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THE FACTORS GOVERNING THE SUMMER REGIME OF THE EASTERN MEDITERRANEAN

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ABSTRACT

The synoptic scale features over the eastern Mediterranean (EM) for July–August are examined using National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis data. The region is subjected to two primary factors: mid–upper level subsidence and lower level cool advection, associated with the Etesian winds.

The interdiurnal variations of these factors were found to be correlated with each other, with a maximum of $r = 0.76$, found between the 700 hPa subsidence and the 925 hPa wind speed. The impact of these factors on the temperature regime was examined through their contributions in the temperature tendency equation at 32.5 °N, 35 °E. A significant correlation was found between them at the 850 hPa level, indicating that they tend to balance each other. This explains the low interdiurnal temperature variations there in summer.

Zonal-vertical and isentropic cross-sections indicate the existence of a closed circulation connecting the EM with the Asian monsoon, and a meridional-vertical cross-section indicates a signature of the Hadley cell across eastern North Africa. Air back-trajectories demonstrate that the EM is connected at the lower troposphere with Europe, at the mid-troposphere with eastern North Africa and at the higher troposphere with the Asian monsoon. Significant correlation was found between the interdiurnal variations in the upward motion over the Asian monsoon and the subsidence over the Levant, with a 1 day lag, implying that the Asian monsoon controls the interdiurnal variations over the Levant.

A detailed analysis shows that the correlation between the two dynamic factors governing the EM results from a linkage existing between each one of them and the Asian monsoon. An intensification of the Asian monsoon enhances both the subsidence over the Levant, via the circulation connecting them, and the Etesian winds, due to the enhanced pressure gradient between the two regions. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: monsoon; Hadley cell; Persian trough; Etesians; Levant; isentropic cross-section; subsidence; teleconnection

1. INTRODUCTION

The weather conditions over the eastern Mediterranean (EM) are highly persistent during the summer season, particularly in July–August. The lower levels are dominated by the so-called 'Persian trough' (Alpert *et al.*, 1990, 2004; Bitan and Saaroni, 1992; Saaroni and Ziv, 2000), a surface low-pressure trough that extends from the Asian monsoon through the Persian Gulf and further, along southern Turkey to the Aegean Sea (Figure 1). As a combined result of the Persian trough and the subtropical anticyclone of the Atlantic (Azores), northwesterly winds, known as the Etesian winds (e.g. Air Ministry Meteorological Office, 1962; Metaxas, 1977; Prezerakos, 1984), blow over the EM. The Etesian winds yield a continual cool advection from eastern Europe and the Mediterranean into the Levant, as seen in the average seasonal 850 hPa temperature and wind fields (Figure 2). The combination of these two average fields implies an average temperature drop of over 2 K per day thanks to this advection.

In contrast, a persistent warming by subsidence, which dominates the EM, counteracts the advective cooling over the region. The prominent features in the 500 hPa ω field, Figure 3, are a pronounced subsidence, centred

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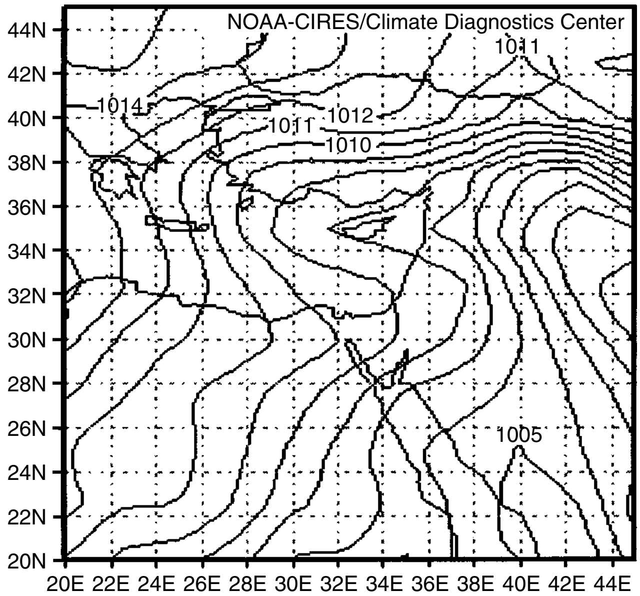

Figure 1. Long-term mean sea-level pressure (SLP) averaged over 1968–96 (hPa, 1 hPa interval) for July–August (National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR CDAS-1) archive; Kalnay *et al*., 1996; Kistler *et al*., 2001)

over western Crete (35 °N, 25 °E), and upward motion centres in southern Asia and Central Africa, representing the major monsoon systems (Barry and Chorley, 1998). The maximum downward motion near Crete, of 0.1 Pa s^{-1} (equivalent to ~ -1.2 cm s^{-1}), is the largest for the entire Northern Hemisphere during summer. Rodwell and Hoskins (1996) pointed at a strong linkage between the Asian monsoon and this subsidence pattern and attributed the persistence of the EM subsidence, along with the lack of rains during the summer season, to the persistence of the Asian monsoon. The upper tropospheric moisture content, averaged for July 1989–91 (Stephens *et al*., 1996) extracted from the TOVS data, indicates that the most significant minimum for the Northern Hemisphere covers the EM, in accordance with subsidence at the upper levels. A similar pattern is seen in the long-term average low specific humidity for July–August averaged over the 500–300 hPa layers (not shown).

The combination of mid-tropospheric subsidence and lower level cool advection enhances the marine inversion, which prevails over the Levant region in summer (at about 700–900 m a.s.l. in Israel; Dayan and Rodnizki, 1999). This inversion has far-reaching environmental implications due to its effects on air pollution (Dayan *et al*., 1988, 2002; Koch and Dayan, 1992) and on heat stress.

This study attempts to examine the interrelations between the two summer-dominating dynamic factors and to understand the connection between them and remote systems better. The study is based mainly on the NCEP-NCAR CDAS-1 archive (Kalnay *et al*., 1996; Kistler *et al*., 2001). Section 2 evaluates the interrelation between the dynamic factors governing the EM and their impact on the temperature regime there. In Section 3, the governing large-scale circulations are studied through vertical and isentropic cross-sections, air trajectory analysis and spatio-temporal correlation. Section 4 integrates these findings and outlines a proposed mechanism through which the Asian monsoon controls the temperature regime in the EM. Section 5 summarizes our main findings and outlines further research.

2. INTERRELATION BETWEEN THE DYNAMIC FACTORS GOVERNING THE EM

The interplay between the two governing dynamic factors over the EM was examined by calculating the correlation between the interdiurnal variation of the lower level wind speed and the mid-level vertical velocity.

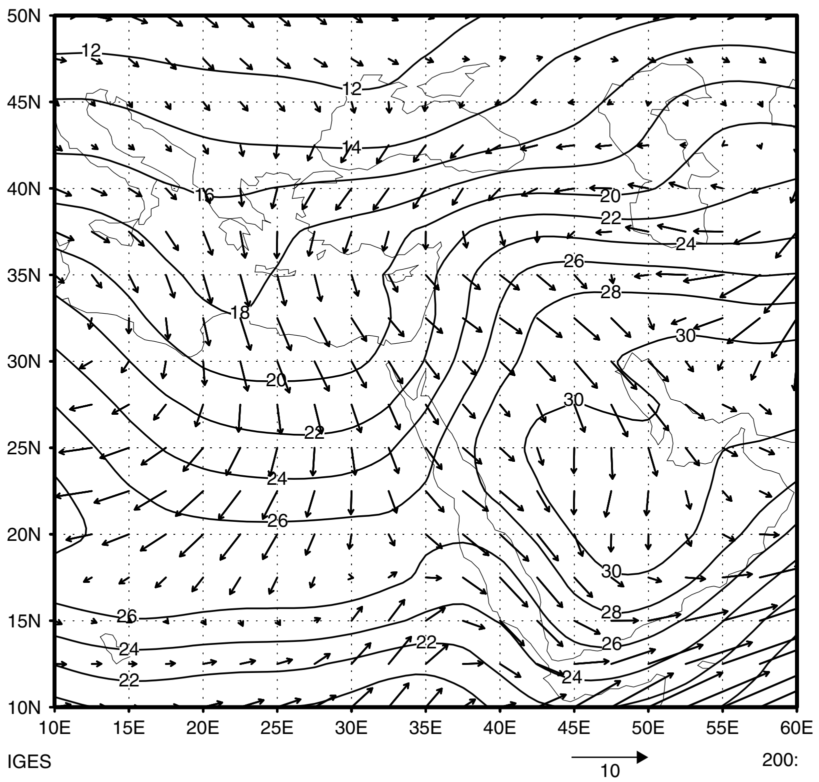

Figure 2. The 850 hPa long-term mean temperature (°C) and wind vectors, averaged over 1968–96, for July–August (NCAR-NCEP CDAS-1 archive)

This was done for a selected summer, July–August 1989, which was an average summer without extreme events. The maximum correlation was obtained between the wind speed at the 925 hPa level and ω at the 700 hPa level. The mapping of the correlation over the EM (Figure 4) shows a distinct strip of significantly high correlation, with a maximum of 0.76 at 37.5 °N, 30 °E. It is worth noting that this strip is more-or-less parallel to the Etesian wind streamlines, as implied by Figure 2.

The interrelation between these two factors is also expressed by their relative contributions to the inter-diurnal temperature variations. The local rate of change in temperature $\partial T/\partial t$ at a pressure level p can be rewritten (e.g. Rodwell and Hoskins, 1996)

$$\frac{\partial T}{\partial t} = -\mathbf{V}\cdot\nabla T - \left(\frac{p}{p_0}\right)^{\kappa} \omega \frac{\partial \theta}{\partial p} + \frac{Q}{C_p} \tag{1}$$

where $\mathbf{V}$ is the horizontal wind component, p_0 is the reference pressure level (1000 hPa), θ is potential temperature, κ is R/C_p (R is the gas constant and C_p is the specific heat at constant pressure), $\omega \equiv \mathrm{d}p/\mathrm{d}t$ and Q is the diabatic heating rate.

The two first terms on the right-hand side of Equation (1) represent the two dynamic factors, i.e. horizontal and vertical temperature advection respectively. Figures 2 and 3 indicate that, on average, the contributions of these terms over the Levant oppose each other. In order to show how these terms are correlated on a daily basis we plotted their variations at the 850 hPa level for July–August 1989 for 32.5 °N, 35 °E, representing the Levant (Figure 5). Indeed, in the majority of this period the horizontal advection term is negative and the vertical one is positive. The curves representing the two terms are more-or-less mirror images of each other, implying that the dynamic warming and advective cooling tend to intensify and weaken at the same time. The correlation r is -0.37 (significant at the 99.5% confidence level).

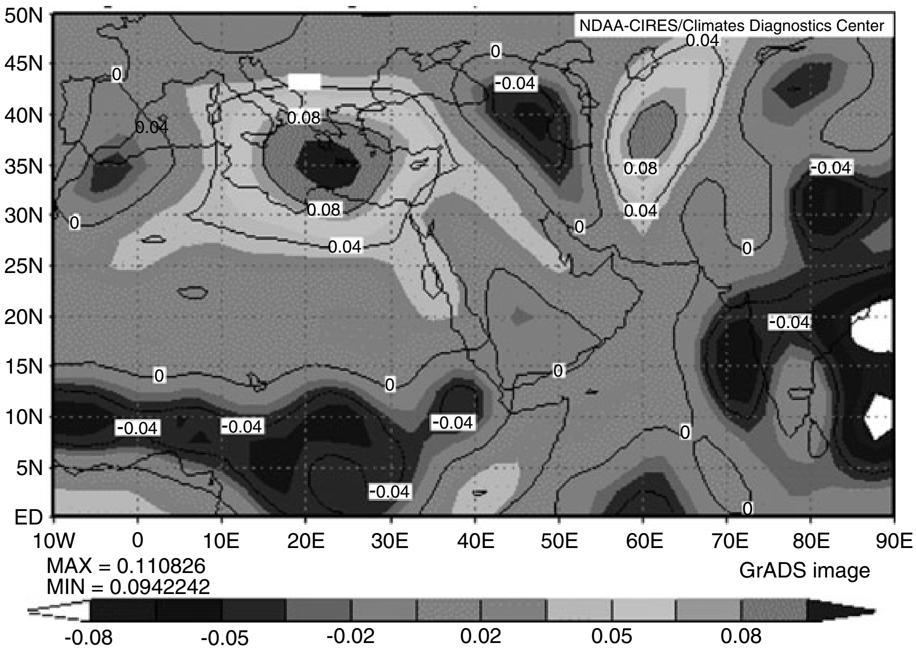

Figure 3. Long-term mean omega (dP/dt; units: Pa s^{-1}) field on the 500 hPa pressure level for July–August (NCEP–NCAR CDAS-1 archive). Positive values represent subsidence

The cancellation between these two factors explains the low interdiurnal variation of the temperature at the 850 hPa level over the Levant, attaining its annual minimum in July–August (Figure 6), in spite of the large horizontal temperature gradient over the region (Figure 2).

3. REGIONAL GOVERNING CIRCULATIONS

The upper level subsidence over the EM in the summer season may be considered as part of the subtropical descending branch of the global Hadley cell, which shifts northward in summer. An alternative approach was presented by Webster (1994), who showed for July–September 1985 and July–August 1987 a distinct closed circulation of the ageostrophic flow that connects the descending motion over the EM (10–50 °E range) with the ascending motion over East Asia (70–150 °E). These findings point at a possible connection between the Asian monsoon and the subsidence over the EM. Rodwell and Hoskins (1996) showed an explicit relationship between the subsidence over the EM and the Asian monsoon through numerical simulations, even though they could not point at any closed circulation connecting the two systems. They suggested that Rossby waves are the means by which the Asian monsoon affects the EM. Eshel (2002) further explained the possible mechanism by showing that the isentropic surfaces along 32 °N reach their minimum height over mid-Asia (due to latent heat release within the convective clouds there) and attain their maximum height over the Atlantic, the coolest region during summer along that latitude. He stated that the Rossby waves smooth the isentropic surfaces by lowering them over the EM via the adiabatic heating associated with the Rossby dynamics.

Rodwell and Hoskins (1996) argued that the Hadley cell is not significant in the zonal averages for the summer in the Northern Hemisphere, and so its role in the subsidence over the EM can be ignored.

3.1. Vertical-zonal, isentropic and vertical-meridional cross-sections

The connection between the EM and the Asian monsoon is first addressed here by a vertical-zonal cross-section, averaged over the 20–35 °N latitudinal band, of the long-term average wind field for July–August

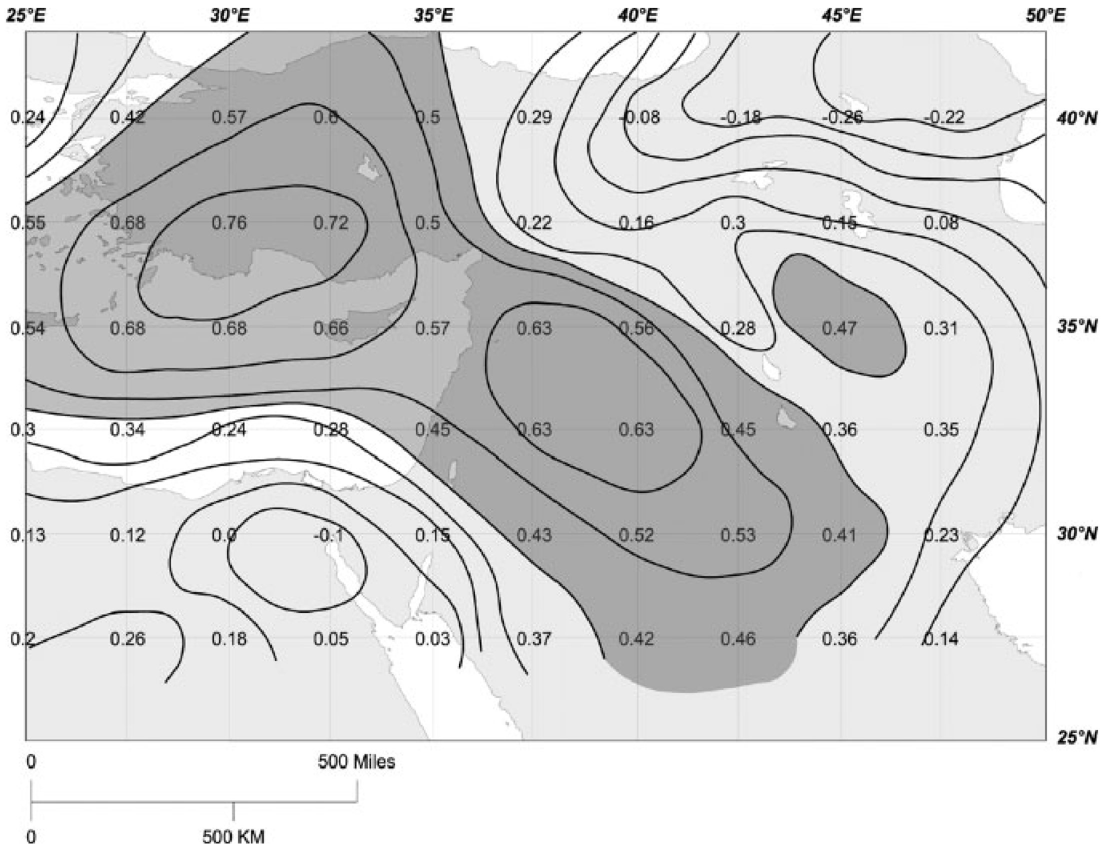

Figure 4. Spatial distribution of the correlation between the 700 hPa omega and the 925 hPa wind intensity for 1 July–31 August 1989

(Figure 7). The wind vectors indicate that the upward motion over mid-Asia (80–100 °E) and the subsidence over the EM (30–40 °E) are connected by a distinct circulation, in agreement with Webster (1994). However, the maximum subsidence, seen over Crete, is connected not only to the Asian monsoon, but also with another circulation to its west. The implied circulation is more clearly seen in isentropic cross-sections of the upper troposphere, represented here by that on the 440 K level (Figure 8).

In addition, the meridional-vertical cross-section (Figure 9) shows a distinct closed circulation connecting the ascending flow above the intertropical convergence zone (or the African monsoon) at 5–15 °N with the subsiding flow over 30–40 °N, which can be regarded as a Hadley circulation. It is worth noting that the ascending branch seems to be much weaker than the descending one, implying that the Hadley circulation may explain the EM subsidence only partially. To clarify our findings further, an air back-trajectory analysis is performed next.

3.2. Air back-trajectory analysis

Air back-trajectories for several cases were generated using the Website of NOAA HYSPLIT4 (Hybrid Single-Particle Lagrangian Integrated Trajectory Model, 1997). An example for a randomly selected day is shown in Figure 10, which reflects the origins of air entering the EM at 1 km, 4 km and 11 km, representing the lower, mid and upper troposphere respectively.

The trajectories indicate that air masses originating from southeast Europe enter the EM at the lower troposphere, air masses originating from the eastern African monsoon enter at the mid-troposphere, and from the Asian Monsoon at the higher troposphere. A similar division was noted in other cases (not shown here), though the details, such as the levels separating the three 'regimes', differ from one event to another.

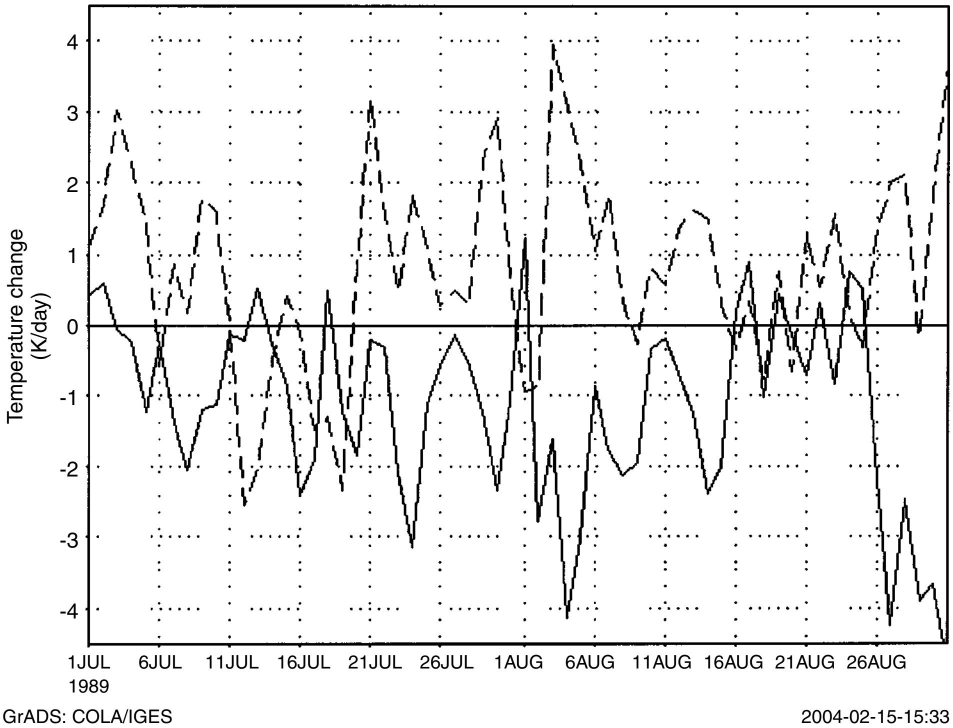

Figure 5. Contribution of vertical (dashed) and horizontal advection (solid) terms (Equation (1)) to the interdiurnal variations of the 850 hPa temperature at 32.5 °N, 35 °E for July–August 1989

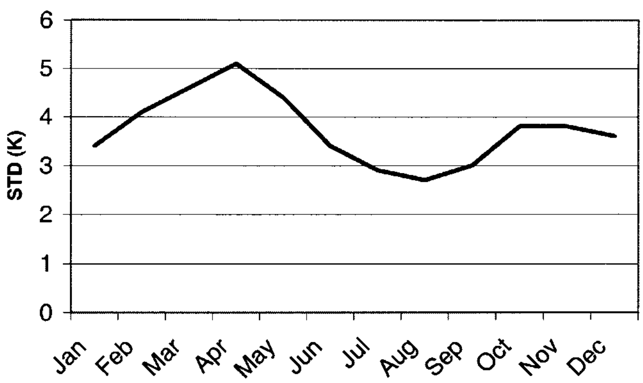

Figure 6. Monthly variation of the total standard deviation (STD) of daily temperature at 850 hPa level at the grid point 32.5°N, 35 °E (NCEP–NCAR CDAS-1 archive)

3.3. Spatio-temporal correlation

A relationship between the EM and each of the remote monsoon systems is expected to be manifested in a significant correlation between the temporal variations of the vertical motion in the pertinent regions. The correlation may be examined for different time scales, such as interdiurnal, interseasonal or interdecadal. Here, we concentrate on the interdiurnal scale. In order to eliminate diurnal effects, each day was represented by the daily average value.

The correlation was calculated for the selected summer noted above (July–August 1989). As a first step the specific locations of the two examined regions were chosen following the vertical branches that appear in the

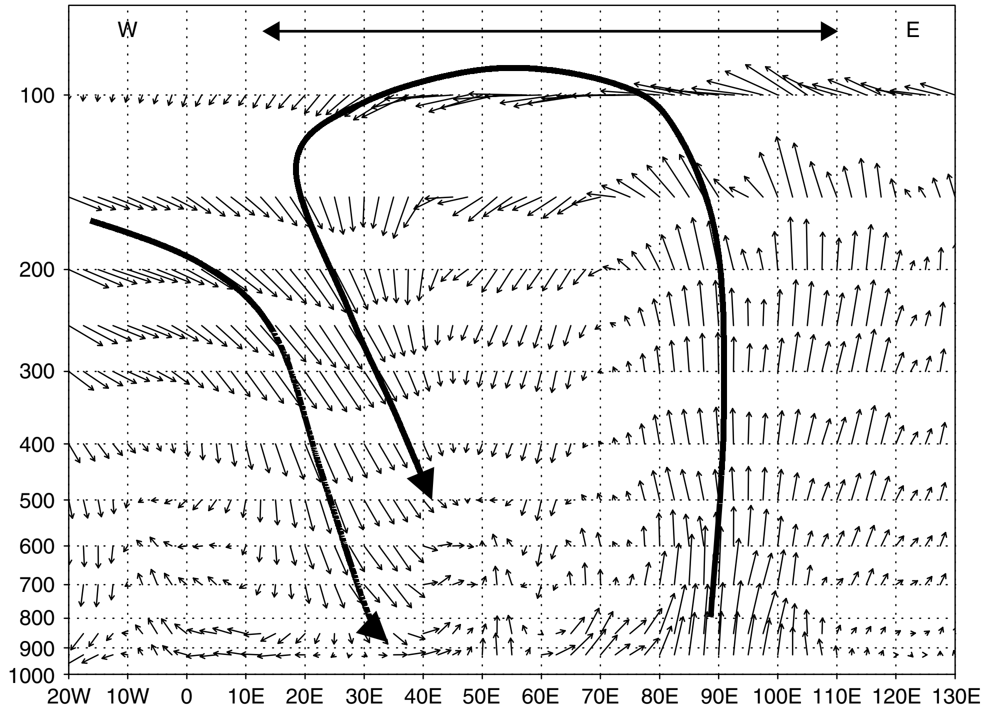

Figure 7. Vertical-zonal cross-section, averaged over the 20–35 °N latitudinal band, of wind vectors for July–August, based on the NCEP–NCAR long-term averages

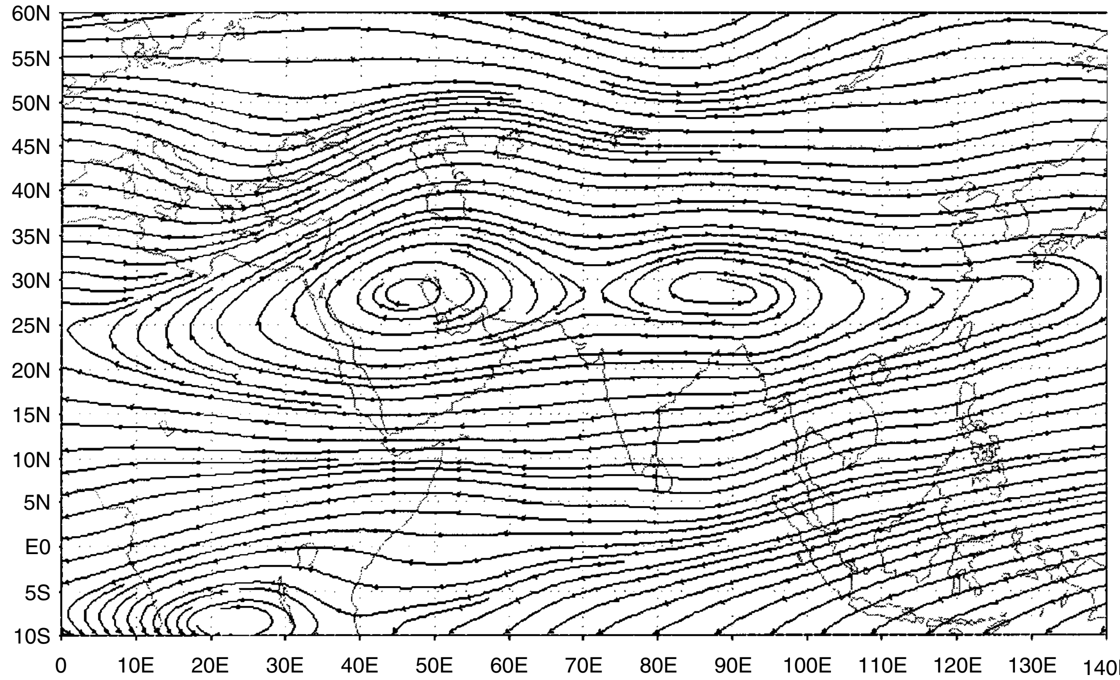

Figure 8. Isentropic cross-section of wind field for July–August at the 440 K level, based on the NCEP–NCAR long-term averages

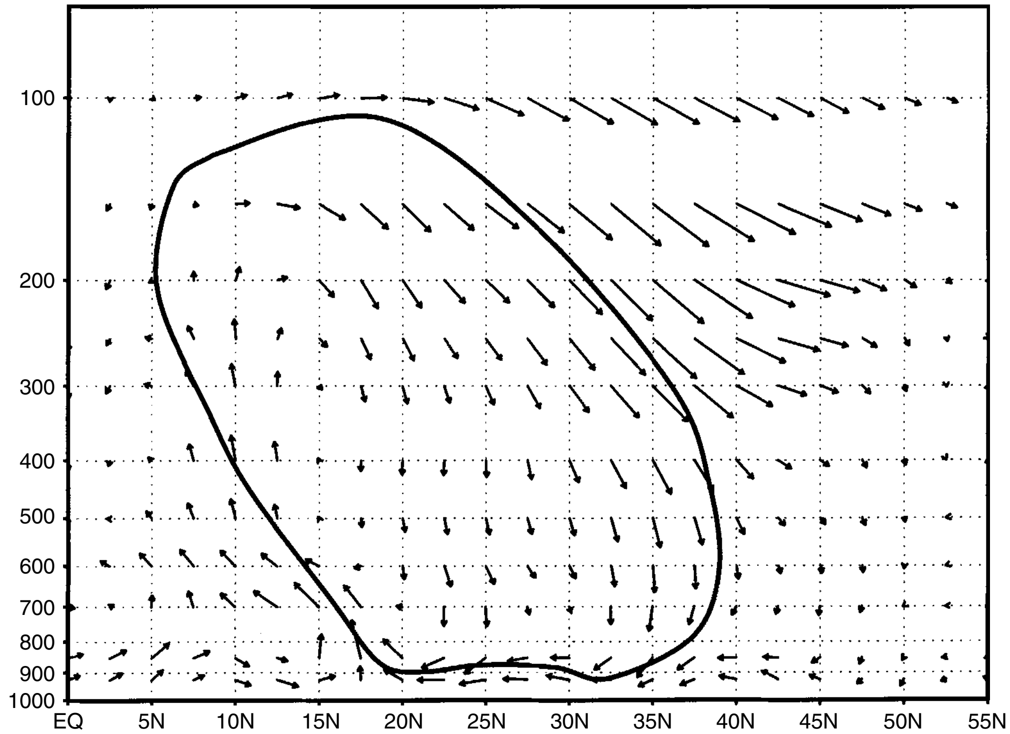

Figure 9. As Fig. 7, but in the meridional direction, averaged over 30–40 °E longitudinal band

vertical cross-sections (Figures 7 and 9) as parts of the circulations found. Then we calculated the correlations between the vertical velocities at the various levels until the most significant correlation was obtained. The correlation was then recalculated while shifting the locations until the most significant value was achieved.

The most significant correlation between mid-Asia and the EM, $r = -0.46$ (significant at the 99.5% level), was found between the 600 hPa level at 20–35 °N, 85–95 °E and the 150 hPa level at 20–35 °N, 30–40 °E. A comparison between the curves representing the interdiurnal variations of the two vertical velocities (Figure 11) demonstrates the inverse relationship between them, i.e. that they intensify and weaken more or less concurrently, but a lag of 1 day can be discerned in the timing of the peaks over the Levant with respect to that in mid-Asia. The lag-correlation between the same regions and levels yielded, indeed, a higher correlation, $r = -0.63$. The lag in the subsidence variations over the Levant with respect to the ascendance over mid-Asia emphasizes that the Asian monsoon determines the weather conditions over the Levant.

A similar procedure was applied for the correlation between the African monsoon and the EM. The most significant correlation, $r = -0.40$, was found between the 850–700 hPa average vertical velocity in eastern North Africa (15–20 °N, 30–40 °E) and the 250 hPa level over the Levant. When a time-lag of 1 day was introduced, the correlation increased to −0.46. Here, the variations over North Africa lagged those over the Levant, indicating the influence of the Levant over the eastern African monsoon. The lower correlation found between the Levant and the African monsoon is consistent with the weaker signal found in the vertical cross-section for that region (Figure 9).

The implied relationships between the Levant region and both monsoon systems may be viewed as a 'chain reaction' between the Asian and African monsoons, via the subsiding flow over the Levant. The correlation between the vertical velocities at the 'end points', i.e. the 600 hPa level over mid-Asia and the 850-700 hPa layer over eastern North Africa, was found to be 0.33, with a time lag of 2 days in Africa with respect to Asia. This supports the idea of an indirect relationship between the two monsoon systems.

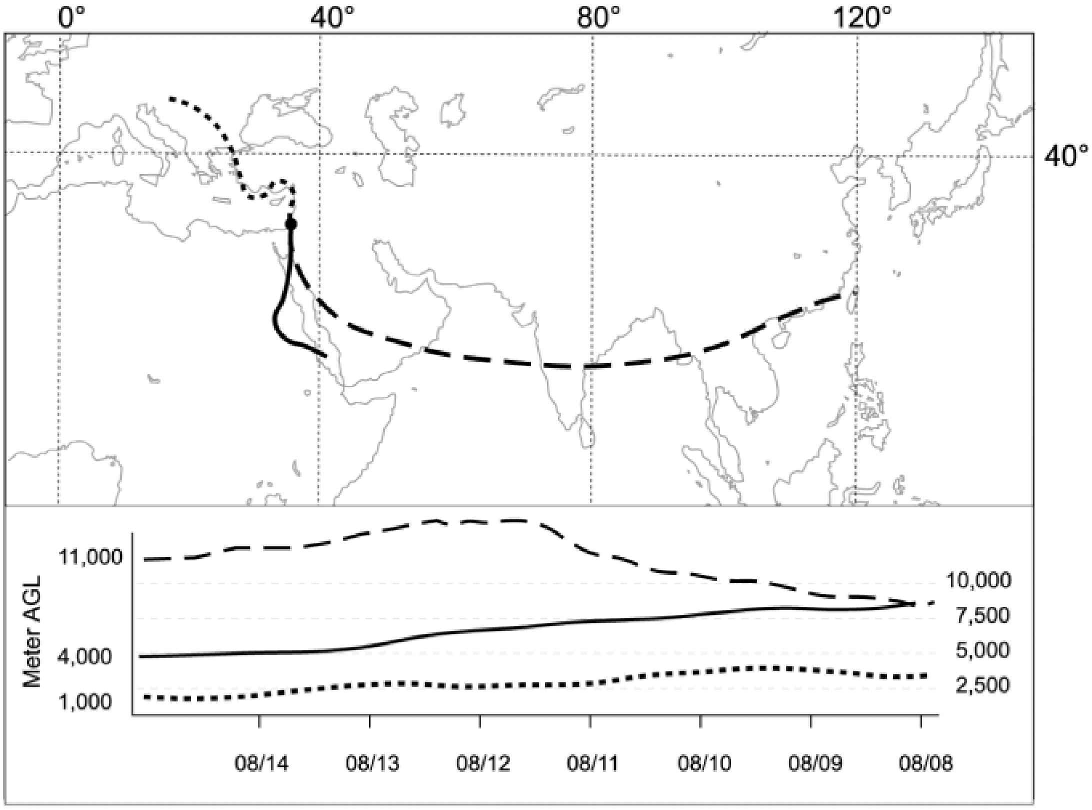

Figure 10. The 168 h back-trajectories for 15 August 1996 (randomly selected) of air entering 32.5 °N, 35 °E at 1, 4 and 11 km (using NOAA HYSPLIT4 Model (1997))

4. THE ASIAN MONSOON AS A CONTROLLING FACTOR

Our central question concerns the source of the correlation between the two dynamic factors governing the EM in July–August. Since correlation of the same sense as found here is common in eastward-moving baroclinic mid-latitude disturbances (Holton, 1992), we examined whether eastward-moving systems exist in the study region during summer. For this purpose, time–longitude sections of geopotential height anomalies at the 500 hPa level were extracted along 32.5 °N and 47.5 °N latitudes for the summer of 1996 (Figure 12(a) and (b), respectively). In these cross-sections, systems that are moving eastward are reflected by elongated features oriented from the lower-left to the upper-right direction. The expected regime was found, at least in part of the summer, only along 47.5 °N, indicating the existence of eastward-moving systems there. However, at 32.5 °N, representing the EM, no indication for moving systems was found. Therefore, it is suggested that an external factor links the subsidence and the Etesian wind to each other, namely the Asian monsoon, i.e. that variations in the intensity of the Asian monsoon control both factors at the same time and sense.

The monsoon intensity may be manifested in several ways, such as daily rainfall, mid-level ascendance or SLP over mid-Asia. An intensification of the Asian monsoon is assumed to control the EM conditions via two routes:

- An increase in the ascending motion over mid-Asia enhances the circulation connecting it with the EM (Figures 7 and 8), including the subsidence over the EM and its implied warming. This is supported by the 0.63 correlation found between them (Section 3.3).
- The increase in the ascending motion over mid-Asia also enhances the upper level divergence, resulting in a pressure drop there. As a result, the pressure gradient across the western margins of the monsoon (i.e.

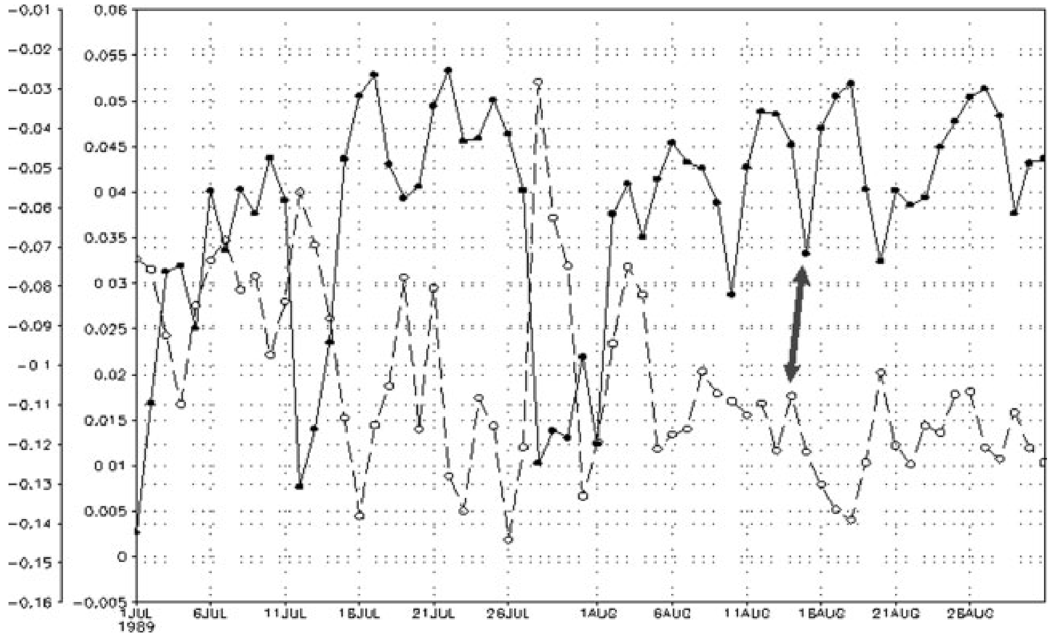

Figure 11. Interdiurnal variation of 150 hPa omega averaged over 20–35 °N, 30–40 °E (dashed, right scale) and 600 hPa 20–35 °N, 85–95 °E (solid, left scale) for July–August 1989. The two-headed arrow demonstrates the 1 day lag in the anti-phase relationship

the Levant), together with its associated Etesian winds, increases as well. This implies an increase in cool advection over the Levant.

The correlation between the interdiurnal variations of the ascending motion and the SLP over mid-west Asia (25–45 °N, 60–90 °E) for July–August 1989 was found to be 0.50. Even when the western end of the region examined was extended to 40 °E the correlation still remained 0.45. No significant correlation was found between the ascending motion over mid-Asia and the SLP over the Levant itself (25–40 °N, 30–40 °E, $r = 0.00$). The above implies that an intensification of the Asian monsoon increases the pressure gradient between the Levant and mid-Asia, and subsequently the Etesian winds. Indeed, a significant correlation (0.43) was found between the ascending motion over mid-Asia and the intensity of the Etesian winds (925 hPa) over the Levant (30–37.5 °N, 32.5–37.5 °E).

It is concluded that a strengthening (weakening) of the Asian monsoon enhances (weakens) both competing dynamic factors over the EM. The control mechanism is illustrated in Figure 13.

5. SUMMARY

The climatic regime and the dynamic factors governing the EM in the summer season were analysed. Two main dynamic factors, competing with each other, were found to affect the EM:

- the upper–mid-level subsidence
- the lower-level cool Etesian winds.

They were found to be significantly correlated with each other. This explains the annual minimum in the interdiurnal variation of the temperature over the EM in that season. The cause for this correlation was investigated. First, the possibility that they are associated with eastward-moving baroclinic systems was examined and eliminated. The focus was then shifted to the Asian monsoon as the controlling factor of the EM summer regime.

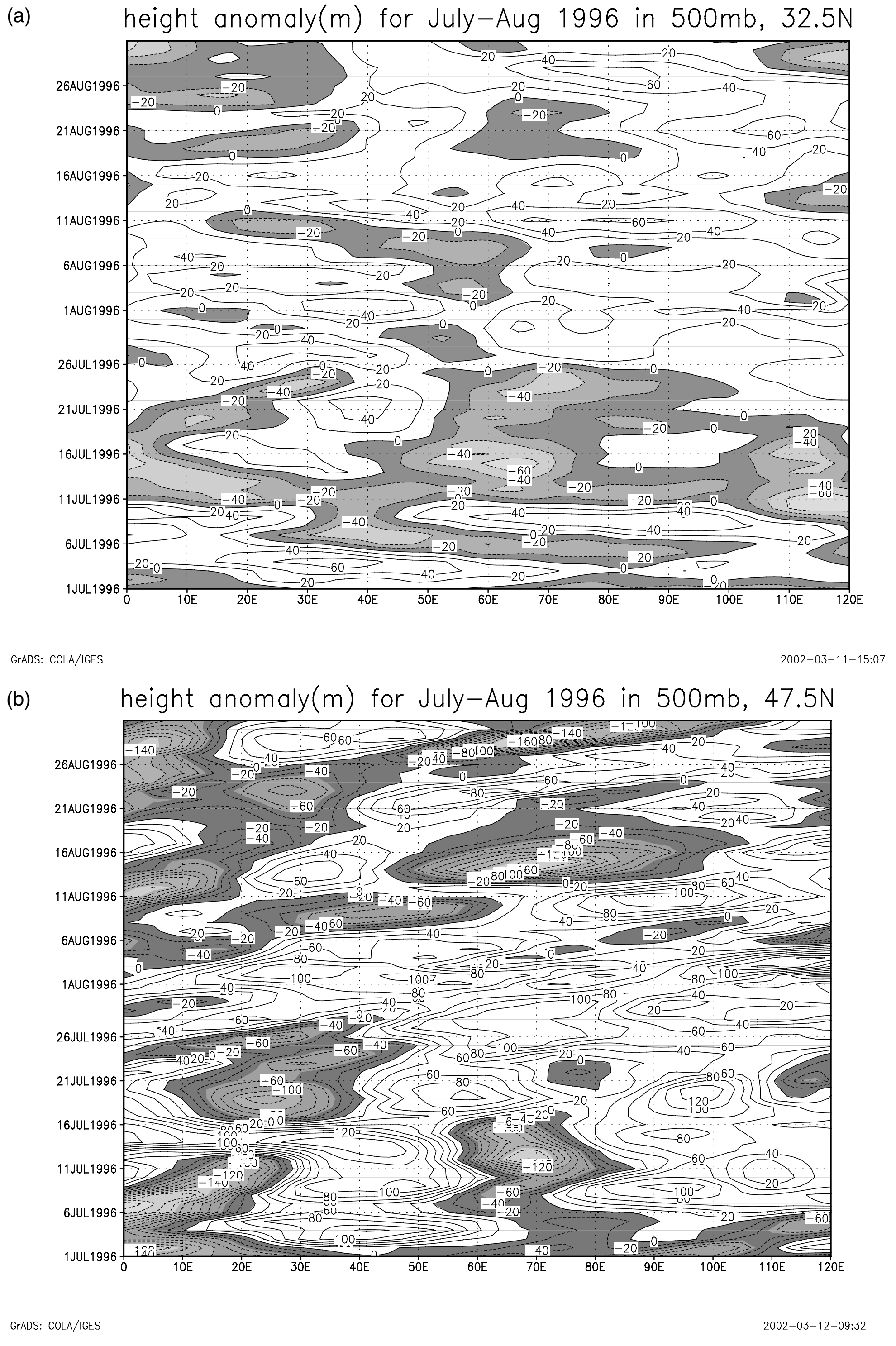

Figure 12. Time–longitude cross-section of geopotential height anomalies of 500 hPa level for 1996 along (a) the 32.5°N and (b) 47.5°N latitudes for a selected summer

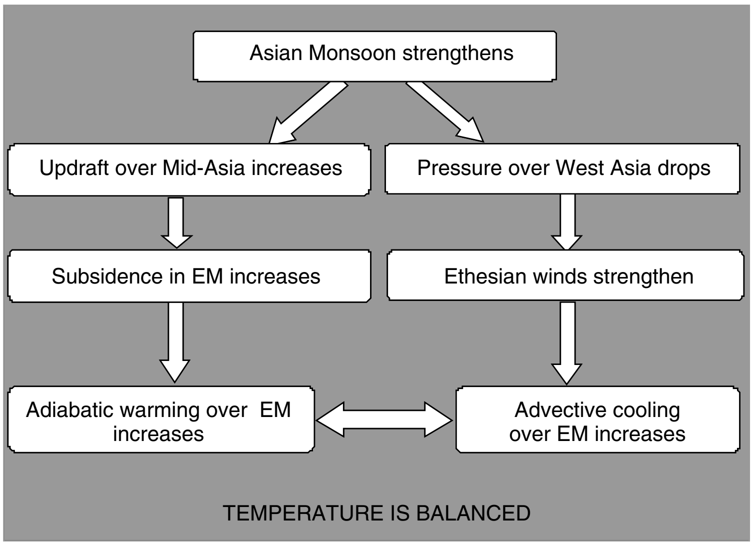

Figure 13. Schematic of the processes through which the Asian monsoon controls the lower level cool advection and mid-level subsidence over the EM in the summer season, and so stabilizes the temperature regime there

The linkage between the Asian Monsoon and the EM summer regime, particularly the mid-level subsidence, has been shown explicitly by Rodwell and Hoskins (1996). They proved, through numerical simulation, that the subsidence centre over the EM owes its location, timing of onset and intensity to the Asian monsoon, and not to the Hadley circulation. However, they did not find a distinct circulation that connects the two systems and did not examine the linkage on the interdiurnal time scale.

The zonal-vertical and isentropic cross-sections show a closed circulation connecting the upward motion maximum at 90 °E and the downward motion over the Levant. An examination of the interdiurnal variations of several dynamic variables and subsequent correlations shows that the two dynamic factors respond similarly to the variations in the intensity of the Asian monsoon. They weaken and intensify at the same time, with a 1 day lag with respect to the monsoon variations.

The vertical-meridional cross-section shows a distinct signature of the Hadley circulation over eastern North Africa, connecting the EM with the African monsoon. This suggests that the absence of a pronounced Hadley cell in the zonal average for the Northern Hemisphere in summer (Rodwell and Hoskins, 1996) can be attributed to the opposing meridional circulation of the Asian monsoon. Also, the ascending branch (15–20 °N) and the descending counterpart over the Levant were found to be significantly correlated ($r = 0.46$), with a 1 day time lag, and the variations over the EM precede those over eastern Africa. The above implies that the fluctuations in the subsidence over the EM control those in the ascending motion over eastern Africa via the northerly winds prevailing in summer over Egypt and the Red Sea. The relationship between the two monsoon systems, the Asian and African, was further validated through a 0.33 correlation between the vertical velocities in the two regions, in spite of the ~6000 km distance separating them.

Two effects were found to result from the linkage between the Asian monsoon and the EM in summer. A first-order effect is the direct control of the Asian monsoon on the interdiurnal variations of the vertical motion over the Levant, and the second the concurrent variations of the Etesian winds and the subsidence. The outcome is the balanced temperature regime over the Levant. Therefore, when the Asian monsoon, or the circulation connecting it with the EM, collapses, this balance may be broken.

A further study will extend the present one for different time scales, such as the interannual and the interdecadal. A special study will be devoted to the detailed structure of the circulations existing over the region prior to and during episodes in which the EM undergoes heat waves or exceptional cold events.

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