# Regional Impact of an Elevated Heat Source: The Zagros Plateau of Iran

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ABSTRACT

The authors propose that a heat-driven circulation from the Zagros Plateau has a significant impact on the climate of the Middle East Plain (MEP), especially summertime winds, air temperature, and aridity. This proposal is examined in numerical experiments with a regional climate model. Simulations in which the Zagros Plateau was assigned a highly reflective, "snowlike" albedo neutralized the heat-driven circulation and produced an extra summertime warming of 1°–2°C in the MEP, measured relative to a control simulation and to the records of the NCEP–NCAR reanalysis project. This effect was largest in midsummer, when heating on the plateau was greatest. Additionally, simulations with high albedo on the Zagros showed reduced subsidence and enhanced precipitation in the MEP. These sensitivities are interesting because the Zagros Plateau lies downwind of the MEP. Analysis of model results indicates that the sensitivity of the upwind subsidence region to Zagros albedo can be understood as a linear atmospheric response to plateau heating, communicated upwind by a steady heat-driven circulation that influences the thermodynamic balance of the atmosphere. This regional phenomenon adds to the large-scale subsidence patterns established by the Hadley circulation and the Asian monsoon. Observed patterns of vertical motion in the Middle East, then, are a combined product of Zagros-induced subsidence and hemispheric-scale circulations.

## 1. Introduction

The Middle East (Fig. 1) is a region of complex geography located at the intersection of large-scale atmospheric circulations. The region contains several large water bodies and significant topography, including the Caucasus Mountains in the north, the Taurus Mountains of Turkey, and the Zagros Plateau in Iran. Intersecting atmospheric circulations include midlatitude cyclones moving eastward from Europe, the *Azores subtropical high* over the Eastern Mediterranean, and the *Persian trough* low pressure system associated with the Southwest Asian monsoon (Bitan and Saaroni 1992). Remote atmospheric phenomena, including the Asian monsoon, Hadley cell circulation, and, perhaps, the African monsoon, are thought to exert an influence on the region as well (Ziv et al. 2004).

Precipitation is greatest in the northern portions of the Middle East, with additional precipitation maxima located along the Mediterranean coast and on the western slopes of the Zagros Plateau (Fig. 2). There is a steep north-to-south precipitation gradient between Turkey and Saudi Arabia, with mean annual precipitation in excess of 1000 mm in the north and less than 100 mm in the south. A land-use transition is associated with this gradient, as rain-fed agriculture is viable in eastern Turkey and portions of northern Syria and Iraq (the historic "Fertile Crescent"), while areas to the south can only be used as seasonal rangelands. The precipitation gradient and land-use transition run across the Middle East Plain (MEP), a broad, low-lying area bounded by the Turkish mountains to the north and the Arabian deserts to the south (Fig. 1).

The precipitation signature of the region is also strongly seasonal. The majority of precipitation falls in winter and early spring (Fig. 2, inset) in the form of snow in the north and rain in the south. Significant precipitation events are almost always dynamically linked to midlatitude storm systems (Eshel and Farrell 2000), though there is evidence that a southerly water vapor flux is an important component of the largest precipitation events (Evans and Smith 2006). In summertime the midlatitude storm track shifts northward and few storm systems penetrate into the Middle East. As a result, large-scale precipitation is limited throughout the region.

Interestingly, convective precipitation is also ex-

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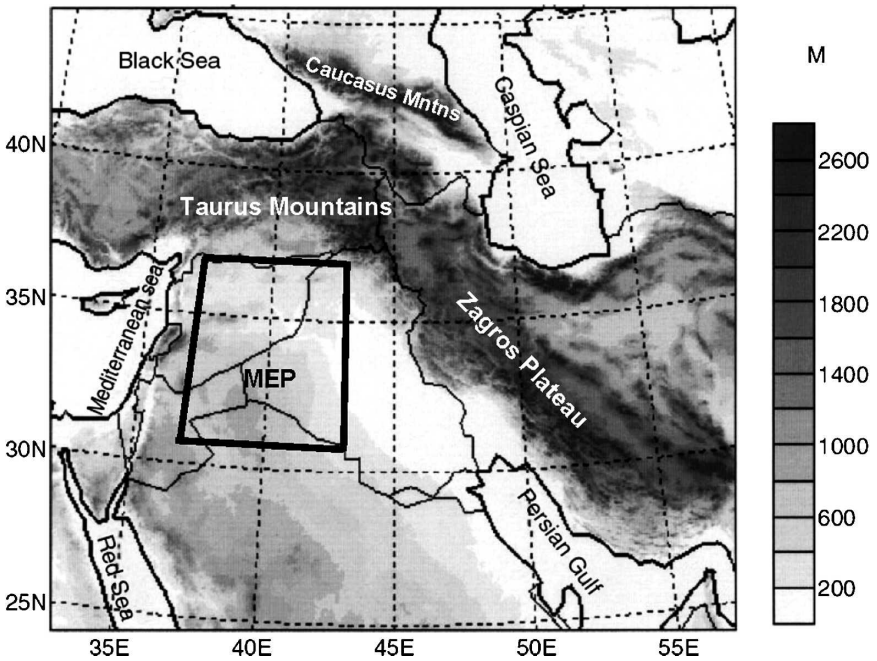


FIG. 1. Geography of the Middle East, indicating the location of the Middle East Plain (MEP box).

tremely limited in summer (Saaroni and Ziv 2000). This would not necessarily be expected in a region with highly evaporative water bodies, active sea breeze circulations, and large surface energy fluxes, and it suggests that there is a dynamic control on convection. This paper tests the hypothesis that topographic contrasts within the region act to suppress convection. Specifically, it is proposed that summertime heating on the Zagros Plateau leads to a seasonally persistent temperature contrast between the atmosphere above the

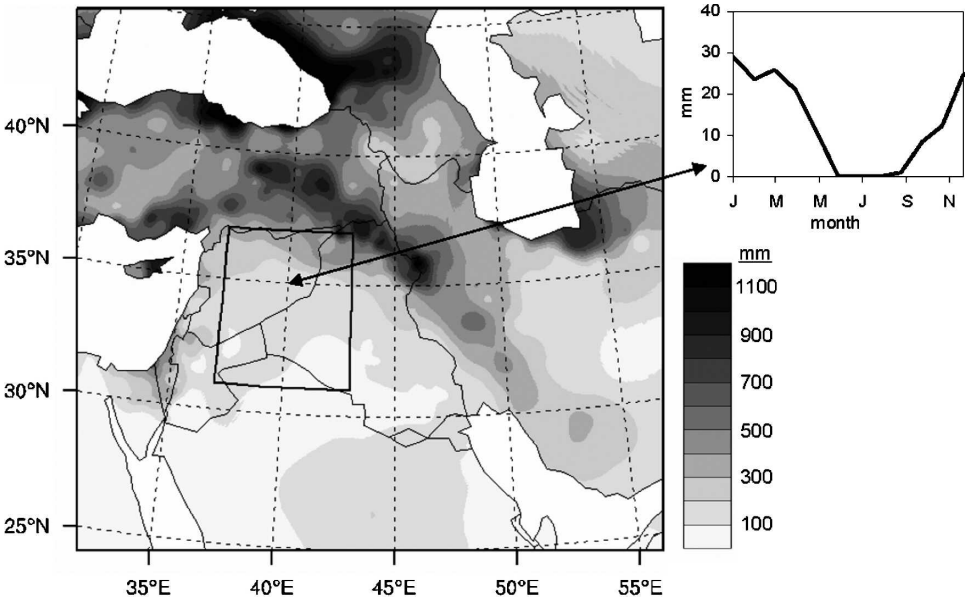


FIG. 2. Mean annual precipitation for the Middle East, interpolated from the Food and Agriculture Organization meteorological station records (1940–73). Inset shows the seasonal cycle of precipitation at 35°N, 45°E.

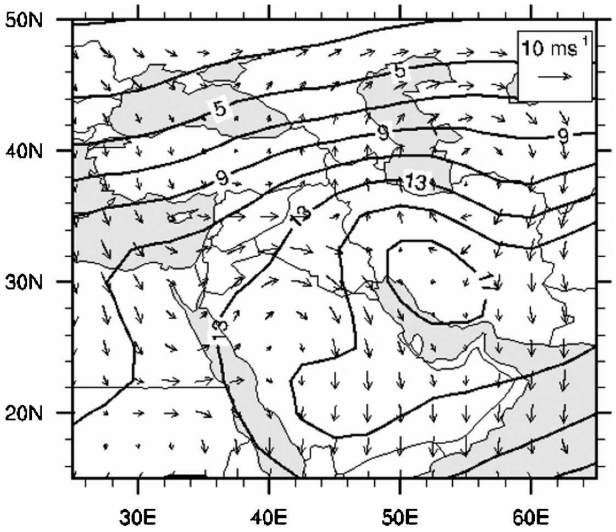


FIG. 3. Air temperature (°C) and winds (m s$^{-1}$) at 700 hPa: climatological mean for the month of July based on the NCEP–NCAR reanalysis (Kalnay et al. 1996).

plateau and that above the neighboring MEP. The temperature contrast, in turn, influences winds and subsidence patterns throughout the region. This hypothesis is motivated in part by earlier modeling studies of the region, which have indicated that diurnal heating on the Zagros Plateau drives a substantial plain–plateau circulation that influences weather and the transport of atmospheric contaminants in Mesopotamia (Shi et al. 2004; Warner and Sheu 2000). Building on these studies, we attempt to isolate the atmospheric impacts of the Zagros as an elevated heat source by performing sensitivity studies with a regional climate model. These impacts are analyzed over year-long simulations in order to assess their role in climate, and the geographic focus includes the entire region as far west as the Mediterranean Sea. Also, in contrast with earlier studies, we concentrate on the warm season (April–October). This season is often neglected due to its aridity and the apparent persistence of weather patterns. From the perspective of Zagros-induced circulations, however, these warm months are expected to be of particular interest. Surface heating on the plateau is at a maximum during this season, when elevated air temperatures over the Zagros Plateau extend to a height greater than 500 hPa (Fig. 3). This substantial warm air mass is persistent over the summer months and it represents the most coherent temperature feature in the midtroposphere of this region.

Of course, any hypothesis regarding locally induced dynamics must be nested in an understanding of the large-scale atmospheric circulations that influence the region. In assessing summertime subsidence in the Middle East, at least two large-scale phenomena warrant consideration. First, the region lies at the northern edge of the Hadley cell subsidence zone, so precipitation might be limited by zonal descent in the midtroposphere. Subsidence in this region is so strong, however, that it cannot be the result of Hadley currents alone. Moreover, the seasonal evolution of subsidence in the Middle East does not follow that of the Hadley circulation. Second, it is possible that subsidence in the Middle East is the product of a dynamic link with monsoon regions in Asia and Africa. Rodwell and Hoskins (1996) proposed a plausible mechanism by which condensational heating in Asia may contribute to subsidence in the Middle East, while Ziv et al. (2004) present evidence of a closed circulation that links rising motion in Asia and Africa to descending motion over the Middle East. These studies of monsoon dynamics are complementary to the hypothesis of Zagros-induced subsidence in that both invoke a thermally direct circulation that is enhanced by topography. The circulations operate on different scales, and it is expected that topographic features like the Zagros Plateau contribute regional structure to the broad patterns of subsidence associated with a remote monsoon forcing (Rodwell and Hoskins 1996).

The potential to distinguish between local and remote drivers of subsidence is evident in the mean pressure velocity fields of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis project (NNRP: Kalnay et al. 1996). At 700 hPa, the signal of local heating is clearly evident in patterns of rising motion over the Zagros Plateau and Saudi Arabian Desert, as well as on the slopes of the Tibetan Plateau and over the Hindu Kush of Pakistan and Afghanistan (Fig. 4a). Each of these regions of ascent has a neighboring zone of subsidence, most notably the Kara Kum Desert of Turkmenistan and the Tigris–Euphrates Basin of the Middle East. These patterns are strong and coherent throughout the summer and early fall, but they are of limited vertical extent. At 300 hPa (Fig. 4b), a "three-point" structure is evident in the pressure velocity field with strong rising motion in the Asian monsoon region and descending air over Central Asia and the Eastern Mediterranean. This pattern is consistent with the hypothesis that large-scale subsidence is a dynamic response to monsoon heating (Rodwell and Hoskins 1996), though it could also be interpreted as zonal, Hadley cell subsidence that is merely interrupted by a monsoon circulation over the eastern Indian Ocean. There is no resolved influence of the Zagros

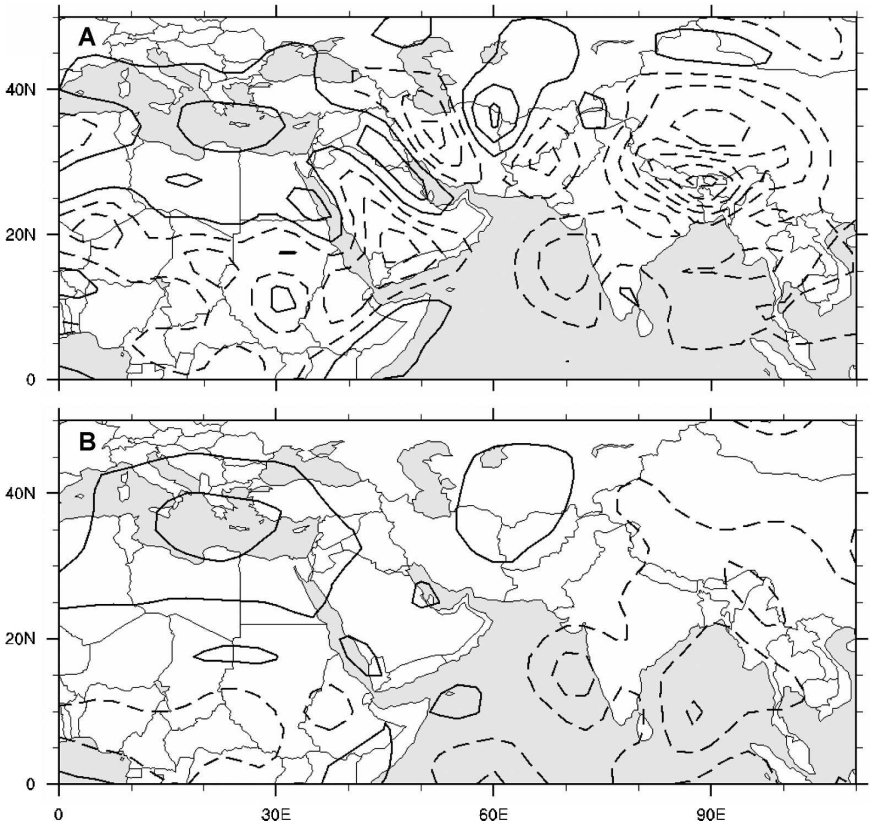


FIG. 4. Pressure velocity (Pa $s^{-1}$) at (a) 700 hPa and (b) 300 hPa: climatological means for the month of July based on the NCEP–NCAR reanalysis (Kalnay et al. 1996). Contour interval is 0.05, centered on zero, with negative contours dashed.

Plateau at this altitude. Remote drivers of vertical motion, then, are most clearly identified in the upper troposphere, while circulations in the lower and middle troposphere appear to respond to local geographic forcings.

In this research the fifth-generation Pennsylvania State University–NCAR (PSU–NCAR) Mesoscale Model (MM5) regional climate model was used to isolate the atmospheric effects of heating on the Zagros Plateau. The model was implemented in a "control" mode designed to produce realistic simulations of the region and in a "mountain snow" mode in which the Zagros Plateau was assigned a bright, "snowlike" albedo that neutralized surface heat fluxes. These numerical experiments are described in section 2. Section 3 summarizes the results of MM5 simulations, with a particular focus on features relevant to climate in the MEP. In section 4 MM5 results are used in conjunction with simple linear and thermodynamic analyses in order to understand the physics underlying the atmospheric response to Zagros heating. Conclusions are offered in section 5.

## 2. MM5 simulations

The PSU–NCAR mesoscale modeling system MM5 is described by Dudhia (1993) and Grell et al. (1994). MM5 is a limited-area nonhydrostatic model that uses a terrain-following vertical coordinate system. It has two-way nesting capabilities and flexible physics options. In this study MM5 was implemented with the Reisner mixed-phase explicit moisture scheme (Reisner et al. 1998), the Medium-Range Forecast (MRF) planetary boundary layer scheme (Hong and Pan 1996), the Rapid Radiative Transfer Model (RRTM) radiation scheme (Mlawer et al. 1997), and the Grell cumulus scheme (Grell et al. 1994).

MM5 is operationally linked with the Noah land surface model (LSM). Noah is a direct descendent of the Oregon State University (OSU) LSM (Mahrt and Pan 1984; Mahrt and Ek 1984; Pan and Mahrt 1987), a sophisticated land surface model that has been extensively validated in both coupled and uncoupled studies (Chen and Mitchell 1999; Chen and Dudhia 2001). The Noah LSM simulates soil moisture, soil temperature,

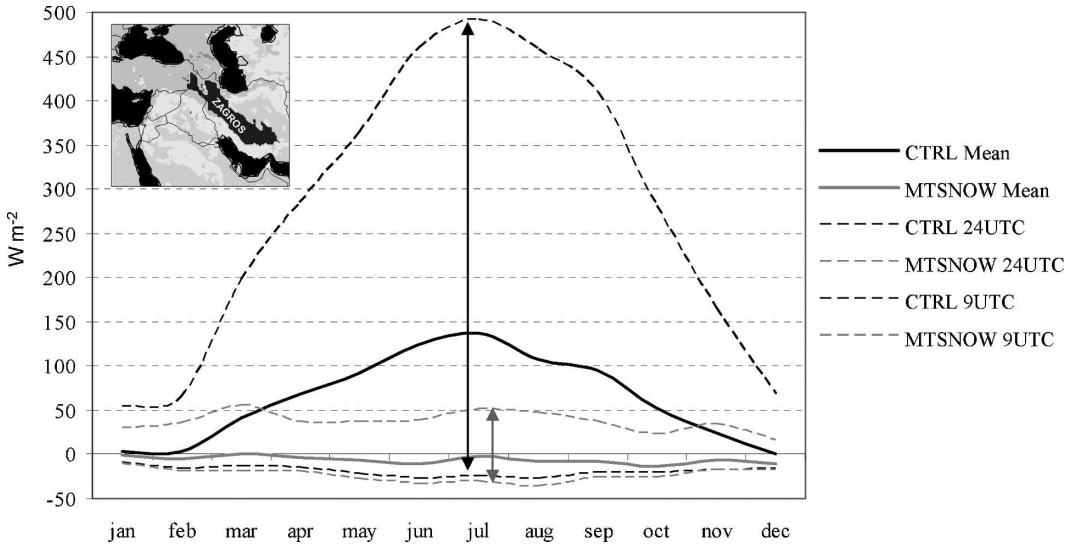


FIG. 5. Annual cycle of surface sensible heat flux on the Zagros Plateau, averaged for MM5 simulations from 1999 and 2003. Solid lines are the mean monthly sensible heat flux for CTRL (black) and MTSNOW (gray). Dashed lines are mean monthly sensible heat flux for 0900 UTC (daily maximum) and 2400 UTC (daily minimum) in each simulation. Arrows indicate diurnal range.

skin temperature, snowpack depth and water equivalent, canopy water content, and the energy flux and water flux terms of the surface energy balance and surface water balance. In its MM5-coupled form Noah has a diurnally dependent Penman potential evaporation (Mahrt and Ek 1984), a four-layer soil model (Mahrt and Pan 1984), a primitive canopy model (Pan and Mahrt 1987), modestly complex canopy resistance (Jacquemin and Noilhan 1990), and a surface runoff scheme (Schaake et al. 1996). Additionally, we have implemented an irrigation scheme that realistically approximates flood irrigation practices of the region (Zaitchik et al. 2005).

In this study we performed four 14-month MM5 simulations. In two control runs (CTRL), we implemented the MM5–Noah coupled system at 27-km resolution for a domain that includes the Middle East and significant surrounding geography (Fig. 1). One simulation was performed for 1 November 1998–31 December 1999 and the other for 1 November 2002–31 December 2003. The years 1999 and 2003 represent contrasting climate conditions, as 1999 was a drought year in the Middle East with weak penetration of midlatitude fronts while 2003 was relatively wet with more frequent precipitation events. The distinction between these climate regimes is not essential for the present study; results from both years are presented simply to demonstrate that heat-driven circulations associated with the Zagros are present under both drought and nondrought conditions. For each simulation the first two months were treated as spinup and results were recorded for the 12 months of the calendar year. Control simulations were paired with "mountain snow" simulations for the same periods (MTSNOW). MTSNOW simulations were identical to CTRL in all respects except that all terrain on the Zagros Plateau above 1500-m elevation was assigned a snowlike albedo of 0.9 for the duration of the simulation. This artificially high albedo neutralized the mountains as a heat source (Fig. 5), providing a theoretical "background state" that would exist in the absence of elevated heating on the Zagros Plateau. Whenever CTRL − MTSNOW difference fields are plotted, the reader can interpret them as the effect of plateau heating on such a background condition. It should be noted that *topography* was not altered in the MTSNOW simulation: the study is designed to examine the role of the Zagros as an elevated heat source, and this can only be accomplished if the aerodynamic influence of the plateau is held constant. Boundary conditions for all simulations were drawn from the NCEP–NCAR reanalysis.

Finally, simulations with zero latent heat effect (ZLH) were performed in order to quantify the significance of condensational processes in the Zagros heating signal. Results from these simulations were nearly identical to CTRL simulations for the months of interest. This indicates that condensational heating is not an important element of Zagros-driven summertime circulations, and the ZLH simulations will not be discussed further.

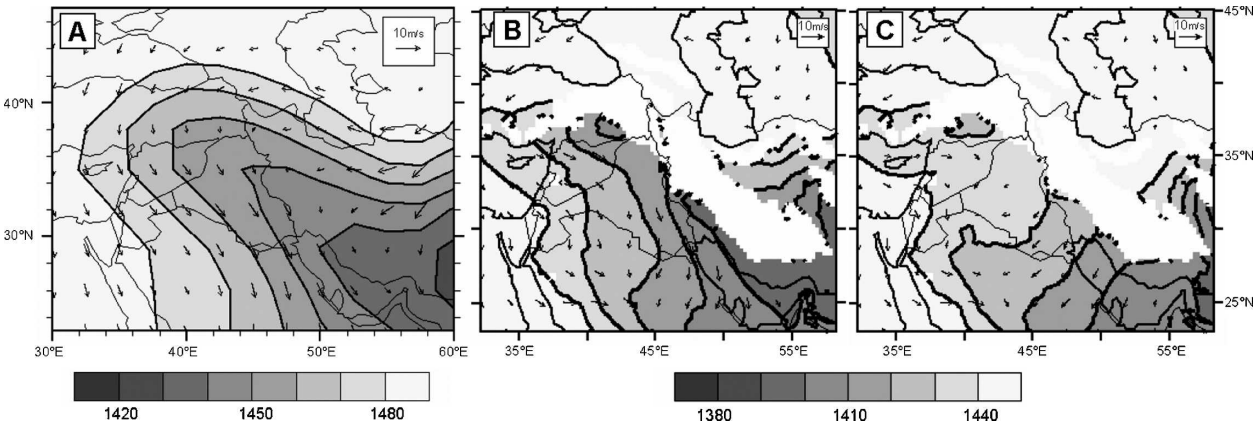


FIG. 6. The Persian trough as captured by the 850-hPa geopotential height field (m) in the (a) NCEP–NCAR reanalysis climatological mean for July, (b) MM5 CTRL mean for July 1999, and (c) MM5 MTSNOW mean for July 1999. The trough is defined as a low pressure system that extends from Iran to western Turkey.

## 3. Results of MM5 simulation

### *a. Control simulation*

In the control simulation (CTRL), MM5 successfully replicates key features of the regional circulation. The summertime low pressure system known as the Persian trough, evident in the NNRP geopotential field at 850 hPa (Fig. 6a), is present in CTRL as a low pressure field that is coherent from the surface to 800 hPa (Fig. 6b). In both the NNRP and CTRL the system develops episodically in May, is persistent from June to August, and decays in late September. The strength of the trough is greatest in July, consistent with the NNRP and with observations from meteorological stations in the region. In monthly climatologies calculated from station data, the trough shows a July maximum of about −7.2 hPa between Mesopotamia in the east and the Levant to the west. CTRL returns a −5.8-hPa differential for July in 1999 and −4.7 hPa for July 2003. Such interannual variability has been identified in earlier studies and is known to correlate with climate variability in the region (Bitan and Saaroni 1992). The strength of the trough did not show consistent diurnal variability in either MM5 or observational datasets.

The Persian trough pressure gradient is associated with low-altitude northerly to northwesterly winds across western Turkey and the MEP. In the Eastern Mediterranean these are known as the *Etesian* winds. They are evident at 850 hPa in the NNRP and in CTRL (Figs. 6a,b). These winds are significant to climate because they advect cool air into the region, moderating summertime temperatures. In the context of the regional circulation, the Etesian winds are part of a cyclonic circulation around the Persian trough that includes easterly winds in the Caucasus region and northerly flow across Saudi Arabia.

At 500 hPa there is a pressure maximum over the southern Zagros Plateau (Fig. 7a). This high pressure center is the product of vertical compression as westerly winds approach the plateau heat dome. A similar feature is observed over the Saudi Arabian Desert, as a result of the extremely deep planetary boundary layer that develops over this desert in summer. Winds passing over these heat domes assume anticyclonic curvature in response to the decrease in absolute vorticity associated with vertical compression, thus conserving potential vorticity (Whiteman 2000). These general features are observed in the NNRP and in CTRL (Fig. 7b), indicating that MM5 CTRL captures the dominant features of the 500-hPa circulation.

MM5 also produces realistic simulation of vertical motions and the vertical distribution of water vapor (Fig. 8). The CTRL simulation returns net neutral vertical motion over the MEP in May, a month that lies in the transition between the spring rainy season and the persistent aridity of summer. By July, there is mean subsidence over the MEP to a height of 500 hPa with a maximum at 700 hPa. This is consistent with the NNRP and with sounding data from the region. Both NNRP and CTRL show that this descending motion is associated with extremely low relative humidity (Fig. 8d).

### *b. Influence of "mountain snow"*

In mountain snow (MTSNOW) simulations the Persian trough is weakened substantially (Fig. 6c). The July sea level pressure gradient between Mesopotamia and the Levant is only −3.6 for 1999 and −2.7 for 2003. This pressure gradient is significantly weaker than that in CTRL; a $t$ test of daily mean pressure differential for the summer months confirms this significance at $p <$ 0.001 for both 1999 and 2003. The MTSNOW-induced weakening of the Persian trough is consistent with ear-

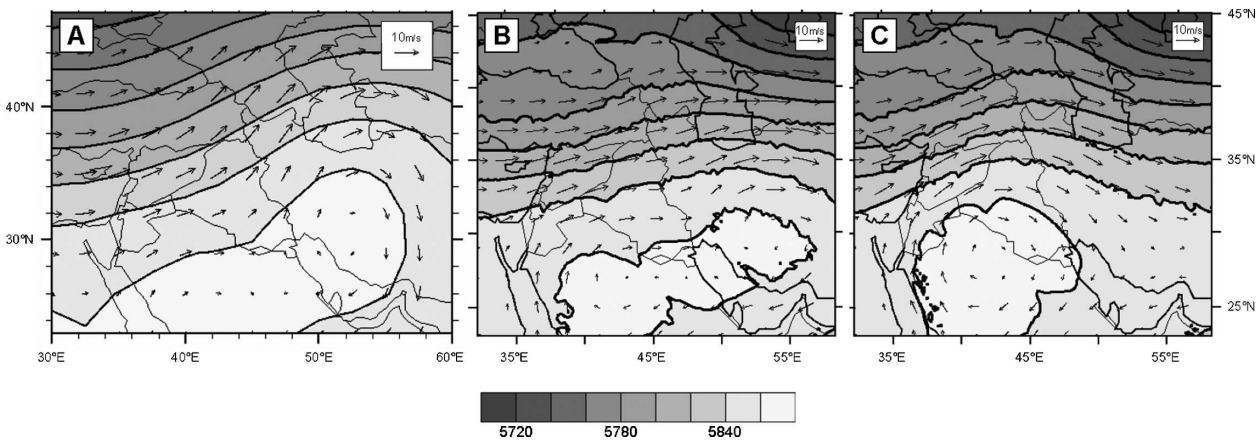


FIG. 7. Geopotential height (m) and horizontal winds at 500 hPa: (a) NCEP–NCAR reanalysis climatological mean for July, (b) MM5 CTRL mean for July 1999, and (c) MM5 MTSNOW mean for July 1999.

lier descriptions of the trough, as the westward extension of the low pressure system is thought to be a product of interactions with topography (Bitan and Saaroni 1992).

The reduced Persian trough in MTSNOW is associated with a change in summertime winds. Average wind speed over the MEP is reduced in MTSNOW relative to CTRL between the surface and 800 hPa throughout the warm season (Fig. 9). The mean wind direction is also affected by MTSNOW, as the predominant summertime wind direction has a pronounced northerly component in CTRL but not in the MTSNOW simulation. The presence of stronger, more northerly winds in the CTRL simulation, that is, strengthened Etesians, causes near-surface cooling. In the CTRL simulation the 2-m air temperature is 1°–2°C cooler than in MTSNOW from June to September (Fig. 9). Both wind patterns and the temperature difference were steady throughout the summer months and were similar for 1999 and 2003. As a point of comparison, studies of long-term warming in the region report trends of 0.008°–0.029°C $yr^{-1}$, some component of which has been attributed to decreasing wind speeds ($-0.042$ m $s^{-1}$ $yr^{-1}$; Saaroni et al. 2003). The impact of Zagros heating on these variables, then, is larger than the effect of climate change over the past 50 years.

The realism of the CTRL temperature and wind fields relative to MTSNOW can be confirmed by com-

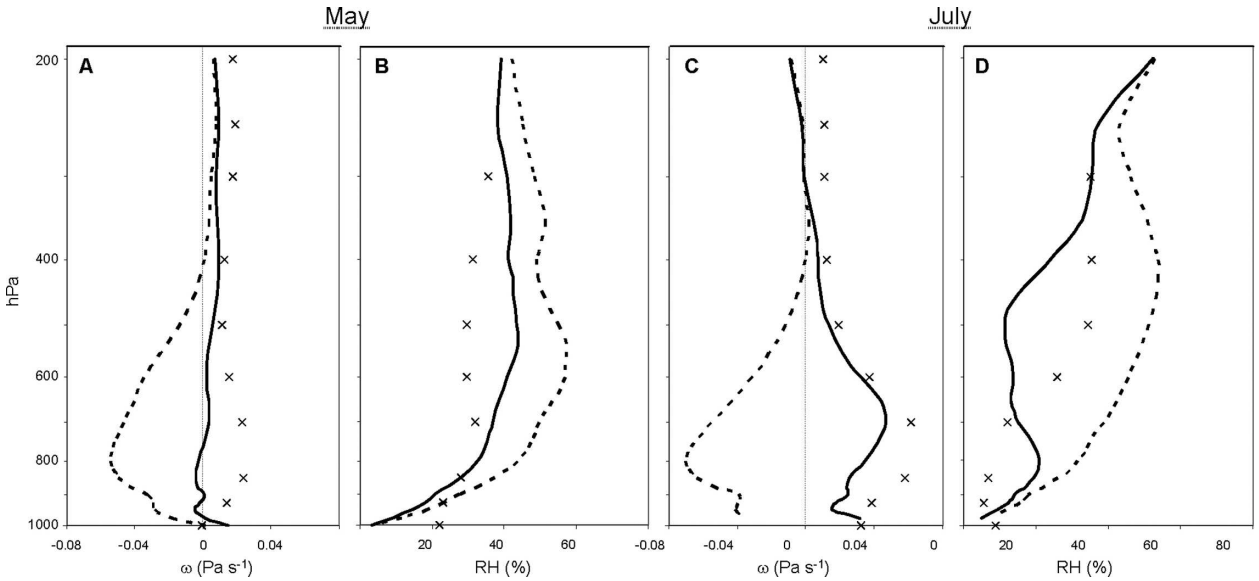


FIG. 8. Mean vertical profile for the MEP for (a), (c) pressure velocity and (b), (d) relative humidity in May and July 1999. Solid line is CTRL, dashed is MTSNOW, and × marks are NNRP.

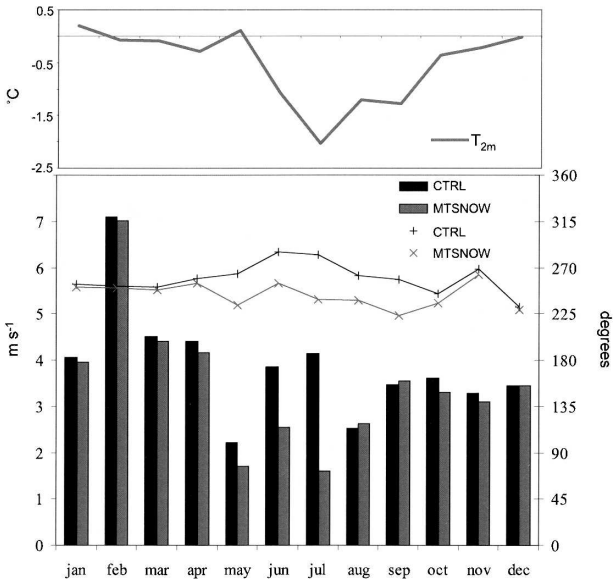


FIG. 9. (bottom) Mean monthly wind speed (bars) and wind direction (marked lines) at 800 hPa in MM5 CTRL and MTSNOW, averaged for 1999 and 2003: (top) difference in mean monthly 2-m air temperature (CTRL − MTSNOW).

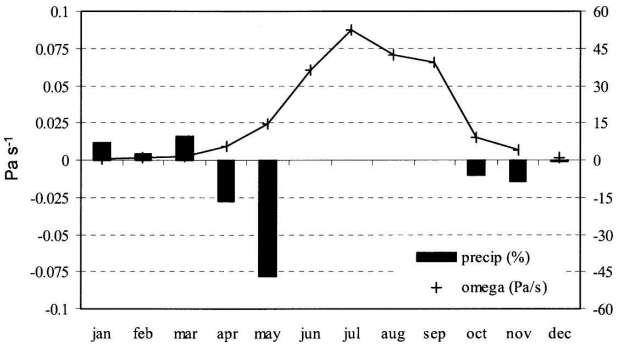


FIG. 10. Pressure velocity and precipitation. The line indicates the difference in 700-hPa pressure velocity, CTRL − MTSNOW, monthly averages for the MEP in 1999 and 2003 combined. Positive values indicate a tendency for greater subsidence in CTRL. Bars show the percent change in precipitation, CTRL relative to MTSNOW, for 1999 and 2003 combined. Negative values indicate a percentwise decrease in precipitation in CTRL relative to MTSNOW, and the months June–September are set to zero because precipitation was negligible in both simulations.

parison with the NNRP. For the summer months (June–September), the period during which near-surface air temperatures are elevated in MTSNOW relative to CTRL (Fig. 8), the mean MEP 2-m air temperature in CTRL is within half a degree of the NNRP estimate (CTRL is +0.5°C warmer for 1999 and 2003 combined), while the mean 2-m air temperature in MTSNOW is considerably elevated relative to the NNRP (+1.7°C). Over the same period, the mean 800-hPa wind direction is 273° in CTRL (nearly due westerly), 239° in MTSNOW (southwesterly), and 283° in the NNRP. These comparisons suggest that the CTRL simulation is, indeed, closer to observations than MTSNOW.

At 500 hPa, MTSNOW has the effect of removing the Zagros Plateau high pressure center (Fig. 7c). This is a direct result of neutralizing surface heat flux on the plateau. In the absence of local heating, the Zagros Plateau develops a stable, shallow boundary layer, allowing background winds to pass over the plateau without compressing vertically. More important from the perspective of MEP climate, the absence of rising motion over the Zagros is associated with reduced subsidence over the MEP. In contrast to the CTRL simulation and the NNRP, the MTSNOW simulation returns strong rising motion over the MEP in both May and July (Fig. 8). This rising motion is a simple response to strong surface heating. It is suppressed in observations and MM5 CTRL by externally imposed subsidence, but in MTSNOW the subsidence associated with the Zagros Plateau is eliminated, allowing for net rising motion over the MEP.

### c. *Precipitation effects*

Zagros-induced subsidence is associated with reduced precipitation in the MEP, particularly in the spring transitional months of April and May (Fig. 10). In 1999 and 2003 combined, there were 22 rain days in May for the CTRL simulation, yielding a total of 12.5 mm, while there were 23 rain days for MTSNOW, yielding a total of 23.6 mm. (A rain day is defined as a day with total precipitation >0.1 mm averaged over the MEP; precipitation yield is also averaged over the MEP.) The majority of this precipitation was convective in origin, and most fell in the northern portion of the area of interest, coinciding with the Fertile Crescent. The fact that the number of rain days was approximately equal for the two simulations indicates that MTSNOW does not significantly alter the likelihood of precipitation; instead, the suppression of Zagros heating in MTSNOW leads to events with larger precipitation yield.

It is tempting to attribute this difference in precipitation yield solely to the differences in subsidence indicated in Fig. 8a. This would be an oversimplification. The summertime climate of the MEP is dry due to the combined effects of atmospheric stability and low relative humidity. Therefore, it is also relevant that MTSNOW shows greater relative humidity than CTRL (Fig. 8c). This increase in humidity is a product of changes in the horizontal wind field. Moist air masses in

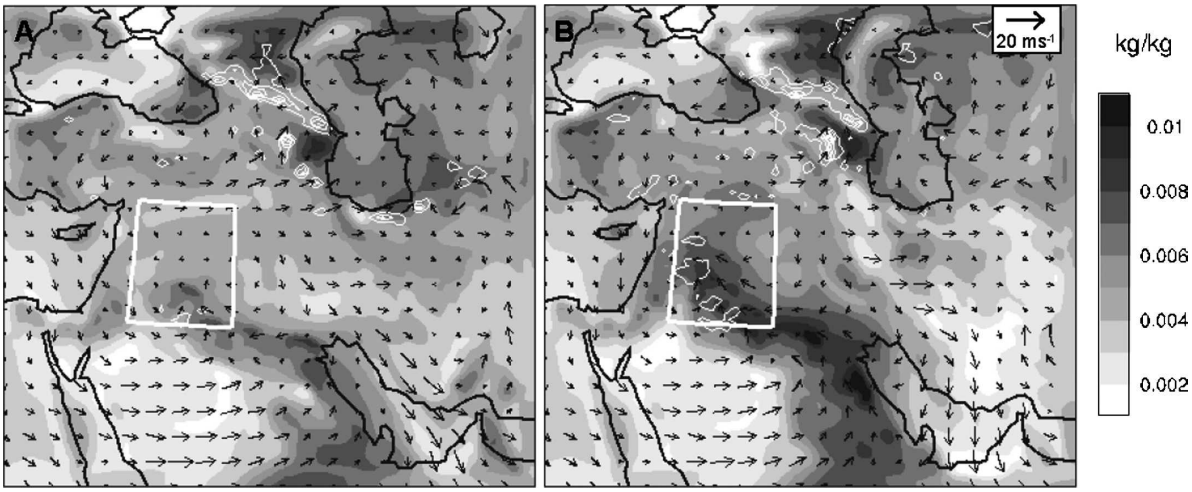


FIG. 11. Winds and specific humidity at approximately 2-km height during the 20 May 2003 precipitation event in (a) CTRL and (b) MTSNOW. White contours indicate zones of active precipitation; white box is the MEP. Note the difference in the vapor tongue extending from the Persian Gulf to the MEP in (a) vs (b).

the Persian Gulf region, which are vented out of the region in CTRL by a combination of upslope winds on the Zagros and down-valley northwesterly flow associated with the Persian trough (Fig. 6), have a longer residence time in the MTSNOW simulation. This allows humid air to accumulate within the region. When there is a reversal to southerly flow in the near-surface winds, as occurs in the majority of large rain events (Evans and Smith 2006), this pool of moist air penetrates more deeply into the region because the background northerly flow is weakened relative to CTRL. In May 2003, the month in which the precipitation difference between CTRL and MTSNOW was greatest for the MEP, the total southerly vapor flux into the MEP was 25% larger in MTSNOW than in CTRL. Influx from the west—the only other direction with positive vapor inflow—was similar in the two simulations.

A useful case study is the rain event on 20 May 2003, which yielded 3 times as much precipitation in the MEP for MTSNOW compared to CTRL. As is typical for large precipitation events, near-surface winds had a southerly component. This was captured by both simulations (Fig. 11). In CTRL, however, the southerly air mass has lower humidity, and southerly winds are checked by northerly flow in the MEP. Some precipitation develops, but the lack of humidity combined with the weak penetration of southerly flow limits the size of the rain event. Stability also plays a role. The MTSNOW rain event involves strong convective motions that are absent in the CTRL simulation, and these updrafts are associated with local precipitation maxima.

As this event demonstrates, three products of Zagros heating act to suppress precipitation in the MEP: upslope flow on the Zagros carries water vapor out of the region, reducing relative humidity in the MEP; strengthened Etesians penetrate farther east, blocking the southerly vapor flux; and enhanced stability acts to suppress the vertical motions associated with large rain events.

## 4. Physical basis for MM5 results

The Zagros Plateau lies downwind of the MEP, so it is not immediately obvious why surface conditions on the plateau would have such significant impacts on temperature and precipitation in the plain. In this section the mechanisms through which plateau heating influences horizontal winds and vertical motion in the upstream region are explored in greater detail.

### *a. Horizontal winds and upstream cooling*

Figure 12 shows the response of the lower- and upper-troposphere geopotential and winds to plateau heating, as expressed in the difference fields between CTRL and MTSNOW simulations. At 800 hPa, a region of low pressure and cyclonic flow is seen (Fig. 12a), while at 500 mb a high pressure region with anticyclonic flow is noted (Fig. 12b). In its broad aspects, this response fits the classical picture of a heat low. The low pressure is associated with heated air in the lower troposphere. The anticyclonic flow aloft is mostly above the region of heat addition to the atmosphere. Its high pressure anomoly is caused by adiabatic ascent farther aloft. The wind field anomolies are primarily in geostrophic balance with the height anomalies. The sense

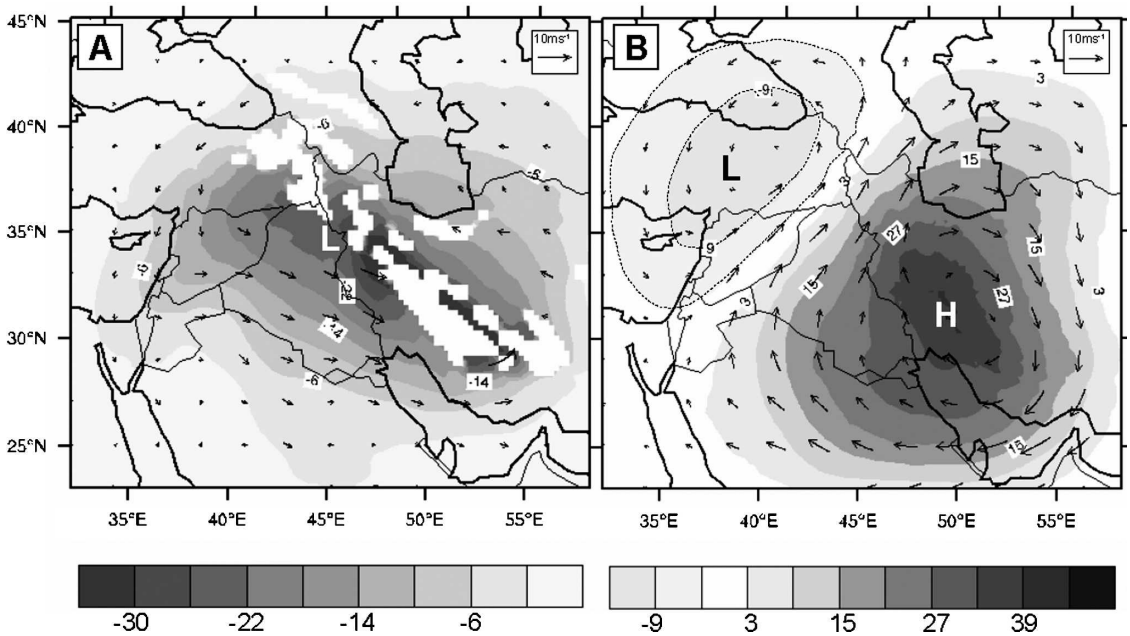


FIG. 12. MM5 CTRL − MTSNOW geopotential height (m) and winds (a) at 800 hPa in July, the approximate height of the Zagros Plateau, and (b) at 500 hPa in August, above the Zagros heating maximum. The "L" and "H" indicate the locations of pressure/geopotential minima and maxima. Negative contours in (b) are dashed.

of the circulation reverses with altitude. Even a linearized model of response to heating in a stagnant stratified atmosphere would reproduce this simple dipole pattern.

The link between winds and near-surface cooling in the CTRL − MTSNOW difference fields can be confirmed by calculating the thermodynamic balance of the atmosphere at 800 hPa, defined as

$$T_t = Q/C_p - \overline{\mathbf{u}} \cdot \nabla_p \overline{T} - (p/p_0)^{R/C_p} \overline{\omega} \theta_p,$$

where $T_t$ is the time rate of temperature change, $Q$ is the diabatic heating rate (W kg$^{-1}$), $C_p$ is the specific heat capacity of dry air, $\mathbf{u}$ is the horizontal wind, $p_0$ is reference surface pressure, $R$ is the gas constant for dry air, $\omega$ is pressure velocity (Pa s$^{-1}$), and $\theta_p$ is the derivative of mean potential temperature with pressure. Overbars indicate time average, and transient terms have been ignored (after Rodwell and Hoskins 2001). On the monthly time scale, $T_t$ is negligible relative to other terms. The rate of temperature change due to diabatic heating, $Q/C_p$, is similar for CTRL and MTSNOW outside of the area of albedo manipulation. This means that for areas away from the plateau the rate of temperature change due to horizontal advection, $-\overline{\mathbf{u}} \cdot \nabla_p \overline{T}$, must be approximately balanced by the rate of adiabatic cooling/warming through vertical motion, $-(p/p_0)^{R/C_p} \overline{\omega} \theta_p$. An independent calculation of the difference between these two terms in CTRL versus MTSNOW for the month of July confirms that enhanced northerly advection in CTRL (i.e., enhanced Etesian winds) is responsible for cooling on the order of 0.1–0.3 (°C h$^{-1}$) at 800 hPa and that this cooling is balanced by the subsidence of warmer air from aloft (Fig. 13).

### b. Subsidence in the upwind region

The influence of plateau heating on vertical motion in the surrounding area is conventionally described as a plain–plateau circulation: rising motion over a warm plateau is associated with converging upslope winds near the surface, outflow aloft, and descending motion over the neighboring plain. Such circulations are known to be strongest during the afternoon when daytime heating has produced a strong temperature contrast between the plateau-warmed atmosphere and the free atmosphere over the plain. At night the plain–plateau circulation weakens and, if radiative cooling is sufficient, the circulation can reverse.

To a large extent, Zagros-induced subsidence in the MEP can be explained as an extensive plain–plateau circulation. The CTRL − MTSNOW difference field shows a circulation of rising motion over the plateau associated with descent in the plain that first organizes in April and builds in strength and extent through August (Fig. 14). The circulation does not reverse at night, as the temperature gradient between the plateau

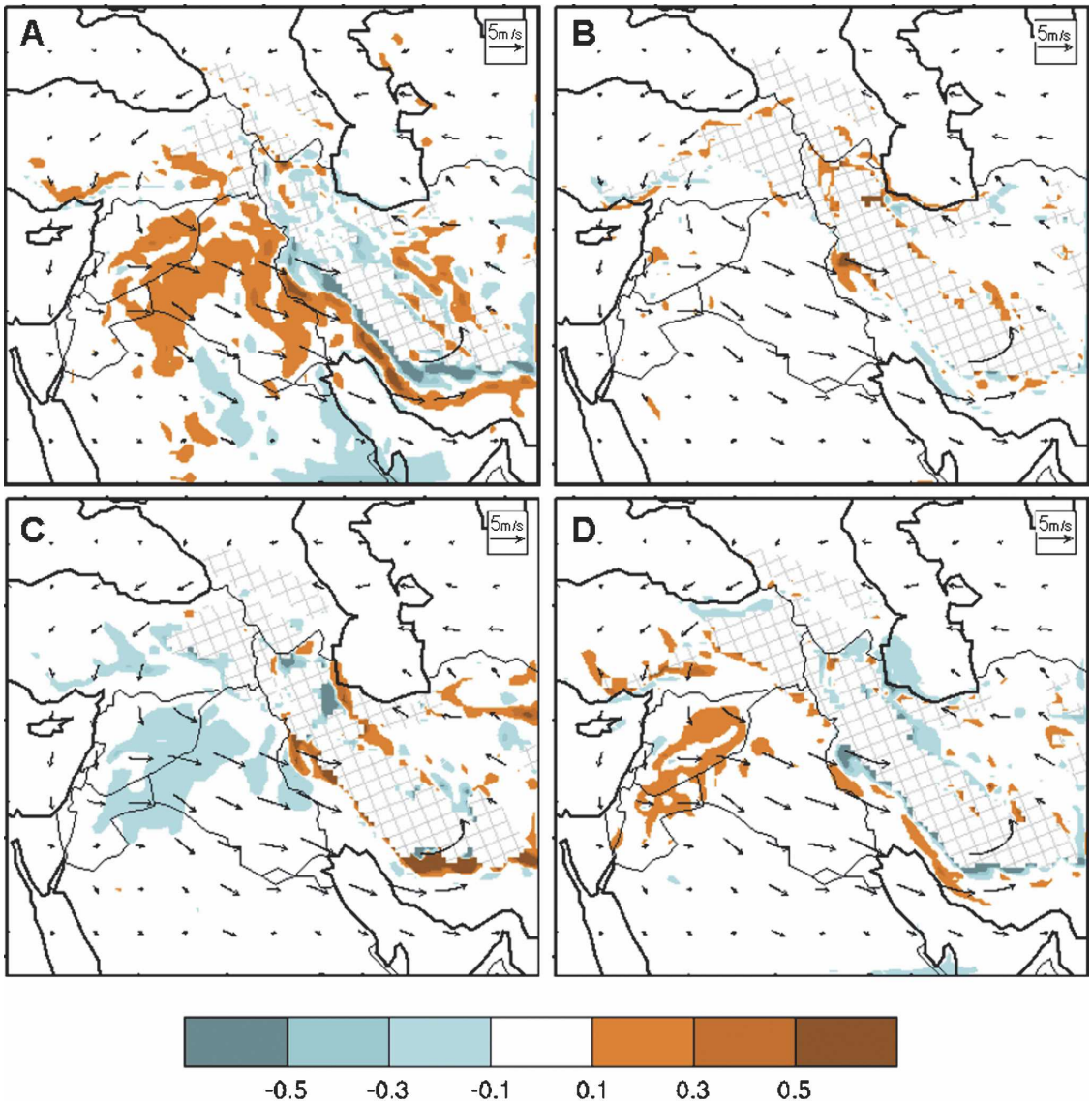


FIG. 13. (a) Pressure velocity (Pa $s^{-1}$) and components of the thermodynamic balance (°C $h^{-1}$) at 800 hPa, CTRL − MTSNOW, averaged for July 1999: (b) the diabatic heating rate, (c) the advective heating rate, and (d) the adiabatic heating rate associated with vertical motion. Hatches indicate areas where topography exceeds 800 hPa.

boundary layer and the neighboring free atmosphere does not completely dissipate. The Zagros can thus be described as an elevated heat source that oscillates diurnally around a nonzero mean.

Significantly, this heat source is operating in the presence of westerly background winds. Background winds are known to hinder the development of a plain–plateau circulation (Lee and Kimura 2001). This tendency is reflected in the MM5 results, as there is a significant negative correlation between the velocity of background westerly winds and the strength of atmospheric subsidence averaged over the MEP. At 750 hPa, the difference in mean daily $\omega$ (CTRL − MTSNOW) decreased by 0.02 Pa $s^{-1}$ for every 1.0 m $s^{-1}$ increase in background wind speed [calculated as a linear regression for all June–August days in 1999 and 2003 combined ($N = 184$, $r = -0.56$, $p < 0.001$)]. As far as the plain–plateau mechanism is concerned, then, Zagros-induced subsidence in the MEP is communicated westward from the plateau only on days when the background westerlies are weak enough to allow the circulation to develop.

Zagros heating also has the potential to influence subsidence in the MEP via the thermodynamic balance. As described above, the linear atmospheric response to Zagros heating includes strengthened northwesterly

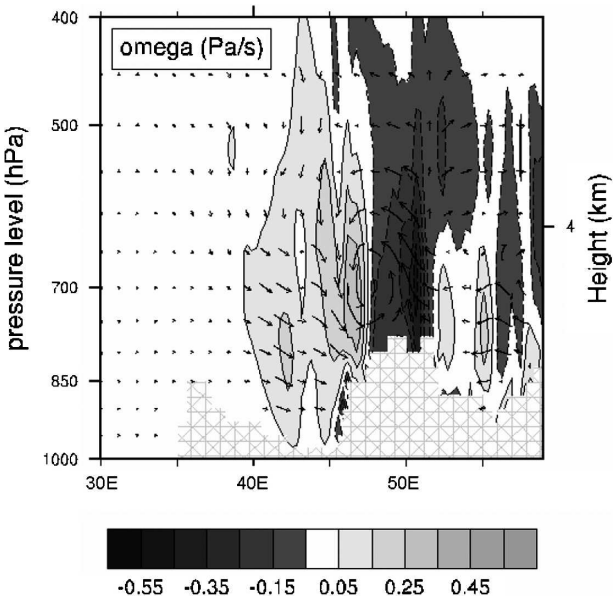


FIG. 14. Mean June pressure velocity (Pa $s^{-1}$) and winds, zonal cross section at 34°N, CTRL − MTSNOW. Negative (positive) values indicate upward (downward) motion in CTRL relative to MTSNOW. Negative contours are dashed, and hatching indicates topography.

winds across much of the MEP. The advective cooling caused by these winds (Fig. 13c) is balanced by adiabatic warming associated with atmospheric descent (Fig. 13d). This results in a secondary maximum in the subsidence field that is located farther west than the region of maximum descent in the plain–plateau circulation (see Fig. 14) and provides an indirect advection mechanism through which the subsidence signal is communicated westward across the MEP.

Finally, a full analysis of pressure and velocity fields indicates the presence of internal gravity waves (IGWs) that propagate westward from the Zagros Plateau, against prevailing background winds (Zaitchik 2006). These waves are an interesting atmospheric phenomenon and are the subject of ongoing research. There was no significant correlation between IGW activity and subsidence in the MM5 simulations, however, so the waves are not thought to be relevant to the present study of climate impacts.

## 5. Conclusions

The findings of this study are summarized in Fig. 15. [1]: Surface heating on the Zagros Plateau leads to rising motion and low pressure at the plateau surface. [2]: A steady cyclonic circulation develops in response to the Zagros low pressure center, strengthening the Etesian winds that cool air temperatures over the Middle East Plain by northerly advection. [3]: The plateau low also leads to vigorous upslope flow that acts to ventilate the MEP. There is a strong diurnal component to these slope winds, but they are upslope in the mean. [4]: When background westerly winds are sufficiently weak, a closed plain–plateau circulation develops, leading to subsidence on the western slopes of the Zagros and on the MEP. [5]: Thermodynamic balance is achieved over the western portion of the MEP by adiabatic warming, leading to Zagros-induced subsidence in an area that lies upwind of the closed plain–plateau circulation. [6]: All local effects occur in the context of the subtropical high that persists over the entire region in summer, imposing broad subsidence in the upper troposphere. For this reason the overall pattern of subsidence can be attributed to the combined effects of the Zagros Plateau and external forcings associated with the Hadley and/or Monsoon circulations.

The combination of increased wind speed [2], ventilating upslope winds [3], and enhanced subsidence [4], [5] act to inhibit precipitation in the MEP. The effect is greatest in April–October, a season when precipitation is already limited due to large-scale atmospheric phenomenon, so the net impact of Zagros heating on MEP precipitation is modest. In a semiarid region such as the MEP, however, even small changes in precipitation can have a substantial impact on ecosystems and agriculture.

The mechanisms through which the Zagros Plateau influences the atmosphere are by no means unique. Major plateaus throughout the world are known to drive circulations that are relevant to climate: diurnal plain–plateau circulations, enforced subsidence in neighboring regions, and remote effects via wave propagation have all been observed, to varying degrees, in other locations (e.g., Bossert and Cotton 1994; Tang and Reiter 1984; Whiteman et al. 2000). The development of any potential atmospheric response to heating depends on topography, atmospheric conditions, and location. Diurnal wind patterns, for example, show great diversity in dissected terrain (Egger et al. 2005). The strength of upslope flow depends on the rate of surface heating on the plateau and on the role of condensation in establishing the plateau heat low (Tang and Reiter 1984). Stiff background winds tend to disturb plain–plateau circulations (Whiteman 2000), while weak winds can reduce the potential for IGW propagation (Smith 1980). Finally, the climatic impacts of any plateau-driven circulation often involve interaction with independent mesoscale phenomena, including atmospheric jets (Tucker 1999) and land–ocean circulations (Hahn and Manabe 1975). Given the regional complexity and climatic significance of plateau circula-

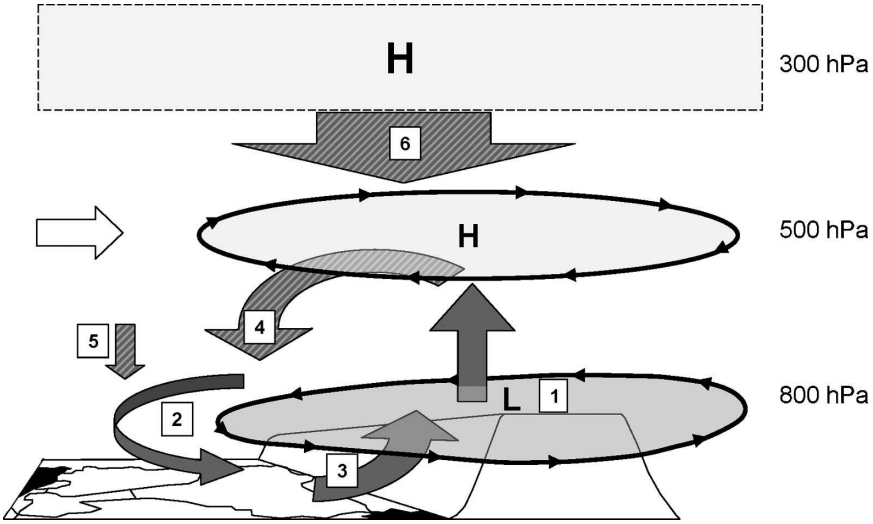


FIG. 15. Schematic summary of findings. Line drawing at bottom shows topography, shaded regions indicate regions of high and low pressure, and arrows represent winds (white arrow is background wind; gray arrows are Zagros-induced circulations). Subsidence is indicated by striped arrows. Numbers indicate [1] low pressure due to plateau heating, [2] strengthened Etesian winds, [3] upslope flow, [4] the closed plain–plateau circulation, [5] adiabatic warming over the MEP, and [6] broad subsidence associated with the subtropical high.

tions, further research on the topic is expected to improve our understanding of regional climate in many parts of the world.

The numerical experiments presented in this paper were designed to enhance understanding of present-day climate dynamics in the Middle East; *mountain snow* was simply a convenient method for assessing the impact of surface heat flux on the Zagros Plateau. Nonetheless, the findings are relevant to the regional response to global climate change. Heat flux on the Zagros is influenced by the presence of glaciers, which were more extensive in the past (Issar and Zohar 2004), and by the endurance of the winter snowpack into spring. Land cover changes, including ecosystem migration and desiccation, would also modify surface heat flux on the Zagros, and similar changes in the neighboring regions could influence the temperature contrast that underlies the heat-induced circulations described in this study. The presence of significant circulations generated by the internal geography of the region underscores the importance of detailed regional studies in any investigation of climate dynamics in the past, present, or future.

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