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ORIGINAL PAPER

The effect of the Zagros Mountains on the formation and maintenance of the Iran Anticyclone using RegCM4

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Abstract Iran anticyclone is one of the main features of the summer circulation over the Middle East in the middle and upper troposphere. To examine the effect of the Zagros Mountains on the formation and maintenance of the Iran anticyclone, an experiment was conducted by Regional Climate Model (RegCM4) in an area between 22°–44°N and 35°–70°E with a 40 km horizontal grid spacing. The NCEP/NCAR re-analysis data set were used to provide the initial and lateral boundary conditions in a control run and in a simulation run by removing the Zagros Mountains. The result reveals that the Zagros Mountains have an important effect on the formation and maintenance of the low-level cyclonic circulation and mid-level anticyclonic circulation in summer. Examining the diabatic heating shows that the elimination of the Zagros Mountains causes a significant change in the heating values and its spatial distributions over the study area. Comparing the diabatic heating terms, the vertical advection term has the main contribution to the total heating. In the absence of the Zagros Mountains, the vertical advection and the mid-troposphere anticyclonic circulation are apparently weak and, therefore, the Iran subtropical anticyclone vanishes over the west of Iran. The study indicates that the Zagros Mountains as an elevated heat source have the main impact in the formation of a thermally driven circulation over the Middle East.

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1 Introduction

The nature of subtropical anticyclones and their formation mechanism has been one of the most challenging subjects in the atmospheric sciences in recent years. The question of stronger summer subtropical anticyclones compared to their winter counterparts, as well as their complex formation mechanism, has provided the necessary motivation for doing much research.

The traditional view on the formation of subtropical anticyclones states that they are the result of the sinking air in the subsidence arm of the Hadley cell (Schulman 1973; Peixoto and Oort 1992). However, recent studies show that either in the free atmosphere or the planetary boundary layer, descent cannot be considered as a mechanism for the formation of subtropical anticyclone (Wu et al. 2004). Many researchers have found that thermal adaptation of the atmosphere to external thermal forcing and potential vorticity forcing is important in the formation of the subtropical anticyclone in the three-dimensional domain. In this view, atmospheric thermal adaptation to the external thermal forcing such as surface sensible heating, latent heating, deep convective condensation heating, and long wave radiative cooling have important roles in the formation of subtropical anticyclones (Liu and Wu 2004).

The result of studies revealed that while lower level subtropical anticyclones strengthen because of the long-wave radiative cooling over the eastern oceans (Hoskins 1996; Rodwell and Hoskins 1996, 2001), the release of latent heat within the monsoon circulation system plays a very important role in the formation of upper level subtropical anticyclones (Chen et al. 2001; Liu et al. 2004). Also, many studies emphasized the role of sensible heating over the high mountains as the elevated heat sources on the formation of middle-level and upper-level anticyclones (Yeh 1982; Liu et al. 2004).

In the review of the progress achieved in the study of summertime subtropical anticyclones, Liu and Wu (2004) showed that the formation of the strong anticyclone of south Asia in the upper troposphere and subtropical anticyclone of the west Pacific Ocean in the middle and lower troposphere is the result of the convective latent heating due to the Asian monsoon circulation, which is affected by high mountains and sensible heating over the surface.

Many studies emphasized the role of high mountains in the formation of summer subtropical anticyclones. Employing pentad averages from 1980 to 1994, Zhang et al. (2002) examined South Asian High activities at 100 hPa during boreal summer. Their result emphasized the relation between the formation of summertime subtropical anticyclones and high mountains as the elevated heat sources. They pointed out bimodality in South Asian High activities; namely the Tibetan mode and the Iranian mode. They concluded that the formation of the Tibetan mode is associated with diabatic heating over the Tibetan Plateau and the Iranian mode is associated with the adiabatic heating in the free atmosphere, as well as diabatic heating over the Iranian plateau. Examining the seasonal variation of the South Asian High, Qian et al. (2002) supported the conclusions reached by Zhang et al. (2002) and estimated the location of the South Asian High in relation to maximum seasonal heating. From the analysis of the temporal and spatial variations of South Asian High, they found that its center always moves toward the relatively large-valued areas of the heating rates and thus has a heat preference. Also, Duan and Wu (2005) proposed that the ascending motion over eastern Asia and the descending over its west induced by continental heating are at least partly overlapped with those induced by large-scale orographic thermal forcing. They concluded that the Tibetan Plateau and Iranian Plateau reinforce the East Asian monsoon rainfall to their east and enhance the dry and hot climate in central and western Asia to their west. Employing a regional climate model, Zaitchik et al. (2007) examined the regional impact of the Zagros Mountains in numerical experiments. They proposed that the heat driven circulation from the Zagros Mountains has a significant impact on the climate of the Middle East Plain, especially in mid-summer when heating on the Zagros Mountains is greatest. They concluded that the observed pattern of vertical motion in the Middle East is the combined product of Zagros-induced subsidence and hemispheric-scale circulation. Similar result was found by Wu et al. (2007) when they were investigating the induced mechanical and thermal forcing of the Tibetan Plateau. They showed that while rising air predominates over the central and eastern parts of both the Tibetan and Iranian Plateaus, sinking air is observed over their west. More recently, Zarrin et al. (2010) investigated the spatial and temporal variations of subtropical anticyclones at lower, middle and upper troposphere over Africa and Asia. They showed that the geographical location of the anticyclone centers is located over the mountainous regions of northwestern Africa, the Arabian Peninsula, and the Iranian Plateau at mid-troposphere. They also found in their vast study domain (60°W–120°E and 0°–45°N) that only the Iranian Plateau is a preferable location for anticyclone centers in both the middle and the upper troposphere. In this area, the center of the anticyclone is located over the west of Iran during June–August and it is called the Iran Anticyclone (Zarrin et al. 2010). Unlike in the extensive studies on the characteristics of South Asian High, the nature and formation mechanism of Iran anticyclone is unknown yet. On this basis, the goal of this paper is to clarify the role of the Zagros Mountains in the formation and maintenance of the Iran anticyclone.

2 Materials and methods

2.1 The regional climate model

The climate model which we used in this research is RegCM4. It is based on the model of Giorgi et al. (1993a, b) with successful upgrades as described in Pal et al. (2007). It is a hydrostatic, compressible model with terrain following sigma vertical coordinate system and the Arakawa-B horizontal grid in which the velocity variables are staggered with respect to the scalar variables.

2.2 Experimental design

The model domain was confined to an area between 22°–44°N and 35°–70°E with a 40 km horizontal grid spacing (Fig. 1). As seen in Fig. 1a, the main topographical feature of the area is the Zagros Mountains. NCEP reanalysis data (Kalnay et al. 1996) were used to provide the initial and lateral boundary conditions for the RegCM4 simulation with the method described by Giorgi et al. (1993b).

In the control experiment mean orography from NCEP re-analysis data set was used. Results from May to

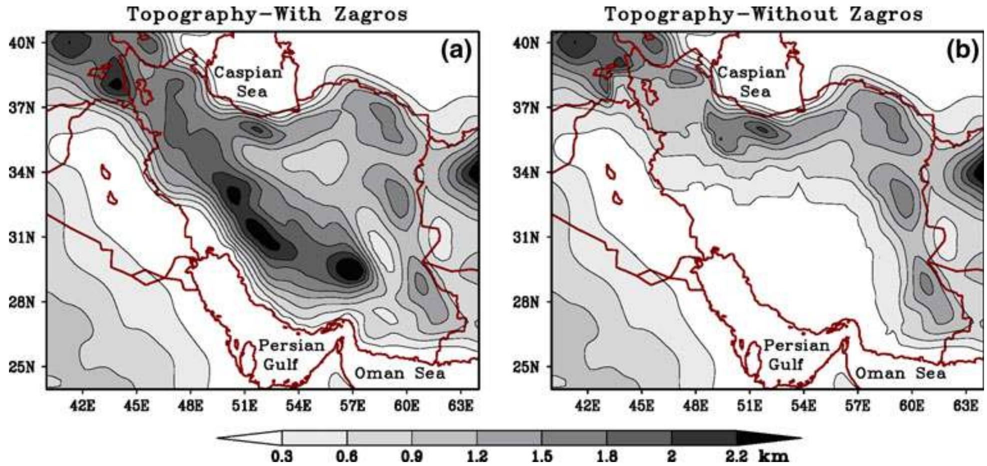

Fig. 1 Topography in the RegCM model. **a** control run, **b** experiment run

September are discussed in the present study. To examine the role of the Zagros Mountains in the formation and maintenance of the Iran anticyclone, an experiment was conducted by removing the Zagros orography (Fig. 1b).

We chose two years, 1990 and 1998, as a normal and abnormal year for running the model. Considering the strength and central cell location of the Iran anticyclone in a 30-year period (1971–2000), the year 1990 was chosen as a normal year and 1998 as an abnormal year for modeling (Zarrin 2008). In 1990, the center of the Iran anticyclone was located over the Zagros Mountains and the geopotential height was approximately normal (Fig. 2a, b). In 1998, mostly the central isobar was located over the Arabian Peninsula far from the Zagros Mountains area and the geopotential height anomaly was high (Fig. 2c, d).

The model was run for the period of May–September to ensure coverage of the warm period of the year. The model was run twice, once as a control and once as an experimental variation. In the experimental run, the Zagros Mountains were omitted from the topographic data (Fig. 1b).

For understanding the thermal forcing of the Zagros Mountains, the diabatic heating was exerted as a residual of thermodynamic equation (1).

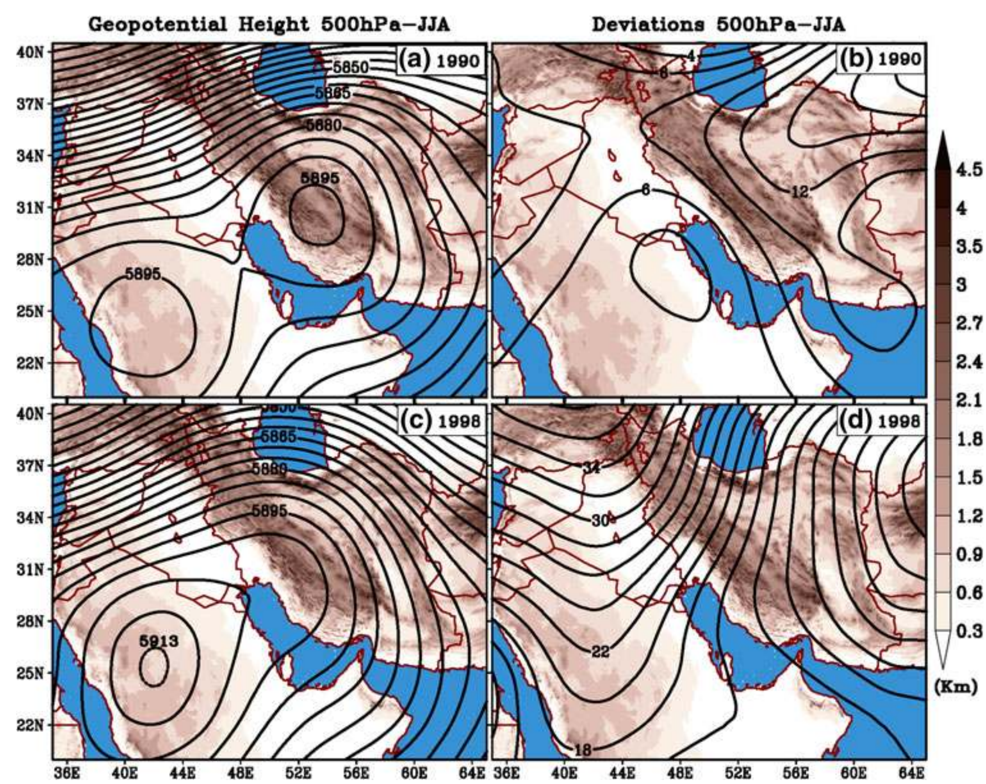

Fig. 2 The average summer (JJA) geopotential height for 1990 (**a**) and 1998 (**c**), respectively. **b** and **d** are anomaly of average summer geopotential height

$$Q = c_p \left(\frac{p}{p_0}\right)^k \left(\frac{\partial \theta}{\partial t} + \vec{V}.\nabla\theta - \omega\frac{\partial \theta}{\partial p}\right), \quad (1)$$

where θ is the potential temperature, V is the horizontal velocity, ω is the vertical p-velocity, and p is the pressure. In the equation, $k = R/C_p$ where R, and C_p are, respectively, the gas constant and the specific heat at constant pressure of dry air, $P_0 = 1{,}000$ hPa and ∇ is the isobaric gradient operator. The local temporal derivative, horizontal advection and vertical advection were compared in the control and experimental runs to investigate the role of the Zagros Mountains as the heat source of the area.

3 Results

3.1 Sensible heating

The increase in sensible heating values over the land during summer, especially to the west of the continents, is a key factor in the formation of subtropical anticyclones over the subtropical continents. Increasing sensible heat elevates the positive total heating over the continent, and the positive total heating is accompanied by surface cyclones and upper layer anticyclones. This can be well understood by using the potential vorticity–potential temperature view, as proposed by Hoskins (1991). On the other hand, high elevated lands over the continents are the preferable location of the maximum sensible heat fluxes.

Figure 3 shows the long-term sensible heat fluxes for April–September. The main location of the maximum sensible heat flux in April is located over the southeastern Iranian Plateau (Fig. 3a).

The maximum sensible heat value of 150 W m^{-2} is seen over the south of Pakistan. With increasing solar heating, the sensible heating flux abruptly increases over the southern part of the Zagros Mountains in May (Fig. 3b). Such an increase of sensible heat over the southwestern Iranian Plateau, compared to its eastern part, indicates the role of elevation in increasing the heat values. Investigating the amount of sensible heat fluxes in summer months emphasizes the role of elevation in the distribution of sensible heat pattern. As we can see, there are three preferable locations of the maximum sensible heat fluxes: the high elevation of the Alborz Range in the north of the Iranian Plateau, Azerbaijan Mountains in northwestern Iran and the Zagros Mountains with a northwest–southeast direction to the west of the Iranian Plateau. The greatest sensible heat flux values occur over the Zagros Mountains in June and July (Fig. 3c, d).

3.2 The thermodynamic equation diagnosis

To further examine the thermal characteristics of the Iran subtropical anticyclone and the effect of the Zagros Mountains on the formation and enforcing of the Iran subtropical anticyclone, the terms of the thermodynamic equation (1) were calculated for the control and simulation runs. Figure 4a shows the summer (JJA) local temporal derivative [term 1 of Eq. (1)] in 1990 at 700 hPa. It is found that obvious warming occurs over the Zagros Mountains at this level. Over the Zagros Mountains, the contours are correlated with the topography. After the Zagros Mountains were removed in the simulation run, the values decreased and did not follow the Zagros topography (Fig. 4b).

Figure 4c and d indicates the summer horizontal advection [term 2 of Eq. (1)] in 1990 at 700 hPa for control and simulation runs, respectively. The maximum horizontal advection values occur over the Zagros Mountains and are coincided with the topography, like the local temporal derivative values (Fig. 4c). It indicates a strong cooling due to ascent over the Zagros Mountains. Removing the Zagros Mountains in the simulation caused the maximum values to disappear over the area (Fig. 4d).

The vertical advection term of the thermodynamic equation [term 2 of Eq. (1)] is shown in Fig. 4e, f for control and simulation runs. Similar to the previous terms, the maximum negative values at 700 hPa are seen over the Zagros Mountains in the control run. In fact, the thermal vertical advection from the Zagros Mountains follows a convergence and cyclonic circulation in lower troposphere and anticyclonic circulation in mid-troposphere. Such a thermally driven circulation finally forms and maintains a mid-troposheric anticyclone over the west of Iran. There is no significant pattern in the distribution of values after removing the Zagros Mountains (Fig. 4f). As we will see later, the vertical velocity values changed when we removed the Zagros Mountains from the model's topography data. This may explain why the model could not simulate the third term very well in the simulation run. The diabatic heating is much affected by the third term, and it is not unexpected that the figures of diabatic heating term (Fig. 4g, h) are similar to the vertical heating term.

In summary, it was shown that the Iran subtropical anticyclone tended to stay over the warm air column. Such a warming is mainly due to the sensible heating in the lower troposphere and the adiabatic heating associated with descent in the middle troposphere. The result is similar to the result of Zhang et al. (2002). They argued that the maintenance of the anticyclone over Iran in the South Asian anticyclonic circulation system mostly depends on ascending motion over Iranian Plateau in the lower troposphere (Zhang et al. 2002, p. 736).

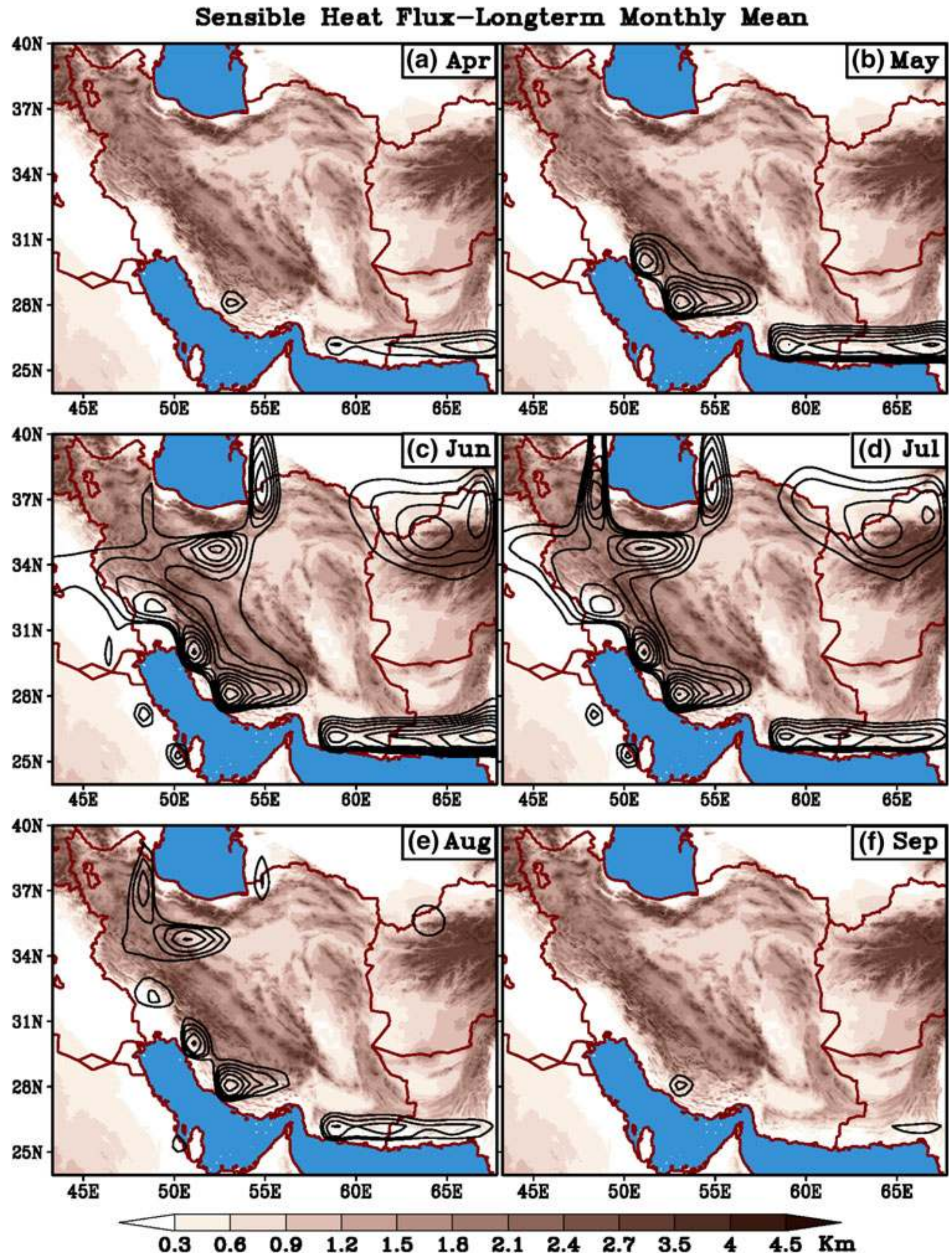

Fig. 3 Long-term monthly mean sensible heat flux (W m^{-2}) from April to September. The values smaller than 140 W m^{-2} are not shown in the figures

3.3 Vertical velocity

Vertical velocity is the other important parameter that we used to examine the effect of removing the Zagros Mountains on the formation of the Iran subtropical anticyclone. Figures 5 and 6 show the mean summer vertical velocity cross-section in control and simulation runs for 1990 and 1998 along 32.5°N.

In the control run, an upward motion is seen along 48°–58°E, where the Zagros Mountains exits (Fig. 5a). The upward motion is drawn to the upper troposphere along 49°–51°N, where the Zagros topography is more elevated.

By removing the Zagros Mountains, the negative values of vertical velocity are substituted by the positive values. This means that all the upward motion along Zagros Mountains changes to downward motion (Fig. 5a, b). In year 1998, the Iran subtropical anticyclone is stronger but as we saw earlier (Fig. 2c), the location of the anticyclone cell is formed far from the Zagros Mountains over the Saudi Arabian Peninsula. The strong upward motion

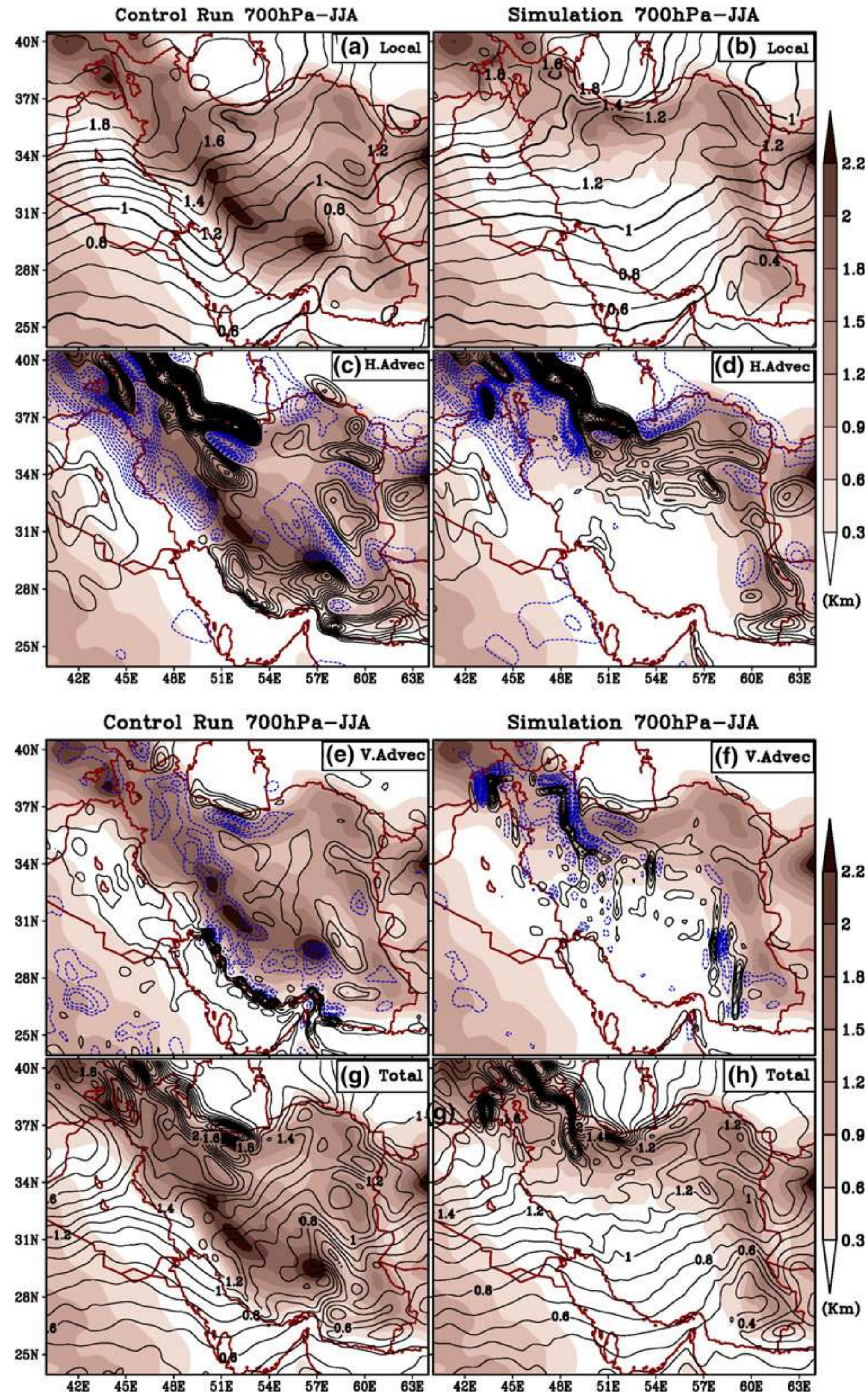

Fig. 4 Summer-mean distributions of different kinds of diabatic heating in 1990 at 700 hPa. **a**, **c**, **e** and **g** control, **b**, **d**, **f** and **h** simulation

(negative vertical velocity values) is seen over the western Zagros (Fig. 6a). Similar to 1990, the upward motion over the Zagros Mountains is changed to a downward motion by removing Zagros Mountains (Fig. 6b).

3.4 Relative vorticity

Relative vorticity is another parameter for investigating the effect of Zagros Mountains on the formation of the Iran

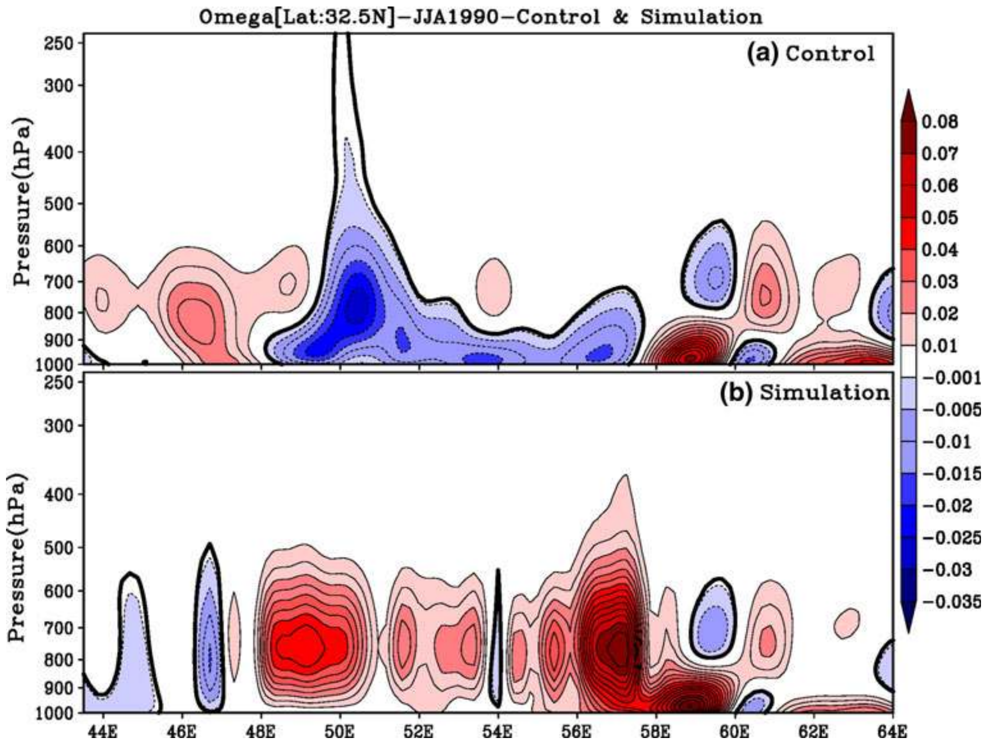

Fig. 5 Mean vertical velocity cross-section (Pa s^{-1}) along 32.5°N for summer (JJA) 1990. **a** Control run. **b** Simulation run

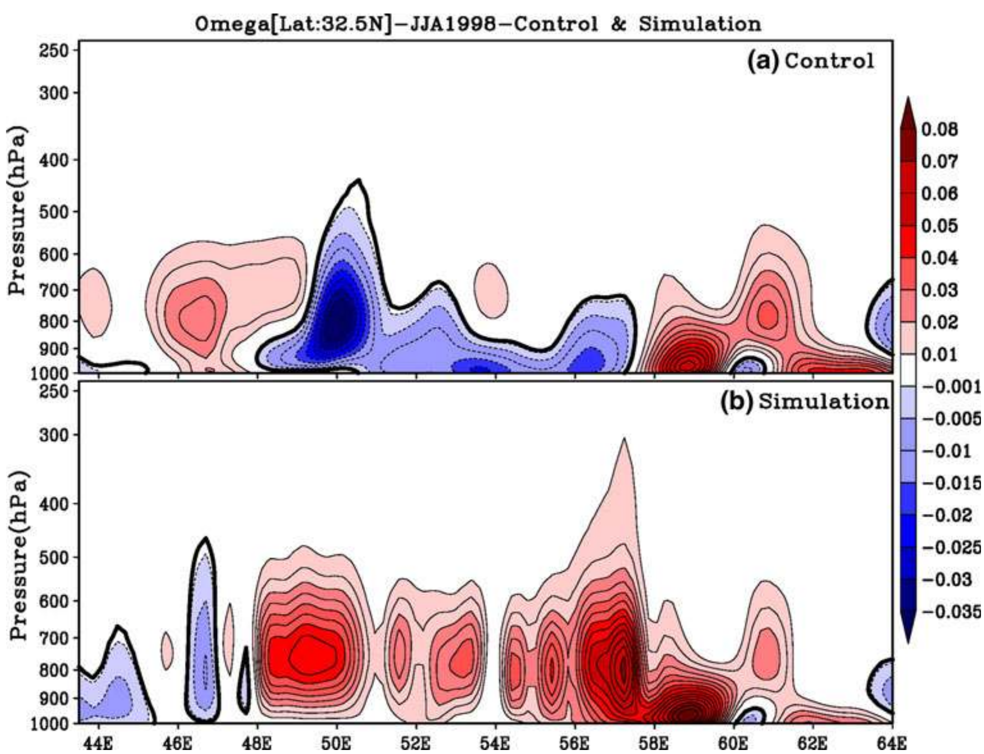

Fig. 6 Mean vertical velocity cross-section (Pa s^{-1}) along 32.5°N for summer (JJA) 1998. **a** Control run. **b** Simulation run

subtropical anticyclone. To understand the effect of Zagros Mountains on the formation of the Iran subtropical anticyclone, the cross-sections of relative vorticity are examined in the control and simulation runs for 1990 and 1998.

Examining the relative vorticity values along 32.5°N, it is seen that there is a strong anticyclone between 700 and 500 hPa along 49°–51°E. The maximum values of negative vorticity exceed -4 and $-5\ s^{-1}$ in 1990 and 1998, respectively (Figs. 7a, 8a). In contrast, positive vorticity

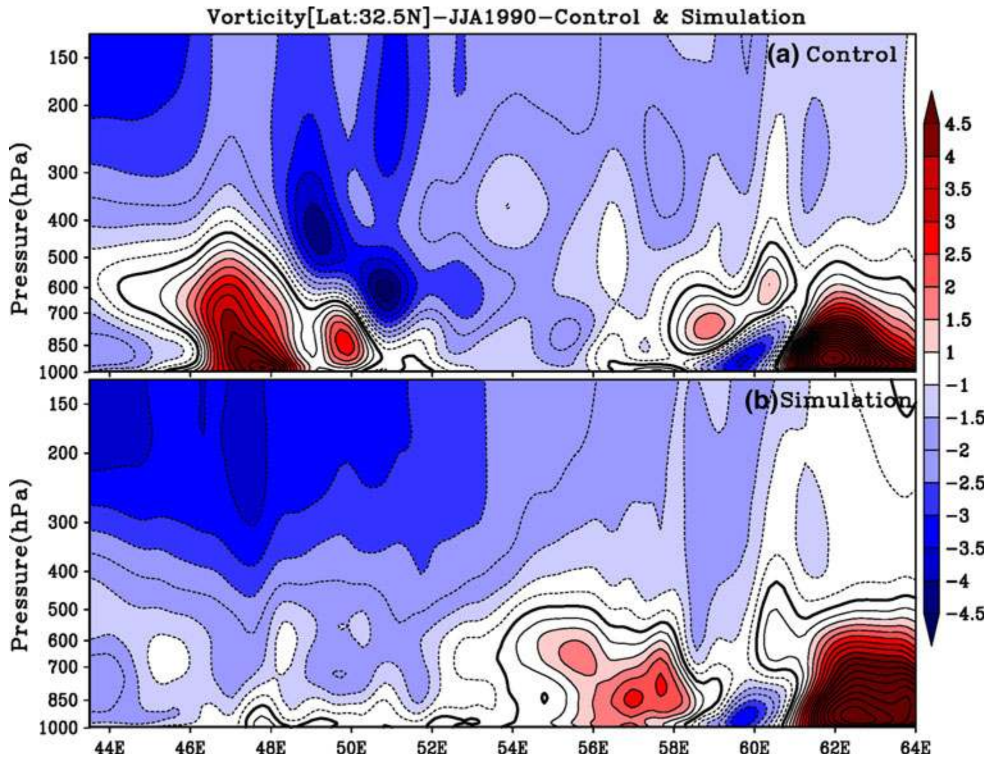

Fig. 7 Mean relative vorticity cross-section (10^{-5} s^{-1}) along 32.5°N for summer (JJA) 1990. **a** Control run. **b** Simulation run

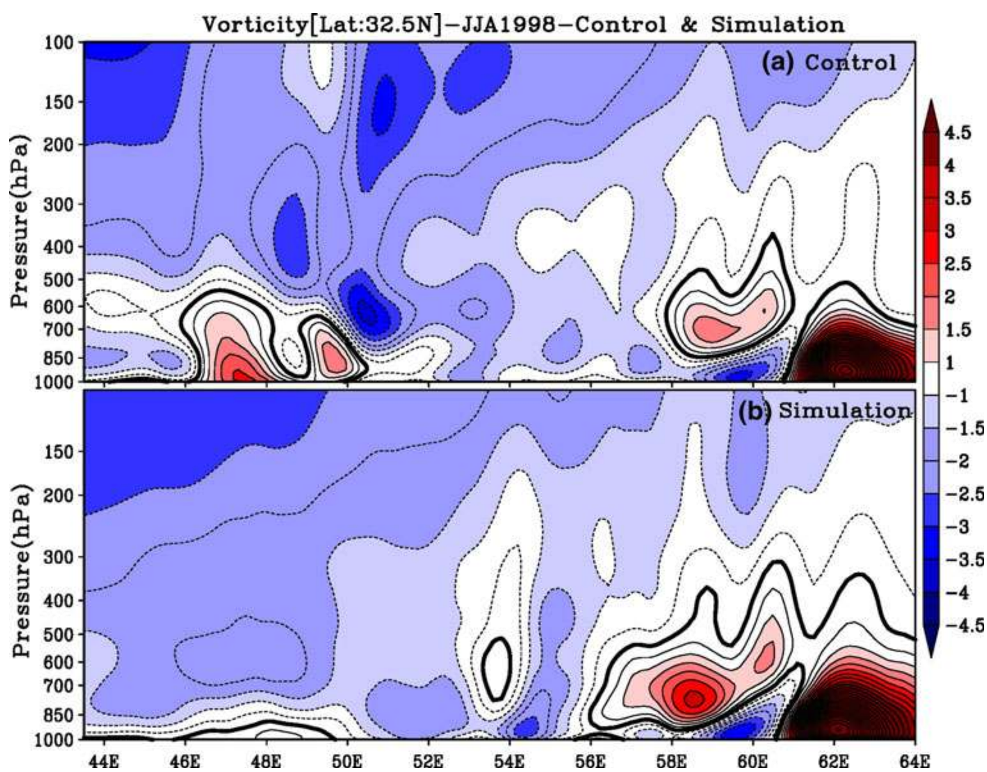

Fig. 8 Mean relative vorticity cross-section (10^{-5} s^{-1}) along 32.5°N for summer (JJA) 1998. **a** Control run. **b** Simulation run

values are increasing below the 500 hPa level along 46°–49°E and cyclonic circulation overcomes the whole region. It is worthwhile to mention that there is also an increase in the negative vorticity values between 200 and 100 hPa (Figs. 7a, 8a). After removing the Zagros Mountains in the simulation runs, the anticyclonic circulation center of the middle troposphere is considerably weakened in both 1990 and 1998. Moreover, the anticyclonic circulation in the

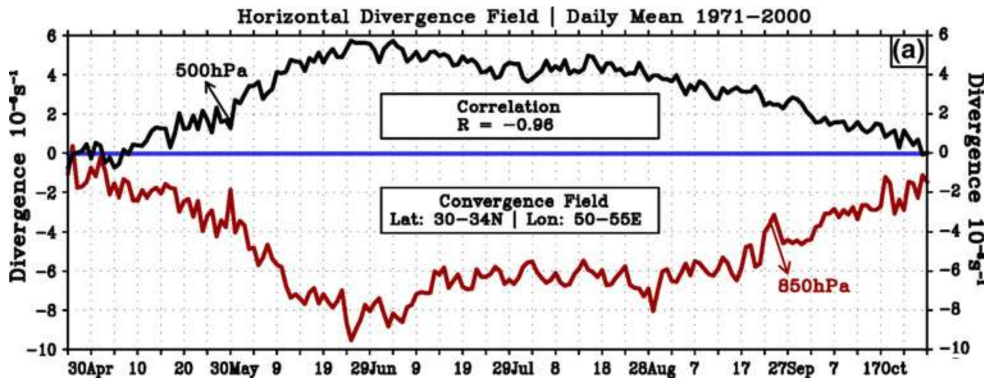

Fig. 9 Long-term daily mean (1971–2000) horizontal divergence field at the Zagros convergence center (850 hPa), and over Iran anticyclone (500 hPa)

upper troposphere is weakened along 50°–52°E. Interestingly, by removing the Zagros Mountains, the cyclonic circulation to the west of Zagros is also substituted by an anticyclonic circulation (Figs. 7b, 8b).

4 Conclusions

Mountains play an important role on the climate system through dynamical and thermo-dynamical effects. In this paper, we have addressed the thermo-dynamical effects of the Zagros Mountain on the formation of a regional-scale mid-tropospheric anticyclone over southwest Asia.

There is a coordination between total heating and the circulation pattern as proposed by Hoskins (1991). Using the potential vorticity–potential temperature (PV–θ) view, Hoskins showed that heating generates lower-layer cyclonic circulation and upper-layer anticyclonic circulation. In the summer subtropics over the western and central parts of each continent, the positive column-integrated total diabatic heating mainly result from the in situ sensible heating (Liu et al. 2004). Hence, over continents the centers of either the surface cyclones or the upper-layer anticyclones are located over the sensible heating areas. All of these facts imply the significance of the continental sensible heating in the maintenance of the summertime subtropical circulations. On the other hand, the maximum of sensible heating coincides with the location of the high mountains. Therefore, the thermally driven circulation from the high mountains has a significant impact on the formation and maintenance of subtropical anticyclone during boreal summer.

During summer, a subtropical anticyclone namely, the Iran anticyclone forms over the Iranian Plateau in the middle and upper troposphere. The center of the Iran anticyclone is located over the Zagros Mountains. This study, which is based on a regional climate modeling, investigates the effect of the Zagros Mountains on the structure of the Iran subtropical anticyclone.

The results indicate that the summer atmospheric circulation pattern over the Middle East is strongly affected by thermal forcing of high mountain ranges. The present study reveals that the Zagros Mountains have an important effect in the formation and maintenance of the low-level cyclonic circulation and mid-level anticyclonic circulation in summer.

The divergence variability over the Iran anticyclone center is completely following the surface convergence variation over the Zagros Mountain during summer (Fig. 9). The correlation between Iran anticyclone center at 500 hPa and the Zagros convergence center at 850 hPa reaches to −0.96. Hence, the surface physical forcing of the Zagros Mountain is a key factor in the formation of the Iran anticyclone in the middle levels.

Examining the diabatic heating shows that the elimination of the Zagros Mountains causes a significant change in the heating values and its spatial distributions over the study area. Comparing the diabatic heating terms, the vertical advection has the main contribution to the total heating. In the absence of the Zagros Mountains, the vertical advection and the mid-troposphere anticyclonic circulation are apparently weak and, therefore, the Iran subtropical anticyclone vanishes over the west of Iran.

Removing the Zagros Mountains, the upward motion over the Mountains changes to downward motion. The negative vertical velocity is substituted by positive value and positive relative vorticity is substituted by negative values in the lower levels. Moreover, the negative values of relative vorticity dramatically decreased in the middle and upper levels. Therefore, the Iran anticyclone vanishes upon removing the Zagros Mountains in both middle and upper troposphere.

The mentioned points indicate that the Zagros Mountains as an elevated heat source have the main impact in the formation of a thermally driven circulation over the Southwest Asia. Our finding confirms the previous results that emphasize the role of the thermal forcing of high mountains on the formation and maintenance of subtropical anticyclones over Asia during the boreal summer (e.g. Hahn and Manabe 1975; Yeh 1982; Liu and Yin 2002; Zhang et al. 2002; Zaitchik et al. 2007; Wu et al. 2007).

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