The Role of Atmospheric Processes Associated with Hurricane Olga in the December 2001 Floods in Israel

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ABSTRACT

Over the period from 0000 UTC 3 December to 0000 UTC 5 December 2001, heavy rains fell in northern Israel. Intensity of the rainfall in some areas exceeded 250 mm (24 h)$^{-1}$. Results of an investigation of the case including back-trajectory evaluations, numerical simulation experiments, and a potential vorticity (PV) analysis are presented. It is demonstrated that the unusual eastern Mediterranean process has been initiated by the formation of a tropical storm that later became Hurricane Olga from 25 to 29 November. The consequent synoptic processes were associated with the development of a large-scale anticyclone to the NE of the tropical storm. Large-scale subsidence in the anticyclone played a central role in the process by leading to a convergence of the moist air masses in a narrow band on the outskirts of the system. The air masses from the area were later transported into the midtroposphere over western Europe. The interaction of these relatively warm and wet air masses with the cold and dry upper-tropospheric air over Europe has led to an intensification of the upper-tropospheric northerly airflow, extrusion of stratospheric air into the upper troposphere, and formation of a PV streamer system over southern Europe. Finally, the positioning and intensity of the PV streamer, as well as the large amounts of air moisture over the Mediterranean region, contributed to the intensity of the 3–5 December 2001 torrential rains over Israel.

1. Introduction

The Mediterranean region is characterized by frequent events of torrential rainfalls and flash floods. The rains are most intense over the western part of the region (Siccardi 1996), where registered accumulated precipitation reaches in some cases up to 750 mm (Jansa 1997), with daily mean values going up to 250 mm day^{-1}. The eastern Mediterranean (EM) torrential rains are normally strong as well (Krichak and Alpert 1998; Alpert et al. 2002), though in most cases they do not reach the intensities of the western Mediterranean (WM) ones. Though some of such cases are associated with deep small-scale cyclones, most of the extreme Mediterranean rainfalls are produced by relatively mild systems (Turato et al. 2004).

Unusually intense EM rains occurred in December 2001. Torrential rains fell over northern Israel from 0000 UTC 3 December to 0600 UTC 5 December, and flash floods were registered. The most intense rains were observed over a narrow coastal zone north of the city of Hadera (32.5°N, 34.7°E) (Figs. 1a,b). About 250 mm of rain (almost 200 mm during the 6-h time interval from 0100 to 0700 UTC of 4 December 2001) fell from 0000 UTC 3 December to 0000 UTC 4 December at the Zichron Yaakov station (32.66°N, 34.95°E). At another neighboring station, Maor (32.42°N, 35.00°E), 74 mm of rain were registered during the 24-h time interval prior to 0900 UTC of 5 December. The rainfall at the third station in the region, Rupin (32.33°N, 34.92°E), was less intense—about 35 mm during the 12-h time period. The system decreased in strength with its southward displacement, though heavy rains (up to 90 mm per 24 h in some places) were also registered over the more southern areas of the country. The case intensity and timing were not accurately predicted by the existing operational modeling systems.

Because of the unusually high intensity of the rains, the period was included by the steering committee of the World Meteorological Organization (WMO) World Weather Research Program (WWRP) Mediterranean Experiment (MEDEX) Project ''On cyclones that produce high-impact weather in the Mediterranean'' in the list of cases for special analysis. It was also selected for a detailed investigation under the German–Israeli Global Wandel des Wasserkreislaufs (Global Change in the Hydrological Cycle; GLO-WA) Jordan River research program.

The current study was performed in accordance with

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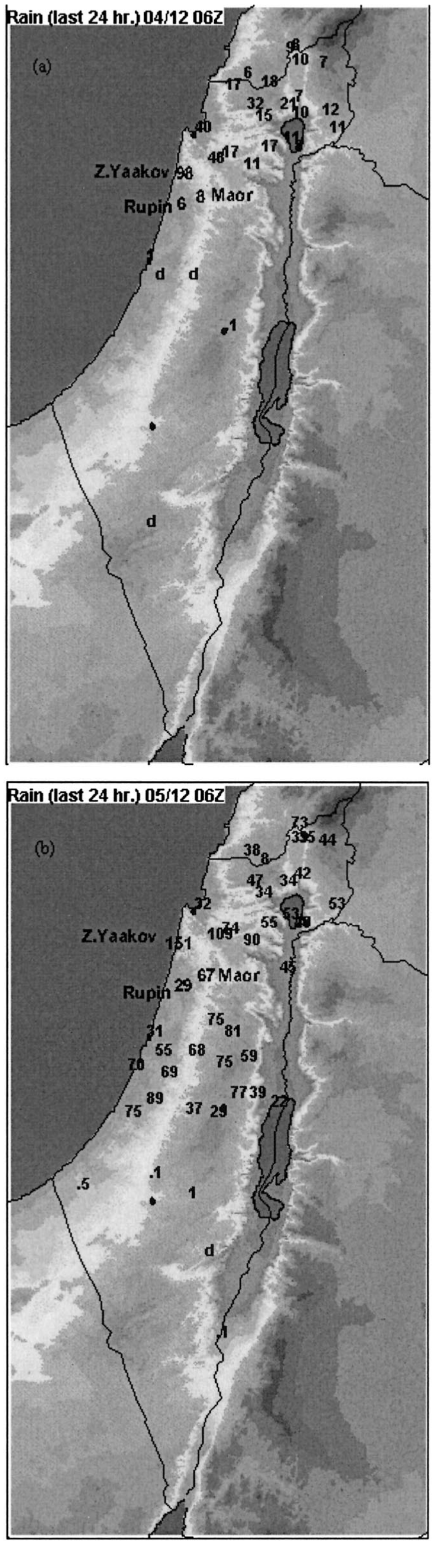

FIG. 1. Observed precipitation in Israel (a) from 0600 LT 3 Dec to 0000 LT 4 Dec and (b) from 0600 LT 4 Dec to 0000 LT 5 Dec 2001.

the objectives of the two research programs. The major emphasis of the article is the determination of the triggering mechanisms and the origin of the high amounts of air moisture that made possible the torrential rains over Israel. It is demonstrated in the following that the unusually intense EM processes of early December 2001 resulted from the development of Hurricane Olga over the tropical Atlantic during the last week of November. Olga's contribution was twofold. During the first stage of its development, strong winds and the airmass convergence in the hurricane led to concentration of large amounts of water vapor. The second important contribution was associated with the hurricane's role in the development of a large-scale anticyclone to the NE of Olga. The development of the anticyclone set the conditions for the long-range wet airmass transport to Europe and the Mediterranean region. This process, in turn, led to the development of a potential vorticity (PV) streamer system over southern Europe that stimulated the transformation of an existing mild Mediterranean cyclone into the Cyprus low system that was responsible for the torrential rains in Israel.

2. Synoptic description

The low pressure system that produced torrential rains in Israel in December 2001 belonged to the type of the Mediterranean cyclones known as Cyprus lows or Cyprus depressions (El-Fandy 1946; Kallos and Metaxas 1980; Alpert et al. 1995; Alpert et al. 2004). Cyclones of this type usually start their development in the westerly flows of the low pressure belt over the southwestern areas of the Mediterranean Sea, and then migrate to the east. During the migration process, the depressions usually weaken, though they often rejuvenate again when approaching Italy. An additional, very significant strengthening of the cyclones is often observed in the Cyprus area, where the lows regenerate in the lee of the Taurus Mountains of Turkey. The process normally takes place in the area of the Gulf of Antalya and Cyprus (Alpert et al. 1995).

The following synoptic analysis is mainly based on data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis project (NNRP; Kalnay et al. 1996; Kistler et al. 2001). The NNRP data are produced with a data assimilation system based on a relatively coarse resolution global spectral model with a T62/28 space resolution (about 210 km, 28 level) and are available at 2.5° latitude $\times$ 2.5° longitude horizontal grid.

The synoptic developments of the 2–5 December 2001 period are illustrated in Figs. 2a–d. A weak large-scale cyclone with central pressure below 1005 hPa occupies the area over Crete in Fig. 2a. The SE part of the system is characterized by high amounts (20–25 kg m^{-2}) of precipitable water (PW) in the air column. The 850-hPa wind distribution indicates the origin of the

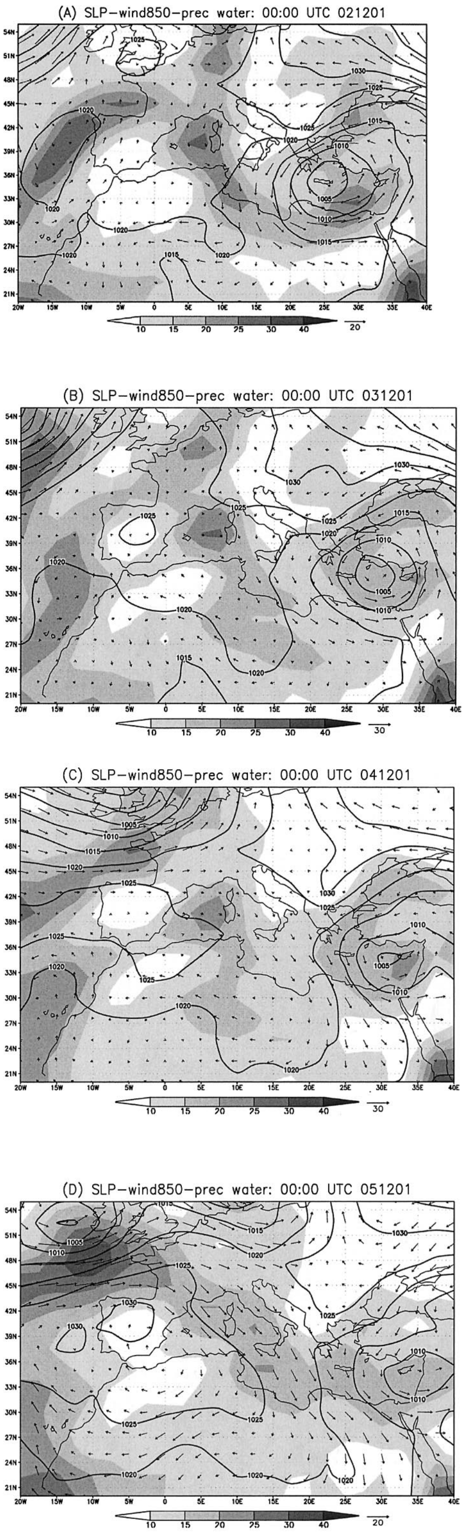

FIG. 2. Distributions of sea level pressure (hPa; isolines), 850-hPa winds (m s^{-1}; arrows), and precipitable water (kg m^{-2}; shading) at 0000 UTC (a) 2, (b) 3, (c) 4, and (d) 5 Dec 2001.

water vapor. Part of the PW is transported to the Mediterranean region by the anticlockwise circulation from the area over the Black Sea. This source of air moisture, however, is not the primary one. The main portion of the air moisture is evidently transported from the west through the northern part of the western Mediterranean and the Pyrenean peninsula. Another zone with a less intense PW transport is positioned over western Europe.

On the following day (0000 UTC 3 December), the cyclone's center was located between Crete and Cyprus (Fig. 2b). At this moment the air moisture transport over western Europe was already mainly directed to North Africa and only partially to the EM. An area with very high PW values (25–30 kg m^{-2}) is found over the WM. The air moisture appears to be of Atlantic origin. A small zone with high (20–25 kg m^{-2}) PW values is found in the area of the cyclone over Cyprus. Change in direction of the airmass transport explains the PW decrease in the area (Fig. 2b).

At 0000 UTC 4 December, the cyclone's center is located to the west of Cyprus (Fig. 2c). The already noted zone with high PW values remains over the WM. A large zone with significant (20–25 kg m^{-2}) PW values is found in the eastern part of the cyclone. At 0000 UTC 5 December (Fig. 2d), the cyclone with the central pressure above 1005 hPa is already positioned over the EM coast. No high PW zones are found over the area.

The mean monthly sea surface temperature (SST) throughout November 2001 (Reynolds and Smith 1994) was 0.7°–1.1°C higher than normal near the eastern zone, located to the east of Cyprus. Another zone with positive SST anomalies of 0.7°–1.1°C existed between the islands of Rhodes and Crete and in the Aegean Sea. The enhanced air–sea temperature gradients may have played a role in determining the frequency of occurrences of intense rains over the area (Stein and Alpert 1991; Shay-El and Alpert 1991). A significant role of dynamic effects in the 3–4 December 2001 precipitation in Israel may be also envisaged.

3. Determining the zone with intense small-scale developments

As a first step of the evaluation, a determination of the zones with intense synoptic processes was performed. The ''poor man's ensemble prediction'' methodology was applied for this purpose. In accordance with this approach (Ziehmann 2000; Kalnay 2004), the areas with a decreased predictability of the synoptic developments may be determined based on the results of a limited number of numerical weather forecasts. The ''low predictability'' areas usually represent those with more intense small-scale cyclogenetic developments (Coiffier 2002). A significant role of such effects in the processes that determined the intensity of the December 2001 torrential rains in Israel may be envisaged.

The results of four slightly differing simulations of the EM 3–5 December 2001 weather developments with a state-of-the-art hydrodynamic atmospheric model have been adapted for the analysis.

a. Model and data used

The numerical simulations were performed using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (Penn State–NCAR) Mesoscale Model (MM5). Detailed description of the model is available in Grell et al. (1994), Dudhia et al. (2001; and also at the MM5 Web site, http://www.mmm.ucar.edu/mm5).

The dataset for the simulations was taken from the global operational analysis/prediction 48-h runs performed at NCEP at 0000 UTC 3 December 2001. Also available for additional assimilation are the observation data from about 400 surface and 40 aerological stations over the Mediterranean region and surrounding areas.

Data from the coarse-resolution predictions at NCEP were used to drive the limited-area MM5 simulation from the lateral boundaries. NCEP data at 0000 UTC 3 December 2001 were adapted as the initialization data for the MM5 simulations in case MM5 objective analysis is not performed. It should be noted that the NCEP initial data were produced using all aerological observations in the region, but only from a limited number of surface stations. Because of this fact, additional assimilation of the aerological data with the MM5 data assimilation (MM5 DA) system led to insignificant modifications of the initial data. However, the assimilation of the surface observations in the high-resolution objective analysis resulted in a more significant alteration of the forecasts results.

b. Design of the experiments and results

The following four versions of the MM5 have been designed for the analysis (Dayan 2003):

- A1: MM5 with two nested domains (one-way interaction); 58×73 and 73×73 grid points with 60- and 20-km horizontal resolution, respectively (larger model domain). Vertical structure of the atmosphere is represented by 27 model layers. Topmost level is positioned at 100 hPa.
- A2: Same as A1, but the vertical structure of the atmosphere is represented by 36 model layers. Topmost level is positioned at 70 hPa. MM5 data assimilation procedure is adapted. The model version is also used for twice-daily quasi-operational runs at Weather Research Center (WeRC) of Tel Aviv University (Web site: http://nasa.proj.ac.il/tau-werc.html).
- A3: Same as A2, but using a 30- and 10-km horizontal resolution (116×146 and 146×146 grid points). No MM5 DA is performed.
- A4: Same as A3, but the data assimilation is performed using the MM5 DA tool.

Within the scope of the current study we consider the model versions as those representing a forecast ensemble. In the following we evaluate the zones with the most unstable dynamics, according to the variance of the modeling results in the ensemble.

Results of the four-member ensemble prediction of the geopotential heights of 500-hPa isobaric surface (H-500) to 48 h are presented in 12-h time intervals in Figs. 3a–d. The isolines in Figs. 3a–d represent the mean H-500 for the four simulations. In the 12-h prediction (Fig. 3a) the area with the highest variations (and a higher probability of an increased instability of the atmospheric processes) is found over southern Turkey. In the following patterns (Figs. 3b–d), two main areas with highest uncertainty levels of the simulation results are present. One of them is gradually displacing to the Caspian Sea. The second area is found in the vicinity of the island of Cyprus, from where the 3–5 December 2001 cyclone originated.

The area of, and to NE of, the northern EM may be considered as that favorable for small-scale atmospheric developments, which constituted the process of conversion of a mild Mediterranean cyclone into the intensively precipitating Cyprus low of 3–4 December 2001. An evaluation of the mechanisms that determined the location of the unstable zone is suggested in the following section.

4. Triggering mechanism: Potential vorticity perspective

In the extratropical atmosphere, intense cyclones often develop in the regions located under upper-tropospheric jet streams. The role of the polar jet (PJ) and subtropical jet (STJ) stream conditions in the Israeli weather has already been demonstrated (Krishnamurti 1961; Dayan and Abramsky 1983; Krichak and Alpert 1998). The upper-troposphere jet streams are often characterized by anomalously high values of PV. The PV is determined as the product of absolute vorticity and static stability. According to Ertel (1942), the PV is conserved along the flow on an isentropic surface under adiabatic and frictionless conditions. Because of its conservative property, PV is used to trace the areas with specific characteristics of the air masses. During short time intervals, the PV calculated on an isobaric surface may also be used as a Lagrangian tracer. The PV approach is widely applied in the analysis of atmospheric processes (Hoskins et al. 1985; Thorpe 1985; Barnes and Colman 1994).

For the extratropics, PV values above 3 potential vorticity units (1 PVU $= 10^{-6}$ K m^2 kg^{-1} s^{-1}) are inferred (Hoskins et al. 1985; Hoskins and Berrisford 1988; Barnes and Colman 1994) to represent stratospheric air (due to high stability there). In the extratropics, PV values of 1.5–3 PVU represent air masses that originated near the tropopause. The PV values of less than 1.5 PVU are considered as those representing the troposphere. Positive PV anomalies in the troposphere are

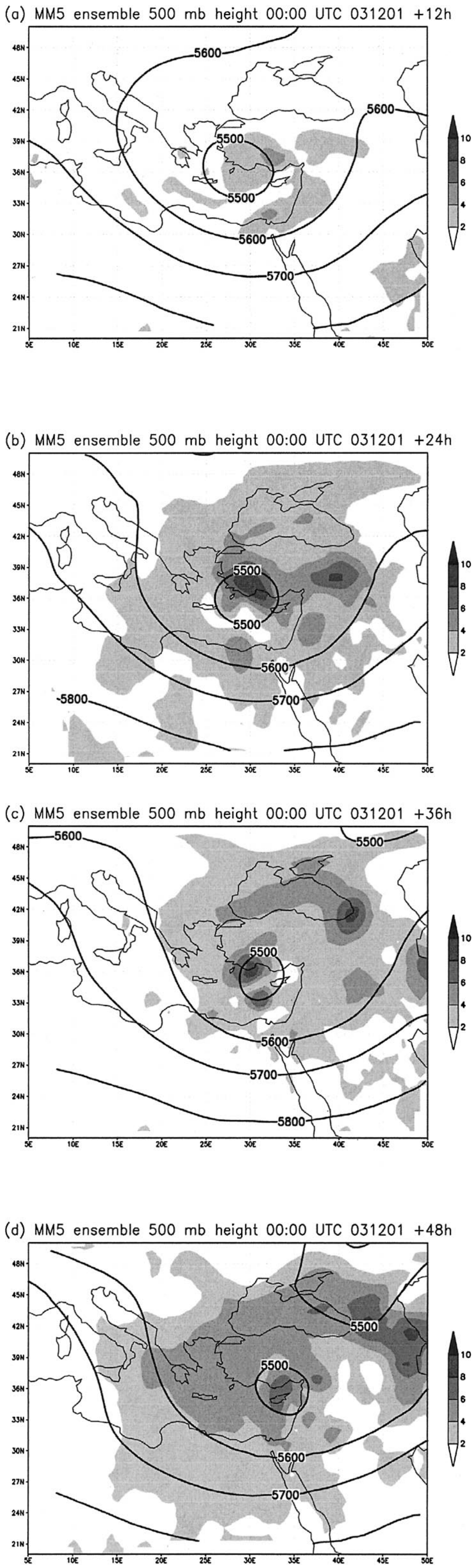

FIG. 3. MM5: ensemble-averaged H-500 predictions (m) and the pertinent variance for the simulation results to (a) 1200 UTC 3 Dec, (b) 0000 UTC 4 Dec, (c) 1200 UTC 4 Dec, and (d) 0000 UTC 5 Dec 2001 in A1–A5 experiments (contour intervals 50 m).

often found in areas with downward propagation of stratospheric air masses.

An important role of the processes developing under the elongated three-dimensional structures, with positive PV anomalies in the jets–PV streamers, has also been noted (Morgenstein and Davies 1999). The streamer conditions influence timing, amplitude, and location of intense surface cyclogenesis and sustained precipitation events (Fehlmann and Davies 1999; Fehlmann and Quadri 2000; Fehlmann et al. 2000). It was suggested (Liniger and Davies 2003) that accurate specification of the prehistory of the tropopause-level fine-scaled PV distribution might be a necessary prerequisite for the successful prediction of hazardous weather events.

The PV calculations on the isobaric surfaces based on the NNRP data are presented in Figs. 4a–d, for four instances from 0000 UTC 2 December to 1200 UTC 3 December 2001. Dashed lines represent PV at 250 hPa, and solid lines PV at 650 hPa. The PW patterns are also represented here by the shaded areas. In the following analysis, the PV-650 patterns are considered as those representing the lower-troposphere dynamics, whereas the PV-250 isolines provide information on the atmospheric circulation in the upper troposphere.

According to the high-resolution PW patterns in Figs. 4a–d, the time period was characterized by the penetration from the central Mediterranean area to the EM region of an elongated zone with high (>25 kg m^{-2}) PW values. The transport of the air moisture to the EM area became possible because of the existence of the previously developed mild central Mediterranean cyclone. The cyclone is indicated in Fig. 4a at 0000 UTC 2 December, by the zone with a PV-650 maximum of 0.6–0.7 PVU, positioned between Crete and the North African coast. The existence of an elongated zone with high PV-250 values (up to 8 PVU) demonstrates intrusion of the cold stratospheric air masses possibly accompanied by the tropopause folding effects (Hoskins et al. 1985; Barnes and Colman 1994). The role of the effects over the EM has already been documented (Neeman and Alpert 1990).

In Fig. 4b, for 1200 UTC 2 December, a farther-eastward propagation of the high PW zone is observed. The zone with the PV-250 maximum in the upper troposphere is shifting southward. A transformation and widening of the area with the PV-650 anomaly over the N of the EM region may be noted. The area with a PV maximum at 250 hPa is present in Figs. 4c and 4d, for 0000 and 1200 UTC 3 December 2001, respectively. A continuation of the process of the southward propagation of the area may be noted. The representing cyclone zone with the PV-650 positive anomaly shifts during the process from its original position to that with the PV maximum located under the front-left quadrant of the corresponding upper-troposphere PV maximum. This illustrates the role of the stable PV-250 system (Hakim 2003) over southern Europe and the Mediter-

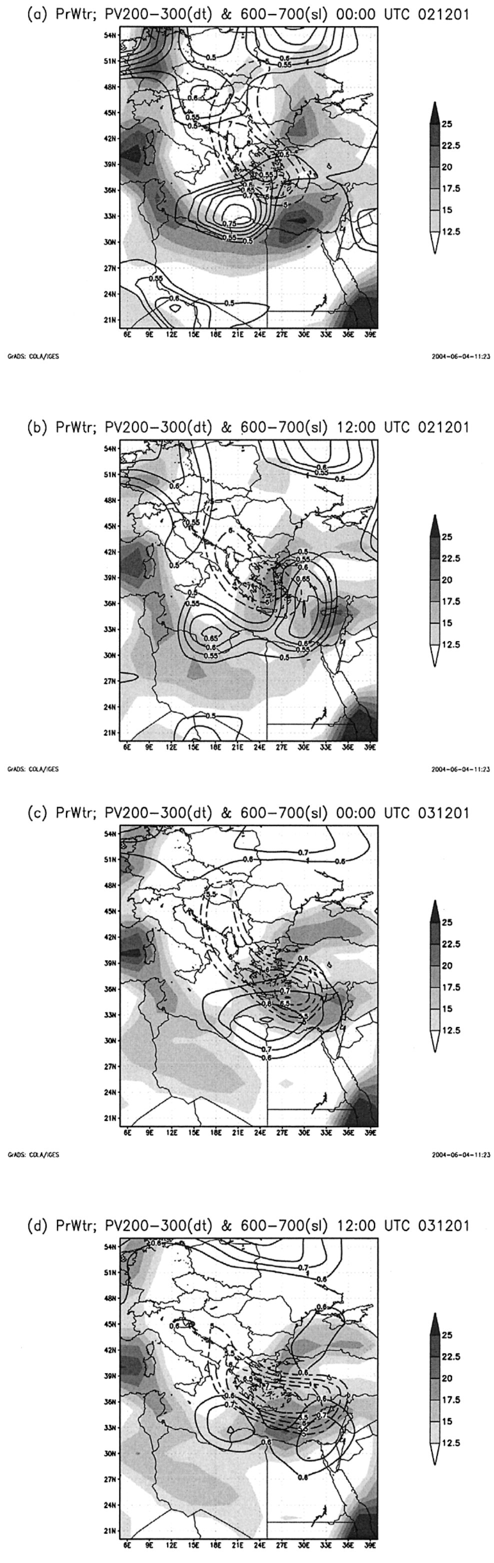

FIG. 4. NNRP: PV patterns for 200–300-hPa layer (PVU; dashed lines), PV patterns for 600–700-hPa layer (PVU; solid lines), and precipitable water (kg m^{-2}; shading) at 0000 UTC (a) 2, (b) 3, (c) 4, and (d) 5 Dec 2001.

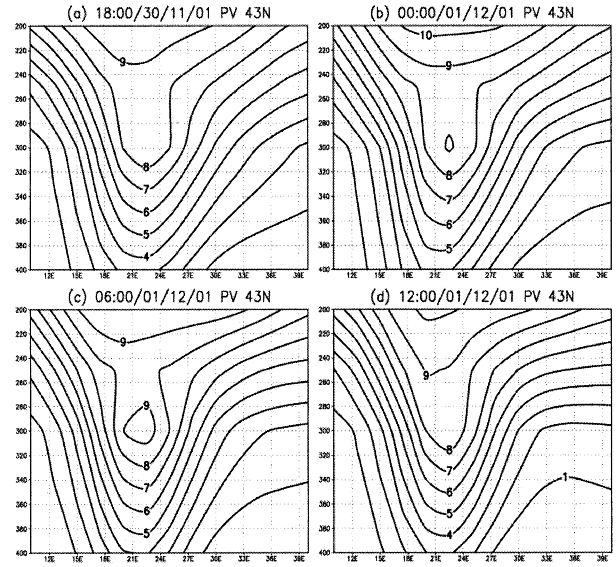

FIG. 5. Vertical PV cross sections along 43°N from 10° to 40°E (contour interval 1 PVU).

ranean region in the development of the intense cyclone over the period. The result is in agreement with the earlier conclusions based on the application of the ensemble approach.

Vertical cross sections of the PV along 43°, 40°, and 37°N made at 1800 UTC 30 November and 0000, 0600, and 1200 UTC 1 December 2001 are given in Figs. 5a–d, 6a–d, and 7a–d, respectively. According to the figures, the PV anomaly system propagated southward during the period to the extent of about 22°E. On the cross section made along 43°N, the process of the downward propagation of the area with the PV anomaly (9 PVU) takes place between 0600 and 1200 UTC 1 December

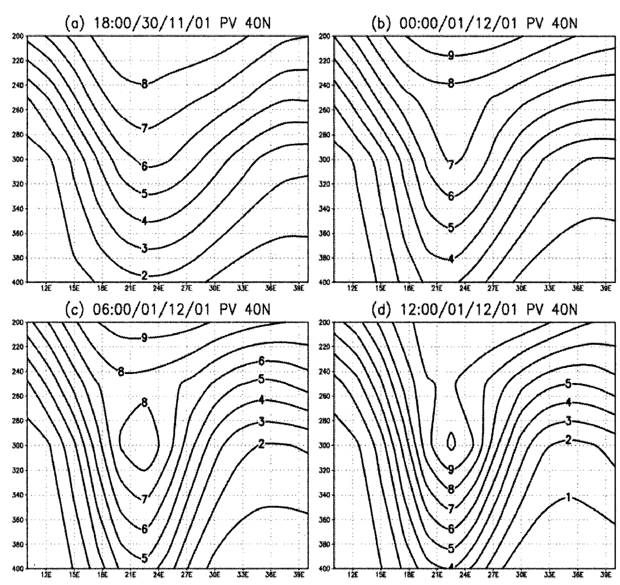

FIG. 6. Same as Fig. 5, but along 40°N.

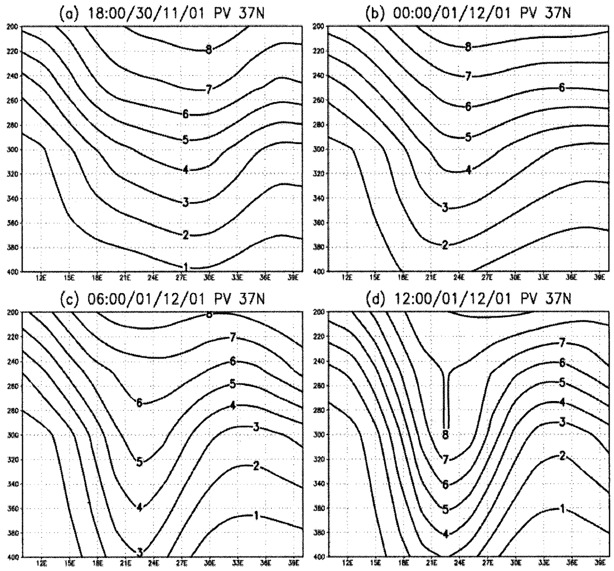

FIG. 7. Same as Fig. 5, but along 37°N.

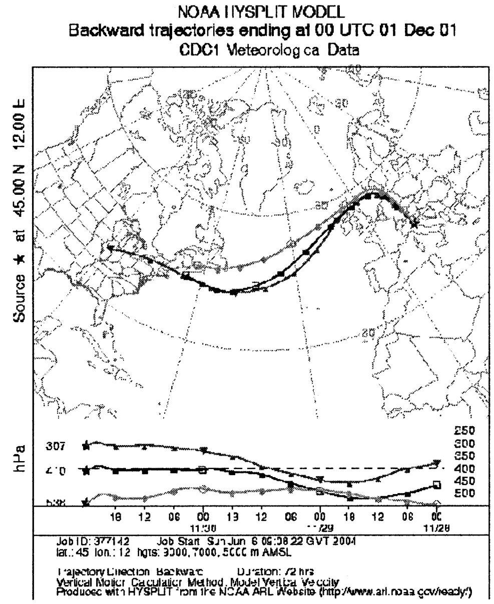

FIG. 8. Backward 72-h trajectories ending at 0000 UTC 1 Dec 2001 at 45°N, 12°E (72 h) at 9, 7, and 5 km.

(Figs. 5b,c). On the cross section along 40°N the anomaly is intensified (up to 10 PVU), but its propagation takes place about 6 h later—between 1200 and 1800 UTC 1 December (Figs. 6c,d). On the cross section along 37°N (Figs. 7a–d) the anomaly is weaker (narrow tongue of PV anomaly of 8 PVU), and the maximum is achieved only at the end of the period (Fig. 7d). The PV anomaly system has a stable three-dimensional structure, and may be identified as a PV streamer.

5. Origin of the air masses: Trajectory analysis

The periods with the air moisture transport from distant areas are typical of the Mediterranean region. Over the WM area the airmass transport from the Atlantic region is (together with the evaporation from the Mediterranean Sea surface in some cases) the predominant air moisture source for heavily precipitating cyclones (Reale et al. 2001). A number of WM events with very intense rainfalls were associated with moist airmass transport from tropical storms/hurricanes (Turato et al. 2004; Buzzi and Foschini 2000; Pinto et al. 2001; Reale et al. 2001). Transports of air moisture from the areas of the Indian Ocean and southern Africa are found to be important for understanding the intensity of torrential rains over the EM region (Krichak and Alpert 1998, 2000; Zangvil et al. 2003; Ziv 2001). As demonstrated in the following, the long-distance transport of the air moisture has also determined the intensity of the PW maximum over the WM region at 0000 UTC 3 December.

Krichak and Alpert (1998), Stohl and James (2004), and Turato et al. (2004) applied the trajectory analysis approach in determining of the origin of air moisture in high-impact cyclones over Europe and the Mediterranean region. This approach is also adapted in the current study. The advanced Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) system, of the National Oceanic and Atmospheric Administration/Air Resources Laboratory (NOAA/ARL), is applied here for a three-dimensional trajectory calculation (Draxler and Rolph 2003) to trace the air masses arriving at the EM. The model uses previously gridded meteorological data to calculate the trajectories, according to Lagrangian approach. The advection of a particle is computed from the average of the three-dimensional velocity vectors for its initial and the first-guess position at each time step. The velocity vectors are linearly interpolated in both space and time. The trajectories used in the analysis below are based on three-dimensional wind vector components from the NNRP.

In accordance with the data from the PV cross sections (Figs. 5a–c, 6a–c, 7a–c) the 72-h backward trajectories ending over southern Europe at 0000 UTC 1 and 2 December 2001 at 12°, 22°, and 30°E along 45°N have been calculated (Figs. 8–10 and 11–13, respectively). The endpoints of the trajectories as well as their heights (5000, 7000, and 9000 m) are selected to represent the processes associated with the PV streamer. As seen in the figures, the 24-h period from 0000 UTC 1 December 2001 was characterized by a stable large-scale airflow with two main branches of the airmass transport arriving to the area from the SW and NW (Figs. 9, 10 and 12, 13, respectively). The midtropospheric trajectories arriving in southern Europe with the southern branch of the airmass transport show the air masses ascending on their way over the ocean. The trajectories start descending after their arrival (and the change of direction of the airflow to the northerly one) over Scandinavia (Fig. 8). The ascent over the central

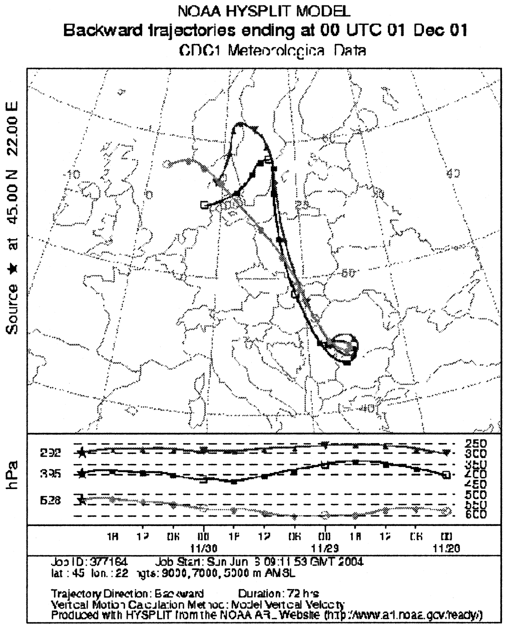

FIG. 9. Same as Fig. 8, but the trajectories ending at 45°N, 22°E.

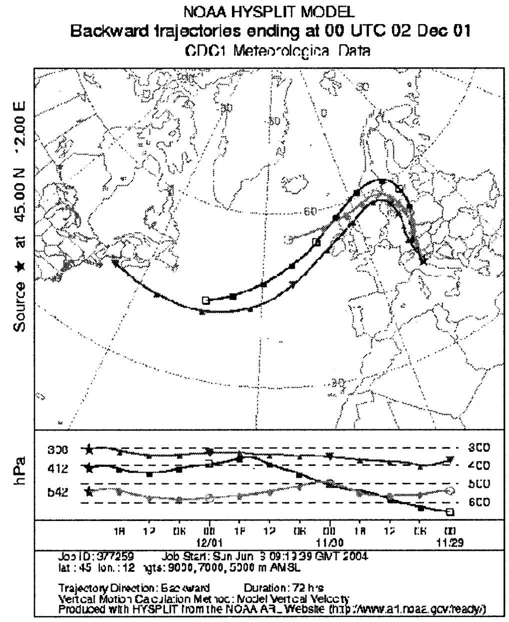

FIG. 11. Same as Fig. 8, but for trajectories ending at 0000 UTC 2 Dec 2001.

Atlantic weakens with time—a less active airmass updraft is demonstrated by the trajectories in Fig. 11.

One of the two airmass transport branches in the trajectories (Figs. 8–13) demonstrates an advection from the regions located over the close-to-tropical Atlantic area. To understand the meaning of this finding in the following section, we will discuss the atmospheric processes that took place over the area several days before.

6. Role of the eastern Atlantic anticyclone

The following analysis is based on the NNRP data. The SLP, 850-hPa winds, and PW patterns over a large part of the area at 0000 UTC 25, 27, 29 November and 1 December 2001, are given in Figs. 14a–d, respectively. At 0000 UTC 25 November, an intense cyclone with a central pressure of 1000 hPa is located at 30°N, 50°W (Fig. 14a). A large-scale high pressure system (with a

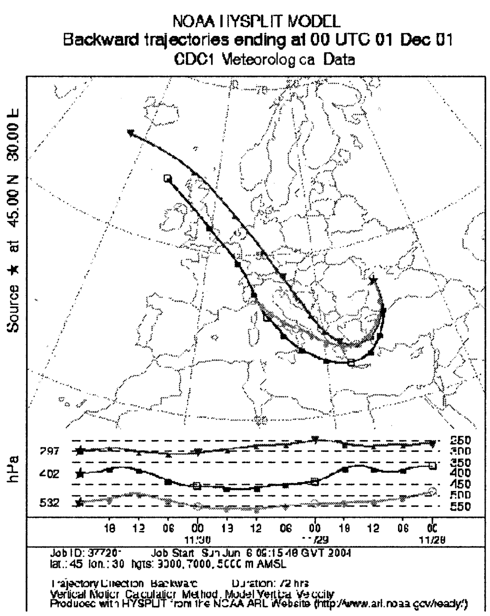

FIG. 10. Same as Fig. 8, but the trajectories ending at 45°N, 30°E.

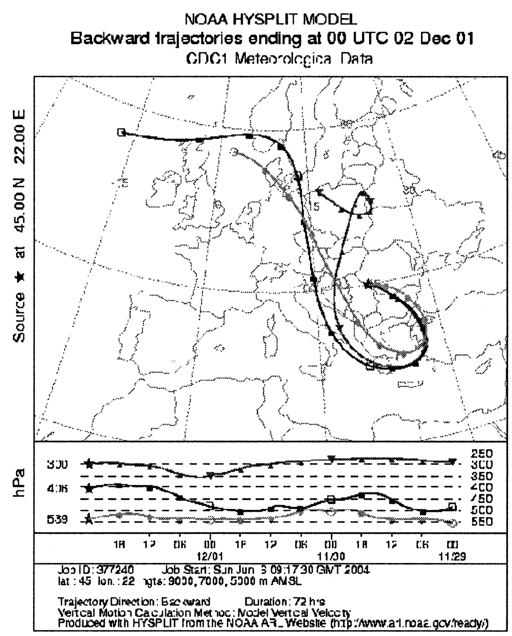

FIG. 12. Same as Fig. 9, but for trajectories ending at 0000 UTC 2 Dec 2001.

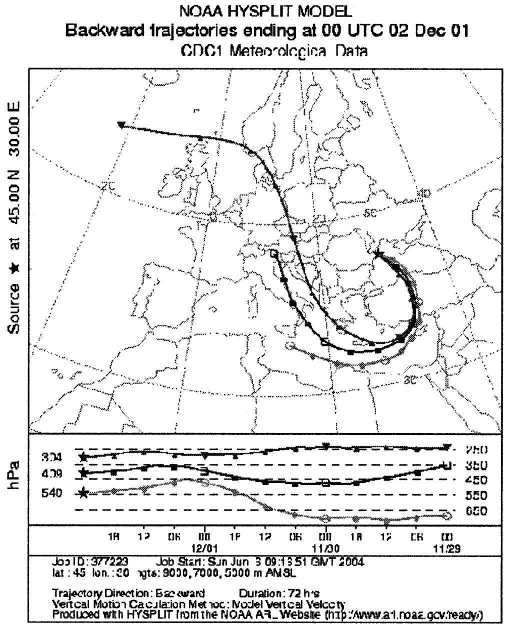

FIG. 13. Same as Fig. 10, but for trajectories ending at 0000 UTC 2 Dec 2001.

central pressure of 1035 hPa) is found to the N of the cyclone. A large zone of very high values of PW is found converging in the vicinity of the cyclone. The 850-hPa wind directions near the cyclone center clearly demonstrate the origin of the water vapor, mainly from the equatorial Atlantic. Within 48 h (0000 UTC 27 November), the cyclonic system is found shifted to the west 30°N, 55°W (Fig. 14b). The anticyclone to the N of the cyclone is significantly weakened (central pressure 1025 hPa) and shifted to the NE. Convergence of the warm and wet air of the tropical Atlantic origin is still in process, though the area with the high PW values is found here significantly expanded to the NE by the clockwise atmospheric circulation to the NE of the cyclone. By 29 November (Fig. 14c), the tropical cyclone in the western part of the pattern is weakened (central pressure, 1010 hPa) and the huge amounts of the air moisture (PW values up to 40 kg m^{-2}) are transported in the direction of Europe by the clockwise circulation in the high pressure system over the eastern Atlantic. It may be noted that the PW in the figure is concentrated over a narrow zone at the NW border of the anticyclone in the eastern Atlantic. Weak subsidence in the area of the anticyclone, and the increased wind speeds in the hurricane, lead to increased convergence of the water vapor at the border between the two centers. This process made possible long-distance transport of the moist air masses from the eastern Atlantic to southern Europe and the Mediterranean region.

Practically no remnants of the former tropical cyclone are found in the patterns as of 0000 UTC 1 December 2001 (Fig. 14d). The eastern Atlantic anticyclone (central pressure 1030 hPa), however, is found shifted to

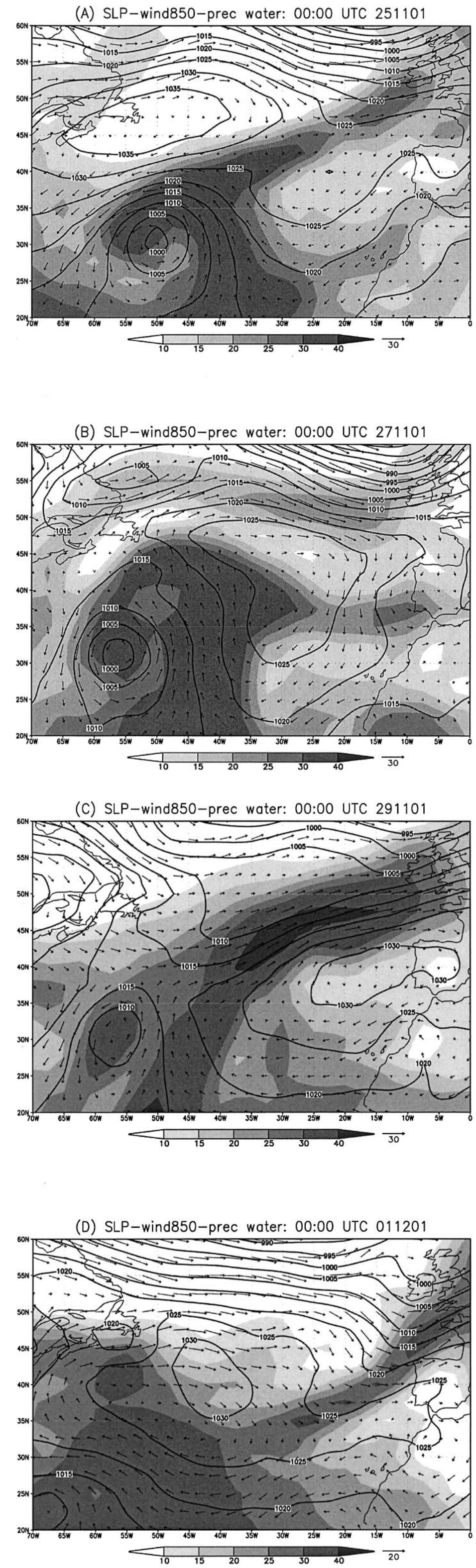

FIG. 14. Same as Fig. 2, but at 0000 UTC (a) 25, (b) 27, (c) 29 Nov, and (d) 1 Dec 2001.

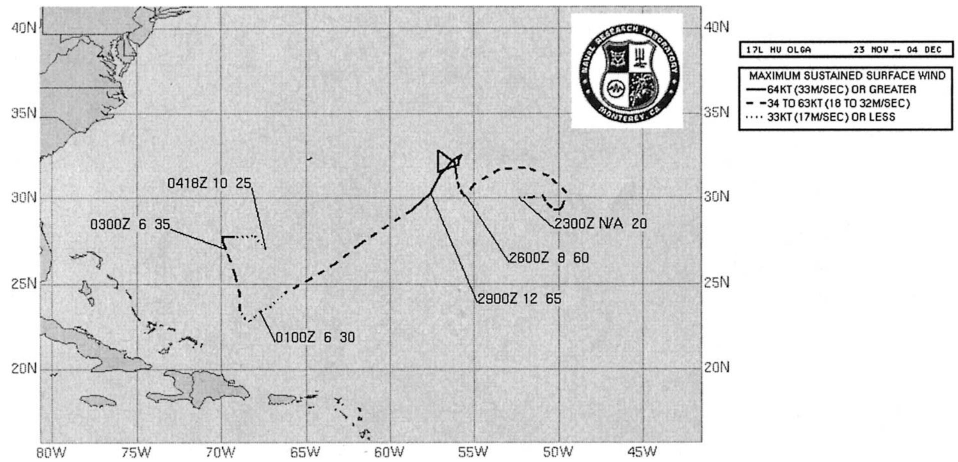

FIG. 15. Olga's track from 0000 UTC 23 Nov to 0000 UTC 3 Dec 2001.

40°N, 40°W. The shift of the system creates the circulation conditions for interruption of the airmass transport to Europe and the Mediterranean region.

According to the analysis, the orientation of the airmass trajectories that brought the water vapor to northern Europe from tropical Atlantic regions was determined by the eastern Atlantic anticyclone in Figs. 14b and 14c, associated with the upward vertical motions and convergence of the moist air in the narrow belt to the NW of the high pressure system. According to the earlier presented results of the PV and trajectory analyses, the location, intensity, and extent of the large-scale anticyclone in late November 2001 made possible the intense weather processes over Europe, the development of the Cyprus low system, and finally the torrential rains of 3–5 December in Israel.

7. Role of Olga

Because of its coarse space resolution, NNRP data provide only broad information about the real synoptic developments during the late-November period. However, much more detailed data on the synoptic processes are fortunately available in Avila (2001). The airmass transport from the Atlantic followed intense atmospheric developments during the last week of November 2001 over the equatorial Atlantic. These processes were associated with the development and consequent decay of an intense tropical cyclone, and then Hurricane Olga. The hurricane was of a nontropical origin and formed from the interaction of a cold front and a small area of disturbed weather in the North Atlantic (Fig. 15). By 1200 UTC 24 November 2001, the activity became more concentrated near the center (29°N, 50°W), when the inner portion of the system had transformed into a tropical storm. Close to normal SST values for November characterized the area (about 22°–23°C). At that time the system was not purely tropical, because it remained embedded within the much larger extratropical circulation. The cyclone moved slowly toward the northeast. As a high pressure ridge built to the north, Olga turned toward the west and west-southwest and gradually intensified. Olga became a hurricane by 1200 UTC 26 November and reached its peak intensity of 40 m s^{-1} and a minimum pressure (32.3°N, 55.9°W) of 973 hPa around 0600 UTC 27 November 2001 (Avila 2001).

From 26 to 28 November, Olga made a double cyclonic loop as it interacted with a large-scale deep-layer cyclonic circulation that was pretty much isolated from the main belt of westerlies. Once it completed its second loop on 28 November 2001, Olga was steered southwestward by another strong area of high pressure to the northwest. It then encountered strong upper-level northerly and then westerly sheer, displacing the convection from the center of circulation. Olga weakened to tropical depression status by 1200 UTC 30 November 2001 (26.9°N, 62.6°W) but again regained tropical storm status at 0000 UTC 2 December 2001. By then, Olga was moving northward and began to make another loop, this time anticyclonic. Olga continued weakening until 5 December 2001, as it made this final loop and another high pressure ridge to the north steered the tropical cyclone west-southwestward.

The huge amounts of the PW in the atmosphere, as well as the positioning and intensity of the eastern Atlantic anticyclone that determined the direction of the airmass transport from the ocean to Europe are explainable by the role of Olga. The strong winds and the airmass convergence in the hurricane during the first stage of its development, from 24 to 27 November 2001, explain the observed concentration of large amounts of wet air over a large area over the tropical Atlantic. Positioning of the hurricane in Fig. 15 until about 27 November 2001 reveals the mechanism that determined that of the large-scale anticyclone over the eastern Atlantic. The formation of the large-scale anticyclone over the eastern Atlantic that determined the long-range wet airmass transport to Europe and the Mediterranean region was also a contribution of Olga.

8. Discussion

The presented results, including back-trajectory evaluations, numerical simulation experiments, and a potential vorticity analysis, may be summarized as follows. It is demonstrated that the unusual eastern Mediterranean process of 3–4 December 2001 was a final stage of a sequence of events initiated by the development of Tropical Storm, and then Hurricane, Olga, during the end of November 2001. The role of a large-scale anticyclone to the NE of the tropical storm was very important for the establishing conditions for long-distance transport of Olga's effects. The large-scale subsidence in the anticyclone allowed the convergence of the moist air masses in a narrow band on the outskirts of the system. The air was later transported into the midtroposphere over western Europe. The interaction of these relatively warm and wet air masses with the cold and dry upper-tropospheric air over Europe led to an intensification of the northerly flow in the upper troposphere and the formation of a PV streamer system over southern Europe. The intensity of the PV streamer, as well as the large amounts of the air moisture over the Mediterranean region, has determined the strength of the 3–5 December 2001 torrential rains in Israel.

The findings have the following major implications. First, the hurricane activity over the near-tropical eastern Atlantic and, especially, such cases with the development of the eastern Atlantic anticyclones in proximity of the African coast during the early winter period, must be carefully monitored for the purpose of accurate prediction of hazardous rains not only over the WM and central Mediterranean (Turato et al. 2004) but also over the EM. Second, the role of the PV streamer systems over southern Europe must be considered as one of the main factors that determine the intensity and location of the area of development of the Cyprus cyclones. Model domains for the limited-area numerical weather prediction must include the areas of southern Europe and the northeastern Mediterranean to allow accurate prediction of extreme rains over the EM region.

To the best of the authors' knowledge, the 3–5 December 2001 case of the torrential rains in Israel is the first registered example of the active interaction between the hurricane activity in the tropical Atlantic and the synoptic processes over the EM. The role of such processes in the intensification of the weather activity over western Europe and the WM region has been demonstrated earlier (Pinto et al. 2001; Reale et al. 2001). The development of the late-season Olga was an uncommon but not a unique event under the recent past and present climate conditions. Additional analyses are required for the determination of the role of the hurricane activity on the EM weather in the past. Such activity has been increasing during the last decade. During 2003 for instance, the Atlantic hurricane season saw the development of 16 named storms, well above the 1944–96 average of 9.8, but consistent with a marked increase in the annual number of tropical systems since the mid-1990s (WMO 2003). That fact demonstrates an importance of the investigation of the role of future climate trends over the tropical Atlantic for the EM precipitation.

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