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Anomalies in Moisture Supply during the 2003 Drought Event in Europe: A Lagrangian Analysis

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Abstract: In the last few decades, many studies have identified an increasing number of natural hazards associated with extreme precipitation and drought events in Europe. During the 20th century, the climate in Central Europe and the Mediterranean region was characterised by an overall temperature increase, and the beginning of the 21st century has been marked by severe and prolonged drought events. The aim of this study is to analyse variations in the moisture supply during the 2003 drought episode that affected large portions of Europe. In order to better characterise the evolution of the episodes across the continent, separate analyses were performed for two spatial domains: Central Europe and the Mediterranean region. These regions were defined according to the 5th Intergovernmental Panel on Climate Change Assessment Report. For both regions, this drought episode was most severe from 1980 to 2015, according to the one-month Standardised Precipitation Evapotranspiration Index (SPEI-1) analysis, which was conducted using monthly precipitation and potential evapotranspiration data from the Climate Research Unit. Analyses of precipitation, potential evapotranspiration, pressure velocity at 500 hPa, and vertically integrated moisture flux were conducted to characterise the anomalous patterns over the regions during the event. A Lagrangian approach was then applied in order to investigate possible continental-scale changes in the moisture supply over the Central European and Mediterranean regions during 2003. This approach is based on the FLEXible PARTicle (FLEXPART) dispersion model, integrated with data from the European Centre for Medium-Range Weather Forecasts (ECMWF): the ECMWF Re-Analysis ERA-Interim. The results indicate that anomalous subsidence, increased evapotranspiration, and reduced precipitation predominated over both regions during the episode. The most intense reduction in the moisture supply over Central Europe was registered for the Mediterranean Sea (MDS) and the Central European region, while for the Mediterranean region, most intense reduction in the moisture supply was observed in the MDS and—in minor-scale—Gibraltar regions.

Keywords: drought; Mediterranean region; Central Europe; Lagrangian method; Standardised Precipitation Evapotranspiration Index

1. Introduction

Climate change is one of the major causes of global temperature increases and the variability of extreme events, including droughts [1]. During the 20th century, the climate in Central Europe and the Mediterranean region was characterised by an overall temperature increase, and the beginning of 21st century has been marked by severe and prolonged drought events [2–6].

Droughts are part of the natural climate cycle. They commonly affect large areas, and are related to a prolonged lack of precipitation. A drought is a complex phenomenon that has an impact on different types of systems (environment, economy, society, agriculture, etc.); it is generally accepted that it is one of the costliest natural hazards [7,8]. Therefore, it is possible to define a drought in

meteorological (rainfall for a specified period is below the normal amount), agricultural (there is not enough soil moisture to satisfy the needs of crop production at a particular time), and hydrological terms (there are deficiencies in surface water supply based on measurements of stream flow and lake, reservoir, and groundwater levels) [7,9–11]. Meteorological droughts represent the primary cause of droughts, while the other types describe the secondary effects of a long-term precipitation deficit on measures such as soil moisture, river flows, and/or economic sectors [5]. Droughts are often considered as concealed phenomena due to the difficulty in estimating when they begin and when they end. The effects of a drought often accumulate slowly, and can last from several months up to years. This can impact all of the components of the hydrological cycle. A precipitation deficit, which typically leads to a drought, combined with high evapotranspiration losses, can cause a deficit in soil moisture [7,8,12]. For this reason, a quantitative assessment of the likelihood of occurrence and expected strength of a drought is crucial for understanding, monitoring, and mitigating the drought. Given the difficulty in predicting the evolution of droughts and their quantification in terms of duration, severity, and intensity, there have been many efforts to develop a drought indicator that is suitable for their monitoring [7,9,13].

In this study, we focus on the 2003 meteorological drought event that occurred in Europe, mainly affecting the Central European region (CEU) and the Mediterranean region (MED) (Figure 1). As a result of its unique geographic location, the MED is particularly vulnerable to climate variability and climate change. This region is located in the transition zone between the African climate regime (hot and dry) in the south and the European climate regime (mild and humid) in the north, thus experiencing large climate variation [14]. In the last few decades, the climate extremes registered in the MED and CEU displayed a relative increase in the duration of heat waves and a relative decrease in precipitation [8,15–19]. The year 2003 was characterised by one of the worst droughts recorded in Europe [15,20,21]. According to Levinson and Waple [15], the annual mean surface temperature in 2003 was above average throughout Europe. The primary reason for the 2003 drought in Europe was the increase in the frequency of warm temperature extremes; the global surface temperature was among the three highest temperatures ever recorded, estimated to be 0.46 °C above the 1961–1990 mean temperature [16,22]. The European heat waves of 2003 have been investigated in previous studies [2,8,23–28]. These heat waves, which represented the combination of anomalously high temperatures across most of the continent, induced a number of health, ecological, societal, and economic impacts. These impacts included forest fires, increased pollution, wilted crops, and excessive mortality of elderly individuals recorded in several countries across Europe [29,30].

A precipitation deficit occurring over an area may also be related to changes in moisture transport [17,31–33]. Thus, it is important to understand the origin of atmospheric moisture to close the atmospheric branch of the hydrological cycle. Understanding the source–sink relationships in the atmospheric water cycle is very important because of the role they play in extreme meteorological events [34]. Lagrangian approaches have been used worldwide in the last few years to estimate humidity changes along trajectories and to identify sources of moisture or sinks. Nieto et al. [35] analysed regions with different climates based on region boundaries defined in the 4th Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). Drumond et al. [32] analysed the variation in the moisture sources related to drier and wetter conditions in regions around the Mediterranean Basin for the period 2000–2005. Gomez-Hernandez et al. [31] extended the study of Drumond et al. [32] for a 21-year period, investigating the seasonal and interannual variability of the main atmospheric moisture sources over eight regions in the Mediterranean Basin. Recently, on a regional scale, Stojanovic et al. [36] investigated the anomalies in the moisture supply into the Danube River Basin during the two most severe meteorological drought episodes (1989/1990 and 2003), which they identified through the Standardised Precipitation Evapotranspiration Index (SPEI) analysis for the period 1980–2014.

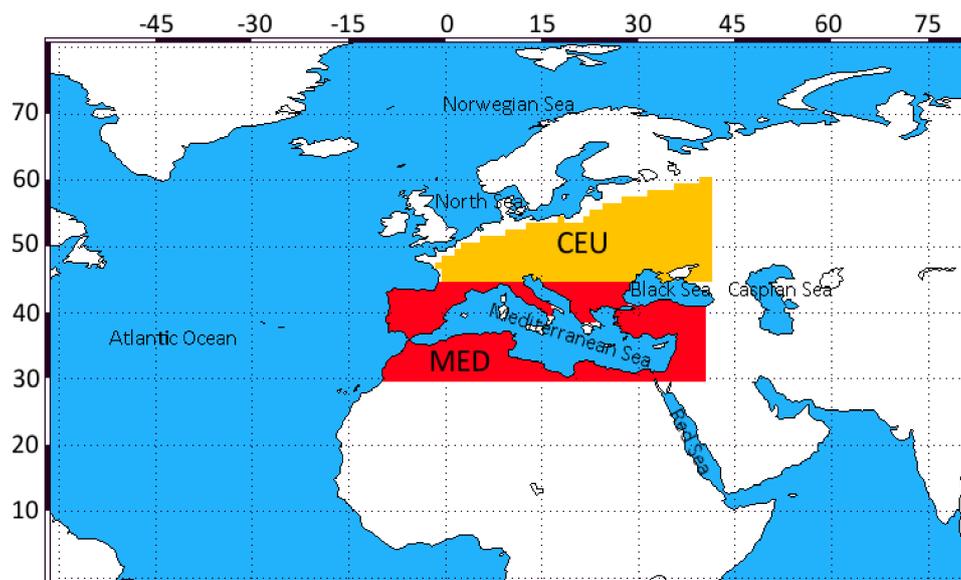


Figure 1. Central European (CEU) and Mediterranean (MED) regions. The respective boundaries were defined in the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC).

In this work, our specific objectives are (1) to identify the main climatological moisture sources for CEU and MED during the period 1980–2015 by tracking the air masses that reached both regions backward in time through a Lagrangian methodology [37,38]; (2) to identify the meteorological drought events that occurred in CEU and MED over the period 1980–2015 through the SPEI [39], in order to characterise and rank the 2003 episode; and (3) to analyse the anomalies in the moisture supply in CEU and MED during the 2003 meteorological drought episode that affected most of Europe. Based on the same methodology that was applied by Stojanovic et al. [36] in their regional study for the Danube River Basin, here we focus on investigating the extension of the 2003 drought conditions across Europe on a continental scale, using a more recent Climate Research Unit (CRU) dataset, for the period 1980–2015. In this study, separate analyses were performed for two spatial domains: Central Europe and Mediterranean region, with the aim of comparing the drought conditions and anomalous moisture supply of both regions.

2. Data and Methods

2.1. Standardised Precipitation Evapotranspiration Index (SPEI)

To identify the meteorological drought episodes that occurred over CEU and MED (the boundaries of which were defined in the 5th Assessment Report (AR5) of the IPCC [6,19]) during 1980–2015, we computed the one-month SPEI (SPEI-1). The SPEI was first proposed by Vicente-Serrano et al. [39] as an improved drought index that was particularly suitable for studying the effect of global warming on droughts [40]. The SPEI follows the same conceptual approach as the Standardised Precipitation Index (SPI), but rather than concentrating on precipitation alone [9,41], it is based on a monthly climatic water balance (precipitation minus evapotranspiration). The SPEI has the advantage of combining multiscalar characteristics with the possibility of including the effects of temperature variability on the assessment of droughts. Therefore, it can point to anomalies in climatic water balance. The climatic water balance was calculated at various time scales (i.e., accumulation periods), and the resulting values were fit to a log-logistic probability distribution in order to transform the original values into standardised units that were comparable in space and time and at different SPEI time scales. The time scale over which the water deficit accumulates functionally separates meteorological, agricultural, and other types of drought. Similar to the Palmer Drought Severity Index (PDSI) [42], the SPEI

takes into account the effect of reference evapotranspiration on droughts, but its multiscalar nature allows for the identification of different types of droughts [40,43,44]. Many studies have shown that increasing temperatures affect droughts [45–47]. The role of temperature was evident in the drought in Central Europe during the summer of 2003. Extremely high temperatures over most of Europe caused the greatest damage to natural systems and increased the rates of evapotranspiration [23,24,30]. Therefore, the use of the SPEI, which includes temperature data in its formulation, is more suitable for identifying the drought episodes than indices that do not use temperature information [39,43]. Complete descriptions of the SPEI and comparisons with other indices are provided in previous studies [39,43,48–50]. For this study, the index was calculated using the Climate Research Unit (CRU) Time-Series (TS) Version 3.24.01 precipitation (PRE) and potential evapotranspiration (PET) data at an original spatial resolution of 0.5 degrees [51]. We then computed time series of PRE and PET averaged over the CEU and MED in order to calculate the SPEI-1 time series representative of each spatial domain. We chose the SPEI-1 time scale, which corresponds to the water balance for one month, because this time scale is closely related to meteorological droughts [52]. A drought episode starts when the SPEI value falls below zero, followed by a value of -1 or less, and ends when the SPEI returns to a positive value [41,53]. The criterion of McKee et al. [53] helped to classify the peak monthly value of the SPEI-1 registered during an episode, according to the four categories presented in Table 1.

Table 1. Drought classification based on the monthly Standardised Precipitation Evapotranspiration Index (SPEI-1) values and the respective time in category, according to the classification proposed by McKee et al. [53].

SPEI Values	Drought Category	Time in Category (%)
0 to -0.99	Mild	~24
-1.00 to -1.49	Moderate	9.2
-1.50 to -1.99	Severe	4.4
≤ -2.0	Extreme	2.3

2.2. Lagrangian Methodology

The Lagrangian approach that was developed by Stohl and James [37,38] was applied to identify the climatological moisture sources for CEU and MED during the period 1980–2015, and to analyse anomalies in the moisture supply over both regions during the 2003 meteorological drought. The approach was based on the FLEXible PARTicle (FLEXPART) dispersion model, which uses global data from the European Centre for Medium-Range Weather Forecasts (ECMWF): the ECMWF Re-Analysis ERA-Interim. This data set has a horizontal resolution of 1° on 61 vertical levels, ranging from 1000 to 0.1 hPa [54]. The application of the ERA-Interim reanalysis in reproducing the hydrological cycle, and in terms of water balance closure, was more realistic than the ERA-40 [55] and the newest reanalysis products, Modern Era Retrospective-Analysis for Research and Applications (MERRA) and Climate Forecast System Reanalysis (CFRS) [56]. As a result of the requirement of the FLEXPART dispersion model to use consistent, high-quality data for wind and humidity, the ERA-Interim reanalysis data were the most appropriate to be used [57].

The main advantage of this methodology was the convenience of establishing the relationship between the source and the receptor. This method was limited by the use of the time derivative of moisture; however, the use of a large number of particles and a large time period minimised the effects of unrealistic fluctuations [37,38,58]. Although other approaches, such as analytical models, box models, and physical water vapour traces (isotopes) can be used for similar purposes, the Lagrangian approach has an important advantage: it is able to calculate the path of moisture over time and enables the identification of the main moisture sources. A comparison of the methodologies and the main advantages and disadvantages of the approach applied in this study is presented in Gimeno et al. [59].

In the FLEXPART simulation, the global atmosphere was divided homogeneously into approximately 2 million particles with constant mass, transported using 3D wind fields. The changes in specific humidity (q) of each particle along its path were computed every 6 h. They could be expressed as follows: $e - p = m(dq/dt)$, where m is the mass of the particle and $e - p$ (evaporation minus precipitation) represents the freshwater flux associated with the particle. By adding $(e - p)$ for all of the particles residing in the atmospheric column over a given area, we obtained the total $(E - P)$ field. This represents the surface freshwater flux connected with the tracked particles, where (E) indicates the evaporation rate and (P) indicates the precipitation rate per unit area.

The trajectories of the particles may be traced using a backward in time analysis to determine the sources of moisture for a given region (areas where the particles obtain moisture, $(E - P) > 0$), and using a forward in time analysis to identify the sinks of the moisture transported by particles leaving a given region (areas where the particles lost moisture, $(E - P) < 0$). The particles were tracked for a period of 10 days, which is the global average residence time of water vapour in the atmosphere [60]. In this study, the trajectories of the particles that reached the CEU and MED regions were obtained by backward tracking for the period 1980–2015, and we identified the moisture sources on an annual basis. Then, the trajectories were tracked forward in time from these defined sources in order to analyse the monthly anomalies in the moisture supply to CEU and MED during the 2003 drought episode. The monthly anomaly was computed as the difference between the monthly average and the respective monthly climatological mean. Therefore, the anomaly for January 2003 is ((monthly mean January 2003) – (climatology January 1980–2015)).

3. Results and Discussion

3.1. Identification of the Major Climatological Moisture Sources for the Central European and Mediterranean Regions

To identify the major climatological moisture sources for CEU and MED, we tracked the air masses over the given regions backward in time for the period 1980–2015. The areas where evaporation exceeded precipitation in the net moisture budget ($(E - P) > 0$) represented the area of the moisture sources. In order to define the threshold that limited the spatial extent of the moisture sources, we used the 95th percentile of the positive values of $E - P$ obtained from the global climatology on an annual scale. The 95th percentile defined those regions where the air masses were likely to take up a large amount of moisture on their path to the target region.

3.1.1. Moisture Sources for Central Europe

According to the threshold of 0.06 mm/day, which corresponded to the 95th percentile of the annual averages of $(E - P) > 0$ obtained from the backward in time experiment (Figure 2a), CEU (Figure 2b) received moisture from seven different oceanic and terrestrial moisture sources: the North Atlantic (NAT), Mediterranean Sea (MDS), Baltic Sea (BAS), Black Sea (BLS), Caspian Sea (CPS), terrestrial moisture sources surrounding the region (TER), and itself (CEU). Through the forward in time analysis from these seven sources towards the CEU sink, the climatological results on an annual scale revealed that the moisture contribution came mainly from two sources: MDS (34%) and CEU (35%). During the boreal summer months, CEU was the main source, while MDS prevailed during the winter months (Figure 2c).

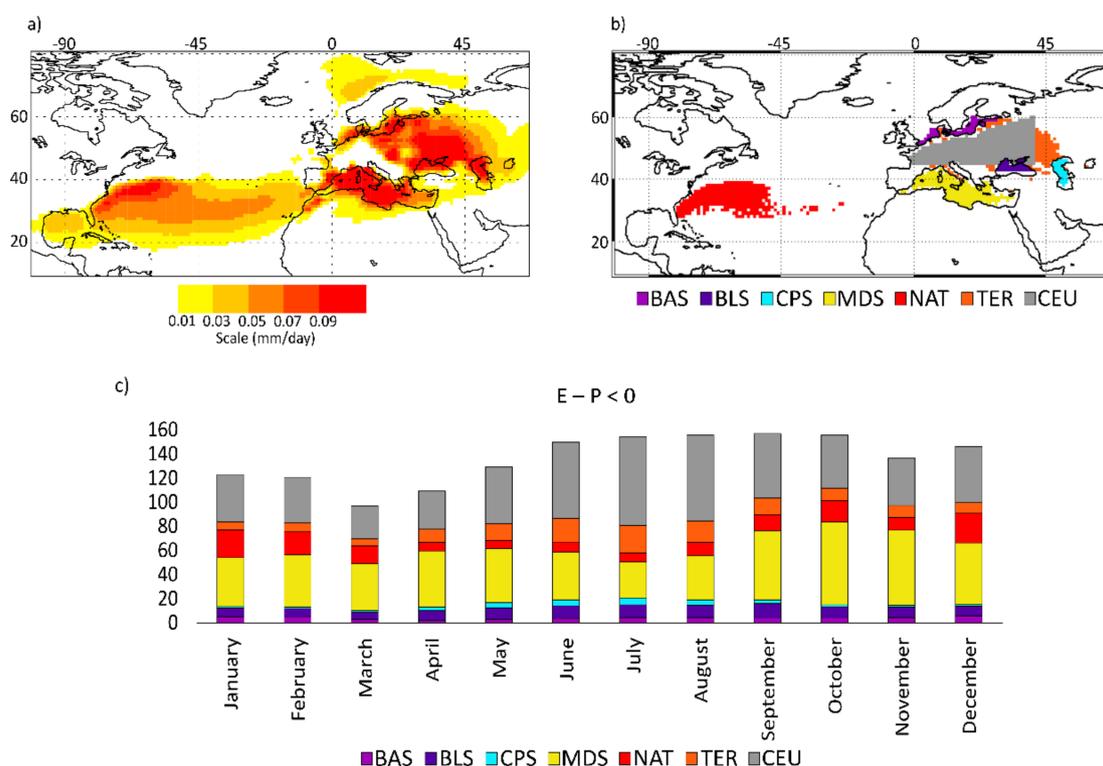


Figure 2. (a) Climatological annual (evaporation (E) – precipitation (P) > 0) values integrated backward in time over 10 days for the Central Europe region (CEU) (mm/day); (b) Schematic representation of the main moisture sources for the CEU during 1980–2015: North Atlantic (NAT), Mediterranean Sea (MDS), Baltic Sea (BAS), Black Sea (BLS), Caspian Sea (CPS), terrestrial moisture sources surrounding the region (TER), and itself (CEU); (c) Moisture contribution (E – P < 0) from the sources to CEU estimated through the forward in time experiment (mm/day).

3.1.2. Moisture Sources for the Mediterranean Region

We tracked the air masses over MED backward in time to identify the sources of moisture. The areas where $E - P > 0$ represented the areas where evaporation exceeded precipitation in the net moisture budget (Figure 3a). The main moisture sources for MED, according to the threshold of 0.04 mm/day (95th percentile of $E - P > 0$), are displayed in Figure 3b. These included the Gulf of Mexico (GMX), Gibraltar (GIB), MDS, BLS, CPS, TER, and itself (MED). Through the forward in time analysis from these sources towards the MED sink, the climatological results on an annual scale revealed that the moisture originated from two main sources: MDS (45%) and MED (33%). During the whole year, MDS appeared to be the major moisture source (Figure 3c).

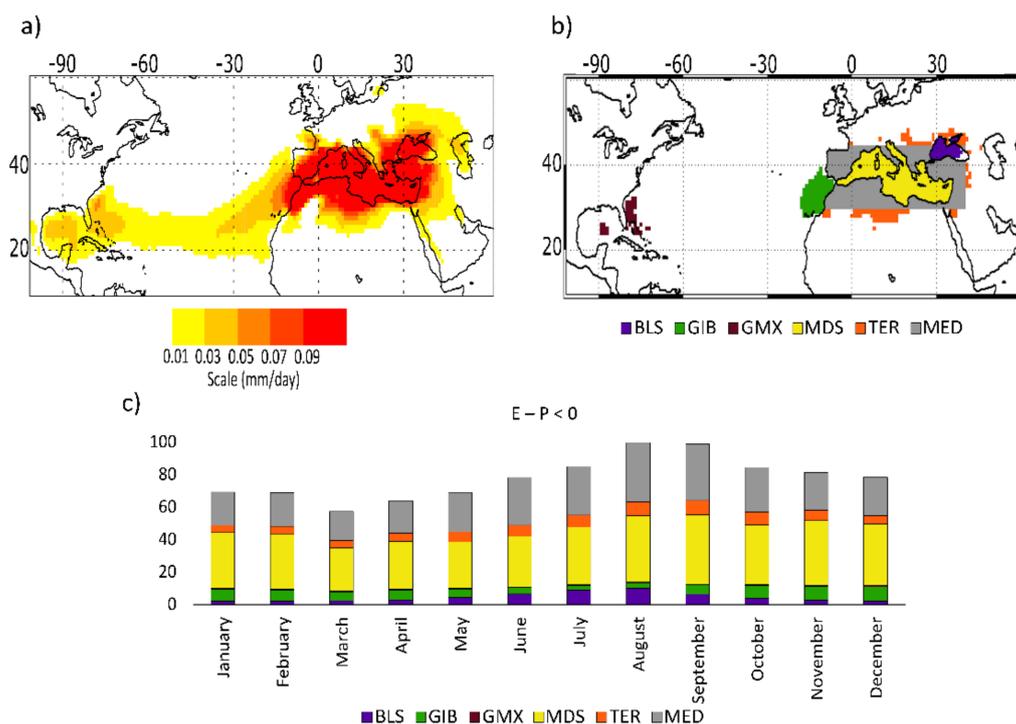


Figure 3. (a) Climatological annual ($E - P > 0$) values integrated backward in time over 10 days for the Mediterranean region (MED) (mm/day); (b) Schematic representation of the main moisture sources for the MED during 1980–2015: Gulf of Mexico (GMX), Gibraltar (GIB), Mediterranean Sea (MDS), Black Sea (BLS), terrestrial moisture sources surrounding the region (TER), and itself (MED); (c) Moisture contribution ($E - P < 0$) from the sources to the MED estimated through the forward in time experiment (mm/day).

3.2. The Extension of the Drought Conditions over Europe during 2003

The meteorological drought episodes over CEU and MED that occurred during 1980–2015 were selected using the SPEI-1 (Figure 4), which corresponded to the water balance for one month. The negative SPEI-1 values indicated dry conditions (red bars in Figure 4). Additionally, accompanying the criteria for the identification of drought episodes from McKee et al. [53], we identified 51 drought episodes that occurred over CEU and 48 that occurred over MED during the analysed period.

Some properties of the drought episodes that occurred over CEU and MED are presented in the Table 2. Severity represents the absolute value of the sum of all of the SPEI values during the episode. Therefore, for the episode that occurred over CEU, the severity was 7.10, while for the episode that occurred over MED, the severity was 7.23. Among all of the drought episodes that occurred over CEU and MED during the period 1980–2015, the 2003 episode was the most severe. A characterization of the 2003 drought episode was also conducted for each region in terms of duration (indicating the number of the months between the first and last months) and intensity (the ration between severity and duration). The number in parenthesis represents the rank occupied by the episode in comparison to the other episodes that occurred over the same region during the period 1980–2015. The 2003 drought episode for CEU lasted from February 2003 to June 2003 (five months)—the fourth longest when considering all of the episodes in the studied period. Although the 2003 episode for MED lasted from May 2003 to August 2003 (four months), it was the 10th longest event that was registered for this region. The SPEI-1 for this CEU drought episode reached a peak of -1.86 (severe), while the MED SPEI-1 reached a value of -2.71 (extreme). The MED episode was the third most intense episode (1.91) registered for this region during 1980–2015, while the CEU episode was not as intense (occupying the 11th rank) when compared to the rest of episodes over the same region. In summary, except for

the severity (both episodes were the most severe for both regions), Table 2 suggests that the 2003 episode appeared to be more significant for the MED region when compared to the rest of the episodes identified over the same region during 1980–2015. This is because it appeared between the three most important events in terms of severity, intensity, and peak SPEI-1 value.

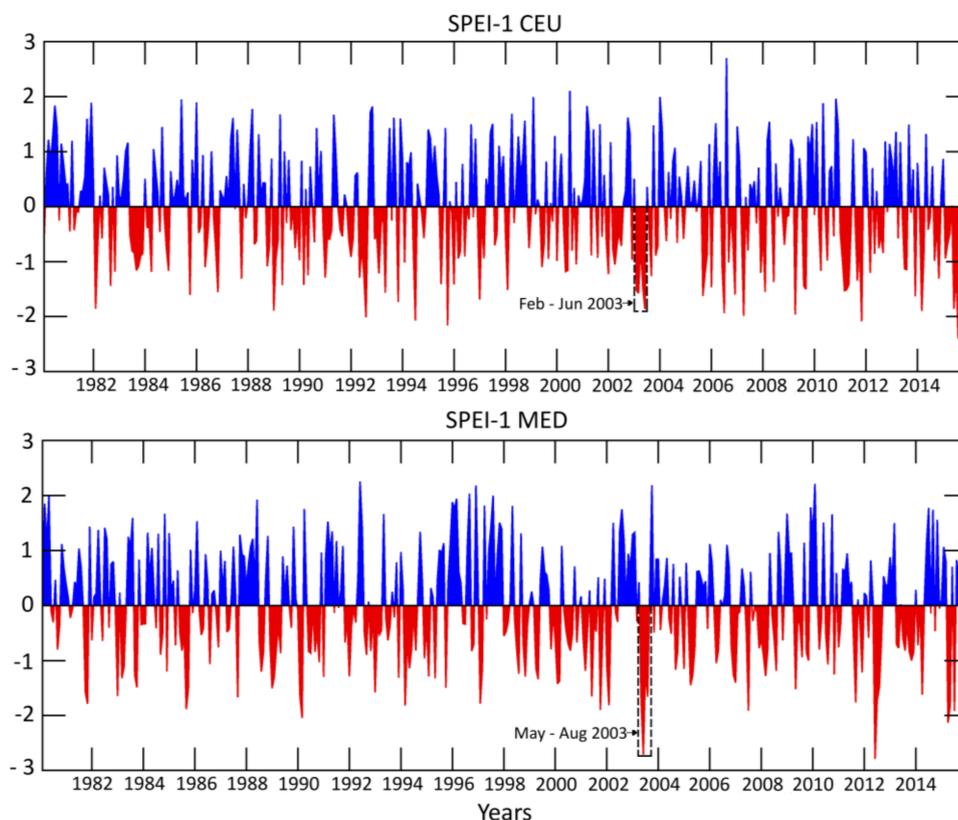


Figure 4. Time series of Standardised Precipitation Evapotranspiration Index for one month (SPEI-1) over the Central European region (**top panel**) and Mediterranean region (**bottom panel**) during 1980–2015. Positive values are in blue and negative values are in red. The black rectangles show the development of the drought episode over the Central European and Mediterranean regions during 2003.

Table 2. Characteristics of the 2003 drought episode that occurred over the Central Europe region (CEU) and the Mediterranean region (MED). The number in parenthesis indicates the rank occupied by the episode in comparison to the other episodes identified over the respective region during 1980–2015. For the peak monthly Standardised Precipitation Evapotranspiration Index for one month (SPEI-1) values, the lowest value observed in the 36-year monthly SPEI-1 time series occupies the first rank position.

Region	Drought Episode	Severity	Duration (Months)	Intensity	Peak Monthly SPEI-1 Value
CEU	February–June	7.10 (1st)	5 (4th)	1.42 (11th)	June −1.86 (11th)
MED	May–August	7.23 (1st)	4 (10th)	1.81 (3rd)	June −2.71 (2nd)

The SPEI-1 maps over Europe during 2003 are represented in Figure 5 in order to illustrate the tempo-spatial evolution of the drought conditions over the continent. In this figure, the SPEI-1 values were calculated at every grid point. The negative SPEI-1 values indicated dry conditions, while the

positive SPEI-1 values indicated wet conditions. Figure 5 shows that during January, positive values of SPEI-1 prevailed over Europe. From February (the beginning of the drought episode over CEU) to June (the end of the drought episode over CEU), the negative SPEI-1 values indicated that dry conditions extended over CEU and reached severe dry conditions in June, with a peak value of -1.86 . From July to December, the dry conditions lessened over CEU. For MED, there was an increase in dry conditions from May to August; June was the month with higher SPEI-1 values over the area of study, reaching the category of extreme drought ($\text{SPEI-1} < -2.0$).

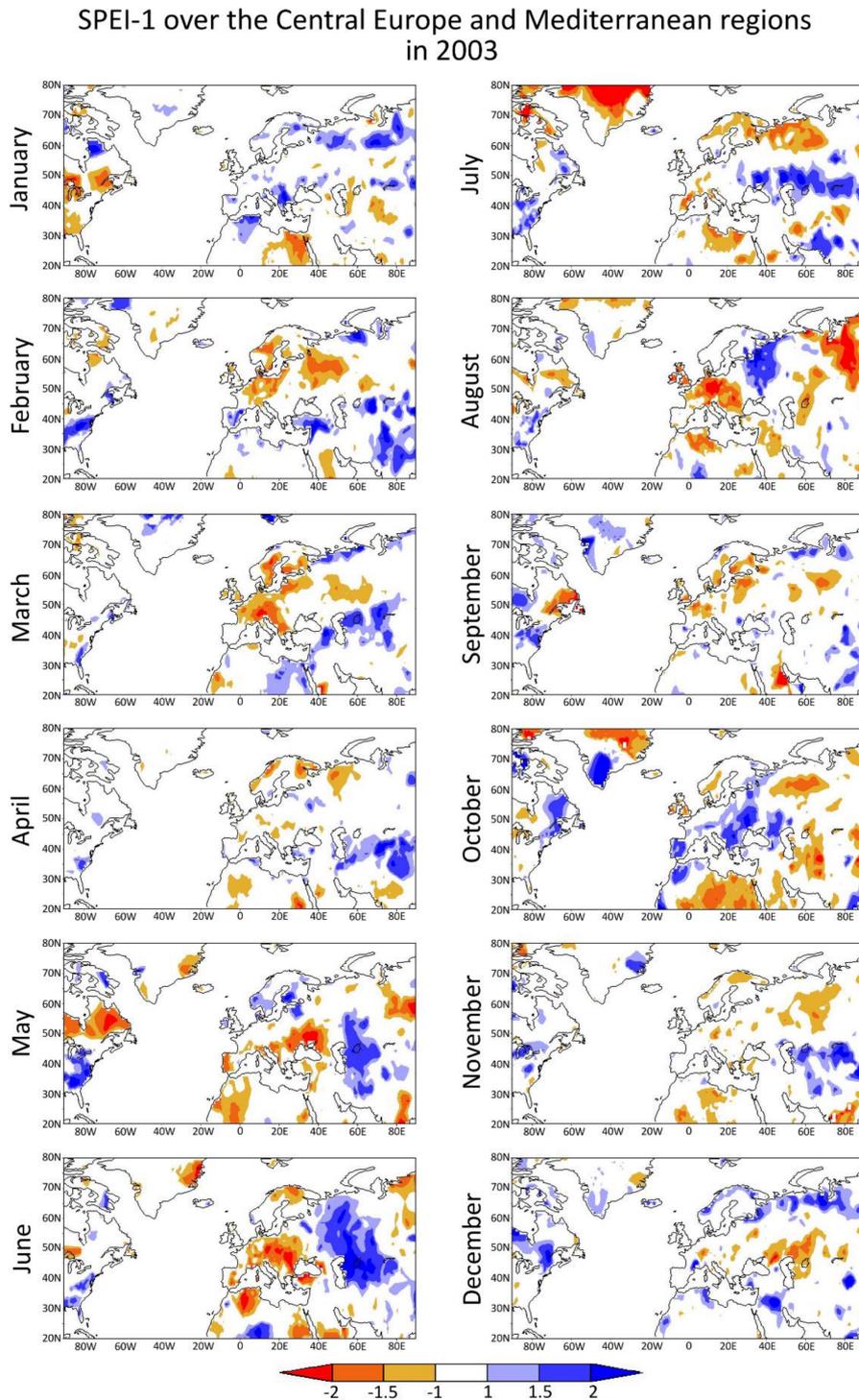


Figure 5. SPEI-1 values in 2003 over the European area.

Figure 6 shows monthly anomalies of the ERA-Interim vertically integrated moisture flux (vector) and its divergence (shaded) during 2003 to illustrate the relationship between the drought and the spatio-temporal variation of the large-scale atmospheric fields. Regions of divergence (reddish colour) prevailed over Central Europe during 2003 (with the most significant exceptions in January, April, July, and October), indicating the reduction of precipitation over this large spatial domain during the year. From April to August, those divergent conditions extended towards the Mediterranean region, prevailing over the central North Africa, Iberian Peninsula, Italy, the Balkan Peninsula, and Eastern Mediterranean. The persistence and predominance of an anomalous anticyclonic circulation over Europe during nearly the whole of 2003 (although displaced over different regions throughout the year) most likely inhibited the moisture transport that occurs climatologically from the Mediterranean towards the continent. This anomalous anticyclonic circulation appeared to be localised over Northern Europe during February and March. In May and June, it was configured over Central Europe, and it appeared centred over the British Isles in August. Between the main contributing factors that were responsible for the occurrence of this drought episode, Garcia-Herrera et al. [25] addressed the role of the northward displacement of the Azores anticyclone in enhancing the summer blocking episodes.

3.3. Anomalies during the Drought Episode That Occurred in 2003 Over Europe

3.3.1. Central Europe Drought Episode: February 2003 to June 2003

Monthly anomalies of the PRE, PET, and pressure velocity (ω) at 500 hPa, averaged over CEU during the drought episode of February to June 2003, are presented in Figure 7a. The bars in Figure 7b represent the monthly anomalies of the moisture supply ($E - P < 0$) over CEU, measured by the particles leaving the sources defined in Section 3.1 and obtained via the forward in time experiment. The lines show the PRE anomalies that were accumulated during the episode (AA-1). The two months before and after the drought episode were also plotted to observe the onset and end of the event.

For every month, bars for each source region are displayed. The height of each coloured rectangle (calculated from the difference between the upper and lower rectangle values) represents the anomalous contribution from the appropriate source. This means that larger coloured rectangles were associated with a more intense anomalous contribution. The superimposition of the anomalous moisture supply allowed us to estimate the accumulated anomalies in the moisture contribution from all of the investigated sources in a given month. The values are indicated by the green triangles.

Figure 7b shows that in February 2003—the onset of the drought episode—the moisture supply to CEU from all sources was reduced, and negative anomalies of PRE and positive anomalies of pressure velocity (indicating subsidence) prevailed (Figure 7a). From March 2003 to June 2003, there was a small increase in the moisture supply from the BAS, NAT, and CEU itself. However, the contribution from these sources was not sufficient to change the sign of the precipitation anomaly. The positive anomalies of PET and pressure velocity, and the most intense negative accumulated anomaly for PRE (AA-1), in June 2003 can be associated with the negative anomaly of PRE during the drought episode. A reduction in the moisture supply from almost all of the sources was also notable. In July 2003, the anomaly of PRE showed positive values (Figure 7a), and the accumulated loss of moisture from all of the sources was negative; the BAS, BLS, and CEU showed positive anomaly contributions. The CEU source was the most important climatological source in July, and it may have impacted the modulation of the precipitation anomalies. During August, the support of moisture from CEU increased to a point such that the sign reversed.

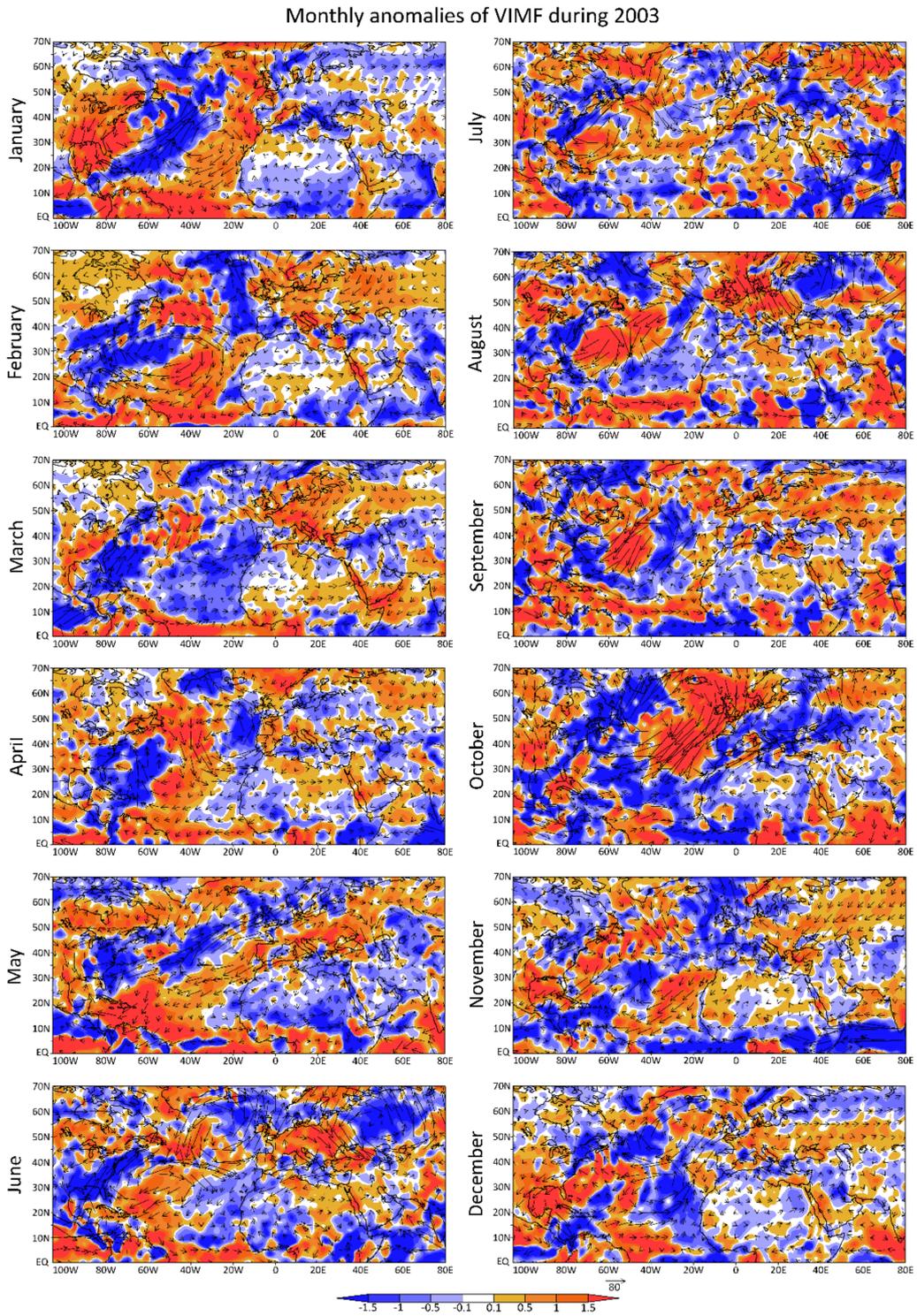


Figure 6. Monthly anomalies of the ERA-Interim vertically integrated moisture flux (VIMF) (vector, kg/(m/s)) and its divergence (shaded, mm/day) in 2003.

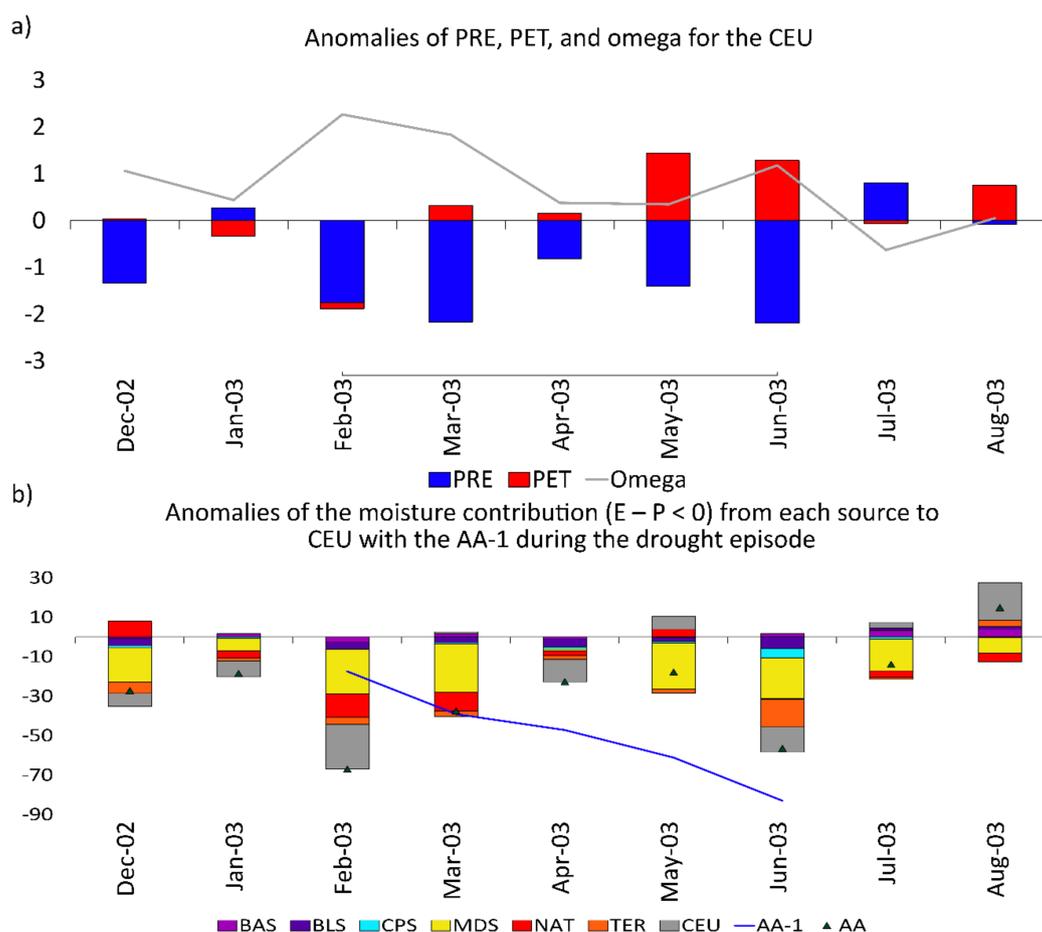


Figure 7. (a) Monthly anomalies of the precipitation (PRE, /10 mm/month), potential evapotranspiration (PET, /10 mm/month) (data from Climatic Research Unit (CRU) Time-Series (TS) 3.24.01), and average pressure velocity at 500 hPa (data from ERA-Interim) over the Central European region (CEU); and (b) Anomalies in the moisture supply ($E - P < 0$) for each source over CEU, obtained via the forward FLEXible PARTicle (FLEXPART) experiment (mm/day) with the accumulated anomaly of the supply from all of the sources (AA, mm/day) and the accumulated precipitation anomalies (AA-1, mm/month) (data from CRU 3.24.01) for the episode from February 2003 to June 2003.

The anomalies in the moisture supply from the sources to CEU that were accumulated during the February to June 2003 episode are displayed in Table 3. There was a predominance of reduced moisture supply from the studied sources. When we compared the accumulated values from the sources, the results indicated that the MDS source registered the most intense accumulated negative anomalies, followed by CEU (−91.95 and −39.42 mm/day, respectively).

Table 3. Anomalies of the moisture supply from the sources to the Central European region that were accumulated during the drought episode from February to June 2003 (mm/day). North Atlantic (NAT); Mediterranean Sea (MDS); Baltic Sea (BAS); Black Sea (BLS); Caspian Sea (CPS); terrestrial moisture sources surrounding the region (TER).

BAS	BLS	CPS	MDS	NAT	TER	CEU
−0.2	−18.2	−7.3	−91.9	−20.4	−23.9	−39.4

Table 4 shows the Pearson correlation coefficients between the time series of monthly anomalies in the moisture supply from the sources to CEU and the SPEI-1, in an attempt to reveal joint linear

variability during the period 1980–2015 (432 times). Although all of the values were positive, the BLS, CEU, MDS, and TER showed the highest annual correlation values (exceeding 0.5). This indicated that an inhibited moisture supply from these sources was linearly associated with dry conditions over CEU on the SPEI-1 scale.

Table 4. Pearson correlation coefficients between the time series of monthly anomalies in the moisture supply from the sources to the Central European region and the SPEI-1 for the period 1980–2015 (432 times). Except for the BAS, the coefficients are significant at 99.9%, according to Student’s *t*-test.

Moisture Sources	Correlation Coefficient
BLS	0.61
CEU	0.60
MDS	0.58
TER	0.57
NAT	0.44
CPS	0.30
BAS	0.04

3.3.2. The Mediterranean Region Drought Episode: May to August 2003

The drought that occurred over MED in 2003 has been investigated in previous studies [25,61–63]. This event received considerable attention because it had adverse social, economic, and environmental effects [25].

Similar to Figure 7, Figure 8a represents the monthly anomalies of the PET, PRE, and pressure velocity (ω) at 500 hPa, averaged over MED. Figure 8b represents the monthly anomalies of the moisture supply ($E - P < 0$) to the MED, measured by the particles leaving the main sources and the MED during the drought episode, together with the accumulated PRE anomalies (AA-1) and the accumulated anomalies of the moisture supply from all of the sources.

Figure 8b shows that in May 2003, the month in which the onset of the episode was observed, the moisture supply from almost all of the selected sources declined (except from the BLS and MED). In June 2003 (when the SPEI-1 value reached its peak), the moisture contribution from all of the sources declined. In July 2003, positive anomalies of moisture contribution prevailed, which were associated with some weakening in the negative anomaly of PRE. The drought episode ended in August 2003, and was associated with positive anomalies of PRE from September onwards. An intensified moisture contribution from the MDS and TER sources occurred in September 2003, while in October 2003, this intensification came mainly from the MDS, GIB, and MED.

In general, during the drought episode from May 2003 to August 2003, the contribution from the principal source of moisture—the MDS—greatly reduced, along with the negative accumulated anomaly of PRE AA-1 and positive anomalies of pressure velocity and PRE. Our findings were in agreement with those of Mariotti et al. [64], Drumond et al. [65], and Lionello et al. [63], who showed the importance of moisture transported by air masses travelling from the MDS.

The anomalies in the moisture supply from the sources to the MED accumulated during the 2003 episode are presented in Table 5, summarizing the effect of each source. In general, a reduction in the moisture supply from the studied sources prevailed during the episode, with the exception of the BLS and TER. The results also indicated that the MDS source registered the highest accumulated negative anomalies (-23.29 mm/day), followed by the GIB source (-4.82 mm/day) and the MED source (-1.82 mm/day).

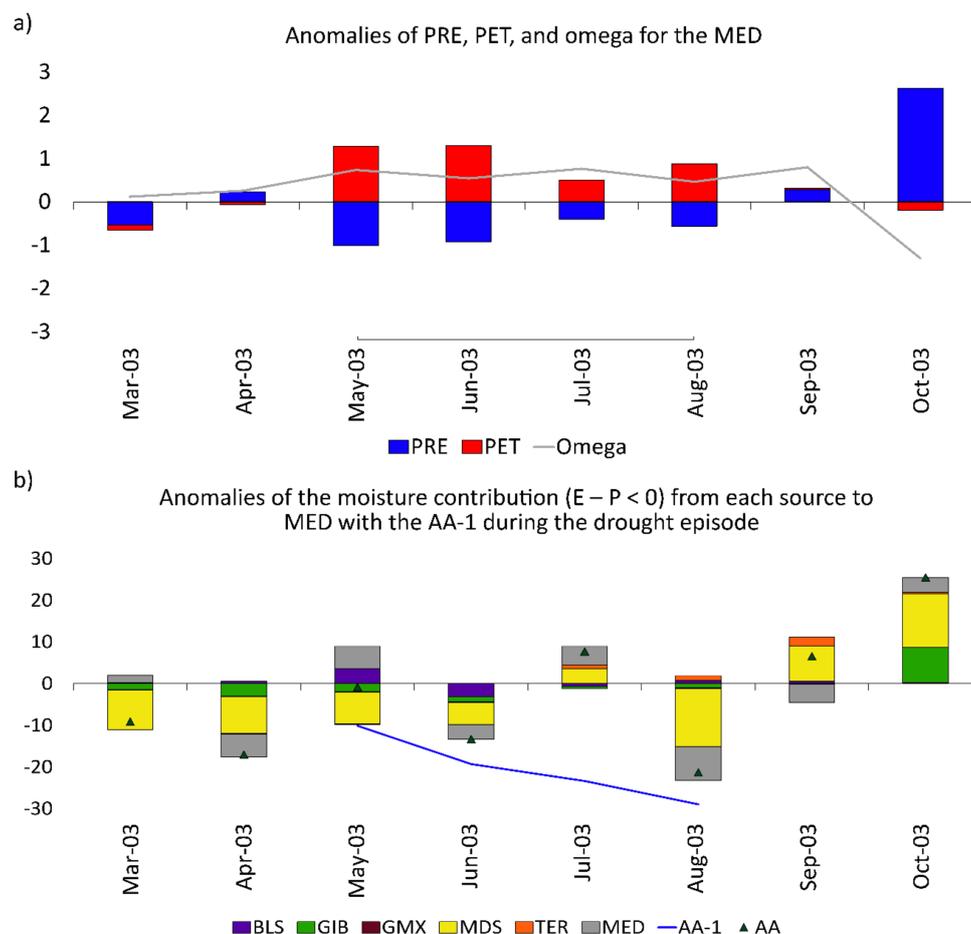


Figure 8. (a) Monthly anomalies of the precipitation (PRE, /10 mm/month), potential evapotranspiration (PET, /10 mm/month) (data from Climatic Research Unit (CRU) Time-Series (TS) 3.24.01), and average ERA-Interim pressure velocity at 500 hPa over the Mediterranean region; and (b) Anomalies in the moisture supply ($E - P < 0$) from each source over the Mediterranean region, obtained via the forward in time experiment (mm/day) with the accumulated anomaly of the supply from all of the sources (AA, mm/day) and the accumulated precipitation anomalies (data from CRU TS 3.24.01) (AA-1, mm/month) for the episode from May to August 2003.

Table 5. Anomalies of the moisture supply from the sources to the Mediterranean region accumulated during the drought episode from May to August 2003 (mm/day). Gibraltar (GIB); Gulf of Mexico (GMX).

BLS	GIB	GMX	MDS	TER	MED
0.66	-4.82	-0.27	-23.29	1.82	-1.82

Similar to Table 4, Table 6 shows the Pearson correlation coefficients between the anomalies in the moisture supply from the sources to the MED and the SPEI-1 time series for the period 1980–2015. The analysis showed that the GIB and TER had the highest correlation values (higher than 0.5), followed by the MED and MDS. Focusing on the maritime sources, this indicated that the reduction in the moisture supply from the GIB and MDS was linearly associated with dry conditions over the MED on the SPEI-1 scale. It is worth noting that although the total contribution from GIB to MED was relatively small—as shown in Figure 8 and Table 5—the correlation analysis (Table 6) reveals some important joint linear temporal variability between the moisture supply and the variability of SPEI-1 over MED.

Table 6. Pearson correlation coefficients between the time series of monthly anomalies in the moisture supply from the sources to the Mediterranean region and the SPEI-1 for the period 1980–2015 (432 times). The coefficients are significant at 99.9% for all of the sources, according to Student's *t*-test.

Moisture Sources	Correlation Coefficient
GIB	0.54
TER	0.51
MED	0.47
MDS	0.41
GMX	0.23
BLS	0.17

4. Summary

The aim of this study was to investigate the anomalies in the moisture supply observed during the meteorological drought episode that occurred over large parts of the European continent in 2003 through the Lagrangian methodology. In order to do this, we first identified the main climatological moisture sources for CEU and MED on an annual scale for the period 1980–2015, by tracking the air masses that reached the regions backward in time.

The results indicated that CEU mainly received moisture from seven different oceanic and terrestrial moisture sources. These included the NAT, MDS, BAS, BLS, CPS, TER, and CEU (itself). The main moisture sources for MED were the GMX, GIB, MDS, BLS, TER, and MED (itself). For both regions, the main climatological moisture source was MDS.

The analysis of the SPEI for CEU and MED revealed that the period from February to June 2003 (five months) for CEU, and May 2003 to August 2003 (four months) for MED, contained the most severe meteorological drought episodes in the regions during 1980–2015, according to this index calculated on a one-month time scale (SPEI-1).

The SPEI-1 for the episode from February to June 2003 (CEU) reached a peak of -1.86 , which belonged to the severe category, while the episode from May to August 2003 (MED) reached a peak of -2.71 , which is contained within the extreme category. The episode initially started in Central Europe (February 2003). For both regions, June 2003 was the month in which the SPEI-1 reached its peak value.

Except for the severity, the results suggested that the 2003 episode appeared to be more significant for the MED region when compared to the rest of the episodes identified over the same region during 1980–2015. This was because it appeared between the three most important events in terms of severity, intensity, and peak SPEI-1 value.

The analysis of the variation in the moisture supply indicated that the beginning of the drought episode over CEU was associated with a reduction in the moisture supply from all of the selected sources. This was the month in which the positive anomalies of pressure velocity reached their peak. The 2003 episode over MED (May to August 2003) was characterised by an anomalous subsidence, increased PET, and reduced PRE, which was associated with the predominance of reduced moisture supply from almost all of the detected moisture sources, with the exception of the BLS and TER. The episode that occurred over CEU ended when CEU itself began to provide moisture, while the episode that occurred over MED ended when MDS began to provide moisture.

MDS, which was the major climatological moisture contributor for CEU and MED, was the source that presented the most intense reduction in moisture supply for both regions. It appeared that the moisture advection from MDS was related to the anomalous anticyclonic circulation, localised over Europe, which inhibited the transport of moisture to the analysed regions. A linear inter-annual correlation analysis indicated that the correlation between the moisture supply from MDS and the SPEI-1 time series over the selected regions was stronger in CEU.

Previous authors have pointed to the importance of the Mediterranean Sea as the source of moisture for different regions in Europe. For example, Sodemann et al. [66] investigated the seasonal

and inter-annual variability of the moisture source for precipitation in the European Alps during 1995–2002, and showed the strong influence that the Mediterranean moisture source has for the Southern Alps. Schicker et al. [67] identified the Mediterranean Sea as an important moisture source for the Mediterranean region.

According to Levinson and Waple [15] and Ogi et al. [68], the summer of 2003 was one of the warmest, and a heat wave affected most of Europe. Two distinct periods of exceptional heat occurred. The first was in June and the second was during July–August. Across Europe, above-normal temperatures were recorded, accompanied by an almost complete absence of rainfall. Recently, Stojanovic et al. [36] found that the 2003 drought episode that occurred over the Danube River Basin was accompanied by a reduction in precipitation and an increase in potential evapotranspiration. Our findings are in agreement with these previous studies on drought. June was the month in which the most intensive negative accumulated anomalies for precipitation (PRE) were recorded across Central Europe. It was also the month in which the moisture contribution from all of the sources reduced over both regions.

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