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Red Sea Trough/Cyclone Development – Numerical Investigation

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With 7 Figures

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Summary

A case of development of a meridionally oriented Red Sea Trough (RST) system and its intensification over the Eastern Mediterranean (EM) region during the ALPEX-1982 3–5 March period, is investigated. The MM4 mesoscale model of Penn State University/National Center for Atmospheric Research was first applied for a large scale investigation of the processes. The relative roles of the different acting factors, i.e., terrain, latent heat release and the surface fluxes were calculated employing the factor separation method. Topography and sensible heat flux were found to be the dominant ones.

The high resolution non-hydrostatic RAMS 3a model of Colorado State University with nested grids of 100 and 20 km illustrated the finer details of the cyclogenetic processes in the mountainous area of the Abyssinean Highlands, Ethiopia, and the Arabian peninsula, where initiation of the trough took place.

Results of the factor separation showed that the topography blocking acted as a cyclolytic factor, preventing the process of the northward trough propagation. The situation changed only after about 30 h of the simulation, when the trough already propagated into the EM area after intensification of the mid-tropospheric westerlies over the central part of the Red Sea area. Starting from this time, terrain was acting as one of two major cyclogenetic factors. The second local effect also working as a cyclogenetic one was the sensible heat flux. Its role was especially important after 36 h of the simulations when strong winds over the sea area caused more active heat transfer from the sea surface to the atmosphere.

1. Introduction

Eastern Mediterranean (EM) region has long been recognized as one of the active cyclogenetic regions of the Mediterranean area. Climatological and synoptic studies (Alpert et al., 1990a,b; Dayan and Abramsky, 1983; Reiter, 1975) clearly demonstrated a strong seasonal character of developments in the region. Several mechanisms like topography, convective processes, latent heat release and sea surface latent/sensible heat fluxes were suggested to be most significant. The upper tropospheric jet streams and their synergistic interactions with the mid-tropospheric diabatic processes also play their cyclogenetic role in many cases. Examples of such interaction and of a joint role of these factors have earlier been found in cases of coastal area cyclogenesis (Lapenta and Seaman, 1990) and, in particular, in case of a Genoa cyclones development (Alpert et al., 1995a).

Buzzi at al. (1985) have documented a case of intensive Genoa cyclogenesis during March 3–6 1982 period. This cyclone is perhaps the most widely studied lee system developed in the Alpine area during the ALPEX Experiment. Numerous numerical simulations of the cyclone performed by Tibaldi and Buzzi (1983); Del'Osso (1984); Black and Mattocks (1984); Tafferner and Egger (1990); Alpert et al. (1996) and many others demonstrated the role of different factors responsible for its intensive development. Among such factors the topographic effects acting together with convection and large scale condensation as well as the effects of the surface latent and sensible heat fluxes were found to be important in contribution to this cyclonic formation – Alpert et al. (1995a), Alpert et al. (1996).

The Genoa cyclone was not the only one low center developing during that period over the Mediterranean. Another coastal cyclone also developed in the area of the EM during the same time interval. This cyclone belongs to a very typical group of eastern Mediterranean weather systems, which periodically form over the southeastern part of the area. Their development is characterized by an almost meridional northward intrusion of a subtropical trough along the Red Sea area. The process often concludes by formation of a cyclonic system over the EM. Such systems are locally called the Red Sea Trough (RST) cyclones after the apparent area of the origin of the trough. These systems are evidently related to the atmospheric processes in the area with the high mountains of the Abyssinean Highlands with maximum height of 4620 m (7° N, 43° E) and Asir mountains with maximum height of 3760 m in the Arabian peninsula (16° N, 48° E).

The aim of the present study was to simulate the processes of the trough and the cyclone development during the ALPEX 1982 March 3–5 period and to analyze the factors, controlling the process. Preliminary results of low resolution numerical simulations of the event have been recently reported by Krichak and Alpert (1994a). It was shown that the trough and the cyclone are not generated in no-terrain simulations. Results of a finer resolution simulations and the roles of other factors were not analyzed earlier.

Recently developed factor separation method (Stein and Alpert, 1993) has been successfully adapted in different applications related to numerical modeling of the atmosphere. In the 3–6 March 1982 Genoa cyclone analysis (Alpert et al., 1995a, 1995b, 1996) the roles of topography (t), surface sensible (s) and latent (l) heat fluxes and convective cloud latent heat release (r) and of their synergistic interactions during the cyclogenetic event were computed. Results of the studies have also clarified the role of the processes developing outside the lateral boundaries of the model during the Genoa cyclogenetic event.

The present study continues the investigation of the case by extending the processes under analysis to the main EM systems which existed during the period in the area. Results of real data simulations are analyzed by means of the factor separation method which is applied for the factors (t, s, l, r) chosen. This allows comparing results of the factor separation for the RST cyclone with corresponding data for the Genoa cyclone.

Discussion of synoptic situation and results of numerical simulations with MM4 and RAMS models are given in Section 2, which consists of three subsections where the following subjects are addressed. In Section 2.1 the low resolution simulations with the MM4 model; in Section 2.2 the higher resolution RAMS model experiments; and in Section 2.3 the factor separation study. Summary and discussion follow in Section 3.

2. March 3–5, 1982 RST Cyclone: Synoptic Analysis and Results of Simulation

The case under investigation is of the well studied ALPEX period with the Genoa cyclogenetic event that occurred on the 3–5 March, 1982 (see Fig. 1a–1c). Detailed analyses of this case were published earlier for instance by Alpert et al. (1996) and Dell'Osso (1984). These studies were focused on the mid-latitude processes in the western and central Mediterranean, since (Dell'Osso, 1984) the Genoa cyclone has developed as a consequence of a gradual displacement of a frontal system expanding from the area of northern Europe to the Mediterranean.

The cyclone, however, was only a part of a much broader pattern and a primary goal of this study is to investigate this larger picture of development. Before the arrival of the frontal system, another cyclone existed over the Ionian Sea (37° N, 22° E). During the period of the Genoa cyclone development this center was rapidly displacing to the south. The cyclone occluded on its way to the North African coast. The low then turned into part of the future RST cyclone system. The RST cyclone with central pressure of 1012 hPa developed over the western part of Arabian peninsula on about 1200 UTC 5 March 1982 (Fig. 1c). To the east of this area an anticyclone with a central pressure of 1020 hPa developed as part of the RST cyclone intensification process.

2.1 *Coarse Model Simulations*

The Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) hydrostatic diabatic limited area model with a terrain following p-sigma vertical coordinate MM4 (Anthes and Warner, 1978; Lapenta and Seaman, 1992) has recently been adapted at the Israel Meteorological Service for operational

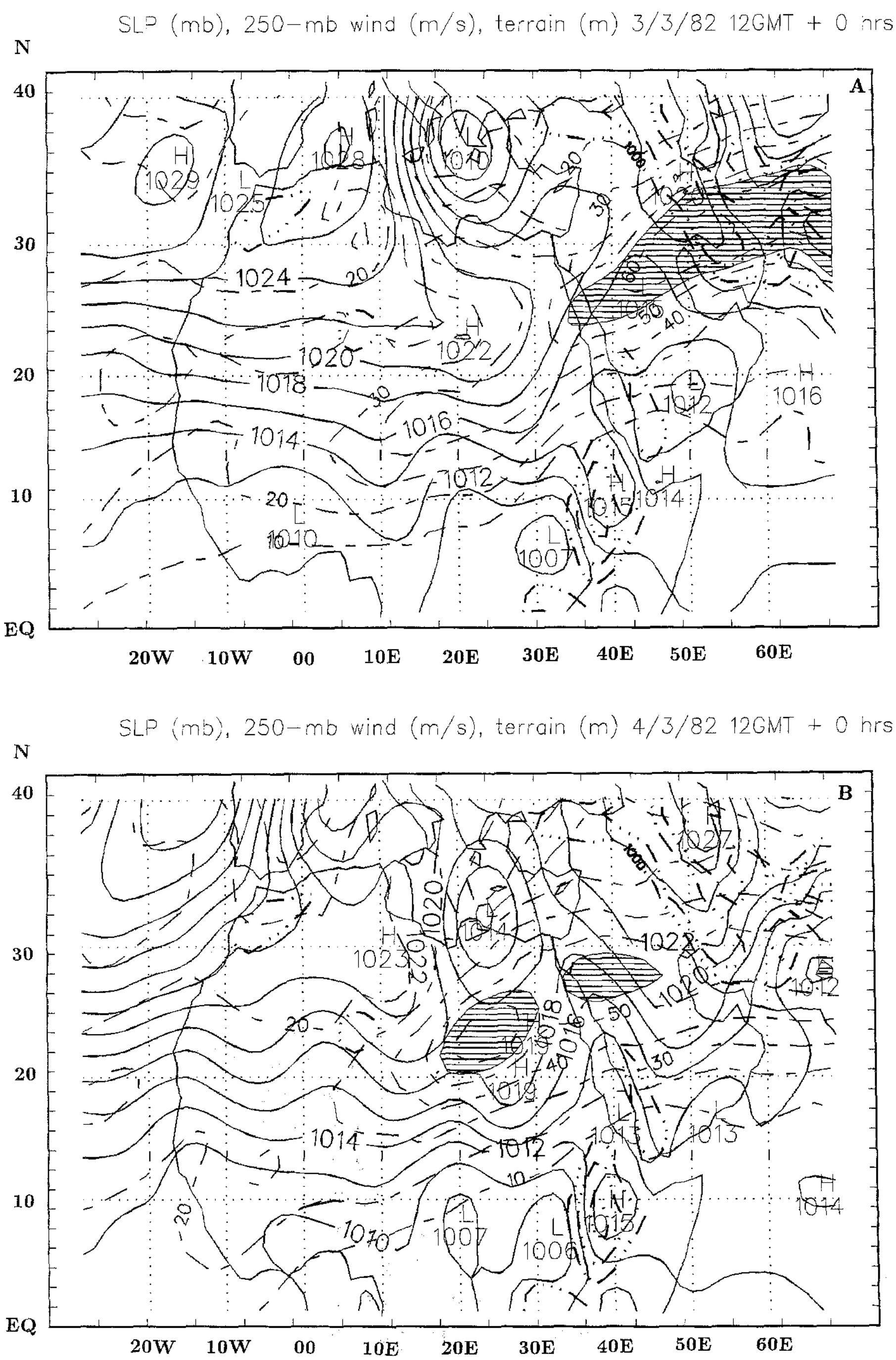

Fig. 1. Objective analyses of the SLP and 250 hPa wind fields for the March, 1982 case, SLP (full lines), contour interval 2 hPa, wind field (dashed lines) contour interval 10 ms^{-1} (A) 3 March 1982 1200 UTC, (B) 4 March 1982 1200 UTC, (C) March 5, 1982, 1200 UTC

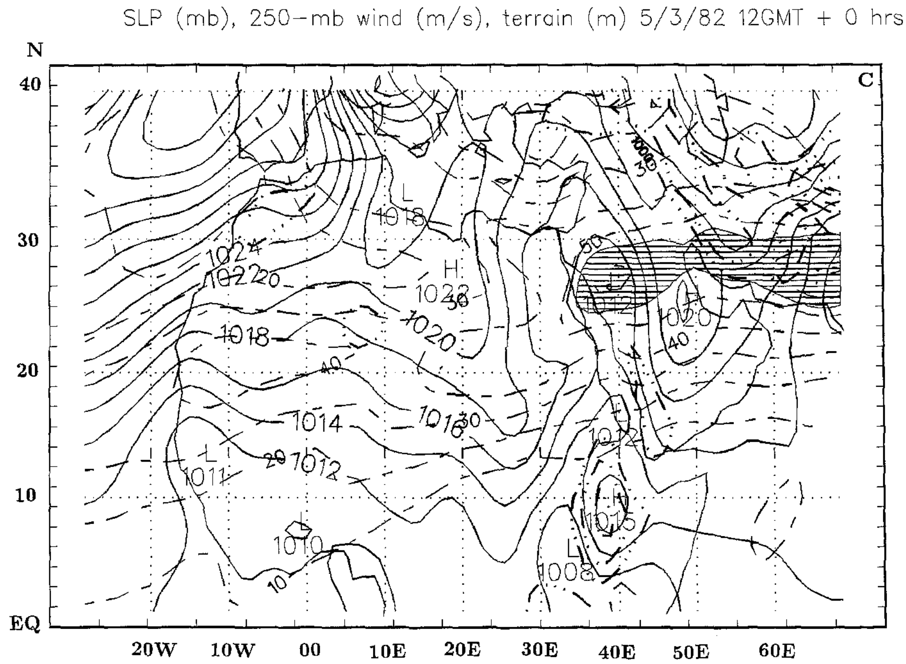

Fig. 1 (*Continued*)

large scale numerical prediction (Krichak and Alpert, 1994b).

The model includes the diabatic processes necessary for short range limited area numerical prediction, i.e long- and shortwave radiation in cloudy conditions, large scale and convective precipitation processes, boundary layer, latent and sensible heat fluxes. The land temperature is computed according to the heat balance equation. (Anthes and Warner, 1978). Initial conditions and the data for time dependent lateral boundaries are the ECMWF initialized analyses available with 2.5×2.5 horizontal resolution on 1000, 850, 700, 500, 300, 200 and 100 hPa. The period covered is 3 March 1200 UTC to 5 March 1982 1200 UTC 1982 with 12 h interval.

Horizontal grid of 41×73 points is used. Fifteen vertical layers represent the atmosphere from the sea/land surface up to 100 hPa. The low resolution runs were performed over a comparatively large area where the development takes place using a coarse horizontal resolution of 150 km. In this case the model covers a large area of $11{,}000\,\mathrm{km} \times 6{,}000\,\mathrm{km}$, which includes North Africa, the Mediterranean region and adjacent areas (0°–50° N, 30° W–70° E). For simulation domain and model topography, sea Fig. 2. The Abyssinean Highlands massif with its central part at about 10° N, 37° E on the western side of the Red Sea area and the Arabian Peninsula mountains located along the eastern side of the Red Sea and the Arabian Sea coast will be especially referenced in the following discussion in association with the Red Sea cyclone generation.

Results of the 24 h and 48 h simulations of sea level pressure and 250 hPa wind fields with the MM4 model starting from 1200 UTC 3 March 1982 are presented on Fig. 3a and Fig. 3b respectively. A trough develops along the eastern side of the Red Sea area after 24 h of the simulations as an extension of a low system existing in the equatorial area (10° N, 35° E) on the initial SLP pattern. Results of the 48 h RST computations are also successful in their main aspects, although the simulated RST central low pressure after 48 h reaches 1015 hPa as compared to the 1012 hPa observed. The anticyclone over the Arabian peninsula is located on the 48 h map almost at the right place with 1024 hPa at its center as compared to the 1020 hPa observed. Although this displacement of the cyclone to the Red Sea area from the Ionian Sea was under predicted, the main feature of the process which was the combination of the former central Mediterranean cyclone with the newly developing RST cyclone is quite well simulated. It is interesting to note that the tropical extension of

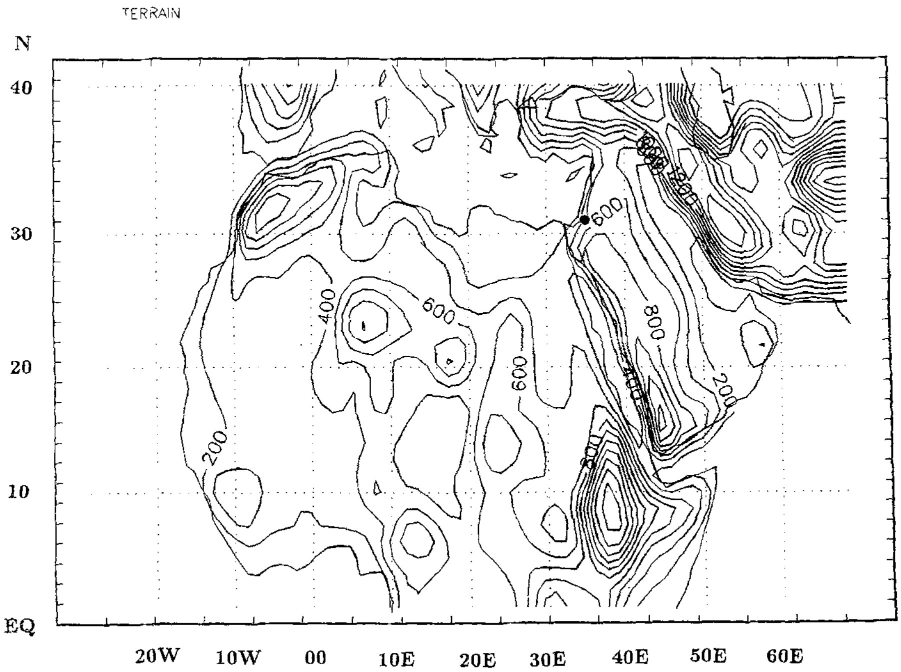

Fig. 2. Low latitude MM4 model domain. The model's topography is contoured with 100 m contour interval from 0 to 500 m and with 200 m contour interval in the other regions

the Genoa system in its later phase was not investigated earlier.

The main features of the 250 hPa wind field modifications in the RST cyclone region are also well simulated (Fig. 3a and 3b). As observed, during the first 24 h the wind maximum shifted to the west from its initial position over Arabian peninsula. During the following day the wind maximum gradually returned to its starting position over the Arabian Desert. This process seems to be of critical importance for the RST development. It follows (Fig. 1a–c and Fig. 3a–3b) that the RST develops after the zone with strong westerlies (indicated by the area with the 250 hPa wind velocity greater than 60 ms^{-1}) displaced to the central part of the Red Sea area (Fig. 1b and 3b). The intensification of the mid-tropospheric westerly flow was a consequence of

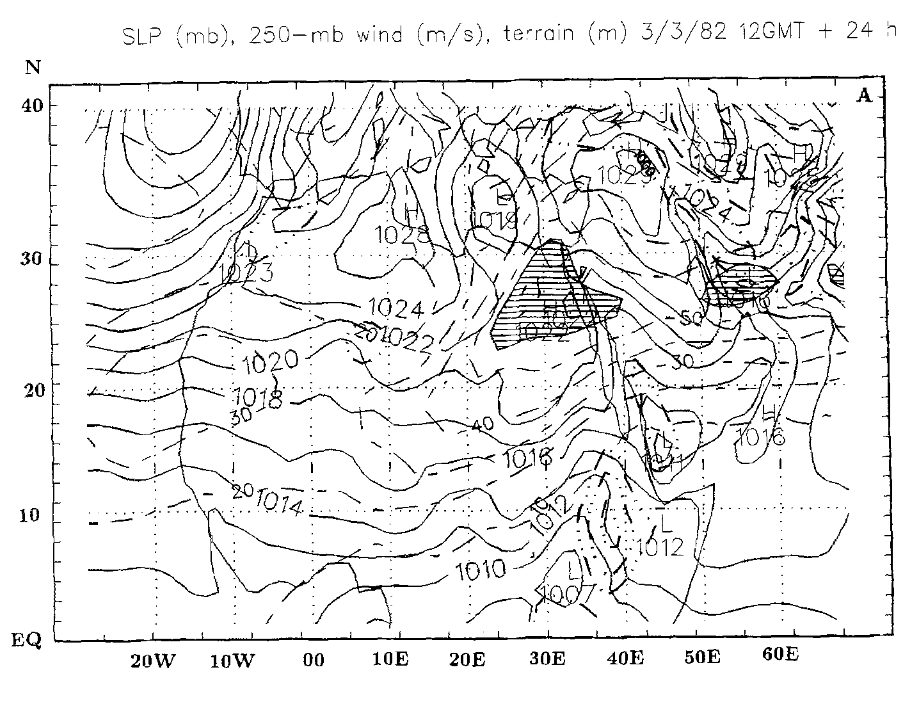

Fig. 3. Same as for Fig. 1, but for the simulation results. (A) 24 h forecast, (B) 48 h forecast

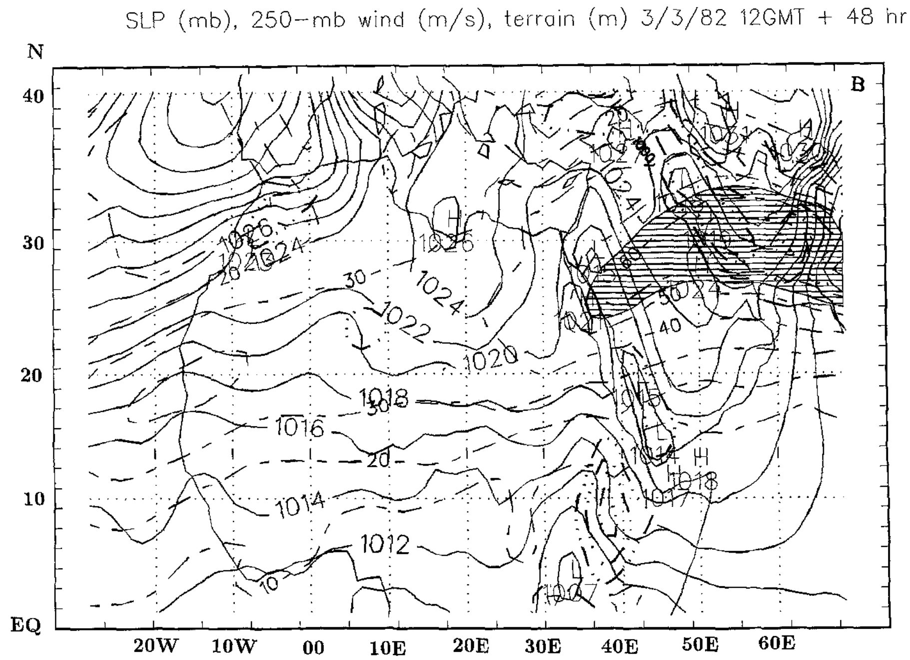

Fig. 3 (*Continued*)

the southward intrusion of the former Ionian Sea mid-latitude cyclone discussed earlier. Additional simulations of this case with 80 km resolution produced similar results (not presented here).

2.2 *High Resolution Simulations*

More detailed analysis of the situation was performed by means of much higher resolution numerical simulations of the case. The high resolution non-hydrostatic Colorado State University Regional Modeling System CSU RAMS 3a (see Pielke et al., 1992 for review) was adapted. The model configuration in our experiments corresponds to that used in Levin et al. (1996). The RAMS mesoscale model makes use of the two-way interactive nested grid structure. The outermost grid has 40×40 points with 100 km horizontal resolution. The second grid consists of 70×70 points with 20 km resolution. Vertical atmospheric structure is described by 30 model levels from the surface up to about 25 km with 200 m grid spacing in the lowest layer and 1.15 times of this value grid stretching in the upper levels with maximum spacing of 1000 m. Terrain is based on the U.S. NAVY data archive.

Same initial and lateral boundary data as in the earlier experiments was used for these simulations. The runs were performed over two regions – the Eastern Mediterranean region and the Red Sea area. Results of simulations with the nested grid system are discussed below based on the streamline/wind vector fields computed at the 850 hPa isobaric surfaces.

Results over the EM area are given on Fig. 4a–4c for 00, 24 and 48 h respectively. The model successfully describes the vortex development in the area. It is clearly seen that during the first 36 h of the simulation the former Ionian Sea

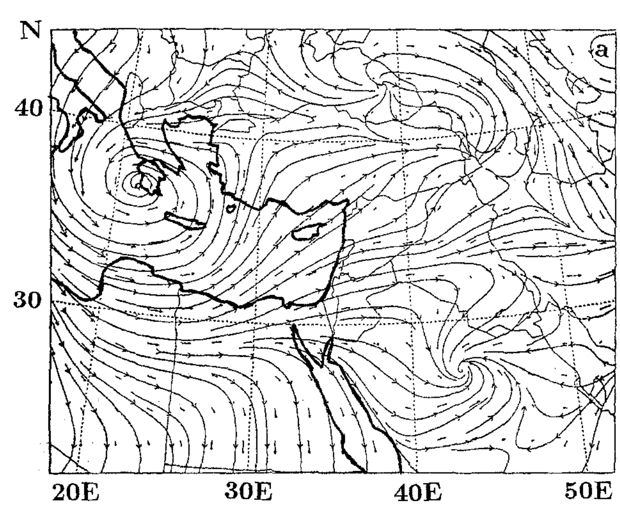

Fig. 4. Streamline/wind vector fields at 850 hPa isobaric surface as simulated with the RAMS model over the EM area, initial data for the simulation are of the 1982 March 3, 1200 UTC case: (a) 00 h (b) 24 h, (c) 48 h

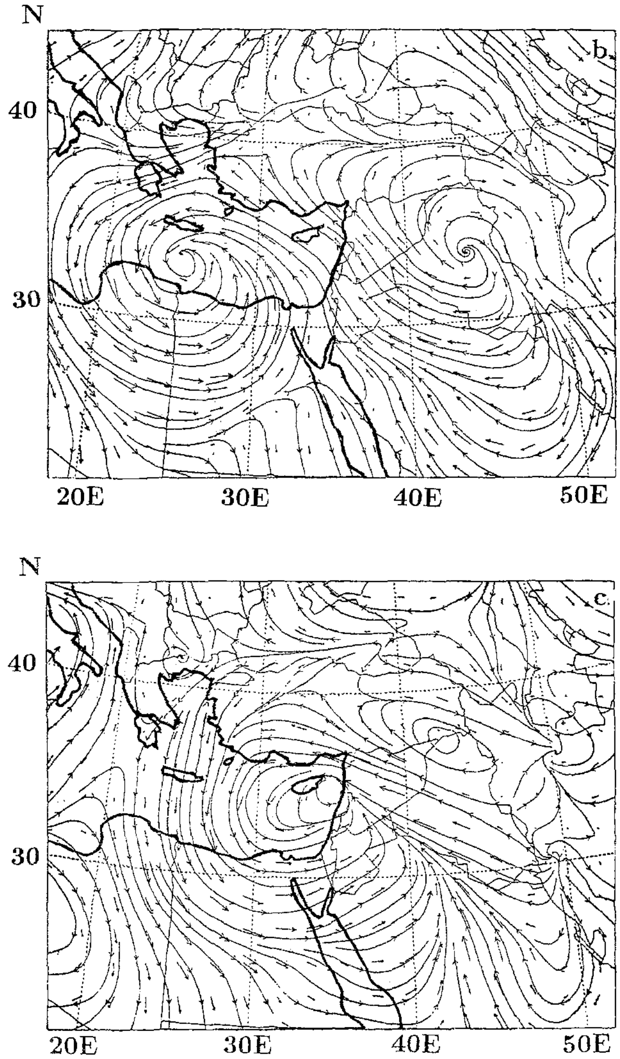

Fig. 4 (*Continued*)

cyclone propagates to the southern part of the EM. Intensity of the cyclone weakens during this period. This process is accompanied by establishment of a northward flow in the Red Sea area. This flow is already noticed in the EM after 12 h of the simulations. A sudden intensification of the cyclone takes place during the 36–60 h period (Fig. 4b, 4c). The intensification may be explained up to some extent by propagation of the trough system and its relatively warm and moist air masses into the EM area. Another probably more correct explanation of the intensification is based on the fact that the further development of the cyclone took place after the formation of the area of strong mid-tropospheric westerly winds over the central part of the Red Sea area. This fact is well illustrated by the results of the numerical simulation (not presented), caused by the southward intrusion of the mid-latitude cyclone.

Results of simulations over the Red Sea area during the same period are presented on the Fig. 5a–5c illustrating the simulation results for 00,

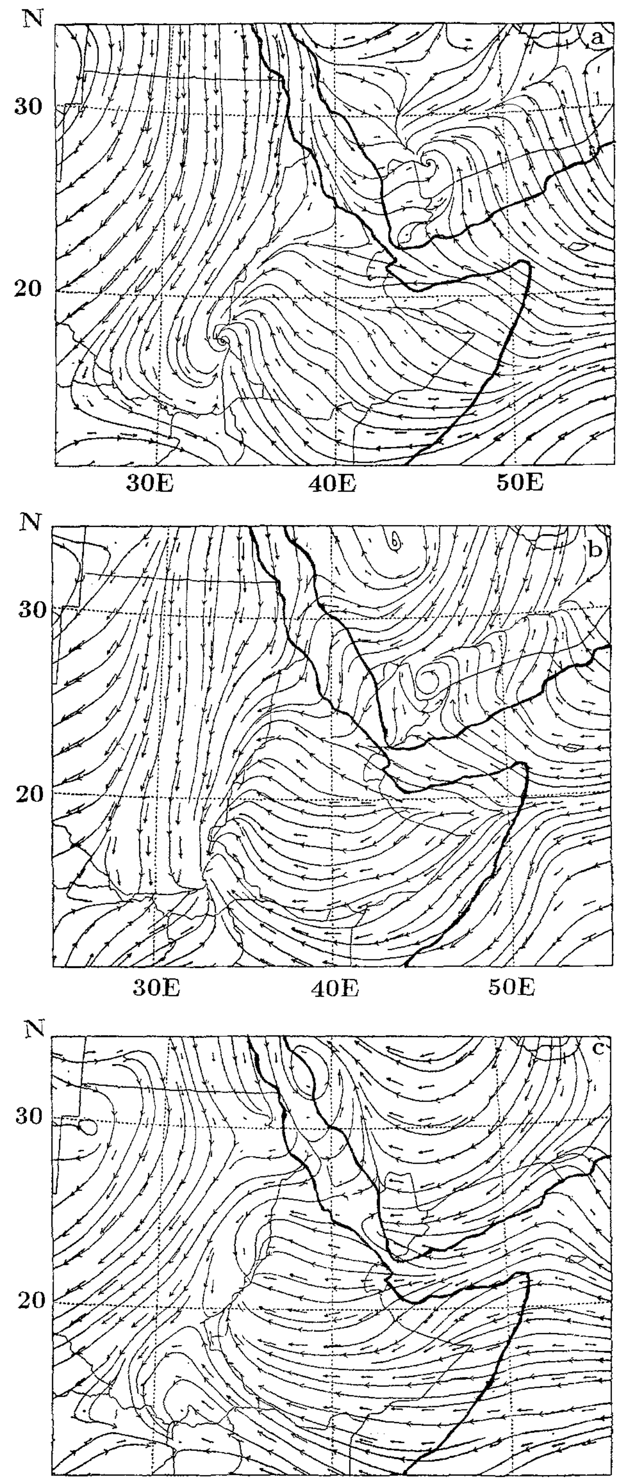

Fig. 5. Same as for Fig. 4, but for the Red Sea area: (a) 00 h, (b) 12 h, (c) 24 h

12 and 24 h of the forecast. As seen from the figures the cyclogenetic process over the Arabian peninsula is present already on the March 3, 1982, 1200 h (Fig. 5a) as a consequence of penetration of the easterlies from the Arabian Sea area and the lee side development associated with it. The cyclone is approximately at the same location on the following 12 h map (Fig. 5b). On the next figure (5c) the cyclone is already shifted to the north where it becomes a part of the RST system.

It appears that the southward flow existing on the 850 hPa surface over the northern part of the E. Africa on March 3, 1982 1200 UTC converged with the easterly flow over equatorial and tropical parts of the E. Africa. This process concluded with the development of a cyclonic system over the Arabian peninsula. The lee cyclone which was formed over the latter has enhanced the RST system intensifying in association with the STJ westerly flow over the Red Sea. Propagation of the cyclonic center to the northwest along the Red Sea area basin was the final stage of the process.

2.3 Factor Separation Analysis

Contribution of four different factors, i.e topography (t), surface latent heat flux (l), surface sensible heat flux (s) and the latent heat release (r) due to cumulus convection as well as of their double and triple interactions to the lee of Genoa 3–5 March 1982 cyclone at the location of its most intensive development were computed by Alpert et al. (1995a, 1996) using the method developed by Stein and Alpert (1993). They showed that topographic blocking was an important factor for the cyclone development. As has been shown separately by Krichak and Alpert (1994a) the RST and its associated cyclone of the 3–5 March 1982 were largely affected by the inclusion of topography effects. This suggests that topography played a central role in this process as well.

Here we follow the same procedures in an attempt to investigate the role of different factors in the EM area during the RST cyclone development. The necessary model simulations were performed with the aforementioned MM4 version. The factor separation was performed for the same EM location where regular meteorological observations (Beit Dagan, Israel (32.0° N, 34.8° E) are taken. The observed sea level pressure (SLP) values are plotted on Fig. 6. Two curves drawn here represent the SLP values measured every 6 h (solid line) and determined from the ECMWF objective analyses with 12 h time resolution (dashed line). Hence, the intensification of the cyclone over the E. Mediterranean area took place during the March 4, 1982 1200–1800 UTC period (i.e 24–30 h after the beginning of the simulation). According to the subjective analyses (Fig. 6) the cyclone had its lowest SLP value of 1013 hPa on the March 5, 1982 1200 UTC.

Figure 7 shows the results of application of the method. Only nine largest factors are presented. During the first 12–18 h of the simulation the

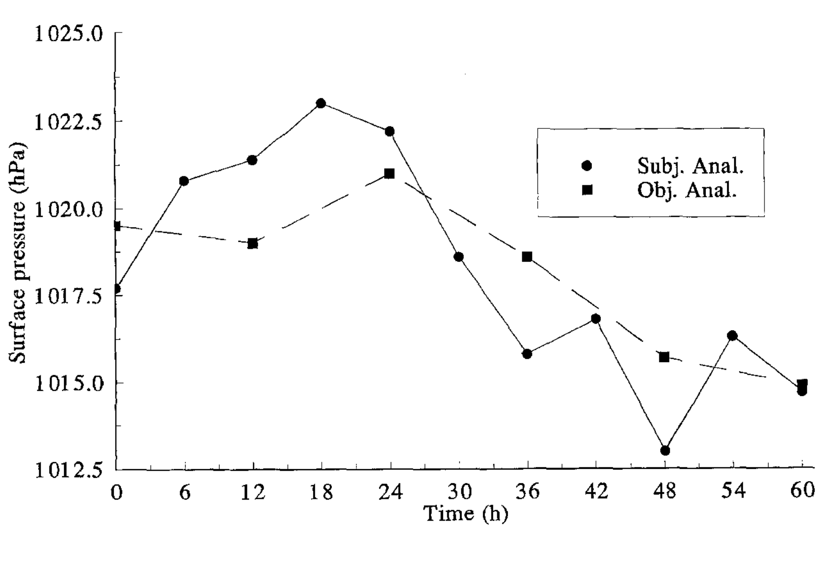

Fig. 6. The SLP variations during the 60 h period starting from March 3, 1982, 1200 UTC. Solid line – meteorological 6 h measurements, dashed line – the ECMWF 12 h objective analyses

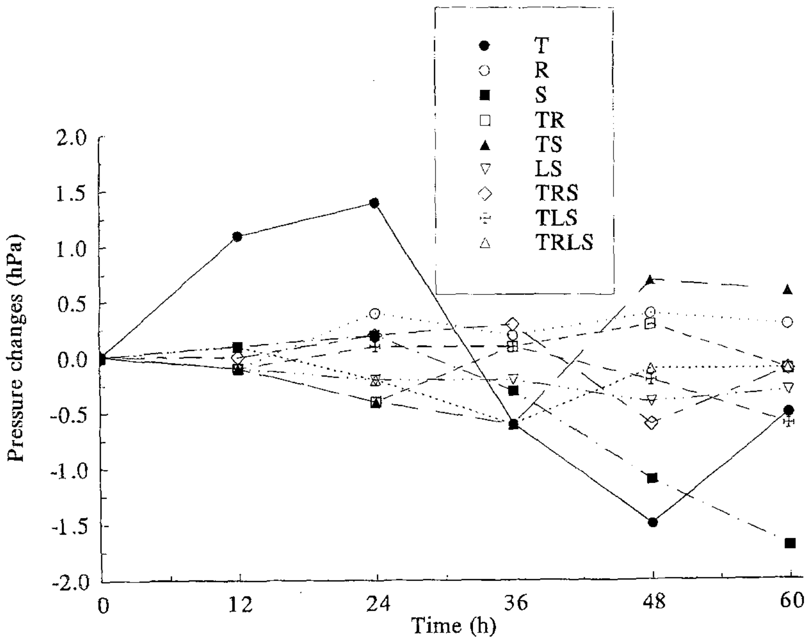

Fig. 7. Nine (out of 16) contributions to the pressure changes over the EM (Beit-Dagan, Israel). The factors are denoted as (T)-topography, (R)-latent heat release, (L)-latent heat flux, (S)-sensible heat flux. The interactions terms are denoted by the letters of their parent factors

SLP was increasing in the EM area. Results of the factor separation show (Fig. 7), that the topography blocking acted as a cyclolytic factor, preventing the process of the northward trough propagation. Only the synergistic interaction processes (tr), (ts) and (trls) supported the cyclogenesis at the location during this period.

The situation changed only after about 30 h of the simulation, when the trough already propagated into the EM area (Figs. 3a and 5b). Local terrain (t) acts now as one of two major cyclogenetic factors. The second local effect also working as a cyclogenetic one is the sensible heat flux (s). Its role is especially important after 36 h of the simulations when strong winds over the sea area caused more active heat transfer from the sea surface to the atmosphere. On the contrary, the synergistic interaction of terrain with the sensible heat flux (ts) has cyclolytic effect during the final stage of the simulation. This counterbalancing of role of the (s) factor is quite typical under the cyclogenetic conditions. In the lee of Genoa as well the topography had a major cyclolytic effect at the later stage of development which was counterbalanced by convection, Alpert et al. (1996). In case of the EM development the convection also counterbalances effects of the topography after the latter starts acting as a cyclogenetic factor. Triple synergistic interaction of terrain, convection and sensible heat flux (trs) and of terrain, sensible and latent heat fluxes (tls) support cyclogenesis only during the last 24 h of the simulations.

Alpert et al. (1995b) suggested criteria for the determination of the type of the Eastern Mediterranean cyclones based on results of the factor separation analysis. It was suggested to classify these cyclones by two main groups – primary and secondary cyclones – depending on the role of different factors in their development. The main contributors to the primary cyclones were found to be terrain and terrain-fluxes interactions. For the secondary systems over the sea the fluxes had the strongest effect. The classification was suggested based on results of analysis of the cyclones developing over the northern part of the EM. From the present analysis follows that the analyzed RST related EM cyclone had a different physical nature than the North E. Mediterranean systems. The cyclone developed as a result of lee type cyclogenetic process over the Arabian peninsula. The role of terrain in this process was demonstrated both by numerical simulations, especially with the high resolution RAMS model, and by the factor separation analysis. However, the northern propagation and the intensification of the low center took place over the Red Sea surface where the sensible heat fluxes played the primary role. The cyclone appears to be of the primary type, having both the terrain and the fluxes as primary factors for its development. This difference of the Red Sea type EM cyclone from the ordinary EM cyclones which originate in the mid-latitudes may provide additional perspectives for analyzing the cyclogenetic processes of the region.

3. Discussion and Conclusion

The Eastern Mediterranean (EM) region is often characterized by development of low pressure trough system propagating to the area from the Red Sea. In some cases the trough intensifies after establishing over the EM and development of a cyclone takes place. These cyclones are a significant source of precipitation in the EM. The rains are especially strong during the autumn and spring months.

The processes of the trough and the cyclone development during the March 3–5 1982 are investigated. Simulations are conducted with two atmospheric models – the MM4 and the RAMS. Both models successfully described the process of the trough development over the Red Sea area and that of the cyclone in the EM area.

The MM4 model simulations accurately described both the process of the RST development and the intensification of the cyclonic center in the EM area. It appears that the RST develops following the displacement of the zone with strong westerlies to the central part of the Red Sea. This intensification of the mid-tropospheric westerly flow over the Red Sea was associated with the southward intrusion of the former Ionian Sea mid-latitude cyclone. An additional numerical study of the Red Sea Trough development has been also performed with the same model using idealized initial data set corresponding to the typical cool season distribution of the atmospheric flows over the Red Sea area. Details of this study will be discussed separately. According to the results intensity and positioning of the mid- and upper tropospheric STJ related westerly flow is one of the main factors participating in the RST development. It implies a special role of the intraseasonal variations of the STJ during the cool season over Northern Africa (Krishnamurti, 1961; Krishnamurti et al., 1973).

High resolution RAMS simulations allowed the detailed analysis of the processes involved in the development of the RST type EM cyclonic system. It follows that the development of the cyclone took place over the Arabian peninsula as a result of the interaction of the southward flow over the northern part of the E. Africa on March 3, 1982 1200 UTC converged with the easterly flow over equatorial and tropical parts of the E. Africa. The southward flow was associated with the southward intrusion of a mid-latitude cyclone. This process led to the development of two cyclonic systems over the area, one over the Abyssinean Highlands and the second over the Arabian peninsula. The lee cyclone which was formed over the latter has enhanced the RST system. Propagation of the cyclonic center to the northwest along the Red Sea area basin was the final stage of the process.

Results of the factor separation showed that during first 30 h the topography blocking acted as a cyclolytic factor, preventing the northward trough propagation. Only the synergistic interaction processes (tr), (ts) and (trls) supported the cyclogenesis at the location during this period.

The situation changed only after about 30 h of the simulation, when the trough already propagated into the EM area after the aforementioned intensification of the mid-tropospheric westerlies over the central part of Red Sea. Starting from this period the terrain was acting as one of two major cyclogenetic factors. The second local effect also working as a cyclogenetic one was the sensible heat flux (s). Its role was especially important after 36 h of the simulations when strong winds over the sea area caused more active heat transfer from the sea surface to the atmosphere. According to the results of the study, the cyclonic system which intensified over the EM area during this period can be classified as a primary cyclone. Some principal difference between this cyclone and those developing over the northern part of the EM should be mentioned. The RST type EM cyclone is found to be an example of the system developing due to the mid-latitude-subtropical area interaction process. This type of the Mediterranean cyclones has not yet been investigated accordingly. Such further analysis is being performed presently.

Acknowledgments

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simulations. NMC wind vector analyses from the NCAR CD-ROM Data Base are used for the wind climatology calculations for the African/Mediterranean region.

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