Water Vapor Sources of the October 2000 Piedmont Flood

BARBARA TURATO*

Centro Interuniversitario di Ricerca in Monitoraggio Ambientale, University of Genoa, Savona, Italy

ORESTE REALE

Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, and University of Maryland, Baltimore County, Baltimore, Maryland

FRANCO SICCARDI

Centro Interuniversitario di Ricerca in Monitoraggio Ambientale, University of Genoa, Savona, Italy

(Manuscript received 21 October 2003, in final form 19 March 2004)

ABSTRACT

Very intense mesoscale or synoptic-scale rainfall events can occasionally be observed in the Mediterranean region without any deep cyclone developing over the areas affected by precipitation. In these perplexing cases the synoptic situation can superficially look similar to cases in which very little precipitation occurs. An example is the major precipitation and flooding event that affected Piedmont, Italy, between 13 and 16 October 2000. The emphasis of this study is on the moisture origin and transport. Moisture balances are computed on different space and time scales, revealing that precipitation exceeds evaporation over an area inclusive of Piedmont and the northwestern Mediterranean region, on a time scale encompassing the event and about 2 weeks preceding it. This is suggestive of an important moisture contribution originating from outside the region. A synoptic and dynamic analysis is then performed to outline the potential mechanisms that could have contributed to the large-scale moisture transport.

The central part of the work uses a quasi-isentropic water vapor back-trajectory technique. The moisture sources obtained by this technique are compared with the results of the balances and with the synoptic situation to unveil possible dynamic mechanisms and physical processes involved.

It is found that moisture sources on a variety of atmospheric scales contribute to this event. First, an important contribution is caused by the extratropical remnants of former Tropical Storm Leslie. The large-scale environment related to this system allows a significant amount of moisture to be carried toward Europe. This happens on a time scale of about 5–15 days preceding the Piedmont event. Second, water vapor intrusions from the African intertropical convergence zone and evaporation from the eastern Atlantic contribute on the 2–5-day time scale. The large-scale moist dynamics appears therefore to be one important factor enabling a moderate Mediterranean cyclone to produce heavy precipitation. Finally, local evaporation from the Mediterranean, water vapor recycling, and orographically induced low-level convergence enhance and concentrate the moisture over the area where heavy precipitation occurs. This happens on a 12–72-h time scale.

1. Introduction

a. Mediterranean floods

The Mediterranean region is characterized by frequent floods and extreme rainfall events on a variety of space and time scales (Siccardi 1996). The uncertainties in the prediction of these events involve both the meteorological and hydrological scales (Ferraris et al. 2001).

From the meteorological perspective, atmospheric forcings ranging through spatial scales contribute to very different types of extreme rainfall events. In some rare cases, intense, localized, subsynoptic-scale cyclones were the cause of extreme and localized rainfall, as in the event of 4–6 October 1996 over Calabria, Italy, in which up to 480 mm of accumulated precipitation were recorded in response to a convective vortex, the scale of which was only about 300 km (Reale and Atlas 2001). A far more common type of cyclone in the Mediterranean region is the baroclinic lee cyclone of the type described by Buzzi and Tibaldi (1978), with a scale of the order of 500–1000 km. Such cyclones can some-

* Current affiliation: ARPAL, Centro Meteo Idrologico Regione Liguria, Genoa, Italy.

Corresponding author address: Dr. Oreste Reale, Code 910, NASA Goddard Space Flight Center, Greenbelt, MD 20771.
E-mail: Oreste.Reale.1@gsfc.nasa.gov

times be quite intense, with center pressure well below 990 hPa, and can occasionally produce heavy precipitation in the Mediterranean.

However, the more frequent and somewhat perplexing extreme rainfall events are the ones in which no intense cyclone is observed within the Mediterranean region. An example of this situation is the November 1994 sequence of floods that affected several Mediterranean countries, from France and Italy to the eastern Mediterranean and the Middle East. Buzzi et al. (1998) investigated in detail this event, focusing on the numerical simulations of the flood over Piedmont (northwestern Italy) between 4 and 6 November 1994. A relatively intense midlatitude cyclone was present over the British Isles, with minimum center pressure of about 985 hPa. However, the sea level pressure was above 1010 hPa over most of the western Mediterranean, and only a hint of a cyclonic circulation could be inferred over the Mediterranean region, for a time shorter than the actual duration of the intense rainfall. Most of the precipitation over Piedmont was associated with a low-level prefrontal jet directed against the orography of northwestern Italy (Buzzi et al. 1998).

There are several other instances in which a sequence of heavy precipitation events can occur without synoptic features that are characteristic of intense cyclonic development within the Mediterranean region. The apparently surprising aspect of these floods is that the synoptic situation can superficially look similar to other cases in which very little precipitation occurs.

The flood cases in which no intense cyclone is present within the Mediterranean are indicative of a possible source of moisture of extra-Mediterranean origin, and of mechanisms of collection of moisture that could occur on time scales much longer than the lifetime of the weather systems involved. So, these extreme rainfall events pose the following questions: 1) What is the origin of the moisture needed to produce the observed amount of precipitation? and 2) How, and on what time scales, is the moisture advected toward the Mediterranean region?

A major contribution to answering these questions has been provided by Krichak and Alpert (1998). In their analysis of the November 1994 series of events [to which the Piedmont 1994 event studied by Buzzi et al. (1998) belongs], they also investigate the floods over the eastern Mediterranean. Their study shows that remote sources of moisture and large-scale transport were important in producing major flood events and very intense rainfall over several Mediterranean regions. The authors used a water vapor back-trajectory technique to determine the moisture sources. One significant result is that a release of moisture from the intertropical convergence zone (ITCZ) was involved.

Following this approach, Ferraris et al. (2001) and Reale et al. (2001) analyzed the October 1998 floods over northern Italy and Slovenia, with the aid of regional model simulations and water vapor back trajectories. In particular, Reale et al. (2001) show that eastern Atlantic hurricanes, after decaying to extratropical remnants, can impact Mediterranean weather by advecting large amounts of moisture into the Mediterranean region. This moisture can be made available to midlatitude cyclones: during the floods of October 1998, only a relatively weak baroclinic lee cyclone (center pressure of about 1000 hPa and scale of the order of 1000 km) was observed in the Mediterranean region.

b. The Piedmont 2000 event

In this work the flood that occurred over Piedmont between 13 and 16 October 2000 is investigated. Between the end of September and the first 10 days of November 2000, the northern Atlantic Ocean was characterized by a sequence of deep and rapidly moving cyclones affecting the northwestern European coasts. Several flash floods and major rainfall events occurred over many European and Mediterranean regions (i.e., 11 October, southeastern England; 13–16 October, northwestern Italy; 20 October, eastern Spain; 22 October, northern Algeria and Morocco; 29 October, United Kingdom and Ireland; 6 November, northwestern Italy). Among them, the flood that affected the northwestern regions of Italy between 13 and 16 October was particularly relevant because of heavy and persisting rainfall over a wide area. This produced flooding, landslides, and severe damage to civil infrastructure. The rainfall maxima, accumulated during the whole period of precipitation, was around 700–750 mm, with daily areal mean values going from 100–150 up to 250 mm day^{-1} (Regione Piemonte 2000). The intensity, persistence, and wide spatial distribution of rainfall affected the most important intermediate catchments of northwestern Italy, producing significant flood waves on the main rivers, with record levels over the northern sector of the Po watershed (Regione Piemonte 2000). The Piedmont flood occurred without the contribution of intense Mediterranean cyclones, but only weak or moderate systems were observed within the Mediterranean region during the event: a lee cyclone with minimum center pressure of about 1000 hPa at its peak intensity was observed at 0000 UTC 15 October between Corsica and Provence, as will be shown later. This cyclone cannot explain the exceptionality of the observed rainfall.

The main goal of this work is to investigate the large-scale atmospheric moisture transport contributing to the Piedmont 13–16 October 2000 event. Emphasis is given to the identification and quantification of different moisture sources and to the understanding of the underlying physical mechanisms.

In the first part of this work the water balance is computed over different areas, to evaluate if, on a synoptic time scale, the total precipitation over the Mediterranean region exceeds the total evaporation from the sea, thus supporting the idea of some contribution from outside the Mediterranean region.

The problem of moisture budget has been examined in a variety of space and time scales in the last four decades, ranging from the annual climatology on global scales (e.g., Starr and Peixoto 1958) to the hydrology of large regions (among others, Rasmusson 1967, 1968; Peixoto and Oort 1991). Mariotti et al. (2002) recently examined the hydrology of the Mediterranean region, focusing on climatology, interannual-to-interdecadal variability, and the relationship between long-term changes and the North Atlantic Oscillation (NAO). The authors point out some relevant features of the water budget over the Mediterranean basin: 1) the NAO affects Mediterranean precipitation, but no significant correlation with the NAO is found for evaporation; 2) the annual mean of evaporation minus precipitation ($E - P$) is positive over the whole Mediterranean, with higher values in the eastern part of the basin; 3) the Mediterranean evaporation appears to be most intense during winter, showing higher values from October to January and a minimum from April to June; 4) the moisture flux into the Mediterranean region comes mostly from the Atlantic Ocean, with a southward component in the eastern part of the basin. This important work however does not investigate the regional water budget over the Mediterranean Sea at the time scales of extreme rainfall events. Moreover, moisture budget studies in general have not emphasized the smaller time scales (Zangvil et al. 2001). In this study we analyze the water balances over the Mediterranean and various surrounding regions, in a time frame inclusive of the October 2000 flood event, to investigate the time and space scales of the processes leading to the floods. In particular, we attempt to discriminate the role of locally originated water vapor from the water vapor supplied from outside the Mediterranean basin.

Then the synoptic and dynamic evolution of the event is discussed, with the focus on possible mechanisms of large-scale moisture transport and synergistic effects between the various atmospheric forcings. The role played by the polar jet stream is investigated. It is recognized that jet streak–induced circulations play a role in cyclogenesis (Mattocks and Bleck 1986; Uccellini and Johnson 1979; Uccellini and Kocin 1987). Particularly, Mattocks and Bleck (1986) emphasize the role of the indirect circulation pattern in the exit region of upper-level jet streaks in the development of cyclones in the lee of the Alps and the Gulf of Genoa. The role played by the extratropical transition of the Atlantic tropical system Leslie is investigated. Previous studies (Reale et al. 2001) suggest that eastern Atlantic tropical cyclones, decayed to midlatitude systems, can affect the weather in the Mediterranean. Warmer-than-average sea surface temperatures (SSTs) over the central Atlantic Ocean are responsible for anomalous sensible and latent heat fluxes. These fluxes averaged over different areas appear to peak in the 10-day period before the flood.

The main part of this study focuses on the analysis of the moisture sources contributing to the event through the use of the quasi-isentropic back-trajectory algorithm developed by Dirmeyer and Brubacker (1999), based on Merril et al. (1986). The study seeks to investigate the possibility of an important moisture contribution from the tropical Atlantic region.

2. Analysis of the Piedmont 2000 event

a. Precipitation and evaporation before and after the Piedmont flood

The precipitation data we used is from the One Degree Daily (1DD) Global Precipitation Data archive, provided by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center's Laboratory for Atmospheres; daily evaporation and water vapor transport are calculated from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kistler et al. 2001). To evaluate the orders of magnitude and the possible scales involved, some gross moisture balances are first performed over several target areas. Of some relevance for our purpose is moisture balance computed over the area we name Q0, inclusive of the western Mediterranean and of the region subject to the flood (from 38.75° to 46.25°N and 3.75°W to 16.25°E). Figure 1a shows the daily values of total evaporation and total precipitation over Q0 for the period from 15 September to 15 November 2000. The third precipitation event, centered between 11 and 15 October, carries the signature of the Piedmont flood. For the first of these precipitation events the total precipitation over the Mediterranean is of the same magnitude as the total evaporation. In the second event (centered around the end of September) there is some imbalance (evaporation is smaller than precipitation), but this disequilibrium is much stronger in the case of the Piedmont flood. In terms of timing, evaporation from the western Mediterranean appears to be directly related to the first and second event, but not as clearly related to the third: the daily evaporation from the western Mediterranean does not reach the maximum values during or shortly before the Piedmont flood, but peaks about 1 week before. This fact suggests that some other moisture contribution occurs at the time scale of the event. We cannot however exclude that the strong evaporation 1 week before the flood, possibly produced by dry air entering the region behind a frontal system, can produce moisture that is maintained over the Mediterranean for a few days in a nonprecipitating weakly subsident environment.

Figure 1b shows the values of the same variables accumulated over the whole period. Land and sea evaporation contribute approximately as much as one-third and two-thirds to the total evaporation, respectively. Being about 50% of Q0 covered by land, land evapotranspiration is therefore quite relevant. The accumulated precipitation has a very sharp increase starting from 10

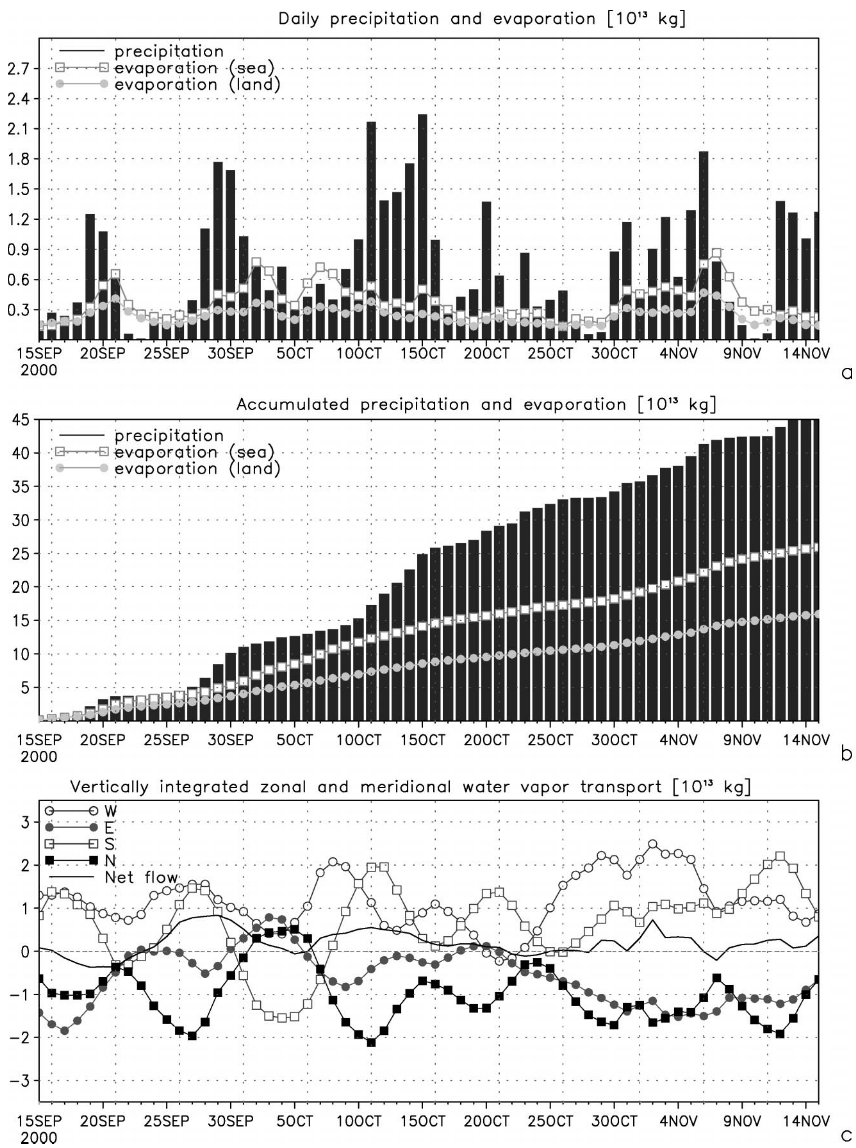

FIG. 1. (a) Daily evaporation and precipitation (10^{13} kg) over Q0; (b) accumulated values of the same variables over Q0; and (c) net moisture daily flux through each wall bordering volume Q0 (W = west, E = east, S = south, and N = north walls) and through the volume enclosed by the walls and the 300-hPa level (10^{13} kg day^{-1}). Precipitation data from the One Degree Daily (1DD) Global Precipitation Data archive, provided by NASA Goddard Space Flight Center's Laboratory for Atmospheres; daily evaporation and water vapor transport calculated from the NCEP–NCAR reanalyses.

October 2000, which is about the onset of intense rainfall over northwestern Italy.

A first-order crude estimate of the amounts of moisture involved is then performed by calculating the time-averaged and vertically integrated moisture flux through each of the boundaries of Q0 (Fig. 1c) and the net moisture flux transiting through the volume enclosed by these boundaries up to the 300-hPa level. We calculate the daily running mean of the integral in latitude (or longitude) of $\int_{p_o}^{p} V_n q\, dp/g$ on each vertical wall of Q0, where V_n and q are the 5-day averages of the normal component of the wind vector **V** and specific humidity, respectively; g is gravitational acceleration; p_o the surface pressure; and p the pressure at the top of the control volume (300 hPa). Fluxes are considered positive if inward, and the net transiting flux is the algebraic sum of the four fluxes. We do not include in this calculation vertical fluxes (sinks or sources of moisture) because the purpose of this calculation is simply to evaluate the magnitude of the external contributions due to horizontal moisture advection.

Figure 1c shows that moisture flux responds well to

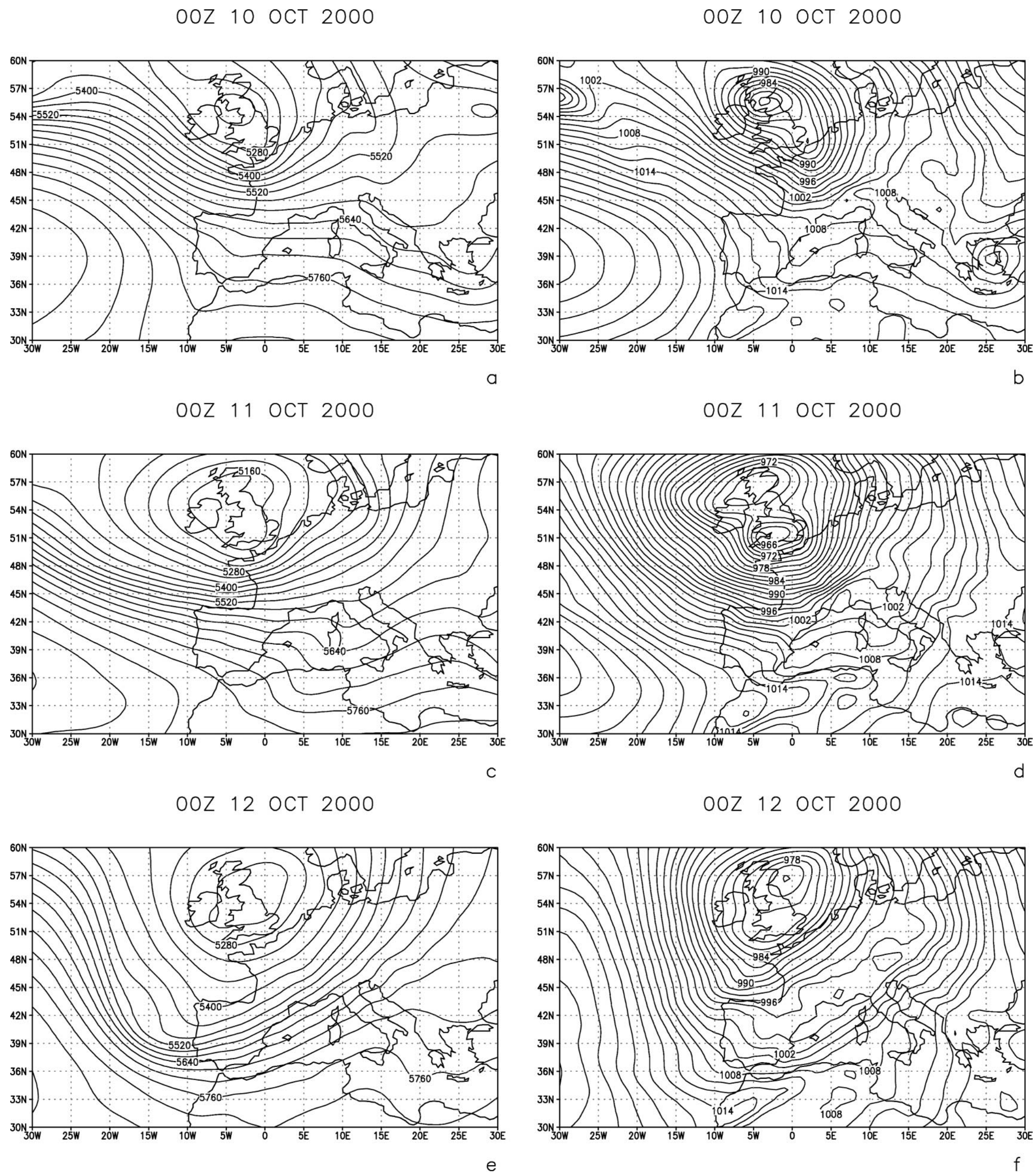

FIG. 2. The (left) 500-hPa geopotential height (m) and (right) sea level pressure (hPa) at (a), (b) 0000 UTC 10 Oct, (c), (d) 0000 UTC 11 Oct, and (e), (f) 0000 UTC 12 Oct 2000. Contour interval is 40 m for geopotential height, and 2 hPa for sea level pressure.

the synoptic-scale variability and that generally, provided periodic changes in sign due to such variability, there is, as expected, prevailing inward flux through the western and southern walls and prevailing outward flux through the northern and eastern walls. However, the most important result is that the *net* moisture flux is almost constantly positive between 23 September and 16 October, indicating that during the analyzed flood and in the 15 days preceding it, there is more moisture entering than exiting the domain. This is only a very crude moisture evaluation but provides some motivation for our study as an indication that extra-Mediterranean sources of moisture are likely to be involved.

b. Synoptic and dynamic analysis

The synoptic situation is herein briefly discussed using the NCEP operational analyses at 1° resolution. At 0000 UTC 10 October, the dominant feature is a deep cyclone (with center pressure of about 980 hPa) close to the occlusion stage over the British Isles (Figs. 2a,b). The cyclone appearing on the extreme left of Fig. 2b is

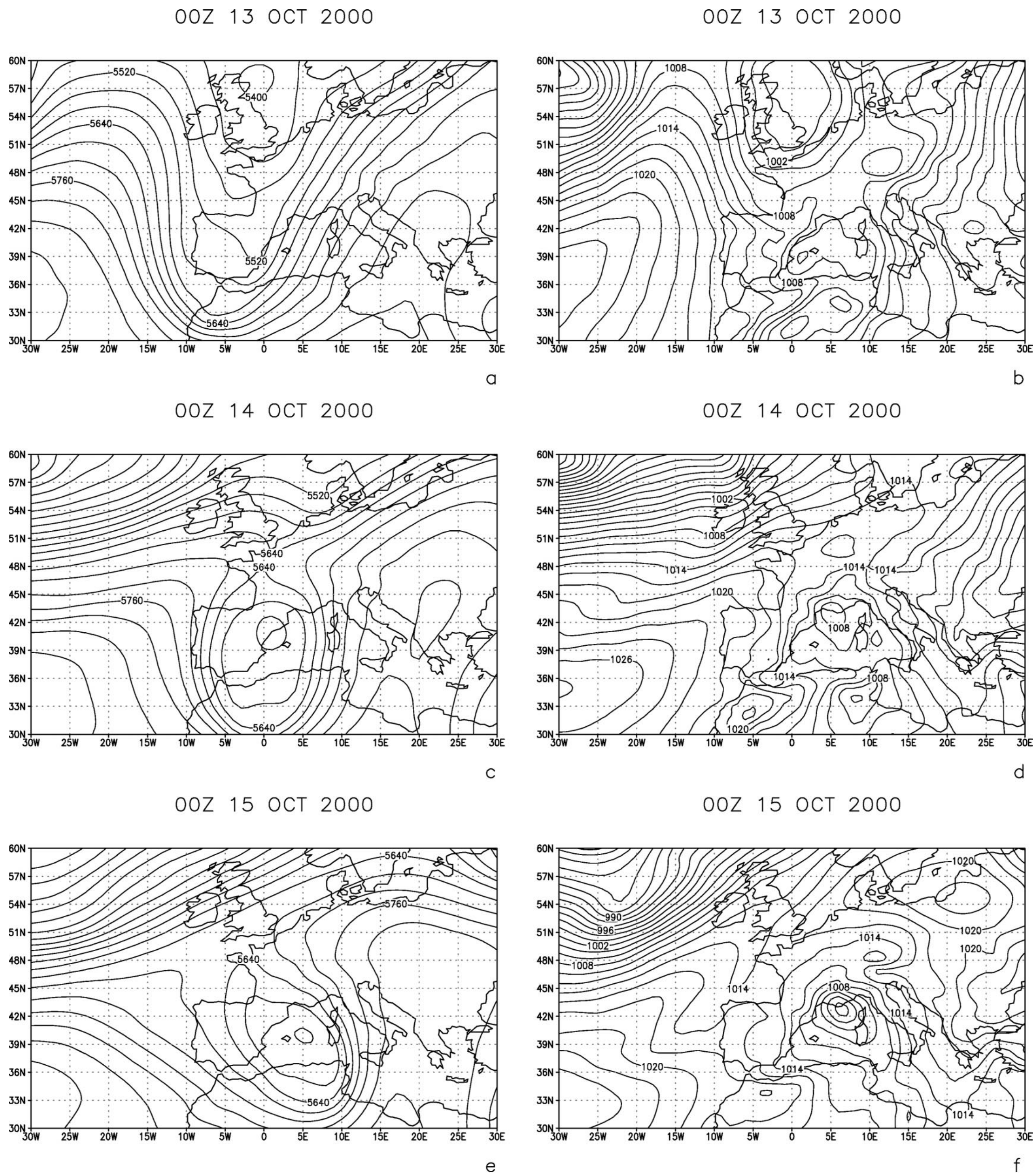

FIG. 3. Same as Fig. 2, but at (a), (b) 0000 UTC 13 Oct, (c), (d) 0000 UTC 14 Oct, and (e), (f) 0000 UTC 15 Oct.

the extratropical remnant of the former Tropical Storm Leslie (Franklin and Brown 2000). By 0000 UTC 11 October 2000, the cyclone over the British Isles has substantially deepened (Figs. 2c,d): its core center pressure reaches 965 hPa. At 0000 UTC 12 October 2000, a profound change occurs in the circulation: a strong predominantly northerly or northwesterly low-level flow, which can be inferred from the surface map between the British Isles and approximately 20°W, replaces the previously zonal flow; geopotential falls aloft in relation to low-level cold advection, and a trough with its axis elongated from the northeast to the southwest direction forms at 500 hPa (Figs. 2e,f). At 0000 UTC 13 October the deepening of the midtropospheric trough accentuates (Figs. 3a,b), and a ridging tendency is evident over the Balkans and eastern Europe. In agreement with the ridging and the sharpening of the trough in the midtroposphere, low-level wind and temperature maps (not shown) confirm warm advection over eastern Europe, and cold advection from Ireland to the Iberian Peninsula, related to the predominantly southerly and northerly flow over these regions (Fig. 3b).

At this point, 500-hPa vorticity maps (not shown) reveal that the entire western Mediterranean is under

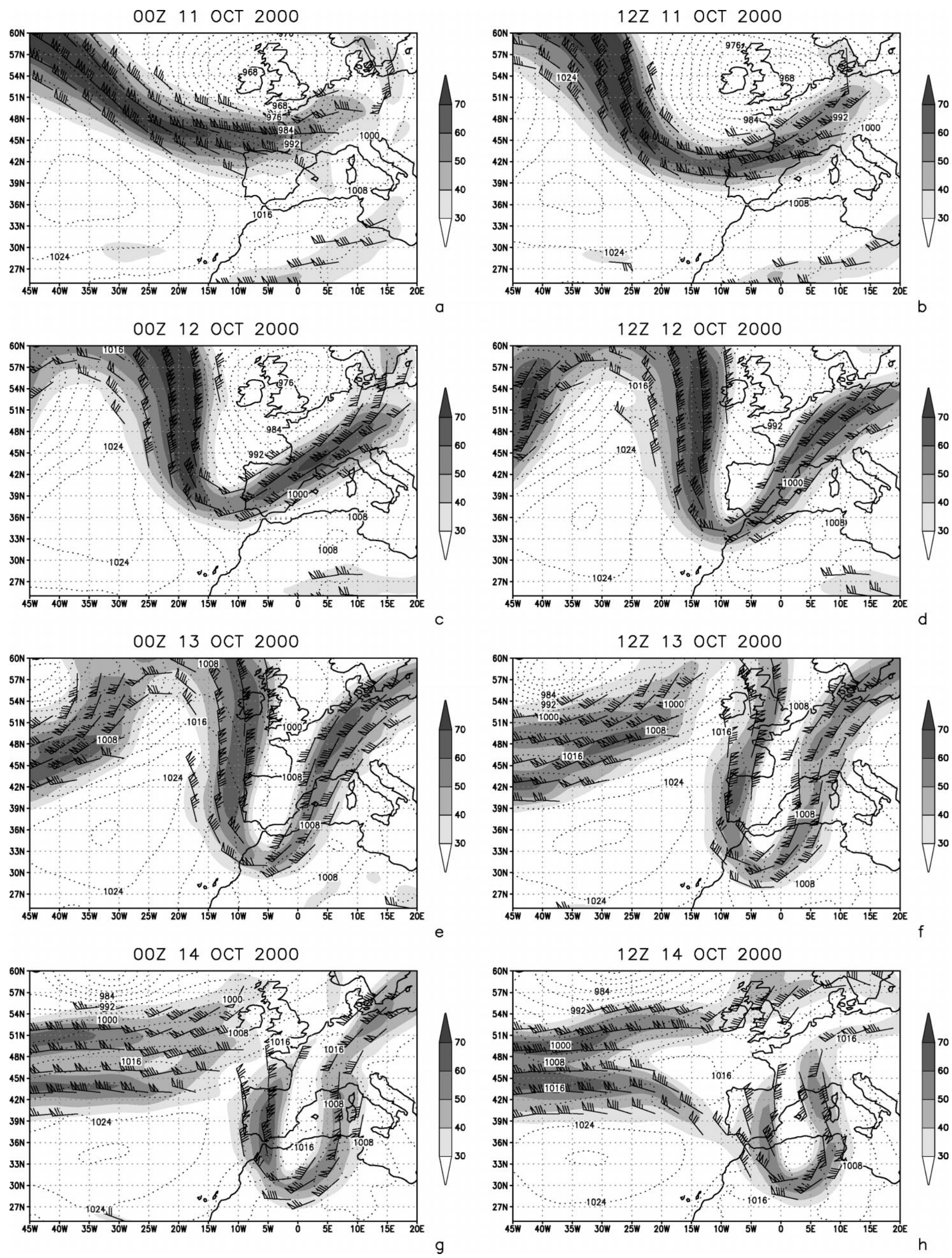

FIG. 4. The 250-hPa wind with speed greater then 30 m s^{-1} (shaded and barbs); sea level pressure (hPa) (dotted) from 0000 UTC 11 Oct to 1200 UTC 14 Oct.

positive vorticity advection and a small-scale baroclinic lee cyclone is formed to the west of the Balearic Islands (Figs. 3a,b), possibly in response to the atmospheric forcing over the orography of the Iberian Peninsula. At 0000 UTC 14 October a midtropospheric cutoff low is isolated and the cyclone deepens and moves over the Gulf of Lion, being still in an area of positive vorticity advection. Cross sections of vertical velocity (not shown) show increasing upward motion over the center of the developing low. The cyclone remains almost stationary, slightly increases its scale, and a further moderate deepening can be seen, reaching about 1000 hPa at its center at 0000 UTC 15 October (Figs. 3c–f). In this work it is shown that this small-scale cyclone, although of only moderate intensity, plays an important role. In fact, it transports and concentrates into the Mediterranean region the moisture previously produced by different mechanisms on larger time and space scales. At the same time, the cyclone over the British Isles rapidly dissipates, suggesting some transfer of kinetic energy from the British Isles to the newly formed low in the Mediterranean.

In Fig. 4 the 250-hPa wind is shown. As will be shown later, the extratropical remnants of Tropical Storm Leslie seem to progress toward the British Isles together with the same jet streak in Fig. 4a. The reinvigoration of the cyclone (Fig. 2d) at 0000 UTC 11 October leads, in the following 24 h, to increased low-level cold and warm advection on either side of the cyclone (Fig. 2f), and to a deepening trough aloft (Fig. 2e), which creates cyclonic vorticity and contributes to drive the jet stream into a sharp, short wave over the western Mediterranean (Figs. 4c,d). Since negligible temperature advection takes place at the jet level (not shown) the upward motion induced in the lower levels is predominantly controlled by the midtropospheric positive vorticity advection and is probably enhanced also by the curved jet stream that can be noted at 1200 UTC 13 October and 0000 and 1200 UTC 14 October; in fact, the developing cyclone is right at the exit of the curved jet (Figs. 4f–h) where generally most development takes place (Carlson 1991). The contribution of jet streaks to the Alpine kind of cyclogenesis was already observed by Mattocks and Bleck (1986). Moreover, we can speculate that the two jet streaks on both sides of the meander are in a favorable position to induce a coupled circulation (Uccellini and Kocin 1987). The general theory of jet coupling assumes straight and predominantly zonal jets; in fact, the curvature strongly modifies the vorticity and divergence fields. However, accepting these limitations, we can speculate that the subsidence caused by the descending branch of the transverse circulation associated with the exit region of the jet streak over France between 12 and 13 October (Figs. 4c–e), does not oppose the effect of the low-level warm advection to the east of the deepening trough aloft (Fig. 2e) and may perhaps cooperatively contribute to the increasing sea level pressure over the Balkans (Figs. 2f and 3b). The anticyclone over the Balkans is important in 1) blocking the eastward progress of the Mediterranean cyclone and 2) driving a predominantly southerly flow toward the Alpine region, thus increasing the low-level moisture flux convergence induced by the upward motion related to the positive vorticity advection aloft.

In Fig. 5 the specific humidity and the wind streamlines are shown at 0000 UTC 13 and 14 October at three different levels: 925, 700, and 500 hPa. In the low levels, there is an indication of a moist flow from the central Mediterranean toward the Alpine region, in agreement with Figs. 3b and 3d. More interesting is the *plume* of tropical moisture that is quite evident at 700 and 500 hPa, also directed against the Alpine region. Although the actual specific humidity values are obviously lower than the values at 925 hPa, the much larger spatial scale is suggestive that this midtropospheric contribution can indeed be very important for the flood. In Fig. 6 the 925- and 850-hPa moisture flux convergence and wind are shown, confirming the concentration of moisture taking place in the lower levels, enhanced by orographic uplift. The microwave satellite image (Fig. 7) confirms the midtropospheric inflow of tropical moisture within the Mediterranean region.

c. The role of Tropical Storm Leslie

Tropical Storm Leslie developed from a subtropical depression appearing off the east coast of Florida at 1200 UTC on 4 October 2000 and remained almost stationary for about 24 h. On 5 October, the subtropical depression tracked eastward and intensified, becoming a weak tropical storm (Franklin and Brown 2000) embedded in a wide area of warm moist air. On 7 October a wide 500-hPa trough over the eastern United States began to slowly rotate counterclockwise as the steep cold-frontal boundary associated with the trough approached the tropical storm. The surface circulation associated with Leslie began to elongate, its vertical structure being altered by the vertical shear, and the cyclone gradually became entangled with the front, until by 1800 UTC 7 October it became extratropical (Franklin and Brown 2000).

In the first phase of the extratropical transition Leslie maintained a tropical structure with very weak vertical wind shear near its center, low-level convergence, and a well-defined warm and moist core. The equivalent potential temperature θ_e at 850 hPa was at about 335 K or more (not shown). As the upper-level trough progressed eastward and began to rotate its axis counterclockwise, Leslie accelerated its motion toward the north and then the northeast, steered by the baroclinic wave. However, the equivalent potential temperature θ_e provides an indication of an intrusion of tropical warm and/or moist air in the midlatitudes, induced by the northward and eastward motion of the remnant of Leslie. Figure 8 shows a plume of substantially warmer air at 850 hPa (θ_e values around 320–335 K) in the wake of the remnant of Leslie. In the six panels of Fig. 8 the latitude is unchanged but the longitude moves to follow the track of Leslie. It is important to note the eastward progression of the 320-K isotherm between 0000 UTC 8 October and 1200 UTC 10 October (Figs. 8a,f), from 32° to 13°W, at approximately 45°N. Recalling Figs. 2b and 2d it can be seen that the moist warm plume enters the cyclonic circulation over the British Isles from its southern side and may therefore contribute to its redevelopment by increasing low-level meridional temperature gradients.

In Fig. 9, the position of Leslie's extratropical remnant is shown together with 300-hPa wind, sea level pressure, and surface latent heat fluxes. The storm crosses the Atlantic Ocean at a remarkable speed, appears to be steered by a predominantly westerly flow, and deepens by about 30 hPa between 1800 UTC 9 October and 1800 UTC 10 October. At this time it reaches 965 hPa and can be therefore classified as a ''bomb'' (Sanders and Gyakum 1980). The deepening phase occurs over an area with positive SST anomalies (Fig. 10), where the surface latent heat fluxes might have contributed to keep the boundary layer equivalent potential temperature (θ_e) close to the saturated equivalent potential temperature of the underlying sea surface temperature. Dia-

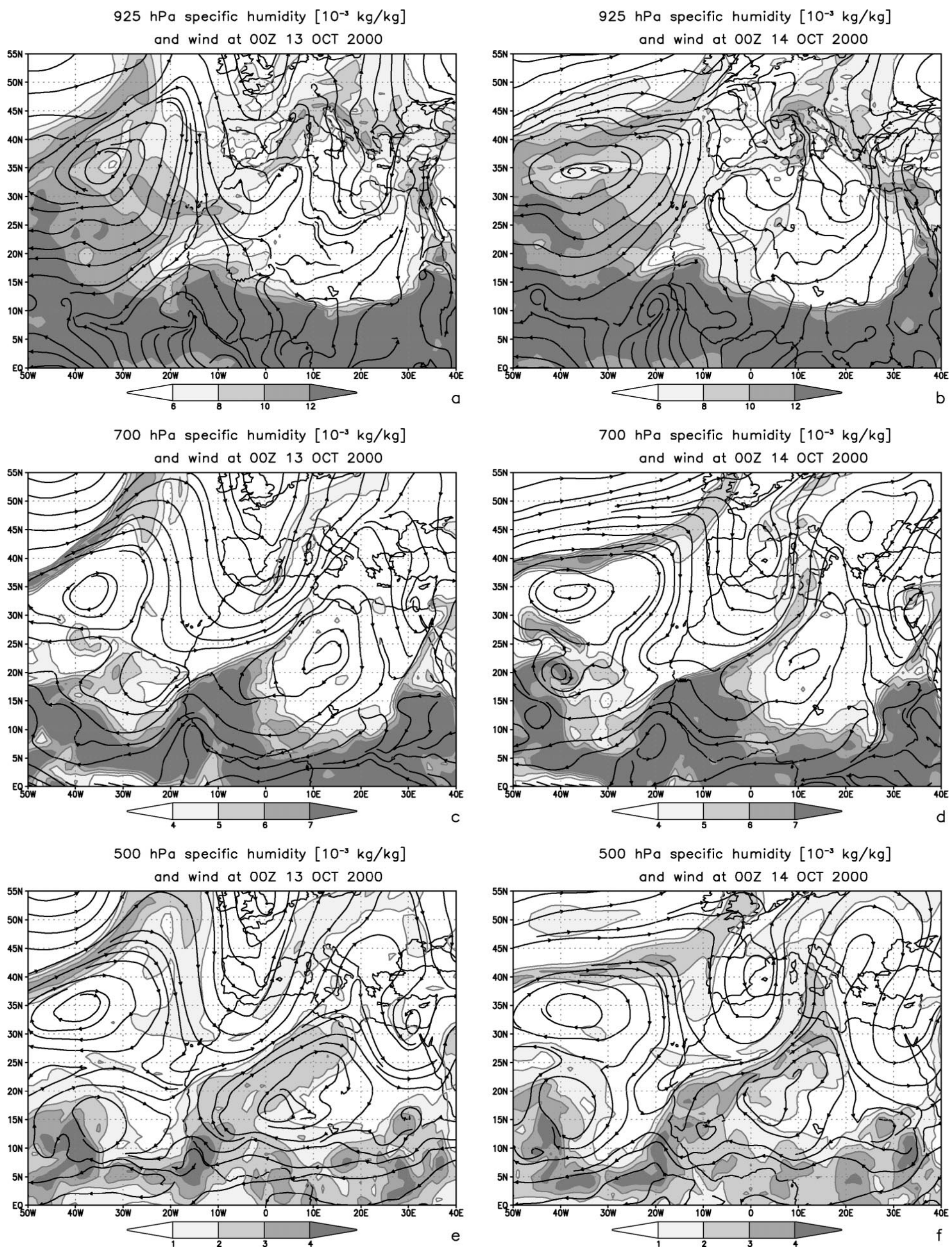

FIG. 5. Specific humidity (10^{-3} kg kg^{-1}) (shaded) and wind streamlines at (a), (b) 925, (c), (d) 700, and (e), (f) 500 hPa at (left) 0000 UTC 13 Oct and (right) 0000 UTC 14 Oct 2000. Note the different contour intervals for specific humidity at different levels.

batic processes might have also played a role in rejuvenating the system through latent and sensible heat release and convection development.

At 1800 UTC 10 October 2000 the remnant of Tropical Storm Leslie merges into the center of the large-scale, preexisting, baroclinic cyclone over the British Isles. The merging coincides with the peak of intensification: the sea level pressure reaches 965 hPa and the related low-level winds strengthen. These events, together with a possible increase in air–sea temperature difference, cause a further increase in latent heat flux particularly evident from 0000 to 1800 UTC 10 October (Figs. 9c–f).

The contribution of Leslie is twofold: 1) it advects moisture in its wake, and 2) it contributes to rejuvenation of the cyclone over the United Kingdom. This cyclone in turn is one of the players in the creation of a favorable environment for a moderate cyclone to develop in the western Mediterranean Sea and for a ridging to the east of it, which prevents eastward progression. All this happens in conjunction with an inflow of tropical air from the ITCZ across northern Africa.

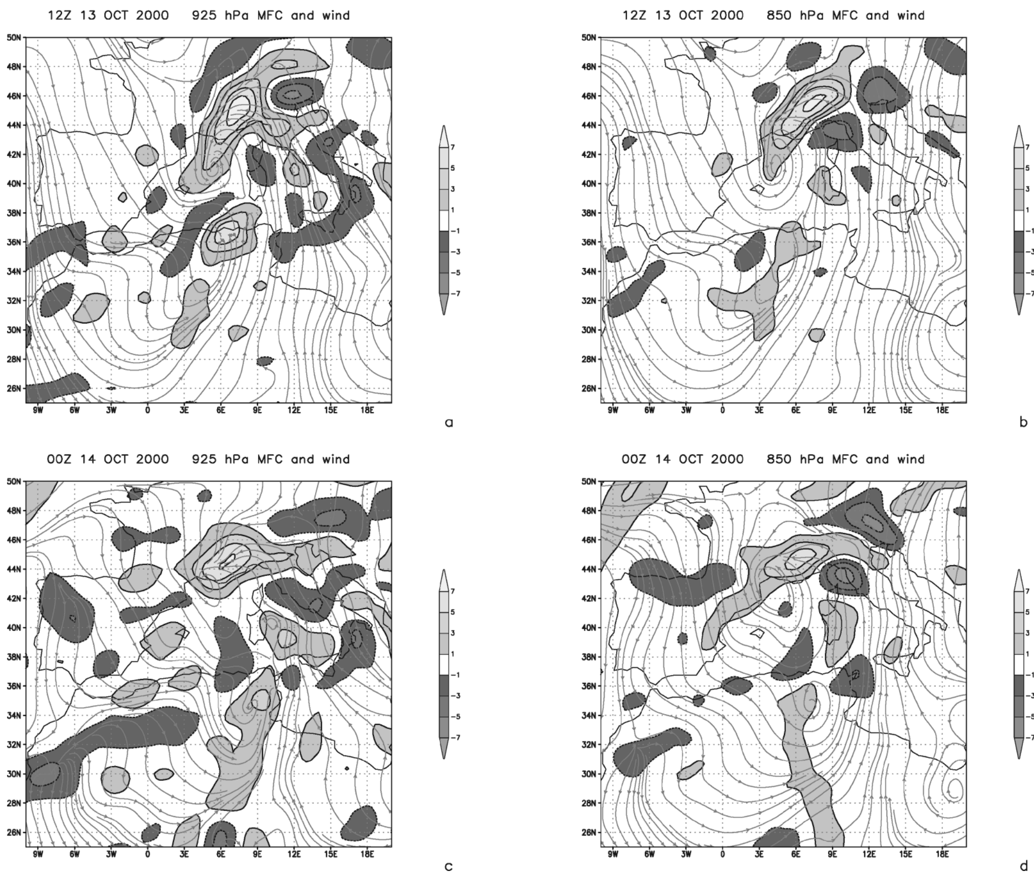

FIG. 6. Moisture flux convergence (10^{-4} g kg^{-1} s^{-1}) and wind at (left) 925 and (right) 850 hPa at (top) 1200 UTC 13 Oct and (bottom) 0000 UTC 14 Oct.

d. Energy fluxes at the sea surface

To investigate the role of surface energy fluxes, intuitively suggested by the map of SSTs (Fig. 10) and by the anomalous life cycle of Leslie, time series of area-averaged latent and sensible heat fluxes are calculated on a number of target areas on which we previously performed the moisture balances. The target area Q0, already defined, is inclusive of the western Mediterranean and of the region subject to the flood; Q1 is chosen to evaluate Mediterranean contributions and possible land contributions on a European scale (from 29.5° to 54.3°N and 9.4°W to 30°E); and the areas Q2 (from 25.7° to 54.3°N and 3.75°W to 30°E) and Q3 (from 10.5° to 60°N and 80.6°W to 3.75°E) are aimed to investigate the Atlantic Ocean, with Q2 involving only the midlatitude portion of the Atlantic Ocean closer to Europe and Q3 covering the entire basin, from the Tropics to the midlatitudes (Fig. 11d).

Surface fluxes are compared with climatological values (fluxes from the ocean to the atmosphere are considered positive). Daily data and long-term monthly means from the NCEP–NCAR reanalyses dataset (Kistler et al. 2001) are used. We compute 5-day running-mean area-averaged surface flux anomalies over each of the three areas between 15 September and 31 October 2000 (Figs. 11a–c). Fluxes are generally higher than climatology over the western Atlantic Ocean and the Mediterranean (Q1 and Q2) and to a lesser extent over the entire Atlantic Ocean, which is consistent with the anomalous SSTs (Fig. 10). We note that latent heat flux, area averaged over the eastern part of the northern Atlantic Ocean and over the Mediterranean (target area Q1), increases and peaks a few days before the first two rainy periods occurring on target area Q0 (recall Fig. 1a) and then quickly decreases and displays minima during the rainfall events, possibly because of condensational cooling and increased atmospheric humidity. This seems to indicate that these two rainfall events over Q0 are controlled by the Mediterranean (Fig. 11a). However, the peak in latent heat over Q1 is smaller on 7 October, corresponding to the third rain event in Fig. 1a, which carries the signature of the Piedmont flood. On the contrary, the relatively largest peaks in latent heat over Q2 (which involves a large fraction of the western Atlantic) and even Q3 (which involves almost the entire northern Atlantic Ocean) occur around 5–10 October, representing the average of the 5 days preceding and during the floods (Figs. 11b,c). This provides

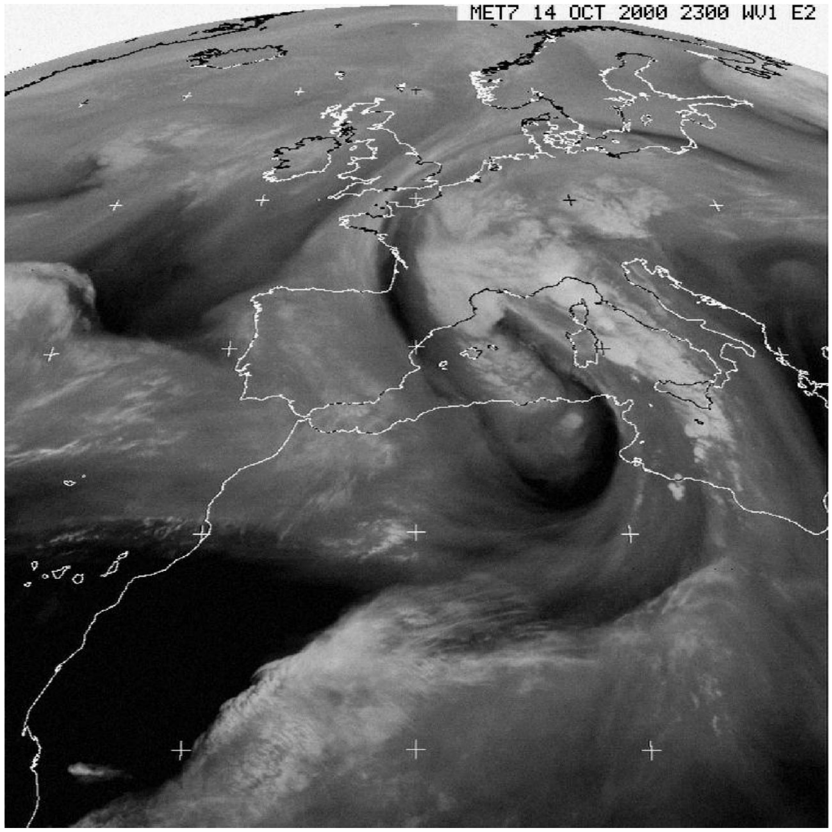

FIG. 7. Meteosat satellite image in the water vapor wavelengths (range 5.7 to 7.1 μm) at 2300 UTC 14 Oct 2000, showing humidity advection from the Atlantic and the African ITCZ. Courtesy of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), through University of Nottingham, United Kingdom.

a further indication that Mediterranean evaporation dominates the first two rainy episodes in Q0 but is not the only and prominent source for the 11–16 October event. Considering the large extent of the target areas the anomalies (peaks up to 70 W m^{-2} over Q2 and 40 W m^{-2} over Q3) are remarkable and provide an insight on the potential involvement of Atlantic moisture in the mechanisms leading to the Piedmont flood. The anomalous fluxes however are by no means sufficient conditions for heavy precipitation to occur (in fact, other peaks occur at the end of October), but they could be concurring agents of a complex synergistic mechanism.

3. Moisture sources for the Piedmont 2000 flood event

a. Method

To investigate surface evaporative sources contributing to the flood event, we adopt a kinematic quasi-isentropic trajectory technique documented in Dirmeyer and Brubacker (1999); used by Reale et al. (2001), Brubacker et al. (2001), and Burde and Zangvil (2001a,b); and based on the fully implicit isentropic algorithm of Merril et al. (1986). Back-trajectory calculations are performed, launching a certain number of parcels from each specified grid square *i* where precipitation has occurred at a certain time step; each parcel represents a unit of precipitation in the grid box *i*. The number of parcels launched at each grid box where precipitation occurs is proportional to the local precipitation rate. If precipitation persists for several time steps, parcels are launched back in time from each time step, throughout a time interval less than or equal to the entire duration of the rainfall event.

It is assumed that precipitation can fall from any level: parcels are vertically located at a random level sampled from $\sigma = 0$ to 1 according to an assigned cumulative distribution function such that the probability (P_c) of a parcel back trajectory's being started at $\sigma \leq c$ is

$$P_c = 1 - \frac{\mathrm{PW}_c}{\mathrm{PW}_i}, \qquad (1)$$

where PW_i is the total precipitable water in the column over grid box $i(PW_i = p/g \int_0^1 q \, d\sigma)$, q is the specific humidity, g is the acceleration due to gravity, and p_s is the surface pressure. Here, PW_c represents the column

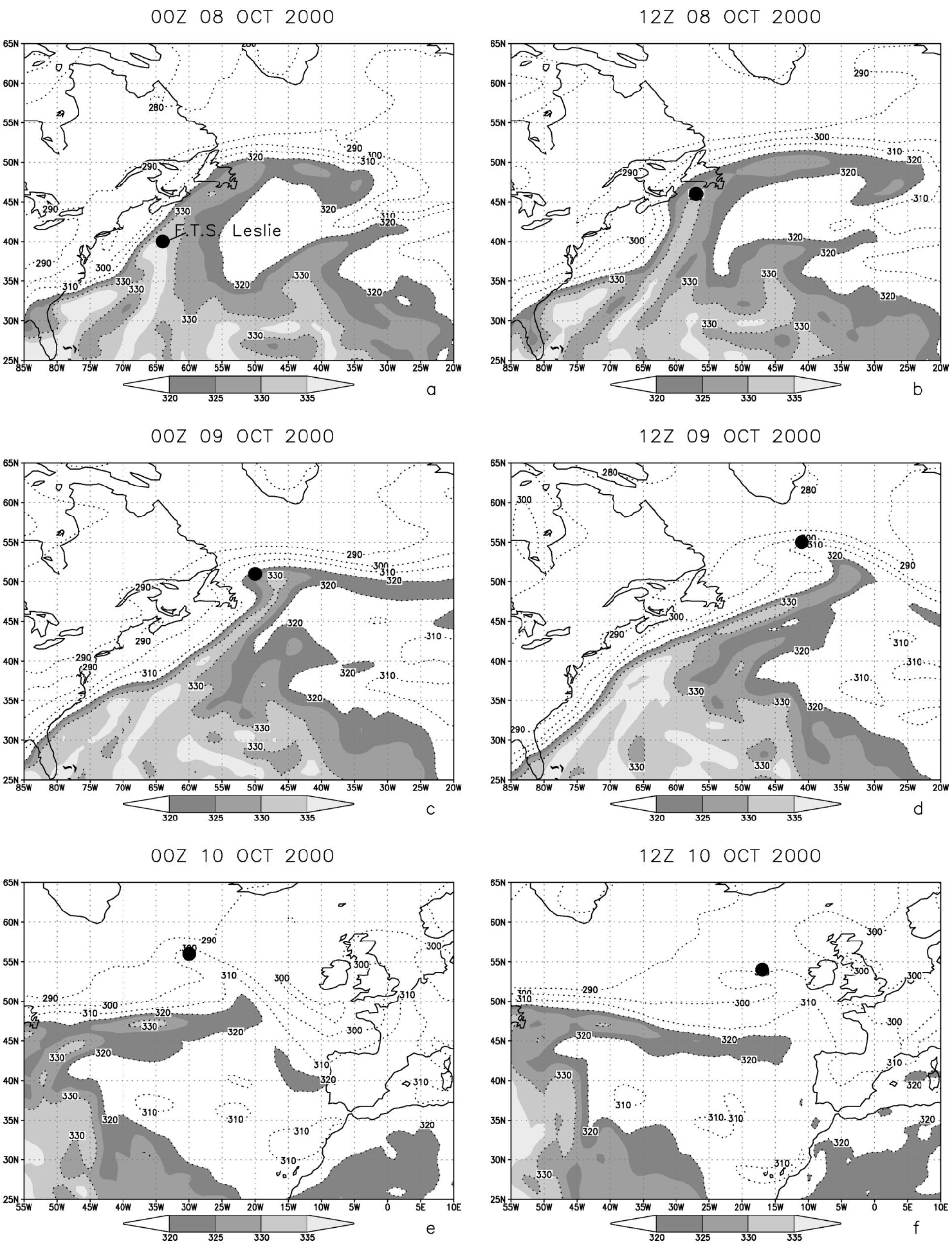

FIG. 8. The 850-hPa equivalent potential temperature (K) (shaded with contour interval at 5 K, and dotted lines with contour interval at 10 K). Position of the extratropical remnant of former Tropical Storm Leslie, according to the National Hurricane Center (NHC) best track (black dots).

precipitable water below the level $\sigma = c$. In this way, the probability that a parcel is being launched from a given level decreases with height: the largest fraction of precipitation comes from the lower levels, where the concentration of water vapor is higher. Parcels are tagged with the ambient potential temperature, which is adjusted assuming diabatic processes when necessary to prevent tracking the parcel into the ground (Dirmeyer and Brubacker 1999).

At each time step n, the horizontal position x^{n-1}, y^{n-1} is calculated by

$$x^{n-1} = x^n + \frac{\tau}{2}(u^{n+1} + u^{n-1*}), \qquad (2)$$

$$y^{n-1} = y^n + \frac{\tau}{2}(v^{n+1} + v^{n-1*}), \qquad (3)$$

where τ is the time interval (negative for back trajectory), and u, v the wind components at the nearest *sigma* level corresponding to the parcel's potential temperature. Two trajectories are averaged: a backward trajectory from point x^n, y^n to point x^{n-1*}, y^{n-1*} using the

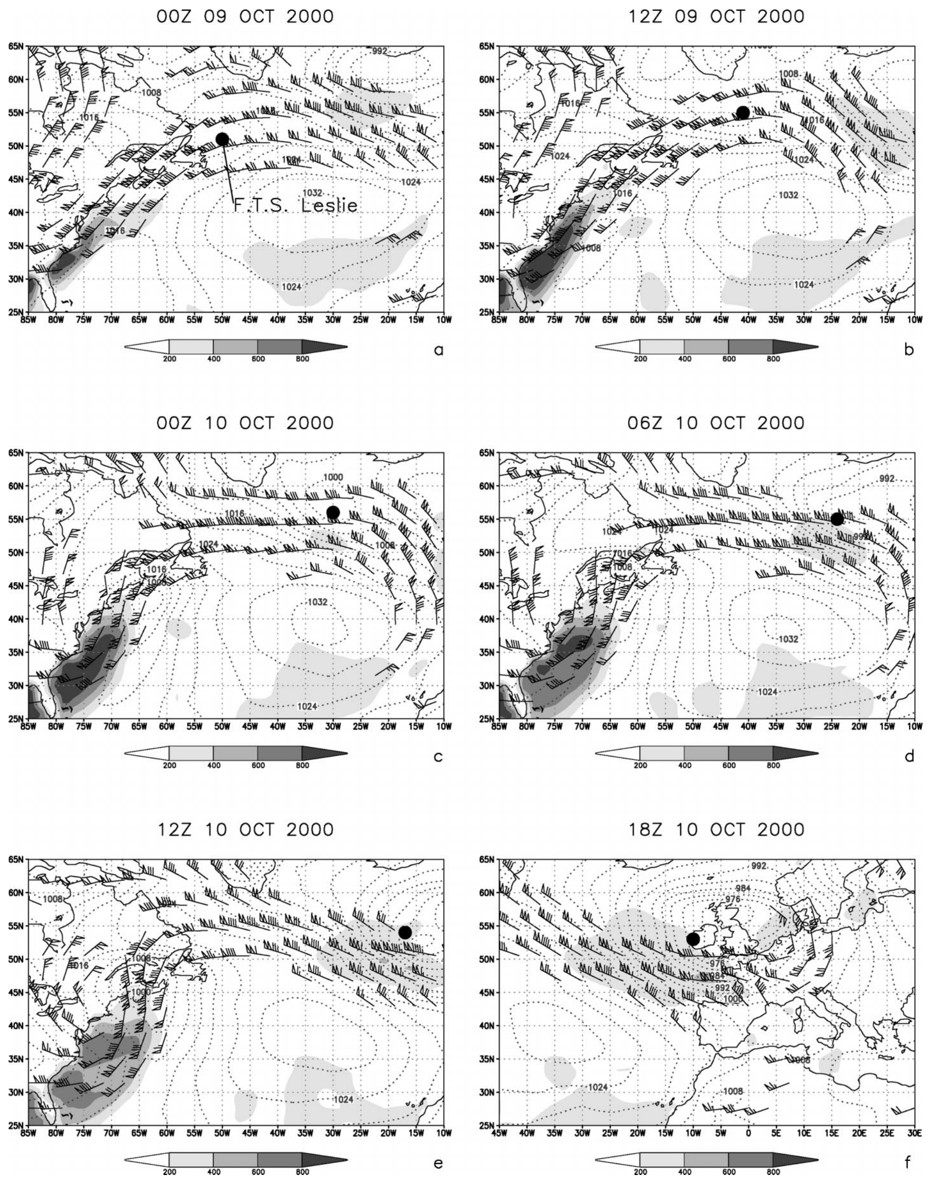

FIG. 9. Surface latent heat fluxes (W m^{-2}) (values greater than 200 W m^{-2} are shaded), sea level pressure (contour interval of 4 hPa), and 300-hPa wind (greater than 30 m s^{-1}). Position of the extratropical remnant of former Tropical Storm Leslie, according to NHC best track (black dots).

wind u^n, v^n (wind u, v at the location x^n, y^n) and a forward trajectory from point x^{n-1*}, y^{n-1*} to point x^{n-1}, y^{n-1} using the wind u^{n-1*}, v^{n-1*} (wind u, v at location x^{n-1*}, y^{n-1*}).

Parcels are traced back in time (assuming that at each time step the evaporation from a grid box contributes to a fraction of the water vapor content of the parcels in transit over that grid box) (a) until 90% of their original mass has been lost, (b) until they reach the border of a domain, or (c) for a prescribed maximum number of days (parameter *n*day), whichever of these three conditions comes first.

Two domains need to be defined: (i) a precipitation domain (PD), in which parcels are launched from each grid point where precipitation occurs, and (ii) a tracing domain (TD), which is the maximum domain where evaporative sources are searched. The precipitation domain PD investigated in this study ranges from 41° to 48.6°N and from 1.875° to 15°E, enclosing the area affected by the 13–16 October 2000 event. The tracing domain TD in which the evaporative sources are searched ranges from 14°S to 73°N and from 90°W to 90°E.

The wind and temperature fields used in this study are from the 6-hourly global atmospheric analysis produced by the NCEP–NCAR reanalysis project (Kistler

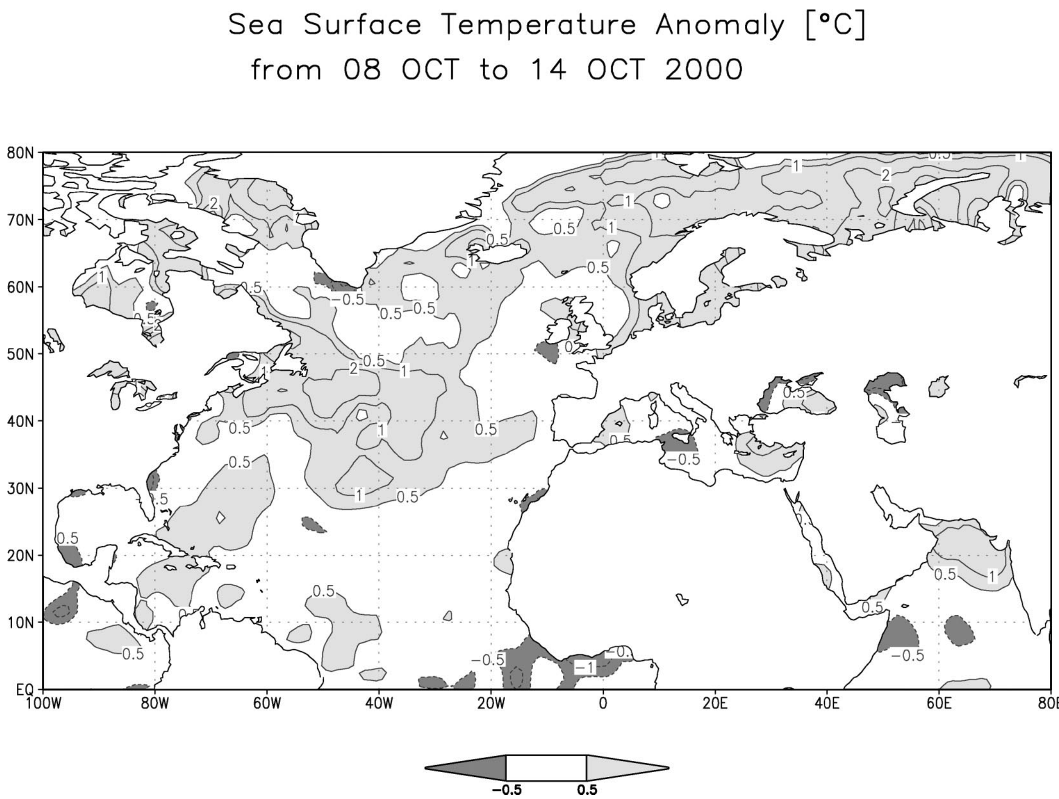

FIG. 10. Weekly sea surface temperature anomaly (°C) from 8 to 14 Oct 2000. The weekly data of the optimum interpolation (OI) SST analysis are produced by NOAA–CIRES Climate Diagnostics Center (CDC). The climatological values used for the computation of the anomaly are given by the long-term daily mean dataset, derived from data for 1982–96.

et al. 2001) at T62 horizontal resolution, linearly interpolated on 28 vertical layers (sigma levels). Precipitation fields are also from the NCEP–NCAR reanalyses. In this work, after several different tests, we have chosen to launch the parcels back in time throughout a time interval of 5 days (pentad) during the duration of the event, that is, between 0000 UTC 10 October and 0000 UTC 15 October. The number of parcels launched in the pentad is about 50 per each grid box of the PD.

The following parameters are evaluated for a quantitative interpretation of the experiment results:

- Total precipitation is given by the sum of all precipitation [6-hourly precipitation heights (mm)] falling over all the grid points of the PD during the pentad, as inferred by the reanalysis dataset.
- Total evaporation represents the sum of the evaporative moisture sources (mm $\sim$ kg m^{-2}) in the TD contributing to precipitation over the PD. This parameter is always smaller than total precipitation. In fact, if parcels escape out of the TD or do not reach 10% of their initial mass within the prescribed number of days (*n*day) starting from the time step in which they fall as precipitation, they are considered lost.
- The percentages are given by the ratio between evaporation over a certain area and precipitation over the PD.

b. Results

The first experiment investigates the time scales involved, by changing the maximum number of days before the beginning of the pentad (parameter *nday*) in which the parcels are traced back. On each of the four panels of Fig. 12 the accumulated evaporative sources contributing to the precipitation occurred over the PD are represented, and the area integrals of the evaporative sources are computed over the entire TD and over some subdomains: Atlantic (A, from 5°S to 70°N, only sea points), Mediterranean (M, from 30° to 50°N and 5°W to 40°E, only sea points), land (L, all the land points in the entire TD), western Atlantic (WA, from 21.90° to 50.48°N and 90° to 50.625°W, land and sea points), northeastern Atlantic (NEA, from 39.05° to 60.0°N and 35.625°W to 0°, only sea points) and Africa (AFR, from 8.57° to 29.52°N and 30°W to 39.375°E, land and sea points).

The following results are obtained:

- About 50% of the evaporative sources contributing to

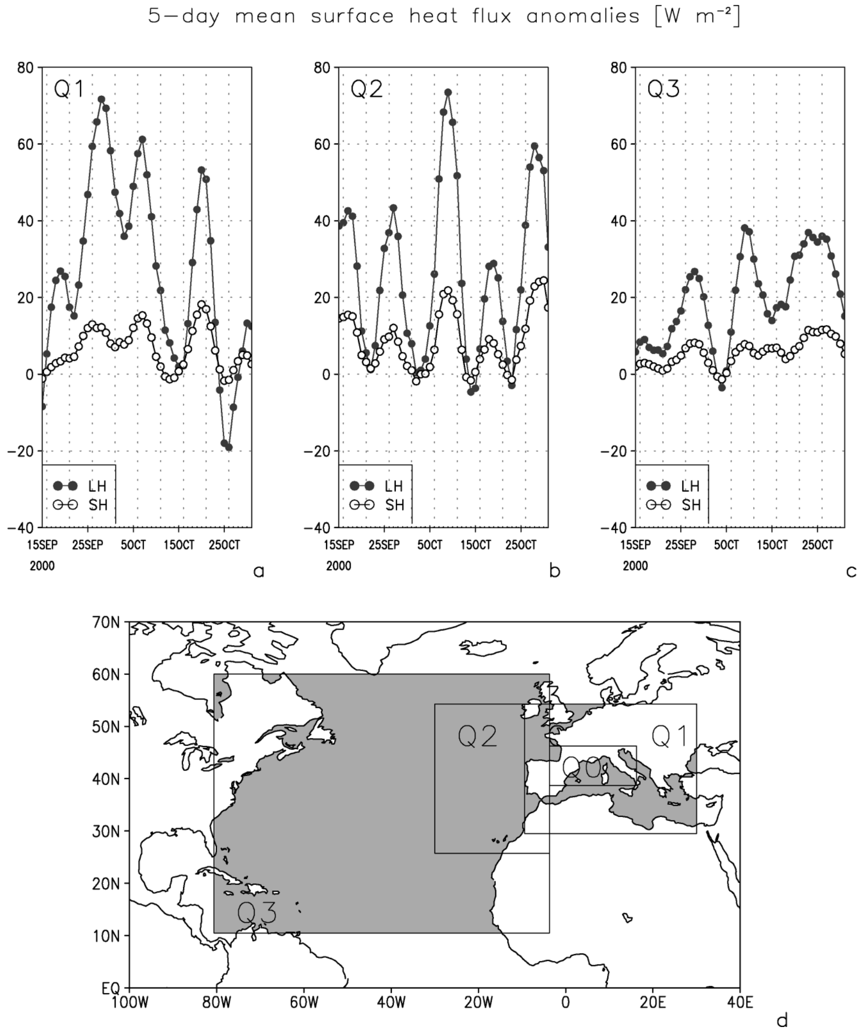

FIG. 11. (a)–(c) The 5-day running means of surface latent heat and sensible heat fluxes anomalies (W m^{-2}) over target areas Q1–Q3 (the fluxes are masked over land). The running means are assigned to the first day of each pentad. (d) Target areas where regional water balance and surface fluxes are computed.

the precipitation that occurred between 1800 UTC 9 October and 1800 UTC 14 October over the PD lay within 1 day before the beginning of the pentad, that is, within 6 days before the end of the event (Fig. 12a), and are mostly located near the Atlantic European coasts (approximately 30%) and in the Mediterranean (about 20%). The contribution from the Atlantic can be reconduced to the generally westerly flow in the northern Atlantic, the cyclone over the British Isles seen in Figs. 2 and 3, and to its merging with Leslie.

- Parcels need to be tracked backward at least for 7 days prior to the beginning of the pentad (1800 UTC 9 October), that is, until 1800 UTC 2 October, in order to recover more than 90% of the moisture sources contributing to precipitation (Fig. 12c).
- By changing the *n*day parameter from 1 day up to 7 days, the fraction of Mediterranean contribution changes little, being less than 20%, whereas the contribution from the Atlantic Ocean increases significantly; in particular, there is even an evaporative contribution from the subdomain WA, which increases from about just 1% to more than 10%.

A further increase in the number of days in which the parcels are tracked (*n*day = 10 and *n*day = 15) brings a more modest increase in evaporation from the Atlantic Ocean (Figs. 12d and 13); this suggests that the timescale characteristic of the event is of the order of 1–2 weeks. On the same figure, the track of Tropical Storm Leslie, before and after its conversion into extratropical, is superimposed to the sources. About 60% of evaporation contributing to the precipitation fallen over the PD originates from the northeastern Atlantic Ocean (40%) and the Mediterranean basin (20%). However, a substantial amount of evaporation can be traced back

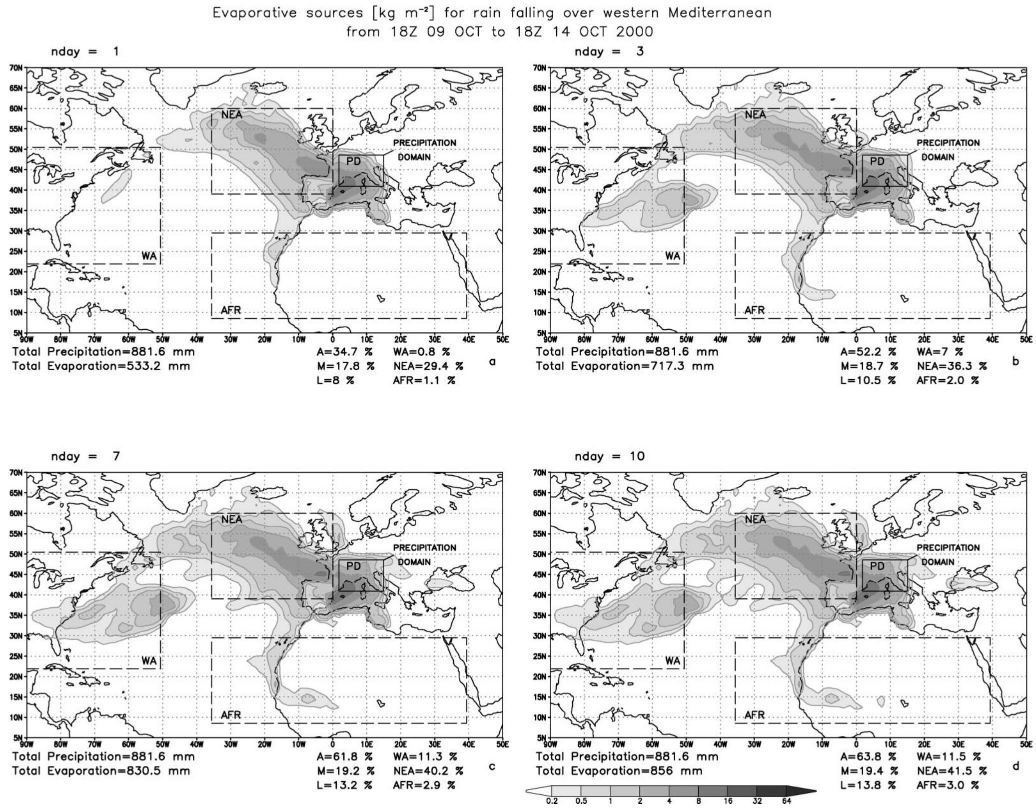

FIG. 12. Accumulated evaporative moisture sources (kg m^{-2}; equivalent to mm of liquid water) collected over TD for rain falling over PD. Sources obtained for different values of the *n*day parameter (number of days in which the parcels are tracked, starting from the beginning of the pentad). Total precipitation fallen over PD and total evaporation collected over TD are on the bottom left of the panel; fractional evaporative sources computed over subdomains A, M, L, WA, NEA, and AFR, as marked on the map, are on the bottom right of each panel.

to a larger spatial scale, extending from Florida to the whole North Atlantic Ocean: this source corresponds remarkably well to the track of the tropical system Leslie and to its extratropical transition.

In fact, more than 10% of the source originates from the western Atlantic Ocean, in proximity of the U.S. East Coast; moreover, part of the evaporation occurring from the central Atlantic Ocean could be traced back to the intrusion of tropical air that follows the remnants of Leslie and to the enhanced evaporation caused by its redevelopment (recall Figs. 8 and 9). Another relatively small but interesting contribution is from the African ITCZ, namely from the Sahel region. It is important to stress then that only 20% of the total precipitation accumulated during the pentad over the PD originates from the Mediterranean basin. This result is related to the particular event. We performed water vapor back tracing in other situations and found that generally the fraction of moisture originated in the Mediterranean is substantially larger when extraordinary precipitation events do not occur (not shown).

The sources shown in Figs. 12 and 13 that represent evaporation accumulated over a relatively long time with respect to the time scale of the event match generally well with the overall low-level circulation inferred from the synoptic discussion. In Fig. 14 we show instead the evaporation collected at individual time steps: the values are perhaps less representative because they are probably subject to large uncertainties. However, it is worth noting that a good correspondence with synoptic features can be found. The time steps of the back tracing most distant in time from the event (between the last days of September and the first days of October; not shown) reveal evaporative contributions from the western tropical Atlantic, consistent with the formation of a broad region of moist convergence and sporadic and disorganized thunderstorms (Franklin and Brown 2000) in which Tropical Storm Leslie develops. As long as we move forward in time showing time steps of the back-trajectory calculation closer to the event (Figs. 14a–e), the evaporative sources at individual time steps seem to follow well the progression of the extratropical remnants of Leslie and the plume of moist air in its wake (recall Fig. 8). At the same time, evaporative contributions are produced by the westerlies associated with the cyclones over the northern Atlantic, and some other contributions arise from the Mediterranean region and the African ITCZ. With the approaching of Leslie to the

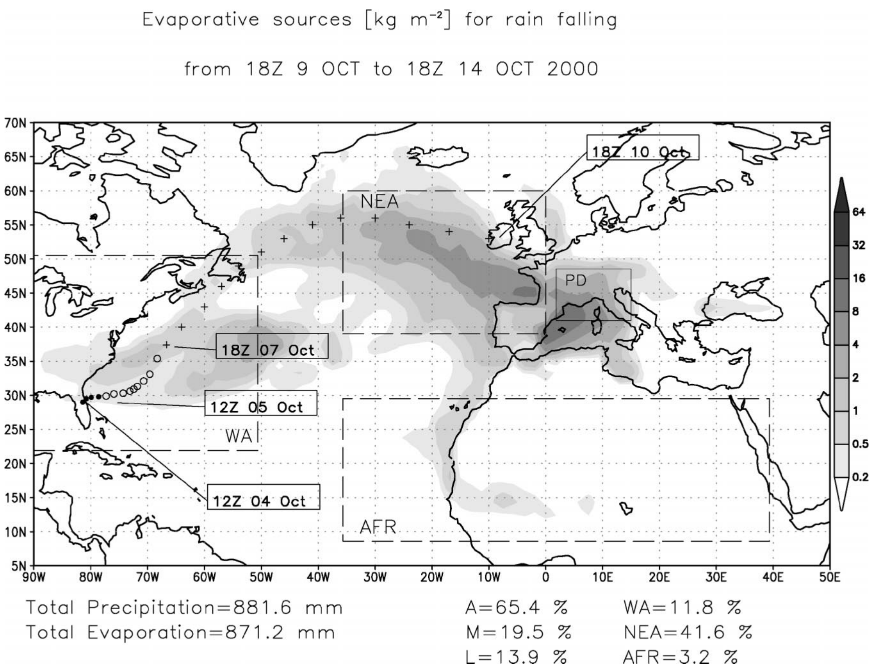

FIG. 13. Accumulated evaporative sources (kg m^{-2}) collected over the entire TD and contributing to rainfall over PD during the period 10–14 Oct 2000 for *n*day = 15. Fractional contributions computed over the same subdomains as in Fig. 13. Track of Tropical Storm Leslie (from the NHC) from 4 to 10 Oct 2000, at various stages: subtropical depression (dot), tropical storm (circle), extratropical system (cross).

British Isles, the evaporative contributions associated with the extratropical remnant of Leslie and with the cyclone over the Isles seem to merge together (Fig. 14f) even before the two cyclones do.

In summary, more than 60% of the evaporation contributing to our event originated in the Atlantic Ocean, and approximately two-thirds of this contribution comes from the northeastern Atlantic. The Mediterranean Sea is responsible only for about 20% of the total evaporation. Although a more rigorous study would require some modeling experiments, and it is not possible to rigidly separate sources or associate them to a specific meteorological mechanism, the sources and time scales found can provide some insights on the processes contributing to the rainfall that occurred between 10 and 16 October 2000. A tentative description is outlined here:

1) A large-scale contribution on a spatial scale of $5 \times 10^3 - 10^4$ km and 5–10 days or more is associated with the environment conducive to the development of Tropical Storm Leslie. Some air from the oceanic large-scale convergent environment that contributes to create Leslie is advected into the wake of Leslie. Moreover, the low-level vorticity maximum that is typically associated with extratropical remnants of former tropical storms contributes to reinvigorate a cyclone over the British Isles.
2) Contributions from the eastern Atlantic Ocean and the Mediterranean, and from the African ITCZ, occur on a spatial scale of about 5×10^3 km and a time scale of 2–5 days.
3) Local contributions, with the aid of possible recycling processes within the PD, dominate the time scale of 1–3 days.

4. Conclusions and discussion

In this study we investigated the role of large-scale moisture sources on the development of a major flood event that predominantly affected the Italian region of Piedmont between 13 and 16 October 2000, producing heavy rainfall and extensive damage. Crude moisture balances reveal that there is a net inflow of moisture during and in the 2 weeks preceding the event, over a domain covering Piedmont and the northern part of the western Mediterranean.

The synoptic analysis confirms that at least three sources of moisture outside the Mediterranean could be involved: a low-level moisture anomaly in the wake of the former Tropical Storm Leslie, moisture from the south of a baroclinic cyclone over the British Isles, and moisture from the African intertropical convergence zone.

Water vapor back trajectories confirm what is intuitively suggested by the synoptic analysis, indicating that about 80% of the moisture needed to produce the rainfall in a domain inclusive of the area affected by the flood originated outside the Mediterranean region. Particu-

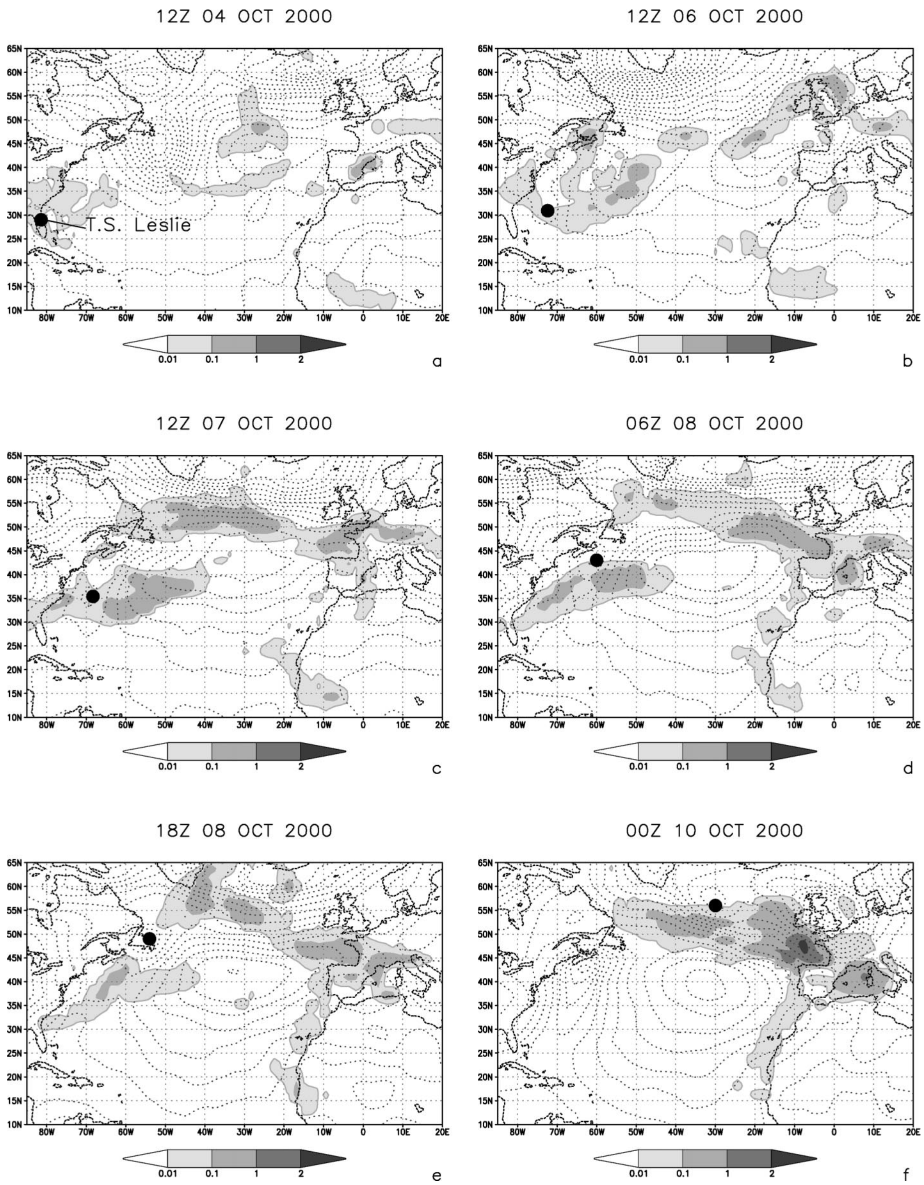

FIG. 14. The 6-hourly evaporative moisture sources (values greater than 10^{-2} kg m^{-2} are shaded) and sea level pressure (dotted line, contour interval every 3 hPa) at (a) 1200 UTC 4 Oct, (b) 1200 UTC 6 Oct, (c) 1200 UTC 7 Oct, (d) 0600 UTC 8 Oct, (e) 1800 UTC 8 Oct, and (f) 0000 UTC 10 Oct 2000. Black dots depict the position of Leslie, from NHC best track.

larly, more than 60% of the evaporation contributing to the precipitation over the analyzed region comes from the Atlantic Ocean. This is in sharp contrast to evaporative sources that are found during ''normal'' precipitation events, in which Mediterranean evaporation dominates. Water vapor back tracing performed at different times in which exceptional precipitation does not occur reveals that generally the percentage of moisture coming from the Mediterranean is much larger. Reale et al. (2001) found the same result in their study of the 1998 floods. It is only at the very *onset* of exceptional events that contributions from these very large scales appear. Even when performing the back tracing starting some time after the onset of an exceptional event, local water recycling effects can mask the importance of the remote source.

Several caveats must be stated. Our tracing method assumes that precipitation can occur from all levels: as a consequence, the amount of moisture that is occasionally transported from tropical to middle latitudes inside continuous bands of nonprecipitating middle-level clouds (*tropical plumes*), associated with the upper-tropospheric trough and/or the subtropical jet streams, is not treated properly. This contribution may be important for some Mediterranean floods (Knippertz et al. 2003; Krichak and Alpert 1998; Turato 2003) and was probably present in our case. A plume stretched across western Sahara can be inferred by the specific humidity fields and satellite picture (Figs. 5 and 7). As a consequence, the evaporative contribution from the African ITCZ is probably underestimated by our tracing method. Another shortcoming in our method is that the only source included comes from the earth surface, and sources coming from evaporation aloft are not included. Moreover, the evaporation does not depend on the altitude of the parcel since it is transfered to the parcel assuming always a well-mixed boundary layer. Finally, different species are not been taken into account, as in, for example, the study by Misra et al. (2000). More precise evaluations should be done with a fully 3D method, or at least by comparing our sources with the 3D wind trajectories obtained in a purely kinematic method. These calculations are beyond the purpose of this study but may be the subject of further research. Finally, it is likely that the method underestimates the contributions of parcels that are moist right from the start (*n*day before the event), since it assumes that parcels collect water from the precipitation event back in time, arriving at the ''final source'' drier. In summary, our method calculates the moisture from the surface only, neglects the contributions from aloft, and might underestimate contributions from remote sources.

However, since the amount of water vapor contained in the boundary layer is a very large fraction of the total water vapor, we think that, in spite of its limitations, the method we adopt provides a reasonable approximation of the evaporative sources when it is used at sufficiently low resolution, and on sufficiently long time scales. The very good agreement found between the evaporative sources and the synoptic discussion suggests that there is some foundation to claim the moisture contributions from subtropical regions can be very important to Mediterranean floods. This result is in full agreement with the previous study of Krichack and Alpert (1998), which investigates the November 1994 flood. Moreover, in agreement with the study of Reale et al. (2001) on the October 1998 floods, the present study also confirms that the presence of the remnants of a former Atlantic tropical storm tracking eastward and approaching Europe can have a major impact on the moisture balance over the Mediterranean. Eastern Atlantic tropical systems, or Atlantic tropical systems tracking eastward, are therefore to be carefully monitored, since they represent a potential source of moisture that may transform even a weak midlatitude depression into a flood-producing weather system, if the synoptic and mesoscale condition is favorable. Leslie's impact is not limited to moisture advection but also involves the strengthening of a baroclinic cyclone over the British Isles, important for setting up the local conditions that cause the release of precipitation over the Piedmont region, namely, a moderate Mediterranean cyclone over the western Mediterranean inducing low-level moisture flux against the orographic barrier of the Alps and persisting for several days. However, synoptic situations locally similar to the one observed at the onset of the October 2000 event occur very often without heavy precipitation. Therefore, the large-scale environment over the Atlantic Ocean is a potential evaporative and synoptic ''conditioner,'' and the contribution of moisture that originated from a wide area in the Atlantic Ocean and in the African ITCZ in the 2 weeks before the October 2000 event is a crucial factor to produce exceptional precipitation. More sophisticated water vapor back-trajectory techniques and modeling experiments may shed more light on the mechanisms involved, possibly to reach a future operational use of the preliminary insights gained from this work.

Acknowledgments. We acknowledge support by the Italian National Research Council through the National Group for Protection from Hydrological Hazards (GNDCI) project for Applied Research in Meteo-Hydrology (RAM). This work is part of the research carried out by the first author in partial fulfillment of her Ph.D. program. We thank Dr. P. Dirmeyer for providing the water vapor tracer used in this study. Thanks are due to Drs. J. Jusem, S. Krichack, and A. Provenzale, and to two anonymous reviewers for valuable suggestions.

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