate the terrestrial ones (28% of the share), considering both Alpine targets. The rest (12%) corresponds to the rain column evaporation. The WC-Mediterranean evaporation prevails (44%) among all marine sources, and most of the rest (16%) evaporates at the Atlantic Ocean, with a residual contribution of the E-Mediterranean and a (unexpected) relative important contribution of the evaporation in the W-Atlantic (west of meridian 40°W). It is noteworthy that for the eastern and western alpine precipitations there is an important difference in both the absolute and relative amounts of rain column evaporation: The western one doubles that of the eastern region (Table 1), and its main origin is the evaporation from rain falling over land, close to the target, at the leeward of the northern Apennines and inside the target region (around 65% of the rain column evaporation totals—not shown in the table), while a nonnegligible fraction of 21% evaporates over the WM at the rainbands identified in Figure 3b.

On the other hand, following the estimations shown in Table 2, the marine sources are even more dominant for the precipitation target in Morocco, being the Atlantic Ocean its main source with a share of 93% of the total attributed evaporation.

A direct comparison of this distribution of sources with the results for the ACEF episode (Gangoiti et al., 2015) indicates a smaller contribution from land sources during the November episode and a concurrent larger contribution of the marine evaporation, as expected from the seasonal changes estimated by Sodemann and Zubler (2010). The rain column evaporation during the November föhn episode (12%) is clearly smaller than the observed for the episode in Central Europe (18%). This is an unexpected result because these types of föhn episodes are supposed to evaporate large amounts of precipitation. After these results, we have

Table 1

| Targets sources | 14–16 November 2002 |
|-----------------|----------------------|
|                 | W-Alps              | E-Alps               |                     |
| Sea             | W-Atlantic 303.62 (8.7%) | 1,979.69 (56.4%) | 368.25 (10.2%) | 2,309.49 (64.2%) |
|                 | E-Atlantic 286.26 (8.1%) |                      | 192.19 (5.3%)   |                     |
|                 | W-C-Med. 1,389.65 (39.6%) |                      | 1,743.25 (48.5%)|                     |
|                 | E-Med. 0.17 (~0%) |                      | 5.80 (0.2%)     |                     |
| Land            | 947.57 (27.0%) | 1,038.47 (28.9%) | 248.53 (6.9%) |                     |
| Rain column     | 582.23 (16.6%) | 248.53 (6.9%) | 248.53 (6.9%) |                     |
| Total           | 3,509.49 (100%) | 3,596.49 (100%) |                     |
Table 2

Total Evaporative Sources (hm$^3$) and Their Land-Sea Relative Contribution (%), Including Direct Rain Column Evaporation (Virga) for the Rainfalls in Morocco During the Same Episode 14–15 November 2002

| Targets sources | 14–15 November 2002 | Morocco |
|-----------------|---------------------|---------|
| Sea             | W-Atlantic          | 651.52 (21.7%) | 2,800.14 (93.2%) |
|                 | E-Atlantic          | 2,147.91 (71.5%) |
|                 | W-C-Med.            | 0.71 (~0%) |
|                 | E-Med.              | 0 (0%) |
| Land            |                     | 109.83 (3.7%) |
| Rain column     |                     | 93.61 (3.1%) |
| Total           |                     | 3,003.58 (100%) |

undertaken a new evaluation of sources during the August episode, changing the targets used in Gangoiti et al. (2015), which were located more to the north (central Europe), to the new targets in W-Alps and E-Alps in order to compare the same target regions. Now marine sources average 38% of the total share, still below the terrestrial ones (52%), being rain column evaporation the remaining 10%. This latter percentage is clearly below the 18% found for central Europe, but it is similar to our evaluation for the November episode (12%). The larger fraction of rain evaporation for the precipitations in central Europe with respect to targets located at the Alps during the August episode can be interpreted in terms of the requirement of larger trajectories over land for the former region during the convergence phase of the episode, where rain evaporation increases rapidly: trajectories over land imply larger rain evaporation than over the sea, assuming that more rain is evaporated while crossing the unsaturated PBL over a warm land than the more saturated marine boundary layer (MBL) over the sea.

Our results show some similarities and differences with respect to the work by Winschall et al. (2011), who estimate vapor sources for the same Alpine episode in November 2002 by using a completely different modeling approach, based in a water vapor tagging technique, first implemented by Sodemann et al. (2009) in the climate high-resolution model. It is also a limited-area model and can be used to evaluate the contribution of preselected source areas. It was implemented using a smaller domain coverage (the W-Atlantic and the sub-tropics were not included), a rainfall target region centered more to the west of the Alps and a different target rain estimation. Even considering the importance of the mentioned differences, they also conclude that marine evaporation had the largest share, with a 45% (vs. 56% for W-Alps in Table 1) of the target precipitation during Days 15 and 16 November 2002 (Day 14 was excluded): 19% came from the Atlantic Ocean and 26% from the Mediterranean (vs. 17% and 39% in Table 1 for W-Alps). Their simulation showed that almost all the Atlantic contribution came from a preselected hot spot region in the eastern N-Atlantic. The contribution from land evaporation changed during the episode (28–33% vs. 27% in Table 1) as well as the nonattributed evaporation that entered into the domain, mainly from the west and northwestern Atlantic boundaries (21–13%).

In the companion paper G19 it is shown that similar episodes can occur with an average frequency of once a year. The episodes show large interannual frequency variability and an autumn seasonal preference. Autumn average vapor sources for the Alpine region have been mapped by Sodemann and Zubler (2010) using Lagrangian back trajectories and ERA-40 reanalysis for a time period of 7 years (1995–2002). Their results show an average more intense Mediterranean signal, which extends to the West of Iberia and the Bay of Biscay. Out of these areas, the evaporation sources weaken and show a faint, almost uniform signal over the N-Atlantic Ocean. The main differences of their surface source distribution with our results, shown in Figures 3a and 3c, are the relative importance of the western N-Atlantic hot spot region and the source located in the North African (N-African) land mass, which includes the tropical region. The October 2000 Piedmont Floods described by Turato et al. (2004), another simultaneous episode with a large-amplitude wave, simulated with the modeling system MesoWat_Source shows also contributions of the African ITCZ and the western N-Atlantic region (Figure S1 in the supporting information). A third simulation of a simultaneous episode (3–5 November 2011) and a following mesoscale formation in the W-Mediterranean (7–9 November 2011), which generated a flow of moist air toward the southern Alps and a new heavy precipitation episode, can be used to observe differences between vapor sources of the episodes, which in that case evolved from a large-amplitude wave (without a cyclone in the region) to a Mediterranean cyclone. It is important to note that for most of the heavy rain events in the W-Mediterranean region, including the southern Alps, there is a cyclonic center in the region, forcing a flow of moist air from the Mediterranean toward the area affected by the heavy rain (Jansa et al., 2001). Thus, the estimations of the associated evaporative source intensity and distribution could be of a paramount interest for these two episodes: They will help to interpret differences and similarities associated with these particular forcing scenarios. Figures 6 and 7 show the evaporative sources of the referred two consecutive episodes of rainfalls in the Alpine region. For both episodes there is a more intense Mediterranean signal, which extends to the West of Iberia and
the Bay of Biscay as shown in the autumn averages estimated by Sodemann and Zubler (2010). However, differences in the source distribution are more evident to the south: for the large amplitude wave episode in Figure 6, the N-African sources and the tropics have a larger contribution, both from surface (Figure 6, left) and rain column evaporation (Figure 6, right).

3.2. Source Activity Before and During the 14–16 November Episode

In the analyses of the ACEF episode, we had already shown that the vapor sources changed along the three rainfall days of the episode (Gangoiti, Gómez-Domenech, et al., 2011, 2015). At that time, the importance of the Mediterranean contribution decreased along the episode and almost disappeared on the last day while the evapotranspiration increased at the European continental landmass, located to the north of the targets, as the main vapor convergence trajectories changed drastically with the evolution of the cyclone pathway. For the November episode, we did not expect such a drastic change of sources, since the elongated trough over the Iberian Peninsula progressed slowly during the precipitation period of 14–16 November. The wave increased its amplitude during the initiation of the episode and slowed down its eastward propagation, as described in G19.

Figures 8 and 9 show, respectively, the sequence of the surface evaporation for the first (14 November) and last (16 November) days of the episode in W-Alps. Each figure represents, in a four-panel arrangement, the sequence of the evaporation for the respective 24-hr precipitation in the target W-Alps, from the beginning of the simulation period (00 UTC, 30 October) to the respective day of the precipitation event. Panel (d) represents, in each figure, the evaporation during a variable time lapse of 1–3 days, depending on the rainfall date, 14 and 16 November, respectively. The remaining panels represent 5 days of accumulated evaporation, attributed to the corresponding 24-hr of precipitation. Thus, panels (a), (b), and (c) are comparable in both figures, because they correspond to the same 5-day period of evaporation. However, the evaporation in panel (d) cannot be compared between figures, because it occurred during a variable evaporation time of 1 and 3 days. The same color shading scale has been kept throughout all the panels. Every panel includes a table.
with the total evaporation (hm^3) attributed to land and sea sources, as well as their relative contribution to the total surface evaporation (%). The addition of all panels included in Figures 8 and 9 together with the surface evaporation of 15 November (not shown) will result in the map of sources represented in Figure 3a.

Following Figures 8 and 9, a large fraction of the Mediterranean evaporation, which is the most important source attending to the results in Table 1, occurs during the final approach to the target over the Mediterranean Sea. This could be easily associated to south-to-north trajectories of the air mass over the Mediterranean and the subsequent direct evaporation from the sea into the MBL (Figures 8d and 9d, concurrent with the period of precipitations in the Alps). During the period 9–13 November, however, there are other large contributions from the Mediterranean as well as from sources in the E-Atlantic and N-Africa. Surprisingly, the type of atmospheric processes behind these sources is not related with the southwesterlies blowing at the right flank of the developing trough, as it is discussed next.

More remote sources in the W-Atlantic are active during the period 3–9 November, and there is also a simultaneous contribution from the Eastern Atlantic (E-Atlantic), during the period (Figures 8b and 9b) within a region of persistent high pressures. The main synoptic features of the period, that is, the Large-scale Atlantic Vapor Accumulation (LAVA) period, are described in G19 and, the atmospheric processes behind the evaporation are discussed in section 4. Attending to the source distribution during the first and last day of the Alpine episode (Figures 8 and 9), it is important to notice that, unlike for the ACEF episode, the evaporative sources do not change substantially during the 72 hr of the episode: Rainfall comes approximately from the same sources. This is also true for the rain column evaporation shown in Figure 10. Neither nearby nor remote sources show significant changes throughout the whole rainfall episode, in agreement with an almost stationary large-scale forcing during the episode.

Figure 11 shows a similar arrangement for the sequence of surface evaporation for the 24-hr precipitation target of day 14 in Morocco. Day 15 shows an almost similar source distribution, without significant changes (Figure S2 of the supporting information). A major fraction of the evaporation occurs over the E-Atlantic,
close to the target, during the last 1–3 days preceding the episode and within the intense northwesterlies blowing at the left flank of the trough, off the west coast of Morocco: the region (red colored in Figures 11c and 11d) is located at the position of the hot spot shown in Figure 5b. However, during the LAVA period (and up to 11 November), more remote regions are active and the W-Atlantic is dominant (Figures 11b and 11c). Corresponding hot spots can be seen in Figure 5a at the eastern coast of North America.

Though the source distribution is maintained almost invariable during the 2-day rainfall episode in Morocco, as for the case of the sources of the Alpine episode, some differences can be observed above latitude 45°N, mainly in Figures 11c and S2c. The differences seem to be related to large-scale changes occurring at the E-Atlantic when the wave increased its amplitude during the episode. This change affected a major fraction of the vapor responsible of the target precipitation in Morocco. According to this, on 14 November the evaporative regions locate under a more direct west-to-east trajectory across the Atlantic, with a rapid connection with the western boundary of the domain, while for the following day the sources locate farther north.

**Figure 8.** Sequence of the accumulated surface evaporation totals (g/m²) at 5-day intervals since 00 UTC, October 30, estimated for the first 24-h rainfall in W-Alps (14 November): (a) from 30 October to 3 November, (b) from 4 to 8 November, (c) from 9 to 13 November, and (d) 14 November. The total evaporation (hm³) and the land-sea relative contribution (%) are also shown in the underlying tables.
### 3.3. Changes in the Evaporation Rate: Contribution From Outer Sources and Leakage of Vapor Across Domain Boundaries

The time sequence of the accumulation of vapor in the atmosphere for the Alpine episode 14–16 November is shown in Figure 12. Surface sources (top) are separated from precipitation sources (bottom), and the two targets (E-Alps and W-Alps) are also represented individually (left-right). The x axis shows the number of days preceding every daily precipitation target. Color bars represent accumulated evaporation (hm$^3$) for each daily target, and the black solid line in the both top and bottom panels correspond, respectively, to the evolution of the surface (terrestrial and marine) and rainfall evaporation totals. The final values (total vapor accumulation of the whole rainfall episode) of the solid black lines (hm$^3$) in Figure 12 correspond to the values shown in Table 1. A similar sequence is represented for the episode in Morocco (Figure 13). The estimated accumulation rates from the surface sources show important differences to those of the rain column sources. The surface sources increase their daily rate of evaporation during a period of 3–4 days preceding the event, while the direct rain evaporation has a shorter period of 2 days, with the exception of the E-Alps target in Figure 12. This short period is similar to the one of the August episode (Gangoiti et al., 2015), and it is most likely related to the increased availability of rain shafts during the final convergence of trajectories. In the other hand, the referred period of rapid accumulation of vapor from surface sources...
during the last 3–4 days preceding the rainfall events contrasts to the longer period of 6–7 days for the convergence trajectories during the evolution of the cyclone in August 2002. This shorter period of 3–4 days is concurrent with the changes in the E-Atlantic, initiated with the formation of the elongated trough over western Iberia on 13 November. These changes resulted not only in the formation of a region of enhanced evaporation within the northwesterlies blowing into Morocco but also in the WM within the simultaneous prefrontal intense southwesterlies into the Alpine targets.

The series of curves depicted in Figure 12 and 13 would not be representing the actual accumulation of the total target vapor of the episodes if the mass of vapor lost by crossing the outer boundaries of the evaporation domain (during the back trajectories) were significant for the represented period, preceding the episode. At this point, remote sources out of the boundaries could not be estimated, and the vapor transporting trajectories, which cross the outer boundaries, would be definitely lost for the calculation. Figure 14 represents the vapor losses through the outer boundaries (percentage relative to totals) for the Alpine episode and Figure 15 the losses for Morocco. Day 18 in the figures corresponds to 30 October 2002.

Vapor losses for the 3-day totals of the Alpine targets are kept at low levels (under 20% of the total precipitation in each target) during the first 13 days preceding the episode. Then, there is a rapid increase of losses, mainly across the western boundary of the domain, up to 40% of the rainfall totals. Considering the 48-hr rainfall totals in the target of Morocco, the vapor losses across the western boundary increased abruptly from 25% to 55% (solid black line in Figure 15) between Days 8–10 before the initiation of the episode. For this

Figure 10. Sequence of the accumulated rain column evaporation totals (g/m²) for the 24-hr precipitation in W-Alps, corresponding to (a and b) the first day and (c and d) the last day of the episode. Remote evaporation (a, c) accumulated during the period 4–8 November is located in the same regions of the N-Atlantic Ocean for both first and last days of the episode. The same is true for the evaporation estimated close to the W-Alps (b–d), where the precipitation are organized in bands parallel to the eastern coast of Iberia and remains active during the approaching trajectories (14–16 November).
case, the percentage over the 48-hr totals hides a large variability of losses depending of the rainfall day: Up to 70% of the vapor responsible of the 14 November precipitations (solid blue line in Figure 15) escapes “prematurely” from the domain as shown in the figure, while for the 15 November the losses are “only” of 36% (solid red line in Figure 15). As described above in this section, the differences were produced after the large-scale changes occurring at the E-Atlantic during the rainfall episode in Morocco (14–15 November).

After this analysis of the sequence of losses, we can establish that the estimated evaporation maps (Figures 8–11) and the sequences of evaporation shown in Figures 12 and 13 are correct in a time interval of 13–14 days before the rainfall episode in the Alps, and 8 days for the target of Morocco. During these periods, different for each target, the contribution of remote sources out of the domain is low and we do not expect significant changes in the vapor loading rates discussed above in the context of the implementation of new simulations with an eventual unlimited model domain. The loss of vapor across the outer boundaries of the domain is more readily related to remote evaporative sources located out of the domain, but it could also have a more local origin, because of recirculations in and out of the borders. In any case, a limited area model, as the one used here, could never be able to evaluate these sources, but instead we can measure and quantify the error margin introduced in our evaluation.

**Figure 11.** As in Figure 8 but for the first 24-hr rainfall in Morocco (14 November).
4. Remote and Local Sources: Discussion of Relevant Meteorological Processes

In this section, the evaporation processes during the previous period of 2 weeks before the episode (since 30 October 2002) are analyzed. For a better description and comparison of evaporation and vapor accumulation processes for the target vapor of Morocco and the Alps, we have subdivided the rainfall episode in a selection of 24-hr vapor targets: The corresponding to the 14 November rainfall in Morocco and the one on 15 November in W-Alps. This selection allows for the comparison of the active areas of evaporation and the process of accumulation in almost the same regions of the N-Atlantic and at the same time. For the discussion of the processes occurring much closer to the targets and the corresponding activation of local sources just before the initiation of the Alpine episode, we have added a new selection: the first 24-hr target precipitations in W-Alps (on 14 November).

4.1. Remote Sources and Large-Scale Circulations (30 October to 12 November)

During the LAVA period, remote regions with active evaporation at the Western N-Atlantic are associated with the formation of hot spots (Figure 5a) at latitudes of 30–45°N under the intense northwestlies blowing offshore from eastern North America, and in the region of midlatitude lows development over the greater temperature gradients of the Gulf Stream. These remote areas of the W-Atlantic concurrently contributed with the evaporation under the high-pressure system located more to the east in the N-Atlantic to feed the 14–16 November precipitations in the Alps (Figures 16a and 16b) and in Morocco the day before (Figures 17a and 17b). GOES-8 Infrared images (Figures 16c and 16d) document the cloud bands associated with the mentioned cyclone formation (6 November) and its movement over the sea, from the coast of North America to the Northeast (7 November), reaching the coast of southern Greenland on 8 November (Figure 16d). There are some differences on the location of sources contributing to the referred precipitations, as can be observed in Figures 16 and 17: The main remote evaporative
area for the target of Morocco is located over the W-Atlantic farther southwest (Figures 17a and 17b), near and in front of a large coastal region centered at the latitude of North Carolina, while for the Alpine rainfall the main remote surface evaporation is located offshore (Figures 16a and 16b), in a vast region centered farther North, in front of New Jersey and East of Nova Scotia (Canada).

The vapor from the mentioned remote sources in the W-Atlantic together with the “background” target vapor entering (mainly) across the western boundaries of the domain are shown in Figures 18 and 19: plan views and cross sections of the mass of vapor responsible for the 15 November rainfall in W-Alps and 14 November rainfall in Morocco, respectively. The figures represent their respective 3-D distribution on 7 November, corresponding with the activation of the surface sources shown in Figures 16 and 17. The mass of vapor responsible for both sequential events, first in Morocco (14 November) represented in Figure 19 and then in W-Alps (15 November) in Figure 18, occupies a similar volume/location over the Atlantic. The vapor entering from the western domain boundary locates in the middle-to-upper troposphere in both panels (Figures 18b and 19b), above the PBL, while over the E-Atlantic the target vapor is kept at lower levels under the large-scale sinking inside the anticyclone. However, the fraction of vapor captured under the western Iberian high-pressure center for the 14 November rainfall in Morocco (Figure 19) is less than the observed for the case of the Alpine target (Figure 18). As estimated in section 3.3, up to 70% of the vapor responsible for the 14 November rainfall in Morocco did not come from evaporation inside the domain. It came from outside the western boundary, entering at latitudes 30–45°N and crossing a region of large-scale sinking (Figure 19) at the eastern coast of North America: The target vapor entered the domain above the PBL, within the intense northwesterlies blowing behind the frontal system marked by the cloud bands parallel to the N-American coast, as shown by GOES in Figures 16c and 16d.

The period comprised between 9 and 12 November (Figure 20), concurrent with the extinction of the LAVA phase, was characterized by a secondary prefrontal circulation in the E-Atlantic, initiated with the transport of a variable fraction of the target vapor accumulated over Western Iberia on 9 November (Figures 20a and 20c), first to the WM and then to N-Africa following an anticyclonic curvature and sinking from the layer 1,000–3,000 m to occupy the lower 1,000–1,500 m of the atmosphere (Figures 20b and 20d). The affected fraction of vapor involved in the observed curved trajectory over the WM (black arrow in Figure 20b) increased during the Alpine episode. During this (prefrontal) trajectory the vapor incorporated new surface sources from the eastern N-Atlantic, the Mediterranean Sea, and from the North African landmass, as revealed by the surface evaporation tracks in Figures 8c and 9c. This circulation works only for the rainfall episode in the Alps but not for the Moroccan one (Figure S3).

A similar circulation, producing the convergence of the moisture into the Alps, has also been observed in other simultaneous episodes (e.g., 3–5 November 2011 and 10–14 October 2000, discussed in section 3.1), which were simulated using the same domains and resolutions. For

**Figure 13.** As in Figure 12 but for the episode in Morocco. Color bars in blue and red stand for the vapor accumulation representing the daily 24-hr rainfall on 14 and 13 November, respectively, while the solid black line represent the 2-day totals in Morocco.

**Figure 14.** Percentage of the mass of vapor lost by crossing the outer boundaries of the largest domain, relative to totals emitted at the rainfall Alpine targets W-Alps and E-Alps. The loss of vapor is represented as a function of time (days) preceding the rainfall episode.
all the cases, the prefrontal circulations incorporated new local sources from the eastern N-Atlantic, the WC-Mediterranean, and N-Africa, but they showed important differences between episodes affecting the amplitude of the circulation and the amount/relative fraction of the transported target vapor.

The remote source contribution and the series of meteorological processes described here are decisive to explain the origin of the background vapor responsible for the episodes; however, as shown in section 3.3, there is a major contribution of “local” sources, working at a time scale within around 3–4 days preceding the rainfall episode. This period is concurrent with the changes in the E-Atlantic, initiated with the formation of the elongated trough over Western Iberia on 13 November, as described in the next section.

4.2. Local Sources: Enhanced Evaporation and Intense S-to-N Transport Over the WM (13–16 November)

Both surface and rain evaporation increased their rate of contribution to the vapor responsible of the episodes as it converged into the respective targets (Figure 15). After the low-pressure system over

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**Figure 15.** As in Figure 14 but for target in Morocco. The sequence of losses, corresponding to the 48-hr totals in Morocco, is represented by a solid black line, and blue and red lines represent each of the 2 days.

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**TARGET: 15 NOVEMBER 24-H RAINFALLS IN W-ALPS**

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**Figure 16.** Remote evaporative sources in the N-Atlantic during the LAVA period: sequence (a and b) of daily surface evaporation (g/m² in 24 hr), corresponding to the 15 November rainfall in W-Alps, together with surface winds simulated by RAMS at midday in consecutive days 6–7 November. Quasi-simultaneous GOES-8 Infrared images (10.2–11.2 μm) document in false color (c–d) the cloud pattern and the convection activity at the outflow of N-America land mass into the Atlantic (source: GIBBS imagery by NOAA; Knapp, 2008).
the British Islands moved and expanded to the south (11–13 November) and a deep trough occupied a large area west of Iberia, the northwesterlies intensified over this region of the E-Atlantic and produced an area of enhanced evaporation west of Iberia (hot spot in Figure 2d), which locked to the region from 12 to 16 November, following the NCEP reanalysis latent heat flux data during the period. At the same time warmer and intense southwesterlies blew at the right flank of the trough, almost parallel to the eastern coast of Iberia. This also created an area of enhanced evaporation at the sea surface of the WM, following the air mass trajectories into the Alps. The joint contribution of both regions, east and west of the Strait of Gibraltar, is illustrated in Figure 21, which represents the 24-hr accumulated surface (Figures 21a and 21b) and rain column evaporation (Figures 21c and 21d) for the W-Alps 24-hr 15 November rainfall target, during both the day preceding the target 15 November (Figures 21a and 21c) and the very day of the target precipitations (Figures 21b and 21d). The same target is used in Figures 16, 18, and 20 to illustrate evaporation in remote regions and large-scale circulation causing vapor accumulation in the E-Atlantic. Following the warm advection during the 14 and 15 November over the WM, now located at the leading edge of the upper level trough, the mesoscale simulation (enlarged views in Figure 21) shows the wind veering from the S-SE at the surface (convergence into the Alps) to the SW at 2,000 m.

METEOSAT-7 infrared images (10.6–12.5 μm) document in false color (Figures 21e and 21f) the cloud bands parallel to Iberia and the deep convection over the WM and Morocco (red and green colors). These clouds patterns over the WM are responsible for the rainbands of convective precipitation, which were already documented and discussed by Buzzi et al. (1998) for the November 1994 Piedmont floods: the cooling, mainly due to rain evaporation over the WM, was shown to be responsible for the formation of multiple rainbands and low level fronts over the sea, causing prefrontal south-to-southeasterly convergence at low levels into the Alps in a similar way as shown by our simulations in Figures 21a and 21b (enlarged wind fields in the figures). For the first time, the described rain evaporation over the sea is also shown to contribute to the rainfall episode in the Alps (Figures 21c and 21d): Direct rainfall evaporation is grouped following the shape of a large rainband, which crosses the WM from SW to NE, parallel to the eastern coast of Iberia in the figures. Though the amount of this “Mediterranean” virga added to the target vapor during the last 24–48 hr is important (Figure 12), the active regions contributing to the total precipitations in the Alps are distributed not only in the WM but also in the eastern and western N-Atlantic (Figure 3).

Similarly, surface and rain column evaporation for the Morocco, 24 hr, 14 November rainfall target is represented in Figure S4, during both the day preceding the initiation of the episode (13 November) and the very day of the episode. At this time, the amount of virga has a lower contribution to the precipitation in Morocco than in the case of the Alps. Figure 21a can be compared with Figure S4b to show that there is a common
Atlantic region of evaporation feeding simultaneously the precipitations in the Alps (on 15 November) and in Morocco the day before.

The plan view and the vertical distribution of the mass of vapor responsible for the first 24-hr rainfalls at W-Alps are shown in Figure 22 at two instants: the day before the episode (Figures 22a and 22b) and at the initiation of the episode (Figures 22c–22e). The horizontal and vertical distributions of winds are also represented: The southwesterlies, under the right flank of the upper level trough, sink over the WM at the leeward of the Atlas Mountains in N-Africa (ER mountains and Middle and Tell Atlas) and at the leeward of the Iberian Peninsula (east of longitude 0°, which delimits the eastern coast of Iberia). Following the mesoscale model results, sinking over the WM affected “only” the lower midtroposphere (up to 3,000–4,000 m above sea level). This dynamic subsidence is already well developed the day before the Alps episode initiation (Figures 22a and 22b) and maintained throughout the 3-day episode. The rest of the atmospheric column

Figure 18. (a) Plan view of the total burden of (target) vapor corresponding to the 15 November 24-hr rainfall in W-Alps (shaded colors). The 2,000-m sigma winds represent “mean transport” of vapor in the free troposphere. (b) Corresponding cross section (30–50°N) and a selection of meteorological data at 40°N: the dynamical tropopause with the potential vorticity values 2 and 2.5 PVU in solid blue lines, and wind vectors composed by the zonal wind ($u$) and vertical velocities ($w \times 1,000$ m/s). The PBL is depicted with a thick solid black line over the profile of the topography at the bottom, and the regions of high relative humidity (70–100%) are shown in contours.
at the right flank of the trough over the WM (above 4,000–5,000 m mean sea level, MSL) shows an ascending motion, which involves the relative warm air running ahead of the cold front. All the represented fields follow a similar scheme to the one used in Figure 18 and following figures with cross sections, being the main difference the use of a narrower thickness to represent the vapor at the cross section, intended to discriminate the detailed vertical distribution of the target vapor both in the Atlantic and in the Mediterranean sectors at both flanks of the trough. The mesoscale model also simulates the target vapor in the Atlantic sector being transported within the cold northwesterlies and inside a process of large-scale sinking, under the folding of the tropopause (solid blue lines in the cross sections of Figure 22), which affects the whole depth of the troposphere.

It is also noteworthy the pronounced west-to-east slope of the target vapor over the WM in Figure 22e (enlarged cross section), consistent with the forced orographic sinking at E-Iberia and N-Africa. After the modeling results, the vapor accumulation over the WM corresponded to an initial accumulation, located in the layer 1,000–4,000 m over the E-Atlantic (Figure 18) corresponding to a time previous to the

Figure 19. (a) As in Figure 18 and for the same time instant (7 November) plan view of the total burden of vapor corresponding to the 14 November 24-hr rainfall in Morocco (shaded colors) and (b) the corresponding cross section (30–50°N) with a similar selection of the represented meteorological variables.

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initiation of the prefrontal secondary circulation over the Mediterranean and N-Africa. After several days, it sank and incorporated new sources from the region and within the prefrontal secondary circulation (Figure 20). Some hours before the initiation of the episode on 14 November, it was transported with the southwesterlies on the MBL of the Mediterranean. The sequence of cross sections of Figures 23b–23d shows the time evolution of the meridional distribution of the target vapor over the WC-Mediterranean in its shallower region at the eastern flank, which took place before, during, and after the initiation of the W-Alps precipitation on 14 November.

The plan view of the total burden of vapor, corresponding to the 24-hr target precipitation of 14 November is represented in Figure 23a, together with both the 2,000-m z-sigma winds (Pielke & Martin, 1981) and the boundaries of the dynamical tropopause at 11,000 m MSL. The latter signal is depicted in blue solid lines with the potential vorticity values of 2 and 4 PVU. Color shading together with the rest of meteorological fields follows a similar scheme to the one used in previous figures, and the represented vapor corresponds to the same 24-hr target precipitation on 14 November. The exception is the vapor in Figure 23d, which represents only the last 12 hr of the 14 November target vapor (the tail of the 24-hr target vapor). The temperature (contours) and the relative humidity (shaded) vertical distributions are also represented for the same cross section in Figure 23e. The figure is a composite of the mesoscale model output at Grids 3 and 4: Black arrows mark the successive orographically induced windward uplifts and leeward sinking (the Tell Atlas to the left/south and the Alps to the right/north). Temperature and relative humidity changes induced by these processes are clearly discernible in the figure. Points marked 1–4 over Figure 23f.
correspond to the position of the orographic lifting (1 and 3) at the upwind slopes of the Alps and sinking (2 and 4) at the leeward. These points are also shown in the vertical section depicted in Figure 23d.

The sequence of cross sections documents the transport of the target vapor over the WM into the Alps as new vapor is added from the sea into the MBL, before and after its final destabilization and orographic lifting. The air mass transporting the target vapor was initially warm and with low relative humidity because of föhn at the leeward of the Tell Atlas (Figure 23e). Recharging of moisture into the MBL near the African coast was made over a relatively cooler sea: Air temperature decreases from south to north over the sea as can be observed in Figure 23e (22 °C at N-Africa and 18 °C at the European coast for the air and 19 °C, 17 °C for the corresponding SST at the same points). Cooling from below caused the stabilization of the MBL, which is more evident in Figure 23e, close to African coast. The air masses in the MBL, with the new added moisture from below, converged into the Alps with a more southerly or even southeasterly direction at the end of the episode, while the southwesterlies blew more persistently above 1,500–2,000 m over the sea.

Figure 21. As in Figure 16, sequence (a and b) of the daily surface evaporation (g/m² in 24 hr) and surface winds simulated by RAMS at midday, in consecutive days 14–15 November, corresponding to the 15 November rainfall target in W-Alps. (c and d) Simultaneous rain column evaporation and 2,000-m sigma winds. Source activity is shown as approaching the targets, during both the day preceding the rainfall target (a–c) and the very day of the rainfall (b–d). (e and f) Quasi-simultaneous METEOSAT Infrared images (10.6–12.5 μm) document the cloud pattern and the convection activity over the area (source: GIBBS imagery by NOAA; Knapp, 2008).
Consequently, the origin of the target vapor inside the Mediterranean MBL and during the approaching trajectories into the Alps was mostly Mediterranean, with an additional contribution from a variety of sources, including Atlantic and land evaporation, which increased with height up to a depth of around 1,500 m MSL (most of it, above the height of a lower MBL). This latter contribution follows the transport patterns and the evaporation processes developed over Iberia and N-Africa during period 9–12 November (secondary prefrontal circulation discussed in section 4.1). On the contrary, at the western flank of the approaching trajectories over the Mediterranean and well above the MBL height, the Atlantic contribution seems to increase following the orographic subsidence of vapor with a full Atlantic origin entering at upper levels. The observed processes are in agreement with the vertical stratification of the Atlantic and Mediterranean vapor, at the time of its arrival into the Alps, described by Winschall et al. (2011) for the same episode, and it could also explain the larger extension to the east of the Mediterranean vapor advection into the Alps at lower levels, included in the same contribution.

The plan view and corresponding constant-latitude cross sections of the mass of vapor responsible for the first 24-h rainfalls in Morocco are shown in Figure S5, the day before the initiation of the episode and at the initiation time. Figure S5 has a similar deployment to Figure 22, which represents the W-Alps, and they are directly comparable: The vapor corresponding to the rainfalls in Morocco locates at a similar place in the western coast of Africa to the one observed for the rainfalls in W-Alps, but it has a larger tail, crossing the N-Atlantic into N-America. Following the Figure 19 (and Figure S3), which represent the same target in Morocco, there is no prefrontal recirculation over the Mediterranean, and consequently there is no contribution of this source, neither do the landmass of N-Africa. The model simulates the target vapor in the N-

**Figure 22.** Plan view and vertical distribution of the target vapor, corresponding to the 14 November 24-h rainfall in W-Alps, as approaching the Alps. Following the same scheme as in Figure 18, (a) plan view and (b) vertical distribution at latitude 39–41°N of the vapor and the related meteorological variables, 12 hr before the initiation of the rainfall, and (c–e) at the time of the initiation.
Atlantic being transported within the northwesterlies and inside a process of large-scale sinking, which affects the whole troposphere. A large fraction of the target vapor is already inside the MBL, which shows high levels of relative humidity in contrast with the low values in the free troposphere, associated with the generalized sinking. The enlarged cross section in Figure S5 shows the orographic lifting preceding the precipitations of the 14 November at the west facing slopes of the ER mountains and the Moroccan Meseta.

5. Evaporation Sources, Hot Spots, and SST Changes During Simultaneous Episodes

The observed formation of regions of enhanced evaporation over the sea during and before the episode (NCEP reanalysis of latent heat flux data) may have an impact in the SST distribution in the N-Atlantic and also in the Mediterranean. In addition, as discussed in sections 3.1 and 4.1, some of these regions are located at the place of the main moisture sources estimated for the extreme rainfalls in the Alps and

Figure 23. As in Figure 22 and for the same target vapor (a) plan view and (b–d) sequence of the vertical distribution of the vapor at longitude 7–8°E, and the related meteorological variables, before, at the beginning, and at midday of the rainfall day, respectively. The dynamical tropopause section at 11,000 m MSL is also shown with the potential vorticity values 2 and 4 PVU in solid blue lines; (e) The temperature and relative humidity distributions in contours and shaded colors, respectively, are concurrent with the vapor distribution in (d). Black arrows in panel (e) show orographic uplifting and sinking of the air masses while entering into the WM at northern Africa (left), then crossing the sea, and moving over the Alps (right). Air flow main direction south to north is depicted in the same panel with the thick arrow. The topography (f) of the Alpine region (Grid #5) is depicted as in Figure 2: points marked 1–4 in the panel (see text) are also shown in the vertical section (d).
Morocco. This does not mean that the observed enhanced evaporation regions feed these episodes/targets exclusively but that a nonnegligible fraction of the precipitations originated in these regions.

Enhanced evaporation maintained during several days over the same regions of the sea could result in cooling, which can be identified in the satellite and field SST observations after a persistent episode associated with a quasi-stationary synoptic forcing: the large-amplitude wave during the episode 14–16 November, forced persistent and intense winds over large regions of the N-Atlantic and the Mediterranean, the ideal conditions for a detectable signal in the SST distribution in the region. Figure 24a represents the SST changes in both the North Atlantic Ocean and the Mediterranean Sea during the evaporation period analyzed in this manuscript (30 October to 17 November). Temperature fields were estimated from the 0.25° × 0.25° resolution data of the National Oceanic and Atmospheric Administration OISSTAMSR-AVHRR Reanalysis (Banzon et al., 2016; Reynolds et al., 2007), available at https://www.ncdc.noaa.gov/oisst: Negative values correspond to cooling and positive to warming between the first and last day of the period. We can observe in Figure 24a that cooling prevailed in most regions of the North Atlantic (yellow and green colors) as well as in the Mediterranean, where it was generalized, affecting the whole sea. In addition, there were discernible regions both in the Atlantic and the Mediterranean with an enhanced temperature decrease of more than 2°. Most of these regions, inside the marked open black ovals in Figure 24a, seem to have a direct correspondence with the main surface evaporation areas attributed to the target precipitations in Morocco (Figure 24b) and the Alps (Figures 24c and 24d), already discussed in section 3.1. The hot spots in the eastern and western sides of the N-Atlantic (Figure 5) can be identified in Figure 24 with the regions of enhanced temperature decrease. In the same way, the greater temperature decrease in the WM, relative to its eastern side, can also be attributed to the intense southerly advection at the region during the episode. The presence of identifiable tracks of enhanced temperature decrease in the N-Atlantic and in the WC-Mediterranean, which in
October/November are suffering from a generalized cooling as corresponding with their seasonal trend, appears to be associated with intense winds and persistence of the meteorological conditions, responsible for the increased evaporation in specific areas over the sea. On the contrary, we found no such tracks for the ACEF episode, probably because the evaporation sources and vapor trajectories showed important changes during the rainfall episode forced by both the rapid evolution of the $V_b$ cyclone and a more limited marine contribution (Gangoiti et al., 2015).

From the perspective of the trajectories of the moist air during the episodes into their targets, the proximity of these marine areas of enhanced evaporation seems to be a key factor of their relative contribution to the target precipitations. Thus, the hot spot at the E-Atlantic, developed during the simultaneous episodes in the Alps and Morocco, seems to have a main role for the precipitations in Morocco but a lower contribution for the Alpine precipitations. Following the same argument, the WC-Mediterranean source is the most important one for the rainfalls in the Alps and the large areas of the central and western N-Atlantic are secondary, even though with a nonnegligible contribution (Tables 1 and 2).

As shown in G19, most of the episodes of simultaneous heavy rainfall in Morocco and the Alps, as the one described here, occurs during autumn, a period with the highest evaporation/latent heat flux records (together with the winter) in the N-Atlantic and the Mediterranean. During the period there is a

**Figure 25.** (a) Mean autumn OND changes (1981–2016) of the sea surface temperature ($^\circ\text{C}$ x 100/day), (b) Composite of sea surface temperature changes during the 24 episodes of the period (OND 1981–2016) and (c) SST changes during an autumn episode, not attributable to the seasonal variations: cooling/warming associated with episodes.
generalized decrease of the SST. The signal is also present during the period 30 October to 17 November considered for the production of Figure 24a. With the objective of removing the effect of the seasonal cooling from the temperature signal and the subsequent identification of the more specific impact of the large-amplitude wave episodes in the SST of the area, we have estimated and mapped in Figure 25a the average autumn SST changes (per unit day) during the period 1981–2016 of data availability (National Oceanic and Atmospheric Administration 0.25 × 0.25 daily optimum interpolation OISST). A total of 24 autumn (October–December, OND) episodes during the period 1981–2016 was identified in G19. The average temperature changes (per unit day) were also estimated for these episodes in Figure 25b. This estimation was made assuming a standard common period of 13 days for all the episodes to be compared: all periods started 10 days before the initiation of the rainfalls and finished 3 days after. This period was considered appropriate to include the average time scales of relevant atmospheric processes involved in the removal of moisture from their sources in the N-Atlantic and the Mediterranean in a typical 3-day rainfall episode. For the episode 14–16 November 2002 described in this manuscript, the period 4–16 November was used for the estimations. Obviously, precipitation episodes longer than 3 days are partially represented, because of an incomplete SST temperature jump, but we opted to avoid calculating the temperature jump in time periods very different with each other and use the same metrics for all of them. Both Figures 25a and 25b have some similarities because they both show the rate of cooling during the autumn in recent years, but the second one contains not only the autumn cooling signal but also a signal from the specific changes associated to the episodes. The differences are shown in Figure 25c, which

Figure 26. (a) NCEP reanalysis autumn OND average (1981–2016) of the surface latent heat flux and 850-hPa winds, (b) composite latent heat flux and 850-hPa winds during the initiation of the 24 episodes during the same period (OND 1981–2016), and (c) latent heat flux and 850-hPa wind anomalies during the 24 episode initiation (b-a); in agreement with Figure 25c and the moisture sources and SST changes in Figure 24.
shows the rate of temperature change during the episodes without the seasonal signal. The observed SST changes in the figure are in good agreement with the surface latent heat flux and wind anomalies observed at midlatitudes in the whole N-Atlantic and the Mediterranean regions during episodes (Figure 26c). The latter figure is the difference between the composite of the surface latent heat flux during the initiation of the 24 autumnal rainfall episodes (Figure 26b) and the autumn (OND) average of the period 1981–2016 (Figure 26a). Hot spot regions in the eastern and western N-Atlantic between latitudes 20–50°N (Figure 26b) during the initiation of episodes cause the evaporation anomalies in Figure 26c and the observed overcooling in the same regions (respect to the mean autumnal cooling) (Figure 25c). Two large regions of cold SST and evaporation anomalies can be distinguished: (1) around the Iberian Peninsula, including the Atlantic and Mediterranean sectors and (2) around the peninsula of Florida and farther north following the Atlantic coast of N-America.

The observed climatology of the evaporation and average SST changes during the episodes agrees with the main moisture sources and the SST changes shown for the 14–16 November 2002 case study (Figure 24).

6. Summary and Conclusions

A mesoscale modeling system, which was previously used to evaluate the evaporation sources during the ACEF is now adapted to analyze the 14–16 November 2002 torrential rains in southern Alps. The episode was documented to affect the Piedmont region, and it was also concurrent with torrential rains in Morocco. Modifications of the modeling system aimed to include both regions and extend the area coverage to search for moisture sources in a larger domain, including the whole N-Atlantic and the eastern coast of N-America at a higher resolution. Episodes with a similar or even larger severity than the one on 14–16 November 2002 and with a comparable synoptic environment have been shown to occur once a year and more likely in autumn [G19].

For the Alpine rainfalls, we have estimated a main marine contribution which amounts up to 60% of the total share. The terrestrial sources contribute only with 28% of it, while the rest (12%) corresponds to the rain column evaporation. The WC-Mediterranean evaporation prevails among all marine sources, with 44% of the total share, coming the rest (16%) from the Atlantic Ocean. For the rain column evaporation, we found important differences between the western and the eastern alpine subregions, being the former twice as large as the latter one with a main origin in the evaporation from rain falling over land inside the Alpine region. In addition, a nonnegligible fraction of 21% of the direct rain evaporation locates over the Mediterranean Sea, at the rainbands identified at the eastern coast of Iberia, already described by Buzzi et al. (1998) for the 1994 Piedmont Flood. The rain column evaporation of 12% of the total share is clearly below the 18% found for the precipitations during the ACEF episode, but changing the target region from central Europe to the Alps would produce a similar contribution from direct rain evaporation (10%) during the August episode. The referred percentages (marine/land evaporation) are in agreement with most of the previous studies and confirm both the prevalence of the marine to the terrestrial sources during these types of episodes in the Piedmont during the autumn and the main role of the WC-Mediterranean source. For the precipitations in Morocco we found a main contribution from the Atlantic Ocean, which amounts up to 93% of the total attribution. The rest corresponds to surface evapotranspiration over land (4%) and rain column evaporation (3%), which locates mainly close to the target. For a variable period of 8 and 13 days before the rainfall episodes in Morocco and the Alps respectively, our vapor source estimations have a limited error attributed to the relative low fraction of the target vapor (20–25%) located out of the model domain: the contribution of remote sources out of the domain is still low and limited to that percentage.

The calculated vapor loading rates from both surface and rain column sources are not constant during the period preceding the episodes. They increase as the date of the initiation of the episode approaches. Surface sources show a rapid increase during a period of 3–4 days preceding the event, while the rain column has a shorter period of 2 days. The latter period is similar to that of the ACEF episode, and it is most likely related to a similar mechanism responsible for the acceleration of the process: the increased availability of rain shafts during the final convergence of trajectories. Conversely, the period of 3–4 days for the surface sources during the November episode contrasts to the longer period of 6–7 days estimated for the August episode, which seems to progress more slowly.
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During the ACEF episode we showed that the vapor sources changed along the three rainfall days, following the evolution of the V₅₅ cyclone. On the contrary, for the November episode the location of main sources shows no significant changes throughout the 3-day rainfall episode in the Alps. This is in accordance with an almost stationary, large-scale forcing during that period. Three areas of intense marine evaporation are observed for both targets in the Alps and Morocco. The WC-Mediterranean is important for the precipitations in the Alps, and the region of the eastern N-Atlantic, near the western coast of Iberia and Morocco, plays a main role for the rainfalls in Morocco and a more secondary role for the precipitations in the Alps. A second Atlantic region with a nonnegligible importance in both episodes is located in the east coast of N-America. The proximity of these marine areas to each target seems to be a key factor of their relative contribution to the precipitations. The described sources are located in regions of identifiable tracks of joint enhanced evaporation and SST decrease and appear to be associated with the wind intensity and persistence of the meteorological conditions.

In addition, the analysis of the episodes has unveiled relevant meteorological processes at different scales from the synoptic (10–12 days) down to the mesoscale (1–3 days). The latter includes regional to local circulations with an important role of the orography.

Prefrontal secondary circulations over the Mediterranean region observed during this type of episodes are responsible for the addition of local sources in the WC-Mediterranean, N-Africa and E-Atlantic, and it works for the Alpine rainfall episode but not for Morocco. The evaporative sources over N-Africa and the E-Atlantic spread out into the tropical area and include both surface evapotranspiration and virga. This seems to be a characteristic signature of similar simultaneous heavy rainfall episodes with a large amplitude wave.

The more “simple” scenario of the vapor arrival into Morocco, following the synoptic subsidence of the intense northwesterlies, which transport the remote uptakes and the new vapor near the N-African coast into the region, contrasts with the more complex scenario in the Mediterranean sector. At the eastern side of the trough a second prefrontal circulation transports an important vapor fraction with a mixed origin to join the Atlantic advection coming from the west before being transported within the southwesterlies in the Mediterranean sector into the Alps. These winds also incorporate an important amount of new vapor, added from a relative cool sea into the warmer MBL of the WC-Mediterranean, which resulted in an enrichment of the “Mediterranean” fraction of vapor in the MBL, close to the Alpine region.

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