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Interaction of Topography and Tropospheric Flow – A Possible Generator for the Red Sea Trough?

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With 5 Figures

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Summary

Numerical investigation of the nature of one of the most typical Eastern Mediterranean atmospheric circulation phenomena – the Red Sea Trough is undertaken. The role of interaction of typical atmospheric flow systems with the local topography of the North African region is analyzed with the help of idealized numerical simulations employing the Penn State and the National Center for Atmospheric Research (NCAR) MM4 modeling system. The simulations are designed, based on results of a climatological evaluation of the 250 hPa wind field. Idealized initial data sets corresponding to typical transient and winter period positions of the upper tropospheric westerly jet stream are constructed. The data for the analysis are from the National Center for Environmental Prediction (NCEP) 25 y (1965–1989) objective analysis archive. It was found that the primary factor in the Red Sea trough generation is the interaction of the mid-tropospheric westerlies with the terrain in the area of the Red Sea.

1. Introduction

The 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, 1986; Dayan and Abramsky, 1983; Reiter, 1975) clearly demonstrated the seasonal character of developments in the region. The upper tropospheric jet streams and their synergistic interactions with the mid-tropospheric diabatic processes also play a 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, 1992; Alpert et al., 1995b) and, in particular, in case of Genoa cyclone development (Alpert et al., 1995a). Among the synoptic processes typical for the Eastern Mediterranean (EM) during the cool season is a phenomenon characterized by an almost meridional northward penetration 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 "Red Sea Troughs" (RST) after the general area of their origin. Such developments take place mostly during the transient periods of the cool season – late autumn and spring months (Alpert et al., 1990 a, b). The aim of this note is to analyze the possible role of the interaction of the wind flows of the North African atmosphere with the main mountains of the eastern part of the region – the Abyssinean Highlands and the Asir mountains on the Arabian peninsula (locations are shown in Figs. 3, 4) in the RST development.

For this purpose idealized zonally homogeneous initial data sets which only differ by the intensity and positioning of the main wind flows over Africa are employed. Characteristics of the idealized data sets are determined according to the data from analyses of mean characteristics of the upper tropospheric subtropical westerly jet stream (STJ) over the Mediterranean area and North Africa.

Results of climatological analyses of the intensity of the upper tropospheric winds over N. Africa during the cool season months are first presented in Section 2. Design and results of the idealized simulations using the MM4 NCAR/Penn State model (Anthes and Warner, 1978) are given in Section 3. Summary and discussion of the results follow in Section 4.

2. Climatological Analysis of the 250 hPa cool Season Extreme Wind Distribution

One of the three quasi-stationary northern hemisphere waves of the winter STJ is normally located over the north African region (Krishnamurti, 1961). Westerlies exist in this area not only in the upper troposphere, but also below, down to 800 hPa. This fact is illustrated by Fig. 1, where the 35° E meridional crossection of u-wind component for March 3 1982 1200 UTC is presented. To the south of the region of the westerly winds the area of the equatorial easterlies is also noticed. Intensity of the jet and the geographical positions of the wind maxima vary during the cool season, Krishnamurti (1961), Krichak and Alpert (1994a), being a part of the intra-seasonal variation of the regional atmospheric circulation.

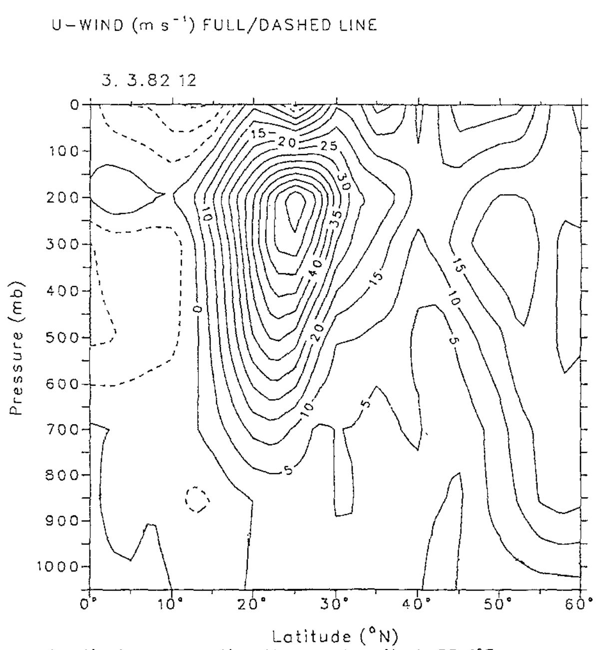

Fig. 1. The U-wind component vertical cross section along longitude 35° E. Isolines every 5 ms^{-1}. 1982, March 3 1200

Mean positions of the jet stream wind maxima during the cool season months during the 25 year period (1965–1989) are computed using data from the NCEP/NCAR CD-ROM archive (Mass et al., 1987). Mean distribution of the areas with percentage of days for the 250 hPa wind velocity greater than 60 ms^{-1} are determined for each month of the year. The data represent predominant positioning of the STJ core. Only the October, January and May patterns – Fig. 2a, b, c respectively are given. During winter (January, Fig. 2b) the area of strong westerlies penetrates to the north over the Mediterranean region. During the transient period months (October and May, Fig. 2a and 2c) the strong winds (over 60 ms^{-1}) are mainly found over western and eastern parts of North Africa.

These variations are related to the African winter monsoon dynamics. Activation of the winter time equatorial cumulus convection, which plays the role of the main driving force for the STJ (Krishnamurti et al., 1973) and an increase of the equatorial-mid-latitude temperature gradient are associated with this displacement of the jet during the winter months.

It follows, that the southern part of the EM region is predominantly located under the STJ wind maxima during the transient seasons. This is not the case during the winter, when the jet ridges, and wind maxima related to them, are mainly located over the North African coast and the Central Mediterranean. The following simulations are designed with the purpose to analyze the role of the intra-seasonal variations of the wind flows over Africa during the cool season.

3. Idealized Initial Data Simulations. Design of Experiments and Analysis of Results

As shown in the previous section there are two main typical patterns characterizing the atmosphere over N. African and Mediterranean region during the cool season. During the whole season the STJ is a permanent feature of the regional circulation. Nevertheless, the intensity of the jet and the position of its core vary significantly during the active winter and the transient periods. During the active winter months the frequency of STJ wind maxima increases significantly over the

Central Mediterranean region. Such northward propagation of the zone with strong tropospheric westerly winds is associated with the easterly flows in the troposphere of the tropical area. During the transient periods the westerlies are much weaker and the core is positioned over the more southern latitudes of the Red Sea.

The initial data for the idealized simulations were constructed with the aim to represent these main elements of the cool season circulation in our experiments. Zonally homogeneous three dimensional initial data sets with different intensities of the flow were constructed. The sets represent the main typical characteristics of the zonal atmospheric flow over the African region – the STJ related westerlies in the subtropics and the easterly winds in the tropical area. The homogeneous initial fields are determined from the real data along a chosen meridian. The meridional v-wind component was put to zero. The procedure provides hydrostatically balanced zonal initial fields. The European Center for Medium Range Weather Forecasting (ECMWF) objective analysis data for March 3 1982 1200

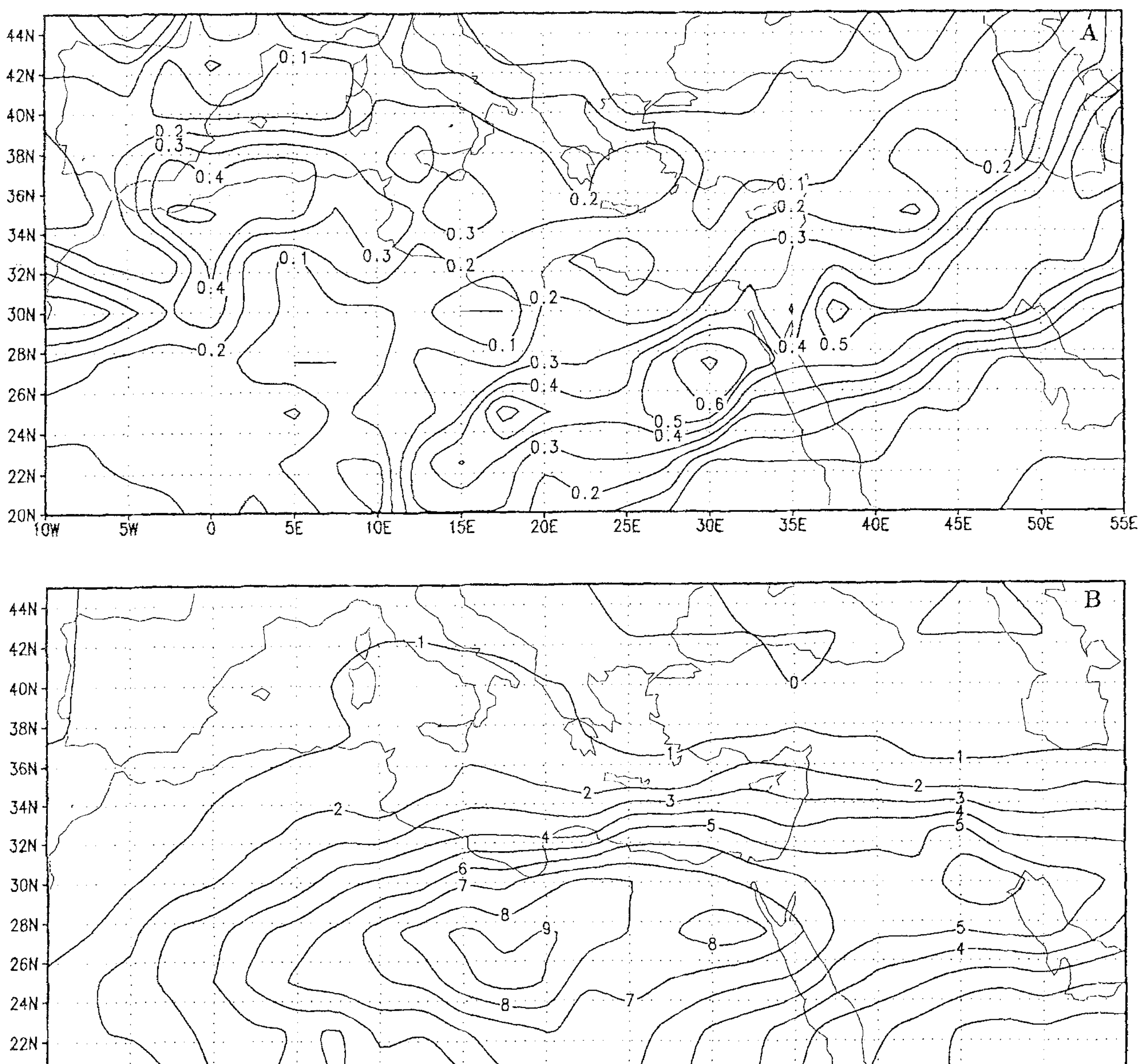

Fig. 2. Percent of cases with 250 hPa winds greater than 60 ms^{-1} over the region of Africa and the Mediterranean (1965–1989) (a) October, (b) January (c) May

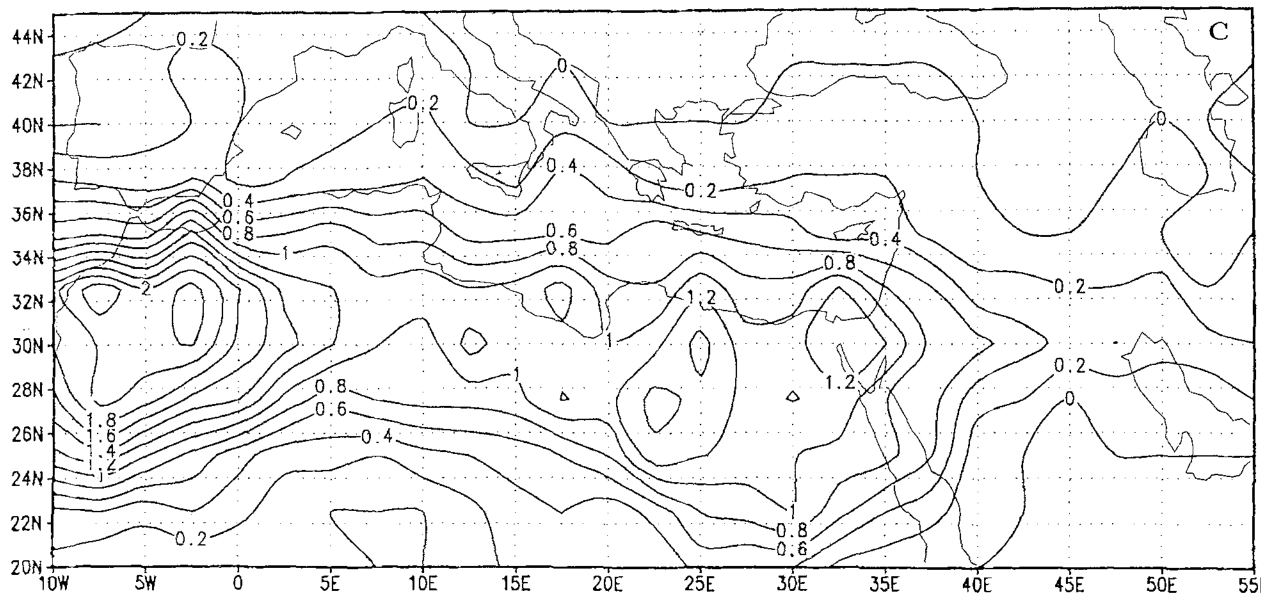

Fig. 2. (*Continued*)

UTC were used for construction of initial data for the simulations. The 35° E meridional cross-section of u-wind component for the March 3, 1982 1200 UTC is given in Fig. 1.

The PSU/NCAR hydrostatic diabatic limited area model with a terrain following p-sigma vertical coordinate MM4 (Anthes and Warner, 1978; Lapenta and Seaman, 1992; Krichak and Alpert, 1994) has been employed. The model includes the diabatic processes necessary for short range limited area numerical prediction, i.e. long- and short-wave 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 are the ECMWF initialized analyses available with 2.5 × 2.5 degrees horizontal resolution on the standard pressure levels at 1000, 850, 700, 500, 300, 200 and 100 hPa.

A horizontal grid of 41 × 73 points is used. Fifteen vertical layers represent the atmosphere from the sea/land surface up to 100 hPa, covering a relatively large area of 11000 km × 6000 km, which includes North Africa, the Mediterranean region and adjacent areas (0°–50° N, 30° W–70° E). A horizontal resolution of 150 km is used. Since the focus here was on interaction with the terrain no sensible or latent heat surface fluxes are included in these simulations; cyclic lateral boundary conditions were adopted.

The simulation experiments consisted of two groups of 24 h MM4 integrations using the idealized data sets. Details of the experiments of the both groups are presented in Table 1.

Experiments of the first group (Ia, Ib and Ic) have used initial data sets differing by the intensities and positioning of the wind flows. Characteristics of the atmospheric flows for each of the simulation experiments are determined according to the results of the discussed climatological analysis of the upper tropospheric winds. The main characteristics of the experiments of the first group are as follows:

(Ia) – The 250 hPa STJ core is at 25° N. Maximum wind velocity is of 25 ms^{-1}. Pattern is typical for transitional periods;

(Ib) – The STJ is at 32° N. Maximum wind velocity is of 55 ms^{-1}. Typical for winter;

(Ic) – As in (Ia), but with maximum winds of 55 ms^{-1}.

Results of simulations (Ia) – (Ic) are presented in Fig. 3a–3c. The most intensive trough in the

Table 1. *Main Characteristics of the Simulation Experiments (Ia–Ic) and (IIa–IIc)*

Experiment	Ia	Ib	Ic	IIa	IIb	IIc
Latitude with STJ (in deg. of lat.)	25	32	25	25	25	25
Max. wind velocity at 250 hPa surface (in ms^{-1})	25	55	55	55	55	55
Shift of terrain (in deg. of lat. southward positive)	–	–	–	5	10	–5

Red Sea area develops in the (Ic) experiment (Fig. 3c). Since the data set for the experiment was one of the two corresponding to the transient periods of the cool season this result appears to be in agreement with the studies showing a trend to the intensification of the RST development processes during the transient periods of the cool season. According to this result the RST development takes place in situations with sufficiently strong westerly flow in the area on the Red Sea. The trough is much weaker in Fig 3a, corresponding to the simulation experiment using the typical transient season data with much weaker tropospheric westerlies.

No trough developed in the simulation experiment Ib, (Fig. 3b), which was conducted using

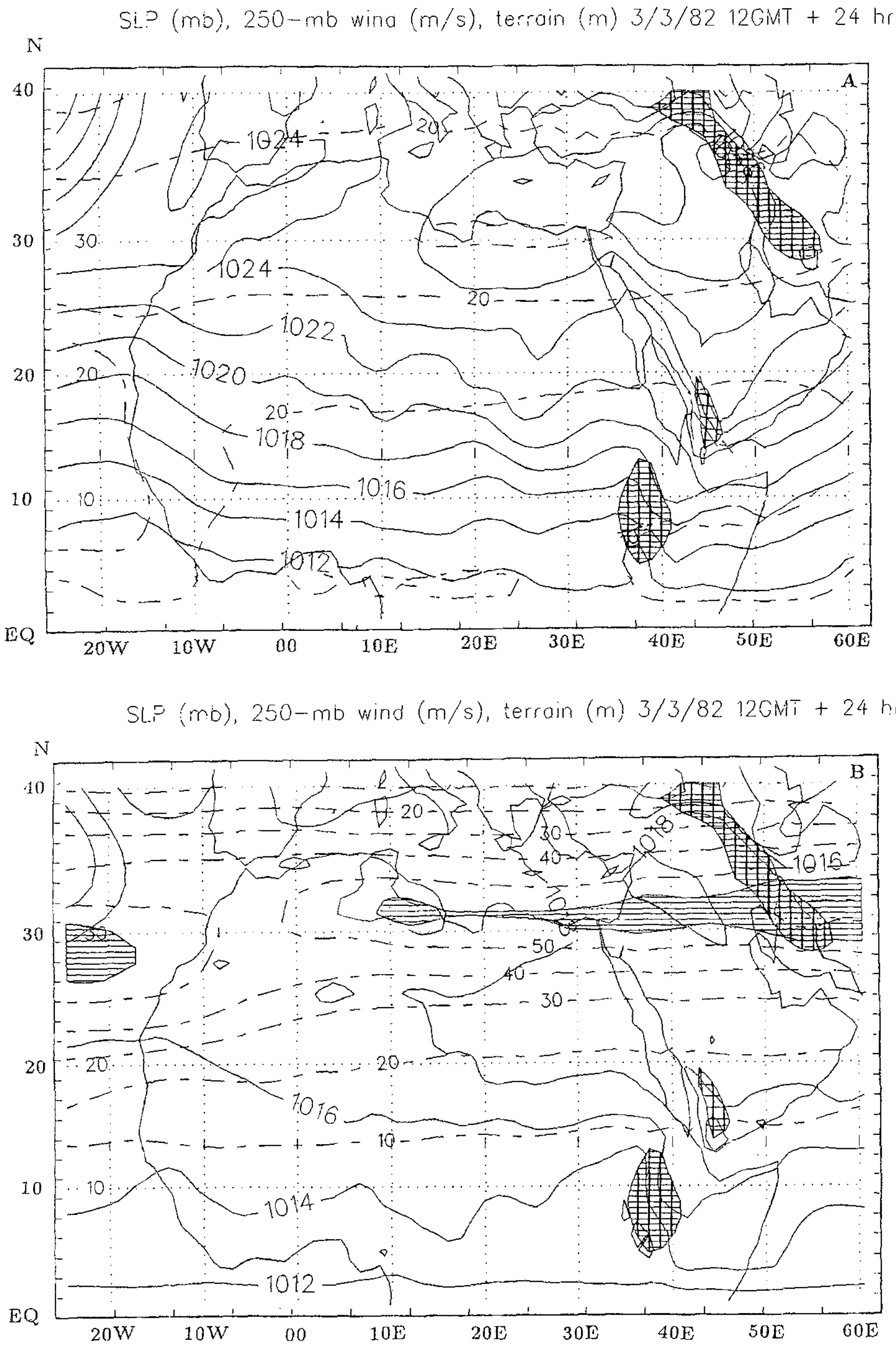

Fig. 3. Results of 24 h simulations of the groups I. (a) – Ia, (b) – Ib, (c)–Ic, SLP and 250 hPa wind fields SLP (full lines), contour interval 2 hPa, wind field (dashed lines) contour interval 10 ms^{-1}. Mountains exceeding 1300 m are indicated by shading – among them Abyssinean Highlands (35°, 8°); Asir mountans at (45°, 15°). Lat/Lon indicates approximate central locations

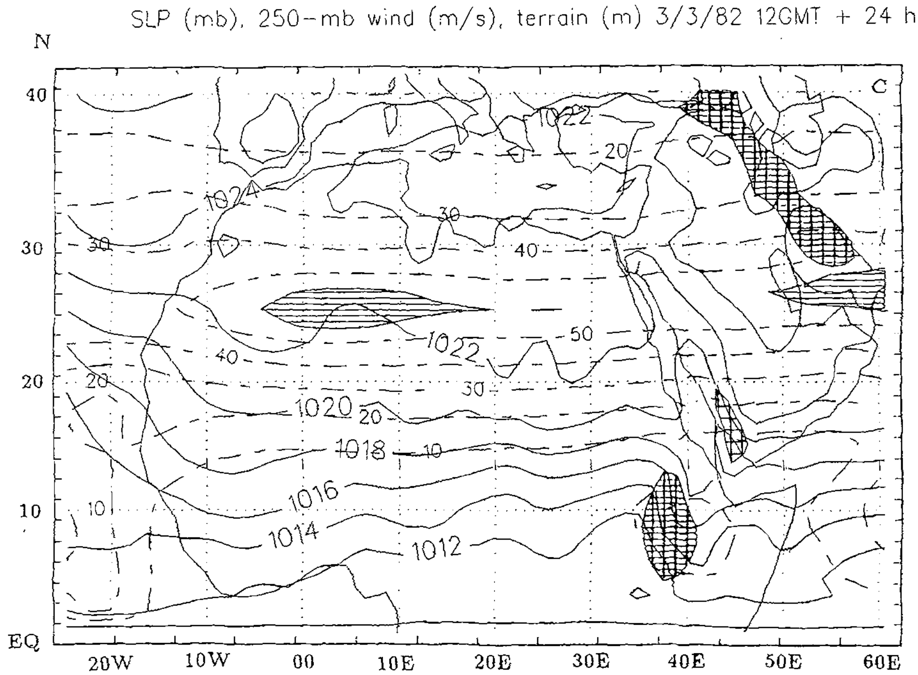

Fig. 3. (*Continued*)

the data with strong westerly flow positioned over the Mediterranean (and relatively weak westerlies over the Red Sea mountains), a situation more typical for winter.

Analysis of the results of the experiments of the second group (IIa, IIb and IIc) provides further insight into the role of the East African mountains in the process of the RST generation. The data set for these simulations is the same as in the aforementioned (Ic) experiment which have produced the most intensive development of the trough system.

Modified terrain fields are constructed for the experiments. The fields are formed by meridional shifts of the real terrain array (isolines of terrain greater than 1000 m are drawn on the Fig. 4a–4c by thick dashed lines).

Details of design of the second group of the experiments are as follows.

(IIa) – the terrain fields is formed by 5° southward shift of the original terrain field;

(IIb) – terrain shifted southward by 10°;

(IIc) – terrain shifted northward by 5°.

It follows from the (IIa)–(IIc) experiments (Fig. 4a–4c), that the process of the RST development is highly sensitive to the relative positions of the high mountains and the areas with tropospheric westerly and easterly flows.

The RST type development takes place in all the three experiments. Still there is a considerable difference which is caused by the positioning of the mountains relative to the flow. The troughs are similar in the (IIa–IIb) simulations compared to the (Ic) experiment. It is oriented exactly along the Red Sea area on the Fig. 4a of the (IIa) experiment which is the closest imitation of the transient season conditions. In case of the (IIb) simulation the trough develops over the area to the west of the Red Sea indicating the role of the easterly flow in the region. The situation produced in the (IIc) experiment is characterized by formation of a trough system over the Arabian Peninsula to the east of the Red Sea basin. This result seems to be physically logical due to the increased role of the westerlies in the area of high mountains of the East African area.

Some additional confirmation of the last statement may be found while comparing results of cross sections along the line shown on the Fig. 4c. One of the cross sections (Fig. 5a) was made for the earlier discussed simulated results (Exp. Ic). The second cross section corresponds to the results of the real data simulations performed, starting from the same base day used for construction of the idealized data (Fig. 5b)

March 3, 1200 UTC, 1982. Detailed discussion of the results of these simulation will be presented separately. We may point out here quite close agreement of the two cross sections.

4. Discussion and Conclusion

Results of our numerical experiments show that the extended limited area model is capable of generating the Red Sea Trough systems after 24 h of integration given appropriate zonally homogeneous initial data. This result is in support of the suggestion that the terrain blocking in the area of the Red Sea is the primary factor in the RST development. Other factors playing significant roles in the process are the characteristics of the atmospheric flow and, first of all, the intensity of the atmospheric flows – tropospheric

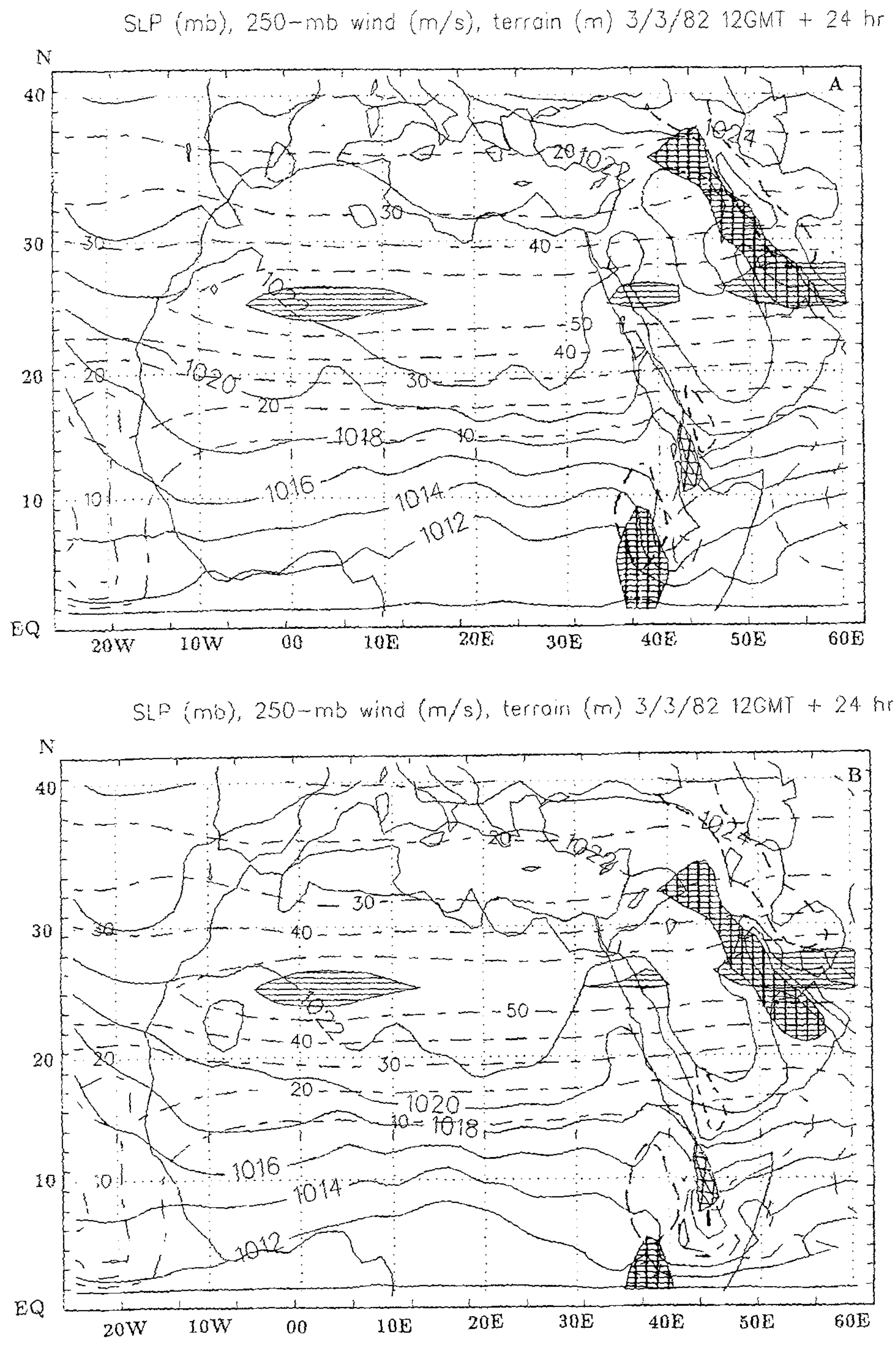

Fig. 4. Same as for Fig. 3, but for the simulations of the group II. (a) – IIa (5° southward shift), (b) – IIb (same – 10° southward shift), (c) – IIc – northward 5° shift of terrain). Locations of the areas with topography exceeding 1300 m are indicated by shading. Locations of these areas on the original terrain field are indicated by dotted lines

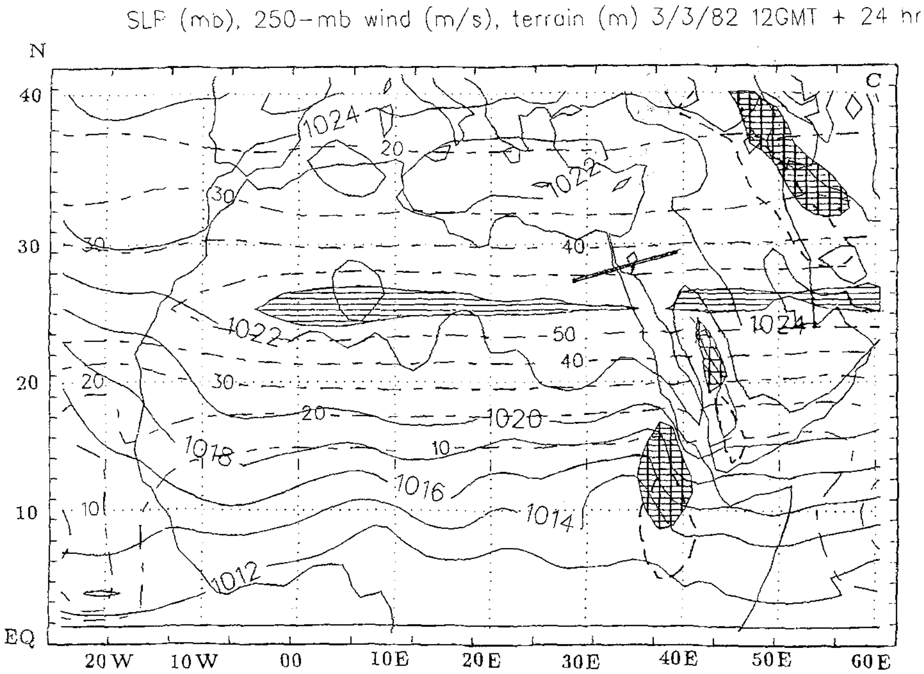

Fig. 4. (*Continued*)

westerly flow of the subtropics and the tropical easterlies.

It appears that the intra-seasonal displacement of the southern border of the STJ-related mid-tropospheric westerlies and, of course, of the northern border of the equatorial easterlies play important roles in development of the RST. So, according to the experiments, the northward propagation of the area with comparatively weak easterlies causes initiation of the trough to the west of the Sea or positioning over it. Such a situation is quite typical for the winter months.

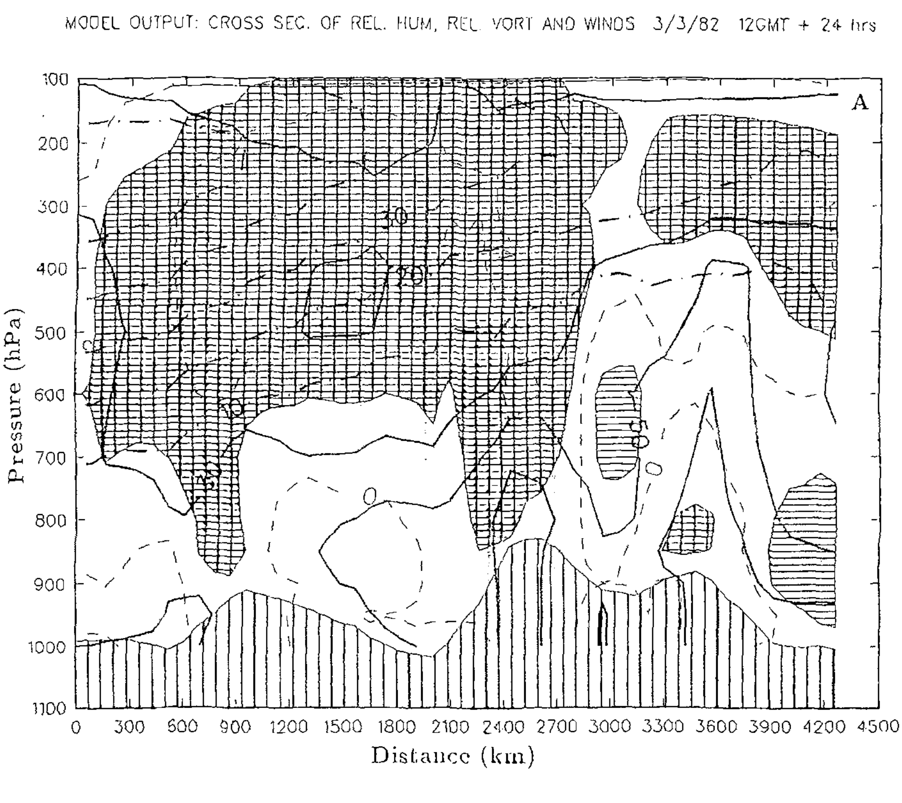

Fig. 5. Cross sections along the heavy solid line perpendicular to the Red Sea basin on Fig. 4c (u-wind component dotted lines, contour interval $10\,ms^{-1}$); relative humidity (full lines, increment 20%); relative vorticity ($10^{-5}s^{-1}$) (dashed lines, contour interval ($1 \times 10^{-5}s^{-1}$)). Fig. 5a – corresponds to results of (Ic) experiment

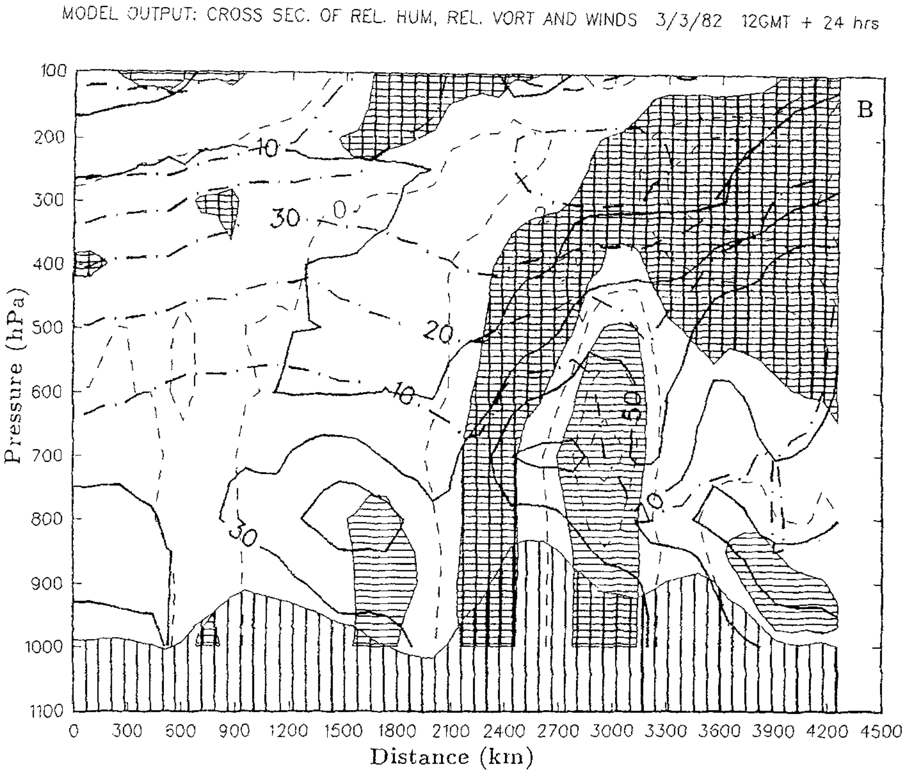

Fig. 5. (*Continued*)

On the contrary, in the experiments with an area of intensive westerlies positioned over the Red Sea development of the trough takes place over the Eastern Mediterranean region or over Arabian Peninsula to the east of Red Sea. Such a situation is also typical but mostly for the transient periods of the cool season.

It is evident that the oversimplified idealistic simulations discussed in this note give only an approximate description of the RST development process. According to the results of the simulations the troughs develop as a result of a lee cyclogenetic process taking place in the area of the Red Sea. The use of the homogeneous initial data sets does not permit investigation of the role of any effects related to other synoptic processes which, no doubt, play an important role in the process. Still it is interesting to note that even the very simplified simulations are capable of describing some of the elements of the real developments in the area.

Acknowledgments

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