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Role of large scale moist dynamics in November 1-5, 1994, hazardous Mediterranean weather

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Abstract. Investigation of the role of moist dynamics in the atmospheric processes during the abnormally intensive stormy period of November 1-5, 1994, over the Mediterranean region is presented. Analysis focuses on the eastern Mediterranean area employing 96-hour model predictions over the Mediterranean region with the Florida State University (FSU) global spectral model. Sensitivity simulations differ only by prescribing the initial moisture fields in the selected regions located in the Arabian Sea, Red Sea, and over large areas in the low and high latitudes. Both the tropospheric trajectories and the model tests suggest that the heavy rains over the eastern Mediterranean were associated with unusually intensive propagation of air masses from the Arabian Sea region, which took place before and during the first 24 hours of the period. Air masses from the Arabian Sea participated also in the intensive developments in Italy and southern France on November 5, 1994. According to the model simulations the convective processes over the equatorial Africa play a major role in the developments. Also, the intensification of the upper tropospheric westerly winds due to the convection over the equatorial Africa stimulates the northward extension of the Red Sea trough which consequently diminishes the moisture influx for the tropical convection and therefore seems to serve as a negative feedback.

1. Introduction

During the 4-day period of November, 1-5, 1994, intensive rains, floods, and strong winds took place in Egypt, Israel, Italy, France, and other countries of the Mediterranean region [*Buzzi and Tartaglione*, 1995; *Doswell et al.*, 1997; *Krichak et al.*, 1997a; *Kallos et al.*, 1997; *Lionetti*, 1996]. As stated by *Obasi* [1997], "heavy rains affected wide parts of Egypt, including the Sinai Peninsula, in November 1994. In that event more than 500 people lost their lives and large areas were inundated... Torrential cloudbursts, reported to be the worst experienced in 80 years at some locations, caused severe, widespread flooding and landslides in southeast France, Corsica and northwestern Italy during the four-day period in early November 1994."

Another period with extremely heavy rainfall took place over Greece several days earlier, on October 21-23, 1994 [*Lagouvardos et al.*, 1996; *Preserakos and Ralli*, 1997]. The analyses show that all these events had similar main characteristics associated with very intensive advection of warm, moist air masses.

The current study focuses on the role of the moist air mass dynamics in the formation of the intensive synoptic processes of this period over different areas with emphasis on the eastern Mediterranean. The Florida State University global spectral model (FSUGSM) described by *Krishnamurti et al.*, [1993] is used for simulation of the processes. Results of the simulation are explored by means of trajectory analysis and synoptic considerations. The role of moist dynamics is analyzed in a series of model sensitivity tests with modified initial moisture fields. It should be pointed out that a large part of the area around the Mediterranean region, especially over the African continent, is nearly data void. In this situation it was considered appropriate to concentrate the investigation on analysis of the comparatively coarse mesh model simulation results with less emphasis on comparison with the available observations. Much higher resolution simulations of the November 1-3, 1994, central and eastern Mediterranean weather conditions, where the same GSM results are used as a source of initial/boundary data (discussed separately), describe the real situation with a high degree of accuracy [*Krichak et al.*, 1997a].

Results of the unperturbed global simulation are discussed first in the following sections 3-4. The sensitivity simulations are discussed in section 5. In section 6, analysis of the results is performed.

2. Model and Organization of Experiments

2.1. Short Description of Model

The FSUGSM [*Krishnamurti et al.*, 1993] is used for the simulations. The model is adapted for the Cray J932 computer of the Israeli Inter-University Computing Center. The hydrostatic atmospheric global spec-

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tral model of the Florida State University has the following main characteristics: (1) independent variables, (x,y,sigma,t); (2) dependent variables, vorticity, divergence, surface pressure, vertical velocity, temperature, and humidity; (3) horizontal resolution, T106 spectral truncation; (4) vertical resolution, 14 layers between 50 and 1000 hPa with four levels in the boundary layer; (5) time differencing scheme, semi-implicit; the explicit time differencing is applied for slow (Rossby type) modes. To handle the fast modes, the implicit approach is adapted; the time step used equals 7.5 min; (6) orography, envelope; (7) vertical differencing, centered for all variables except for humidity which is handled by an upstream scheme (energy conserving); (8) horizontal diffusion, fourth order; (9) cumulus parameterization, Kuo type; (10) shallow convection; (11) dry convective adjustment; (12) large scale condensation; (13) surface fluxes via similarity theory; (14) vertical distribution of fluxes utilizing diffusive formulation where the exchange coefficients are functions of the Richardson number; (15) long wave and short wave radiative fluxes based on a band model; (16) diurnal cycle; (17) parameterization of low, middle, and high clouds based on threshold relative humidity for radiative transfer calculations; (18) surface energy balance coupled to the similarity theory; and (19) nonlinear normal mode initialization, 5 vertical modes.

2.2. Model Setup, Initial Data, and Organization of Experiments

The European Center for Medium-Range Weather Forecasts (ECMWF) objective analysis data globally determined at 13 surfaces (1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, and 50 hPa) with 1.15^o horizontal resolution are used. For verification purposes the ECMWF analysis data are available with 12-hour time resolution for all the period of the simulations.

The global simulations were initiated at 1200 UTC, November 1, 1994, and continued for 96 hours. The aim of the simulation experiments was twofold:(1) to evaluate the role of the atmospheric moisture advected to the Mediterranean area from the chosen regions during the period of the intensive Mediterranean synoptic developments of November 1-5, 1994. (This is of particular interest since most rainfall events rely on local moisture sources, the Mediterranean, or from the Atlantic Ocean [*Shay-El and Alpert*, 1991; *Stein and Alpert*, 1991; *Alpert and Shay-El*, 1994]); (2) to evaluate the role of the rain-producing atmospheric processes in different regions in the atmospheric developments of the period.

Five model runs were performed starting from the same initial time moment from which four runs were made with perturbed initial moisture values over chosen regions in the Mediterranean vicinity. The relative humidity (RH) is used in the model as the parameter-controlling convective activity, large-scale condensation, and radiation. In our simulations, initial values of the relative humidity are limited by an arbitrary chosen value (20%) in four different regions. This allows to limit all the main types of moist dynamics activity inside the regions chosen and to reduce the moisture advection outward. This procedure simulates the potential consequences of such real effects as changes of the soil moisture availability, sea surface temperature variations, intensive advective processes, interhemispheric interactions, etc.

The surface-atmosphere interaction processes and especially the surface fluxes to the atmosphere tend, of course, to compensate the lack of the air moisture in the perturbed regions in the process of the simulations. The 96-hour time period of the integration is chosen as an upper limit for the simulations of the type.

Because of the computational reasons, results of the simulations with the modified initial relative humidity are less reliable in the vicinity of the boundaries of the modified domain. In our experiments, however, this effect was insignificant.

3. Discussion of Results of Control Run 4-day Simulation

Figures 1-3 present the sea level pressure, 850 hPa streamlines, and 850 hPa relative humidity for every 48 hours of the simulation starting from 1200 UTC, November 1, 1994. Each consists of three parts, a,b,c, corresponding to 00, 48, and 96 hours of the integration, i.e., to 1200 UTC of November 1, 3, and 5, respectively. All of the figures are for the geographic region 0^o-80^{o}E; 0^o-60^{o}N.

3.1. Sea Level Pressure

At the beginning of the period the most intensive system of the surface pressure field is located over northern Europe. It is zonally oriented and covers a large area from the North Atlantic region to the east (Figure 1a). The cyclone in the eastern Mediterranean has not yet developed, but the Red Sea trough (RST) is already present. The pattern is different in 48 hours, at 1200 of November 3, 1994 (Figure 1b). The former European cyclone has shifted to the Russian part of Asia, and another area of low pressure extends northward from western Spain to Iceland (only partly presented in the figure). These two low-pressure systems are separated by a high over central Europe. The narrow RST system is found over the Arabian Peninsula, and a small-scale eastern Mediterranean cyclone is developed over the southeastern part of the sea. In the following 48-hour forecast, at 1200 of November 5, 1994 (Figure 1c), the area of low pressure has moved eastward over Europe, creating conditions for positioning of the south-southwest flow over Italy and the frontal zone extending to southern France and southeastern England. The anticyclone is found over eastern Europe with an almost exactly predicted pressure value in its center (1045 hPa) [*Lionetti*, 1996]. All these characteristics of the simulated sea level pressure fields are in a good agreement

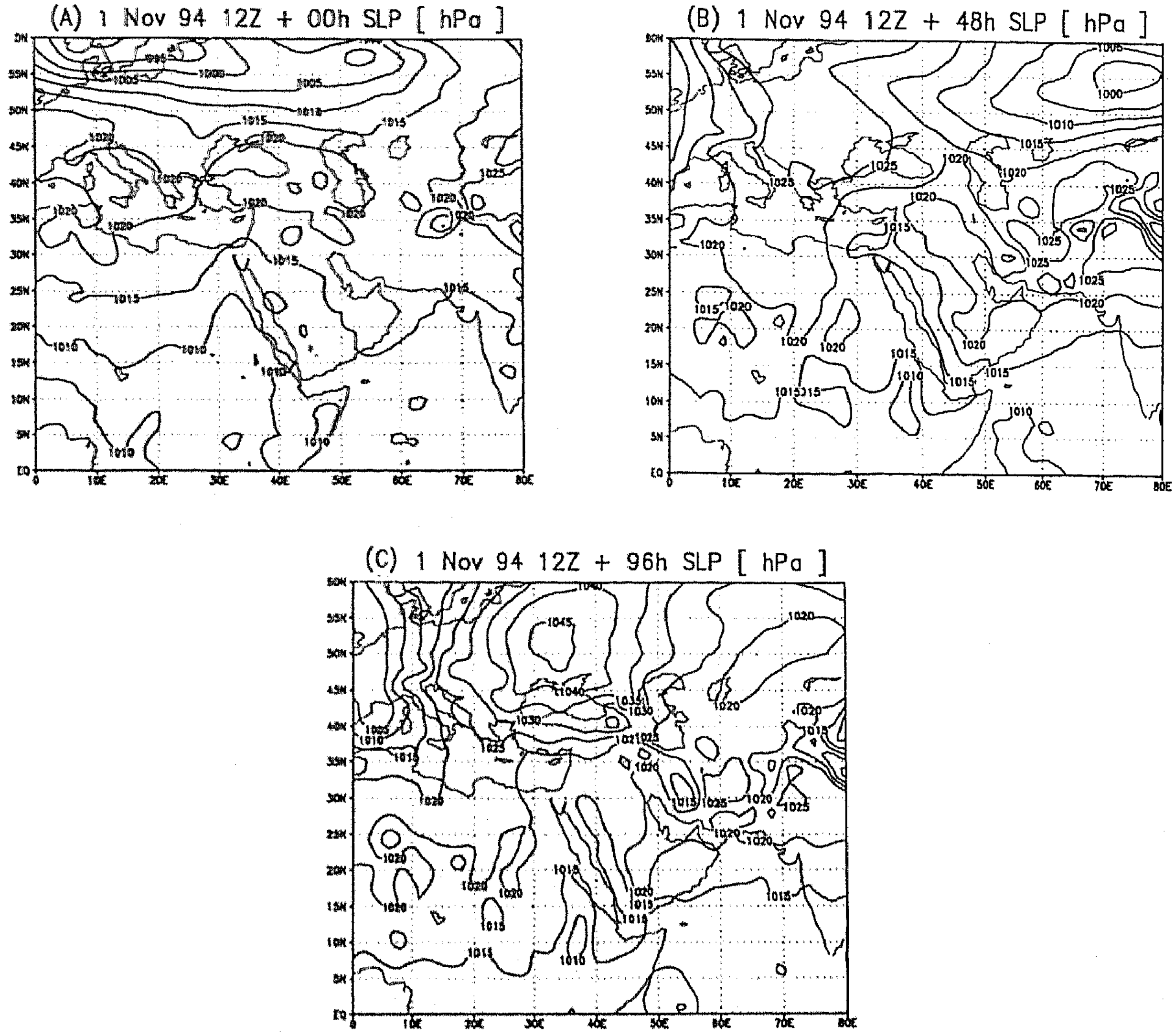

Figure 1. Initial and predicted sea level pressure (SLP) patterns corresponding to the control run with the Florida State University global spectral model (FSUGSM) model. Contour interval equals to 5 hPa. (a) 1200 UTC November 1, 1994; (b) 1200 UTC November 3, 1994; (c) 1200 UTC November 5, 1994

with the weather conditions registered by the Meteorological Services of the region.

3.2. 850 hPa Streamlines

Streamline analysis supports the results of the earlier section. On November 1, 1994, map (Figure 2a), air masses from the Arabian Sea do not penetrate to Africa. The air originating over the sea splits into two main directions, to the north and to the south. The northward branch transports moist air masses to the Mediterranean area. On November 3, 1994 (Figure 2b), only a some small portion of the streamlines from the Arabian Sea penetrate to the area of the Mediterranean Sea, where the eastern Mediterranean cyclone is well represented by the the cyclonic vortex. The anticyclone in the area over the Arabian Peninsula is also well developed at this time. The steamlines from the Arabian Sea already penetrate to central Africa and then to the central Mediterranean regions and Europe. On November 5, 1994 (Figure 2c) the situation is quite different and the streamlines originating over the Arabian Sea penetrate to the area of equatorial Africa and further to the west. Both the eastern Mediterranean cyclone and the anticyclone over the Arabian Peninsula are much weaker than on the previously discussed figure.

3.3. 850 hPa Relative Humidity

Figures 3a-3c illustrate the penetration of moist air masses into the Mediterranean. As indicated by Figure 3a, the Red Sea area has already very moist air at the initiation of the simulation, November 1, 1994, 1200 UTC. The source area of this moisture content is located in the Arabian Sea. The northern part of the sea is also wet. High values of the RH-850 are also found over northern Africa. Another area with moist air masses is located to the north of Italy. The northern regions of the area under analysis have large amounts of moist air with relative humidity values higher than

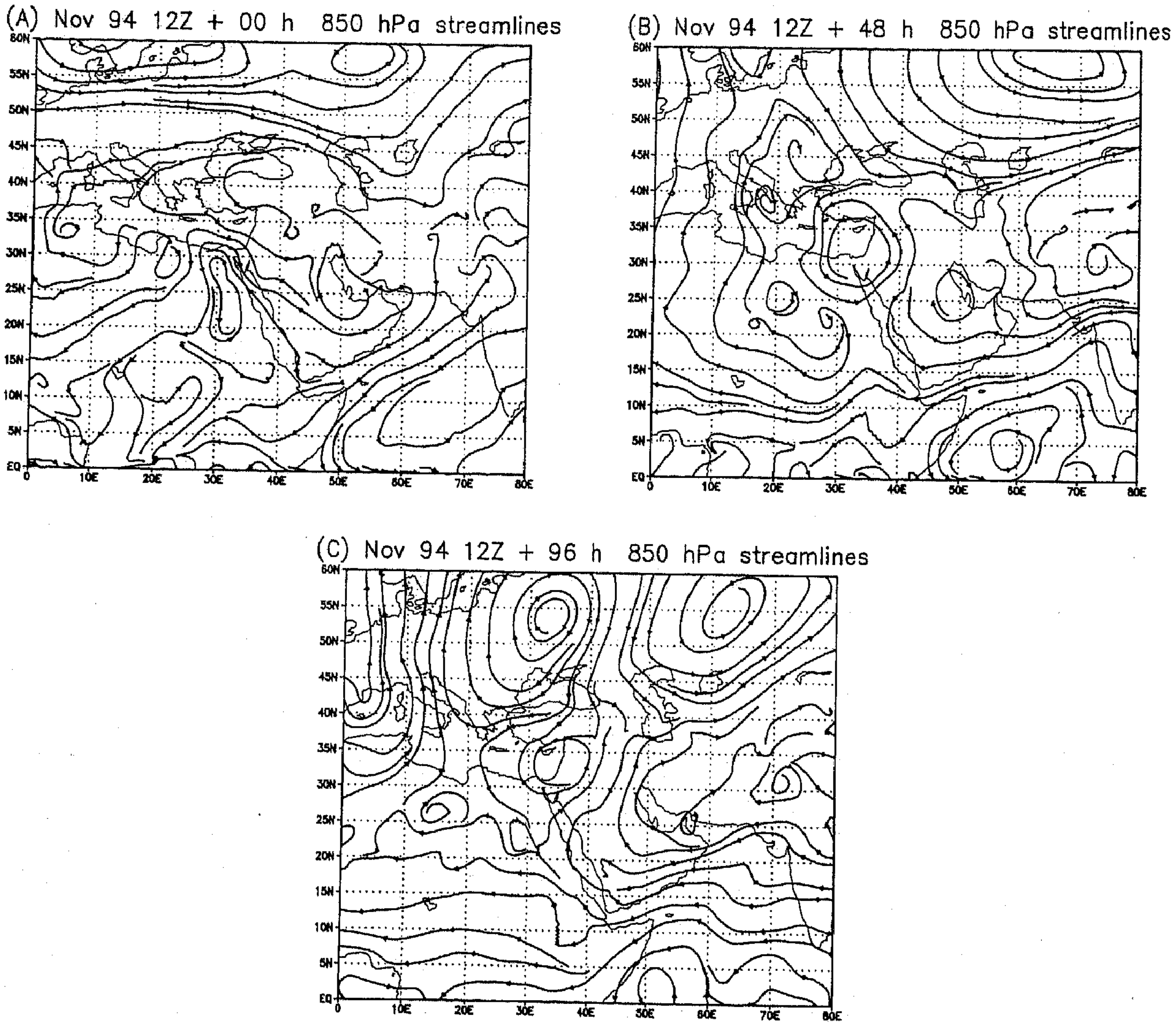

Figure 2. Same as for Figure 1 but for 850 hPa streamlines

70-80. Equatorial Africa is also among the regions with air masses of high moisture content. On November 3 the penetration of air masses from the Arabian Sea area to the Mediterranean region appears to be less intensive than 48 hours earlier (Figure 3b). On November 5, 1994 (Figure 3c), new wave of the moist air is approaching the Mediterranean region and western Europe from the west and from the south. A dry air belt separates now the wet areas in the eastern and the western Mediterranean.

4. Trajectory Analysis

Back trajectory analysis code recently developed at the Swiss Institute of Technology by Wernli [*Schar and Wernli*, 1993; *Massacand et al.*, 1997] has been implemented at Tel Aviv University by Tsidulko. The code is used for the analysis of results of the FSU GSM simulation determined on a 1° latitude/longitude grid at eight isobaric surfaces, 1000, 950, 850, 700, 500, 300, 200, and 100 hPa.

4.1. Lower Tropospheric Trajectories

Trajectories of air parcels in the 1000-700 hPa layer moving with the speed of 7 m s^{-1} and higher at the beginning of the trajectory calculation are presented in Figures 4a-4d. The trajectories are determined separately for each of the 24-hour time intervals. Trajectories corresponding to the time interval from November 1, 1994 1200 UTC to November 2, 1994, 1200 UTC are given in Figure 4a. The next three 24 hour periods are presented in Figures 4b, 4c, and 4d, respectively.

Most of the trajectories reaching the Mediterranean region during the first of the 24-hour periods originate over the Arabian Sea (Figure 4a). Practically no trajectories penetrate to the equatorial Africa from the Arabian Sea area during this time period. It is evident, that the Arabian Sea area is the primary source of the air masses and moisture for the eastern Mediterranean region during this period. In the following 24-hour time interval (Figure 4b) the formation of a cyclone takes place in the EM. This process is well presented on the

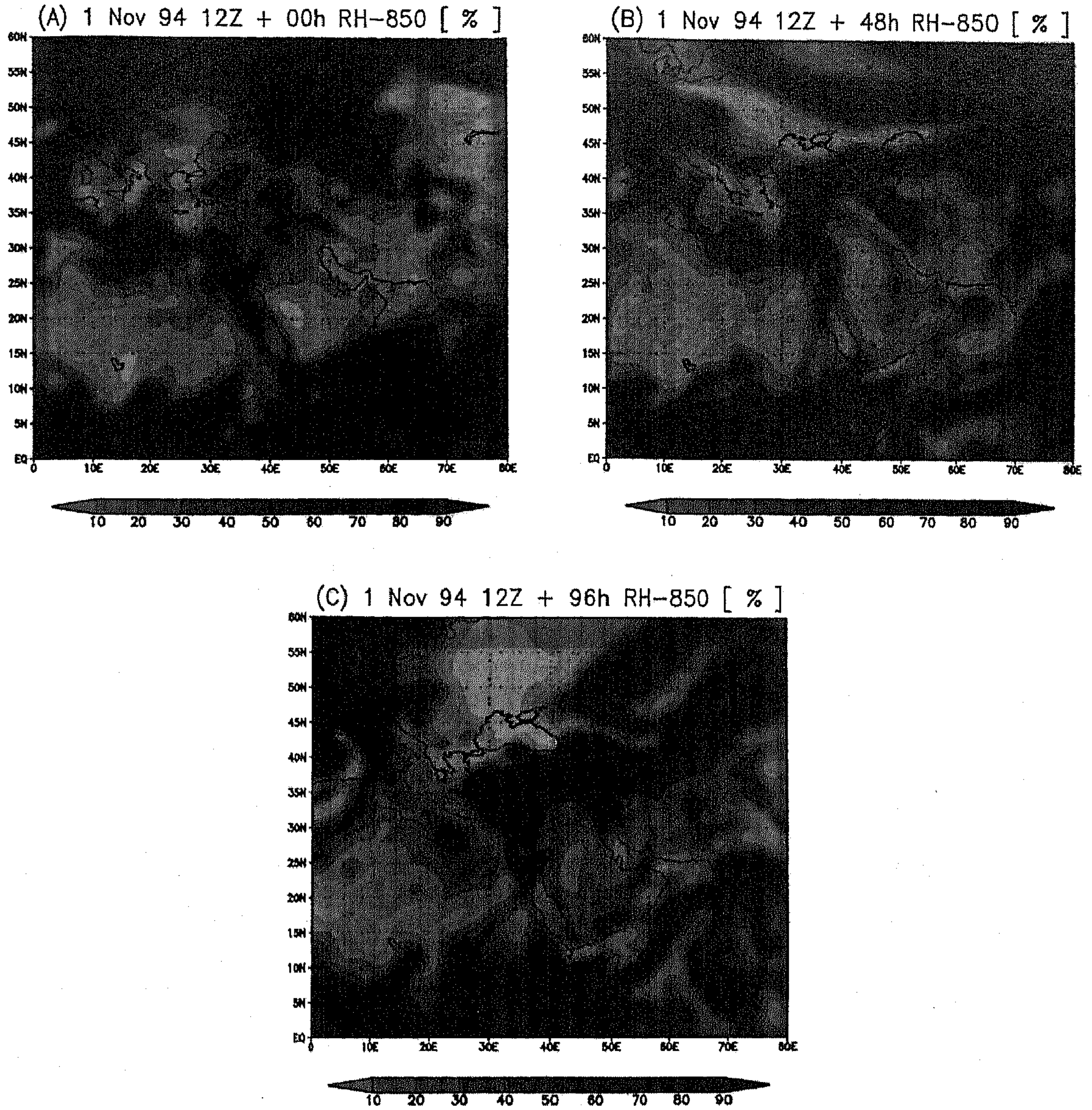

Figure 3. Same as for Figure 1 but for 850 hPa relative humidity pattern. Shading interval, 10%

trajectory pattern. The EM area continues to be the region receiving a lot of moist air from the Arabian Sea, but now a portion of trajectories from the Arabian Sea area penetrate also to the equatorial Africa. This change of the circulation regime supports the transport of the moist air masses from the Arabian Sea area to the regions of central Africa. During the time period from November 3, 1200 UTC to November 4, 1200 UTC 1994 (Figure 4c), only a smaller part of the trajectories originating over the Arabian Sea penetrates to the EM region. Most of the trajectories are found now over the equatorial regions of Africa. During the following time interval (Figure 4d) practically no Arabian Sea trajectories penetrate to the EM, and the air mass transport from the Arabian Sea is mainly toward equatorial Africa. Part of the trajectories from central Africa propagate now to the central Mediterranean area with the south-southwest flow indicated earlier.

4.2. Upper Tropospheric Trajectories

The specific role of the upper tropospheric subtropical jet stream related westerlies in the development of the RST in the eastern part of north Africa has been discussed recently by *Krichak et al.*, [1997b, c]. It was suggested, that the trough development may take place as a result of a lee-type cyclogenetic process in association with the position of the jet over the area to the west of the northern part of the Red Sea area. Figures 5a-5d present the simulated trajectories with wind velocity greater than 40 m s^{-1} in the 300-100 hPa layer computed separately for each of the 24-hour intervals from 1200 UTC November 1 to 1200 UTC November 5, 1994,

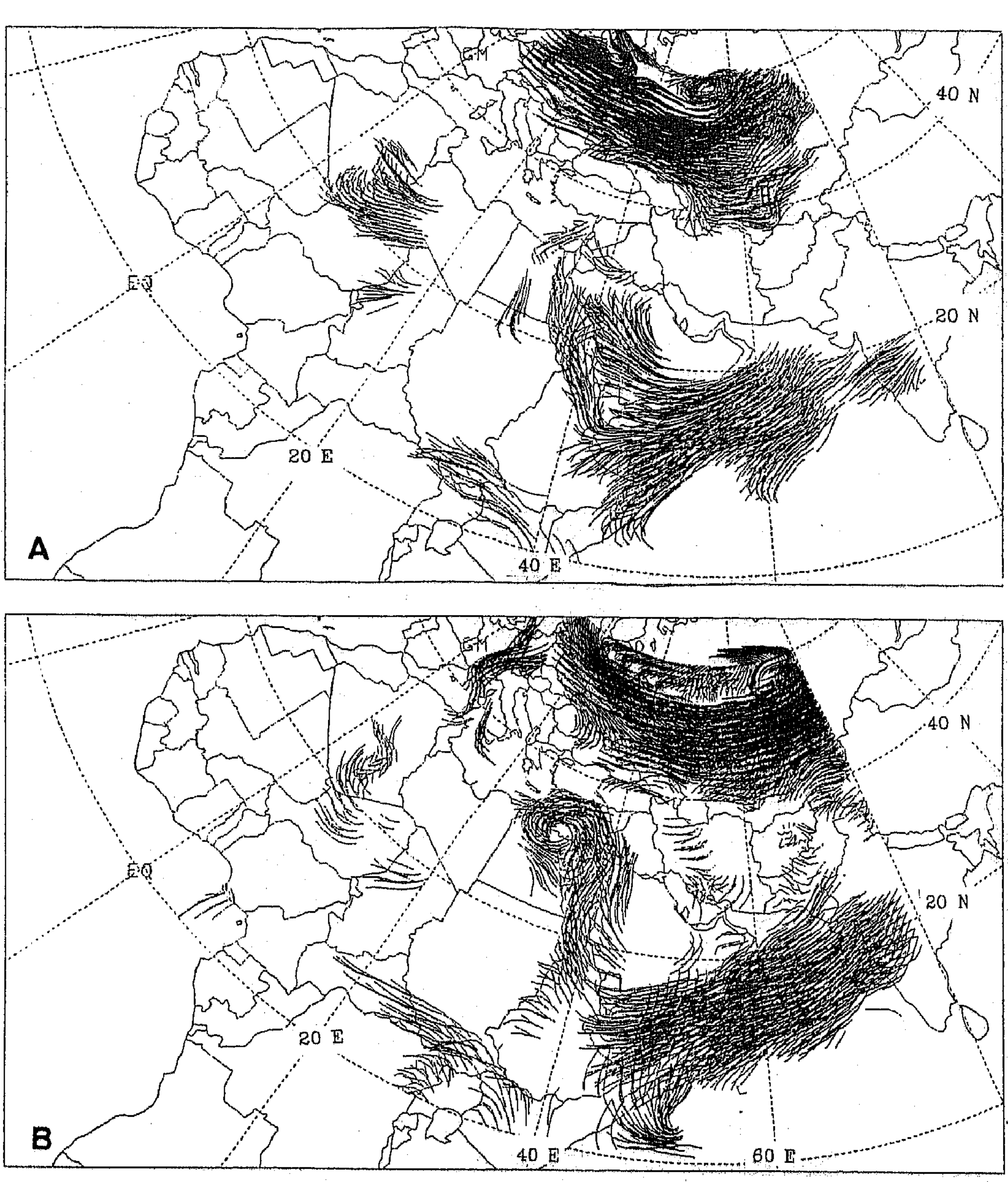

Figure 4. Backward trajectories with wind magnitude larger than 7 m s^{-1} in the layer 1000-700 hPa computed from the model simulation control run. Time intervals are for 24 hours starting from 1200 UTC. (a) November 1-2, 1994, (b) November 2-3, 1994, (c) November 3-4, 1994, (d) November 4-5, 1994.

respectively. Accordingly, the whole period was characterized by the existence of a strong polar jet stream over Europe. Prior to the development of the RST, however, strong westerlies have developed also over the area over northcentral Africa and the Red Sea (Figure 5a). Such a situation was found to be favorable for development of the RST [*Krichak et al.*, 1997b, c]. During the following 48 hours, the upper tropospheric subtropical westerly jet stream (STJ) winds are weaker over northern Africa (Figures 5b, 5c). During the last 24-hour interval of the simulation (Figure 5d) a strong wind area is found again over Africa. The jets core, however, is now located farther to the south (20°N). According to the already referenced study such a position of the jet is less favorable for trough development.

5. Analysis of the Role of Moist Dynamics

The recently developed factor separation method by *Stein and Alpert*, [1993] allows evaluation of the role of different processes acting in the atmosphere. Direct application of this approach is quite time consuming, especially in the case of the global model simulations. In the current work the investigation focuses on only one effect: a cumulative role of a number of processes which may be associated with moist dynamics in the atmosphere.

As already stated, our aim is to analyze the role of potential distant moisture sources in the eastern Mediterranean storm as well as the role of the moist processes

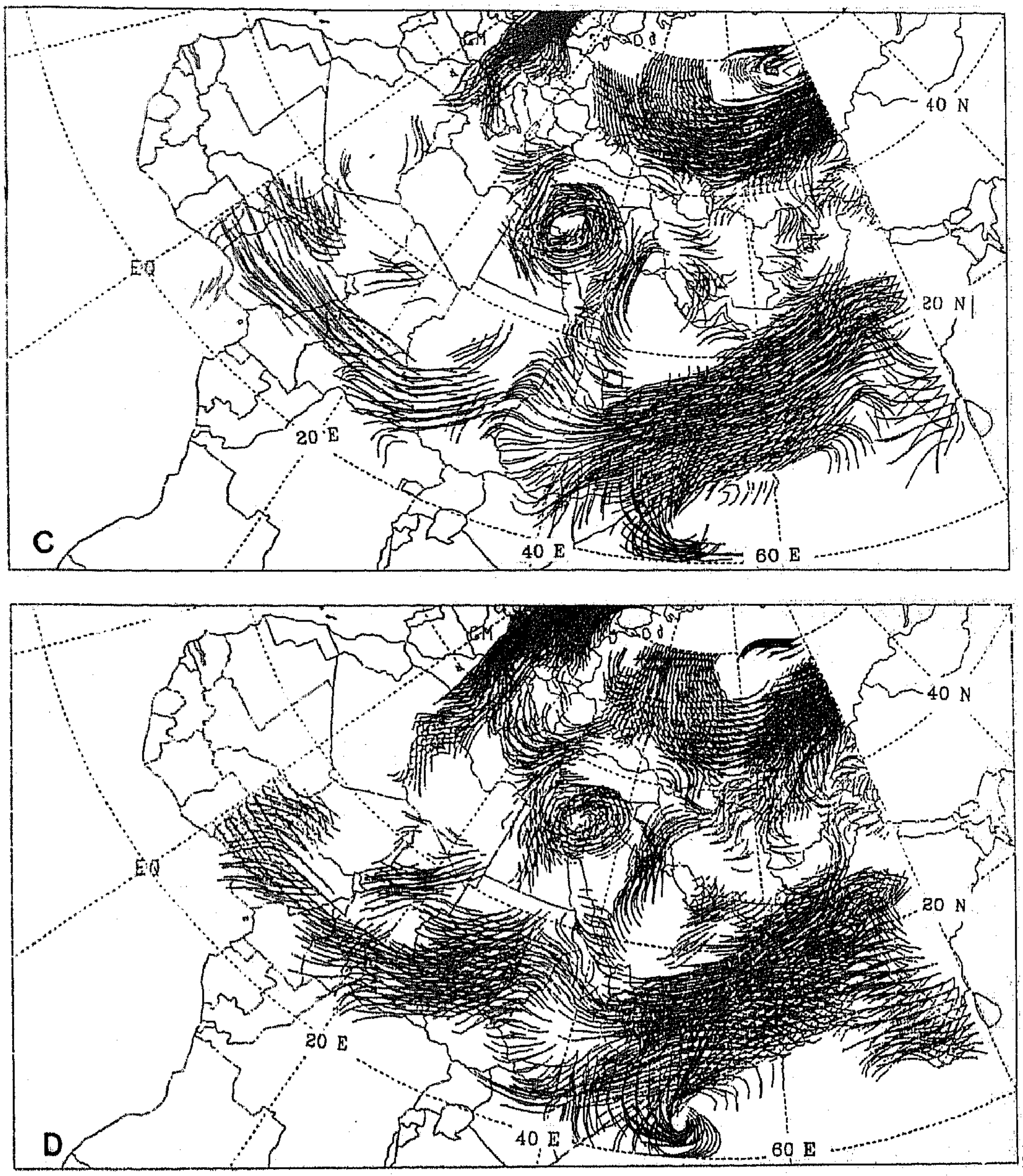

Figure 4. (continued)

in the several different geographic regions in the atmospheric developments over the Mediterranean during November 1-5, 1994. In the following discussion the experiments will be referenced by the the first letter representing locations of the chosen regions: R, Red Sea; A, Arabian Sea; S, south; N, north. The regions are indicated in Figures 7a and 9a-11a by the solid line rectangles. Positioning of the regions is chosen according to the results of moisture and trajectory analyses based on Figures 3a-3c and 4a-4d. (Note that the A region is much smaller compared to the other regions.)

The 96-hour time period is sufficient for propagation of the air masses, say, from the area of the Arabian Sea to the regions of central Africa in the situations with appropriate wind flow. In the following, such air masses are considered as those that originated over the sea.

Patterns of the 96-hour SLP, RH, wind magnitude (WM) and wind streamline (WS) deviations from those of the control run (control minus experiment) are discussed below. Original patterns of the control run and S simulations (not the deviations) are also presented for comparison in Figures 6a and 6c-6f and 8a-8f. Results of the control run SLP simulated pattern are already presented in Figure 1c.

Analysis of the deviation patterns is quite straightforward. In the case of the SLP deviation patterns, for instance, negative (positive) values of the local deviations represent higher (lower) experimental SLP values than in the control one. The negative values correspond to the areas where real moisture and moist processes tend to decrease to SLP values. The wind deviations are presented in the form of "additional" circulations, existing in results of the control run simulations due to

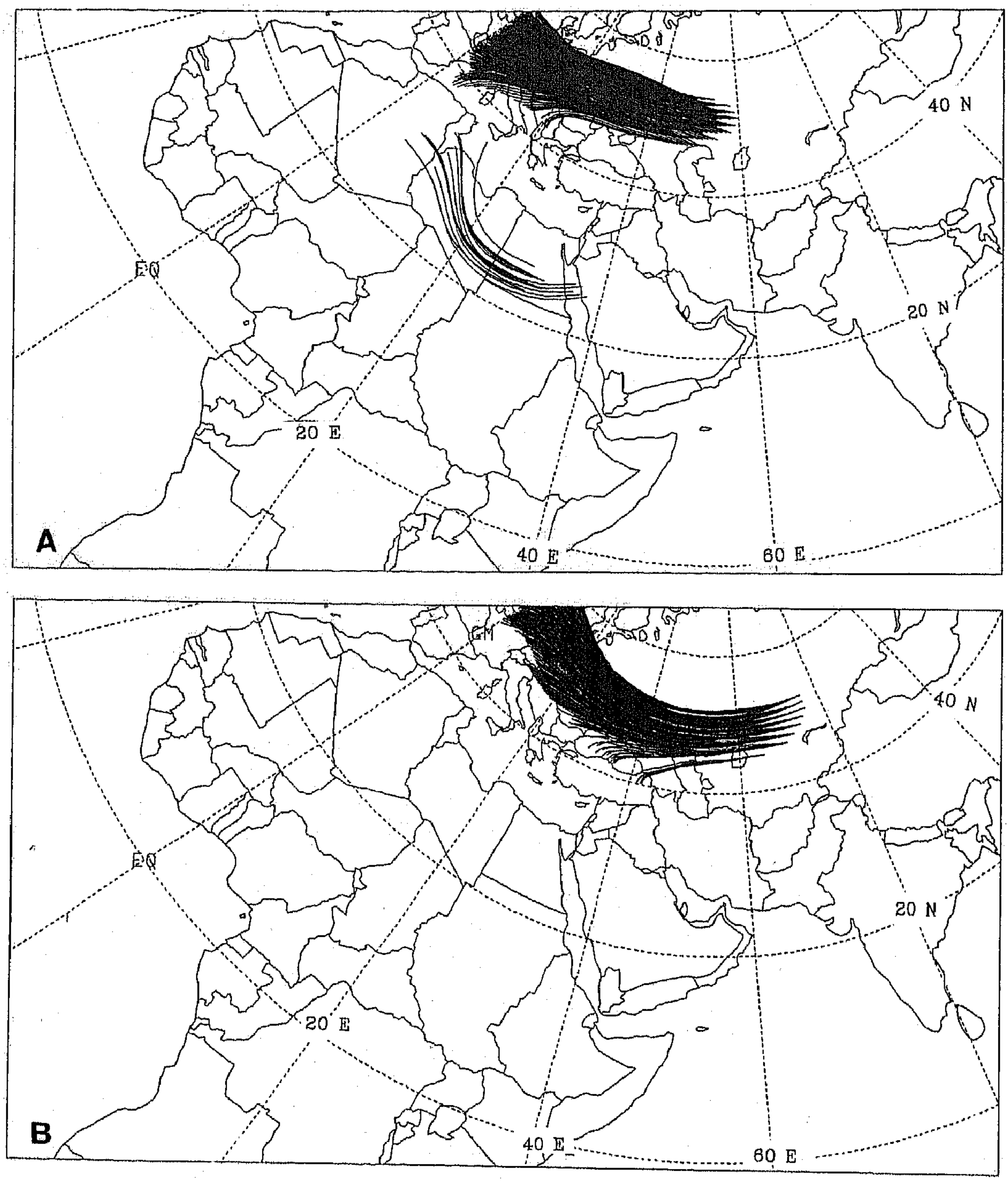

Figure 5. Backward trajectories with wind magnitude larger than 40 m s $^{-1}$ in the layer 300-100 hPa computed from the model simulation control run. Time intervals are for 24 hours starting from 1200 UTC. (a) November 1-2, 1994, (b) November 2-3, 1994, (c) November 3-4, 1994, (d) November 4-5, 1994.

the role of the real moist dynamics in a particular region. Analysis of results is performed in the following subsections.

5.1. Large Scale Moisture Variation Experiments

5.1.1. S experiment. The RH-700 and the SLP deviations from the control run are presented in Figures 7a and 7b, respectively. The large area with perturbed RH values is located over equatorial Africa and the Arabian Sea. The area with large negative values of the SLP deviations (Figure 7b) is also located in the EM (6-7 hPa), indicating the region mainly affected by the limiting of moisture import from- and the weakening of moist dynamics in the area (S). It is worth to note that a smaller region with comparatively high negative deviations (4 hPa) is found in the western part of the Mediterranean, i.e. almost exactly in the area where the intensive rains took place on of November 5. According to the earlier analysis a southern wind flow develops over this region in the simulations. The S experiment WM-700 deviations (Figure 7c) have their maxima over three main areas, one in the EM and two others in the Arabian Sea and the Atlantic ocean. Such a distribution of the WM deviation maxima indicates the regions that were most sensitive to the moisture variations in the lower troposphere. The corresponding wind deviation 700 hPa

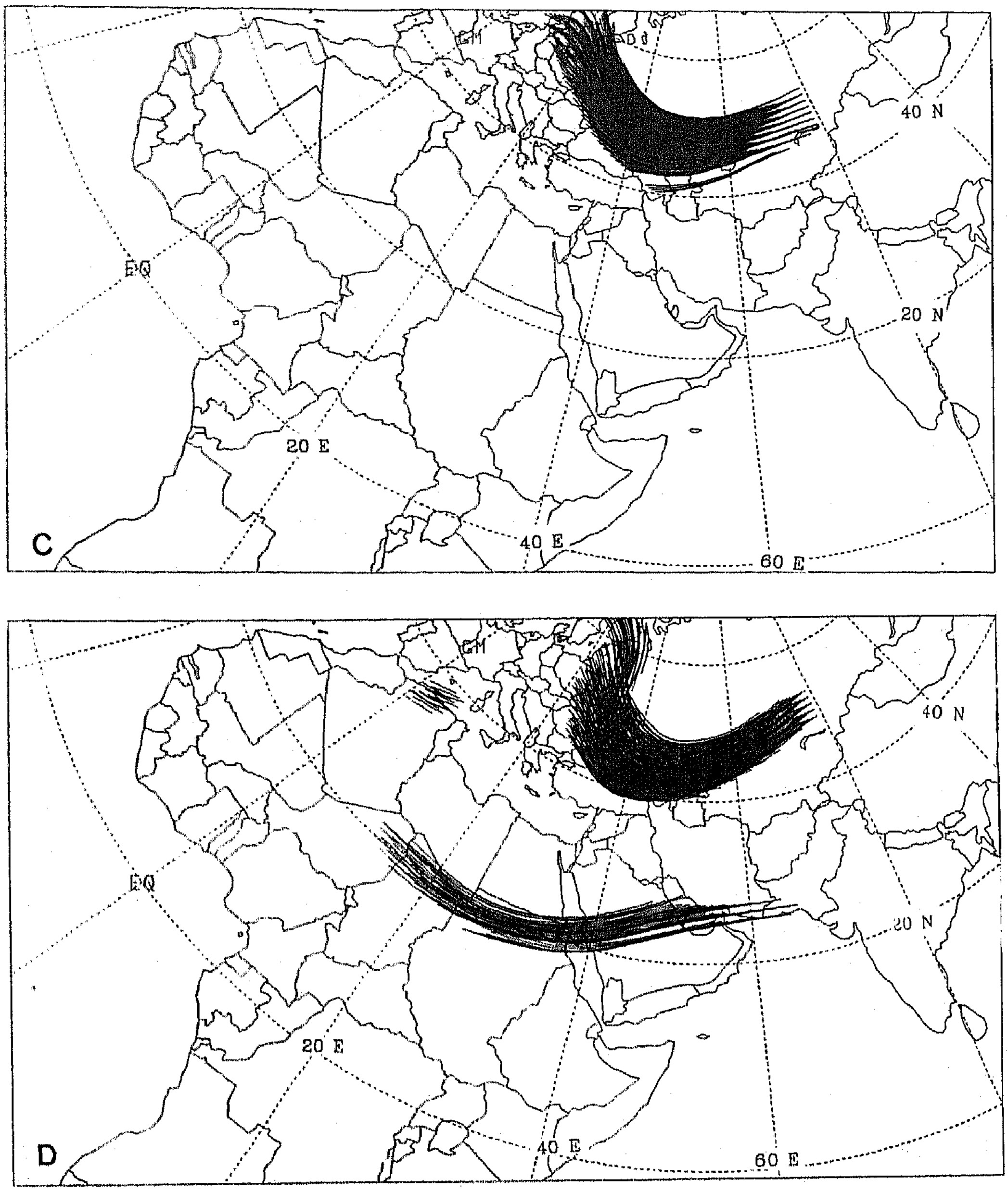

Figure 5. (continued)

(WS-700) streamline pattern (Figure 7d) illustrates the additional counterclockwise circulation due to the role of tropical moisture over the EM region. An additional southern flow due to the real moisture content in S area is found over the central Mediterranean and Italy. This flow is a part of a larger system of the additional counterclockwise circulation over Europe.

The S WM deviations on the 200 hPa surface are strong, reaching values up to 22 m s^{-1} (Figure 7e) in the regions where the STJ is positioned (Figure 5). Two upper tropospheric areas of additional clockwise circulation (WS-200, Figure 7f) are found over the Arabian Peninsula, the northern part of the Arabian Sea, and over tropical Africa (20° N). Location of the centers seems to be associated with convective processes in equatorial Africa which acted as the driving force for the STJ intensification during the November 1-5, 1994, period [*Krishnamurti*, 1961; *Krishnamurti et al.*, 1973].

For comparison, the S run simulations are also presented in Figures 8a-8f. As was already stated, the main area, with large control run S differences, is located in the Red Sea and the EM. The SLP fields (Figures 6d, 8b) differ significantly in this region, practically no developments of the initial RST pattern (Figure 1a) took place in the S simulation. The wind 700 hPa patterns (WM-700 and WS-700 (Figures 8c, 8d) also differ from those in Figures 6c and 6d in this area. It may also be indicated that the 200 hPa winds at about 15-25°N are much stronger in the control run (60 m s^{-1}) than in the S experiment (50 m s^{-1}).

5.1.2. N experiment. The N simulation experiment used initial RH fields with the values modified

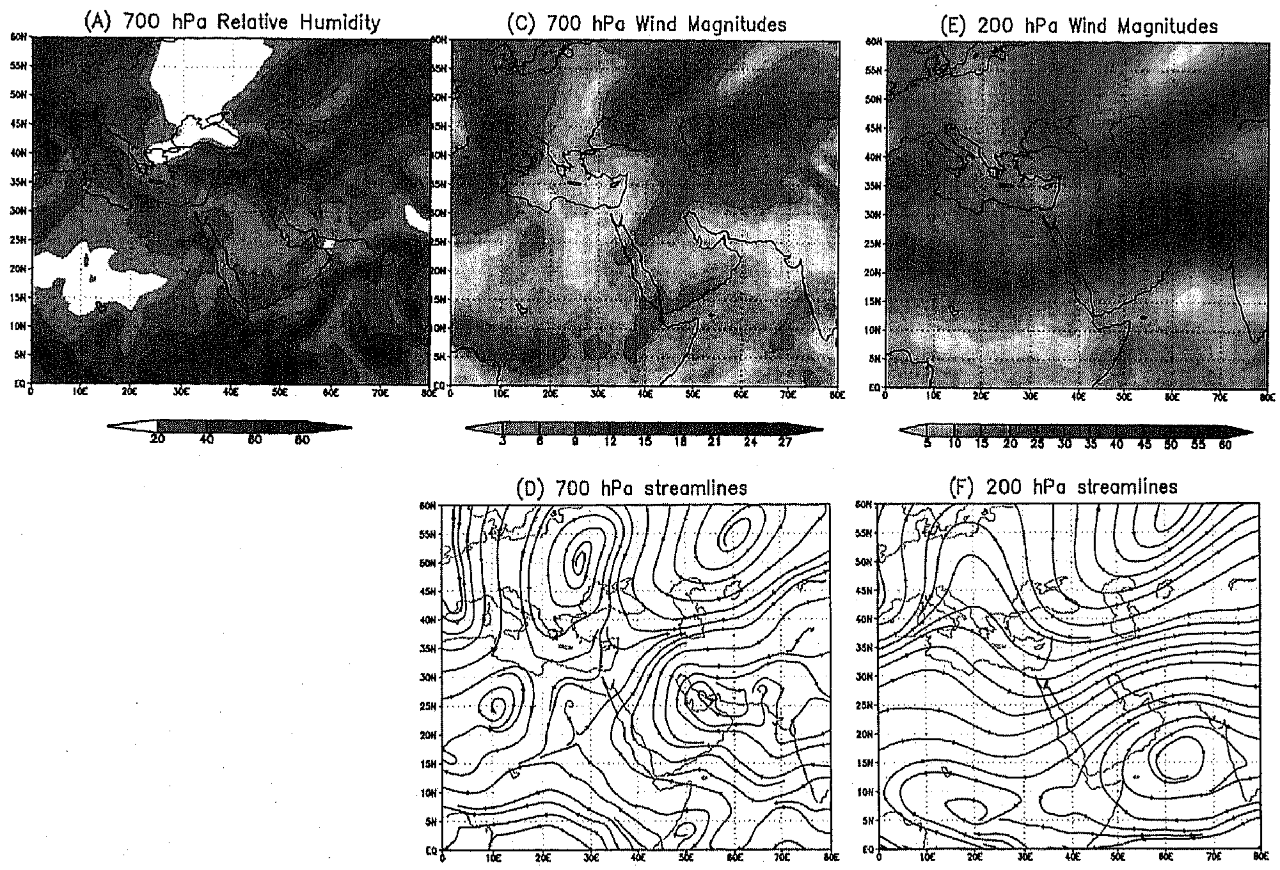

Figure 6. Results of the 96-hour model simulation in the control run. (a) Relative humidity at 700 hPa; shading interval, 20%. (c) Wind magnitude at 700 hPa surface; shading interval, 2 m s^{-1}, (d) Streamlines at 700 hPa surface, (e) Wind magnitude at 200 hPa surface, shading interval, 2 m s^{-1}, (f) Streamlines at 200 hPa surface.

over Europe. This allows evaluation of the role of this part of the atmospheric moisture in the Mediterranean weather developments of the period. According to the simulation this role was not significant. Figures 9a and 9b show that the SLP and RH-700 deviations are relatively small in the vicinity of the EM region. Also, the 700 and 200 hPa WM and WS patterns also hardly change in the Mediterranean region due to moisture perturbation in the N area, (Figures 9c-9f). Instead, the area of the significant values of the deviations is found over northern Asia. The maximum deviations are of the order of 60SK, -8 hPa, 12 m s^{-1}, and 4 m s^{-1} in the case of RH-700, SLP, WM-700, and WM-200, respectively.

A clarification is needed for the correct interpretation of the results. The fact that the reducing of RH over northern Europe did not affect the processes in the EM region does not mean of course that the latter was insensitive to the moist processes over the higher latitudes. Only the role of the air masses which existed over Europe on November 1, 1994, has been evaluated. The results mean that these moist air masses did not participate in the development of the the November 2, 1994, EM cyclone. According to Figures 3a and 3b the acting zone of the moist air was located mainly to the south of the Mediterranean Sea. The N experiment does not give any information on the role of moisture in the more western regions over the higher latitudes which could be among important factors in the process of intensification of the upper tropospheric jet streams over the region.

5.2. Small-Scale Moisture Variation Experiments

Experiments R and A are illustrated in Figures 10-12, respectively. As in the section 5.1.2, the Figures 10a-12a correspond to the 700 hPa RH deviations from the RH values in control run, (b) SLP; (c and d and e and f) to the differences in the WM and WS on 700 and 200 hPa isobaric surfaces, respectively.

5.2.1. R experiments.

The R simulation experiment 700 hPa RH pattern (Figure 10a) demonstrates the role of the air moisture content of the Red Sea area, which already existed there on the 1200 UTC of November 1, 1994. The SLP deviation pattern (Figure 10b) shows this role in the surface pressure development (the EM SLP in the control ex-

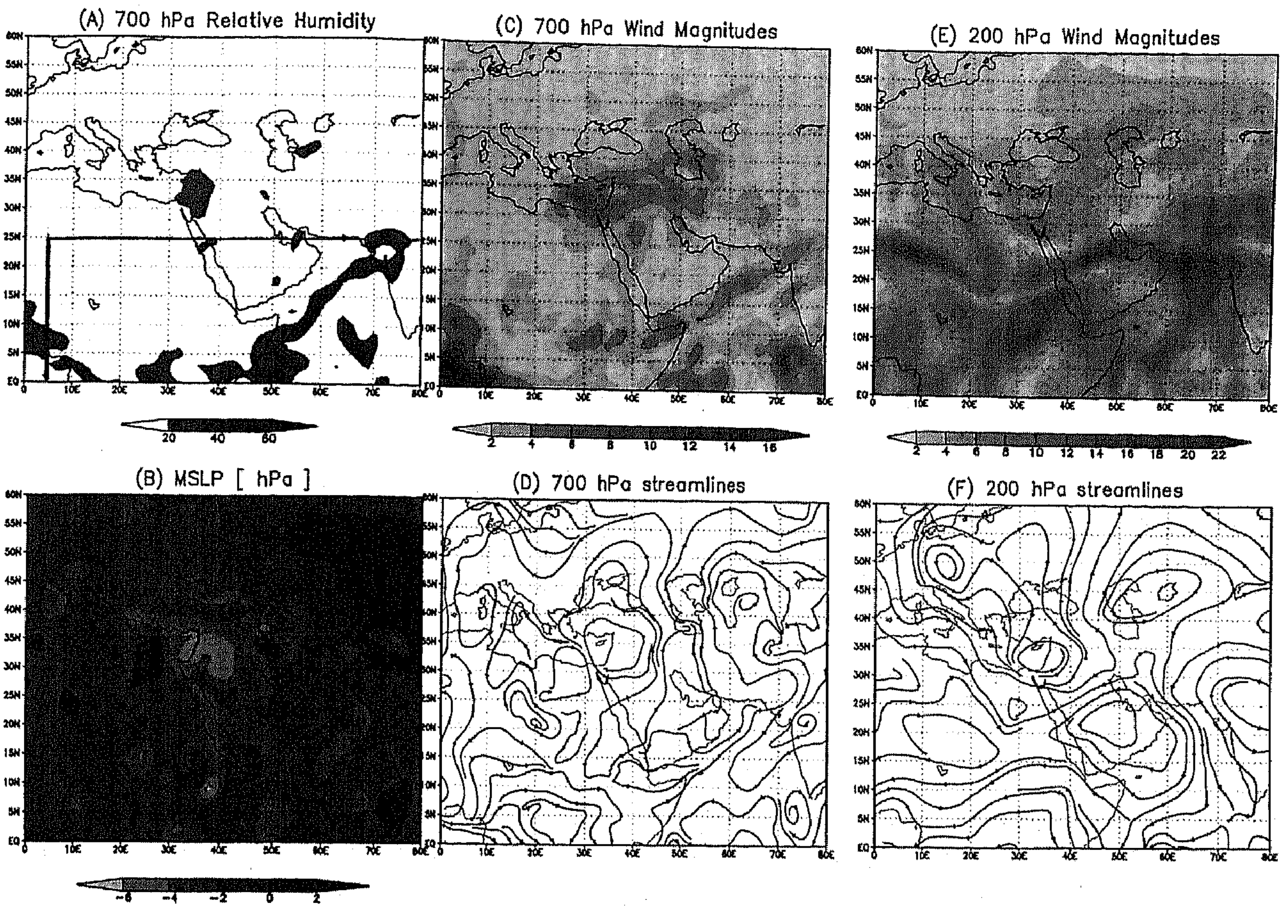

Figure 7. Deviations of the 96-hour model simulation results for S experiment (control minus experiment). (a) Relative humidity at 700 hPa; shading interval, 20%. The S area is indicated by the rectangle in the pattern. (b) SLP, shading intervals, 2 hPa. (c) Wind magnitude at 700 hPa surface; shading interval 2, m s^{-1}. (d) Streamlines at 700 hPa surface, (e) Wind magnitude at 200 hPa surface; shading interval 2, m s^{-1}. (f) Streamlines at 200 hPa surface.

periment is lower than in the R simulation by more than 4 hPa). Both the SLP and the RH-700 deviations demonstrate the propagation of the cyclonic system to the northeast, according to the direction of the 700-hPa steering flow in Figure 6d. Additional counterclockwise circulation is found in the EM area and a part of Europe in the WS-700 pattern (Figure 10d). This additional flow is not so strong as in the S simulation. In the central Mediterranean this effect does not play any significant role. In Figures 10e and 10f an area of additional clockwise circulation due to the moist dynamics over the R area is found over a large region from northeastern Africa to the Caspian Sea in the upper troposphere. The STJ winds are much weaker (16 m s^{-1}) over southern Asia and India due to the same reason.

5.2.2. A experiment.

Results of the A experiment are presented in Figures 11-12. The A simulation represents the role of the atmospheric moisture in the area of the Arabian Sea.

The 96-hour 700 hPa RH deviations are shown in Figure 11a. Two areas with significant changes are present. One of them is located over the Arabian Sea, while the second, much smaller, is found in the region of western Europe and the western Mediterranean. A small area of relatively high values of the negative SLP deviations is also found in Figure 11b in the western Mediterranean. A similar area is found in this region in Figure 11c representing the WM-700 deviations. The WS-700 pattern (Figure 11d) shows that a narrow zone of well-organized additional northward flow (about 8 m s^{-1}) extends in the 96-hour simulation over northern Africa. The additional counterclockwise circulation in Europe due to the role of the A area moisture in the EM processes is negligible.

The wind patterns corresponding to the A experiment at 200 hPa are given in Figures 11e and 11f. Again, as in the S experiment, the largest values of the deviation are found in the area of the STJ over Africa, Arabian Sea, and India. Over the Arabian Sea itself the convective processes of the region produce a clockwise circulation, which intensifies the STJ over the Arabian Peninsula. The zone with additional clockwise circulation is oriented here from the EM area to the northern regions

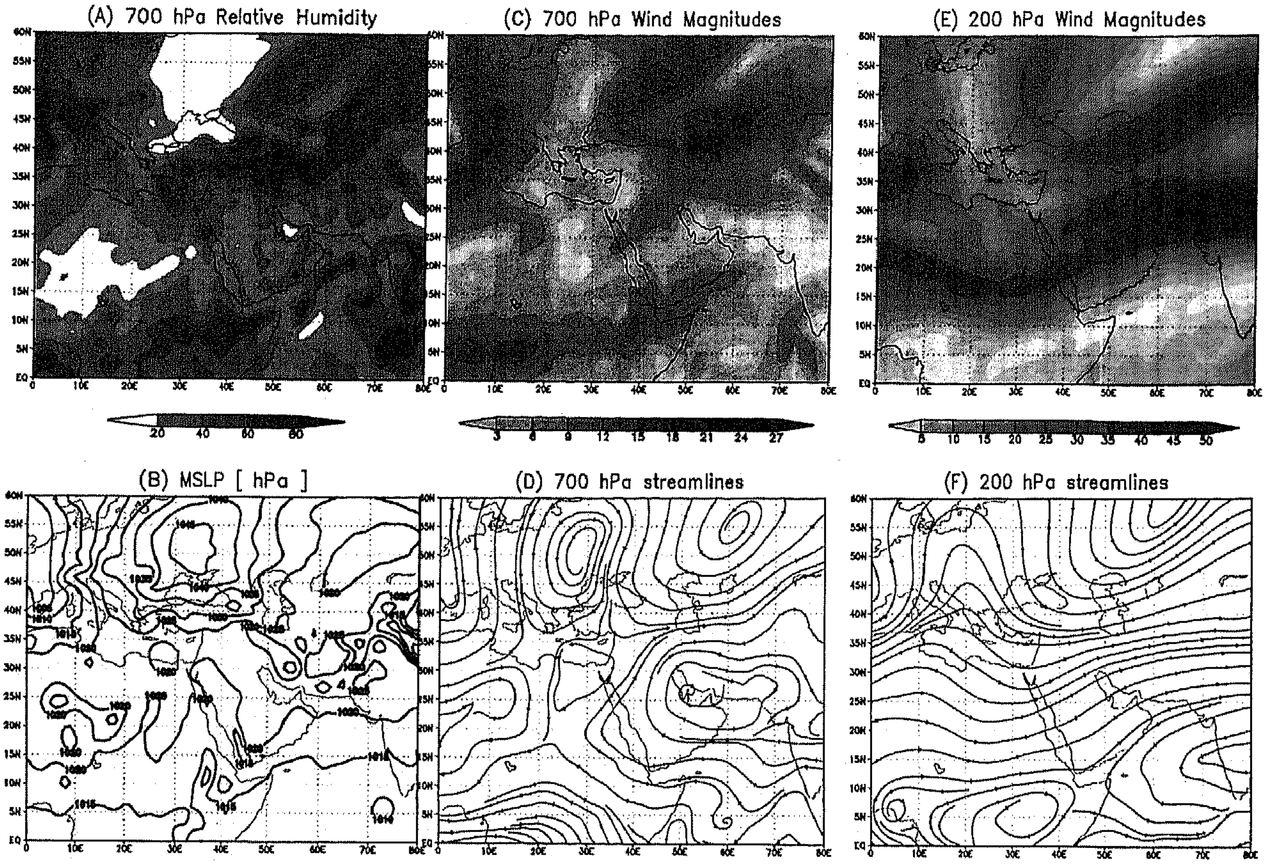

Figure 8. Results of the 96 hour model simulation in the (S) run. (a) Relative humidity at 700 hPa; shading interval, 20%. The S area is indicated by the rectangle on the pattern. (b) SLP, countur intervals, 5 hPa, (c) Wind magnitude at 700 hPa surface; shading interval, 2 m s^{-1}, (d) Streamlines at 700 hPa surface, (e) Wind magnitude at 200 hPa surface; shading interval, 2 m s^{-1}, (f) Streamlines at 200 hPa surface.

of the Arabian Sea. Over Africa this effect leads to a weakening of the westerly flow in the upper troposphere.

Additional information is available from Figure 12, representing the A and S deviation patterns. The A area is located inside of the S region. Because of it the A-S deviations provide information on the role of the atmospheric moisture of the entire S area except the A to S-A region. Comparison of the deviation patterns with those of the S experiment (Figure 7) shows that the role of the A region moisture was not significant in most of the regions around the Mediterranean Sea.

Arabian Sea air masses of November 1, 1994, played a small role in the EM cyclone development (about 2 hPa out of the total 6 hPa in the C-S SLP deviation (Figures 7b and 12b). It means that the air moisture of the S-A region was responsible for the main part (4 hPa) of the deepening of the EM cyclone due to the S area moist dynamics. The area with negative values of the SLP S-A deviations extends to western Europe. There is another maximum of the SLP deviations (4 hPa) located over western Europe (Figure 12b). Existence of the area demonstrates the role of the air moisture and that of the moist dynamics over equatorial Africa in intensification of the western Mediterranean cyclone of November 5, 1994. This effect is also present in the RH deviation pattern given in Figure 12a. The additional counterclockwise circulation over Europe is found also in the WM-700 and WS-700 patterns (Figures 12c, 12d). As in the case of the S experiment (Figure 7d), an additional southern flow is found over Italy. This flow creates conditions for advection of air masses from central Africa. In the upper troposphere the S-A region processes intensify the STJ flow over Africa and the Arabian Peninsula (not presented).

6. Summary and Conclusion

The Mediterranean region experienced unusually intensive rains, floods, and other disastrous events during a 2-week period from October 20 to November 5, 1994. The study focuses on the role of the moist dynamics in the processes which took place during the last four days of this period.

The 96-hour FSU global model control run is initiated at 1200 UTC November 1, 1994. The main elements of synoptic situation over the Mediterranean are successfully simulated by the model. Analysis of the results of the simulation includes the synoptic investigation of the

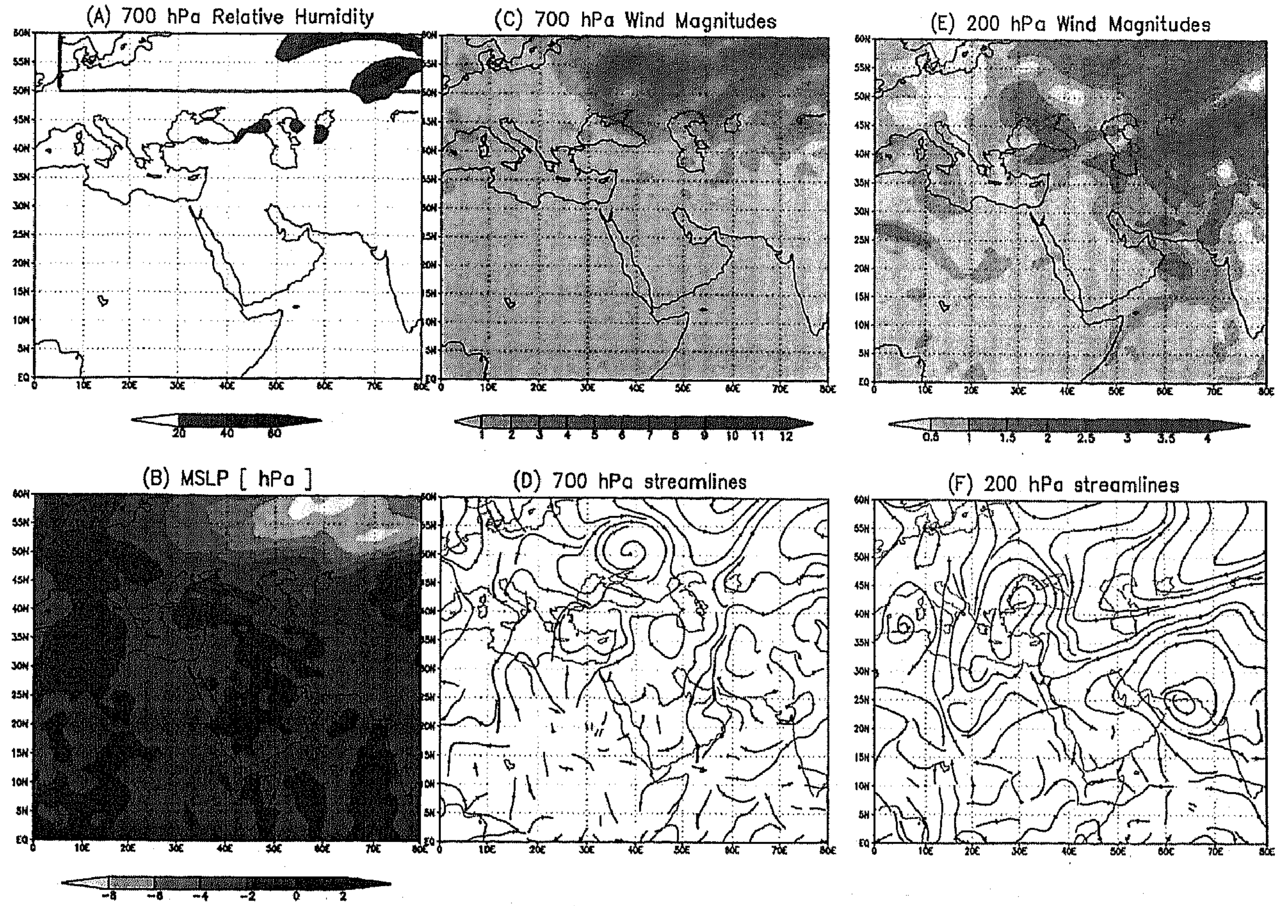

Figure 9. Same as for Figure 7 but for the N experiment. (c) shading interval, 1 m s^{-1}.

case and determination of trajectories of the air particles. According to the results the air masses of the eastern Mediterranean region were already very moist on the 1200 UTC November 1, 1994. The moisture has originated from the Arabian Sea area. This result is in agreement with the earlier study by *Leguy et al.*, [1983].

Model sensitivity experiments with regards to moisture are performed in the study using the results of the 96- hour global model simulations. The investigation mainly focuses on the roles of moisture advection from and that of moist dynamics in the four perturbed regions.

The following results may be listed:

Development of the eastern Mediterranean cyclone of November 2, 1994, took place as a result of intensive propagation of the air masses from the Arabian Sea area to the Red Sea area.

Advection of moist air to the Red Sea area took place mainly prior to November 1, 1994: the EM developments are not sensitive to the moisture perturbations of the experiment A (Arabian Sea).

According to S (south), R (Red Sea), and (A) simulations the African and the Arabian Sea tropical convection supported intensification of the upper tropospheric jet stream over the Red Sea. Initiation of such a process several days before November 1 1994, could have stimulated the development of the RST circulation.

No development of the RST system is found in results of the S experiment. Only the southern part of the Red Sea region in located inside of the S area. It means that not only the air moisture of the region was responsible for the development of the EM cyclone. According to our earlier results [*Krichak et al.*, 1997b, c], the intensification of the STJ in the region may play the role of a forcing mechanism for such a process.

Experiments A, R and S also show the existence of two centers of additional clockwise upper tropospheric circulation in the area of the STJ. Moist dynamics over the Red Sea area (Arabian Sea) stimulates northward propagation of the eastern (western) part of the area with additional clockwise circulation. This suggests that the observed intensification of the STJ over the Red Sea region could be associated with the moist convective processes over tropical Africa and the Arabian Sea. This intensification in its turn stimulated the RST development over the EM region. Such a development may play as a self-regulatory mechanism in the Mediterranean region; advection of large amounts of moist air to the equatorial Africa stimulates developments which tend to interrupt the advection process and turn it northward.

Several main stages of this process may be listed: (1) Advection of large amounts of moist air to equatorial Africa stimulates convective activity in the region; (2)

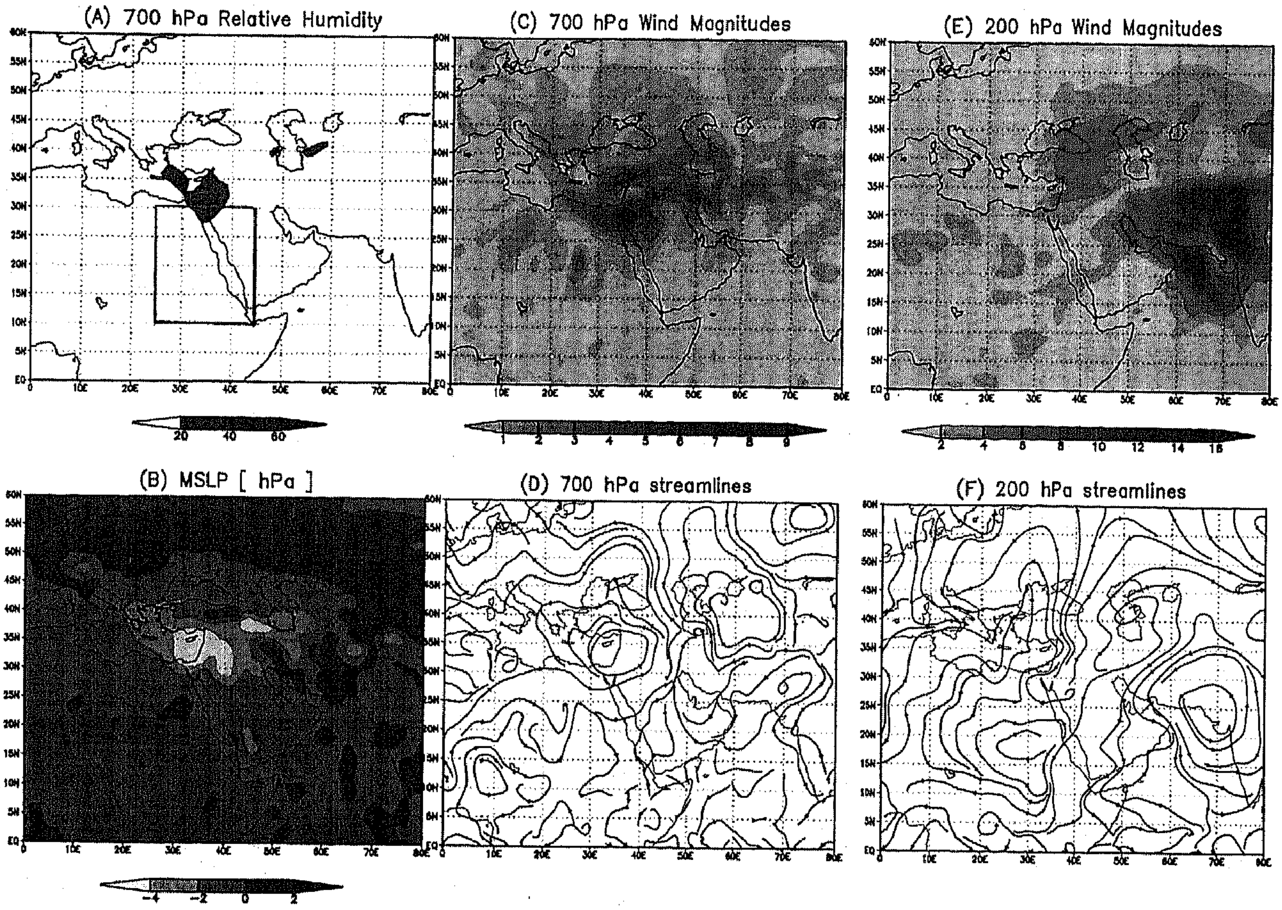

Figure 10. Same as for Figure 7 but for the R experiment.

STJ intensifies over the Red Sea area; (3) Intensification of the STJ stimulates development of the RST cyclone; (4) Development of the RST causes modifications in the moisture advection from the Arabian Sea; moist air masses are advected northward into the Red Sea area; (5) During/after the EM cyclogenesis the STJ and RST weaken and advection of the moist air masses from the Arabian Sea is again directed toward tropical Africa.

In the case studied, the stage 1 took place prior to the starting date of the run; stage 2 is represented by Figure 5a; stages 3 and 4 are illustrated by Figures 4a and 4b; Figures 4c and 4d illustrate the stage 5 of the process.

The fact that the intensive rains took place in the eastern Mediterranean already in the last decade of October 1994 [*Kallos et al.*, 1997; *Lagouvardos et al.* 1996; *Prezerakos and Ralli*, 1997] suggests that the process of the moist air advection due to the tropical-area-midlatitude interactions has already been active several days before the intensive developments over the Sinai peninsula took place.

According to the control run simulation, two main synoptic processes of the November 1-5, 1994, period may be indicated in the lower troposphere of the Mediterranean area. These are the development of the EM cyclone and the formation of an intensive northward airflow with high moisture content over the western Mediterranean. This airflow was associated with the hazardous weather of November 5, 1994. According to the observations and to the results of the experiments, prior to November 1, 1994, tropical convection in Africa intensified due to large amounts of moisture available in the air masses already advected from the Arabian Sea.

The following interpretation of the simulation results may be proposed:

The active convective processes caused intensification of the upper tropospheric jet stream over the Red Sea area. This intensification created conditions for development of the Red Sea trough circulation which supported advection of the moist air from the Arabian Sea to the Red Sea area. In its turn this process created conditions for development of the November 2, 1994, eastern Mediterranean cyclone and also of a large zone of additional counterclockwise circulation over Europe. As a result, the November 5, 1994 western Mediterranean rainy weather [*Lionetti*, 1996] was also influenced by this additional advection of air moisture from Africa, which originated earlier from the Arabian Sea area.

According to the results, both the eastern Mediterranean cyclogenesis of November 2 and the intensive rains of November 5, 1994, in the area of the systematic development of the central Mediterranean cyclones

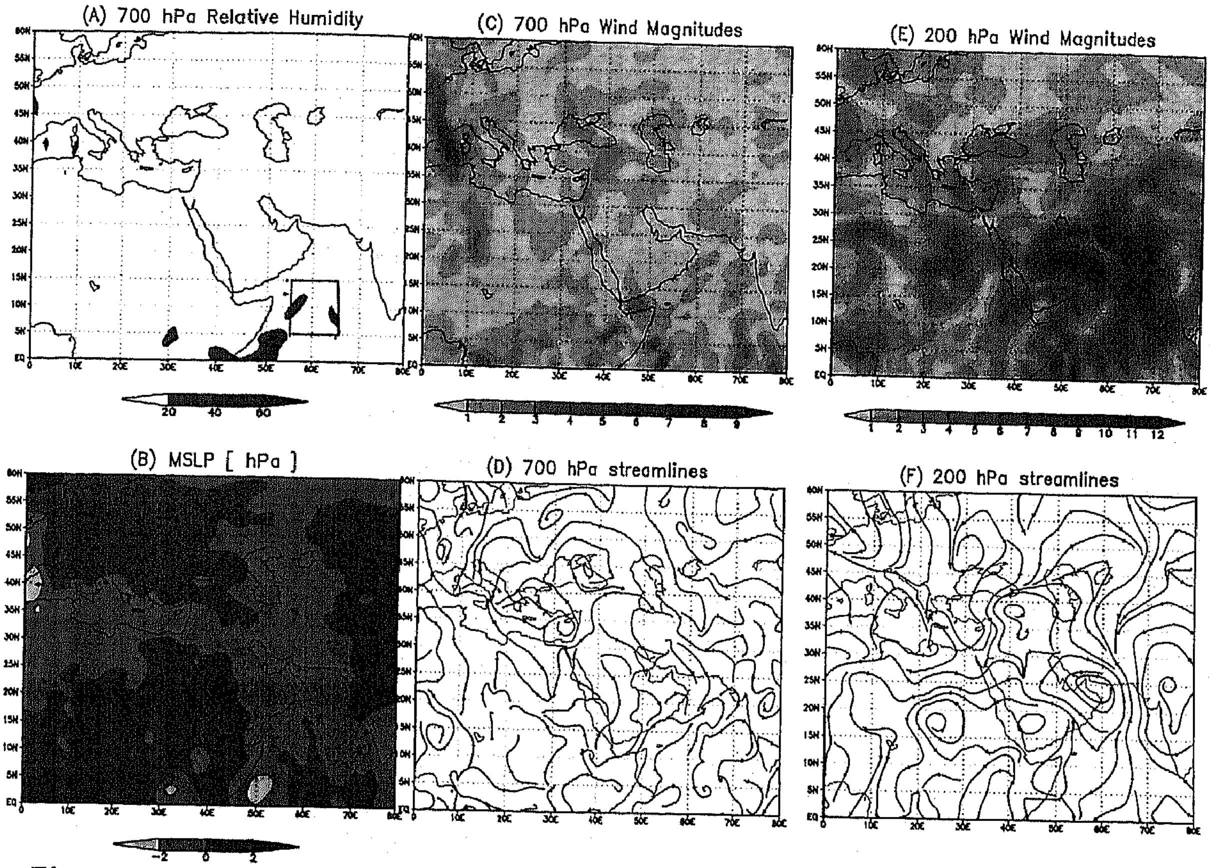

Figure 11. Same as for Figure 7 but for deviations of the 96-hour model simulation results for the A experiment (control minus experiment).

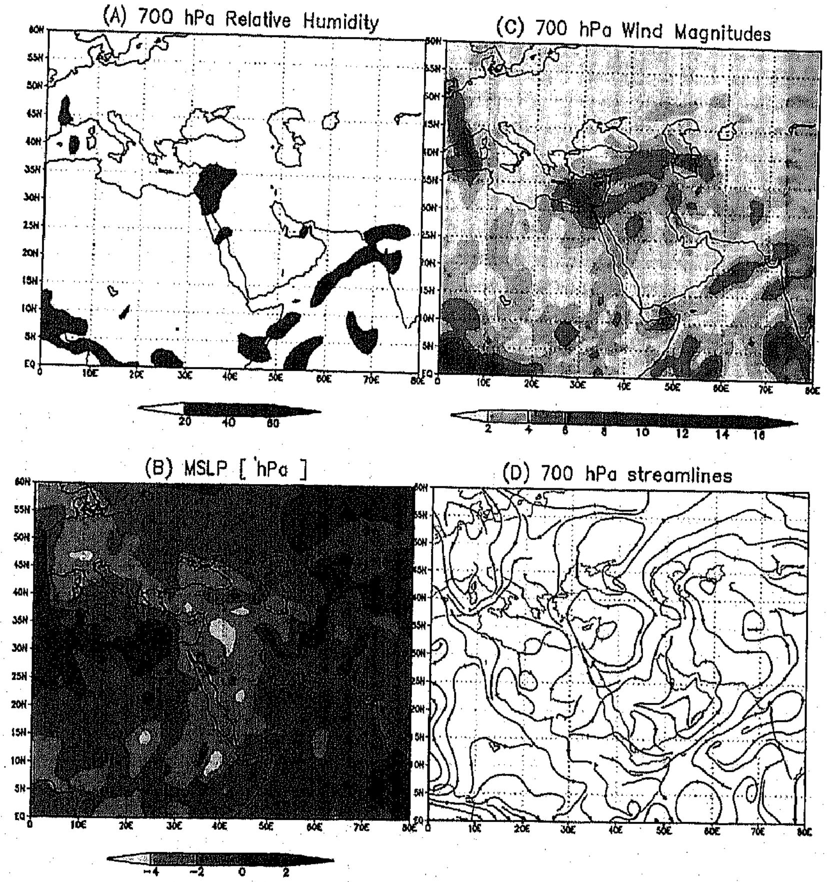

Figure 12. Same as for Figure 7 (for (a-d)) but for deviations of the 96 hour model simulation results for the A experiment from those of the S experiment (A - S).

[*Jansa*, 1986, 1997; *Pettersen*, 1956; *Reiter*, 1975] were influenced by the same tropical-area-midlatitude interaction process. This fact may be an indication of a more permanent relationship between the cyclogenetic processes in the central and the eastern Mediterranean. An example of such relationship has already been demonstrated by *Krichak et al.*, [1997c].

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References

Alpert, P. and Y. Shay-El, The moisture source for the winter cyclones in the eastern Mediterranean, *Isr. Meteorol. Res. Pap.*,*5*, 20-27, 1994.

Buzzi, A., and N. Tartaglione, Meteorological modelling aspects of the Piedmont 1994 flood, *MAP Newslett.*, *3*, 27-28, 1995.

Doswell, C.A., R. Romero, C. Ramis and S. Alonso, Diagnosis of two heavy rainfall cases in the western Mediterranean, paper presented at the International Symposium on Cyclones and Hazardous Weather in the Mediterranean, INM/World Meteorol. Organ., Palma de Mallorca, Spain, 14-17 April, 1997.

Jansa, A., Genoa cyclones and other western Mediterranean cyclones. *WMO/TD128*, Append 8, pp. 59-70, World Meteorol. Organ., Geneva, 1986.

Jansa, A., A general view about Mediterranean meteorology: Cyclones and hazardous weather, paper presented at the International Symposium on Cyclones and Hazardous Weather in the Mediterranean, INM/World Meteorol. Organ., Palma de Mallorca, Spain, 14-17 April, 1997.

Kallos, G., V. Kotroni, K. Lagouvardos, S. Nickovic, D. Jonic, O. Kakaliagou, A. Papadopoulos, Torrential rains in the northeastern Mediterranean, paper presented at the International Symposium on Cyclones and Hazardous Weather in the Mediterranean, INM/World Meteorol. Organ., Palma de Mallorca, Spain, 14-17 April, 1997.

Krichak, S.O., P. Alpert and Z. Levin, Numerical simulation of hazardous weather conditions during the November 2, 1994 E. Mediterranean cyclone development, paper presented at the International Symposium on Cyclones and Hazardous Weather in the Mediterranean, INM/World Meteorol. Organ., Palma de Mallorca, Spain, 14-17 April, 1997a.

Krichak, S.O., P. Alpert and T.N. Krishnamurti, Interaction of topography and tropospheric flow-a possible generator for the Red Sea trough? *Meteorol. Atmos. Phys.*, *63*(3-4), 149-158, 1997b.

Krichak, S.O., P. Alpert and T.N. Krishnamurti, Red Sea trough/cyclone development-Numerical investigation, *Meteorol. Atmos. Phys.*, *63*(3-4), 159-170, 1997c.

Krishnamurti, T.N., The sub-tropical jet stream of winter. *J. Meteorol.*, *18*, 172-191, 1961.

Krishnamurti, T.N., M. Kanamitsu, W. Koss and J.D. Lee, Tropical east-west circulation during the northern winter. *J. Atmos. Sci.*, *30*, 780-787, 1973.

Krishnamurti, T.N., H.S. Bedi and K. Ingles, Physical initialization using SSM/I rain rates. *Tellus*,Ser. A, *45*, 247-269, 1993.

Lagouvardos, K., V. Kotroni, S. Dobricic, S. Nickovic and G. Kallos, On the storm of 21-22 October 1994 over Greece: Observations and model results. *J. Geophys. Res.*, *101*, 26,217-26,226, 1996.

Leguy, C., M. Rindsberger, A. Zangvil, A. Issar and J. Gat, 1983: The Relation between the ^{18}O and Deuterium Contents of Rain Water in the Negev Desert and Air-Mass Trajectories. *Isotope Geosci.*, *1*, 205-218.

Lionetti, M. 1996: The Italian Floods of the 4-6 November 1994. *Weather 51*, 18-27.

Massacand, A., H. Wernli and H. Davies, An Upper-Level Precursor for Heavy Precipitation South of the Alps, paper presented at the International Symposium on Cyclones and Hazardous Weather in the Mediterranean, INM/World Meteorol. Organ., Palma de Mallorca, Spain, 14-17 April, 1997.

Obasi, G.O., Address, paper presented at the International Symposium on Cyclones and Hazardous Weather in the Mediterranean, INM/World Meteorol. Organ., Palma de Mallorca, Spain, 14-17 April, 1997.

Pettersen, S., Weather Analysis and Forecasting, vol. 1, 428 p., New York: McGram-Hill, New York, 1956.

Prezerakos, N.G. and P. Ralli, Analysis and Diagnosis of the Atmospheric Circulation Systems Associated With an Event of Mixed Type Heavy Rain Resulting in Extensive Floods Over Greece, paper presented at the International Symposium on Cyclones and Hazardous Weather in the Mediterranean, INM/World Meteorol. Organ., Palma de Mallorca, Spain, 14-17 April, 1997.

Reiter, E.R. *Handbook for Forecasters in the Mediterranean.* I, *General Descriptionof the Meteorological Processes*, Nav. Environ. Predict. Res. Facil., Monterey, California, 344 pp., 1975.

Schar, C. and H. Wernli, Structure and Evolution of an isolated semi-geostrophic cyclone. *Q. J. R. Meteorol. Soc.*, *119*, 57-90, 1993.

Shay-El Y. and P. Alpert, A diagnostic study of winter diabatic heating in the Mediterranean in relation with cyclones. *Q. J. R. Meteorol. Soc.*, *117*, 231-243, 1991.

Stein, U. and P. Alpert, Inclusion of sea moisture flux in the Anthes-Kuo cumulus parameterization. *Contr. Atmos. Phys.*, *64*, 231-243, 1991.

Stein, U. and P. Alpert, Factor separation in numerical simulations, *J. Atmos. Sci.*, *50*, 2107-2115, 1993.

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