Popular summary for "Large Scale Water Vapor Sources Relative to the October 2000 Piedmond Flood. (submitted to Journal Hydrometeorology)

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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. These situations could possibly baffle the operational weather forecasters.

In this article, the major precipitation event that affected Piedmont (Italy) between 13 and 16 October 2000 is investigated. This is one of the cases in which no intense cyclone was observed within the Mediterranean region at any time, only a moderate system was present, and yet exceptional rainfall and flooding occurred.

The emphasis of this study is on the moisture origin and transport. Moisture and energy 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 two 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 towards Europe. This happens on a time-scale of about 5-15 days preceding the Piedmont event. Second, water-vapor intrusions from the African Inter-Tropical 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 hour time-scale.

Large scale water vapor sources relative to

the October 2000 Piedmont flood

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Abstract

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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 towards Europe. This happens on a time-scale of about 5-15 days preceding the Piedmont event. Second, water-vapor intrusions from the African Inter-Tropical 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 hour 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 uncertainties on both the meteorological and hydrological scales (Ferraris et al. 2002).

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, sub-synoptic scale cyclones were the cause of extreme and localized rainfall, like 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 (Reale and Atlas 2001).

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 which affected several Mediterranean countries. Buzzi et al. (1998) investigated in detail the event over Piedmont (Italy). A relatively intense cyclone was present over the British Isles, but only a moderate cyclone was observed over the Mediterranean region. Most of the precipitation was associated with a low-level prefrontal jet directed against the orography of northwestern Italy.

There are several other instances in which a sequence of heavy precipitation events can occur without synoptic features which are characteristic of intense cy-

clonic 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 which could occur on time-scales much longer than the life-time 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; 2) how, and on what time-scales, the moisture is advected towards the Mediterranean region; 3) how the moisture is conserved in the process.

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, they investigate also the floods over the eastern Mediterranean. Their study shows that large-scale sources of moisture 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 Inter Tropical Convergence Zone was involved.

Following this approach, Ferraris et al. (2001) and Reale et al. (2001) analyzed the October 1998 floods, with the aid of regional model simulations and water-vapor back-trajectories. Their results show that eastern Atlantic hurricanes, after decaying to extratropical remnants, can still impact Mediterranean weather

by advecting large amounts of moisture into the Mediterranean region. This moisture can be made available to weak or moderate mid-latitude cyclones, thus producing floods which appear much more intense than what could superficially be inferred by looking at the synoptic situation at the time in which heavy precipitation occurs.

b. The Piedmont 2000 event

In this work the flood which occurred over Piedmont (northwestern Italy) between 13 and 16 October 2000 is investigated. Between the end of September and the first ten days of November 2000 the northern Atlantic was characterized by some degree of cyclogenetic activity, with a sequence of deep and rapidly moving cyclones affecting the north-western European coasts. Several flash floods and major rainfall events occurred over many European and Mediterranean regions. Among them, the flood which 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 inundations, landslides and severe damages to civil infrastructures. The rainfall maxima, accumulated during the whole period of precipitation, was around 700-750 mm, with daily areal mean values going from 100-150 mm day^{-1} 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

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contribution of intense Mediterranean cyclones: only weak or moderate systems were observed within the Mediterranean region during the event.

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 vapor and energy budget are computed over different areas. The calculations show consistently that on a synoptic time-scale including the event itself and the few days preceding it, the total precipitation over the Mediterranean is larger than the total evaporation from the sea. This supports the idea of some contribution from outside the Mediterranean region.

Then the dynamics of the event are discussed, with the focus on possible mechanisms of large scale moisture transport and synergistic effects between the various atmospheric forcings. In particular, the roles played by the jet-stream and by the extratropical transition of the Atlantic Tropical System Leslie are investigated.

The central 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). The results support the idea of an important contribution from the tropical Atlantic region.

The main conclusion is that this precipitation event involves evaporative moisture sources on space- and time-scales larger than the ones typical of mid-latitude weather disturbances.

These findings have two implications. First, in agreement with Reale et al.

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(2001), the presence of tropical systems or their remnants in the eastern Atlantic, in proximity to the European coasts, is to be carefully monitored, since it represents a potential source of moisture which may transform a weak mid-latitude depression into a flood-producing weather system, if the synoptic and mesoscale condition is favorable. Second, that the large-scale environment over the Atlantic is a potential "conditioner" for the development of some extreme precipitation events over the Mediterranean region.

2. Regional water and energy budgets over the Mediterranean Sea

a. Previous studies

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, Rasmusson 1968, Peixoto and Oort 1991).

Mariotti et al. (2002) have recently examined the hydrology of the Mediterranean region, focusing on climatology, on interannual to interdecadal variability and on 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

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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 in 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 and the heat fluxes 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.

b.   Precipitation and evaporation before and after the Piedmont flood.

To evaluate the orders of magnitude and the possible scales involved, six target areas are chosen to compute gross moisture balances and fluxes (Fig. 1). The target area Q0 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, the areas Q2 and Q3 are aimed to investigate the Atlantic, with Q2 involving only the mid-latitude portion of the Atlantic closer to Europe, and Q3 covering the entire basin, from the Tropics to the mid-

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latitudes. Q4 and Q5 are designed to investigate possible contributions from the Indian Ocean: Q4 covers the Red Sea and Q5 includes the Arabian Sea.

Fig. 2a shows the daily values of total evaporation and total precipitation over Q0 for the period going 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 of 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 well related with the first and second event, but not as well with 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 one week before. This fact is suggestive that some other moisture contribution occurs at the time-scale of the event.

Fig. 2b shows the values of the same variables accumulated on the whole period. The contribution of land evapotranspiration to total evaporation is more than half the marine evaporation, and is therefore quite relevant. However, there is a noticeable increase in the difference between total accumulated precipitation and total accumulated evaporation, starting from 10 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. 2c) and the net moisture flux transiting through the volume enclosed by these boundaries up to the 300 hPa level. We calculate the integral in latitude (or longitude) of $\int_{p_o}^{p} V_n q \ dt \frac{dp}{g}$ on each vertical wall of Q0, where V_n and q are the 5-day averages of the normal component of the wind vector $\mathbf{V}$ and specific humidity respectively, g is gravity 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 contributions due to horizontal moisture advection.

Fig. 2c shows that moisture flux responds well to 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, together with the previous findings, some motivation for our study, being an indication that extra-Mediterranean sources of moisture are likely to be involved.

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c. Energy fluxes at the sea surface

Surface heat fluxes (latent heat, sensible heat and net heat) are calculated and compared with climatological values of the same variables over the target areas labelled as Q1..Q5 in Fig. 1 (fluxes from the ocean to the atmosphere are considered positive). Daily data and long-term monthly means from the National Center for Environmental Predictions (NCEP) - National Center for Atmospheric Research (NCAR) reanalyses data set (Kistler et al. 2001) are used.

Fig. 3 shows the 5-day average surface fluxes anomalies over each of the five areas between 15 September and 31 October 2000. At each time, the 5-day mean surface flux represents the mean during the pentad starting with that day. The following facts can be outlined:

- Fluxes are substantially higher than climatology over the western Atlantic and the Mediterranean (Q1 and Q2) and to a lesser extent over the entire Atlantic (Q3).

- The synoptic-scale variability is very evident over Q1 and Q2 (dominant wavelength of 7-8 days). Over Q3, the scale is larger than the scale of the baroclinic waves; as a consequence the synoptic signal is smoothed.

- Recalling Fig. 2a, it can be seen that energy fluxes over Q1 are quite well related with the first two precipitation events over Q0: in fact, fluxes increase and peak few days before the rainy periods occurring on target area Q0, and

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then quickly decrease and display minima during the rainfall events, possibly because of condensational cooling. This seems to indicate that these two rainfall events over Q0 are controlled by the Mediterranean. However, the third rain event in Fig. 2a, which carries the signature of the Piedmont flood, does not seem to be related with fluxes over Q1. In fact, the net flux anomaly over the area Q1 does not peak on October 7th (which represents the mean value between 7 and 11 October, just before the flood). This agrees with Fig. 2c and provides a further indication that Mediterranean evaporation is not the prominent source for the 11-16 October event, unlike what happens for the other precipitation events in Fig 2a.

- A substantial positive anomaly in the surface latent heat flux starts from the beginning of October over the Atlantic ocean (areas Q2 and Q3). Over both areas there is a large peak right on October 5-10 (Fig. 3) which represent the average of the 5 days preceding and during the floods. Considering the enormous extension of target area Q3, the anomaly is very remarkable, and provides an insight on the potential involvement of Atlantic moisture in the mechanisms leading to the Piedmont flood. The anomalously high sea surface temperatures (SSTs) over the Atlantic contribute to the intense latent heat fluxes and also possibly to the anomalous life-cycle of the tropical-storm Leslie, which approaches the European coasts during the first ten days of October, as it will be discussed in the next sections.

- Surface heat fluxes over Q4 and Q5 (Red Sea and Arabian Sea) do not show

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any pattern obviously related with the October 2000 Piedmont flood.

3. Synoptic analysis

The synoptic situation is herein briefly discussed using the National Centers for Environmental Predictions (NCEP) operational analyses at 1° resolution. At 0000 UTC 10 October, the dominant feature is a deep cyclone close to the occlusion stage over the British Isles (Fig. 4a,b). The cyclone appearing on the extreme left of Fig. 4b is the extra-tropical remnant of the former tropical storm Leslie (Franklin and Brown 2000). In the subsequent hours, as it will be discussed later, the remnant of Leslie merges with the cyclone and re-intensifies it. By 0000 UTC 11 October 2000, the cyclone over the British Isles has substantially deepened (Fig. 4c,d). At 0000 UTC 12 October 2000, a profound change occurs in the circulation: a predominantly northerly or northwesterly low-level flow can be inferred from the surface map; geopotential falls aloft in relation to low-level cold advection and a sharp trough with axis elongated from the north-east to the south-west direction forms at 500 hPa (Fig. 4e,f). At 0000 UTC 13 October the deepening of the mid-tropospheric trough accentuates (Fig. 5a) 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 mid-troposphere, warm advection over eastern Europe, and cold advection from Ireland to the Iberian Peninsula can be inferred from the sea level pressure map (Fig. 5b).

At this point, an upper-tropospheric feature becomes important: a markedly cyclonically-curved jet-stream affects the western Mediterranean, as it will be

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shown later, and as a consequence a cutoff low is isolated and a small-scale baroclinic lee-cyclone is formed on the Gulf of Lion at 0000 UTC 14 October. The cyclone deepens slightly and moves eastward in the next 24 hours (Fig. 5c,d,e,f). In this work it will be shown that this small-scale cyclone, although of only moderate intensity, is important to transport and concentrate into the Mediterranean region the moisture previously generated with the contribution of different mechanisms on larger time- and space-scales. At the same time, the cyclone over the British Isles rapidly dissipates suggesting some transfer of energy from the British Isles to the newly formed low in the Mediterranean.

In Fig. 6 the 250 hPa wind is shown. The jet-streak in Fig. 6a is probably responsible for steering the extra-tropical remnants of tropical storm Leslie towards the British Isles, as it will be shown later. The reinvigoration of the cyclone (Fig. 4d) at 0000 UTC 11 October leads, in the following 24 hours, to increased low-level cold and warm advection on either side of the cyclone (Fig. 4f), and to a deepening trough aloft (Fig. 4e), which contributes to drive the jet stream into a sharp shortwave over the western Mediterranean (Fig. 6c,d). At 1200 UTC 13 October and 0000 and 1200 UTC 14 October the two jet-streaks on both sides of the meander (Fig. 6f,g,h) are in a favorable position to induce a coupled circulation (Uccellini and Kocin 1987) which can provide some support to the developing Mediterranean cyclone (Fig. 5d) and might be a cause of its moderate deepening (Fig. 5f). Moreover, subsidence caused by the descending branch of the transverse circulation associated with the exit region of the jet streak located over France between the 12th and 13th of October (Fig. 6c,d,e) probably contributes to the

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increasing sea level pressure over the Balkans (Figs. 4f and 5b). The anticyclone over the Balkans is important in blocking the eastward progress of the Mediterranean cyclone and in driving a predominantly southerly flow towards the Alpine region, thus increasing low-level moisture flux convergence.

In Fig. 7 the specific humidity and the wind direction 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 towards the Alpine region, in agreement with Fig. 5b,d. More interesting is the *plume* of tropical moisture which 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 mid-tropospheric contribution can indeed be very important for the flood. In Fig. 8 the 925 and 850 hPa moisture flux convergence and wind are shown, confirming the accumulation of moisture taking place in the lower levels, enhanced by orographic uplifting. The microwave satellite image (Fig. 9) confirms the mid-tropospheric inflow of tropical moisture within the Mediterranean region.

4. Dynamical considerations

a. The role of upper-level jet

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, Uccellini and Kocin (1987) show how the indirect and di-

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rect transverse circulations, located in the exit and entrance regions of the northern and southern side of the jet streaks, respectively, are related with the rising/sinking motions on the cyclonic/anticyclonic side of the jet. Mattocks and Bleck (1986), on the other hand, 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.

In agreement with these earlier works, it can be observed that two upper-level jet-streaks generated on both sides of the trough are tightly coupled and might contribute to the surface pressure fall over the western Mediterranean (Fig. 6g, h) and on the formation of the cyclone over the Gulf of Lion (Fig. 5d,f). However, the corresponding upper-level divergence is not very strong (not shown) and there is not perfect alignment between the low-level and the upper-level vorticity maxima; so the deepening of the cyclone is only moderate.

b.   The role of Leslie

Tropical Storm Leslie develops from a subtropical depression appearing off the east coast of Florida at 12 UTC on the 4th of October 2000 and remains almost stationary for about 24 hours. On the 5th, the subtropical depression tracks east-ward and intensifies, becoming a weak tropical storm (Franklin and Brown 2000), embedded in a wide area of warm-moist air. On the 7th of October a wide 500-hPa trough over the U. S. begins to slowly rotate counterclockwise as a steep cold frontal boundary approaches the tropical storm. The surface circulation associated with Leslie begins to elongate and the cyclone is gradually entangled with

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the front, until by 18 UTC it becomes extratropical (Franklin and Brown 2000).

In the first phase of the extra-tropical transition Leslie maintains 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 is at about 335 K or more (not shown). As the upper-level trough begins to rotate its axis counterclockwise, Leslie accelerates its motion northeastward, steered by the baroclinic wave. However, the equivalent potential temperatures θ_e provides an indication of an intrusion of tropical warm and moist air in the mid-latitudes, induced by the northward and eastward motion of the remnant of Leslie. Fig. 10 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 Fig. 11, the position of Leslie's extratropical remnant is shown together with 300 hPa wind, sea level pressure and surface latent heat fluxes. The storm appears to be steered by the jet-stream and crosses the Atlantic at a remarkable speed. The fast speed is also related with strong deepening. Between 18 UTC 09 October and 18 UTC 10 October the extratropical storm deepens by 30 hPa, and it can be classified as a "bomb" (Sanders and Gyakum 1980). The deepening phase occurs over an area with strong positive Sea Surface Temperature (SST) anomalies (Fig. 12). Diabatic processes might have played a role in rejuvenating the system through latent and sensible heat release and convection development. The resulting strong surface latent heat fluxes might also have helped to keep the boundary layer equivalent potential temperature (θ_e) close to the saturated equivalent potential temperature of the underlying sea surface temperature.

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At 1800 UTC 10 October 2000 the remnant of tropical storm Leslie merges into the center of a large-scale, preexisting, baroclinic cyclone over the British Isles. The merging coincides with the peak of intensification: the sea level pressure reaches 966 hPa and the related low-level winds strengthening, together with a possible increase in air-sea temperature difference, causes a further increase in latent heat flux particularly evident from 0000 to 1800 UTC 10 October (Fig. 11c,d,e,f).

The contribution of Leslie is two-fold: on the one hand it advects moisture in its wake, on the other hand, it contributes to rejuvenation of the cyclone over the UK. The rejuvenation causes a sudden increase in cold-air advection which creates a deep trough aloft, which contributes to drive the jet stream into a tight meander over the Mediterranean. The meander provides a favorable environment for a moderate cyclone to develop, 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.

In summary, it is likely that intrusions of moist air masses coming from the Inter Tropical Convergence Zone are involved. Therefore, we use a water-vapor back-trajectory technique, to investigate surface evaporative sources and transport of moisture contributing to the October 2000 flood event.

5. Moisture sources for the Piedmont 2000 flood event

a. Method

We adopt a kinematic quasi-isentropic trajectory technique documented in Dirmeyer and Brubacker (1999), used by Reale et al. (2001), Brubacker et al. (2001), 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 amount of parcels from each specified grid square i where precipitation has occurred at a certain timestep; each parcel represents a unit of precipitation in the grid box i.

The number of parcels launched at each gridbox where precipitation occurs is proportional to the local precipitation rate. If precipitation persists for several timesteps, parcels are launched back in time from each time step, throughout a time interval minor 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 being started at $\sigma \leq c$ is

$$P_c = 1 - \frac{PW_c}{PW_i} \tag{1}$$

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

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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 timestep 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 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 timestep 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 have been lost, or (b) until they reach the border of a domain, or (c) for a prescribed maximum number of days (parameter *nday*), 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 gridpoint where precipitation occurs (ii) a **trac-**

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ing domain (TD), which is the maximum domain where evaporative sources are searched. The precipitation domain PD investigated in this study ranges from $1.875°$ to $15°E$ and from $41°$ to $48.6°$ N, enclosing the area affected by the 13-16 October 2000 event. The tracing domain TD in which the evaporative sources are searched ranges from $90°W$ to $90°E$ and from $14°S$ to $73°N$.

The wind and temperature fields used are from the 6-hourly global atmospheric analysis produced by the NCEP-NCAR reanalysis project (Kistler et al. 2001) at T62 horizontal resolution, linearly interpolated on 28 vertical layers (sigma levels). Precipitation fields are also from the NCEP-NCAR reanalyses. 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 5-day period (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 *nday* 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.

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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. 13 the accumulated evaporative sources contributing to the precipitation occurred over the PD (extending from $1.875°$ to $15°E$ and from $41°$ to $48.6°$ N) are represented, and the area integrals of the evaporative sources are computed over the entire TD and over some sub-domains (Atlantic A, Mediterranean M, Land L, western Atlantic WA, north-eastern Atlantic NEA and Africa AFR).

The following results are obtained:

- About 50% of the evaporative sources contributing to the precipitation occurred between 18 UTC 09 October and 18 UTC 14 October over the PD lies within one day before the beginning of the pentad, i.e., within six days before the end of the event (Fig. 13a) and is mostly located near the Atlantic European coasts (approximately 30%) and in the Mediterranean (about 20%).

- Parcels need to be tracked backward at least for 7 days prior to the beginning of the pentad (18 UTC 09 October) i.e. until 18 UTC 02 October, in order to recover more than 90% of the moisture sources contributing to precipitation (Fig. 13c)

- By changing the *nday* parameter from 1 day up to 10 days, the fraction of Mediterranean contribution is unchanged (20%), whereas the contribu-

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tion from the Atlantic increases significantly: in particular, there is even an evaporative contribution from the sub-domain western Atlantic (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 (*nday*=15) brings a more modest increase in evaporation from the Atlantic (Fig. 14); this suggests that the time-scale characteristic of the event is of the order of two weeks. Fig. 14 is therefore the most meaningful representation of the evaporative moisture sources for the Piedmont flood event. On the same figure, the track of the tropical storm Leslie, before and after its conversion into extra-tropical, is superimposed to the sources. About 60% of evaporation contributing to the precipitation fallen over the PD originates from the north-eastern Atlantic (40%) and the Mediterranean basin (20%). However, a substantial amount of evaporation can be re-conduced to a larger spatial scale, extending from Florida to the whole north Atlantic: 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 could be re-conduced to the intrusion of tropical air which follows the remnants of Leslie and to the enhanced evaporation caused by its redevelopment (recall Fig. 10). Another relatively small but interesting contribution is from the African ITCZ, namely from the Sahel region. It is important to stress then that only the 20% of the total precipitation accumulated during the pentad over the PD originated from the Mediterranean basin.

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, or even dominant (not shown). Reale et al. (2001) have 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.

The sources shown in Figs. 13 and 14 which represent evaporation accumulated over a relatively long amount of time with respect of the time-scale of the event match generally well with the overall low-level circulation inferred from the synoptic discussion. In Fig. 15 we show instead the evaporation collected at individual time-steps: the values are perhaps less representative because 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) show evaporative contributions from the western tropical Atlantic, consistently with the formation of a broad region of moist convergence and sporadic and disorganized thunderstorms (Franklin and Brown 2000), in which T. S. Leslie develops. As long as we move forward in time showing time-steps of the back-trajectory calculation closer to the event (Fig. 15a,b,c,d,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 her wake (recall Fig 10).

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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 British Isles, the evaporative contributions associated with the extra-tropical remnant of Leslie and with the cyclone over the British Isles seem to merge together (Fig. 15f) even before the two cyclones do.

The sources and time-scales found can provide some insights on the mechanisms involved. Although a more rigorous study would require some modeling experiments, a tentative description of the evaporative processes concurring to the rainfall occurred between 10 and 16 October 2000 is here outlined:

1. A large-scale contribution on a spatial scale of $5 \times 10^3 - 10^4$ km and 5-10 days or more is related 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 which is typically associated with extra-tropical remnants of former tropical storms contributes to reinvigorate a cyclone over the British Isles.

2. Contributions from the eastern Atlantic and the Mediterranean, and from the African ITCZ, occur on a spatial scale of about 5×10^3 km and a time-scale of and 2-5 days.

3. Local contributions, with the aid of possible recycling processes within the PD, dominate the time-scale of 1-2 days.

A caveat 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 non-precipitating middle-level clouds (*tropical plumes*), associated with 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 7 and 9). As a consequence, the evaporative contribution from the African ITCZ is probably under-estimated by our tracing method.

6. Conclusions

In this study we investigate the role of large scale moist dynamics on the development of a major flood event which affected predominantly 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 two 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 extra Mediterranean sources of moisture 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 Inter Tropical Convergence Zone.

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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, was of extra-Mediterranean origin. Particularly, more than 60% of the evaporation contributing to the precipitation over the analyzed region comes from the Atlantic. This is in sharp contrast with evaporative sources that are found during 'normal' precipitation events, in which Mediterranean evaporation dominates.

Moreover, this study suggests that moisture contributions from sub-tropical regions of the Atlantic can be very important. In particular, in agreement with previous works, it is found 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.

Leslie's impact is not limited to moisture advection, but also involves the strengthening of a baroclinic cyclone over the British Isles. This is important for setting up the local conditions which cause the release of precipitation. In fact, increased low-level cold and warm advection related to this cyclone contribute to the formation of a deep upper-level trough over the western Mediterranean and a ridge over the central Mediterranean and the Balkans. The trough and the ridge create the actual local conditions for the Piedmont flood: 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, the most important factor is the large-scale moisture dynamics. Systems similar to the moderate Mediterranean cyclone observed at the onset of the

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October 2000 event occur very often without heavy precipitation. It was the contribution of moisture that originated from a wide area from the tropical Atlantic to the African ITCZ in the two weeks before the October 2000 event, which made this unimpressive system capable of producing a very high amount of precipitation.

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Target areas

Figure 1: Target areas where regional water balance and surface fluxes are computed.

Figure 2: a) Daily evaporation and precipitation [10^{13} kg] over Q0; b) accumulated values of the same variables over Q0; c) net moisture 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 by 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 Reanalysis daily surface latent heat flux [$Watt$ m^2].

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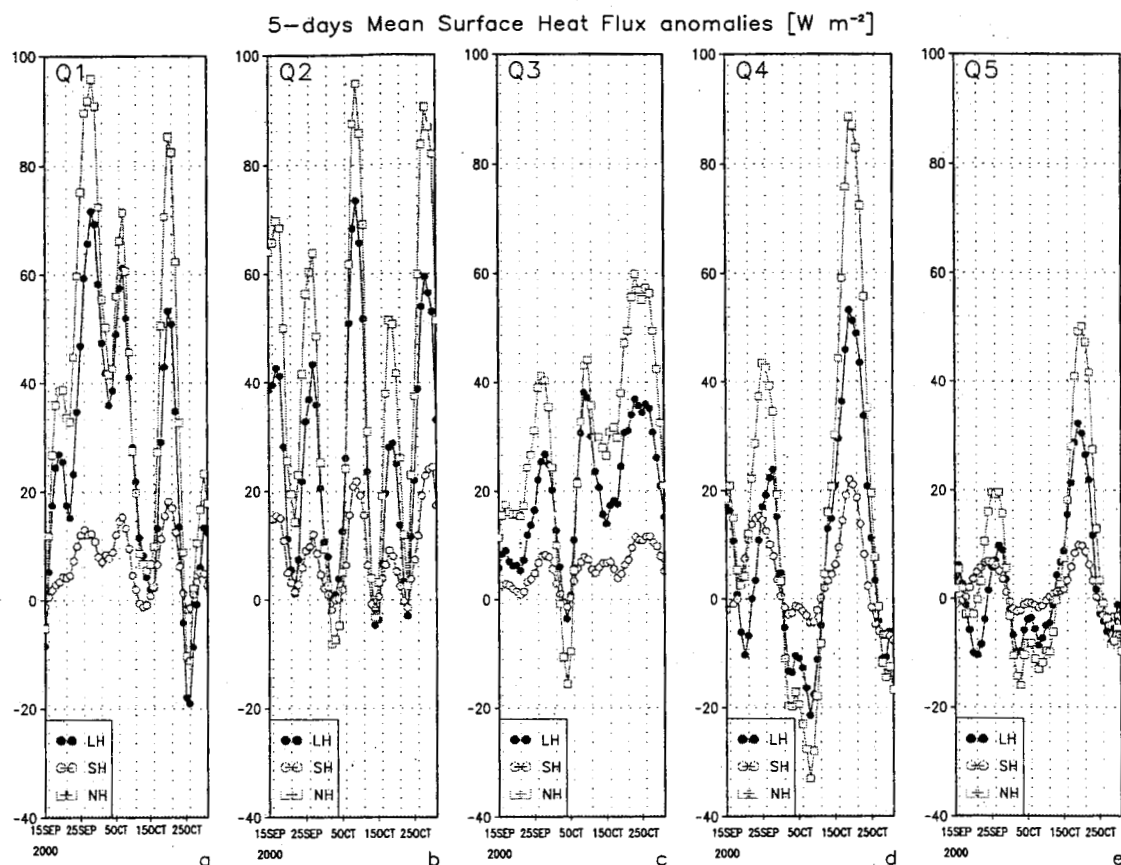
Figure 3: a-e) Surface Latent Heat, Sensible Heat and Net Heat fluxes anomalies over target areas Q1-Q5 $[W\ m^{-2}]$ (the fluxes are masked over land).

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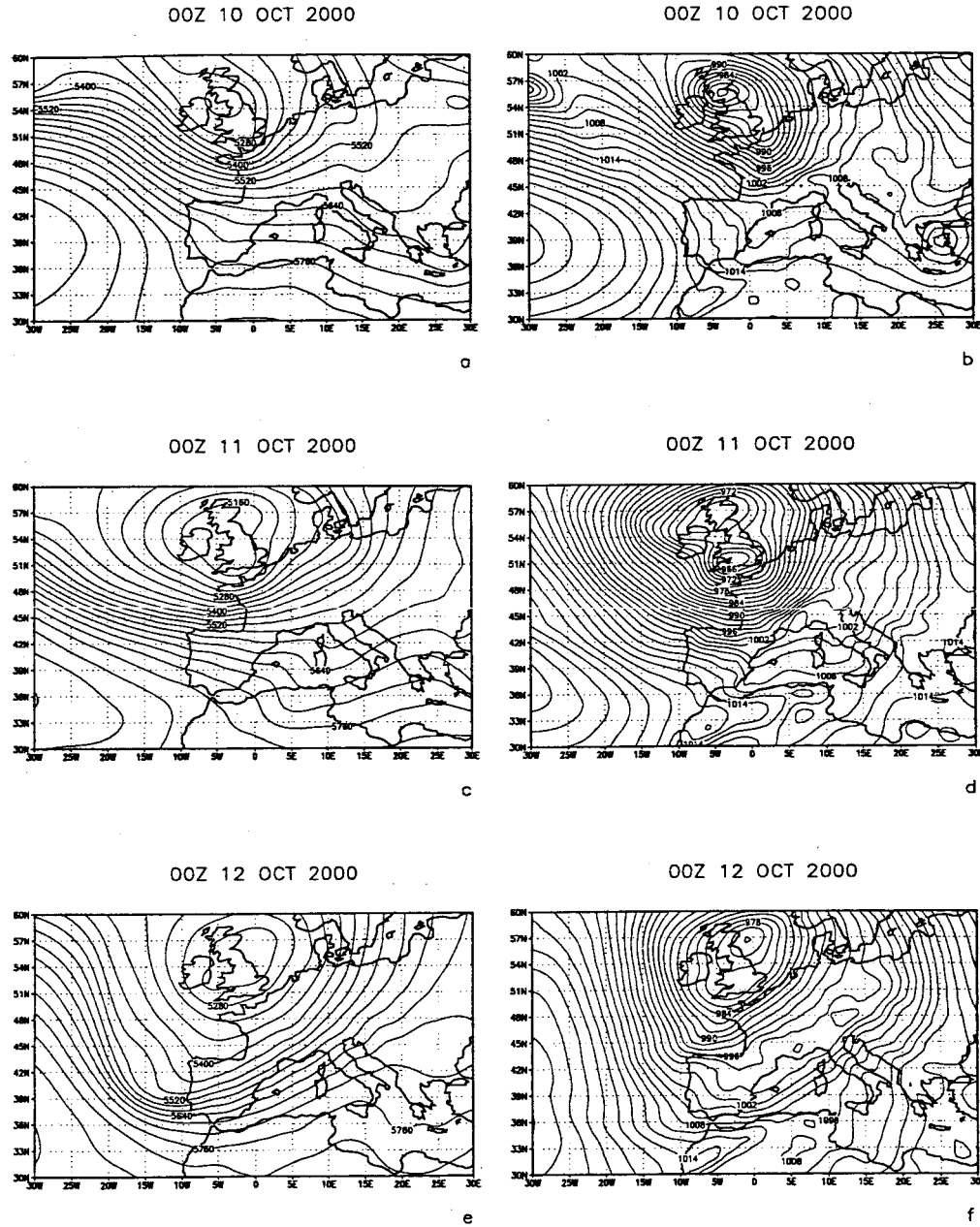
Figure 4: 500 hPa geopotential height [m] (left panels) and sea level pressure [hPa] (right panels) at 00Z 10 October (a,b), 00Z 11 October (c,d) and 00Z 12 October 2000 (e,f). Contour interval 40 m for geopotential height, 2 hPa for sea level pressure.
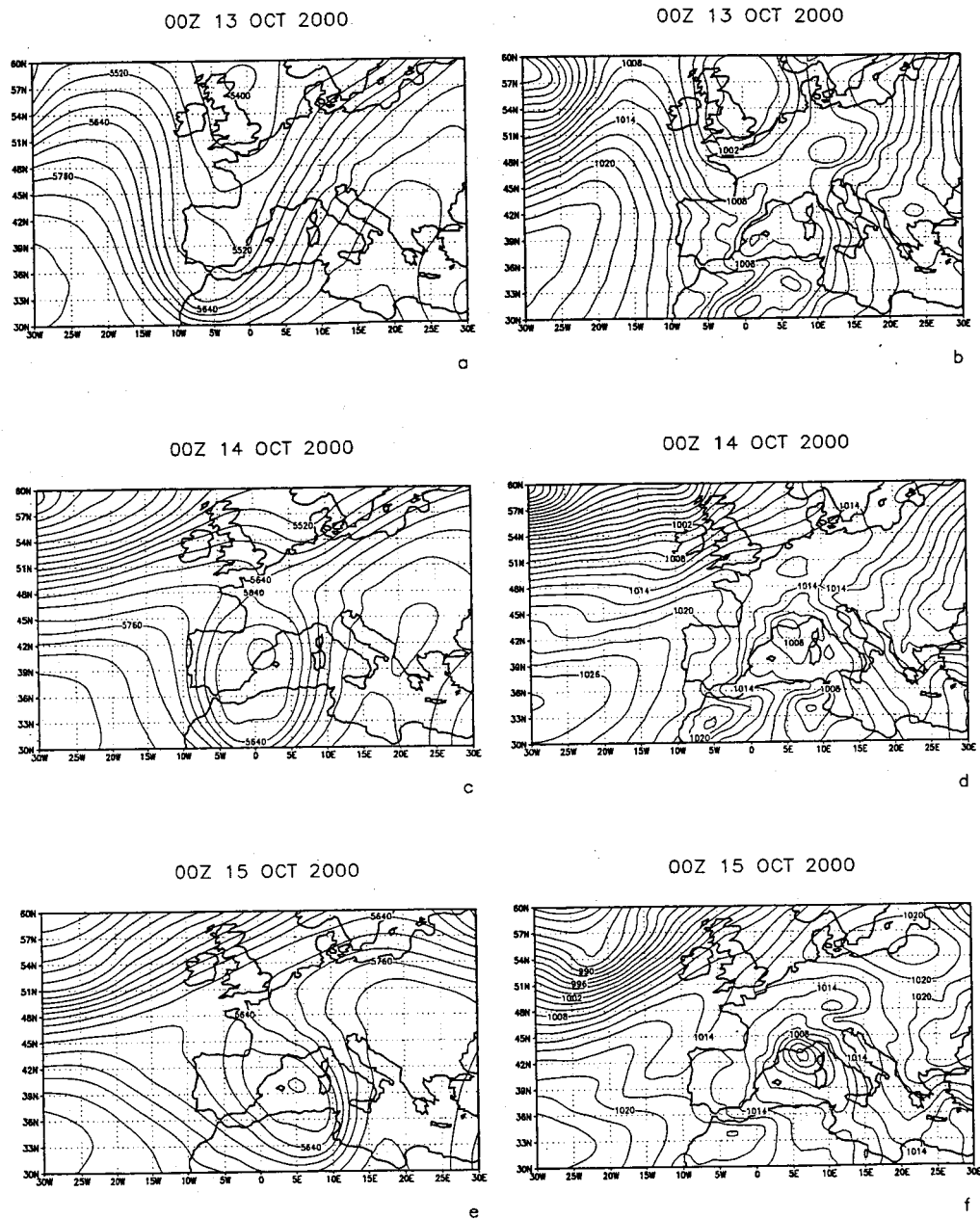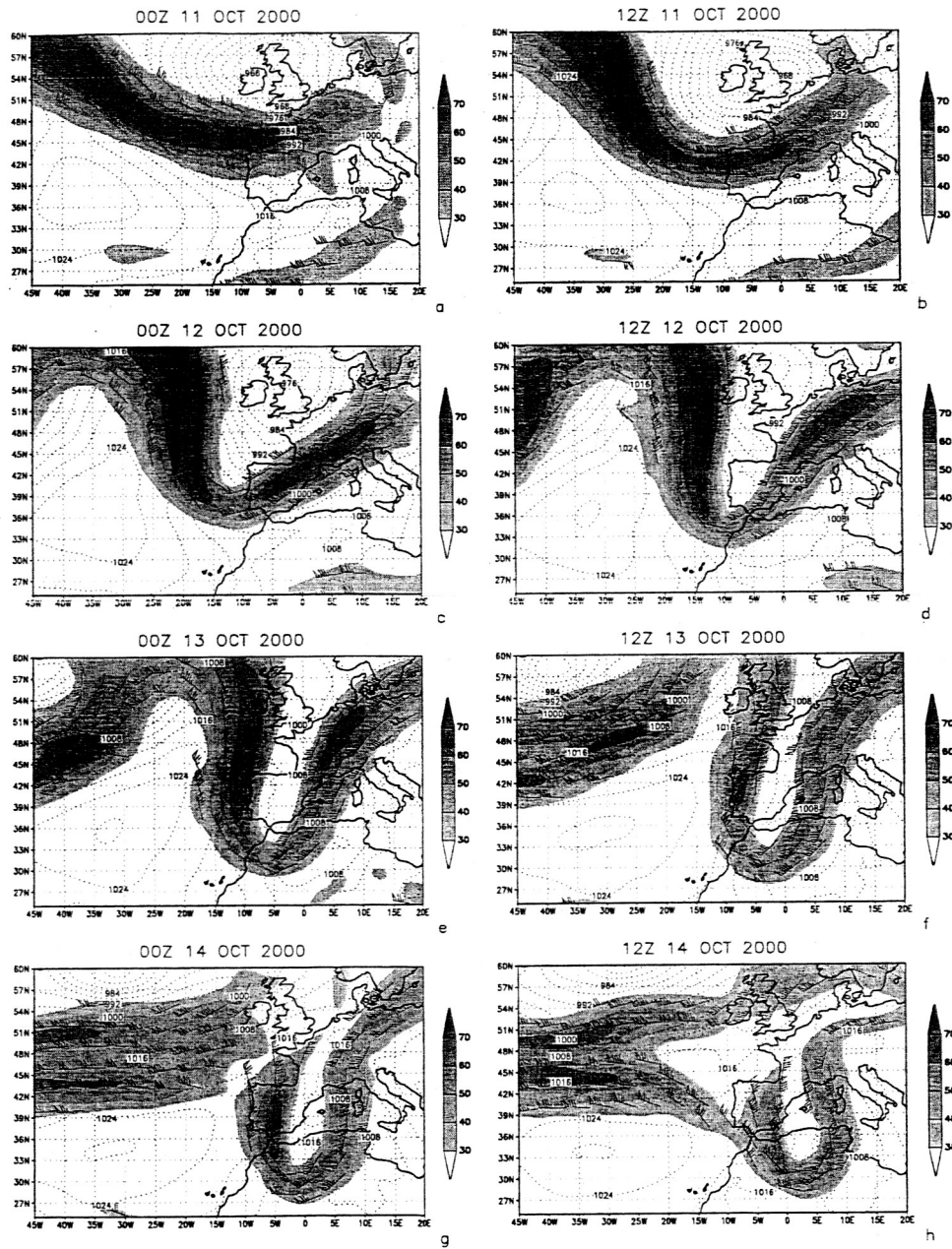
00Z 13 OCT 2000

00Z 13 OCT 2000

00Z 14 OCT 2000

00Z 14 OCT 2000

00Z 15 OCT 2000

00Z 15 OCT 2000

Figure 5: 500 hPa geopotential height $[m]$ (left panels) and sea level pressure $[hPa]$ (right panels) at 00Z 13 October (a,b), 00Z 14 October (c,d) and 00Z 15 October (e,f). Contour interval 40 m for geopotential height, 2 hPa for sea level pressure.

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Figure 6: 250-hPa wind with speed greater then 30 $m\ s^{-1}$ (shaded and barbs); sea level pressure [hPa] (dotted) from 00 UTC 11 October to 12 UTC 14 October.
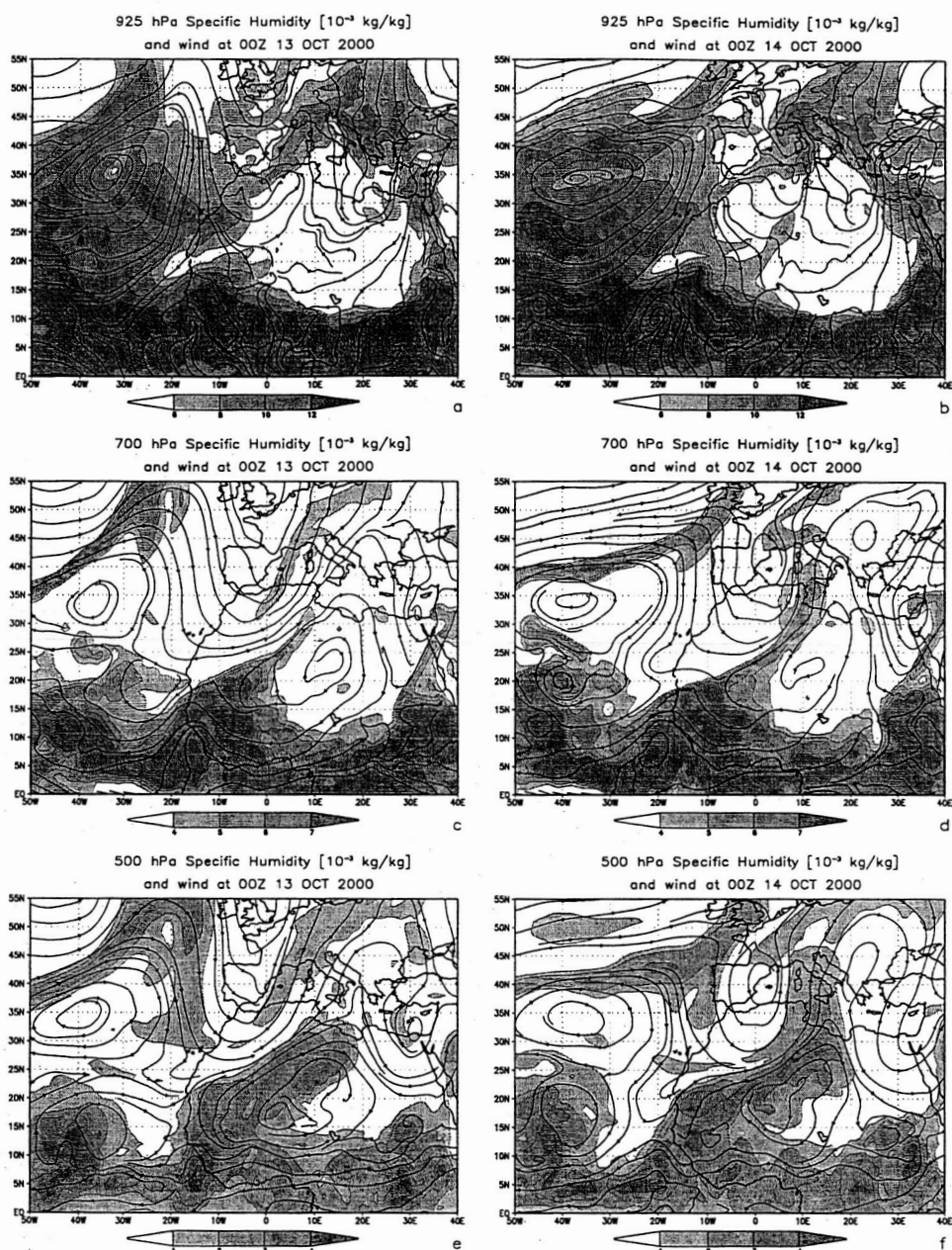
Figure 7: Specific humidity $[10^{-3} \; kg \; kg^{-1}]$ (shaded) and wind streamlines at 925- (a, b), 700- (c, d) and 500 hPa (e, f), at 00Z 13 October (left panels) and 00Z 14 October 2000 (right panels). Note the different contour intervals for specific humidity at different levels.
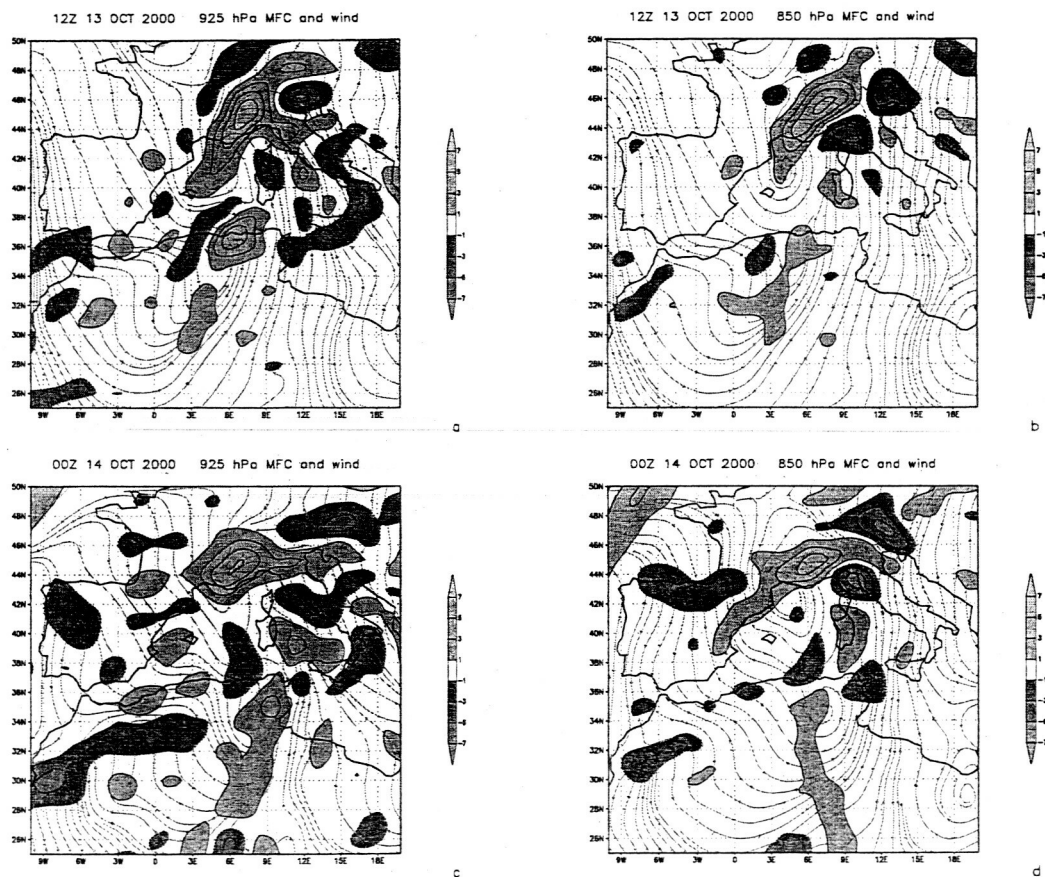
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Figure 8: Moisture flux convergence [$10^{-7}\ s^{-1}$] and wind at 925- (left panels) and 850-hPa (right panels) at 12 UTC 13 October (upper panels) and 00 UTC 14 October (bottom panels).

Figure 9: Meteosat satellite Image in the WV wavelengths (range 5.7 to 7.1 microns) referred to 23 UTC 14 October 2000, showing humidity advection from Atlantic and from African Inter Tropical Convergence Zone (ITCZ). Courtesy of EUMETSAT, through University of Nottingham, United Kingdom.
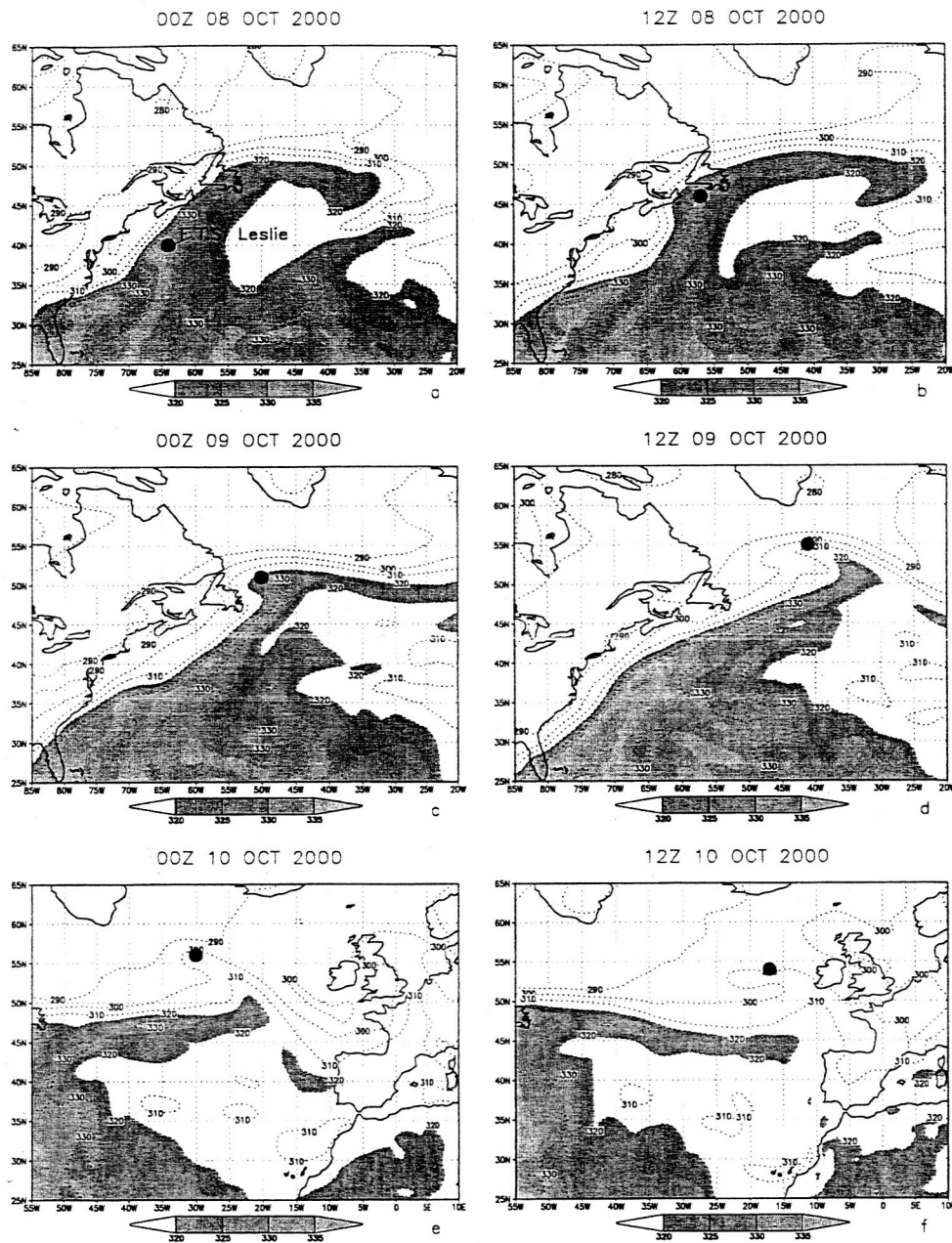
Figure 10: 850 hPa Equivalent Potential Temperature [K] (shaded with contour interval at 5 K and dotted lines with contour interval at 10 K). Position of the extratropical remnant of former tropical storm Leslie, according to the National Hurricane Center (NHC) best track (black dots).
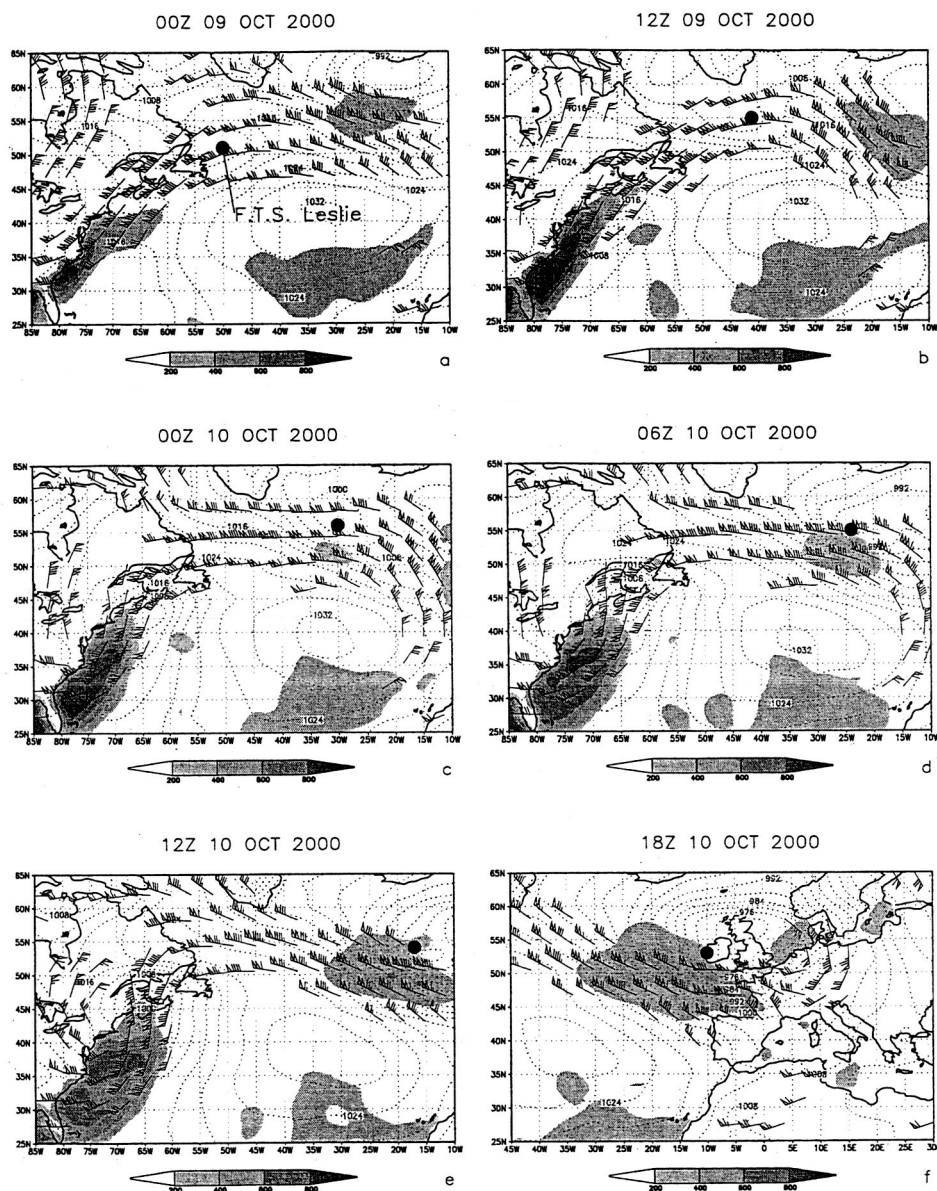
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Figure 11: Surface Latent Heat Fluxes [$W\ m^{-2}$] (values greater than 200 $W\ m^{-2}$ are shaded), Sea Level Pressure (contour interval of 4 hPa) and 300-hPa and wind (greater then 30 $m\,s^{-1}$). Position of the extratropical remnant of former tropical storm Leslie, according to NHC best track (black dots).

Sea Surface Temperature Anomaly [°C]
from 08 OCT to 14 OCT 2000

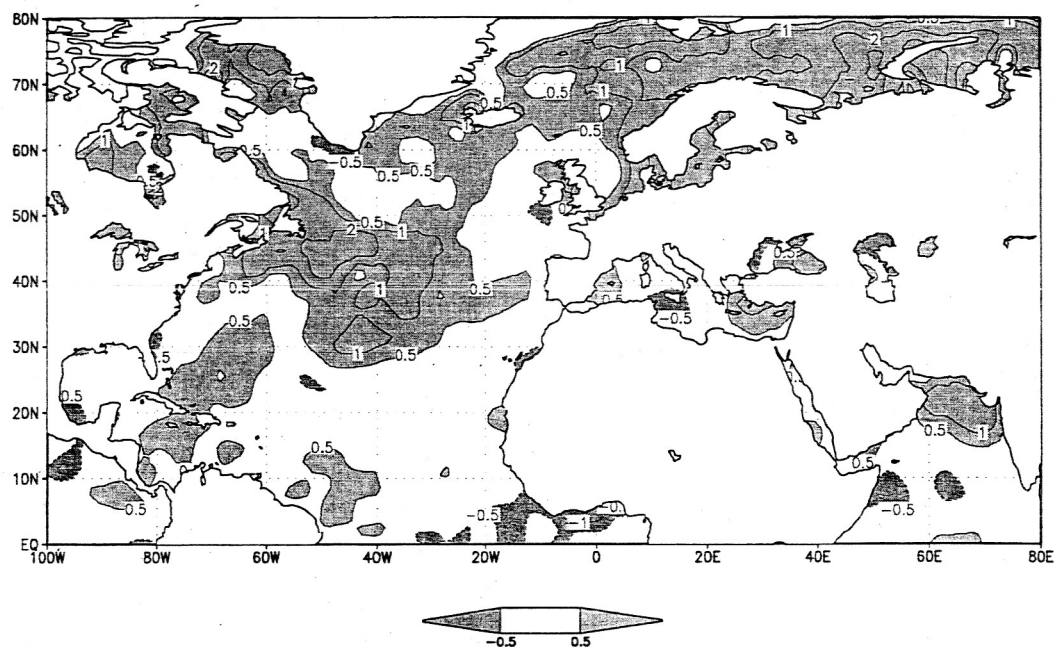
Figure 12: Weekly Sea Surface Temperature Anomaly [^oC] from 08 October to 14 October 2000. The weekly data of the optimum interpolation (OI) sea surface temperature (SST) analysis are produced by Climate Diagnostics Center, NOAA/OAR/CDC. The climatological values used for the computation of the anomaly are given by the long-term daily mean dataset, derived from data for 1982 - 1996.
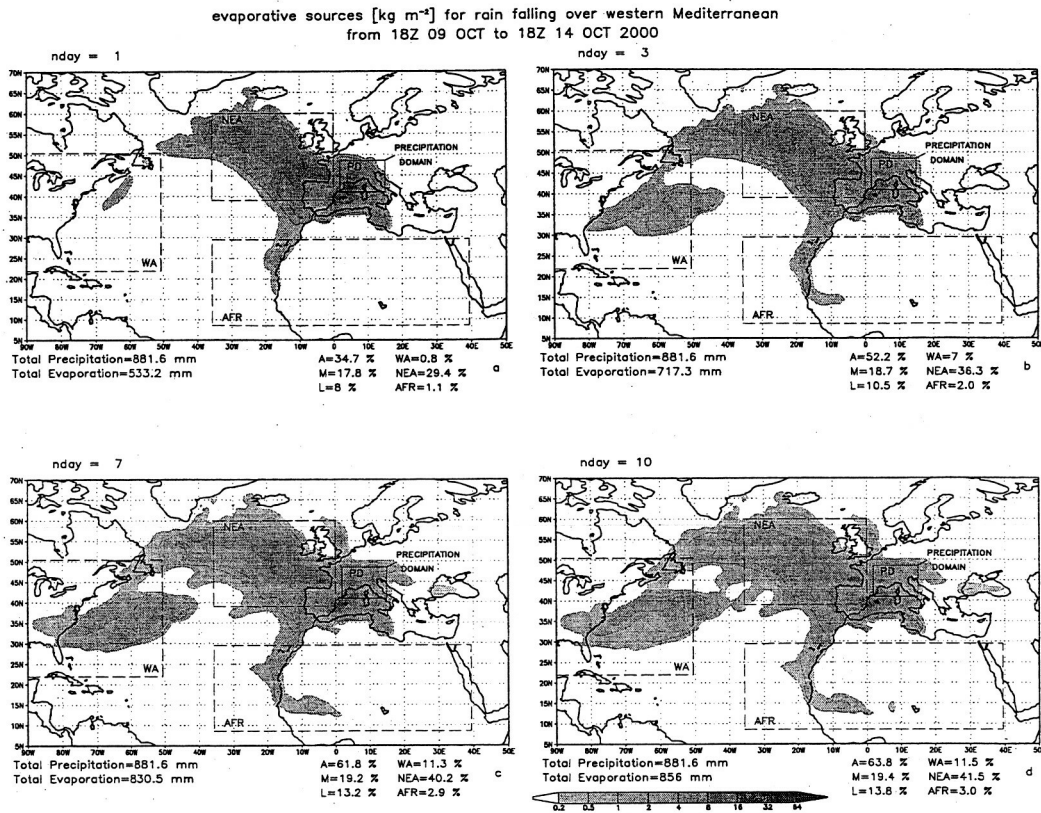
evaporative sources [kg m⁻²] for rain falling over western Mediterranean
from 18Z 09 OCT to 18Z 14 OCT 2000

Figure 13: Accumulated evaporative moisture sources ($[kg\ m^{-2}]$, equivalent to mm of liquid water) collected over the tracing domain TD for rain falling over the precipitation domain PD. Sources obtained for different values of the *nday* 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 bottom left of the panel; fractional evaporative sources computed over sub-domains A (Atlantic, from latitude 5°S to 70°N, only sea points), M (Mediterranean, from 30° to 50°N and 5°W to 40°E, only sea points), L (Land, all land points in the entire TD) and WA (Western Atlantic, land and sea points), NEA (north-eastern Atlantic, only sea points), AFR (northern Africa, land and sea points) as marked on the map, are on bottom right of each panel.

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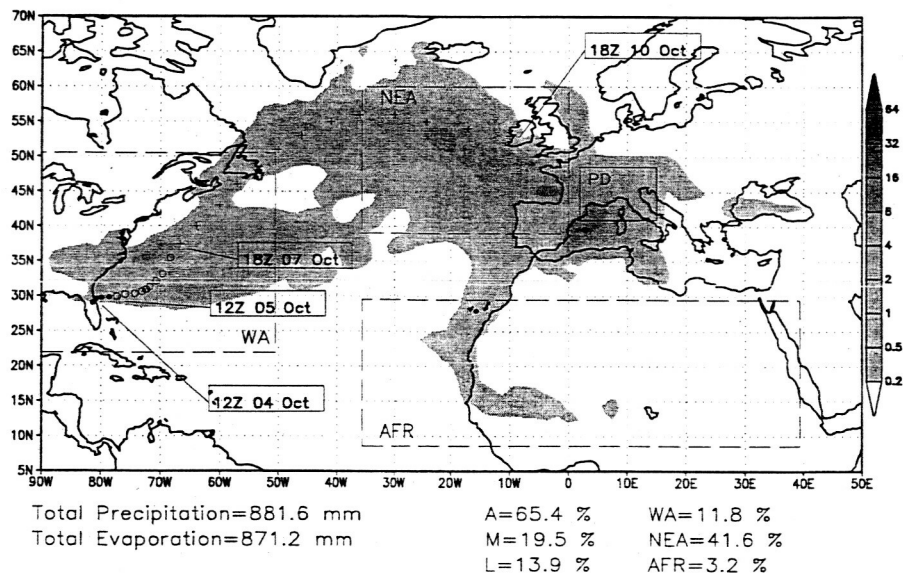Evaporative moisture sources [kg m⁻²] for rain falling

from 18Z 9 OCT to 18Z 14 OCT 2000

Figure 14: Accumulated evaporative sources ($[kg\ m^{-2}]$) collected over the entire TD and contributing to rainfall over PD during the period 10-14 October 2000 for *nday*=15. Fractional contributions computed over the same sub-domains as in Fig. 13. Track of Tropical Storm Leslie (from the National Hurricane Center) from 4 October to 10 October 2000, at various stages: subtropical depression (dot), tropical storm (circle), extra-tropical system (cross).
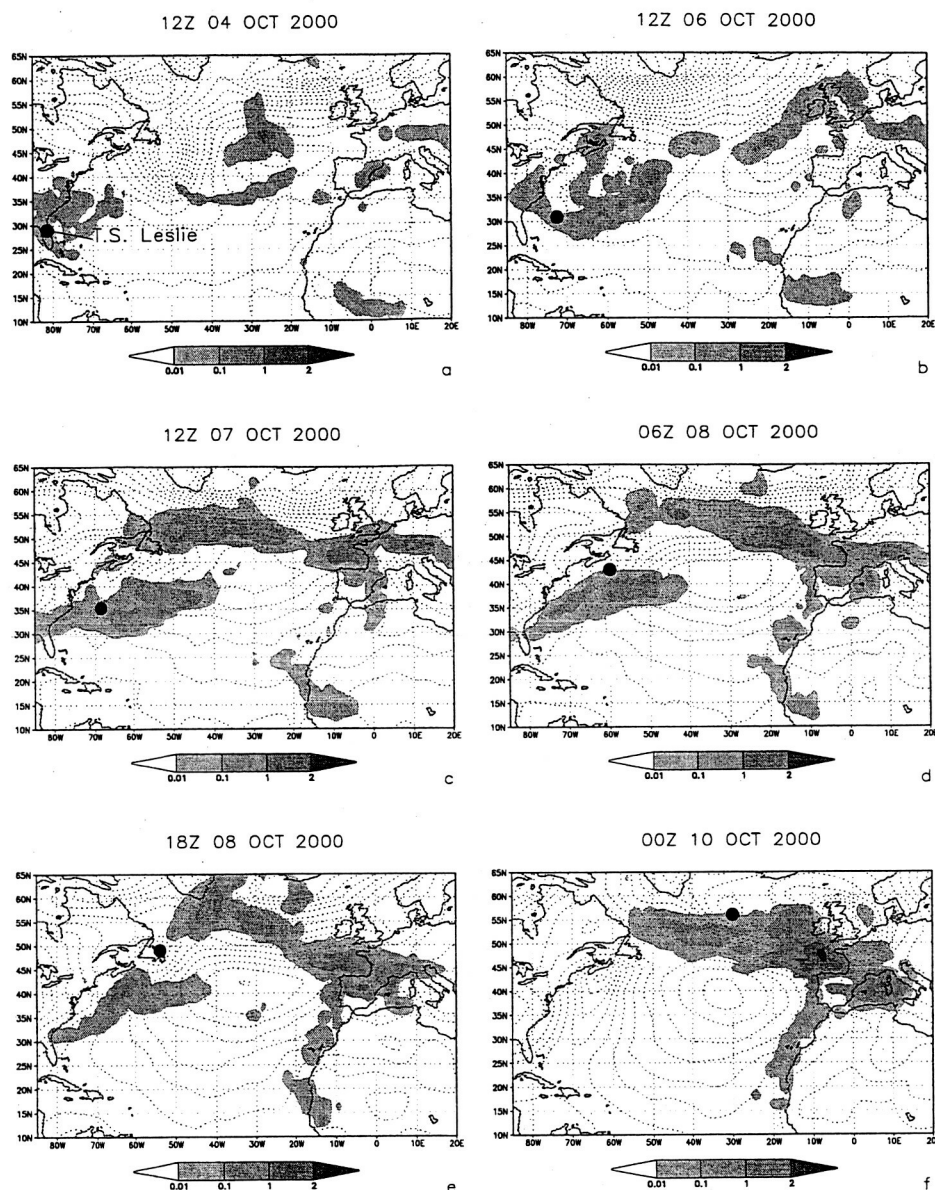
Figure 15: 6-hourly evaporative moisture sources (values greater than $10^{-2}\ kg\ m^{-2}$ are shaded) and sea level pressure (dotted line, contour interval every 3 hPa) at a) 12 UTC 04 October, b) 12 UTC 06 October, c) 12 UTC 07 October, d) 06 UTC 08 October, e) 18 UTC 08 Oct, f) 00 UTC 10 October 2000. Position of Leslie, from NHC best track (black dots).