GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L15708, doi:10.1029/2008GL034515, 2008

Intra-seasonal atmospheric variability and extreme precipitation events in the European-Mediterranean region

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Received 30 April 2008; accepted 7 July 2008; published 9 August 2008.

[1] The low frequency atmospheric variability over the European-Mediterranean region is described by the weather regimes, obtained by using a clustering algorithm applied on the September-December geopotential height at 500 hPa. Links between the European-Mediterranean weather regimes and extremes of precipitation over Europe are examined. We focus on the autumn season, when heavy precipitation episodes are likely to occur over the Mediterranean coasts. In the second part of this paper, we study whether the European-Mediterranean weather regimes can be related to the phases of some intra-seasonal atmospheric oscillation. By using the Multi-Channel Singular Spectrum Analysis (MSSA), we identify a 50-day oscillation over the European-Mediterranean region. The phases of this oscillation are found to be consistent with the preferred weather regimes transitions. This could influence intra-seasonal predictability and suggests that links between the episodic (weather regimes) and oscillatory (intra-seasonal oscillations) approaches may also apply to the regional scale. **Citation:** Sanchez-Gomez, E., L. Terray, and B. Joly (2008), Intra-seasonal atmospheric variability and extreme precipitation events in the European-Mediterranean region, *Geophys. Res. Lett.*, *35*, L15708, doi:10.1029/2008GL034515.

1. Introduction

[2] Large-scale atmospheric circulation is frequently described in terms of a few of preferred and recurrent patterns in the atmospheric state space, the so-called weather regimes. They are commonly identified through clustering analysis [*Michelangeli et al.*, 1995], that determines a few number of atmospheric patterns spatially well-defined. The low-frequency atmospheric variability can be characterized by the alternation between the weather regimes and their transitions. A number of studies identified 4 weather regimes for the North Atlantic sector [*Vautard*, 1990]. These large-scale patterns contribute to a significant fraction of the daily to seasonal variability of the European weather. Links between the weather regimes and local extremes episodes have been also examined for different regions in mid-latitudes [*Robertson and Ghil*, 1999; *Yiou and Nogaj*, 2004; *Cassou et al.*, 2005]. It has been shown that transitions between the weather regimes are also associated with extreme events occurrence [*Sanchez-Gomez and Terray*, 2005].

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0094-8276/08/2008GL034515$05.00

[3] In this work, we identify the weather regimes for the European-Mediterranean region, which has peculiar characteristics because of its location and morphology. The southern part of the region is mostly under the influence of the descending branch of the Hadley cell, while the northern part is more linked to the mid-latitude variability (the North Atlantic Oscillation (NAO) and other mid-latitude patterns). Mediterranean climate presents a strong seasonal and land-sea contrast, and it is often the theatre of climate extreme episodes, as heat waves and heavy precipitation. In particular, in autumn, western Europe is regularly affected by extreme precipitation events (EPE), that produce important societal damages [*Nuissier et al.*, 2008].

[4] The second objective of this work is to assess whether European-Mediterranean weather regimes can be related to the phases of some intra-seasonal atmospheric oscillation. Previous works [*Plaut and Vautard*, 1994; *Kondrashov et al.*, 2004] have used the Multi Channel Singular Spectrum Analysis (MSSA) to identify low frequency atmospheric oscillations connected to Northern Hemisphere weather regimes. We apply the MSSA method to search for intra-seasonal oscillations over the European-Mediterranean sector. We examine the relationships between the oscillation phases and weather regimes. This study can help to understand some aspects of the low frequency atmospheric dynamics on the Mediterranean region, as the transitions between weather regimes. We also examine the links between the phases of the European-Mediterranean intra-seasonal oscillation and the occurrence of EPE at local scale over two selected regions in the Mediterranean basin.

[5] The outline of this paper is as follows: Data are presented and a brief review of the statistical methods is given in section two, the results are summarized in section three and discussed in section four.

2. Data and Methodology

[6] The atmospheric variable used to characterize the European-Mediterranean weather regimes is the geopotential height at 500 hPa (Z500) from the ERA40 reanalysis dataset [*Uppala et al.*, 2005]. The spatial domain is (20°W–45°E, 20°N–60°N). European-Mediterranean weather regimes are identified by clustering analysis based on the *k-means* partitioning algorithm [*Michelangeli et al.*, 1995]. Before the classification, a Principal Component Analysis (PCA) is performed for the Z500 anomalies, computed by removing the seasonal cycle. Then the *k-means* algorithm is applied to the first 10 principal components, capturing about the 90% of the total variance.

[7] Links between the European-Mediterranean weather regimes and EPE, are examined with daily precipitation records from the European Climate Assessment (ECA)

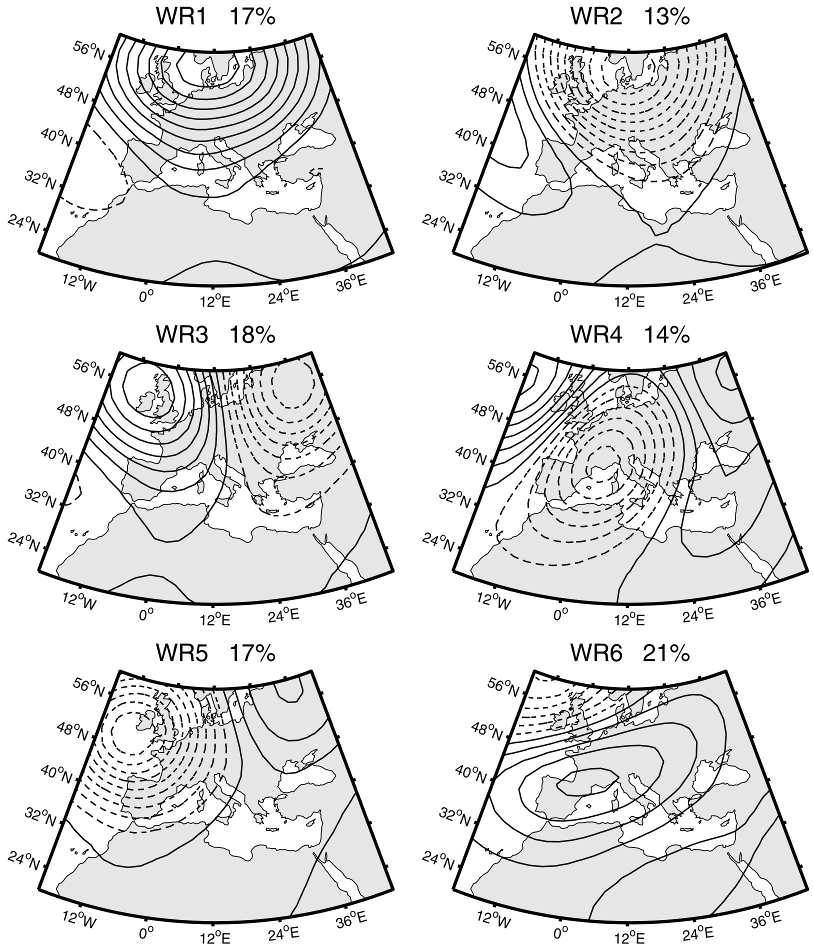

Figure 1. European-Mediterranean weather regimes obtained from the September–December Z500 field by using the *k-means* clustering algorithm. The isolines are the Z500 composite (solid lines are positive and dot dashed are negative values). Contour interval is 20 gpm. The mean frequency of occurrence for each weather regime is also indicated.

[*Klein-Tank et al.*, 2002]. We focus on the autumn season, from September to December, when EPE are likely to occur specially in western Mediterranean coast. EPE are defined simply as those days exceeding the 95th percentile of the daily precipitation values. As pointed by *Yiou and Nogaj* [2004], a definition of extremes based on a threshold value is preferred when the variable distribution is not Gaussian. The choice of 95th percentile allows for events presenting large deviations of the climatological values and a reasonable number of EPE required to our study. Relationships between weather regimes and EPE are analysed by determining whether the occurrence of a given regime modifies the probability to have a EPE episode.

[8] Intra-seasonal atmospheric oscillations over the European-Mediterranean region are identified by using the MSSA method [*Plaut and Vautard*, 1994; *Ghil et al.*, 2002]. The daily Z500 anomalies from January to December are previously filtered by a PCA, retaining the first leading eigenmodes. The associated coefficients, the principal components, are called the channels. The MSSA consists of diagonalizing the lag-covariance matrix of the multichannel time series, with lags ranging between 0 to M-1, where $W = M\Delta t$ is called the window length with Δt the sampling interval. We use as window length W = 90 days, that allows the distinction of oscillations with periods in the range (18,90) days. An oscillatory pattern is formed by two consecutive eigenmodes when their values and associated frequencies are nearly equal, and the two corresponding eigenvectors and the associated coefficients are in quadrature. The original Z500 field is reconstructed from the oscillatory mode identified by MSSA, and thus the signal is extracted from the raw data. Statistical significance of the eigenmodes is assessed by testing the null hypothesis of red noise, by constructing surrogate time series for each channel [*Allen and Smith*, 1996]. Once the Z500 field is reconstructed with the oscillatory components of interest, the technique of phase composite [*Moron et al.*, 1998] is applied to obtain the oscillation patterns in the physical space. We select eight categories (phase one to phase eight) and we construct eight composites by averaging over the different phases.

3. Results

3.1. European-Mediterranean Weather Regimes

[9] After applying the *k-means* algorithm, the optimal partition is obtained for k = 6 European-Mediterranean weather regimes (Figure 1). The first weather regime (WR1) presents a blocking cell centred over Scandinavia

Table 1. Probability of Transition Percent[a]

	WR1	WR2	WR3	WR4	WR5	WR6
WR1	–	6.2	**34.0**	11.3	20.6	27.8
WR2	12.9	–	24.2	17.7	**19.4**	25.8
WR3	20.2	**19.1**	–	12.8	19.1	**28.7**
WR4	19.7	**19.7**	18.2	–	22.7	19.7
WR5	**23.5**	9.4	*7.1*	**23.5**	–	**36.5**
WR6	**31.6**	14.9	**25.4**	10.5	17.5	–

[a]Relative frequency of occurrence (%) of a weather regime transition. The sense of the transition goes from the left to the right. Significant probabilities at the upper (bold) and lower (italics) 95% significance level are indicated.

that dominates the whole Mediterranean basin. The WR2 can be considered as nearly the opposite pattern to WR1, with a strong low over Europe. The WR3 is a clear dipole between eastern (negative anomalies) and western (positive anomalies) Europe. The WR4 and WR5 display a strong negative anomaly located over the Lyon Gulf and the British Islands respectively. Both regimes are associated with positive anomalies in eastern Europe. Finally the WR6, which presents the highest residence frequency (21%), can be viewed as the positive phase of the NAO.

[10] For the identification of weather regimes all the days are classified in a first stage. Then, we determine the transition days as described by *Sanchez-Gomez and Terray* [2005] for the 4 North Atlantic weather regimes. In this work, since the number of weather regimes is high, we reduce the duration of a weather regime episode from 4 to 3 days. Table 1 summarizes the probabilities for the 30 weather regimes transitions. Statistical significance of transitions is addressed by a Monte Carlo test consisting of randomly reordering the sequence of weather regimes episodes [*Kondrashov et al.*, 2004].

[11] Relationships between European-Mediterranean weather regimes and EPE are examined in terms of the relative changes in the probability of EPE occurrence when a weather regime is present (Figure 2). As an example, a change of 100% corresponds to the multiplication by 2 of the probability for EPE to happen. WR1 and WR3 are associated to a decrease of EPE probability in most of Europe, although the WR1 favours locally the EPE occurrence over the Spanish and French coasts. For WR1 the maritime air entrance over the Lyon Gulf combined with the persistent blocking cell favours the heavy precipitation values to accumulate over several days. When WR2 is present, the probability of EPE occurrence increases significantly in most of Europe, except for the Spanish and French coast and Scandinavian Peninsula. WR4 favours the risk of EPE in eastern Europe, specially over the Balkan Peninsula. WR5 is associated with a sharp increase of probability of EPE occurrence in western Europe. This structure can be identified as the Scandinavian pattern [*Barnston and Livezey*, 1987], which has been connected to the anomalous wet conditions over UK in autumn 2000 [*Blackburn and Hoskins*, 2001]. The WR6 shows the signature of the positive phase of the NAO, with an increase of EPE probability over northern Europe and a decrease in the south. Once the European-Mediterranean weather regimes and their links with EPE are examined, we investigate whether the oscillatory approach can be related to weather regimes transitions.

3.2. European-Mediterranean Intra-Seasonal Oscillation

[12] By applying MSSA on the Z500 data, we identify a oscillatory mode with period of 50 days. This oscillatory pattern is formed by the components three and four that explain 5.2% of variance of the total field. To examine the oscillation sequence in the physical space, we construct the eight phase composites for the autumn season (Figure 3). The 50-day European-Mediterranean oscillation is a succession of positive and negative geopotential anomalies that propagates westward over Europe. We determine the correspondence with the weather regimes by examining the number of days corresponding to each regime, and simultaneously belonging to the categories of the 50-day European-Mediterranean oscillation (Table 2) [*Plaut and Vautard*, 1994]. The spatial similarity between the weather regimes and the phases of the oscillation show the link between the two approaches. In view of results in Table 2, the phases of the 50-day oscillation are consistent with the following sequence of preferred transitions in Table 1: WR1 → WR3 → WR2 → WR5.

[13] This result confirms the view of weather regimes transitions governed in part by regular phenomena rather than by purely random atmospheric disturbances. This fact has important consequences for the predictability of atmospheric conditions and even of the extreme events occur-

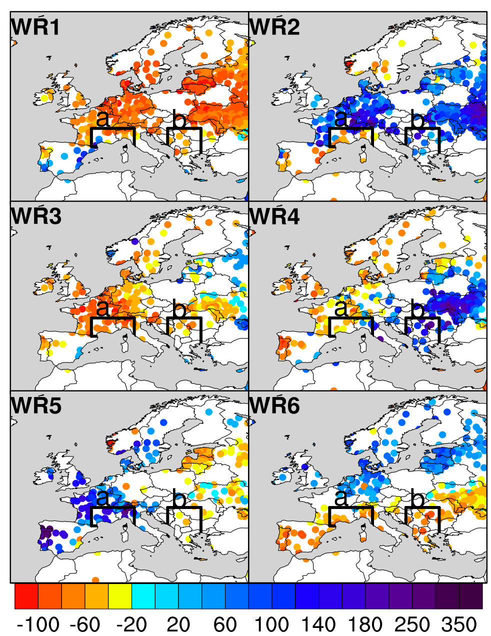

Figure 2. Relative changes (%) in probability of EPE occurrence for the European-Mediterranean weather regimes for the autumn season. Positive (negative) values indicate an increase (decrease) of likelihood for an EPE to occur. A significance test is elaborated by determining the empirical confidence limits by creating a number of artificial time series. Only the stations where the values are significant at 95% are plotted. Zone a is defined as 2°E–11°E, 42.5°N–46.5°N. Zone b is defined as 18°E–25°E, 35.5°N–46.5°N.

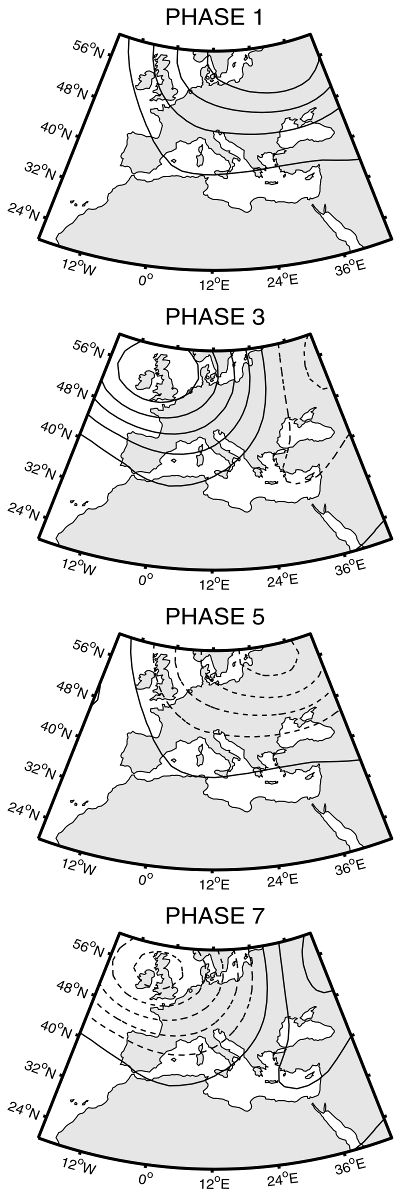

Figure 3. Sequence of the intra-seasonal oscillation (period = 50 days) for the European-Mediterranean region, obtained using the phase composite technique [*Moron et al.*, 1998]. The isolines are the Z500 anomalies (solid lines are positive and dot dashed are negative values). Contour interval is 10 gpm.

rence on Mediterranean region. Following this idea, we examine the links between the 50-day oscillation and the EPE over two specific regions in the domain (Figure 2). We compute the linear correlation between any day exceeding the 90% (EPE90), 95% (EPE95) and 99% (EPE99) percentiles and each of the phases. Then we construct the histogram of probability for EPE occurrence displayed in Figure 4. We observe that, for the Lyon Gulf coast region (domain a), the risk of EPE90 and EPE95 occurrence starts at phase six, it amplifies to 15% in phase seven and eight, and disappears for phase one. These results are consistent with the changes in probability of EPE occurrence in Figure 2. The large-scale atmospheric Z500 pattern characteristic of EPE occurrence on the Lyon Gulf region is often associated to a blocking cell located north-eastern Europe, sometimes accompanied by a strong low centred over the British islands [*Romero et al.*,

Table 2. Weather Regimes[a]

Phase	WR1	WR2	WR3	WR4	WR5	WR6
PH1	**118**	10	46	43	56	51
PH2	**147**	16	82	36	25	**62**
PH3	**111**	25	**104**	28	11	**59**
PH4	**71**	46	**119**	29	16	49
PH5	13	89	**93**	27	44	**74**
PH6	17	**90**	47	31	85	**65**
PH7	8	46	31	60	**120**	42
PH8	43	36	24	67	**86**	45

[a]Number of days corresponding to each European-Mediterranean weather regime (columns) and simultaneously belonging to the phases of the 50-day European-Mediterranean oscillation (rows). Significant values at 95% level are indicated in bold. The statistical significance is assessed by randomly reordering the weather regimes classification 1000 times and performing the same counting algorithm [*Plaut and Vautard*, 1994].

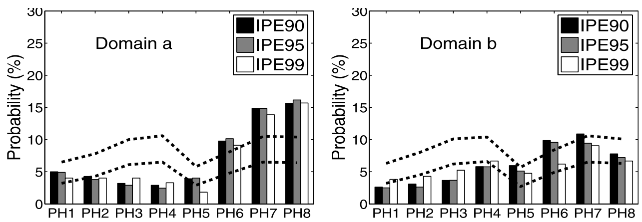

Figure 4. Probability of EPE occurrence (threshold values 90%, 95%, 99%) over two selected domains (black boxes in Figure 2) for the eight phases of the intra-seasonal European-Mediterranean oscillation. Dotted lines represent the upper and lower 5% significance limits. The statistical significance is assessed by performing a random selection the days (not necessarily EPE) from the whole dataset and recalculating the probabilities for each phase. This procedure is repeated 1000 times.

2006]. For the Balkan Peninsula (domain b), EPE are likely to occur during the phases six and seven.

4. Conclusions

[14] The large scale atmospheric dynamics on the European-Mediterranean region is characterized in terms of 6 weather regimes obtained by cluster analysis applied to the Z500 daily anomalies. This study shows a link between these large–scale patterns and the extreme precipitation events over the domain, indicating that European-Mediterranean weather regimes can provide a good description of climate variables at local scale. We investigate whether the weather regimes can be related to the phases of an intra-seasonal atmospheric oscillation. By using the MSSA technique, we identify a 50-day European-Mediterranean oscillation, characterized by a sequence of negative and positive Z500 anomalies moving from east to west. This oscillation may be associated to the westward traveling perturbations (WT) described by *Doblas-Reyes et al.* [2001]. By space-time spectral analysis they determined an oscillatory mode of 20-40 days period over the European-Mediterranean sector. The WT perturbations are governed by Rossby waves dynamics and their variance is stronger in regions where the mean zonal flow is weak. Analyzing the correspondence with the European-Mediterranean weather regimes, we find the transition WR1 → WR3 → WR2 → WR5 to be consistent with the phases of the oscillation. Our results confirm the links between episodic (weather regimes) and oscillatory approaches. Weather regimes can then be viewed as being part of an oscillatory and thus a potentially predictable phenomenon. This may have an impact on the intra–seasonal range atmospheric forecast.

[15] Further work would be needed to investigate whether the interactions between the tropical phenomena, such as the African and Asian monsoons, and the atmospheric dynamics on the European-Mediterranean region play a role in generating or modulating the intra–seasonal oscillations.

[16] **Acknowledgments.** The ACI French Institutution (CYPRIM project) has provided the financial support of this work. A special thanks is directed to the three anonymous reviewers and the editor for their useful remarks.

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