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An evaluation of the role of hurricane Olga (2001) in an extreme rainy event in Israel using dynamic tropopause maps

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With 7 Figures

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Summary

During the period from end of November to early December 2001, a sequence of extremely intense synoptic developments occurred over the area from the Atlantic to Mediterranean. These included the formation of hurricane Olga, an intensification of the Icelandic Low, strengthening of the subtropical westerly jet stream (STJ) over North Africa, formation of the Red Sea Trough (RST) and Cyprus Low cyclones, which resulted in torrential rains in Israel on December 4–5. The evolution of the synoptic processes over a large area from the Atlantic to Western Europe and the Mediterranean region during November 25–December 2 is investigated here with the help of dynamic tropopause patterns calculated based on reanalysis data. It is shown that the chain of extreme weather events was triggered by the acceleration of a coherent tropopause disturbance (CTD) over the Labrador Sea. Two branches of the process may be distinguished, southern and northern. The southern one was associated with the transformation of a tropical storm into hurricane Olga, strengthening of the STJ and eventually the formation of the RST cyclone. The RST contributed to the intensification of the transport of moist air masses from equatorial Africa to the Mediterranean region. The northern branch was determined by an eastward drift of the CTD, moist air mass transport from the area of the hurricane to the North Atlantic and the European-Mediterranean region, strengthening of the Icelandic Low and formation of an upper troposphere potential vorticity-streamer system over western Scandinavia. Displacement of the streamer to the Mediterranean region and its interaction with the RST system played a major role in the development of the powerful Cyprus Low cyclone over the northeastern Mediterranean region.

1. Introduction

A particularly notable synoptic event with torrential rains took place in Israel during the period 00:00 UTC, December 4 to 00:00 UTC December 5, 2001. Total rainfall of up to 250 mm, of which about 200 mm fell during the 01:00 UTC–07:00 UTC time interval of December 4 was observed over a narrow coastal zone in the northern part of the country (~32.5° N; 34.7° E). No such precipitation intensities have been previously described over the area where the annual precipitation is only about 650 mm. Rains also fell over other parts of the country, though their intensity decreased southwards. The rainfall event was associated with the activity of a Cyprus Low (CL) cyclone (El-Fandy, 1946; Kallos and Metaxas, 1980) during 2–5 December 2001.

Intense synoptic developments characterized the time period prior to the CL formation (Krichak et al, 2004, hereafter KAD). The most powerful among them was the formation of hurricane Olga (Avila, 2001). Olga started its development as an extratropical cyclone. It arrived in the tropics as an intense storm (see the track in Fig. 15, KAD). As a tropical cyclone it was first recognized at 00:00 UTC November 23, 2001 (30° N; 53° W). Olga had become a hurricane by 12:00 UTC, November 26, 2001 and reached its peak wind intensity of 40 m s^{-1} and a minimum pressure of 973 hPa (32.3° N; 55.9° W) around 06:00 UTC, 27 November (Avila, 2001). The hurricane weakened to tropical depression status by 12:00 UTC 30 November, 2001 (26.9° N; 62.6° W). It again regained tropical storm status at 00:00 UTC, 2 December, 2001. Olga continued its weakening until 5 December, 2001 when a high pressure ridge to the north steered the tropical cyclone west-southwestward. An anticyclone to the northeast of Olga with south-westerly mid-troposphere winds in its western sector determined the northeastward transport of the Olga-associated moist air masses from the eastern Atlantic in the direction of Europe (KAD).

Long-range transport of air masses from areas populated with hurricanes often leads to intense extratropical synoptic development. A number of cases with extreme synoptic events in mid-latitudes associated with the extratropical transitions (ET), i.e., transformation of tropical cyclones into midlatitude systems have been described previously (Abraham et al, 2004; Agusti-Panareda et al, 2004; Evans and Prater-Mayes, 2004; Hart and Evans, 2001; Jones et al, 2003; Ma et al, 2003; Matano and Sekioka, 1971; McTaggart-Cowan et al, 2004; Röbcke et al, 2004; Sinclair, 2002; Thorncroft and Jones, 2000). Important extratropical effects upon the processes which develop before and during hurricane formation are also known (Lazear and Morgan, 2006). Geographical peculiarities and local topographical effects in particular regions also contribute to the hurricane-associated processes over different areas of the world (Jones et al, 2003).

It has been suggested (KAD) that the torrential rains of December 4–5, 2001 in Israel resulted from Olga's activity. The hypothesis is analyzed below by means of an investigation of the large-scale synoptic developments that preceded the extreme weather event.

Section 2 describes the data used as well as the principles of dynamic tropopause evaluation together with trajectory computations and their application in the analysis of synoptic developments. Section 3 presents a synoptic-dynamic tropopause analysis of the weather developments occurring during the time period from the formation of the hurricane on November 25 to the establishment of the CL cyclone over the Mediterranean region on December 2, 2001. Section 4 summarizes the results obtained.

1. Data and methodology

1.1 NCAR-NCEP reanalysis data

The data from the National Center for Environmental Prediction/National Center for Atmospheric Research Reanalysis Project (NNRP) archive (Kalnay et al, 1996; Kistler et al, 2001) for the period from November 25 to December 3, 2001 are adopted. The NNRP data are derived through a consistent assimilation and forecast model procedure, which allows the incorporation of all available observation data. The NNRP data assimilation system includes the T62/28-level global spectral model with horizontal resolution of about 210 km. The reanalysis data are available with a 2.5° lat × lon horizontal spacing. KAD has demonstrated the reliability of the NNRP data for understanding the relevant weather processes for the period under study.

1.2 Dynamic tropopause patterns

Hurricanes are typically characterized by positive moisture and a potential vorticity (PV) anomaly in the lower part and a negative PV anomaly in the upper part of the vortex (Lazear and Morgan, 2006; Thorpe, 1985; Wu and Kurihara, 1996). To investigate the PV effects in the hurricane-associated mid-latitude synoptic developments the Ertel (1942) PV approach (Agusti-Panareda et al, 2004, Barnes and Colman, 1994; Haynes and McIntyre, 1990; Hoskins et al, 1985; Morgenstern and Davies, 1999; Thorpe, 1985; Tsidulko and Alpert, 2001) is applied in the study. The PV effects significantly stimulate the moist air transport by extratropical cyclones (Brennan and Lackmann, 2005; Lackmann, 2002; Lackmann and Gyakum, 1999).

The PV approach also allows the depiction of the upper-tropospheric features of atmospheric processes by determining the dynamic tropopause (DT) level. The tropopause pressure is defined as that the pressure at the atmospheric level with a representative tropopause PV value. For the extratropics, PV values above 3 PVU (potential vorticity units, 1 PVU $= 10^{-6}\,K\,m^2\,kg^{-1}\,s^{-1}$) are inferred to represent stratospheric air (Barnes and Colman, 1994; Hoskins et al, 1985). A PV value of 1.5 PVU is often used to determine the tropopause.

A computer tool has been developed which allows the determination of the DT pressure (PRDT) based on the PV patterns calculated according to the absolute vorticity on isobaric surfaces (Hoskins et al, 1985; Ma et al, 2003). The DT is defined as the first 1.5 PVU surface determined in a downward search from 200 hPa. After the PRDT values are found, the interpolation of the relative humidity (RHDT), potential temperature (THDT) and DT wind components to the dynamic tropopause surface is performed.

1.3 Air mass trajectories

The area of origin of the air masses participating in synoptic processes is often determined by means of trajectory computation (e.g., Krichak and Alpert, 1998; Turato et al, 2004). This approach is also adopted here. The Advanced Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) system of the National Oceanic and Atmospheric Administration Air Resources Laboratory (NOAA ARL) is applied for a three-dimensional trajectory calculation (Draxler and Rolph, 2003). The model uses previously gridded meteorological data to calculate the trajectories according to a 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.

2. Synoptic dynamic-tropopause perspective

Synoptic processes during the period from November 25 to December 2 over northern Atlantic, Europe and North Africa are discussed below based on the 300 hPa patterns using maps of wind magnitude, sea-level pressure (SLP), 700 hPa specific humidity (SHUM), dynamic tropopause pressure (PRDT), isobaric PV at 700 hPa (PV-700) and deep layer wind shear arrows (wind at DT minus wind at 700 hPa).

2.1 Upper troposphere winds

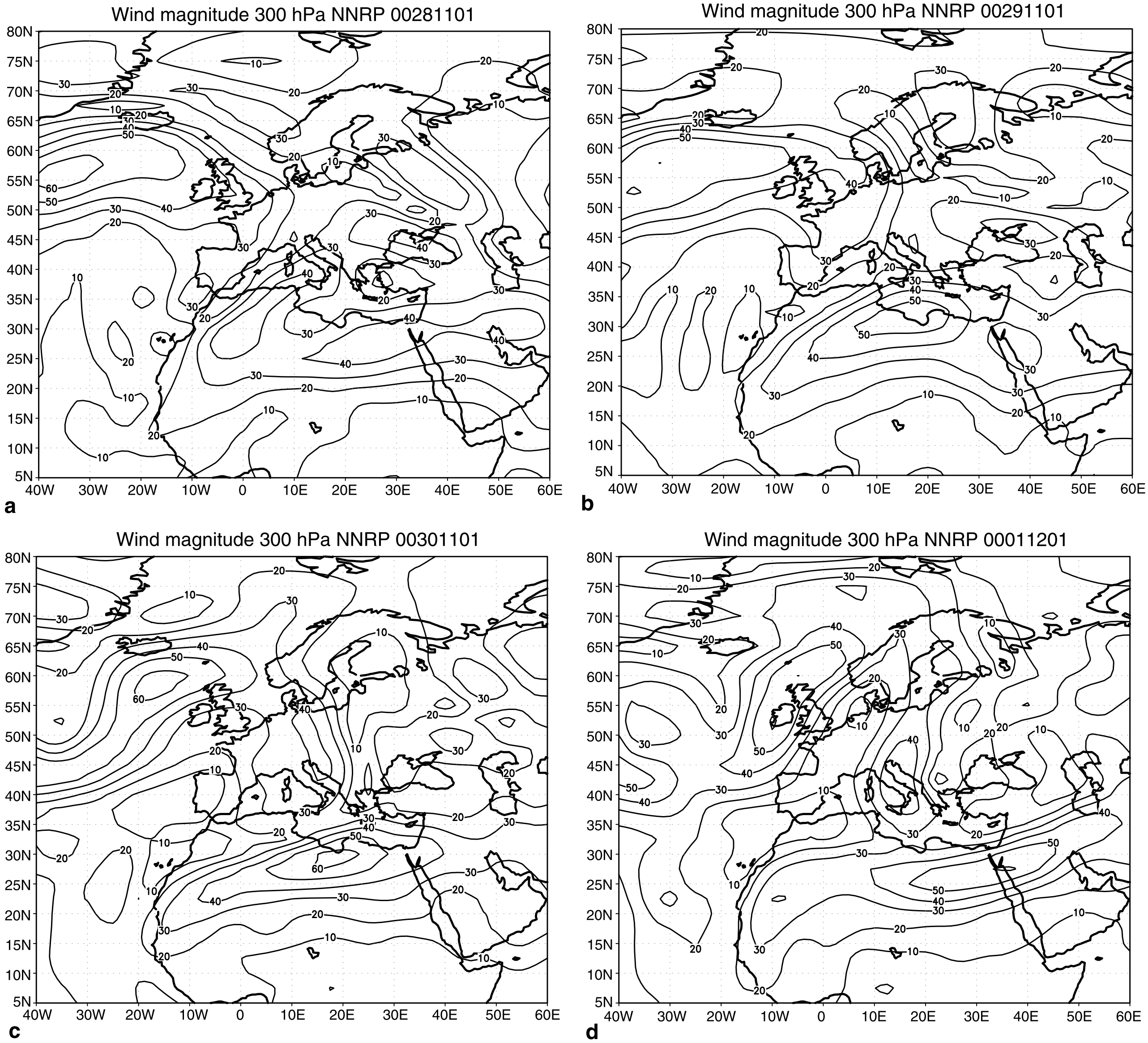
The evolution of the wind magnitude field in the upper troposphere (300 hPa) over the eastern part of the region comprising North Atlantic, western Europe and North Africa at 00:00 UTC during the period November 28–December 2, 2001 is presented in Fig. 1a–e for each of the days, respectively.

A broad zone with strong upper troposphere winds (up to $60\,m\,s^{-1}$) can be seen in Fig. 1a at 00:00 UTC November 28 over the eastern part of the North Atlantic. The upper troposphere jet stream extended eastward in the direction of British Isles and Perinea Peninsula. The wind field over the southern Mediterranean and Red Sea area, where the subtropical westerly jet stream (STJ) is typically found during the cool season (Krichak et al, 1997a, b; Krishnamurti, 1961) is characterized by the wind maximum of $40\,m\,s^{-1}$. Figure 1b shows the jet over the Atlantic at 00:00 UTC November 29 in the same area as earlier but the front part of the jet ($40\,m\,s^{-1}$) has now shifted to the Scandinavian Peninsula. We note an intensification of the STJ (up to $50\,m\,s^{-1}$) occurred over the central part of the southern Mediterranean.

A significant change in the wind magnitude pattern took place over Europe at 00:00 UTC on November 30 (Fig. 1c). An upper troposphere jet stream ($40\,m\,s^{-1}$) was situated from the Baltic Sea to the Alpine and Adriatic Sea areas. The zone with strong upper troposphere winds over the Atlantic also shifted eastward. An additional intensification of the STJ (to $60\,m\,s^{-1}$) is evident.

Figure 1d shows the further evolution of the wind pattern at 00:00 UTC December 1. This also shows that the upper troposphere zone with strong winds ($40\,m\,s^{-1}$) was situated over Europe stretching from the west over British Isles to the east over the Alpine – Central Mediterranean area. The maximum wind intensity over North Africa decreased ($\sim 50\,m\,s^{-1}$) however, though the zone with the strongest winds has shifted to the Red Sea area (25° N).

Figure 1e, at 00:00 UTC December 2, shows the further evolution of the upper troposphere wind field. Notably, the former Atlantic wind maximum moved to the south of Spitzbergen. The second strong wind zone in the polar jet system occurred over the Mediterranean where it partly merged with the subtropical jet stream (STJ) further south.



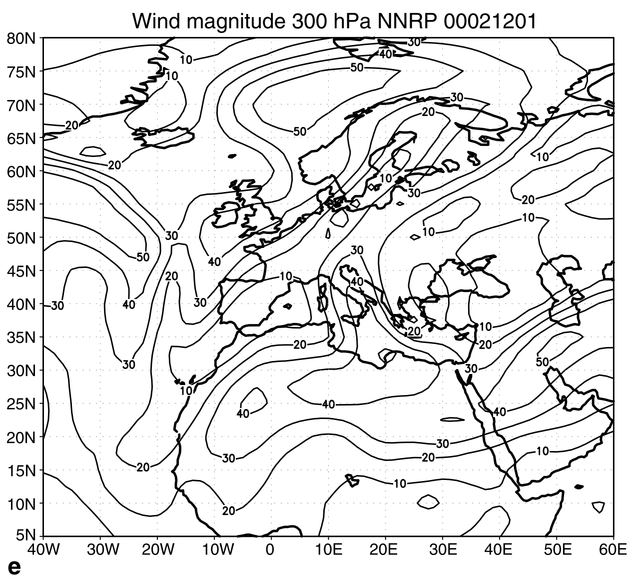


Fig. 1. Wind magnitude (contour interval $10\,\mathrm{m\,s^{-1}}$) at the 300 hPa isobaric surface over Europe at 00:00 UTC (**a**) 28 November, (**b**) 29 November, (**c**) 30 November, (**d**) 1 December, (**e**) 2 December 2001

The STJ decreased in intensity and was displaced east of the wind maximum.

The synoptic developments are considered separately below for the Atlantic and European regions.

2.2 Mid-troposphere synoptic developments over Atlantic region

The SLP and SHUM patterns over the Atlantic are given in Fig. 2a–d from 12:00 November 25 to

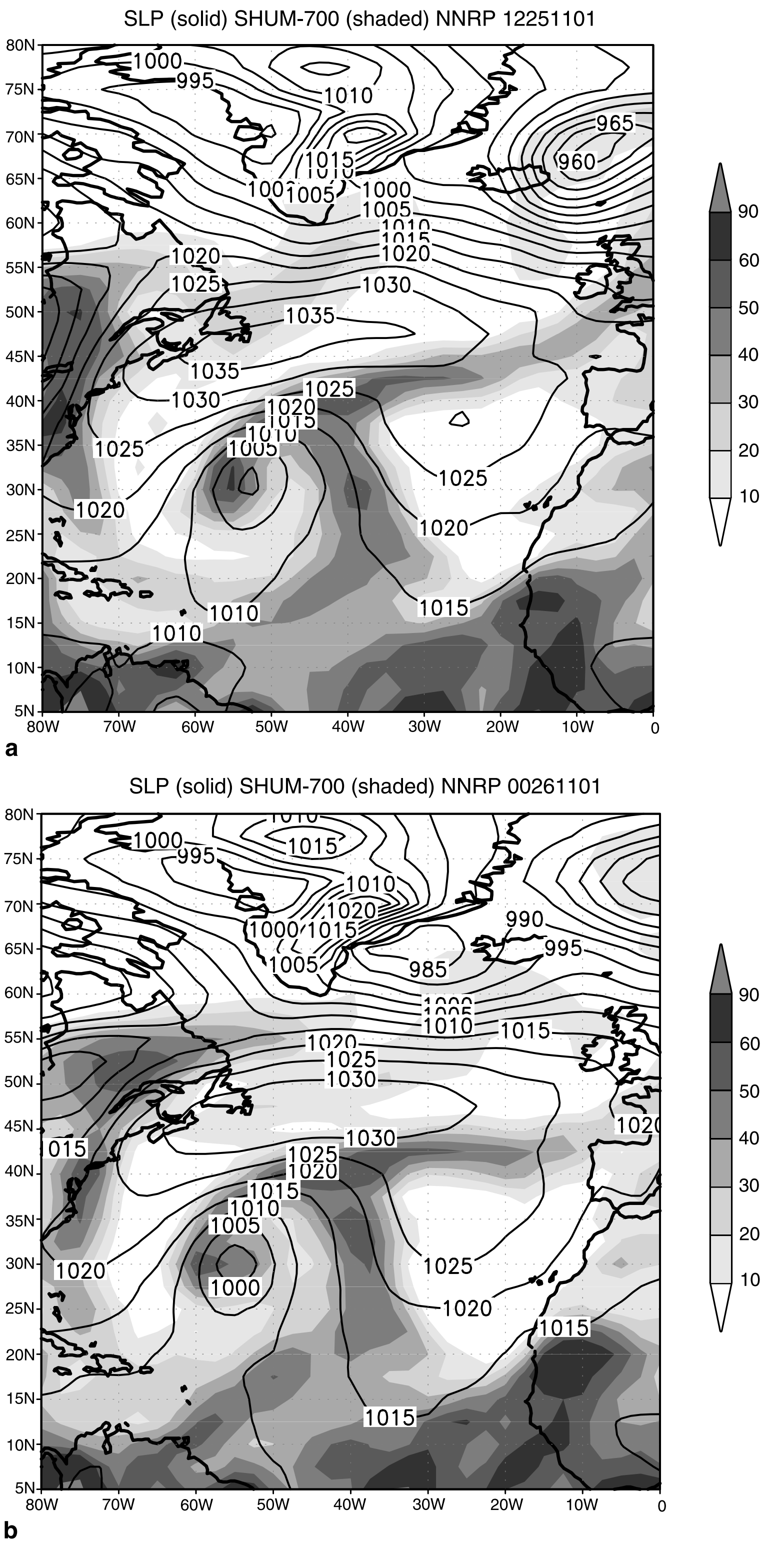


Fig. 2. Sea-level pressure (hPa, solid lines), and 700 hPa specific humidity (g kg^{-1}, shading) over the Atlantic at (**a**) 12:00 UTC 25, (**b**) 00:00 UTC 26, (**c**) 12:00 UTC 26, (**d**) 00:00 UTC 27 November 2001

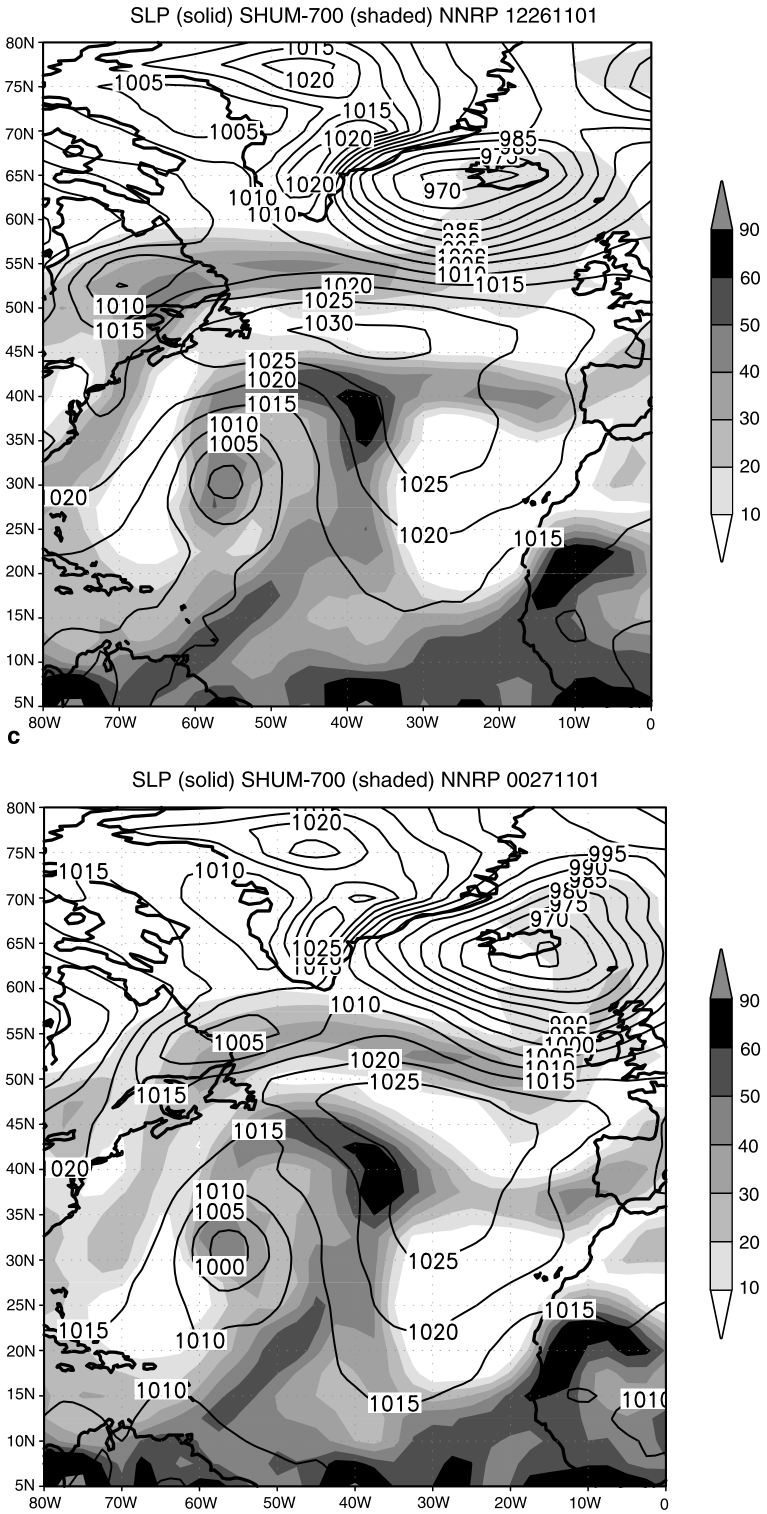


Fig. 2 (*continued*)

00:00 UTC November 27 at 12 hr intervals, respectively. Figure 3a–d shows PV at 700 mb and the PRDT (greater than 0.6 PVU) as well as deep layer wind shear arrows indicating positioning of the areas with strong deep layer wind shear and strong upper tropospheric winds which are favorable for organized thunderstorms and super-cells (Craven and Brooks, 2004, Raymond, 1992).

Figure 2a shows the tropical storm (Olga) at 12:00 UTC, November 25 represented by a low-pressure system located at 55° W, 32° N with a minimum pressure of 1000 hPa. The SHUM pattern was characterized by the advection of moist air to the area of the storm from the tropical Atlantic, Africa and North America. Three main cyclones positioned over Iceland (with the mini-

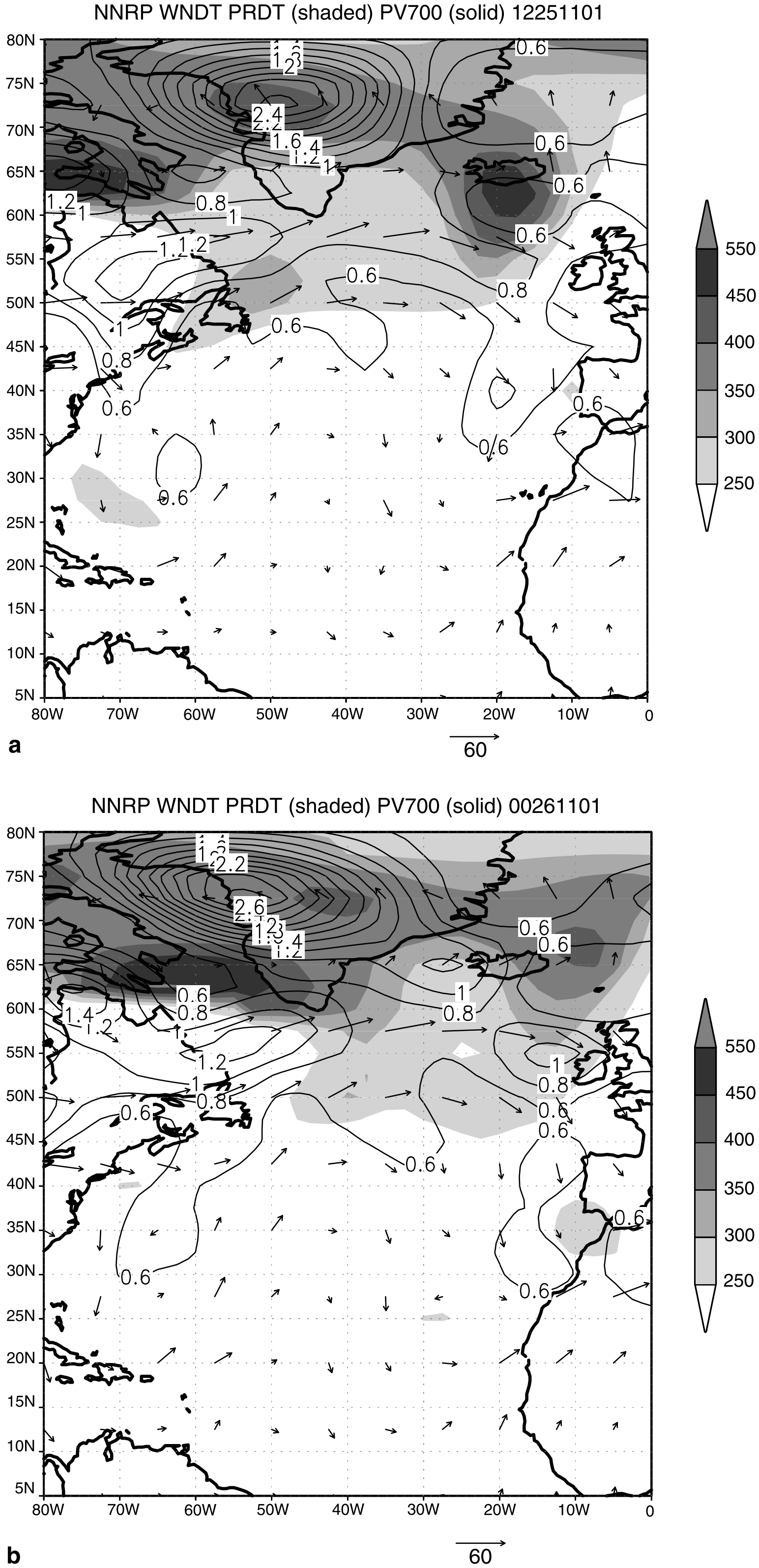


Fig. 3. Potential vorticity (PV) in the 600–700 hPa layer (PVU, solid lines), and pressure at dynamic tropopause (hPa, shading) over the Atlantic at (**a**) 12:00 UTC 25, (**b**) 00:00 UTC 26, (**c**) 12:00 UTC 26, (**d**) 00:00 UTC 27 November 2001

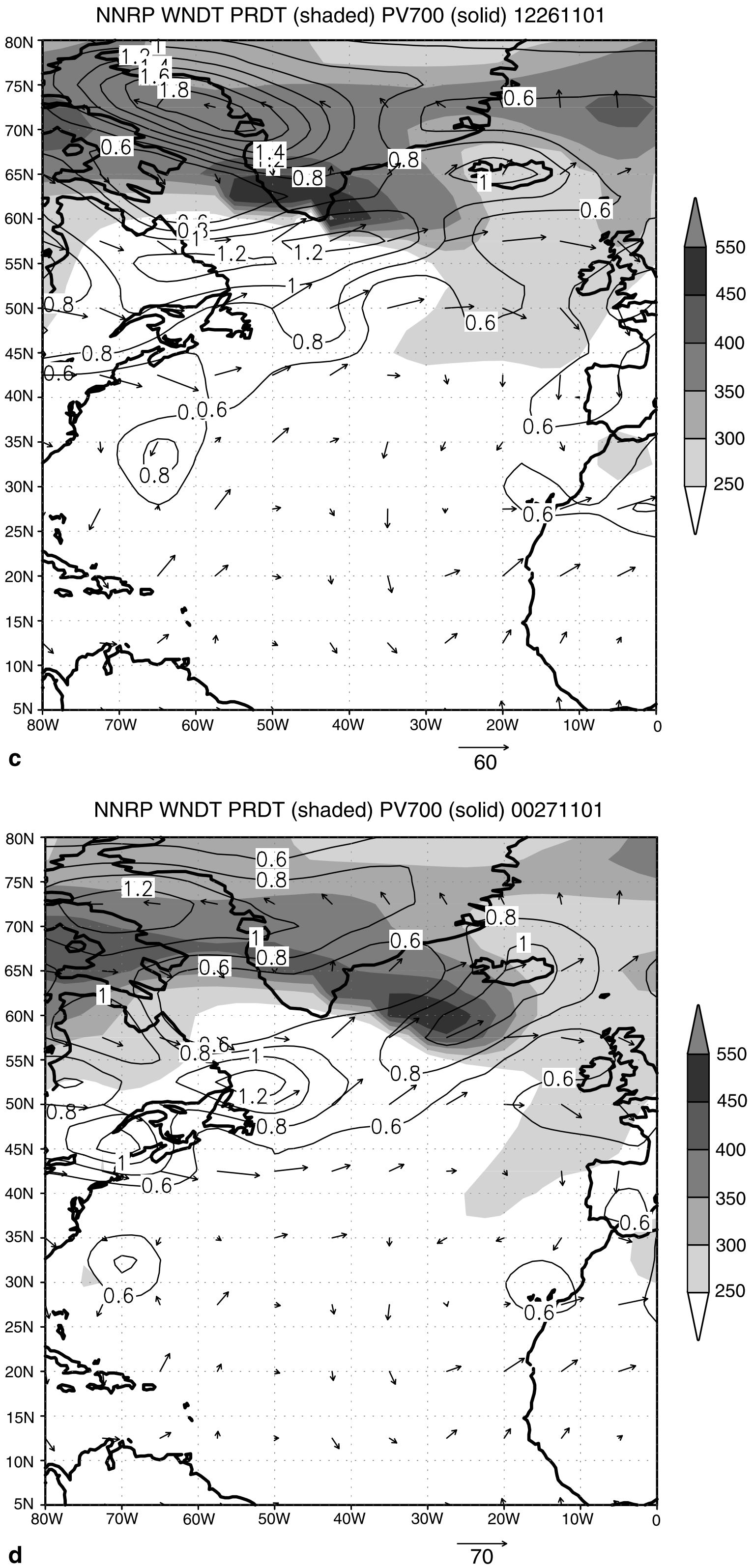


Fig. 3 (*continued*)

mum pressure of 960 hPa); over the southwestern Greenland (with the minimum pressure of to 995 hPa); and a North American cyclone located to the west of the Labrador Peninsula are evident. A tongue of moist air was directed towards Iceland, which allowed intense convection over the area. A narrow, zonally oriented anticyclone (1035 hPa) to the north of the hurricane is also present. An intense high PRDT band (up to 450–500 hPa) covered the area from the eastern coast of North America (Baffin Island) to Iceland along southern Greenland. Two high PV-700 zones over Greenland and Baffin Island (up to 2.4 PVU and 1.2 PVU, respectively) and two PRDT maxima (up to 550 hPa), (over Newfoundland and Iceland) are present. One more PRDT anomaly (up to 300 hPa) is found over the western part of the tropical Atlantic A high-PV ridge is directed from the Labrador Peninsula southward to another PV maximum (0.6 PVU) located over the tropics (62° W; 30° N). The location of the high-PV zone is clearly determined by that of tropical storm Olga.

An element having significant influence over DT evolution is a cyclonic disturbance manifested as a local DT depression (high pressure and low potential temperature) and characterized by spatially-localized vortex-like structures at the tropopause, that is, coherent tropopause disturbances (CTD). When formed, the structures may

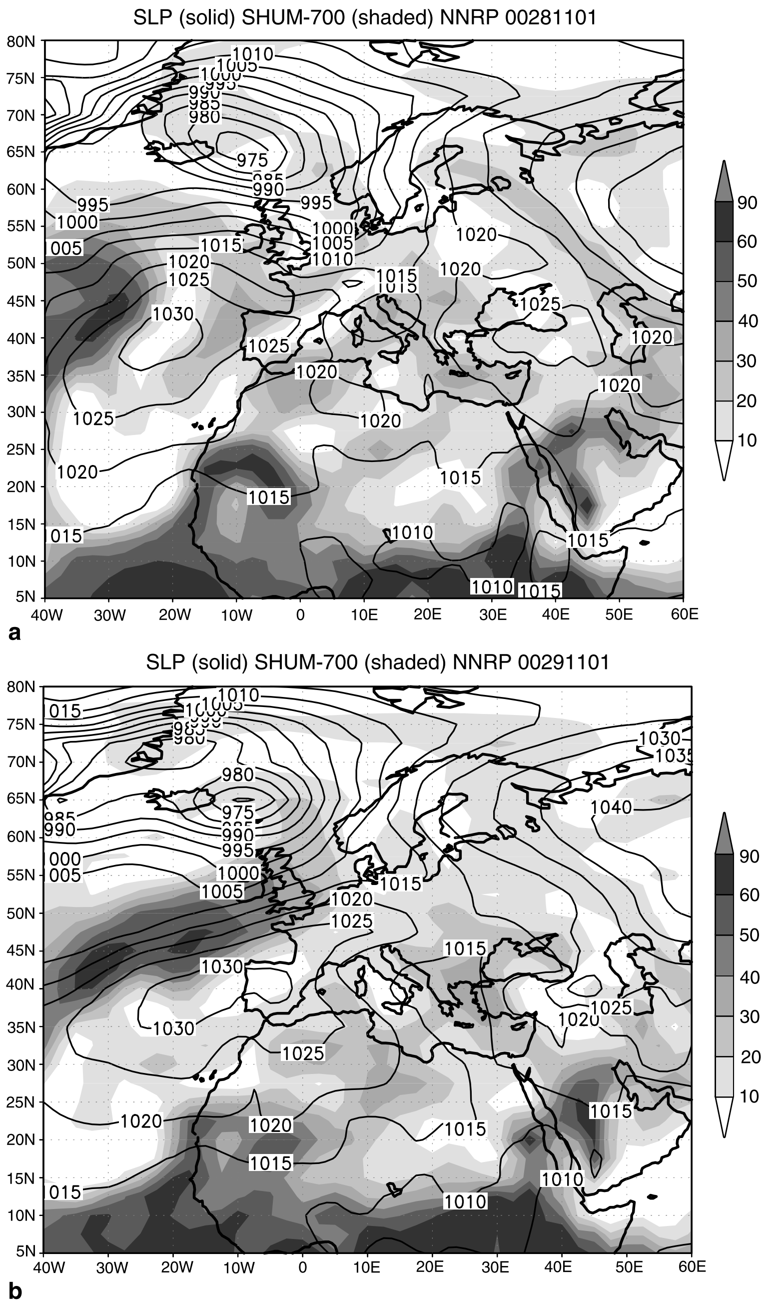


Fig. 4. Same as in Fig. 2, but over Europe at 00:00 UTC (**a**) 28 November, (**b**) 29 November, (**c**) 30 November, (**d**) 1 December, (**e**) 2 December 2001

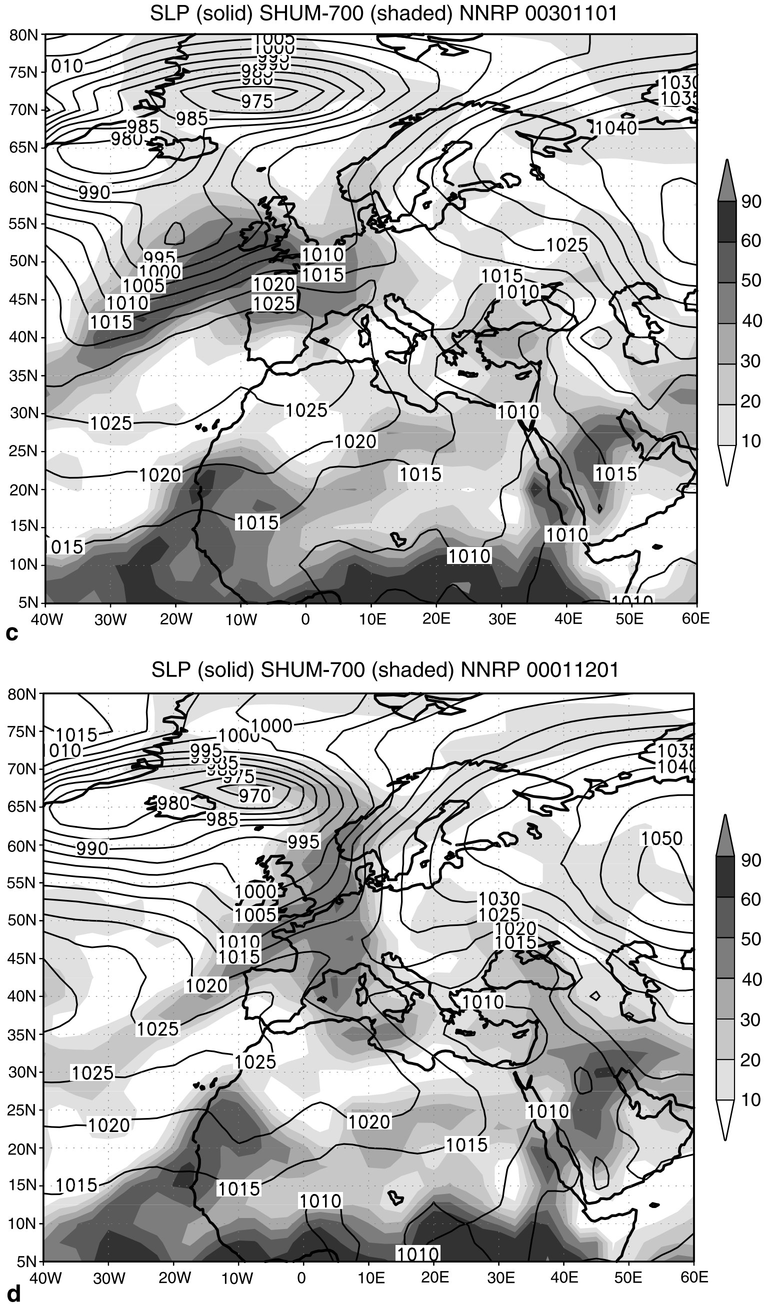


Fig. 4 (*continued*)

significantly determine the weather conditions by strengthening horizontal PV gradients beneath leading to intense cyclonic developments to the right of DT depressions (Davis and Emanuel, 1991). Periods of existence of such tropopause disturbances are usually quite long (up to 10–15 days, Pyle et al, 2004).

Figures 2b and 3b present the patterns at 00:00 UTC of November 26, i.e., at the time of transformation of the tropical storm into hurricane Olga. Figure 2b shows the tropical cyclone present in almost the same location as before. The area with the anticyclone in Fig. 2b is somewhat wider than in Fig. 2a. The North American cyclone, with minimum pressure of 1005 hPa, has a warm sector characterized by a high concentration of moist air. Development of an intense cyclone having minimum pressure of 985 hPa took place to the west of Iceland. The area with the Icelandic cyclone (Fig. 2b) was covered by a zone with high (1.2 PVU) PV-700 values. A high PRDT zone (up to 550 hPa) was positioned over Labrador Sea. The PV anomaly in the upper troposphere was found situated to the north of the

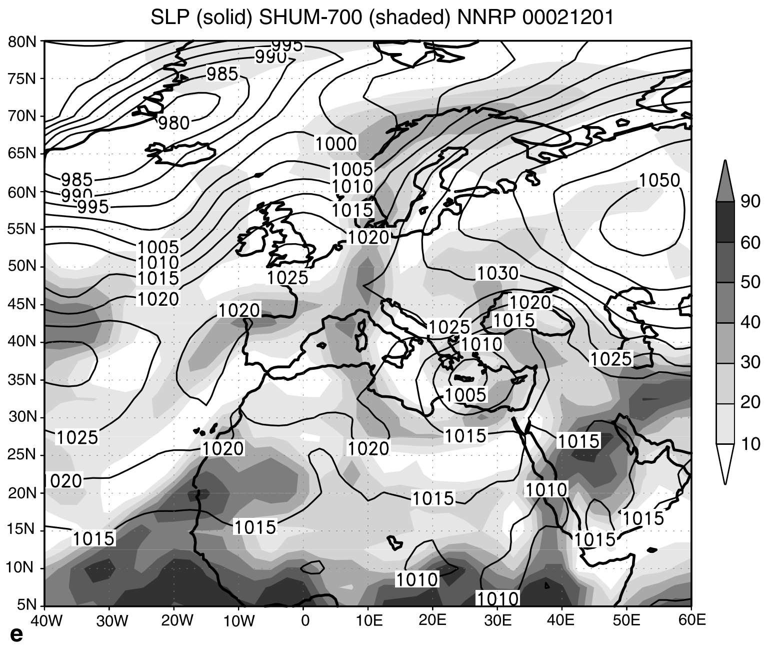


Fig. 4 (*continued*)

developing hurricane (Fig. 2b). The CTD was situated about 5° northward of the high PV-700 (1.2 PVU) zone (Fig. 3b) and shows acceleration over Labrador Sea. A high PV ridge linked the area with the PV-700 maximum with that of the hurricane. A band with a positive PV-700 anomaly along the warm front of the eastward moving North American cyclone may be indicated.

Figure 2c shows high amounts of moist air (up to 90 g kg^{-1}) that had built up by 12:00 UTC November 26, concentrated over central Atlantic. The Icelandic cyclone had deepened also (minimum pressure equals to 970 hPa). The cyclogenetic process is apparently affected by the moist air entering the area along the warm frontal zone over the Labrador Peninsula cyclone with a minimum pressure of 1010 hPa. In Fig. 3c, the CTD has shifted eastward to southern Greenland. The PV-700 pattern is also modified – the transformation of the PV-700 field appears associated with the shift of the tropopause disturbance. The orientation of the high-PV-700 system suggests that the hurricane has a role in the strengthening of the high PV zone from the western part of tropical Atlantic to Iceland (Fig. 2c). A notable enhancement of upper-level jet downstream of the hurricane subsequently occurred. The development was apparently associated with the effects of the negative PV anomaly with an associated anticyclonic circulation in the upper part of the vortex. There was also some intensification in the downstream advection of positive PV in the region of the tropopause and a further eastward propagation of the CTD as well as an eastward shift of the Azorean anticyclone.

At 00:00 UTC November 27 (Fig. 2d) the Azorean anticyclone was situated to the northeast of Olga (minimum pressure 1000 hPa). The minimum pressure of the Icelandic Low was 965 hPa. The enhanced surface development over Iceland was characterized by moist air advection and latent heat release processes indicated by the high deep layer wind shears here. The former North American cyclone continued to drift eastward. It was centered over the western Atlantic. The moist air from the cyclone had already been dragged into Icelandic cyclone. Furthermore, there's an additional eastward displacement of the CTD (now situated over Iceland) (Fig. 3d). A narrow PV-700 zone is connected to the CTD area with the developing Icelandic cyclone. The high PV-700 zone here had the potential to be linked to that of the hurricane.

2.3 Mid-troposphere synoptic developments: European-Mediterranean region

The SLP and SHUM patterns over the Atlantic are given in Fig. 4a–e from 00:00 November 28 to 00:00 UTC December 2 at 24 hr time interval, respectively. The corresponding PV-700 and the PRDT (greater than 0.7 PVU) patterns as well as deep layer wind shear arrows for the same time moments are given in Fig. 5a–e.

At 00:00 UTC November 28 (Fig. 4a) an intense moist air advection from the eastern Atlantic occurred towards Scandinavia and Europe. The moist air was already present over western Europe due to the presence of the Icelandic cyclone (minimum pressure of 975 hPa). CTD were found over Iceland (Fig. 5a) to the left of the cyclone. These can be linked with another PRDT maximum located near the Black Sea. A high-PRDT zone was directed to Pyrenean Peninsula. Formation of the PRDT ridge illustrates acceleration of the CTD. It appears from Fig. 4a that the process was taking place over the area with intense inflow of the moist air from the Atlantic (Fig. 4a). A part of the moist air mass was also found steered to the Mediterranean area together with a zone with high SHUM values over the Arabian Peninsula.

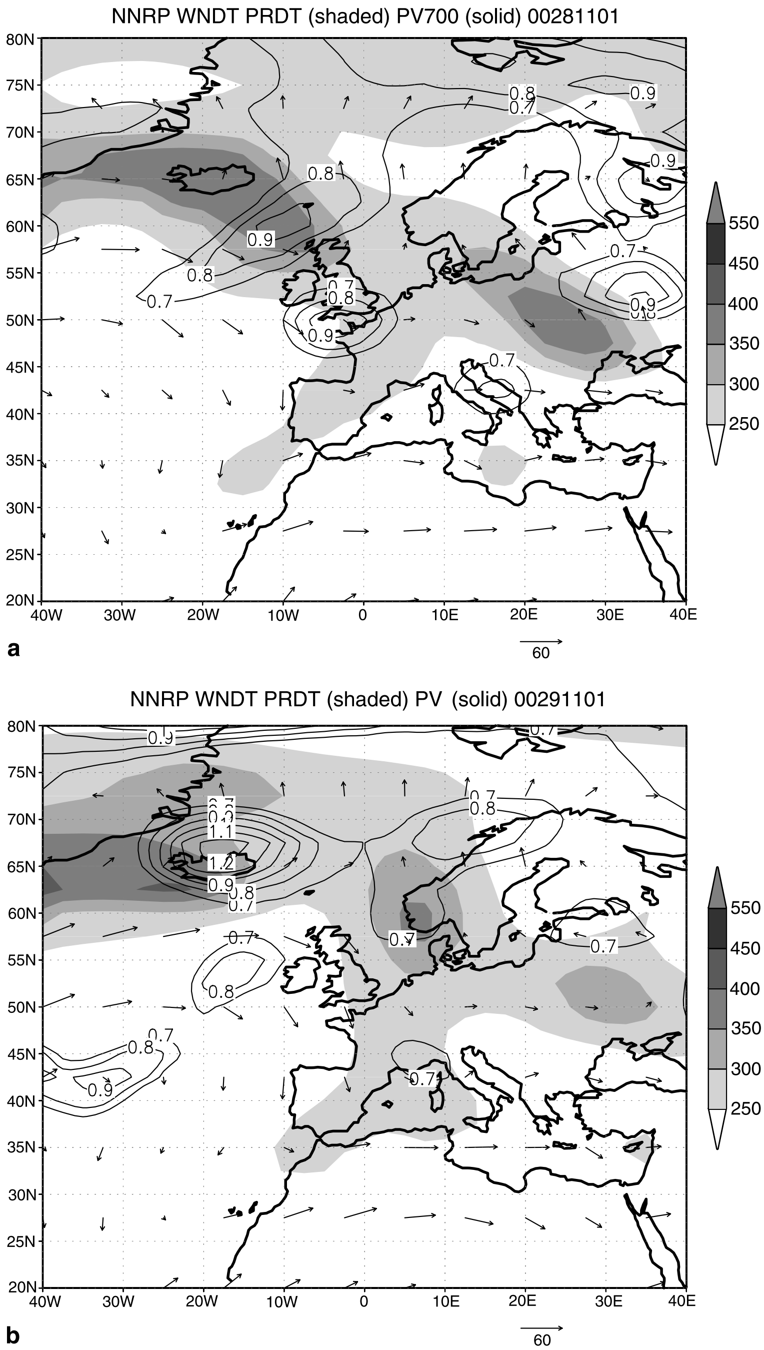


Fig. 5. Same as in Fig. 3, but over Europe at 00:00 UTC (**a**) 28 November, (**b**) 29 November (**c**) 30 November, (**d**) 1 December, (**e**) 2 December 2001

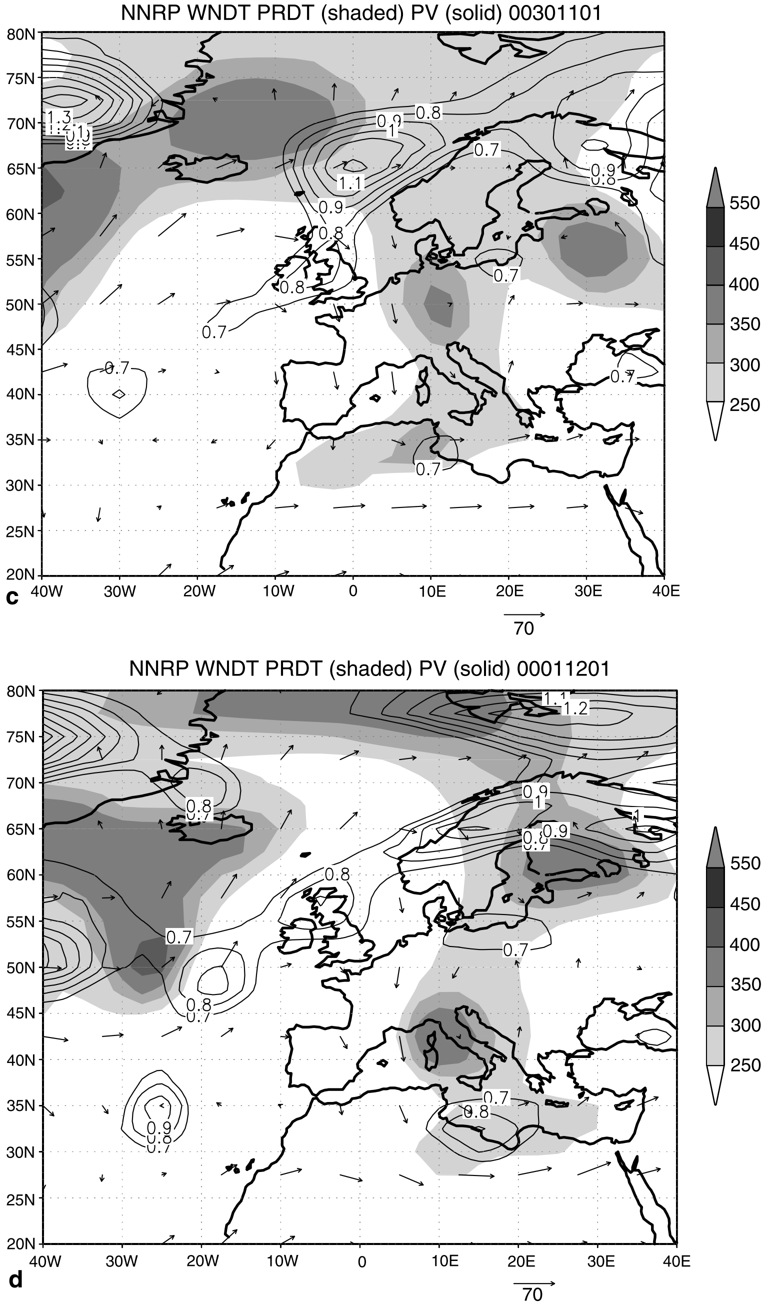


Fig. 5 (*continued*)

At 00:00 UTC November 29, 2001 (Fig. 4b) the moist air zone from the Atlantic approached the British Isles. Significant amounts of the air reached the area to the southeast of Iceland where the Icelandic cyclone was represented by two low pressure centers with the southern one having minimum pressure of 970 hPa. Positioning of the centers is also in agreement with that of the moist air zones indicating the role of latent heat release processes (Brennan and Lackmann, 2005; Deveson et al, 2002; Lackmann, 2002; Lackmann and Gyakum, 1999) in the cyclone development. A notable re-intensification of the CTD (Fig. 5b) over west-Scandinavia may also be explained by the latent heat release effects. The cyclone developments took place when the CTD was located over western Scandinavia (Fig. 5b). This was together with a southward shift, eastward displacement and narrowing of the Azorean anticyclone as well as westward displacement and strengthening of the Siberian high system (central pressure 1040 hPa) (see Fig. 4b).

At 00:00 UTC November 30 (Fig. 5c) a CTD was over western Europe moving toward the

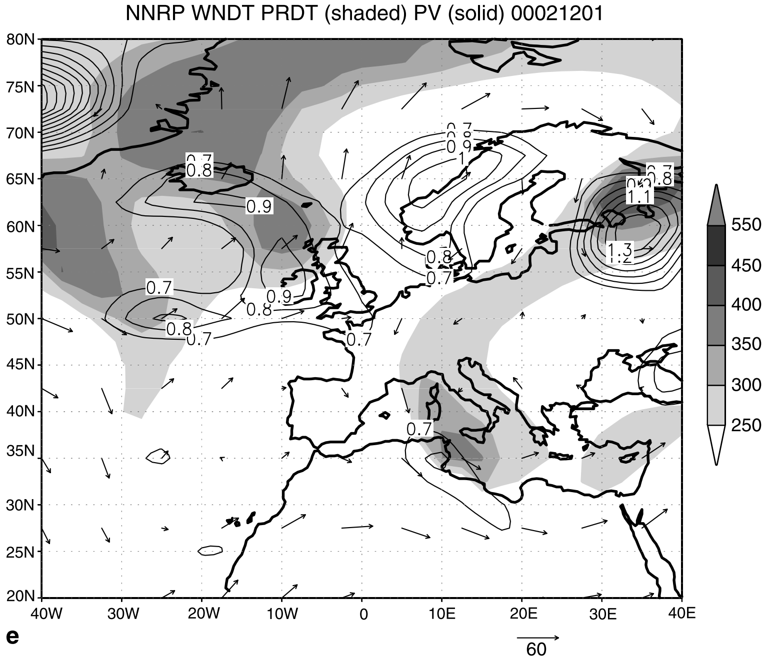


Fig. 5 (*continued*)

Alpine area leading to an interaction between the two European CTDs. A zone with a high concentration of moist Atlantic air was already over British Isles and western Europe (Fig. 4c). A new cyclone (minimum pressure 990 hPa) with high SHUM values had moved into the area west of

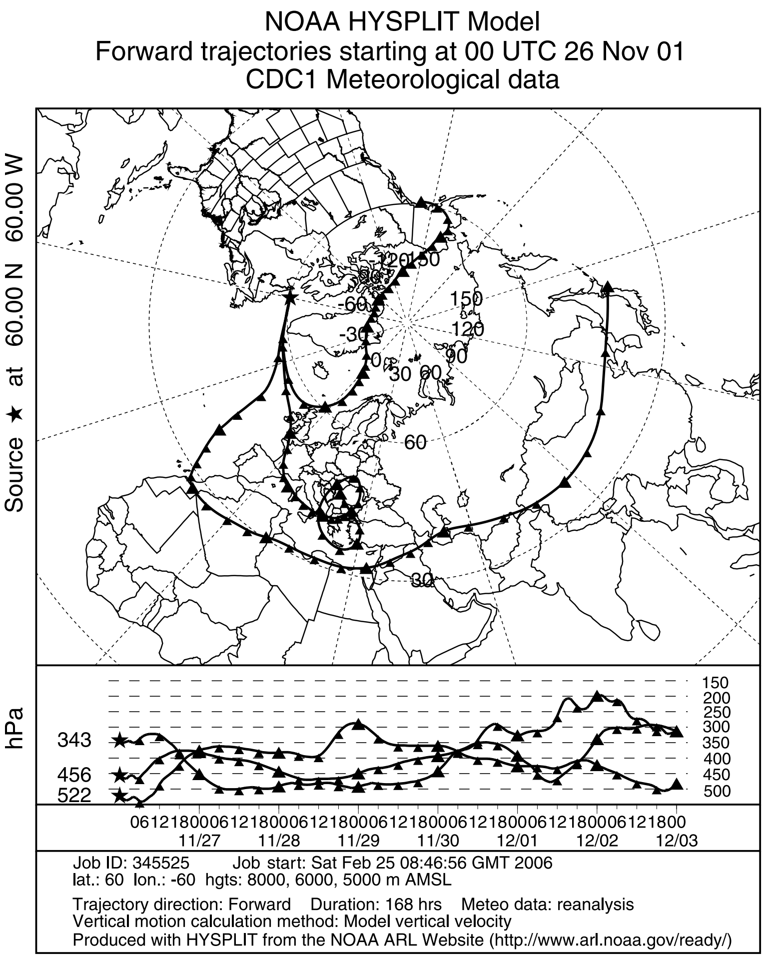


Fig. 6. NNRP: Forward trajectory starting at 00 UTC 27 November 2001 at 54° N; 55° W at 8000, 6000, and 5000 m heights calculated for 168 hrs

the British Isles. Figures 1c, 4e show the development of an RST system under the left-front part of the strong wind STJ zone over North Africa as well as formation of a cut-off low (minimum pressure of 1010 hPa) over Asia Minor.

Figure 4d shows that at 00:00 UTC December 01 there was a strengthening and westward shift of the Siberian high (central pressure 1050 hPa) as well as an eastward shift of the southeastward branch of the Azorean anticyclone. A zone with moist air from equatorial east Africa was propagating northward over the Arabian Peninsula in the direction of the developing EM cyclone. Another moist air zone from the Atlantic moved southward in the direction of the Mediterranean region. In Figure 5d two CTDs are already found united in a long high PRDT ridge extending southward from Arctic Sea area to the Mediterranean Sea. The zone with the PV-streamer is characterized by several PV-700 maxima associated with intense PV generation in the lower troposphere.

At 00:00 UTC December 2 (Fig. 4e) the PV streamer can be seen over the north-eastern part of the Mediterranean area (Fig. 5e). From the quasi-geostrophic perspective the CL development (minimum pressure 1005 hPa) here may be explained as a consequence of the effects of an imbalance between the pressure gradient and Coriolis forces (Bjerkness, 1951; Pyle et al, 2004; Uccellini, 1980) under the streamer's left-front quadrant.

2.4 Air mass trajectories

Additional information on the atmospheric developments over the period is available from the forward air mass seven-day trajectories initiated at heights of 8000, 6000, and 5000 m from a location to the north of the hurricane (over Labrador Sea, 60° N; 60° W) starting 00:00 UTC, 26 November 2001 (Fig. 6) as well as the 72 hr backward trajectories calculated at a location with the coordinates 31° N; 44° E (Middle East) at 1000, 2000 and 3000 m (Fig. 7).

In Fig. 6, the 5 km trajectory goes eastward around Greenland and then to Alaska. The upper

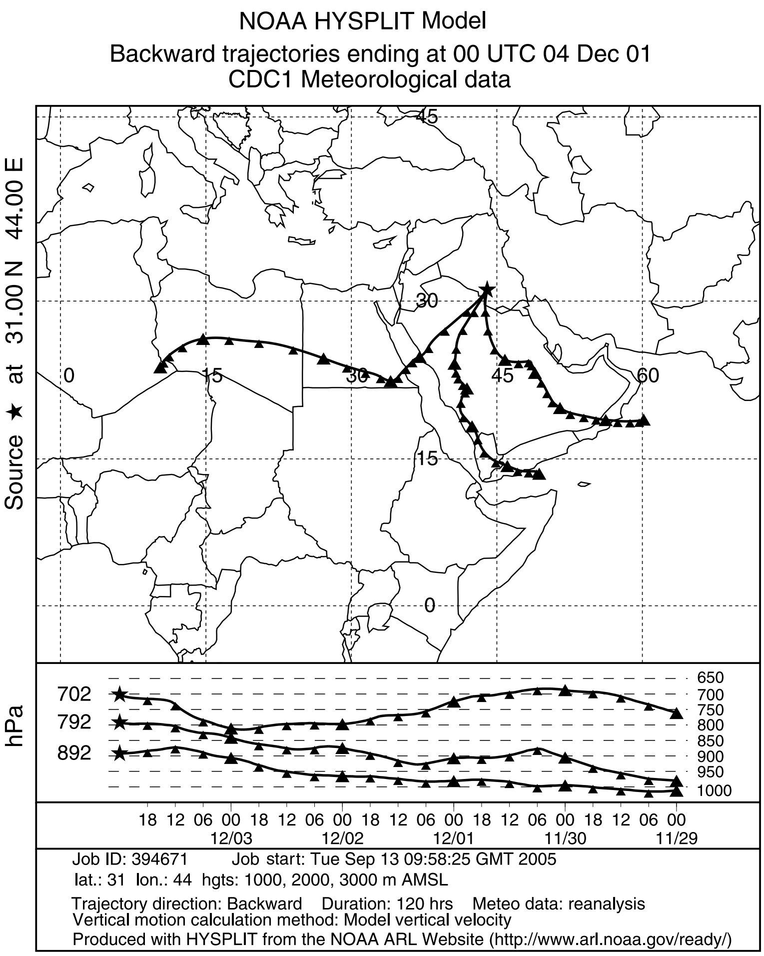


Fig. 7. NNRP: Backward trajectory ending at 00 UTC 4 December 2001 at 31° N; 44° E at 1000, 2000 and 3000 m calculated for 72 hrs based on the NNRP data

level (8 km) trajectory is directed towards Africa, from where it goes over the southern part of the Mediterranean region and then over the whole Asia to Japan indicating high values of the wind speed in the flow. The air parcel from the initial location has already arrived above the Red Sea by 00:00 UTC November 30. The trajectory initiated at 6 km demonstrates participation of the air from the area of the hurricane in the EM cyclogenetic event of December 3–5. The 72 hr backward trajectories in Fig. 7 demonstrate that the air masses from the Arabian Sea and tropical east Africa area also participate in EM synoptic development.

5. Discussion and conclusion

Results of the analysis demonstrate that the development of the CL cyclone of December 4–5 2001 in the Mediterranean region resulted from the acceleration of an upper tropsphere potential vorticity anomaly and formation of a coherent tropopause disturbance (CTD) over the Labrador Sea which was a part of the process of transformation of the tropical storm into hurricane Olga. The further synoptic developments have been strongly affected by the effects of the CTD. It can be hypothesized that the CTD developed at about 12:00 UTC November 25 as a consequence of intense latent heat release in a moist air zone situated over the Labrador Peninsula (Fig. 2a). The zone was associated with a transient mid-troposphere North American cyclone characterized by an upper troposphere PV anomaly (Fig. 3a). The high concentration of moist air in the zone was apparently affected by the early stage development of the Olga cyclone.

The PV anomaly was drifting eastward with the upper troposphere air flow. Transformation of the tropical storm into a hurricane took place when the upper troposphere PV anomaly became positioned to the north of the storm. The process also led to an acceleration of the tropopause anomaly over Labrador Sea (Fig. 3b). The shallow band of a positive PV anomaly along the warm front of the moving eastward North American cyclone in Fig. 3b demonstrated development of a baroclinic wave produced by latent heat release in the area at 00:00 UTC November 26.

A notable enhancement of the upper-level jet downstream of the hurricane followed. The development was affected and associated with the negative PV anomaly anticyclonic circulation in the upper part of the vortex. Importance of such atmospheric developments over the north Atlantic area has already been indicated (Agusti-Panareda et al, 2004; Röbcke et al, 2004). Intensification of the downstream advection of positive PV in the region of the tropopause was followed by a further eastward propagation of the CTD as well as an eastward shift of the Azorean anticyclone (Fig. 2c). The change in the shape and positioning of the Azorean anticyclone determined the direction of further transport of the air masses from the area.

According to the trajectories in Fig. 6 a part of the upper troposphere air went southeastward, leading to the intensification of the westerly upper-tropospheric subtropical jet stream over North Africa. A part of the mid-troposphere air was transported to the Mediterranean region. Direction of the transport of the air masses from the area of the hurricane was steered by the CTD which was drifting in the direction of Iceland (Fig. 1a–e; Fig. 3a–d). The process was accompanied by moist air advection which apparently stimulated latent heat release in the lower troposphere.

Explosive cyclone development (Fig. 2a–d) during November 28–30 took place when the depression reached a favorable position to the west, from the PV perspective, (Fig. 4a–c) (it was over Iceland at 00:00 UTC 28 November, Fig. 3a, and over west Scandinavia, at 00:00 UTC 29 November, Fig. 5b).

According to Figs. 1a–e and 5a–e the CTD was drifting with the upper troposphere wind flow along the coastal zone of Scandinavia and then southward. The disturbance re-intensified at 00:00 UTC 29 November, (Fig. 5b) over West Scandinavia apparently due to intense latent heat release processes.

A further drift of the CTD over western Europe in the direction of the Mediterranean Sea took place from November 30 to December 2. The initial development of the Cyprus Low system at about 00:00 UTC December 2 under the left-front quadrant of the streamer demonstrates the role of quasi-geostrophic imbalance conditions in the process. The PV-streamer continued its drift to the Alpine region and south-eastern Mediterranean region during the period from November 29 (Fig. 5b) to December 2 (Fig. 5e). The process led to an eastward shift of the zone with the Azorean anticyclone as well as a westward shift of the Siberian anticyclone.

Important synoptic processes were associated with the development of the Red Sea Trough cyclone. From November 30 to December 1 the STJ expanded further to the east and its exit turned slightly to the left so that the zone of its intersection with the steep mountains of the Red Sea area moved to 25° N latitude. These features meet the required speed and latitude of intersection ($>55\,\mathrm{m\,s^{-1}}$ and 25° N, respectively) given in Krichak et al (1997a, b) and additionally tested by Ziv et al (2004) as favorable for the development of an RST directed toward Middle East.

According to the results presented the large-scale synoptic process which ended up with torrential rains in Israel over December 4–5 was a co-product of the same intense North Atlantic development which led to the transformation of a tropical storm into hurricane Olga on November 26, 2001. A further investigation of additional cases with the associated synoptic development with such extratopical transition of hurricanes' formation processes may be required. The fact that the formation of Olga occurred during the end of the hurricane season when the wintertime upper troposphere jet streams (Krishnamuri, 1961) were already fully developed was apparently the main reason for the intensity of the large-scale synoptic process. One may hypothesize that similar atmospheric developments have also been happening in the past. An increase in the frequency of occurrence of such events as a result of climate change processes in the future (Landsea et al, 1998) may not be excluded.

Our findings have the following major implications. First, additional research efforts are required for a more in-depth investigation of the role of the intense North Atlantic cyclones in the European weather. In particular, the situation with the development of strong near-tropical cyclones in the North Atlantic, characterized by the formation of intense CTD over the Labrador Sea and accompanied by concentration and further eastward transport of high amounts of wet air masses may be considered as a precursor for possible intense weather processes over the southeastern Mediterranean region. Second, synoptic developments characterized by a deep eastward shift of the eastern (southward) branch of the Azorean anticyclone must be considered among the precursors for the development of intensively precipitating cyclones during the situation with the PV-streamer formation over the southeastern Mediterranean region.

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