Simultaneous Episodes of Heavy Rainfall in Morocco and Southern Alps: 1. Mesoscale Simulations and Episode Climatology (1979–2016)

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Abstract  The torrential rain and southerly föhn episode on 14–16 November 2002 in the Alpine southside, which affected the Piedmont region, was concurrent with heavy rains in the northwest flanks of the Middle and High Atlas in Morocco. Both simultaneous rainfalls are analyzed, as well as the recent climatology of similar episodes. A mesoscale modelling system is used first to simulate the relevant atmospheric processes and then to map the evaporative sources of both targets. Moderate Resolution Imaging Spectroradiometer water vapor products, National Centers for Environmental Prediction reanalysis data sets, radiosondes, wind profilers, and surface rain gauges are used to substantiate the simulations. The evaporative source estimation is discussed in a companion article. The simultaneous episodes originated after the development of a narrow meridionally elongated upper level trough extending southward from the British Islands into Iberia, associated with a semi-stationary large amplitude wave. A total of 43 similar episodes have been identified during the 38-year period 1979–2016, averaging one episode per year. However, there is a large interannual variability, with several years with no episodes and, others, which can accumulate up to four episodes. The episode length shows also a high variability, from 2 to 7–8 days. The longest episodes usually include an enlarged “Mediterranean phase” for the rainfalls in the Alps. With respect to their seasonal variability, the largest fraction concentrates in autumn (60%), and no episodes are found from June to August. November accumulates the highest case occurrence (37%) and the observed variability cannot be explained by changes in the phase of the North Atlantic Oscillation.

1. Introduction

In a preceding contribution (Gangoiti et al., 2015), we set up a new tool to explore vapor sources associated to a target precipitation. The estimations of this modeling system MesoWat_Source were based on transporting parcels of vapor, representing the target precipitation, across a set of nested grids covering a large area at different resolutions. Vapor sources were diagnosed using the meteorological output of a mesoscale model, which was then used to estimate the back trajectories and to redistribute the vapor back into its release points. The model can discriminate terrestrial and oceanic sources as well as evaporation from falling precipitation occurring below clouds. It can also detect with greater precision the relative importance of remote versus local sources, together with the sequence of evaporation of a rainfall event down to a time resolution of 1 hr. This allows the identification of atmospheric processes behind the whole water cycle of a selected rain event from its sources into the target. Alternative modeling systems developed to investigate vapor sources behind selected rainfall episodes were discussed in Gimeno et al. (2012). To our knowledge, our modeling system is the only one which can evaluate and map both surface and rainfall sources. As discussed in Gangoiti et al. (2015), the main difficulties to evaluate evaporative sources from falling precipitation are both the need of using an adequate, very short time step for the rainfall evaporation computation (seconds to minutes for trajectories across rain columns), and the nonavailability of the precipitation rate changes with height in the standard output of mesoscale and global models. The latter is a key 3-D variable, needed for the evaluation. In addition, differently from the alternative more recent Eulerian approaches (Insua-Costa & Miguez-Macho, 2018), the modeled evaporation sources can be distributed in detailed map sequences together with the target vapor, without the need of using prescribed areas (sea-land-air boundaries), used in Eulerian models, which will always show a uniform distribution of vapor sources inside the prescriptions.
The model was applied to investigate the vapor sources distribution and their evolution during the 11–13 August 2002 Central-European Floods (ACEFs) in the Alpine region. The southern Alpine rim has also shown a high frequency of heavy precipitation events and a positive trend for autumn episodes during the last century (Frei & Schär, 1998; Schmidli & Frei, 2005). Contrary to the referred ACEF episode, some autumn extreme rainfall episodes in the region can occur without a cyclone in the Mediterranean and with relative high sea level pressures over the area. For example, Turato et al. (2004) described this type of events and evaluated the water vapor sources during the major precipitation and flooding that affected the Piedmont region, Italy, between 13 and 16 October 2000. At the synoptic scale, the dominant feature is a deepening trough aloft extending north to south from the British Islands into Iberia and Northern Africa (N-Africa), forcing intense southerly winds into the northwestern and north central Mediterranean and bringing intense precipitations in the whole Alpine region. An earlier study by Buzzi et al. (1998) put the focus in the role of the orography and latent heat exchange processes in the atmosphere of the Western Mediterranean (WM) during the 3–6 November 1994 intense precipitation that affected the same region, the Piedmont. Most of the precipitation over that area was associated with a southerly low-level prefrontal jet crossing the WM against the orography of the western Alps and northern Apennines, and the precipitation was mainly shown to form through an orographic forced ascent favored by the latent heat released by condensation during lifting. As it is shown in section 5, both Piedmont episodes are simultaneous with heavy rainfalls in Morocco, the Er-Rif (ER) mountains and Middle and High (MH) Atlas, on their northwestern Atlantic facade. They also share a similar synoptic forcing, associated with a narrow meridionally elongated upper level trough extending southward from the Atlantic storm track latitudes into Morocco. Following the contribution by Massacand et al. (1998), this upper-level precursor of heavy precipitation on the Alpine southside takes the form of a narrow streamer of high Potential Vorticity (PV) air.

Similarly to the aforementioned autumn episodes, the 14–16 November 2002 severe rainfall episode affected also the Piedmont region, and it has been widely studied under different perspectives. It was first documented by Milelli et al. (2006) in the context of the nature of the synoptic forcing and the resulting precipitation distribution considering the role of the topography of the region. The same exceptional episode was addressed by Zängl and Hornsteiner (2007), who put the focus in the description of the detailed structure of this “unusually” long southerly föhn and precipitation episode, which lasted almost 3 days and affected unequally the western and eastern Alpine regions. More recently, the same episode was analyzed by Winschall et al. (2011) to put in evidence the contribution of the eastern North Atlantic (N-Atlantic) evaporation hot spots on this type of rainfall events. They also included a climatological analysis (10 years) of hot spots located to the west of the Iberian Peninsula. They showed that their frequency of occurrence (around 4 days/year) was similar to that of the intense precipitation events in Central Europe, being characterized by an upper level trough and PV structure similar to that described by Massacand et al. (1998). However, as shown by Winschall et al. (2011), not all the cases of heavy precipitation in the Alpine southside include a pronounced hot spot in the eastern N-Atlantic region. They arrived to this result after the analysis of the four case studies described by Massacand et al. (1998) and the climatology (1966–1999) of heavy precipitation days in the Swiss Alpine southside shown by Martius et al. (2006). As it will be discussed next, this type of hot spots, west of Iberia and Morocco, might be more related with a type of large amplitude wave which also affects N-Africa and not only the Alpine region. In fact, all the mentioned Piedmont rainfall episodes in the literature have this type of large amplitude waves and they were concurrent with both an intense precipitation in Morocco and a hot spot area west of the Iberian Peninsula, as the one described by Winschall et al. (2011). Thus, the objective of this manuscript is to explore this type of episodes of concurrent heavy rainfall in Morocco and southern Alps, characterized by a narrow elongated upper level trough extending southward from the latitudes of the British Islands into Morocco. We also investigate their time of recurrence and the simultaneous occurrence of hot spots in the N-Atlantic. Additionally, we perform a high-resolution simulation of the meteorology of the 14–16 November 2002 episode, define the main precipitation targets in Morocco and the Alps, and evaluate the performance of the mesoscale model by comparing its results with rain, surface and upper level winds, and satellite water vapor transport observations. These results feed the source estimations discussed in the companion paper.

In this respect, the manuscript is organized as follows: the synoptic scenario during the precipitation episode on 14–16 November 2002 in the Alpine southside and in Morocco is described in section 2. Section 3
is devoted to the description of the modeling system, including the multiple domain coverages and resolutions of the meteorological model. The evaluation of the meteorological simulation is included in section 4 and the climatology (episode identification) during the period 1979–2016 in section 5. Finally, in section 6, we summarize the main results. In the subsequent companion paper (Gangoiti et al., 2019; referred to as G19), we map and quantify the marine/terrestrial moisture sources together with direct rainfall evaporation (virga) during the episode 14–16 November 2002 in both target regions, the Alps and Morocco. The time evolution and area coverage of the evaporative regions of both targets are estimated and compared; as well as the relation, if it exists, between the evaporative sources and the hot spot areas observed in the N-Atlantic.

2. Synoptic Forcing

The meteorological situation during the episode on 14–16 November 2002 has already been described by other authors (Milelli et al., 2006; Winschall et al., 2011); however, their analysis of the preexistent conditions starts only 1 to 2 days before the episode. It is shown in G19 that circulations at the scale of the whole N-Atlantic contribute to accumulate vapor from sources distributed at its eastern and western boundaries at least 10 to 12 days before the episode. This “background” water vapor, accumulated from remote Atlantic sources, together with that generated mostly out of the western boundaries of the domain, was transported into the target regions after the development of a meridionally elongated trough at the eastern N-Atlantic. This trough extended from the British Islands into Iberia and N-Africa and forced a rapid convergence into the wind facing slopes of our targets in Morocco and the Alps.

Figures 1a and 1c show the reanalysis by the National Centers for Environmental Prediction (NCEP) (Kanamitsu et al., 2002) during the Large-scale Atlantic Vapor Accumulation period (30 October to 11 November), characterized by high pressures at the eastern N-Atlantic at latitudes 30–50°N and relative low pressures at the western side. The period finished on 11 November as shown in G19, after the eastward movement of a low pressure from southern Greenland to the British Islands, initiated on 9 November (Climate Forecast System (CFS) reanalysis in http://www.wetterzentrale.de). The vertical cross sections of the relative humidity, temperature, and wind at 40°N constant latitude, depicted in Figure 1c, illustrate a midlatitude low formation at the western N-Atlantic, to the East of the outflow of the drier N American continental northwesterlies (Figure 2c) and over the greater temperature gradients of the Gulf Stream (see also in G19). This is a known region of cyclogenesis after the combined effects of baroclinicity induced by the Gulf Stream and the concurrent upper level vorticity advection (Minobe et al., 2008; Sanders, 1986).

Following the reanalysis in Figure 1c, in this region, water vapor from the evaporation at the western N-Atlantic can reach the tropopause (marked in blue lines with potential vorticity values of 2 and 2.5 PVU, in Figures 1c and 1d) and a fraction of it is expected to condensate and precipitate out within the same area. A region of deep sinking is also observed at the rear side of the incipient cyclone (65°W in Figure 1c). The latter area, located under a wave of the jet stream (Figure 2a), produced an evaporation hot spot (latent heat flux greater than 250 Wm⁻² in Figure 2c), in an area of intense winds and surface divergence in the western N-Atlantic between 30–40°N and 60–70°W. Wind data in Figure 2 (as in Figure 1) correspond to the 6-hourly NCEP-reanalysis II, available at https://rda.ucar.edu/datasets/ds091.0/ website. The latent heat flux is also a 6-hourly NCEP/DOE AMIP-II reanalysis at https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.gaussian.html website.

As shown in Figure 2d, these midlatitude hot spots can develop simultaneously at either side of the N-Atlantic. When these regions are far from the rainfall targets, the probability of the vapor originated there to precipitate at the targets is low: under these conditions, a larger dispersion of the vapor is expected as it moves away from its source. Consequently, we expect a higher contribution of the hot spots located at the eastern N-Atlantic to the precipitations in Morocco and the Alpine region (as shown in G19). Figures 1a and 1c also show large areas of sinking associated with Atlantic anticyclones out of the region of cyclogenesis in the W-Atlantic. These anticyclones can contribute both to trap/sink the water vapor, previously vented into the upper troposphere in more remote regions, down to the middle and lower
troposphere, and to accumulate vapor in the marine boundary layer after evaporation from the sea surface (shown in G19).

On 14 November, the rainfall episode initiated almost simultaneously in both targets after the low-pressure system over the British Islands moved and expanded to the south (11–14 November, following the CFS reanalysis in http://www.wetterzentrale.de). At the beginning of the rainfall episode, a deep trough occupied a large north-to-south area (right panels in Figures 1 and 2) from the British Islands into N-Africa, under an elongated polar jet stream reaching Morocco (Figure 2, right). This wave increased its amplitude during the episode, slowing down its eastward propagation and remaining almost stalled during the 15 and 16 November. Consequently, intense northwesterlies veering to the north during the episode were forced into N-Africa, at the back of the trough (Atlantic sector), while prefrontal southwesterlies blew ahead of the slowly moving through over the WM and into the Alpine region (Mediterranean sector). In the WM, the wind showed a characteristic vertical shear: southwest at the middle troposphere, veering to the south at lower levels and to the southeast during the final stage of the Alpine episode. The series of processes related with the final evaporation and convergence of vapor into the Alps over the WM occurred under these local conditions, as discussed in G19.

Figure 1. NCEP-reanalysis fields before (left) and at the initiation (right) of the episode: (a and b) mean sea level pressure MSLP–1000 (hPa) in shaded colors and 500–to 1,000-hPa thickness (dam) in contour lines; (c and d) corresponding vertical cross sections at constant latitude 40°N, showing relative humidity (%) in shaded colors, temperature (°C) in contour lines, and winds, represented with the zonal ($u$) and pressure vertical velocities ($-1 \times 10^{-2}$ Pa s$^{-1}$). The dynamical tropopause is marked in blue lines with potential vorticity values of 2–2.5 PVU.
3. Setting Up the Mesoscale Modeling System

The MesoWat_Source modeling system (Gangoiti, Gómez-Domenech, et al., 2011; Gangoiti et al., 2015) was designed to evaluate the evaporation sources of a prescribed target precipitation. It is based on a series of software modules (Figure 3), which share meteorological and positional information of water vapor parcels moving in back-trajectories initiated at the precipitation levels above the target rainfall.

The Regional Atmospheric Modeling System (RAMS v6.0) (Pielke et al., 1992) and the HYbrid PArticle Concentration and Transport (v1.5) model (Tremback et al., 1993) are used for modeling the meteorology and the back-trajectory transport of moisture from the rainfall target back into the evaporative sources, respectively (Figure 3). The RAMS/REVU/GrADS module in Figure 3 uses the postprocessing utilities of RAMS to select a series of meteorological two- and three-dimensional fields from the RAMS analysis output and to record them in a GrADS gridded binary data file format (Doty & Kinter, 1995). The 3-D variables estimated by the mesoscale model are recorded either at constant sigma levels or interpolated at constant heights above sea level. These GrADS binary files, with the packed meteorological variables, are then used either for depiction of variables or for feeding the vapor-emission and source-attribution modules. The evaporation sources estimated by the rest of modules out of the dotted contours in Figure 3 are shown in the companion paper G19.

Figure 4a shows the topography, coverage, and resolution of the RAMS domains, with the target regions marked with open squares (Figures 4b and 4c) and the 6-hourly CFS Reanalysis (CFSR) area-averaged precipitation for the three targets (Figure 4d). The reanalysis is at a resolution of 33 km (0.313°).
latitude/longitude, available at [https://rda.ucar.edu/datasets/ds093.0/](https://rda.ucar.edu/datasets/ds093.0/). Six two-way nested grids are used for the mesoscale RAMS simulation, and the highest resolution grids #5 and #6 completely cover the extreme precipitation areas of the three target regions: Western and Eastern Alps (W-Alps and E-Alps) in Europe and the MH Atlas and ER Mountains in N-Africa (Morocco). The results will be discussed in section 4. The largest domain (grid #1) is greater than the one used for the ACEF episode (Gangoiti, Gómez-Domenech, et al., 2011; Gangoiti, Sáez de Cámara, et al., 2011). Now, the west-to-east domain width doubles that of the August episode and, it is also enlarged to the south, crossing the equatorial line. The use of a much larger domain provides the opportunity to map more remote sources, mainly those located at low latitudes and in the western N-Atlantic, decreasing thus the fraction of nonattributed vapor in our limited domain modeling system, due to trajectories crossing the outer boundaries, which are definitely lost for calculation.

The vertical coverage of all grids is 22 km for the mesoscale simulation, with a maximum resolution at lower levels (30 m) decreasing to a minimum of 1,000 m above the 11-km height. Four-dimensional data assimilation is used for the model run, with Newtonian relaxation toward the 6-hourly NCEP reanalysis data (available at [https://rda.ucar.edu/datasets/ds091.0/](https://rda.ucar.edu/datasets/ds091.0)): A variable relaxation time was used, with the highest values (weak nudging) at the center of the large domain (grid #1) and lowest values (strong nudging) at the boundaries. Topography and land cover were interpolated from the USGS global 30” database, available at [https://lta.cr.usgs.gov/GTOPO30](https://lta.cr.usgs.gov/GTOPO30) (Gesch et al., 1999) and [https://lta.cr.usgs.gov/GLCC websites](https://lta.cr.usgs.gov/GLCC websites). Daily Sea Surface Temperature (SST) data, with an original resolution of 0.25° × 0.25°, was interpolated from the optimum interpolation SST (OISST) AMSR-AVHRR analysis, available at [https://www.ncdc.noaa.gov/oisst](https://www.ncdc.noaa.gov/oisst) (Banzon et al., 2016; Reynolds et al., 2007) into the model grids. Our setup of the mesoscale model included a prognostic turbulent kinetic energy (level 2.5) parameterization (Mellor & Yamada, 1982), with modifications for a case of growing turbulence (Helfand & Labraga, 1988), and a full-column two-stream parameterization that accounts for each form of condensate (seven species) for the calculations of the radiative transfer through clouds and gases in the model (Harrington et al., 1999). The cloud and precipitation scheme by Walko et al. (1995) was applied in all domains with all (seven) species activated, and the LEAF-3 soil vegetation scheme was used to calculate sensible and latent heat flux exchanges with the atmosphere, using prognostic equations for soil moisture and temperature (Walko et al., 2000). The run of the mesoscale model from 30 October to 16 November 2002 was performed continuously.
4. Evaluation of the Meteorological Simulation

Evaluation of the vapor source estimations is not a straightforward task for any of the existing modeling systems (Gimeno et al., 2012), as water from vapor sources (marine-land-virga), including local to remote differential contributions, can barely be distinguished by measurements. However, in order to ensure that the model estimations of the vapor source location/intensity are based on a correct representation of the observed meteorological fields, total column water vapor (TCWV) products and precipitation from satellites, such as the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA), can be used for evaluation, as well as precipitation from surface stations (Gangoiti, Sáez de Cámara, et al., 2011). Other reanalysis products can also be used for rainfall validation (Winschall et al., 2011) as well as vertical profiles from wind profiler radars and free soundings from a selection of National Meteorological Centers (Gangoiti, Sáez de Cámara, et al., 2011). For the same purpose of evaluation, we used here: (a) the intensity/distribution of rainfall from several independent sources, (b) vertical profiles of a selection of wind profiler radars (WPRs) to follow the hourly evolution of the wind estimations at different heights, (c) a selection of wind profiles from free soundings (6–12 hourly resolution), and (d) Moderate Resolution Imaging Spectroradiometer (MODIS)-TERRA satellite TCWV products for the vapor distribution and movement, which will show us whether the simulation of the transport of vapor fits the corresponding satellite observations.

The hourly wind speed and direction calculated by the model and the experimental measurements from a selection of three radiosonde stations and two WPRs are represented in Figures 5 and 6. These are located at the eastern and western coast of Iberia concurrent with the positions of the two "legs" (Lisbon and Murcia) of the semistationary wave during the rainfall episode and inside the target Alpine area (Payerne...
and Milan, located in Switzerland and northern Italy, respectively). The simulated and observed wind profiles agree satisfactorily: The simulation was able to capture both the intensity and the timing of the winds recorded in Lisbon, Murcia, and Milan in Figure 5. The initiation of the intense northwesterlies on 14 November in Lisbon and the simultaneous southwesterlies in Murcia, which persist until the 17 November are well represented in the simulations (Figures 5d and 5e). Wind veering to the SE, also observed in the mesoscale analysis by Buzzi et al. (1998) during a similar episode, associated with the low-level convergence from the western-central Mediterranean (WC Mediterranean) into the W-Alps, is also well represented by the model during the 15 and 16 November in the Milan sounding (Figure 5f). The agreement goodness can also be concluded from the comparison of the modeled wind profiles with the WPR outputs at Bilbao and Payerne (Figure 6). The statistical values defined by Zhong and Fast (2003) (bias, root-mean-square error, and correlation) for the simulation period 30 October to 17 November 2002 are summarized in Table 1, and they confirm the agreement between experimental measurements and simulations. RAMS was able to simulate wind profiles with statistical scores comparable to those of other similar studies (Gangoiti, Sáez de Cámara, et al., 2011; Hanna & Yang, 2001; Zhong & Fast, 2003).

The evolution of the Tcwv is represented in Figure 7 for 5 and 14 November, as shown by MODIS TERRA IR images (Figures 7a and 7b) and the simulation by RAMS (Figures 7c and 7d). These days correspond to the intensification of a high-pressure area at the eastern N-Atlantic (left) and the initiation of the rainfall episodes (right) almost simultaneously in Morocco and the southern flanks of the Alps. Figures 1 and 2 show the NCEP reanalysis at the same time. MODIS images have a resolution of 1° × 1°, and areas with no data (in white color) correspond to clouds, which could be concurrent with the precipitation and water vapor removal from the column. Model output can be used to fill the gaps in these cloudy areas. Both model results and MODIS images show a similar distribution of vapor and a synchronous movement during the whole period of simulation.

The high-pressure area at the eastern N-Atlantic (Figure 1a) lasted until 11 November and accumulated water vapor in a large-scale circulatory motion (Figures 7a and 7c), as described in G19. Figures 7b and 7d correspond to the initiation of the rainfall events in Morocco and the Alps: The WM region lies under an elongated band of clouds which crosses the whole area from SW to NE in Figure 7b (in white) where there is no satellite signal. Satellite data and RAMS estimations for the total column water vapor show a similar distribution during the whole period of simulation.

The high variability of the precipitation in a region of complex terrain, such as the Alps, makes it challenging the task of evaluating any simulation of both the amount and the distribution of local precipitation. Figure 8 shows a composite of four panels with the topography of the Alpine region and the 72-hr-accumulated rainfall from 0000 UTC 14 to 0000 UTC 17 November in the area: (a) estimated by the mesoscale model at the 8-km resolution in grid #5, (b) the NCEP CFSR at a resolution 0.313° latitude/longitude, and (c) the TRMM MPA 3B42 version 7, at a 28-km resolution (https://doi.org/10.5067/TRMM/TMPA/3H/7). Huffman et al. (2007, 2010) describe the TMPA-3B42 product. A selection of station maxima (data provided by Arpa Piemonte and Arpa Veneto), accumulated during the same 72-hr period, is also represented with the TRMM data. Panel (c) in Figure 8 shows the topography, together with the main wind direction during the rainfall episode. The precipitation scale is the same for all three panels.

All precipitation maps shown in Figure 8 have a similar maxima-minima distribution: The areas of peak values, marked inside the open white circles, show precipitation relative maxima located in the windward regions of the Apennines and the Alps, while lower values are located following the dotted lines at the leeward side of the main ranges in the three panels. The surface stations with the highest 72-hr precipitation totals in Figure 8d, up to 535 mm, are located inside the regions of relative maxima, at each side of the rain shadow bands, depicted with dotted lines. Even though the distribution of the precipitation totals has similar features in the panels, none of them is exactly equal to any other. For example, a difference can be observed at the region to the north of the W-Alps target, where the TRMM locates a relative maximum of 140 mm (44 mm at the nearest station of Freudenstadt in Germany) in Figure 8d. This maximum is located more to the south by RAMS, on the north facing slopes of the Swabian Alps (Figure 8c) and inside the target W-Alps region. Alternatively, the NCEP-CFSR analysis shows an area of smaller values between the two locations north of the border. Other comparisons of the precipitation totals, estimated for the same region and rainfall episode can be found in Winschall et al. (2011).
Figure 5. (a–c) Observed rawinsonde wind profiles and (d–f) simulated (vectors) at Lisbon (a and d), Murcia (b and e), and Milan (c and f) from 12 to 17 November, which includes the rainfall period between the vertical solid white lines (14–16 November). Shaded colors correspond to the simulated wind directions. The three sounding sites (LSB, MRC, and MLN) together with the wind profiler locations (PYR and BIL) are shown (g) in a topography map with the same scale as in Figure 4.

A similar arrangement of rainfall distributions selected for Figure 8 is also used in Figure 9 for the target of Morocco.

RAMS evaluations, NCEP-CFSR precipitation, TRMM, and topography are shown following the same arrangement. The scale used for the precipitation color bar in Figure 8 is now changed to adapt it to a shorter range of precipitation values, which represent 48-hr rainfall totals. Even though the 48-hr totals in Morocco are lower than the 72-hr totals in the Alps, the area-averaged hourly precipitation for the target region in Morocco (black open rectangle) shows a similar intensity signal than in the Alps, as shown also in the sequence of the Figure 4d, marked with a solid blue line. A selection of station maxima, accumulated during the same 48-hr period, is also represented with the TRMM data. Again, as in Figure 8, precipitation maps are similar. Areas of precipitation relative maxima locates in the windward regions of the Moroccan Plateau (Meseta), the MH Atlas, and ER mountains (inside the open white ovals), while lower values are observed in broad band inside the Plateau and at the leeward side of the referred mountain ranges in the three
panels (dotted lines). However, it is important to notice that contrary to the Alpine region, the areas of precipitation maxima seem to be located out of the coverage of the available surface stations. The time evolution of the area averaged precipitation inside the respective targets simulated by the mesoscale

Figure 6. (a, c) Observed Wind Profiler Radar wind records and (b, d) simulated (barbs) at Payerne (a, b) and Bilbao (c, d) from 12 to 17 November, which includes the rainfall period between the vertical solid white lines (14–16 November). Shaded colors correspond to wind directions as in Figure 5.
model RAMS is compared with the CFSR reanalysis and the TRMM multisatellite estimations in Figure 10. Important differences are observed in the TRMM analysis with respect to the other two, mainly in Morocco and W-Alps, with peak TRMM values well above the estimations of both CFSR reanalysis and RAMS. Differences are concentrated during the initiation and ending of the TRMM episode (Figure 10c). Similar poor performances in the sequence of TRMM areal averaged data have been observed with respect to CFSR daily and monthly sequences in other studies (Worqlul et al., 2014, 2017). For the precipitation totals of the episode, they all show a better agreement: relative differences between TRMM and CFSR (TRMM-CFSR)/CFSR are +0.28 for the Alpine region and +0.39 for Morocco, while the same differences between RAMS and CFSR are +0.32 and −0.34, respectively.

5. Climatology of Simultaneous Heavy Rainfall Episodes (1979–2016)

It is important to know how intense and how frequent is this type of episodes, which show a narrow elongated upper level trough extending north to south from the latitudes of the British Islands into Morocco and which give rise to heavy rainfalls in both Morocco and southern Alps. We will show their latent heat anomalies (N-Atlantic hot spots distribution and strength) together with synoptic wind, pressure, and precipitation anomalies in the N-Atlantic and the surrounding continental land masses. We also explore their seasonal and interannual variability to find out whether a seasonal preference exists or a connection with the most important large-scale mode of climate variability in the north Atlantic sector: the North Atlantic Oscillation (NAO).

In order to identify the episodes, we use the 6-hourly NCEP-CFSR gridded precipitation data at the highest available resolution: 0.3° latitude/longitude for the period 1979–2010 (Saha et al., 2010) and at a greater resolution of 0.20° for the more recent period 2011–2016 (Saha et al., 2011). For the same purpose of episode identification, we use wind data at prescribed regions and heights over the N-Atlantic and the WM. For this case, the 6-hourly NCEP reanalysis gridded products at 2.5° latitude/longitude resolution (Kanamitsu et al., 2002) are used for the whole period 1979–2016.

The first step in the identification of a precipitation 6-hourly event susceptible to be included in a Moroccan-Alpine episode is the evaluation of the accumulated 6-hourly area-averaged precipitation in E-Alps, W-Alps, and Morocco (areas inside the open squares represented in panels b and c of Figure 4). These regions are exactly those defined as targets for the vapor source analysis. The area-averaged precipitation (prec) selected for a preliminary identification is \( \text{prec} > 0.2 \) mm accumulated in 6 hr for all the three regions (E-Alps, W-Alps, and Morocco). This threshold is equivalent to 0.033 mm/hr in Figure 4d, and it is enough for this previous step of rain identification before accounting for the accumulated rainfall during a full episode of various days. Concurrent intense northwesterly winds west of Iberia and southerly winds over the WM are needed for the effective identification of a wave similar to that found during the episodes. Therefore, we define a region on the eastern N-Atlantic, inside a box from 20°W to 10°W and from 33 °N to 40 °N, for area-averaged wind evaluation at 850 hPa. A similar-sized region on the WM inside a box from 3°E to 13°E and from 37°N to 44°N is also defined for wind evaluation at the same pressure level. These boxes are represented in all maps of anomalies in the episode initiation with respect to the average climatology discussed in this section 5. Winds are strong during these episodes in both the equatorward and poleward side of the jet, located over the eastern N-Atlantic and the WM, respectively. We found sensibly weaker winds over the Mediterranean. After checking a series of known episodes, we take the following thresholds for the selection of events: \( V > 7 \) m s\(^{-1}\) for the wind velocity on the Atlantic and \( V > 5 \) m s\(^{-1}\) on the Mediterranean. For the wind direction, we use the Eulerian components of the area-averaged values: \( u > 0 \) and \( v < 0 \) on the Atlantic (northwesterly winds) and \( v > 0 \) (southerly winds) on the Mediterranean. All these conditions (precipitation, wind directions, and velocities) have to be simultaneously fulfilled for an individual event (6-hourly data) to be selected. This preliminary selection gives an average of 85 events per year during the 38-year period, with a large interannual variability.

### Table 1

|        | Bilbao | Payerne |
|--------|--------|---------|
| BIAS \( u \) | 1.59   | 0.64    |
| BIAS \( v \) | 0.87   | 0.45    |
| RMSE \( u \) | 3.43   | 3.66    |
| RMSE \( v \) | 2.30   | 3.54    |
| Correlation \( u \) | 0.67   | 0.79    |
| Correlation \( v \) | 0.91   | 0.85    |

Note: Bias is defined as simulated minus observed. RMSE is root-mean-square error.
A large fraction of this selection (preliminary list of events) is conformed either by isolated events or grouped into periods of several days without collecting enough precipitation to be considered exceptional. In this respect, and based on the NCEP-CFSR gridded data, we use the 95th percentile (P95) of the 24-hr area average precipitation to define a period of exceptional precipitation. The estimation of P95 is based on precipitation days with rainfall \( \geq 0.1 \) mm/day. Our three target regions give slightly different values: The P95 for Morocco is 14 mm/day, while for W-Alps and E-Alps are 16 mm/day and 17 mm/day, respectively. For comparison the P99 is 25 mm/day for Morocco and 26 and 29 mm/day for W-Alps and E-Alps, respectively. The latter values are in agreement with the estimation for the period 1966–1999 (29 mm/day) by Martius et al. (2006) based on a dense rain-gauge measurement (25-km resolution, approximately) in the south Alpine region. As the differences in the P95 values of the three regions are low (less than 10%), we opted to use the same value for the definition of a 24-hr exceptional precipitation for the three regions: 17 mm/day. Persistency is also an important ingredient in the identification of these episodes associated with large amplitude waves. Consequently, short episodes of less than 36 consecutive hours (six events) were removed from the preliminary list: We only kept consecutive 6-hourly events of the largest episodes (more than six events), which could accumulate at least 17 mm in four events (24 hr) in both Morocco and in at least one of the two Alpine regions. It is known that (heavy) precipitations are not uniformly distributed in the whole southern Alpine rim (Martius et al., 2006). After our analysis, we have been able to identify episodes with heavy precipitations in W-Alps with simultaneous lesser precipitation in E-Alps and vice versa.

After running the code for the final selection of episodes, we realized that some of the identified periods were too short, and they excluded a final phase of heavy rains in the southern Alpine region. This final phase occurred when the meteorological conditions (precipitation and/or wind) in the Atlantic sector had

![Figure 7. Total column water vapor (cm) before (left) and at the initiation (right) of the episode, as in Figures 1 and 2, corresponding to (a and b) MODIS TERRA images and (c and d) RAMS model simulations.](10.1029/2019JD030432)
changed and were out of the prescribed values, since the adequate meteorology still remained in the Mediterranean sector: intense southerlies and heavy rains in the Alps. After modifying the code to deal with this enlarged Mediterranean phase of some episodes, we obtained a total of 43 episodes of different lengths. The initial and final day of these episodes are shown in Figure 11, distributed by months and years. There are seven "short" episodes lasting 2 days whereas the remaining are longer, up to 7–8 days for the exceptionally longest episodes, as the ones on 11–17 October 1979 and 11–18 November 1996, finishing both of them with an enlarged Mediterranean phase, affecting only to the southern rim of the Alps, whereas at the Atlantic sector (Morocco) the precipitation rate decreased with the onset of the north-easterlies west of Iberia, associated to the progressive weakening of the upper level trough and the simultaneous reinforcement of the Azores High over the Bay of Biscay (see Figure 4 for referred locations). On average, there is approximately one episode/year, affected by a large interannual variability, with an episode occurrence minimum between 1981 and 1985 (one episode in 5 years) and a maximum in the year 2014 (four episodes in 1 year). The observed seasonal variability (Figure 11b) shows that the largest fraction of episodes occurs in autumn from October to December (OND, 60%), with no episodes during the warm period from June to August. The number of episodes increases rapidly from September (one case) to reach a maximum in November, which accumulates 37% of all cases.

These results are in agreement with the seasonal variations of the extreme precipitation days in southern Alps reported by Martius et al. (2006): They found that a larger fraction (73%) of days with extreme precipitations in southern Alps along a year had associated a streamer centered over western France and that although the presence of such streamers could be found along the year with no seasonal

Figure 8. Precipitation totals (mm in 72 hr) during the episode 14–16 November in the Alps: (a) simulated by RAMS, (b) high resolution NCEP-CFSR reanalysis, (c) TRMM multisatellite precipitation product, and (d) topography of the Alpine region inside the RAMS grid #5, using the same color scheme as in Figure 4. The open arrows show the main wind direction during the rainfall episode. Areas of peak values are marked inside the open white circles (mountain windward regions) while lower values locate following the dotted lines at the leeward side of the main ranges. The location of surface stations with the highest 72-hr precipitation totals is shown inside the regions of relative maxima in panel (d).
preference, the autumn (in this case, September to November) accumulated the largest fraction (44%) of the extreme precipitation days in the southern Alpine region. They used a completely different approach, with different data sets, methodology, and even a different period (1966–1999), but the strong autumn signal which is present in the Alpine extreme precipitation days is also present in the simultaneous episodes of heavy rains in Morocco and the Alps. It is important to note that not all the Alpine extreme precipitations associated with streamers over western France/Iberia are concurrent with extremes in Morocco. In fact, only one of the four case studies of heavy rainfalls on the Alpine southside described by Massacand et al. (1998) corresponds with simultaneous heavy rainfalls in Morocco (the Piedmont case on the 5 November 1994). The episodes selected with our method do not include isolated days (which also make a difference in our approach) and are related with large amplitude waves, which can reach at least the Moroccan coast. The autumn signal was attributed in Martius et al. (2006) to an increased southerly moisture flux over the Alpine region in autumn. The question regarding the origin of that moisture is addressed in G19.

Simultaneous seasonal positive anomalies of precipitation in Morocco and the Alpine regions correspond to the two circulation modes of the negative phase of the wet-seasonal NAO index defined by Sáez de Cámara et al. (2015). However, after inspection of each of the episodes shown in Figure 11a, we found them distributed across the five modes of circulations defined in the referred article (included the “mixed” and the two positive mode categories). Thus, the main synoptic forcing needed for these episodes to occur can be found in
any year, independently of the preferred wet-seasonal circulation mode in the N-Atlantic. In addition, at a shorter time scale, the phase of the monthly NAO index can be either positive or negative during the episodes, and this is also true even for the daily NAO index (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml). The latter result was surprising, because one could expect a unique synoptic forcing associated with the observed large amplitude waves during the episodes. After inspection of the surface and upper level charts, we realized that the elongated upper level troughs, which are always present during the identified episodes, were not always concurrent with low pressures at the surface. Instead, relative high pressures were observed at the surface under the upper level trough for some episodes. Consequently, the phase of the NAO index, built on the mean sea level pressure anomalies, is not appropriate to characterize the rainfall episodes: In this respect, the episodes 15–25 May in 1984, 30 January to 3 February in 1986, 2–6 April in 1989, and, more recently, 9–12 November in 2014, among others, show a positive phase of the daily NAO index while a negative phase is observed during the more recent episodes 8–12 May and 21–25 November, both in 2016.

Figure 12 shows the composite (12b) of both the surface latent heat flux and the 850-hPa winds, at the initiation of the 43 episodes listed in Figure 11a, the average (12a) for the 38-year period (1979–2016), anomalies of latent heat flux and wind (12d) obtained from the difference of both Figures (12b and 12a), and the composite (12c) of the same variables at a time instant of 9 days before the initiation of the episodes. The period of 9 days was selected to approximate to the time instant inside the larger period of evaporation-accumulation of vapor from remote sources (Large-scale Atlantic Vapor Accumulation), before the shorter period of the intense evaporation from local sources near the targets, as it is discussed in G19. Areas of enhanced positive latent heat flux anomalies (100–250 W m⁻²) can be observed both at eastern and western N-Atlantic during the initiation of the episodes (Figure 12d), between latitudes 30 and 50°N, corresponding to regions of hot spots (latent heat flux >250 W m⁻²) in Figure 12b. As in Figure 2, the represented data correspond to the 6-hourly NCEP/DOE AMIP-II reanalysis. The eastern N-Atlantic positive latent heat flux anomalies are
also concurrent with more intense northwesterly winds, while concurrent intense southwesterlies are also observed at the WC Mediterranean associated with positive latent heat flux anomalies (0–100 W m$^{-2}$) in the region. After inspection of the 43 identified episodes, hot spots are observed in all of them, located west of Iberia and/or N–Africa, at least during the first 24 hr since their initiation. Alternatively, negative anomalies (−50 W m$^{-2}$) are present at the eastern Mediterranean and at the central N–Atlantic (−100 W m$^{-2}$) during the initiation of the episodes.

The latent heat flux distribution 9 days before (Figure 12c), which characterize the large-scale/background evaporation upwind of the targets, differs from their distribution at the initiation of episodes and it is more similar to average conditions (Figure 12a). However, there are some important differences with the average evaporation in Figure 12a: More intense and also larger regions of evaporation are observed in the N–Atlantic above latitude 50°N and also in the eastern coast of the USA, which can be directly related with an increased background moisture flux (from remote sources) over the target regions during the episodes (Martius et al., 2006), which are more frequent in autumn. The argument of an increased moisture flux into the targets can also be hold for the added moisture from more local sources (western coast of Morocco and WC Mediterranean) as shown in Figures 12b and 12d.

In this respect, there are marked seasonal changes in the latent heat flux of the N-Atlantic and the Mediterranean regions. Figure 13 shows the seasonal anomalies with respect to the average during the period 1979–2016 shown in Figure 12a. The most intense evaporation rates in the N-Atlantic and the
Mediterranean Sea appear during autumn (OND), while summer from July to September (JAS) has the lowest values. Taking into account that the presence of streamers over the area can be found along the year with no seasonal preference (Martius et al., 2006), we could infer an increased moisture flux from the N‐Atlantic and the WC Mediterranean into the target regions of Morocco and the Alps during Autumn and a reduced flux in summer, which is more likely behind the observed seasonal preferences of the episodes.

The same deployment from Figure 12 is used in Figure 14 to show the jet stream position and wind intensity during the initiation of the episodes and the anomalies with respect to its average values (streamlines). The position of the upper level trough at the initiation of the episodes (Figure 14b) is consistent with the observed intensity of the northwesterly winds throughout the whole troposphere in the eastern N-Atlantic and the formation of an enhanced evaporation region (hot spot) at the left of the upper level trough (Figures 12b and 12d) with relative dry air sinking (dashed contours in Figure 14b) through the entire tropospheric column. Concurrently, intense southwesterly winds are observed to the right of the trough over eastern Iberia and the WM following a generalized ascending motion (solid contours in Figure 14b). As in Figure 12, 9 days before the initiation of the episodes (Figure 14c), the prevailing conditions of the represented variables are similar to the average conditions (Figure 14a).
In Figure 15, surface high/low pressure systems (shaded colors) and upper level troughs/ridges (contours of the 500- to 1,000-hPa thickness) are identified during the initiation and before the episodes as in Figures 12 and 14. The average climatology is also represented. Cold and warm advections into Morocco and the WM can be observed during the episode initiation in Figures 15b and 15d, respectively, while 9 days before the atmospheric conditions resembled the average meteorology.

The anomalous accumulation of precipitation during the episodes and its spatial distribution for the whole N-Atlantic and Mediterranean regions can be observed in Figure 16: The interannual 38-year averaged precipitation (represented as accumulated in 72-h) is shown in Figure 16a, and the composite average for the first 72 hr of the 43 episodes in Figure 16b. The differences between both estimations (i.e., the precipitation anomalies during the initiation of the episodes) are represented in Figure 16c. Greatest positive anomalies occupy Iberia (mainly its Atlantic coast), Morocco, and the whole Alpine region, but the latter two regions show peak precipitation anomalies, of more than 60 mm, that are not found anywhere else.

In order to confirm the precipitation anomalies observed in the reanalysis during the episodes, alternative precipitation records can be used over a relatively long period. Averages and anomalies for the same 72-
hr-accumulated precipitation have now been estimated using the TRMM multisatellite data. The evaluations, shown in the Figures 17d–17f, have been made using the same latitude-longitude window as in Figure 16 but for a shorter time range (1998–2016) because this satellite product is not available before 1998. In addition, there is no TRMM precipitation data above latitude 50 N, a region in the northern boundaries of the CFSR precipitation anomalies. Figures 17a–17c show the same CFSR precipitation averages and anomalies as in Figure 16 for the period of 19 year, coincident with the period of TRMM data availability, to adjust the comparisons to the same time interval. NCEP-CFSR precipitation averages and anomalies show similar patterns for the two time intervals in Figures 16a–16c and Figures 17a–17c. Consequently, the 19-year 1998–2016 period can adequately represent the precipitation climatology of the longer period 1979–2016. TRMM averages (Figure 17d) are similar to the observed CFSR values (Figure 17a), and the main differences around the target regions can be better appreciated with the precipitation anomalies in the Figure 17e: TRMM precipitations show an underestimation with respect to CFSR in the Atlantic coast of Iberia and overestimation over the sea in the WM region. Morocco lies in the middle of both regions. Despite these differences, precipitation anomalies inside the target regions are well reproduced in both databases.

Figure 14. (a) NCEP reanalysis of the 300-hPa wind streamlines and intensity (shaded colors) for the period 1979–2016. (b) Composite of the same variables for the initiation of the (43) episodes during the same period. (c) Composite of the selected variables 9 days before the initiation of the episodes and (d) anomalies during the episode initiation. As in Figure 12, open black boxes represent key regions for identification of wind patterns associated with large amplitude waves.
Figure 15. (a) NCEP reanalysis of the mean sea level pressure MSLP-1000 (hPa) in shaded colors and the 500- to 1,000-hPa thickness (dam) in contour lines for the period 1979–2016. (b) Composite of the same variables for the initiation of the episodes during the same period. (c) Composite of the selected variables 9 days before the initiation of the episodes and (d) anomalies during the episode initiation. As in Figure 12, open white boxes represent key regions for identification of wind patterns associated with large amplitude waves.

Figure 16. NCEP-CFSR reanalysis precipitation accumulated in 72 hr (mm) (a) average for the period 1979–2016. (b) Composite of the average accumulation during the first 72 hr of the episodes (1979–2016) and (c) anomalies for the first 72 hr of the episodes with respect to the 38-year average.
6. Summary and Conclusions

The torrential rain and southerly föhn episode on 14–16 November 2002 in the Alpine southside, which was documented to affect the Piedmont region with floods and landslides was concurrent with heavy rains in Morocco. Up until now, the Piedmont heavy rainfall episodes described in the literature have been studied under a scenario of intense precipitations affecting the southern rim of the Alps and its surrounding regions, excluding other more distant areas. Both heavy rainfall episodes, in the Alps and Morocco, are analyzed in this manuscript as well as the recent climatology of this type of simultaneous episodes, their time of recurrence since 1979, and the possible occurrence of hot spots in the eastern N-Atlantic during their initiation.

The MesoWat_Source modeling system (Gangoiti, Gómez-Domenech, et al., 2011; Gangoiti et al., 2015) is used for the detailed mesoscale simulation of the simultaneous episode and the subsequent estimation of moisture sources. The main/largest domain of the mesoscale simulation has been enlarged with respect to previous studies (Gangoiti, Sáez de Cámara, et al., 2011) in order to include more remote sources: to the south, down to the equator, and also to the west, to include the N-Atlantic Ocean up to the eastern American coast.

The simulated meteorology has been evaluated by comparison with a selection of independent measurement records: (1) Wind speed and direction agrees satisfactorily with a selection of National Meteorological Center radiosonde soundings and high resolution hourly data from wind profiles radars located near the Atlantic and the Mediterranean moisture sources outside and inside the Alpine region. (2) Precipitation totals estimated for the episode cover a similar area with an identical maxima-minima distribution as the recorded data (CFSR reanalysis, TRMM MPA and surface stations), with comparable resolution in both targets, Morocco and the Alps. Areas of relative precipitation maxima locate in the windward regions of the
Apennines and the Alps, as well as in the Moroccan Plateau, the MH Atlas, and the ER mountains, while lower values are observed in bands, at the leeeward of the referred mountain ranges. (3) TCWV products from MODIS TERRA images show a similar distribution of vapor and a synchronous movement with the simulated total vapor column estimated by the model even in remote areas in the N-Atlantic 9 to 14 days before the episode. The evaluation is important for an adequate estimation of moisture sources for each episode and to elucidate whether the episodes share the same moisture sources or they are completely different. The mapping of sources with a discussion of the relative importance of marine, continental, and virga sources is included in the subsequent companion paper [G19].

The Alpine southside episodes have also been shown to be associated with a narrow meridionally elongated upper level trough extending southward from the British Islands into Iberia (PV streamers), following the case studies by Massacand et al. (1998) and other more recent contributions (Hoinka & Davies, 2007; Martius et al., 2006). The affected rainfall region, inside the Alps, has been observed to change with the orientation and exact position of the elongated trough (Martius et al., 2006). In addition, hot spots (large regions of enhanced surface latent heat flux > 250 W m⁻²) in the eastern N-Atlantic, west of Iberia, have also been shown to be concurrent with the mentioned streamers. However, as observed by Winschall et al. (2011), not all the streamer cases of heavy precipitation in the Alpine southside include a hot spot in the eastern N-Atlantic. Hot spots are important potential sources of moisture for specific target regions downwind of their location, and the referred area west of Iberia/N-Africa is shown here to be more directly related with the type of (simultaneous) episodes described in this manuscript. Using 6-hourly NCEP gridded precipitation and wind reanalysis data for the period 1979–2016 and after building an original method intended to identify simultaneous episodes of heavy rainfalls in Morocco and the Alpine region associated with a persistent wave-like configuration of the wind field in both the WM and the eastern N-Atlantic, we identified a total of 43 simultaneous heavy rainfall episodes during the whole 38-year period. This makes approximately one episode per year, but there is a large interannual variability, with several years with no episodes and others which can accumulate four episodes. Episode length shows also a high variability, from 2 to 7–8 days, including the enlarged Mediterranean phase for the longest episodes. There is also a large seasonal variability, with the largest fraction occurring in autumn (OND, 60%), and with no episodes at all during the warm period from June to August. During the autumn, the number of episodes increases rapidly from September (one case) to reach a maximum in November, which accumulates the 37% of all cases. After inspection of the identified episodes, hot spots are observed in all of them, located west of Iberia and/or N-Africa, at least during the first 24 hr since their initiation. They all show a large amplitude wave associated with an upper level trough, but their formation and subsequent evolution can vary considerably from one episode to the other. The observed variability of the episode occurrence cannot be explained by changes in the NAO phase, since both positive and negative daily NAO index are observed during the formation and evolution of the identified episodes: The elongated upper level troughs, which are always present during the episodes, are not always concurrent with low pressures at the surface. Instead, relative high pressures are observed at the surface under the upper level trough, which can explain the differences in the NAO index between episodes.

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