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ON THE LINK BETWEEN INDIAN SUMMER MONSOON AND THE ETESIAN PATTERN OVER THE AEGEAN SEA

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ABSTRACT

The Indian summer monsoon (ISM) is a key factor influencing the eastern Mediterranean climate. During early summer period, the thermal low over Pakistan and northwestern India extends towards the Mediterranean through inner Iraq and Turkey. On the other hand, the Azores high expands eastwards and meets the Balkan high pressure system, forming one common system. Greece lies at the transitional zone between these two pressure systems, where persistent northeasterly wind currents form especially over the Aegean, known as the Etesians.

The objective of this study is to investigate the interrelation between the ISM and the Etesian winds over the Aegean Sea during summer for an extended period of 44 years (1958-2001) with the aid of composite and correlation analyses and ERA 40 datasets. More specifically, the study will focus on the ISM activity during and prior to or after 'Etesian episodes' in order to determine the extent to which one system may lead another.

The present analysis reveals that during enhanced monsoon years two upper level ridges prevail over the greater area of interest, one over western Europe and northern Africa, which is part of the Azores high and a second one over Pakistan region, Persian Gulf and Middle Asia, which extends to the west and connecting to the first one forms a slight trough over Eastern Mediterranean. At lower levels, an intensification of the thermal Asian low as well as of the high pressure system prevailing over western and central Europe is apparent. Concurring with this pattern in upper and lower troposphere, anomalously strong northerlies appear over the Aegean during periods with enhanced monsoon activity, as horizontal surface wind anomalies depict. In agreement with previous studies, mid-level subsidence during excess monsoon rainfall periods is found to be more intense over the Eastern Mediterranean, Iraq, Saudi Arabia and east of the Caspian Sea.

KEYWORDS: Indian summer monsoon, Etesians, Eastern Mediterranean, composite analysis, correlation analysis

1. INTRODUCTION

During boreal summer, eastern Mediterranean (EM) regime is governed by two dynamic factors (Ziv *et al.*, 2004); the Etesian winds, which appear in a region of enhanced baroclinicity in the middle of two pressure systems, the Balkan anticyclone and the Asian thermal low, and a persistent subsidence, which has been traditionally attributed in the past to the descending branch of the Hadley cell (Rodwell and Hoskins, 1996). Previous studies have proposed the existence of a closed circuit, connecting the ascending motion over South Asia and the large-scale subsidence over the EM area (Webster, 1994; Ziv *et al.*, 2004). Other studies, implementing primitive equation models, have shown that the diabatic heating associated with the Indian summer monsoon (ISM) induces an equatorially trapped Rossby wave to the west of the heating source, which interacts with the southern flank of the mid-latitude westerlies and produces a region of adiabatic descent over North Africa and EM. The Etesians can be considered as the low-level equatorward flow that appears below the subsidence area, according to the Sverdrup balance, and thus are interrelated remotely to the ISM forcing (Rodell and Hoskins, 2001).

In this frame, the objective of this study is to investigate the interrelation between these two dynamic factors, which prevail during summer over the EM and the ISM. In- and out of phase relationship between the ISM and the atmospheric circulation over the EM region is examined, employing composite and correlation analysis with the aid of gridded monthly and daily data and composite maps. The study will focus on the ISM activity during and prior to or after 'Etesian episodes' in order to determine the extent to which one system may lead another.

2. Data and Methodology

The major dataset that was used in this work is the ERA-40 Reanalysis Data of the European Center for Medium-Range Weather Forecast (ECMWF; Uppala *et al.*, 2005), on a 2.5ºx2.5º grid and at various standard pressure levels. Geopotential height, horizontal wind components and vertical velocity data, covering boreal summers (June-September) from 1958 to 2001, were employed. Additionally, 6-hourly data of horizontal wind components in 1000hPa were used, which are available on a 1°x1° grid from the reanalysis product of the ERA Interim for summer months (June-August) of period 1997-2011, in order to identify periods of strong northerlies over the Aegean Sea ('Etesians'). The time period was selected so that it coincides with the period of rainfall data availability. A highly resolution (1°x1°) gridded daily rainfall dataset from the Global Precipitation Climatology Project (Huffman et al., 2001) was employed for the construction of the rainfall composite patterns over India during and prior to or after 'Etesian episodes'.

The All India Rainfall Index (AIRI), as was described by Parthasarathy *et al.* (1994, 1995), was employed to select the extreme ISM years. AIRI is defined as the area-weighted average of rainfall observed at well-distributed rain-gauge stations all over India and is the most widely used measure of the intensity of the planetary scale monsoon over India. Strong (weak) ISM years are defined as years when the magnitude of AIRI departs from its climatology by +0.65 standard deviation (below -0.65 sigma). As a result, twelve strong ISM years and twelve weak ISM years were derived.

Seasonal (JJAS) mean anomalies of the above mentioned data were calculated as the seasonal deviations from the climatological seasonal means for the period 1958 – 2001, separately for strong and weak ISM years. Additionally, correlation maps were constructed between the gridded monthly data and the AIRI. Statistical significance for both correlation and composite anomaly maps was calculated using a two-sided Student's *t* test. Derived anomaly composites and correlation maps of representative fields (geopotential height, zonal and meridional wind components) are presented.

Daily mean 1000 hPa wind direction and speed were calculated for all the JJA days during the ERA Interim period, which then were averaged over the Aegean Sea (23.5-28.5ºE, 35-41ºN). 'Etesian days' were set as days when the average wind direction over the Aegean was between 40ºW and 30ºE and the average intensity was over 4 m/sec (Tyrlis *et al.*, 2011). Finally, composite rainfall anomalies over India were calculated for a period of 15 days prior and after the onset of the Etesian episodes respectively.

3. Results and Discussion

3.1. In-phase relationship

The spatial correlation between the geopotential height at 850 hPa (Z850) and AIRI is depicted in Figure 1. The correlation pattern reveals that an intensifying ISM is accompanied by an enhanced Azores subtropical anticyclone and a deeper Asian thermal low. At the same time the central Europe anticyclone appears enhanced during strong ISM years and expands over the Balkan region and the EM. Greece lies in the middle of two anomaly fields, the central Europe high and its extension, the Balkan anticyclone on the one hand and the Asian thermal low on the other hand. As a result meridional flow is established over the EM, as a strong east-west pressure gradient appears/following the meridional orientation of the isobars in the region.

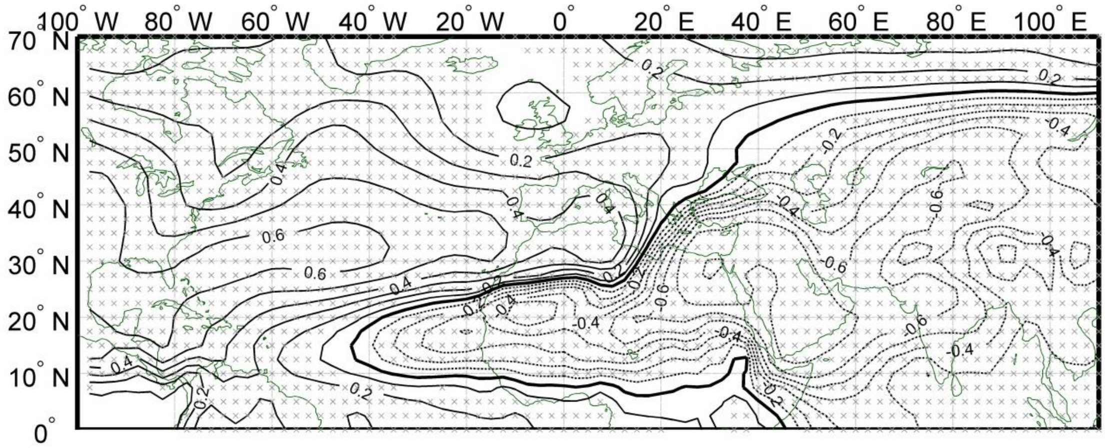

Figure 1. Correlation map between monthly anomalies of Z850 and AIRI. Dashed contours correspond to negative values, solid contours to positive values and thick solid contours to zero. Grid points where the correlations meet the 99% confidence level are denoted with "x" symbols. Contour interval is 0.1.

Figure 2 illustrates the correlation between the velocity field, in the lower (Figure 2a), middle (Figure 2b) and upper troposphere (Figure 2c), and AIRI. Enhanced northeasterly winds that are associated with above normal ISM are evident over central and eastern Mediterranean. This anomalous northerly current prevailing over EM corresponds to the Etesian winds blowing over the Aegean Sea during summer. At the same time, enhanced southwesterly winds are apparent over the Arabian Sea and Indian peninsula during strong ISM years, as expected.

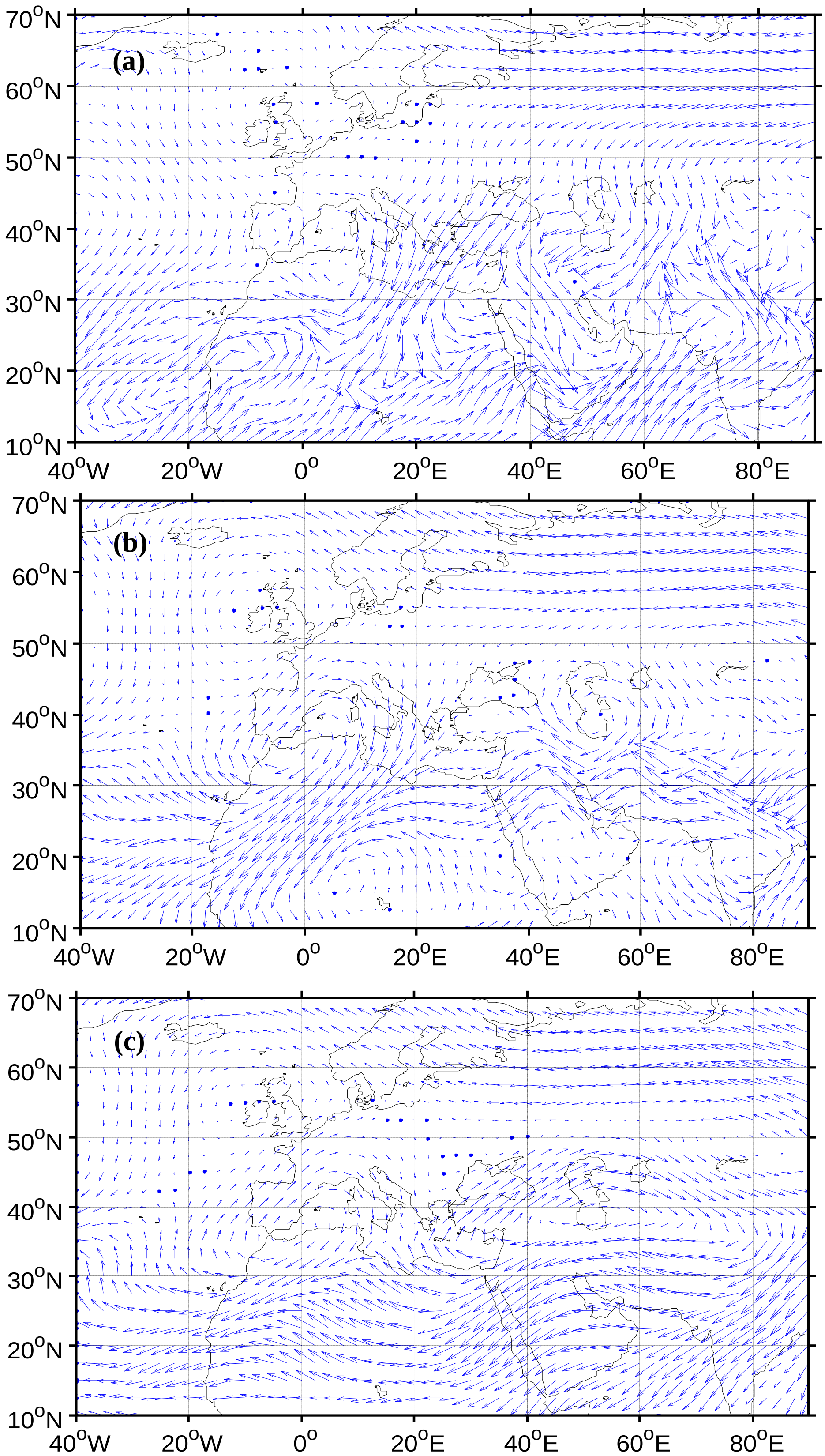

Figure 2. Correlation spatial pattern, between AIRI and a) velocity in 850 hPa, b) velocity in 500 hPa and c) velocity in 300 hPa.

In the upper troposphere (Figure 2c), the correlation map between the wind velocity and AIRI represents a regime being characterized by a strong anticyclonic flow over west-central Asia, a weaker anticyclone over western-central Europe and western Mediterranean and a weak cyclonic flow over the British Isles. Prominent features are the westerly subtropical jet, which appears meridionally, being shifted to the north, and the easterly tropical jet, which extends poleward of its mean position, up to 30° N. Over EM the wind blows from southerly directions while over central Mediterranean the wind is weak and still of a north direction. On the other hand, in the middle troposphere (Figure 2b) a weak northerly flow is still evident over EM, while over the central Mediterranean the northern flow remains strong. The above findings are strongly related with the manifestation of the Etesians in the lower troposphere and the shallow Pakistan (thermal) low that plays a crucial role in the formation of the Etesians.

The corresponding seasonal anomalies in the 500 hPa geopotential height (Z500) are displayed in Figure 3. It is evident that an intensifying ISM is accompanied by strong positive anomalies centered over central and northern Europe while the central and western Mediterranean lie at the southern margin of this anomaly pattern. Positive anomalies are also found over west-central Asia, where the central Asian high is established in the upper troposphere (300 hPa). The central Mediterranean is dominated by significant large-scale positive anomaly, whereas the EM is influenced by significant negative anomalies. The presence of an anomaly trough over EM, extending from northwestern Russia to the south and west, reaching the eastern part of the Mediterranean, may contribute to a transfer of cold air masses above the area which can substantially reinforce the low pressure system that covers EM on the surface (Arseni-Papadimitriou *et al.*, 1987).

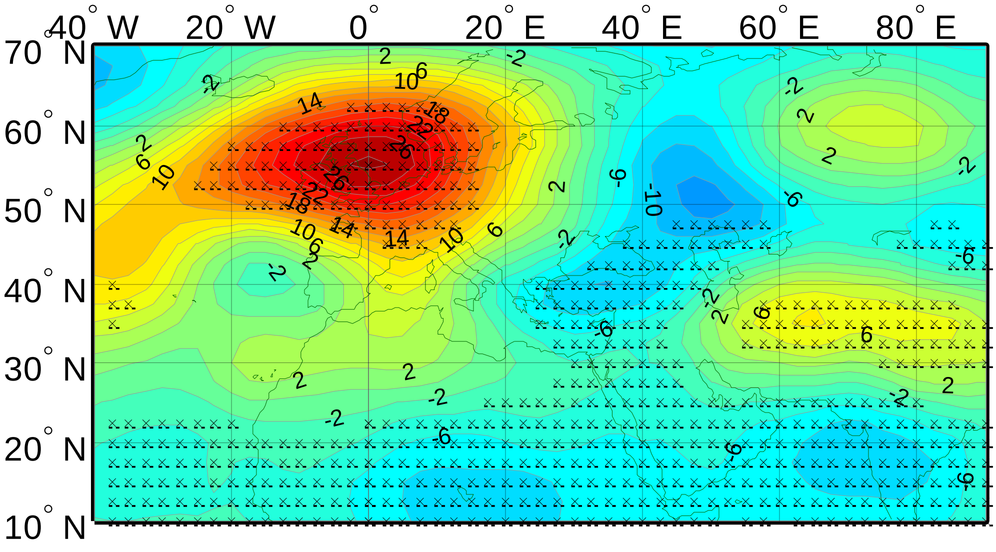

Figure 3. Composite difference in Z500 (gpm) between strong and weak ISM years. Grid points with anomalies that are significantly different from zero above the 90% confidence level are denoted with "x" symbols.

Regarding the vertical motion, the 500 hPa vertical velocity (ω) anomaly fields (not shown) depict anomalous subsidence over the EM for the strong ISM years while an anomalous upward motion in the weak ISM years. The correlation map between AIRI and ω (Fig. 4) shows that significant positive correlations are found over central and eastern Mediterranean, implying subsidence in the area during strong ISM years and that significant negative correlations exist over the Indo-Pakistan region and the northern part of the Arabian Sea, which correspond to enhanced ascending motion during strong ISM years. Weak but significant negative correlations between AIRI and ω are also found over a large area in the tropics, stretching from tropical Africa till the Bay of Bengal, indicative of the enhanced convection over these areas during strong ISM years.

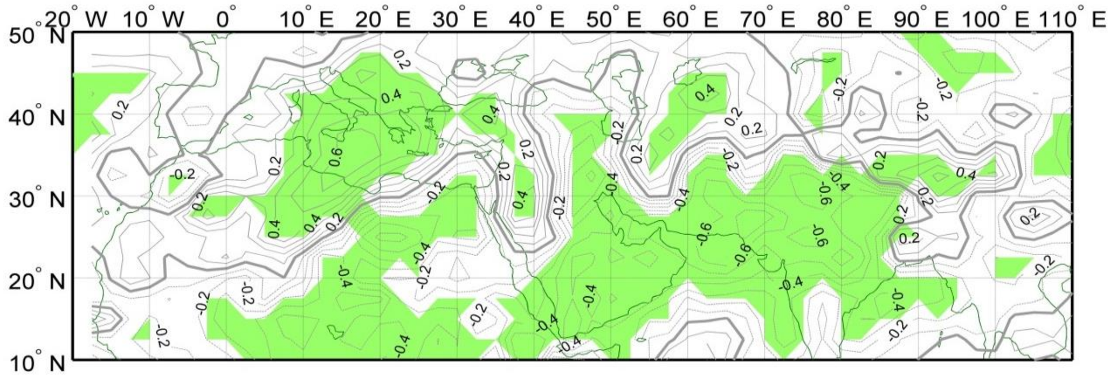

Figure 4. Correlation map between anomalies of monthly 500 hPa vertical velocity and AIRI. Dashed contours correspond to negative values, solid contours to positive values and thick solid contours to zero. Correlations meeting the 99% confidence level are shaded. Contour interval is 0.1.

4.2. Out of phase relationship

The anomaly rainfall patterns for -7 and +7 days relative to the onset of the Etesian episodes are depicted in Figure 5 (*a* and *b* respectively). It becomes evident that the most significant anomalies among a period of 15 days leading and 15 days, lagging the Etesians' onset. The composite pattern of the daily rainfall anomalies for 7 days prior to the onset of the Etesian episodes (Figure 5a) shows that the western part of India experiences excess rainfall, especially the Western Ghats region. Positive anomalies cover central India, Arabian Sea and eastern Bay of Bengal as well, while over the northern Bay of Bengal and Bangladesh there is evidence of negative rainfall anomalies. The aforementioned pattern resembles the composites of rainfall anomalies for strong monsoon years that have been presented in previous studies (i.e. Krishnamurthy and Shukla, 2000). The rainfall anomalies for 7 days lagging the onset of the Etesians depict strong positive anomalies over the north-eastern part as well as the south-western part of India. Weak negative anomalies are found over central India. The latter pattern corresponds to the onset phase of the ISM and the former one to the persistence state of the ISM (Krishnamurthy and Shukla, 2000).

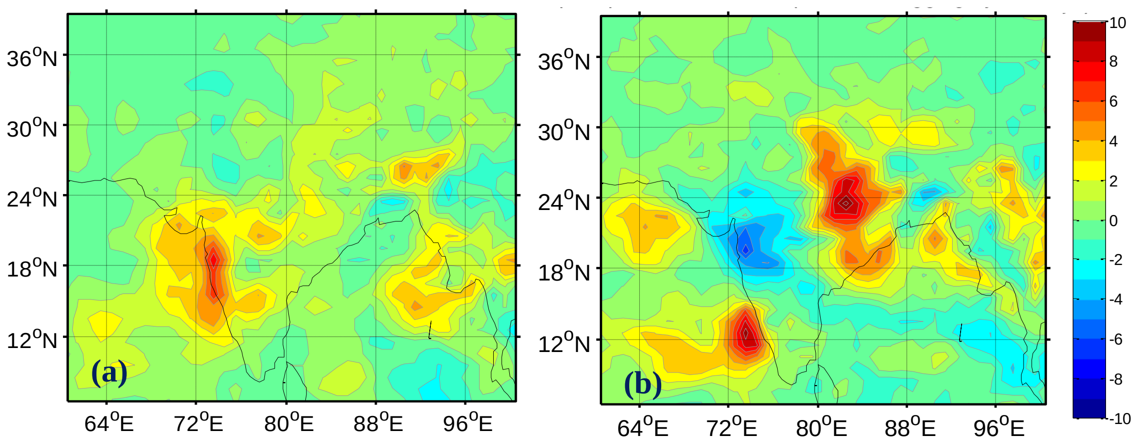

Figure 5. a-b) Composite rainfall anomalies for -7 and +7 days relative to the onset of JJA Etesian episodes, respectively (in mm/day).

5. CONCLUSIONS

In this study, eastern Mediterranean regime during boreal summer was investigated under the influence of the ISM. An intensification of the central Europe anticyclone and the thermal Asian low was found during strong ISM years. As a result, enhanced northerlies appear to dominate over central and eastern Mediterranean in the lower troposphere, the so called Etesian winds, blowing over the Aegean sea. In the middle troposphere, there is slight evidence of the Etesian pattern while in the upper troposphere the flow is reversed over the EM. At the same time, enhanced mid-level subsidence was identified over the EM, which appears synchronously with enhanced ascend over the Indo-Pakistan region. These two dynamic factors, the Etesian winds and mid-level subsidence over EM, are found to be enhanced during strong ISM years. Moreover, they are expected to compete with each other regarding their influence on the temperature regime of the area. Finally, a first attempt to further examine the ISM behavior before and after the onset of the Etesians revealed that a week before the onset of the Etesian episodes the ISM appears to be in a state of fully establishment. On the other hand, a week after the Etesians' burst the ISM appears as in a break or onset phase.

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