Moisture Sources and Large-Scale Dynamics Associated With a Flash Flood Event

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In November 1983, an extreme precipitation event occurred on western Iberia in the city of Lisbon region, Portugal, which produced flash flooding, urban inundations, and landslides causing considerable infrastructure damage and human fatalities. We found that this event was triggered by the transport of tropical and subtropical moisture associated with an extratropical cyclone. The low favored a large stream of (sub)tropical air that extended over more than 10° of latitude and across the North Atlantic Ocean, carrying a large amount of moisture originally from lower latitudes, a so-called atmospheric river. The stationary position of the jet stream along the East Atlantic Ocean through Iberia caused a strong enhancement of the precipitation associated with the moist air. A Lagrangian methodology was employed to show that the evaporative sources for the precipitation falling over the area of Lisbon were distributed over large sectors of the tropical-subtropical North Atlantic Ocean and included a significant contribution from the (sub)tropics. This study aims to provide an example of the application of distinct Lagrangian techniques to achieve a better understanding of the relation between extratropical cyclones and the occurrence of a heavy precipitation event on the Iberian Peninsula.

1. INTRODUCTION

Extratropical cyclones correspond to one of the most prominent features of the midlatitude climate and represent a major mechanism for poleward transport of heat and moisture [*Peixoto and Oort*, 1992]. Extratropical cyclogenesis occurs typically between the warm subtropical air and the cold polar air masses over the midlatitudes of both hemispheres. The space-time variability of the dominant storm tracks, of the frequency and/or intensity of cyclones, may notably affect surface climate, particularly the precipitation regimes [*Trigo et al.*, 2000].

Over the Northern Hemisphere, mature extratropical cyclones typically undergo a strong intensification phase over the North Atlantic (NA) Ocean, propagate eastward, and reach Europe, where they exert a dominant influence on local weather [e.g., *Pinto et al.*, 2009]. On short time scales, intense extratropical cyclones are often associated with extreme weather conditions in terms of precipitation and wind extremes [e.g., *Raible*, 2007], being among the most severe natural hazards affecting Europe [*Liberato et al.*, 2011].

Over the Iberian Peninsula, the hydrological cycle is especially sensitive to the timing and the location of the winter storms as they move into the region [*Ulbrich et al.*, 1999; *Trigo et al.*, 2002]. Most of the severe cyclone events affecting Iberia during winter are associated with moderate-to-strong precipitation and other hazards such as cyclone "Klaus" in 2009 [*Liberato et al.*, 2011].

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Lagrangian Modeling of the Atmosphere
Geophysical Monograph Series 200

10.1029/2012GM001244

In order to understand the origin of moisture associated with a given precipitation event, it is necessary to evaluate the relative roles played by each identified moisture source. To achieve this aim, it is necessary to assess the advection of moisture from distant regions and to evaluate the rate of precipitation and evaporation along the transport pathways.

Precipitation occurring in a region has one of the following origins: (1) moisture already present in the atmosphere, (2) advection of moisture into the region by the winds, or (3) water evaporated within the given region that precipitates in the same region (recycling). Over long periods, the first source can be considered negligible, implying that there are two major sources in the troposphere that govern the moisture transport: advection and evaporation [*Nieto et al.*, 2010].

The importance of a tropical-subtropical source of moisture for the North Atlantic/European sector has been reported in studies of other western Europe regions even at higher latitudes than the Iberian Peninsula [e.g., *Nieto et al.*, 2007; *Sodemann et al.*, 2008; *Stohl et al.*, 2008; *Lavers et al.*, 2011]. *Gimeno et al.* [2010a, 2010b] showed that the NA is the main source area of moisture for precipitation over continents at the global scale, in particular, for Europe and for Iberia.

There are a few narrow bands of water vapor across the midlatitudes in each hemisphere where approximately 90% of poleward atmospheric water vapor transport is concentrated [*Zhu and Newell*, 1998]. Because of the elongated nature of these regions, they are known as atmospheric rivers (AR) [*Newell et al.*, 1992; *Ralph et al.*, 2006]. The large amount of water vapor that is transported can lead to extreme precipitation events and flooding since AR can trigger elongated convective storms over the oceans and heavy orographically forced rain events when making landfall, such as is the case in Norway [*Stohl et al.*, 2008] or in California [*Ralph et al.*, 2004; 2006]. The study of the contribution of AR to extreme precipitation events has not been extended to many regions of the globe, as most studies have been developed for the North Pacific and their associated impacts on the contiguous North American west coast. However, AR may extract moisture from tropical reservoirs in many other regions of the globe [*Knippertz and Wernli*, 2010]. AR are located in the lower troposphere within the warm sector of extratropical cyclones [*Bao et al.*, 2006; *Neiman et al.*, 2011] and are characterized as regions with (1) concentrations of integrated water vapor in the atmospheric column of more than 2 cm [*Ralph et al.*, 2004] and (2) wind speeds greater than 12.5 m s^{-1} in the lowest 2 km of the atmosphere [*Ralph and Dettinger*, 2011]. The existence of AR and tropical moisture has been confirmed over the Atlantic Ocean [*Eckhardt et al.*, 2004; *Knippertz and Wernli*, 2010], but it was only recently linked to heavy precipitation events and floods in Norway [*Stohl et al.*, 2008] and the United Kingdom [*Lavers et al.*, 2011].

Here we focus on the extreme precipitation event that took place on 18–19 November 1983, when the region of Lisbon, capital of Portugal (western Iberia), was struck by the heaviest precipitation event during the twentieth century, immediately followed by widespread urban flash flooding and dozens of landslides around Lisbon [*Zêzere et al.*, 2005].

Thus, the main aims of this chapter are to provide an example of the application of distinct Lagrangian techniques to achieve a better understanding of the relation between midlatitude cyclones and the occurrence of heavy precipitation events. More specifically, the objective of this study is twofold: (1) to apply a storm-tracking Lagrangian methodology to the analysis of the midlatitude low-pressure system using an objective approach developed by one of the authors [*Trigo et al.*, 1999; *Trigo*, 2006], which will be complemented by the analysis of several thermohydrodynamical reanalysis fields during the lifetime of the cyclone and (2) to apply the Lagrangian diagnosis method developed by *Stohl and James* [2004, 2005] to identify the moisture sources and sinks associated with a certain extratropical cyclone and the main sources of moisture in the overlying air column during a certain flash flood event.

Section 2 provides a brief description of the data and presents the Lagrangian approach used to identify the moisture source region contributing to the cyclones and continental precipitation. Section 3 presents a general description and impacts of the flash flood event in the region of Lisbon on November 1983, while the large-scale atmospheric conditions associated with the extreme event are depicted in more detail in section 4. In addition, a Lagrangian approach is used in order to identify the main moisture sources feeding the cyclone over the Euro-Atlantic region, associated with the flash flood event, as well as moisture sinks and transport (section 5). Finally, a summary and conclusions are given in section 6.

2. DATA AND METHODOLOGY

2.1. Meteorological Data

We have used the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses (ERA40) [*Uppala et al.*, 2005], namely, the geopotential height fields, temperature, wind components and wind divergence data and the specific humidity at all pressure levels and mean sea level pressure (MSLP) and total column water vapor (TCWV) for the Euro-Atlantic sector (100°W to 50°E, 0°N–70°N). These fields were extracted for November 1983, at full temporal (six hourly) and spatial (T159; 1.125° regular horizontal grid) resolutions available, to analyze the large-scale conditions associated with the development of the studied storm. Moreover, the equivalent-potential temperature at the 850 hPa pressure level is used as an indicator of the combined effect of latent and sensible heat [e.g., *Bolton*, 1980].

A new high-resolution (0.2° × 0.2°) daily precipitation gridded data set developed for mainland Portugal (PT02) [*Belo-Pereira et al.*, 2011] and for Spain (SPAIN02) [*Herrera et al.*, 2010], which covers the period from 1950 to 2003, was also used. Finally, we used the daily precipitation data recorded since 1864 at the Dom Luiz Observatory in Lisbon, Portugal.

2.2. Lagrangian Approach to Identify the Moisture Source Region to the Cyclone and Continental Precipitation

The Lagrangian analysis of the transport of moisture in the Euro-Atlantic sector was performed based on the methodology developed by *Stohl and James* [2004, 2005]. Using the FLEXPART model, backward runs were computed for the region comprising the NA as well as Europe, defined as a box of coordinates (110°W to 50°E, 0°N–60°N). FLEXPART simulations were performed using 1° resolution and 60 model vertical levels in ERA-40 reanalyses [*Uppala et al.*, 2005] at 00, 06, 12, 18 UTC and forecast input for the intermediate time steps (03, 09, 15, 21). Trajectories were computed 10 days backward in time for the event under analysis using 1 million particles, which have constant mass and are distributed homogeneously in the atmosphere within the box defined above: 110°W to 50°E, 0°N–60°N and the top of the atmosphere at 0.1 hPa according to the distribution of atmospheric mass. The information of the trajectories allows the computation of moisture variations by means of specific humidity changes in time (dq/dt).

A box is centered in the target region for a specific time, and all the particles within the box are selected. Those particles are traced backward in time, and their variations of specific humidity at each time step are integrated as described in the work of *Stohl and James* [2004]. This allows obtaining an estimate of the net freshwater flux, i.e., evaporation minus precipitation (E-P), over the days for which the integration was performed into the air masses that finally arrived within the target region defined by the box. The (E-P) values were calculated as an average over each 1° × 1° gridded area. (E-P) back trajectory values for specific days are denoted by (E-P)^{-n} (the negative sign denotes that the analysis is performed backward in time to be consistent with the convention defined in the work of *Stohl et al.* [2005]). So, for instance, (E-P)^{-1} shows where the particles gained or lost moisture on the previous day of the trajectory. Values of (E-P) integrated over more than one day forward are denoted by (E-P)^{1-m}, with 1 being the initial day and m the last one.

In this work, this procedure is applied to track the source of the moisture associated with precipitation (1) over Lisbon during the flash flood event and (2) within the cyclone core that remained to the west of Iberia during that period. With this approach, we aim to highlight, using a Lagrangian perspective, the role of an extratropical cyclone in the transport of moisture from the NA to the areas of interest.

3. FLASH FLOOD EVENT IN THE REGION OF LISBON (NOVEMBER 1983)

Flash floods are one of the natural hazards that produce the most economic damage and human casualties in western Mediterranean countries [e.g., *Llasat et al.*, 2005]. On 18–19 November 1983, the region of Lisbon, in Portugal, was affected by a heavy precipitation event, soon followed by urban flash flooding and a burst of landslides around Lisbon [*Zêzere et al.*, 2005]. With a total of 95.6 mm in 24 h observed at the longest serving station in Portugal (Lisbon's Dom Luiz Observatory), this was the rainiest day during the twentieth century and one of the rainiest registered since 1864 [*Fragoso et al.*, 2010].

It should be noted that daily precipitation records obtained at classical stations in Portugal for any given day n correspond to the precipitation registered between 0900 UTC of day $n - 1$ and 0900 UTC of day n. Therefore, the maximum at Dom Luiz Observatory on 19 November reflects the 24 h rainfall that fell between 0900 UTC of 18 November, and 0900 UTC of 19 November. Nevertheless, precipitation continued through the morning and afternoon of 19 November, although precipitation registered after 0900 UTC was reported for the following day (20 November). Several other meteorological stations in the region registered the highest daily precipitation values to date, with a few stations around Lisbon depicting values even higher than 100 mm. To get an idea of the relevance of this event for the hydrology of the region, we may refer that at the station of São Julião do Tojal, the mean annual precipitation (climatological year) value from 1956 to 2000 was about 750 mm, the annual precipitation for the hydrologic year 1983–1984 was slightly over 800 mm [*Trigo et al.*, 2005], and 164 mm of which precipitated on the first 24 h of the event at this station. We were able to extend the assessment of this intense precipitation event to the rest of the country using the new daily precipitation gridded data set of *Belo-Pereira et al.* [2011]. Fortunately, there were plenty of stations operating during the 1980s, with more than 600 during the year 1983 that are considered sufficient to characterize the entire country as shown in Figure 1. It is evident that the strongest pouring of rain

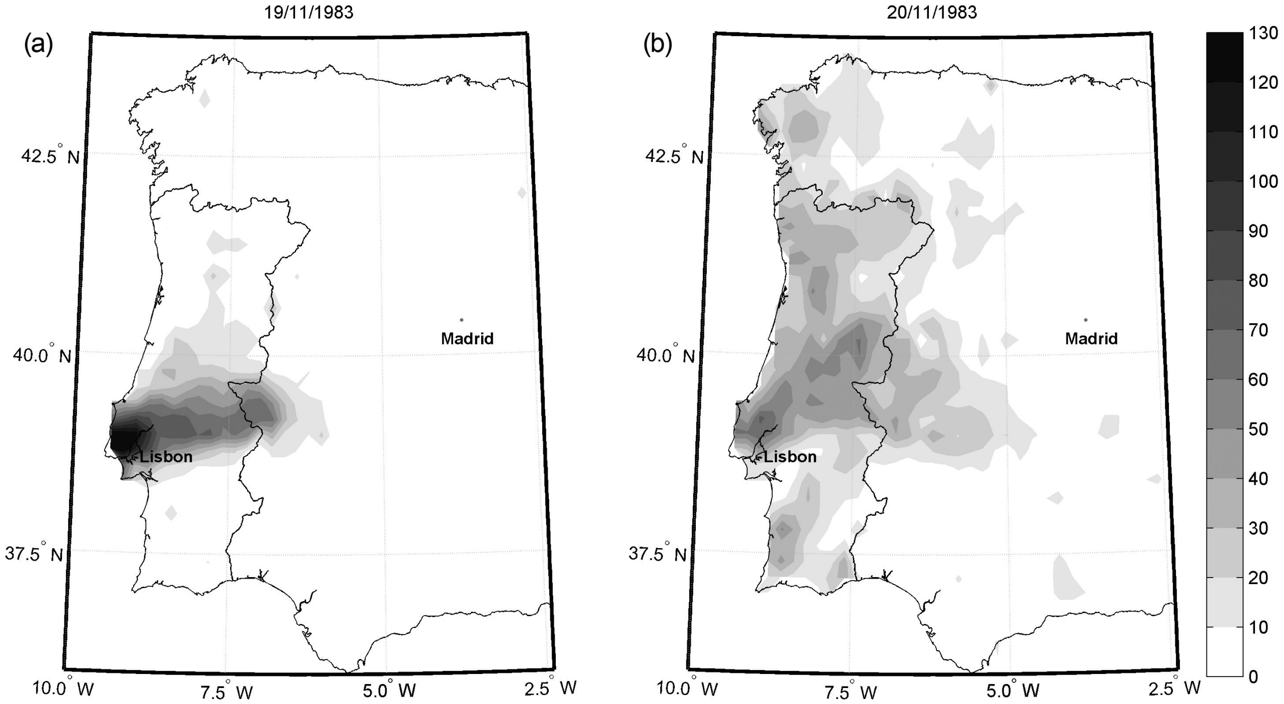

Figure 1. Daily precipitation in high-resolution (0.2° × 0.2°) gridded format relative to (a) 19 November 1983 and (b) 20 November 1983. Values below 10 mm d^{-1} are not shown to facilitate reading.

occurred around the Lisbon area on the evening of 18 November 1983 (Figure 1a) and continued through the night until the afternoon of 19 November (Figure 1b). Interestingly, on both days, there is a clear strip of very high precipitation values with relatively similar SW-NE alignment. Moreover, on the second day, the maximum values of precipitation are clearly observed slightly northward of Lisbon in a region that suffered dozens of landslide movements [*Zêzere et al.*, 2005] as a consequence of the precipitation that fell on both days.

This extreme rainfall event was responsible for a diversity of negative impacts, namely, flash flooding, urban inundations, and landslides. Despite the absence of an official report on the impacts of this event, the total loss of human lives was estimated to be of 10 fatalities, with additional large financial losses due to electric power blackouts and road and rail links blocked.

4. LARGE-SCALE ATMOSPHERIC CONDITIONS ASSOCIATED WITH THE EXTRATROPICAL CYCLONE DEVELOPMENT

The synoptic description and the main aspects of the large-scale atmospheric circulation and related physical mechanisms that were responsible for the development of the low-pressure system associated with the 18–19 November copious amounts of rainfall in the region of Lisbon are discussed in detail in this section.

Using an objective cyclone detecting and tracking scheme [*Trigo et al.*, 1999; *Trigo*, 2006] the storm track and lifetime cycle characteristics were assessed. The low-pressure system was first identified at 54°W and 36°N on 15 November 1983 (Figures 2a–2b). The low propagated eastward on the following days and experienced an intensification southwest of the Azores on 16 November (Figure 2 c-f).

The cyclone developed on 15 November 1983 on the southern part of an area of enhanced meridional temperature and humidity gradient, as shown in the map of equivalent potential temperature, θ_e, at 850 hPa (Figure 2a); the use of θ_e allows the evaluation of the combined effect of latent and sensible heat. The upper-level jet stream was meandering across the NA, between 30°N and 40°N, and at 12 UTC, the cyclone was located downstream the jet exit (approximately 35°N; 62.5° W) (Figure 2b). The position of the initial perturbation with respect to the upper-level jet favored its amplification within enhanced low-level baroclinicity. The cyclone path, defined here by the successive positions of the system minimum pressure in the ERA-40 reanalyses data determined by the objective Lagrangian methodology, followed very closely the region with the largest gradient of equivalent potential

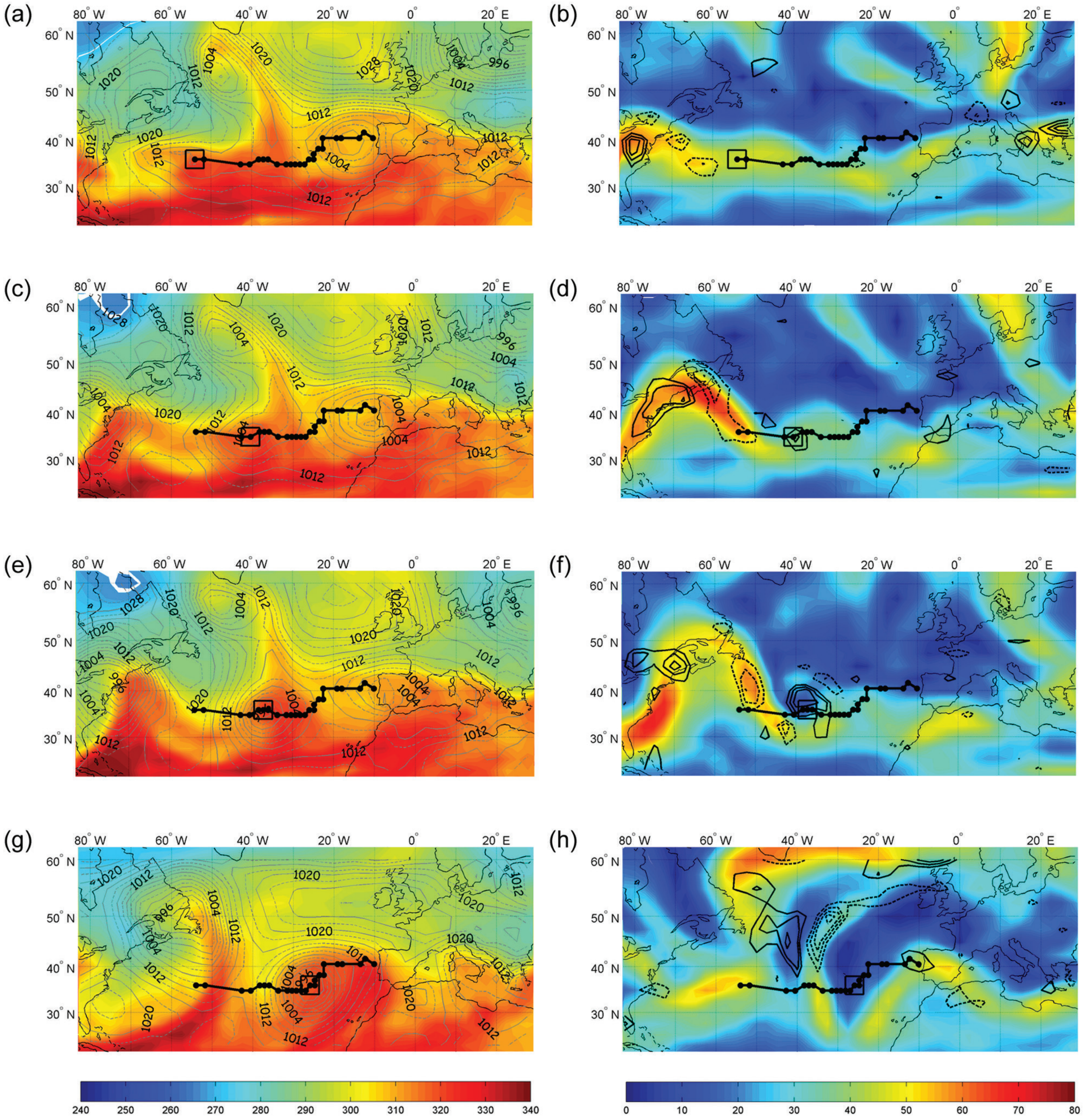

Figure 2. Large-scale conditions associated with the development of the cyclone. (a) Equivalent potential temperature (θ_e) field at 850 hPa (shaded; K) and the mean sea level pressure (MSLP) field (contour interval 2 hPa) for 12 UTC on 15 November 1983. (b) Wind speed (shaded; m s^{-1}) and divergence (contours every 10^{-5} s^{-1}, delimiting areas above 2 (solid lines) and below -2 (dashed lines)) at the 250 hPa level for 12 UTC on 15 November. (c) As in Figure 2a but for 06 UTC on 16 November. (d) As in Figure 2b but for 06 UTC on 16 November. (e) As in Figure 2a but for 18 UTC on 16 November. (f) As in Figure 2b but for 18 UTC on 16 November. (g) As in Figure 2a but for 00 UTC on 19 November. (h) As in Figure 2b but for 00 UTC on 19 November 1983. Cyclone track is displayed in black, and position at corresponding time is marked with a square.

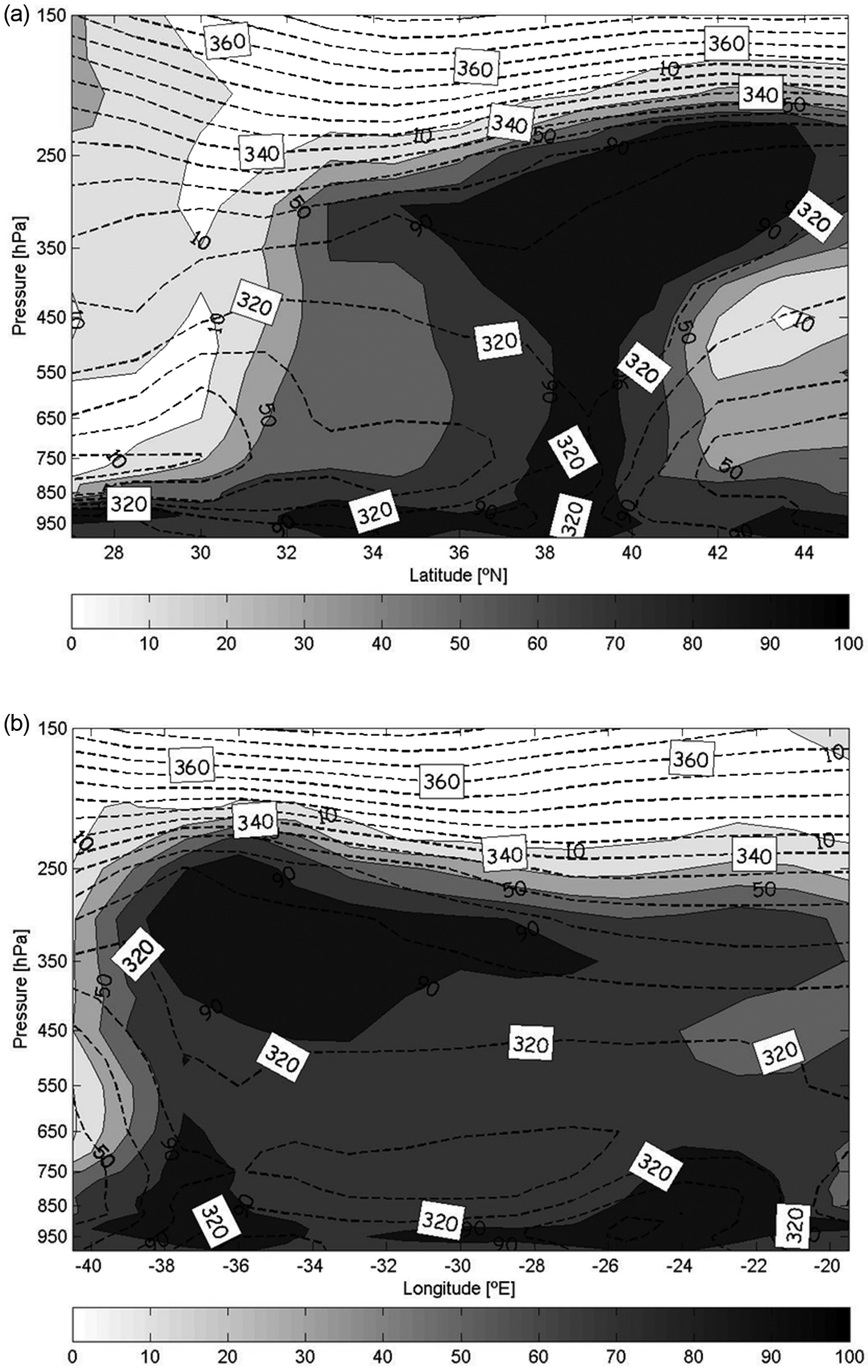

Figure 3. (a) South-north-oriented sections of the relative humidity field (shaded; percent) and the θ_e field (dashed lines, contour interval 4 K) for 12 UTC on 17 November 1983 at longitude 30°W. (b) As in Figure 3a but for west-east-oriented sections at latitude 36°N.

temperature, in the transition between subtropical and polar air masses (see, e.g., positions for 06 UTC and 18 UTC on 16 November, Figures 2c and 2e). The simultaneous display of MSLP, θ_e at 850 hPa and the cyclone trajectory in Figure 2 reveals a maximum of latent and sensible heat availability [e.g., *Pinto et al.*, 2009] in the lower troposphere.

While the upper-level flow over the subtropical western NA became unstable (Figures 2d and 2f), the system exited to the north of the jet stream (Figure 2d) and remained in a region of lower wind speed (Figure 2f) as a cyclone. The vertical signature is well identified on 16 November at 18 UTC and further analyzed in Figure 3 showing vertical cross sections of θ_e and relative humidity for a N-S transect at 30° W (Figure 3a) and E-W at 36°N (Figure 3b). These clearly indicate that the development was fed by very warm and moist air. During the following 2 days, the cyclone remained almost stationary around 28°W, 36°N, southwest of the Azores, confined by the meanders of the jet stream (Figure 2h), while the large values of θ_e at the 850 hPa pressure level also persisted (Figure 2g). From 17 to 19 November, the low-pressure system grew in size through continuous advection of warm and moist subtropical air embedded in the warm conveyor belt. During that period, the minimum core pressure remained at values within the range 989–992 hPa.

Even though this was an outstanding rainfall episode over the region of Lisbon, this high-impact episode cannot be considered as an extreme case of cyclogenesis in the sense of a rapidly deepening extratropical cyclone (usually known as “bombs”) [e.g., *Liberato et al.*, 2011]. In this case, during the maturing stage, the rates of deepening were 13.2 hPa per 24 h (1001.5–988.3 hPa during 16 November), which after being geostrophically adjusted to the reference latitude of 60°N [*Trigo*, 2006] is equivalent to 19.6 per 24 h; this is less than the 24 hPa per 24 h required to be classified as a “bomb.”

Figure 4 presents thermal IR satellite imagery for 15:52 UTC of 18 November, based on radiation in the 10.3–11.3 μm channel from the advanced very high resolution radiometer (AVHRR) on the NOAA polar-orbiting satellite AVHRR/NOAA obtained from the Natural Environment Research Council Satellite Receiving Station, Dundee University, Scotland (http://www.sat.dundee.ac.uk/). The low is already in the occlusion phase with the center located west of Iberia. A large SW-NE-oriented cloud band with cold (high) cloud tops associated with widespread development of cumulonimbus (Figure 4) is responsible for the anomalous rainfall on 18–19 November 1983 over Lisbon region. If we examine Figure 2h thoroughly, representing the upper-air wind speed and divergence at the jet stream level (250 hPa pressure level), it is worth noting that there is a branch of the upper-level jet, SW-NE oriented. This feature persisted over the Southeastern Atlantic Ocean and western Iberia for a few days (from 17 to 20 November 1983), with an area with strongest upper-level divergence over Lisbon at 00 UTC on 19 November, with values above $4 \times 10^{-5}\ s^{-1}$.

Concurrent with the evolution of the jet stream, at lower levels, there was a humidity plume with a SW-NE orientation (Figure 5) of a tropical air mass. Therefore, this outstanding humidity surplus, confirmed by the specific humidity at the 850 hPa pressure level (Figure 5), reached the Iberian coast at the moment when other favorable dynamical mechanisms for deep convection were already established, i.e., frontal uplift associated with upper-level divergence. Figure 5 also shows low-level moisture convergence, with values below $-3 \times 10^{-5}\ s^{-1}$, at 850 hPa, which also favors large-scale precipitation, supporting the notion that the large-scale conditions in the area of Lisbon were optimal for torrential precipitation between the afternoon of 18 November and the morning and early afternoon of 19 November. This tropical moisture source, transported within the warm sector of the cyclone, is in accordance with the occurrence of an AR (as described in the Introduction). According to Figure 6, which shows the TCWV (left panels) and wind speed and direction at 850 hPa (right panels), the criteria for an AR event were reached: a long plume of tropical air with values over 25 mm is observed within the warm sector of the stationary low at 12 UTC on 17 November (Figure 6a), coinciding with an area of relatively strong winds (wind speed greater than 12.5 ms^{-1}, Figure 6b). During the following 36 h, this high-humidity plume moved further NE toward Iberia, where it arrived on the evening of 18 November (Figures 6c–6h).

Favorable large-scale conditions for vertical movements (uplift mechanism, which induced deep convection activity) in addition with the presence of the AR (high specific humidity) contributed to enhanced precipitation. These facts support the hypothesis that large-scale forcing was crucial to the occurrence of this extreme event. In the following section, another kind of Lagrangian methodology will be used to identify and confirm the origin of the main moisture sources associated with this event.

5. MOISTURE SOURCES, SINKS, AND TRANSPORT

This section is devoted to discuss the main sources of moisture in the overlying air column over western Iberia during the extreme rain and flash flood event of 18–19 November 1983, as well as the air mass and moisture sources, sinks, and transport associated with the extratropical cyclone described before. This is achieved through the application of the Lagrangian diagnosis method developed by *Stohl and James* [2004, 2005]. The air particles in a selected

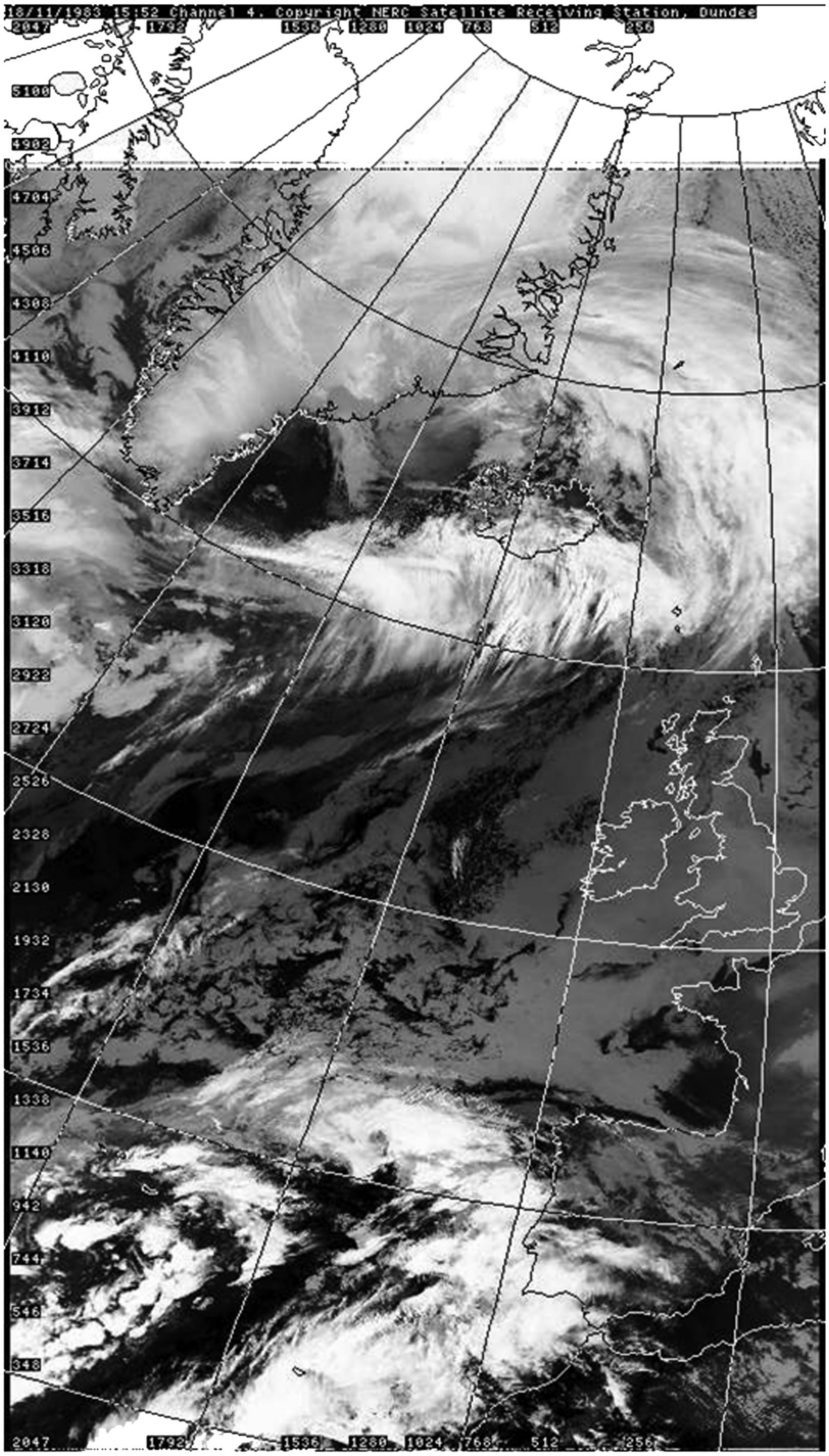

Figure 4. Thermal IR satellite imagery for 15:52 UTC of 18 November 1983, based on radiation in the 10.3–11.3μm channel from the advanced very high resolution radiometer/NOAA obtained from the Natural Environment Research Council Satellite Receiving Station, Dundee University, Scotland (http://www.sat.dundee.ac.uk/).

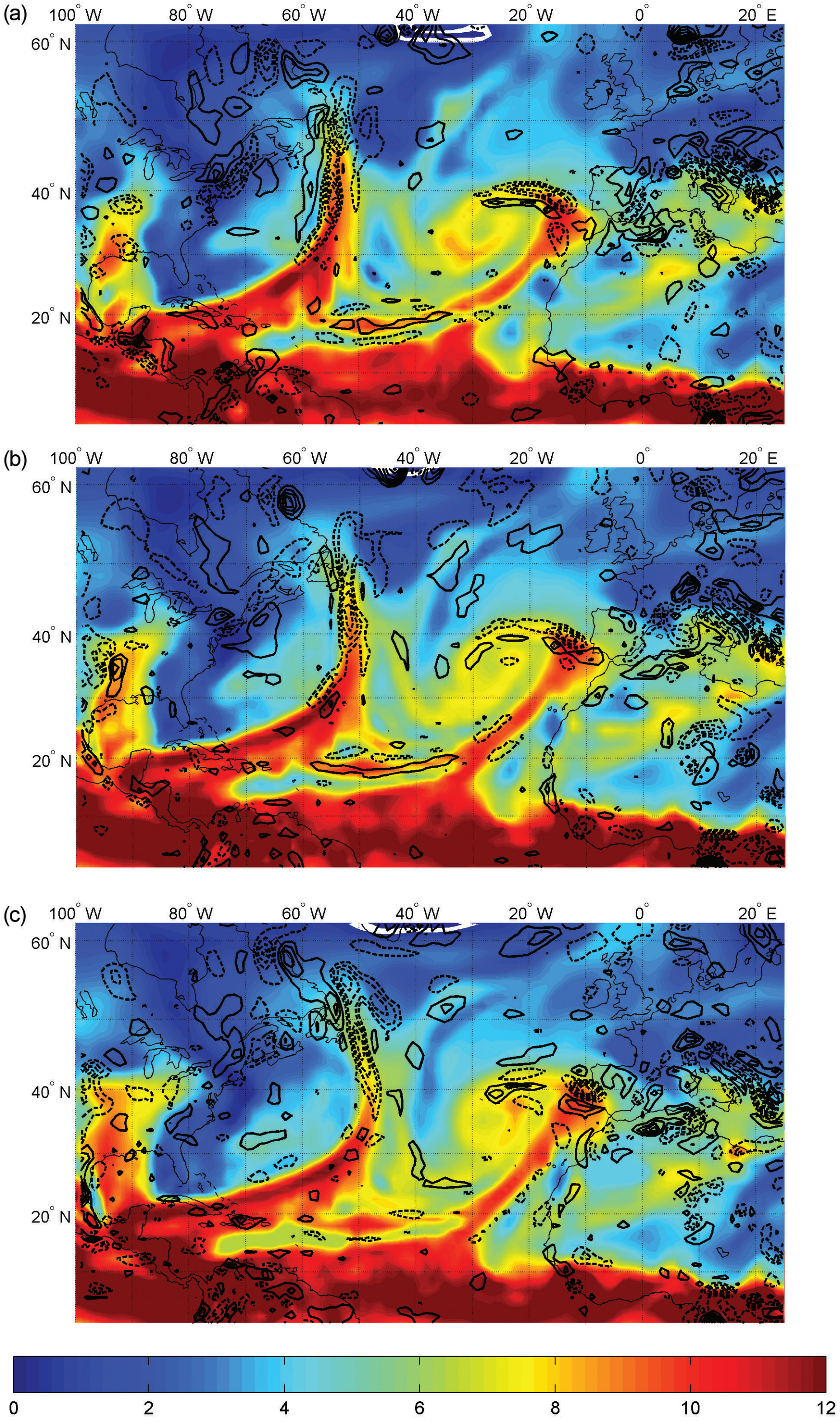

Figure 5. Specific moisture content (shaded; g kg^{-1}) and divergence (contours every 10^{-5} s^{-1}, delimiting areas above 2 (solid lines) and below −2 (dashed lines)) at the 850 hPa geopotential level for (a) 12 UTC on 18 November, (b) 18 UTC on 18 November, and (c) 00 UTC on 19 November 1983.

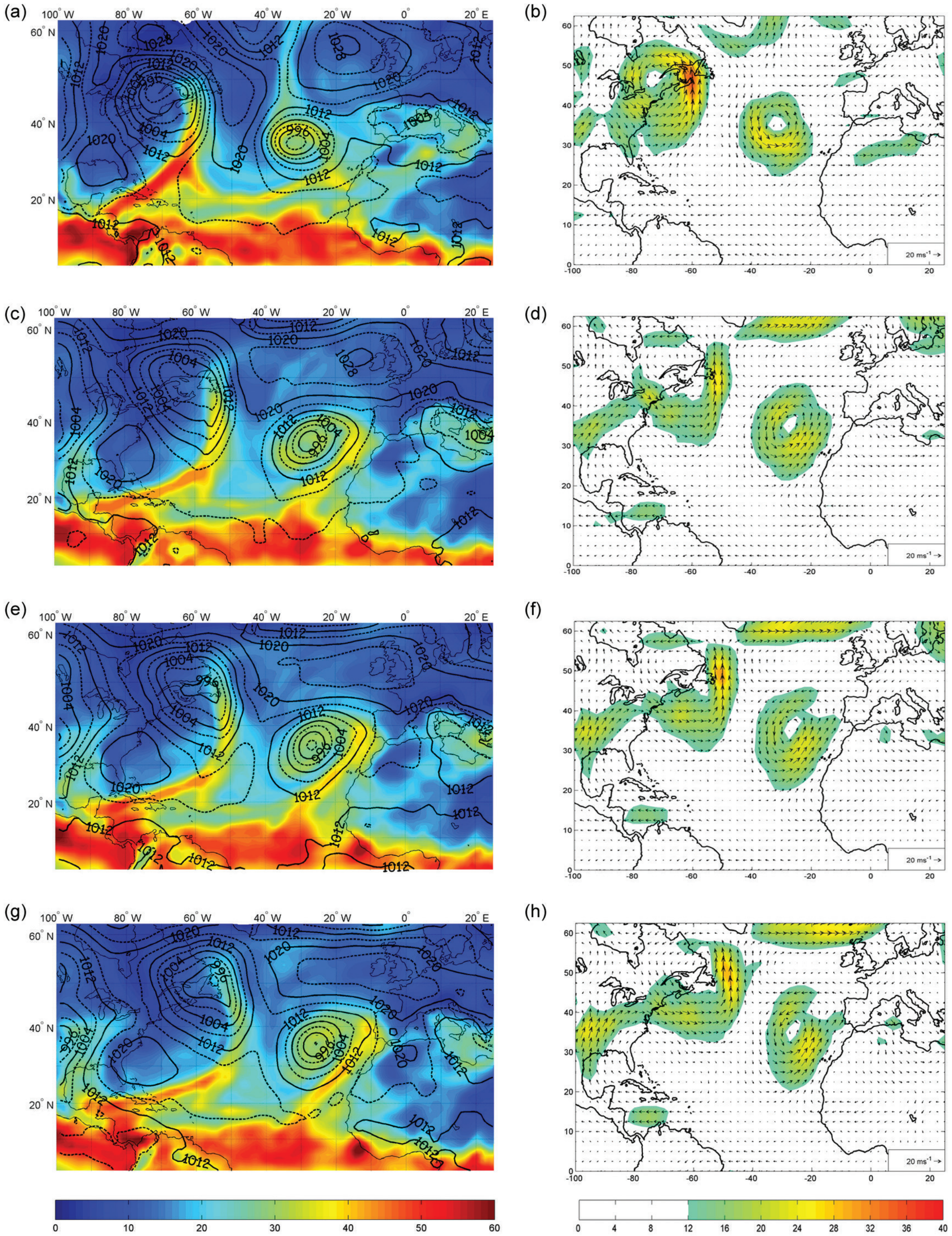

Figure 6. The atmospheric river associated to the 18–19 November 1983 flash flood event. (left) The MSLP field (contour interval 4 hPa) and total column water vapor (shaded; mm). (right) The vector wind and wind speed (shaded; m s^{-1}) at 850 hPa. (a and b) For 12 UTC on 17 November, (c and d) for 12 UTC on 18 November, (e and f) for 18 UTC on 18 November, and (g and h) for 00 UTC on 19 November.

box centered on the center of the cyclone and over the region of Lisbon were tracked backward 10 days to determine where the air parcels gained or lost moisture along their trajectory. Results allow identifying the regions in the Euro-Atlantic sector where moisture uptake occurred (sources) and the regions where air parcels lost moisture (sinks) with the former being identified in yellowish and the latter in bluish colors.

Analyses of daily (E-P) fields were computed as well as accumulated values for 3, 3 to 5, and 5 to 10 days. In a first step (based on the cyclone radius results from the objective detecting and tracking method), a 10° × 10° box was defined around the cyclone central position at 00 UTC on 19 November. The particles that are located within that box were selected to estimate the net freshwater flux (E-P) represented in Figure 7.

The analysis of these patterns provides a good representation of source and sink regions of moisture for particles inside the extratropical cyclone. In the regions characterized by positive (E-P) (yellowish and contour lines in Figure 7), the excess of evaporation over precipitation indicates a net moisture gain. From Figure 7a, we perceive that air masses inside the cyclone had essentially experienced a net loss of moisture during the previous 24 h as indicated by regions where precipitation dominated evaporation (E-P < 0). Therefore, the region inside the midlatitude cyclone acts as a sink of moisture. This temporal scale of 1 day limits the spatial extent of the influence to those areas that are near the center of the cyclone. Results shown in Figure 7a illustrate the relevance of precipitation for the final stages of the extratropical cyclone in the inner parts of the cyclone in good agreement with the known vertical structure of such a system, where subsidence motions become stronger as the cyclone matures. When comparing with Figure 4, these patterns seem to be closely related to the cloud fields, where cloud-free areas are dominated by moisture gains due to evaporation and cloudy areas by moisture losses due to precipitation. However, it should be noticed that Figure 7a is an integrated field from 24 h, while the satellite image is an instantaneous view of the domain at 15:52 UTC.

Figures 7b–7d present the spatial patterns relative to the accumulated (E-P) values over 3, 3 to 5, and 5 to 10 days prior to 19 November. The spatial extent of the moisture source and sink regions expands and is generally less intense with time. As mentioned before, the low-pressure system was almost stationary for 2 days prior to 19 November, with the associated loss of moisture being mostly confined to the squared region between 40°W–20°W and 20°N–40°N (Figure 7b). In Figure 7c, the region where precipitation dominated evaporation (E-P < 0) farther to the west is associated with the initial stages of the cyclone. On the contrary, gains of moisture in the cyclone are associated with regions outside its core (Figures 7a–7b). Moreover, there is also a plume of moisture coming from the NW Iberia Peninsula that is feeding the cyclone (Figure 7b). When analyzing the 5 to 10 day integration of moisture (Figure 7d), a new region with positive (E-P) appears associated with the Gulf stream.

These results confirm two important mechanisms associated with the midlatitude cyclone: (1) moisture being transported with the cyclone from distant regions and (2) important moisture gains and losses during the lifecycle of the cyclone. In summary, from Figure 7, we may conclude that air within a cyclone core releasing its moisture through precipitation originally gained this moisture through evaporation in regions over the ocean several hundred to thousands of kilometers away, in the present case, for instance, over the warm waters of the Gulf stream but also over regions northeast and south of the cyclone. On the other hand, when air masses are approaching the cyclone, net gain in moisture is gradually changing into net loss with loss dominating during the last 1–2 days before reaching the core.

Figure 8 shows maps of (E-P) diagnosed from 10 day back trajectories of all the target particles arriving in the region centered on Lisbon (14°W to 4°W and 36°N to 41°N) at 00 UTC on 19 November 1983. As expected from the results of the last section, the map of (E-P) reveals a strongly negative band over the Atlantic ocean off Lisbon, a region where precipitation dominated evaporation (E-P < 0), with a net freshwater flux represented by a minimum value of approximately −40 mm stretching back to about 30°W and 20°N on the first day (Figure 8a) in accordance to the position of the AR.

This pattern is similar if we consider 3 days; but in this case, the plume stretches zonally at low tropical latitudes up to about 40°W (Figure 8b). Figure 8a is in clear agreement with the previously described Figure 5, showing that this band is largely due to precipitation occurring during the previous 24 h before the air arrived in the target area. It is also interesting to note the positive band closer to the African coast on the first day (Figure 8a) that also stretches zonally through the tropical NA region when considering longer time periods (Figure 8b). For even longer time periods, considering the accumulated (E-P) values over 3 to 5 (Figure 8c) and 5 to 10 (Figure 8d) days prior to the 19 November, we confirm that the moisture source is, indeed, the tropical region around 20°N between 60°W and 35°W and not the Gulf stream region as before (compare Figures 8c–8d to Figures 7c–7d).

It is evident when comparing Figures 8 and 7 that those sinks are not related to moisture associated with the center of the cyclone but to moisture advected within the warm conveyor belt. The small source area for day −1 reflects the nature of the intense moisture transport associated with the

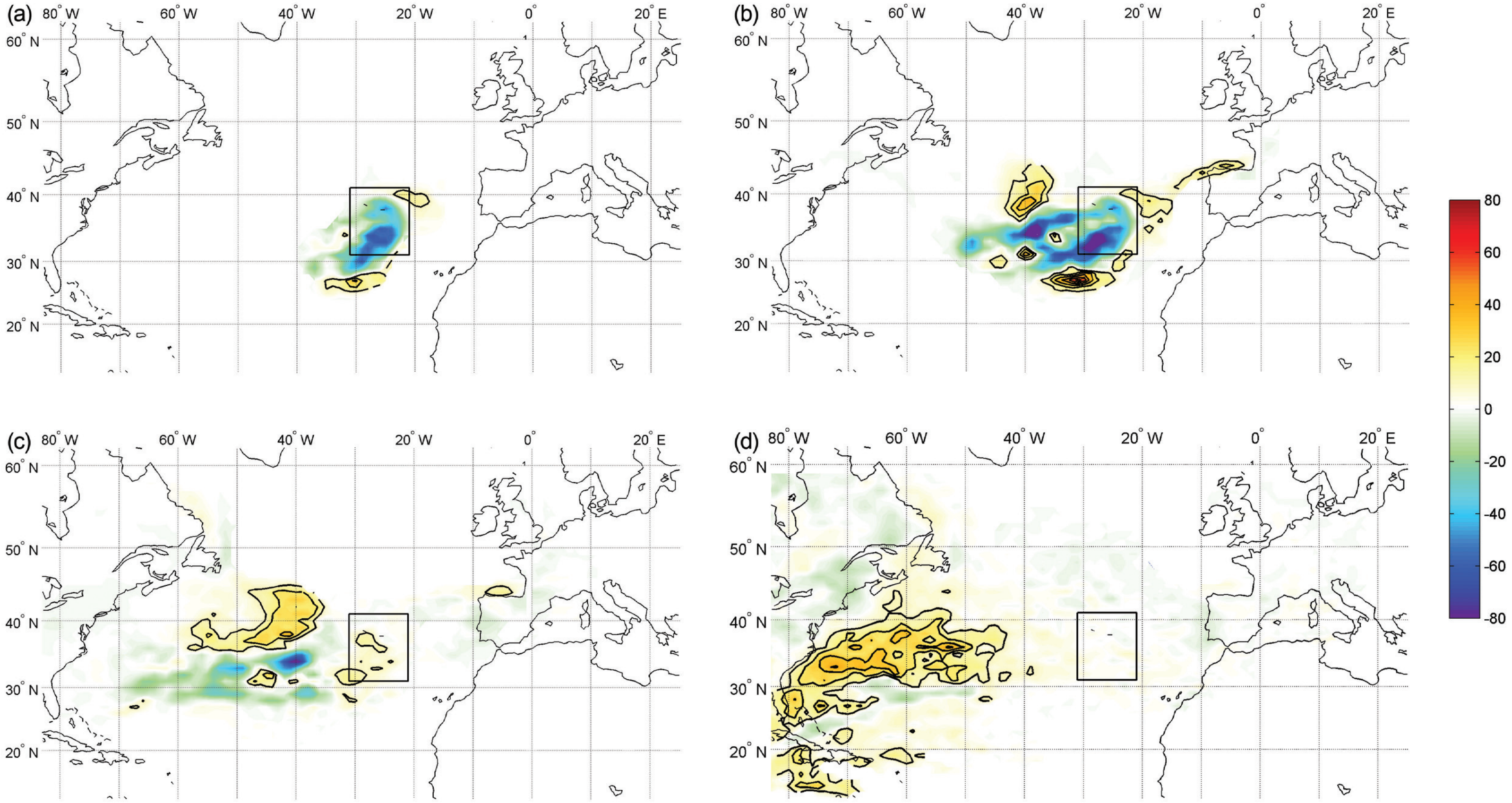

Figure 7. Values of (a) $(E\text{-}P)^{-1}$ ($\mathrm{mm\,d^{-1}}$) and integrated values of (b) $(E\text{-}P)^{-(1-3)}$, (c) $(E\text{-}P)^{-(3-5)}$, and (d) $(E\text{-}P)^{-(5-10)}$, diagnosed from 10 day back trajectories of the target particles arriving in the box of 10° latitude/longitude centered on the cyclone position as detected by the tracking scheme at 00 UTC on 19 November 1983.

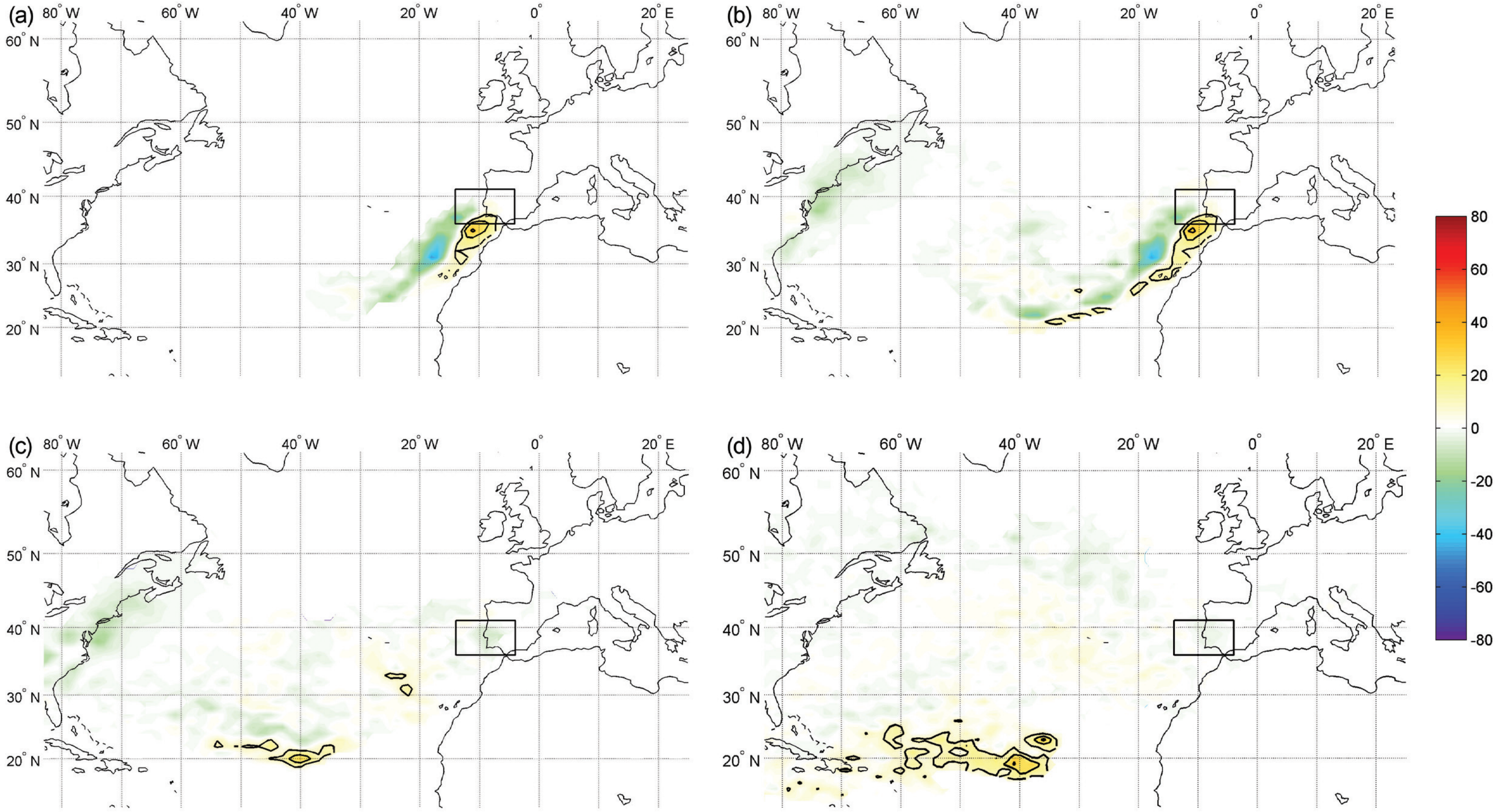

Figure 8. Values of (a) $(\text{E-P})^{-1}$ and integrated values of (b) $(\text{E-P})^{-(1-3)}$, (c) $(\text{E-P})^{-(3-5)}$, and (d) $(\text{E-P})^{-(5-10)}$, diagnosed from 10 day back trajectories of the target particles arriving in the region centered on Lisbon (14°W to 4°W and 36°N to 41°N) at 00 UTC on 19 November 1983.

AR, where only a minor fraction of the moisture arriving into Lisbon was evaporated close to the North African coast (Figure 8a).

The dominant part of the moisture must have originated over the central and western NA Ocean, both in the middle latitudes and the subtropics, since this is where positive values of (E-P) integrated on the 5 to 10 day scale are found (Figure 8d). Positive values can be found at 20°N indicating that some of the moisture was transported from the subtropics and eventually from the tropics, across more than 20° of latitude and 50° of longitude before precipitating out over Lisbon, Portugal.

This analysis confirms that moisture in this heavy rain event was mainly transported from remote locations rather than originating locally and that the source region is predominantly subtropical in agreement with climatological results obtained by *Gimeno et al.* [2010b]. Moreover, it shows that the southeastern NA Ocean contributed only a minor fraction of the moisture falling as precipitation in the target area. It is now clear that the availability of moisture in the AR in addition to the high values of positive divergence associated to the jet stream near Iberia (Figure 5b–5c) were the main mechanisms responsible for the heavy precipitation event.

6. SUMMARY AND CONCLUDING REMARKS

This study was motivated by the application of two distinct Lagrangian techniques to thermodynamical fields in order to better understand the relation between a large extratropical cyclone and the occurrence of a heavy precipitation event (followed by flash floods and landslides) in the Lisbon area (western Iberia).

We have, herein, applied the objective Lagrangian cyclone detecting and tracking scheme [*Trigo et al.*, 1999; *Trigo*, 2006] to the detailed analysis of a specific extratropical cyclone track, lifecycle, characteristics, and dynamics, which was associated with a particularly strong flash flood event in the Lisbon area, Portugal. In addition, a distinct Lagrangian methodology was used to identify the main moisture sources feeding this North Atlantic extratropical cyclone and to evaluate its role in transporting moisture toward the region in the western Iberia affected by the flash flood event.

An important result from this study is the confirmation that this high-impact episode was associated with a midlatitude, quasistationary low-pressure system, which could not be considered as an extreme cyclone (usually known as "bombs"). The assessment of the large-scale atmospheric flow associated with the storm development suggests that this extreme rainfall and flash flood episode resulted from the fortunate merging of favorable thermodynamical conditions, including (1) a lower-than-usual latitudinal location of the jet stream related to the presence of a strong meridional temperature gradient slightly southward of its usual latitude, (2) a prolonged formation of cumulonimbus structures fed by intense vertical instability in an area of upper-level divergence, and (3) the presence of an AR structure, i.e., a SW-NE-oriented plume of high humidity and wind speeds at the surface, which reached Iberia on 18 November 1983, transporting moisture from the primary source region over the subtropical North Atlantic [*Gimeno et al.*, 2010b]. On the other hand, it was shown that the evaporative sources for the precipitation falling over Lisbon area were distributed over large sectors of the tropical-subtropical North Atlantic Ocean and included a significant contribution from the (sub)tropics.

Acknowledgments. This work was partially supported by the Portuguese-Spanish integrated action funded by CRUP (E-63/2010) and MCYT (PT2009-0064) and by FEDER funds through the COMPETE (Programa Operacional Factores de Competitividade) Programme and by national funds through FCT (Fundação para a Ciência e a Tecnologia, Portugal) through project STORMEx FCOMP-01-0124-FEDER-019524 (PTDC/AAC-CLI/121339/2010). Margarida M. L. Liberato was also supported by a postdoctoral grant (SFRH/BPD/45080/2008), and Alexandre M. Ramos was supported through a doctoral grant (BD/46000/2008), both from the FCT. A.M Durán-Quesada was supported by a joint grant of the University of Costa Rica and Fundación Carolina. This chapter also results from research supported by project INCITE09 383 278 PR co-funded by FEDER. The authors thank the Portuguese and Spanish Meteorology Institutes for gridded precipitation data set used in this work (data sets PT02 and SPAIN02, respectively). The authors acknowledge Orlando García-Feal for IT support. The authors are indebted to the editor and to two anonymous reviewers for their constructive comments that helped to improve the manuscript.

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