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Key Points:

- Dry spell is defined as a number of consecutive dry days
- Seventy-six very long dry spell events are detected during the wet season in the Mediterranean Basin for the 1957–2013 period
- A slight increase in the cumulative number of days affected by VLDS events per wet season is observed

Correspondence to:

F. Raymond,
florian.raymond@u-bourgogne.fr

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Extreme dry spell detection and climatology over the Mediterranean Basin during the wet season

Florian Raymond¹, Albin Ullmann¹, Pierre Camberlin¹, Philippe Drobinski², and Carmela Chateau Smith³

¹Centre de Recherches de Climatologie, Biogéosciences, Université de Bourgogne Franche-Comté, CNRS, Dijon, France,

²IPSL/LMD, Ecole Polytechnique, Palaiseau, France, ³UFR S.V.T.E, Université de Bourgogne Franche-Comté, Dijon, France

Abstract The E-OBS precipitation gridded data set v.10.0 is used to detect very long dry spell (VLDS) events over the entire Mediterranean Basin for the 1957–2013 period, during the wet season (September to April). The main objective is to characterize these events as climatic objects, in terms of location, spatial extent, duration, and temporal variability. In this study, 76 VLDS events were detected in the Mediterranean Basin and grouped into four spatial patterns: scattered localized (with 25 events), northeast Mediterranean (11 events), West Mediterranean (15 events), and southeast Mediterranean (25 events). Each pattern shows seasonality in events. Most of the scattered localized, northeast, and southeast events begin in September, at the beginning of the wet season. In contrast, most of the West Mediterranean events begin in the middle of the wet season. Over time, there is a slight but not significant increase in the cumulative number of days per season affected by VLDS events.

1. Introduction

The Mediterranean climate is characterized by long, hot, dry summers, and mild winters during which rainfall occurs. The Mediterranean Basin is considered to be a major “hot spot” subject to strong warming and drying [Intergovernmental Panel on Climate Change, 2013], with increasing consequences on drought occurrence and severity. An absence of rain over long periods during the wet season may have strong environmental and societal impacts with, for instance, an increasing demand for irrigation to meet agricultural needs and therefore increasing pressure on global water resources [Plan Bleu, 2014].

Absence of precipitation during long periods lowers groundwater levels, possibly leading to restrictions on irrigation in the subsequent months. Likewise, long periods without precipitation during the wet season deplete soil moisture and put rainfed crops at risk. Rainfed systems are still very important in Mediterranean countries (64% of cultivated areas in Italy and 90% in Morocco) [Jacobsen *et al.*, 2012], and most smallholder farmers are reliant on them. Soil moisture depletion also promotes the development of summer heat waves [Ferranti and Viterbo, 2006; Zampieri *et al.*, 2009; Stefanon *et al.*, 2012a, 2012b, 2014a], which can increase crop depletion through heat stress [Wang *et al.*, 2004; Bauweraerts *et al.*, 2013; Stefanon *et al.*, 2014b].

Recent studies using in situ measurements have highlighted worsening drought conditions in the Mediterranean Basin during the twentieth century. Gonzalez-Hidalgo *et al.* [2001] showed an increase in drought conditions in the eastern part of the Iberian Peninsula (decrease in amount of winter rainfall), while Brunetti *et al.* [2002] showed an increase in drought conditions over the whole of Italy during winter (increase in proportion of dry days). Koleva and Alexandrov [2008] showed an increase in drought conditions, more particularly after the 1980s, in Bulgaria (decrease in amount of annual precipitation), and Tornos [2010] showed a similar increase, between 1960 and 1991, in the Levant. Croitoru *et al.* [2012] showed a decrease in the number of dry spells, but an increase in dry spell duration, in the second half of the twentieth century, in the eastern part of Romania.

At a larger scale, Kostopoulou and Jones [2005] showed an increase in the maximum number of consecutive dry days in the eastern part of the Mediterranean Basin. Lelieveld *et al.* [2012] showed an increase in drought conditions in the same region, based on monthly mean precipitation.

Considering a surplus or deficit of precipitation at a monthly time step for the Mediterranean Basin as a whole, *Sousa et al.* [2011] showed an increase in drought conditions in the central and western Mediterranean. *Hoerling et al.* [2012] also observed an increase in drought conditions in the entire basin, mainly after the 1970s. *Hertig et al.* [2013] observed an increase (decrease) in drought conditions in the western (eastern) Mediterranean during autumn, an increase (decrease) in drought conditions in the central and eastern (western) Mediterranean during winter, and a general increase in drought conditions during spring.

Many studies around the Mediterranean Basin have already shown increases in drought conditions, by observing local monthly precipitation anomalies, or by locally counting days without precipitation, or sequences of days without precipitation. Yet none of these studies has clearly defined the notion of droughts or dry spells as climatic objects, based on their spatiotemporal characteristics (location, extent, and recurrence) at the Mediterranean scale. Within the framework of the HyMeX program (Hydrological cycle in the Mediterranean Experiment) [*Drobinski et al.*, 2014], this study explores very long dry spell (VLDS) events during the wet season, over the entire Mediterranean Basin, for the 1957–2013 period, by characterizing them as climatic objects, in terms of location, spatial extent, duration, and temporal variability. We focus here on defining VLDS as meteorological drought events, rather than as agricultural droughts, to provide a sound basis for our forthcoming work on the associated atmospheric forcing.

In section 2, we describe our data set, and our methodology, based on a spatial sliding scan approach, used here to identify VLDS events. In section 3, our methodology is applied to the period between 1957 and 2013, for VLDS events occurring over the entire Mediterranean Basin. Section 4 discusses the validity of the methodology and concludes the study by indicating future applications of this methodology to investigate the factors involved in VLDS events in order to predict future trends.

2. Methodology

2.1. Data Source

The E-OBS precipitation gridded data set v.10.0 is provided by the European Climate Assessment & Dataset project (ECA&D) [*Haylock et al.*, 2008] at 0.25° resolution. The gridded data set is obtained by interpolation of observed time series over Europe, the Middle East (Anatolia and Levant), and North Africa. We removed a total of 2358 grid points over parts of the Middle East and North Africa because too few meteorological stations were available for interpolation or because more than one complete year was missing from the time series [*Brunet et al.*, 2014]. As Mediterranean rainfall occurs mainly in autumn, winter, and early spring, this study focuses on the period from September to April (“wet season” hereafter), over an area 10°W–40°E and 28°N–46°N (“study area” hereafter), from 1957 to 2013. All analyses are therefore based on 13,552 days (56 wet seasons of 242 days) for 4343 grid points with complete data (grid points in gray/color in Figures 1a2 and 1a4).

2.2. Very Long Dry Spell: Definition and Classification

2.2.1. Thresholds for Rainfall Amount and Spell Length

Rainy days are defined as days with at least 1 mm of precipitation. Dry spells are defined as consecutive days with less than 1 mm of precipitation and are classified as follows: very short dry spells (VS DS), shorter than the 20th percentile of dry spell duration; short dry spells (SDS), between the 20th and 40th percentile; medium dry spells (MDS), between the 40th and 60th percentile; long dry spells (LDS) between the 60th and 80th percentile; and very long dry spells (VLDS), longer than the 80th percentile. Percentiles of dry spell duration were computed for each grid point over the 1979–2013 period. This contemporary reference period is best adapted for the characterization of dry spells observed in recent years, as the World Meteorological Organization recommends using a minimum reference period of 30 years. The 1979–2013 reference period is also used in regional climate simulations within the framework of the HyMeX and Mediterranean region COordinated Regional climate Downscaling EXperiment (MED-CORDEX) programs [*Ruti et al.*, 2015], to which this dry spell database will be compared in future work. A binary matrix was constructed with “1” at a given grid point, in the case of VLDS and “0” in all other cases (rainy days, dry spells shorter than the 80th percentile, or grid points above the Mediterranean Sea). This binary matrix was then used to characterize VLDS events.

2.2.2. Spatial Extent

Like heat waves, droughts are not local phenomena. The identification method therefore assumes a certain amount of spatial coherence. Following the work of *Stefanon et al.* [2012a] on the identification of heat waves, a sliding scan is performed over the entire study area, with a square window of 6° in longitude and latitude (0.5° sliding span in our study). For a given square, the date is counted as part of a VLDS event if 50% of the grid points are flagged 1; only those grid points flagged 1 are retained for VLDS event characterization.

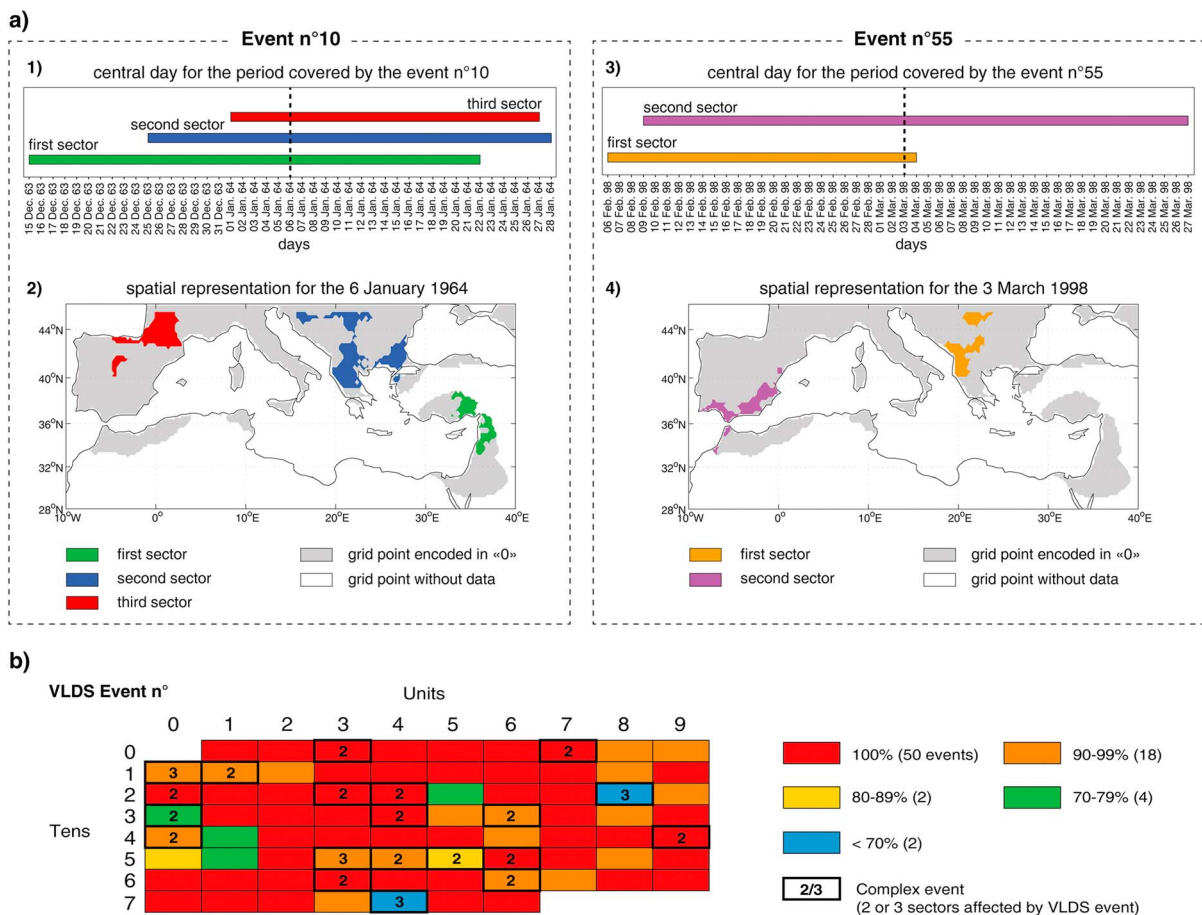


Figure 1. (a) Two examples of complex events (event n°10 with three affected sectors and event n°55 with two affected sectors). Figures 1a1 and 1a3 show the duration of event n°10 (n°55) and the central day (dotted vertical line) for the period covered by the events. Figures 1a2 and 1a4 show the spatial patterns for the central day of each event (binary matrix). The 4343 grid points with data are shown in gray or color. Grid points without data (nonanalyzed) appear in white. (b) Maximal spatial extent characteristics of the central days for the 76 VLDS events. In red, the central days representing 100% of the maximum extent of the event. In orange, the central days representing between 90% and 99% of the maximum extent of the event; in yellow, between 80% and 89%; in green, between 70% and 79%; and in blue, less than 70%. Black boxes represent complex events, and the numbers (2 or 3) in the box indicate the number of different sectors affected by the event.

This eliminates isolated grid points and structures too limited in spatial extent. The sensitivity of this method, to the size of the square, and to the grid point percentage threshold, was tested. Squares of less than 6° retain some local events without spatial coherence, and squares of more than 6° retain only a few events, with patterns covering nearly half of the study area. Using a smaller (greater) percentage has the same effect as using smaller (larger) windows.

The sliding scan procedure identified 76 VLDS events during the 1957–2013 period, covering a total of 4423 days. Of these events, 56 are “simple dry spell” events, where only one coherent sector of the entire study area is affected by the event. The other 20 events are “complex,” because they affect two or three separate sectors within the study area, at the same time, but for different durations. For complex events, sectors are considered separate when, between them, there is at least one sliding square window where no VLDS event is detected. Figure 1a presents two different complex events, event n°10 with three sectors, and event n°55 with two sectors.

2.2.3. Clustering

A clustering approach (a hierarchical ascendant classification) is used to identify persistent and recurrent spatial patterns of VLDS in the Mediterranean Basin. In order to classify the 76 VLDS events, it is necessary to select the most representative day for each event. The clustering approach cannot be used for all 4423 days. The central day was used as the representative day for each event. The central day is the date that best characterizes the mean spatial extension of the event (see next paragraph). The central day is the date exactly in

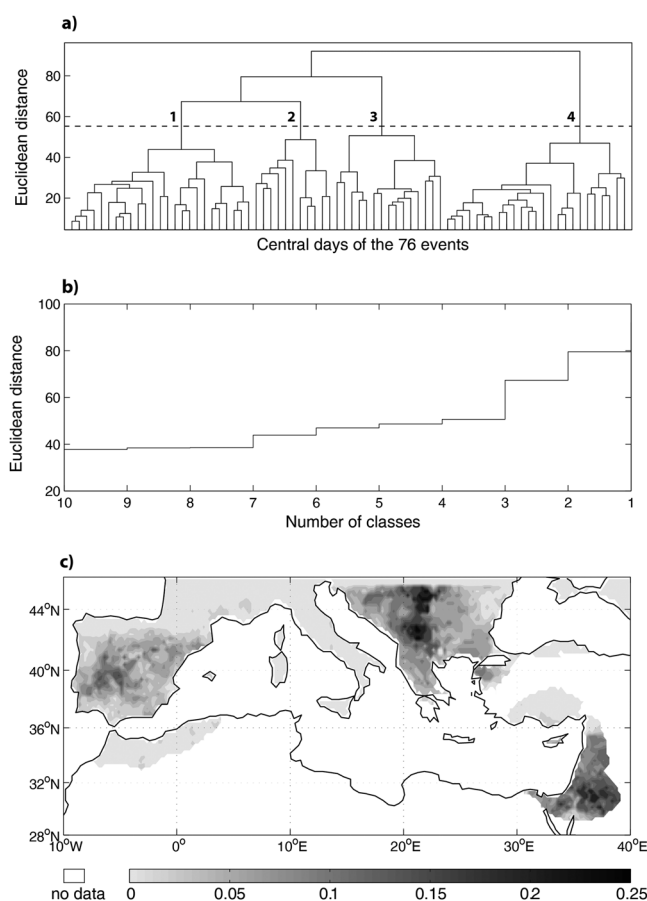


Figure 2. (a) Hierarchical Ascendant Clustering (HAC) tree of the central days for the 76 VLDS events. The numbers on tree branches correspond to clusters. (b) Graph of the HAC (number of classes between 2 and 10). In the graph, a long Euclidean distance means that intraclass variance is strong (intracluster Euclidean distance). Conversely, a short distance means that intraclass variance is low. It is better to select a number of classes affected by low intraclass variance. (c) Light to dark shading: intercluster variance between the four clusters retained. Intercluster variance is obtained for the 76 central days by calculating the ratio of VLDS events affecting each grid point for each cluster. The darker grid points represent those grid points best discretized by the four clusters.

the middle of the period affected by the event. For example, for complex event n°10 (which impacted three sectors), the first day affected by the event is 15 December 1963 (with VLDS in southeastern Anatolia and the northern Levant), and the last day affected by the event is 28 January 1964 (with VLDS in the Balkans). The central day of this complex event is 6 January 1964 (Figures 1a1 and 1a2). Based on the same principle, the central day of event n°55 is 3 March 1998 (Figures 1a3 and 1a4).

The representativeness of the central day to characterize an event is assessed by comparing the spatial extent of the VLDS at that date to the maximum spatial extent over the whole duration of the event. Figure 1b shows that for 50 of the 76 VLDS events (65%), the central day represents the maximum spatial extent of the event (maximum number of grid points flagged 1). For 68 VLDS events (89%), the central day represents more than 90% of the maximum spatial extent of the event. The central day is not representative of the maximum spatial extent for only two complex events (both with three different sectors impacted by VLDS).

The hierarchical ascendant classification algorithm (using the Euclidean distance metric) is applied to the binary matrix (defined in section 2.2.(i)), but only for the central days of the 76 VLDS events detected.

The final decision about the best number of clusters to be retained is still an unresolved problem, prone to subjectivity, and generally dictated by the researchers experience [Gong and Richman, 1995].

In the cluster tree and graph (Figures 2a and 2b), the first partition to show weak intraclass variability is class 4. Figure 2c shows that for four clusters, intercluster variance explains a sizable fraction of local variance for VLDS events in the Mediterranean Basin. Classifications based on 5, 6, 7, or 8 classes contained some overlap in the

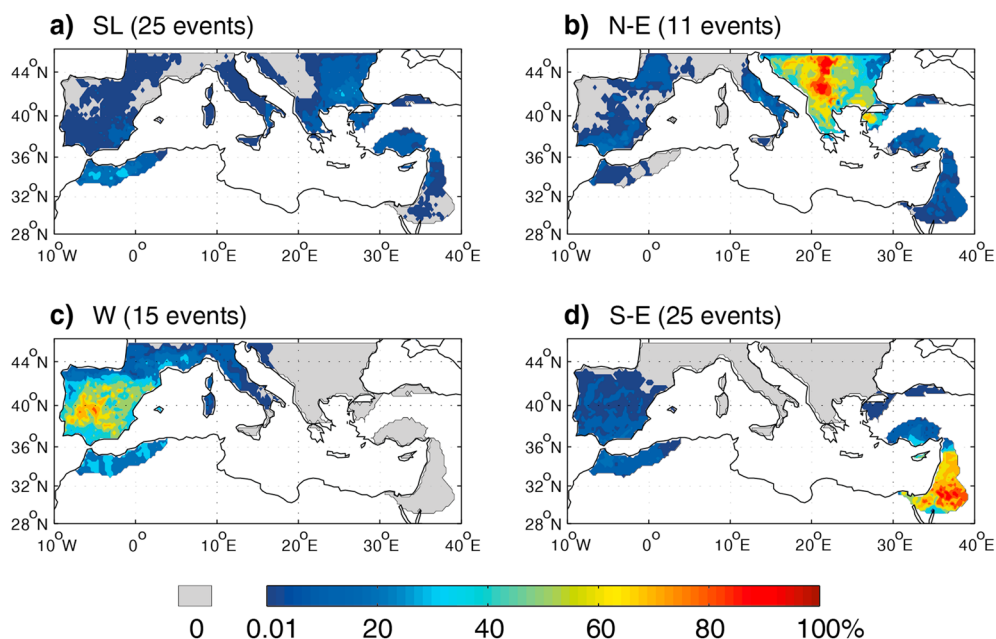


Figure 3. The four very long dry spell clusters obtained by hierarchical clustering for the Mediterranean Basin: (a) “scattered localized” (SL), (b) “northeast Mediterranean” (N-E), (c) “West Mediterranean” (W), and (d) “southeast Mediterranean” (S-E). Colors: for each cluster, the percentage of VLDS events affecting each grid point. In white, grid points not analyzed in the study.

geographical patterns of two or more clusters (not shown). Therefore, the final decision to keep four clusters is based on both quantitative arguments usually used in clustering analysis and expert assessment of the resulting patterns.

3. Results

3.1. Spatial Pattern of Very Long Dry Spells

Figure 3 shows, for each cluster, the percentage of VLDS events affecting each grid point. The first spatial pattern (Figure 3a) shows VLDS occurring in different areas around the Mediterranean Basin. This pattern is composed of 25 scattered localized VLDS, including three complex events. The second pattern (Figure 3b), northeast Mediterranean, is composed of 11 VLDS centered over the Balkans, including six complex events. The third pattern (Figure 3c), West Mediterranean, is composed of 15 VLDS events centered over the Iberian Peninsula, including one complex event. The fourth pattern (Figure 3d), southeast Mediterranean, is composed of 25 VLDS, centered over the Levant, with 10 complex events also affecting the Iberian Peninsula and Maghreb sectors. This pattern is very similar to the Iberian heat wave pattern described by *Stefanon et al.* [2012a].

3.2. Spatiotemporal Characteristics of Very Long Dry Spell Clusters

Figure 4a shows the mean duration, spatial extent, and monthly distribution of the four VLDS clusters. The southeast Mediterranean pattern (events centered over the Levant) has the longest VLDS events, with a mean duration of 69 days. The mean VLDS event duration is slightly shorter in the northeast Mediterranean (62 days) and West Mediterranean (56 days). These results can be explained by the frequency distribution of rainy days around the Mediterranean Basin. During the wet season, the rainyday frequency over the Iberian Peninsula and the Balkans ranges from 20% to 40% [*Raymond et al.*, 2016]. In the Levant, the rain-day frequency is much lower (from 0.1% to 25%), leading to much longer dry spells. The higher mean duration in the southeast Mediterranean and the northeast Mediterranean patterns may result from the higher proportion of complex events in these areas (Figure 4a: S-E 10/25; N-E 6/11).

The shortest VLDS events are found in the scattered localized pattern (46 days per event). This pattern is also characterized by the smallest average spatial extent. The average number of grid points flagged 1 (SL 251) for this pattern is half as large as for the other three patterns (Figure 4a: N-E 629; W 527; S-E 428). The high proportion of complex events in the northeast Mediterranean pattern means that more sectors are involved,

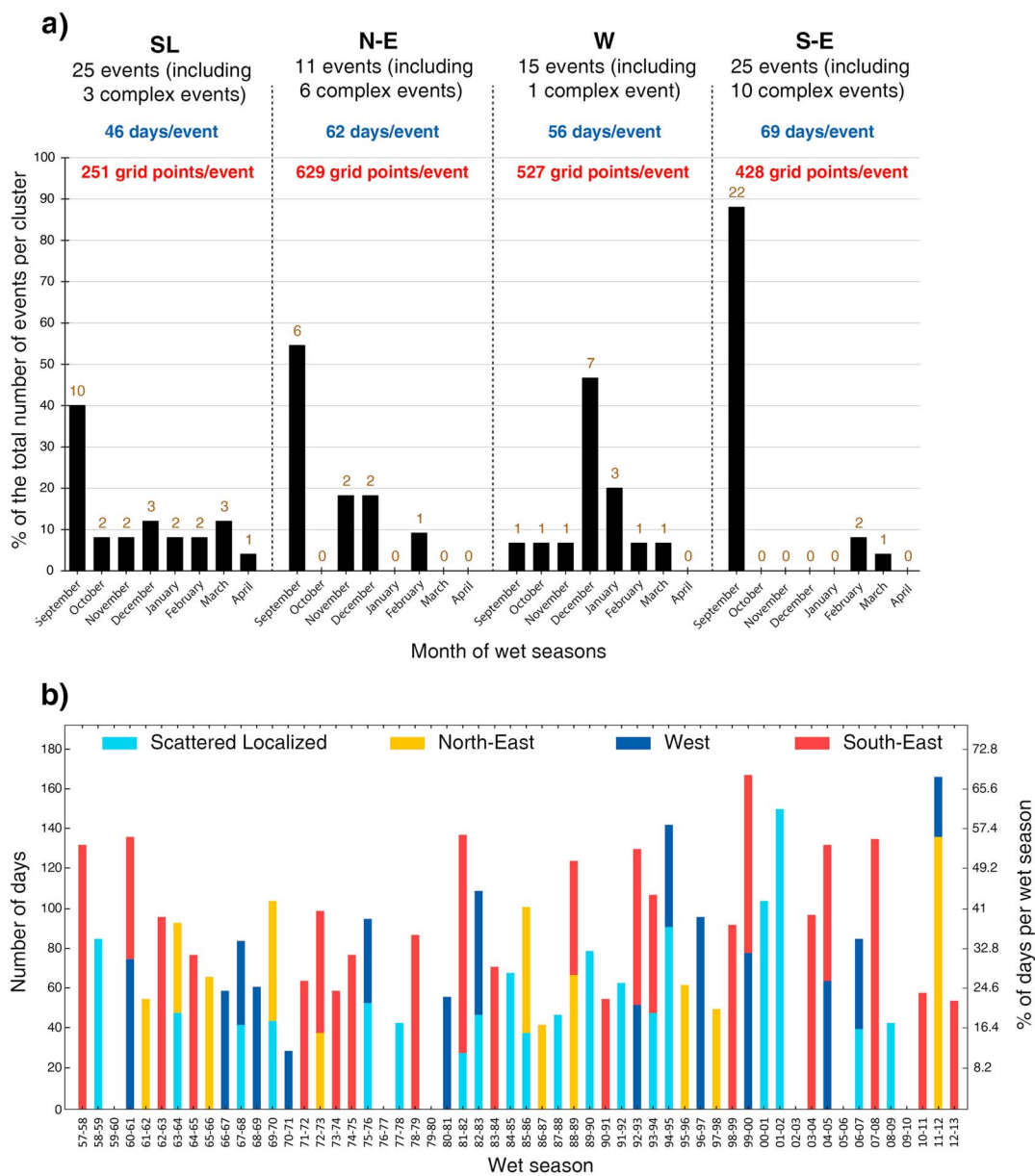


Figure 4. (a) Characteristics and seasonality of the four very long dry spell clusters detected by the cluster analysis procedure for the Mediterranean Basin during the 1957–2013 period. In blue, the mean duration of events per cluster. In red, the mean spatial extent of events per cluster. Histograms show the percentage of events starting during each month, for each cluster. In brown, the number of events starting during each month. (b) Very long dry spell climatology in the Mediterranean Basin between 1957 and 2013 identified by cluster.

thus increasing the number of grid points flagged 1. A similar analysis applies to the southeast Mediterranean pattern, but to a lesser extent, as the proportion of complex events is lower. In contrast, the West Mediterranean pattern has only one complex event, but the VLDS events in this sector, centered over the Iberian Peninsula, generally affect a much larger region, extending from the Maghreb to Italy.

Figure 4a also illustrates the seasonality of the VLDS events for the four clusters. The histograms in Figure 4a show the month when the event begins. An event shown as starting in September does not imply that only September will be affected by the event; the following months are probably also affected by the same event (especially if the event starts near the end of the month). The southeast Mediterranean pattern clearly shows some seasonality in VLDS events. Almost 90% of the events begin on the first day of September (22 out of 25). The other three occur near the end of the wet season (dry spells beginning in February and March; Figure 4a).

Saaroni *et al.* [2015] noted that many very long drought events typically occur from September to October, and from March to April, in the Levant, and therefore proposed a “rainy season” from mid-November to mid-March. Our results, based on the E-OBS data set, indicate that the mean cumulative precipitation from May to September in the Levant, between 1957 and 2013, was only 7 mm. The September VLDS events detected over the Levant, which also include 6 out of 10 events in the scattered localized pattern, could therefore be the continuation of the summer dry season. If no true VLDS events are found in the Levant, then there can be no true seasonality in both the southeast Mediterranean and scattered localized patterns. More than 50% of the VLDS in the northeast Mediterranean pattern also begin in September, but mainly from mid-September onward (in contrast with the Levant events, which all begin on the first day of September). This pattern is therefore affected by seasonality, like the West Mediterranean pattern, where more than 66% (10 out of 15) of VLDS events begin in December or January, in the middle of the wet season. Yet, according to the E-OBS data set, in the western part of the Mediterranean Basin, the highest mean monthly precipitation occurs during these 2 months. This paradoxical result, with most of the VLDS events occurring during the wettest period of the season, may have a negative impact on water resource renewal.

The interannual variability of VLDS events is shown in Figure 4b. At the scale of the Mediterranean Basin, a slight increase in cumulative days affected by VLDS event per wet season is observed during the 1957–2013 period, but this increase is not statistically significant. Six wet seasons were not affected by any VLDS events (1959/1960, 1976/1977, 1979/1980, 2002/2003, 2005/2006, and 2009/2010). This result does not necessarily mean that these wet seasons were wetter than average, but simply that any dry spell events were shorter than VLDS. Somewhat surprisingly, the 2002/2003 season was not affected by any VLDS events, although many studies have shown that this season was affected by extreme dryness during spring, leading to a strong heat wave over Europe during the summer of 2003 [Fink *et al.*, 2004; Ferranti and Viterbo, 2006; Fischer *et al.*, 2007]. This is not necessarily a paradox, however, because our study focused on very long periods without precipitation (consecutive days with less than 1 mm of precipitation). An extremely dry period, with strong negative precipitation anomalies (i.e., agricultural drought), might remain unaffected by VLDS, if the limited number of rainy days (days with at least 1 mm of precipitation) is nevertheless spread over the entire dry period. There was, however, a long dry spell event (LDS: from the 60th to the 80th percentile) during spring 2003, over the Iberian Peninsula, France, and the Balkans. Only three wet seasons have more than 150 VLDS days (62% of wet season days), and they are all in the last quarter of the period studied (Figure 4b: 1999–2000, 2001–2002, and 2011–2012).

The northeast Mediterranean pattern was strongly affected during the 2011–2012 wet season (Figure 4b), with a complex VLDS event lasting 136 days (affecting Anatolia, the Balkans, the Iberian Peninsula, and the Maghreb), followed by a shorter West Mediterranean event lasting 30 days (affecting the Iberian Peninsula and France). An account of the critical drought conditions in the Iberian Peninsula during 2011–2012 can be found in Trigo *et al.* [2013].

No trend is observed for the number of events per wet season. Raymond *et al.* [2016] show that, in the Mediterranean Basin, there is a decrease in the amount of seasonal precipitation and in the number of rainy days. The drying observed throughout the Mediterranean Basin in previous studies is confirmed here by a slight increase in the cumulative number of days affected by VLDS events, rather than by an increase in the number of VLDS events per wet season. Focusing on the number of events per wet season would be less useful for trend detection, as the duration of VLDS events is extremely variable (from 23 to 136 days). The cumulative number of days affected by VLDS events per wet season should prove more reliable in detecting trends over the period studied (1957–2013).

4. Discussion and Conclusion

A climatic object approach to the detection of VLDS events was developed in this study and applied to the Mediterranean Basin as a whole. This method is based on the analysis of dry spells and serves to characterize VLDS events, based on their spatiotemporal characteristics (location, spatial extent, duration, and temporal variability) at the scale of the Mediterranean Basin. This approach can be used at a finer temporal scale, that of the VLDS event, to complement studies of dryness trends or precipitation anomalies. A total of 76 VLDS events are detected and grouped into four clusters: three recurrent VLDS clusters, the northeast, West, and southeast Mediterranean patterns, and a fourth cluster of localized events spread over the entire Mediterranean Basin,

the scattered localized pattern. A slight increase in the cumulative number of days affected by VLDS events per wet season is observed.

Although other data sets could be used (Era-Interim or GPCP, for example), we decided to use the E-OBS data set, which is unique in its spatial extent and resolution, with many more observation stations in the Mediterranean Basin than other regional or global data sets [Haylock *et al.*, 2008]. As precipitation data sets can be sensitive to data interpolation, the spatial extent and duration of the VLDS events detected here might be slightly different if other data sets with a different resolution and gridded interpolation were used. In complex topographic characteristics areas, as the Mediterranean Basin, we need to use the available data set with the highest spatial resolution (i.e., E-OBS data set). However, the methodological choices made in this study have produced demonstrably robust results.

This study paves the way for further research on present and future wet season very long dry spell variability in the Mediterranean Basin. A forthcoming study will use National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis data to identify the large-scale atmospheric conditions associated with VLDS events detected during the 1957–2013 period. The final objective will be to assess future trends in long and very long dry spell events, based on Regional Climate Model and Coupled Model Intercomparison Project Phase 5 (CMIP5) General Climate Model simulations, within the framework of the HyMeX and MED-CORDEX programs.

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Erratum

In the originally published version of this article, it was stated in section 2.2.2 that “the date is counted as part of a VLDS event if 90% of the grid points are flagged.” The percentage has been corrected to 50%. The present version may be considered the authoritative version of record.