Agricultural and Forest Meteorology 218–219 (2016) 135–145

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

The outstanding synergy between drought, heatwaves and fuel on the 2007 Southern Greece exceptional fire season

Célia M. Gouveia[a,*], Ioannis Bistinas[b], Margarida L.R. Liberato[a,c], Ana Bastos[a,e], Nikos Koutsias[d], Ricardo Trigo[a]

[a] Instituto Dom Luiz, IDL, Faculdade de Ciências, Universidade de Lisboa, Portugal
[b] Department of Meteorology, University of Reading, Early Gate RG6 6BB, United Kingdom
[c] Escola de Ciências e Tecnologia, Universidade de Trás-os-Montes e Alto Douro (UTAD) , Vila Real, Portugal
[d] Department of Environmental and Natural Resources Management, University of Patras, G. Seferi 2, GR-30100 Agrinio, Greece
[e] Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris -Saclay, F-91191 Gif sur Yvette, France

ARTICLE INFO

Article history:
Received 25 September 2015
Accepted 26 November 2015
Available online 28 December 2015

Keywords:
Drought
Heatwaves
Fuel availability
Wildfires
NDVI
Greece 2007

ABSTRACT

The fire season of 2007 was particularly devastating for Greece, achieving the new all-time record of estimated burnt area (225,734 ha) since 1980. The season was remarkably severe in Peloponnese Peninsula, in southern continental Greece, being considered the most extreme natural disaster in the recent history of Greece. Moreover during the hydrological year of 2007, Peloponnese was struck by a severe winter drought that corresponds to the second lowest annual accumulated value since 1951. However, the subsequent spring was very wet partially attenuating the effect of the previous drought. Additionally, the region was stricken by three heat heaves during summer, being the number of hot nights especially noticeable, surpassing more than 35 nights over the Southern Greece. Here we show that the central and Northern sector of Peloponnese Peninsula become the most susceptible to wildfires due to the combined effect of the two extreme meteorological events, drought and heatwaves which was confirmed by the location of the main burnt areas of 2007 fire season. Additionally, the analysis showed that during the extreme days of fire activity in 2007, strong northerly advection of very hot and dry air over the region, favored fire occurrence.

The study attempts to bring new light to the synergistic effect between fuel availability and weather conditions that created extraordinary conditions for fire propagation. We focused on the largest burnt areas and the respective NDVI behavior is assessed throughout the pre fire periods. We found that vegetation dynamics are related to the extreme climatic events that occurred in these periods. Moreover, our results confirm that the higher fire incidence in areas with higher vegetation activity and density seems to indicate that the large burnt areas of 2007 fires season in Peloponnese Peninsula appear to be more sensitive to fuel availability and vegetation density than to vegetation dryness.

1. Introduction

Drought episodes in Mediterranean region are responsible for negative impacts on the vegetation that result in significant crop yield losses (Rodríguez-Puebla et al., 2007; Schillinger et al., 2008), increased risk of forest fires (Pellizzaro et al., 2007) and forest decline (Vicente Serrano et al., 2010; Besson et al., 2014). The Mediterranean region is prone to frequent drought episodes, as a consequence of the large intra and inter-annual variability of precipitation. Very intense drought episodes are relatively common, with prolonged periods without precipitation (Vicente Serrano and Beguería, 2003). The dependence of vegetation dynamics on water accessibility in the Mediterranean regions has been extensively documented (Udelhoven et al., 2009; Gouveia et al., 2009; Vicente Serrano, 2007; Lindner et al., 2010; Koutsias et al., 2013).

Fire regimes in the Europe, namely in Southern Mediterranean areas have been changing in the last decades, mainly due to land-use changes and climate driven factors (Fried et al., 2004; Pausas and Fernández-Muñoz, 2012), such as increasing temperatures and extreme events such as droughts and heatwaves. Dimitrakopoulos et al. (2011) used a well-known drought indicator, the Standard Precipitation index (SPI) and found a positive correlation between burned areas in Southern and Central Greece and summer droughts (drier and warmer regions), for the period 1961–1997. Moreover,

* Corresponding author.
E-mail address: cmgouveia@fc.ul.pt (C.M. Gouveia).

http://dx.doi.org/10.1016/j.agrformet.2015.11.023
0168-1923/

the study showed a significant increase of burned area and drought episodes in regions (Northern and Western Greece) characterized by higher annual precipitation and lower mean temperatures. The other regions of the country did not show any significant change in drought episodes although presenting always high fire activity. Koutsias et al. (2013) and Xystrakis et al. (2014) emphasized the opposite role of spring and summer precipitation in fire occurrence in Greece over the last century, being the summer precipitation associated with negative values of burned area whereas the high spring precipitation matches years large burned areas. Good et al. (2008) and Dimitrakopoulos et al. (2011) pointed out to an obvious outperformance of precipitation related variables in comparison with temperature related variables. Similarly, an assessment of the impact of dryness conditions in Mt. Taygetos, Southern Greece, showed that the drivers of the recent fires in 1998 and 2007 were both low precipitation and high temperature in summer, which enhanced the synergy between climate and fuel availability and consequently led to intense fires (Sarris et al., 2013).

The fire season of 2007 in Greece was catastrophic by most accounts. The authorities reported more than 60 human fatalities, more than 100 villages spoiled (Boschetti et al., 2008; Gitas et al., 2008; Koutsias et al., 2012) and, additionally, the new record of estimated burnt area (225,734 ha), since 1980. The fire season was especially severe in the Peloponnese Peninsula, in southern continental Greece, with 189,952 ha burnt area (ca. 1.5% of Greek land surface; 117,188 ha of forests and forested areas burnt), and considered to be the most extreme natural disaster in the recent history of Greece (Koutsias et al., 2012). Albeit the main forest fires are the result of arson and negligence, several studies attempted to assess the causes for this exceptional fire season, with a focus on climatic factors (Founda and Giannakopoulos, 2009; Amraoui et al., 2013; Koutsias et al., 2012; Sarris and Koutsias, 2014), but also highlighting a synergy of land use changes and climate (Koutsias et al., 2012).

The year of 2007 was warmer than the average conditions, with a strong effect in Southern Europe and the Middle East. Surface air temperature anomalies were 1–2 °C above the 1961–1990 average over most of the continent and, according to Luterbacher et al. (2007) and the winter of 2006–2007 was probably the warmest of the last 500 years. The temperature anomalies in January reached more than 11 °C in Eastern Europe. Moreover, Greece suffered three exceptional heatwaves in June, July and August of 2007 that represented the highest maximum temperatures of the last six to seven decades (Tolika et al., 2009). The prevailing synoptic situation during the heatwaves of summer 2007 corresponded to the occurrence of a long wave ridge with axis oriented from SW to NE, at 500 hPa, along with the horizontal advection of dry and warm air masses from north-western Africa to the central and eastern Mediterranean and further north to the Balkans (Founda and Giannakopoulos, 2009). On the other hand, according to Amraoui et al. (2013), the air masses were further heated by adiabatic compression associated to strong subsidence in the layer 800–500 hPa. Additionally, at the surface there was strong northerly advection of very hot and dry air over the region, favoring the occurrence of severe wildfire episodes. These authors show that the unusually large and severe fires occurred in Peloponnese, particularly in August, are located in the area of higher values and stronger positive anomalies of FWI (Fire Weather Index that is part of the Canadian Forest Fire Weather Index System). The comparison with future projections obtained using regional climate models shows that these extreme high temperature values have more than 50% of probability to happen by the end of the 21st century (Founda and Giannakopoulos, 2009; Tolika et al., 2009).

The impact of extreme drought events and heatwaves on vegetation has been widely assessed by means of remote sensing data (Kogan, 1997; Gouveia et al., 2009, 2012; Vicente-Serrano et al., 2013; Gobron et al., 2005; Lobo et al., 2003). Several vegetation indices have been used to analyze the behavior of vegetation, been the Normalized Difference Vegetation Index (NDVI) the most commonly used (Stöckli and Vidale, 2004; Julien et al., 2006; Gouveia et al., 2008; Vicente-Serrano et al., 2013).

Several authors have stressed that one extreme climatic event or a conjugation of two extreme climate events do not always imply an extreme ecological response of the ecosystem (e.g. Kreyling et al., 2008; Smith, 2011; Jentsch et al., 2011). Considering these limitations Smith (2011) proposed a variety of approaches to broaden our knowledge on the vulnerability of ecosystems to climate extremes. In this context, the main goals of this work are the following:

1. To characterize drought and heatwave events of 2007;
2. To evaluate the relationship of drought, heatwaves and wildfires during 2007 fire season;
3. To evaluate the impact of drought on vegetation dynamics on the months preceding the fire season using NDVI.

2. Data and methodology

2.1. NDVI

Vegetation dynamics was assessed using Normalized Difference Vegetation Index (NDVI) data as obtained by the VEGETATION sensor on board of SPOT4 and SPOT5 satellites. VEGETATION provides daily high quality global monitoring data since 1998, in four channels at 1 km^2 resolution (Hagolle et al., 2005).

We extracted NDVI data from S10 products of VITO database (http://free.vgt.vito.be). The 10-day composites were obtained after applying the Maximum Value Composite method (MVC) which allows removing pixels with clouds (Holben, 1986). The selected period for the data spans from September 1998 to August 2009 for the area of interest: 34°N to 44°N and 17°E to 27°E. MVC-NDVI data were already corrected for atmospheric and radiometric effects and calibrated geometrically (Maisongrande et al., 2004). With the aim to create a consistent dataset of vegetation dynamics, we further corrected the yearly time-series of MVC-NDVI using the approach described in Stöckli and Vidale (2004) and Gouveia et al. (2009).

We obtained the large burnt areas for 2007 with *K*-means clustering of monthly MVC-NDVI anomalies over each hydrological year (Gouveia et al., 2010). The method aims to detect mainly large burned areas and, in this study, we used an improved version that is applicable to broader areas such as the entire Iberian Peninsula (Bastos et al., 2011; Gouveia et al., 2012). The method was applied to MVC-NDVI anomalies for 2007 over Greece and a set of six large burnt scars over Peloponnese, hereafter referred to as A1 to A6 (Fig. 1). Then we used some of those areas to monitor the respective NDVI behavior. Monthly means and anomalies of NDVI from September to August were computed over the period of 1999–2009. Drought persistence was evaluated by adding up (for each pixel) the number of months between November 2006 and July 2007 with NDVI anomalies lower than −0.010 (Gouveia et al., 2009, 2012; Trigo et al., 2010).

Vegetation behavior of the main vegetation types over the study area was also assessed by means of a cluster analysis on the monthly NDVI means. Seven main clusters corresponded to the main vegetation communities over the studied area. The relationship between these clusters and the main land cover types was performed using the Global Land Cover 2000 (GLC2000) classification for the studied area.

2.2. Meteorological data

With the aim of visualizing the spatial extent of the 2007 drought we used the monthly precipitation dataset from GPCC

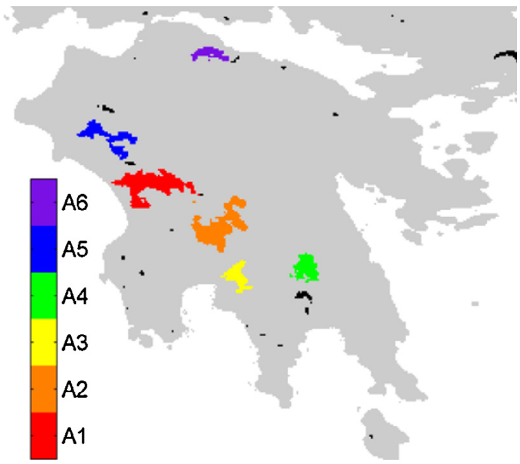

Fig. 1. Selected burnt areas over Peloponnese, A1–A6.

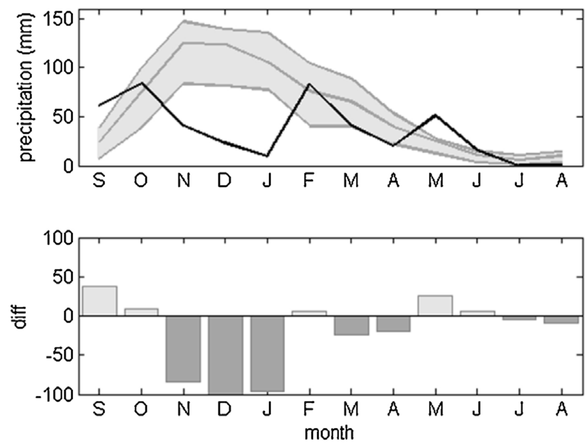

Fig. 3. Climatological (1951–2000) annual cycle of monthly precipitation averaged over Peloponnese Peninsula during the hydrological year 2006/2007. The shaded areas include the 25th–75th monthly percentiles obtained from the 1951–2000 precipitation time series, with the median in between. Dashed line shows the time series for the hydrological year 2006/2007, with the corresponding monthly departure from the climatological mean being represented in the bottom graphic.

(Rudolf and Schneider, 2005) on a 0.5° latitude by 0.5° longitude grid (http://gpcc.dwd.de). We extracted data for the Mediterranean region for the spatial extent: 34°N to 44°N and 17°E to 27°E. For the accumulated precipitation percentages of the hydrological year, we took into account the corresponding climatological (1951–2010) normals. The definition of a hydrological year is the period spanning between September of year y to August of year $y+1$. To assess the rank of this drought in the climatology of the region, we have computed the average of accumulated monthly precipitation over the Peloponnese Peninsula (box defined in Fig. 2 left panel) for the hydrological year. The evolution of the associated climatological accumulated monthly precipitation distribution for the Peloponnese box is also shown using a box and whiskers plot (Fig. 2, right panel). In order to present a more detailed analysis of the temporal evolution over this hydrological year, the precipitation for the Peloponnese Peninsula was spatially averaged and the obtained monthly time series of precipitation is presented in Fig. 3. The climatological median and the 25th and 75th percentile curves, all computed with the entire 60-year long available period (1951–2010) are also presented.

Several indices are currently used to characterize extreme temperature events (Zhang et al., 2011). One of the standard indices is the 95th (or 90th) percentile of the maximum temperature. However, the 95th (or 90th) percentile of the minimum temperature is also used very often (Trigo et al., 2009; Orlowsky and Seneviratne, 2012). With the aim to establish a link between drought and heatwaves we define the number of hot nights per month (NHN) as the number of nights with a minimum temperature exceeding the 95th percentile. This index was constructed using minimum temperature from the E-OBS gridded data version 11.0 spanning from 1950 to 2011 (Haylock et al., 2008) covering the above mentioned window and the NHN was accumulated for the summer period between June and August. The years within the entire period of data were ranked based on the accumulated NHN accumulated for summer. The grid points with missing data over the analyzed window were spatially interpolated using nearest technique. Finally, in order to evaluate the combined effect of drought and heatwave the ratio between the accumulated NHN and the accumulated precipitation during the hydrological 2006/2007 year was also computed.

To characterize the synoptic circulation, we used horizontal fields of Interim Reanalysis (ERA-Interim), which were obtained from the ECMWF. ERA-Interim is the latest ECMWF global atmospheric reanalysis available since 1979 up to the present (Berrisford et al., 2009; Dee et al., 2011). The following meteorological variables were extracted, each day at 12 UTC, over the Mediterranean area (0–40°E, 30–50°N) for July and August 1981–2010, and then projected onto a 0.75° x 0.75° latitude/longitude grid:

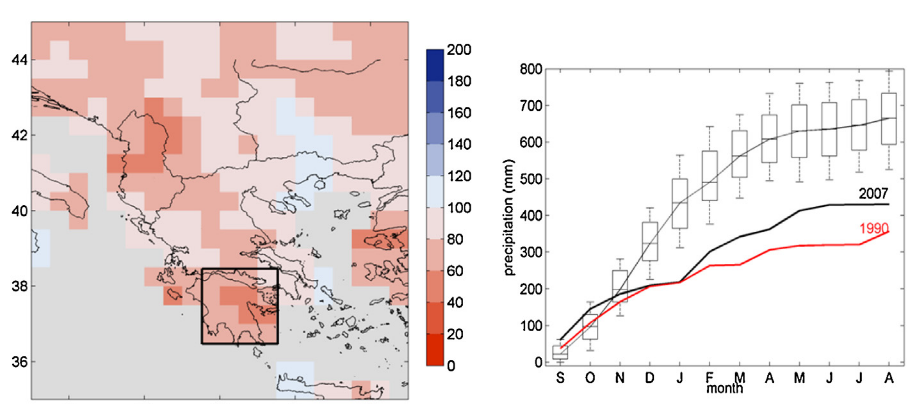

Fig. 2. Left: Spatial distribution of the accumulated monthly precipitation (in percentage relative to the 1951–2010 normals) during the hydrological year 2006/2007 (i.e., between September 2006 and August 2007). Black box approximately delimits regions with maximum deficit in accumulated precipitation in Peloponnese Peninsula; Right: Accumulated monthly precipitation averaged over Peloponnese Peninsula during the hydrological year 2006/2007 (black line). Gray lines indicate the climatological median evolution in region, with boxes (whiskers) representing the 0.5 sigma level (10th–90th percentiles) obtained from all hydrological years between 1951 and 2010. For the sake of comparison, the most severe drought event within the 1951–2010 period (1990) is also indicated.

- air temperature at 2 m height (hereafter T2);
- horizontal wind vectors at 10 m height (hereafter U10);
- 500 hPa geopotential heights (hereafter Z500);
- temperature, relative humidity and horizontal wind vectors at 850 hPa (hereafter T850, RH850 and U850).

Due to the extreme meteorological conditions in July–August 2007, we analyzed the main characteristics of the atmospheric circulation in that period by means of daily (12 UTC) fields and 7-day anomaly composites of multiple atmospheric fields. The 7-day anomaly composites simply consist of departures of 7-day arithmetic means over the period July–August 2007 of the considered 12 UTC fields from the respective 7-day climatology computed over the same period July–August 1981–2010. For example, the anomaly field of 7-day composites on 8th July 2007 corresponds to the anomaly field between the mean of days from 5 to 11 July 2007 (at 12 UTC) and the grand mean of days from 5 to 11 July for the 30-year period (1981–2010).

3. Results

3.1. Burnt areas

The burnt areas obtained from the *K*-means clustering (Fig. 1) are in good agreement with previous ones obtained by Boschetti et al. (2008) and Gitas et al. (2008). The former authors presented a map of burned areas and day of burn in Greece, using MODIS Burned Area Product with 500 m of spatial resolution. Results obtained by these authors and those attained here agree that the location of the largest burned areas is in southwest Greece, in particular in the Peloponnese and close to Athens. Over Peloponnese, the first large fires occurred in late July, and the rest in the last week of August. Gitas et al. (2008) used data from the Disaster Monitoring Constellation (DMC) image from NigeriaSat-1, with a nominal resolution of 32 m pixel size, supplied by DMCii through the International Charter, obtained compatible results for July and August. With the purpose of localizing temporally the selected burned areas a visual comparison with the results of the previous studies was performed and despite the different resolutions of sensors it is possible to assert that burn areas A1 to A5 correspond to fires occurred during August while A6 matches fires occurred in late July.

In line with results from Koutsias et al. (2012), the most affected land cover types over Peloponnese Peninsula in 2007 were “land principally occupied by agriculture, with significant areas of natural vegetation” (25.78%), Sclerophyllous vegetation (14.95%) and transitional woodland shrubs (11.85%). However, when compared with the recent history in the region (2000–2006), only the former land cover type presented a remarkable increase (from 17.48% to 25.78%). The same authors showed also that the main burned areas are predominantly located in the lowest elevation zones (0–500 m: 59.98%; 500–1000 m: 32.76%) and in very high fire occurrence zones (66.20%), while a small number of fires (4.89%) occurs in non-fire prone areas.

3.2. Drought and heatwave assessment

The drought assessment shows lower than average values of accumulated precipitation in most of the area assessed. However, the decline in precipitation during the hydrological year of 2006/2007 over the Peloponnese region is evident with 40% less rainfall over eastern Peninsula (Fig. 2, left panel).

The accumulated monthly precipitation averaged over the Peloponnese Peninsula (box defined in Fig. 2, left panel) for the hydrological year reveals the severity of this drought in the climatological context of the region. Despite the higher than average precipitation values during September and October 2006, the deficit of precipitation increased significantly during the winter months of 2007 (Fig. 2, right panel). Accumulated precipitation increased regularly during spring and summer months (similar to the climatological average). At the end of the period the total precipitation (∼400 mm) is roughly 2/3 of the mean value (less than 600 mm) corresponding to the second lowest value since at least 1951. The lowest value corresponds to the extreme drought event of 1989–1990. This last hydrological year is also represented in Fig. 2 (right panel in red), which presents the accumulated precipitation (∼300 mm) almost half of the mean value. The winter period was particularly dry, with three months (November to January) below the 25th percentile. Moreover, despite the relative wet February, in March and April 2007 the precipitation over Peloponnese drops again to values close to the 25th percentile. However, during May 2007 the precipitation values increased to values higher than the 75th percentile, attenuating the effect of the drought months in 2006–2007.

In order to analyze the connection between the extreme heatwaves and drought and, consequently, their impact on the wildfire activity over Greece, the NHN was obtained using the 95th percentile and the spatial distribution of the index is presented in Fig. 4 (left panel). With the aim to assess the exceptionality of the 2007 summer, all the 65 years within the period of available data (1950–2011) were ranked based on the accumulated NHN for summer. Grid points characterized by a top ranking position in 2007 are highlighted with white circles. A few grid points had to be interpolated due to lack of sufficient data, in these cases the NHN are represented with a black circle. The NHN is higher over the Southwest part of Greece (including the North-western Peloponnese) achieving 40 nights and being almost of them the record within the 60-year period considered.

The main burned areas in 2007 are located over the northern and western sectors of the Peloponnese, i.e. an area substantially smaller than the one represented by record high temperatures in the summer of 2007. Therefore, with the purpose of better understanding the mechanism behind this fairly restricted location of large fires, we computed the ratio between the accumulated NHN for summer and the accumulated Precipitation and its spatial distribution is represented in Fig. 4 (right panel). The higher values of the ratio are located over the northern part of Peloponnese Peninsula being in good agreement with the results of Fig. 1.

3.3. Heatwaves characterization

We compute the 7-day (12 UTC) anomaly composites of multiple atmospheric fields consecutively, with 5-day steps (Julian day 8, 12, 16, 20, 14 and 28) for each month (July and August) with the aim to characterize the two heatwaves that occurred in the region. The onset, development and persistence of the July 2007 heatwave on Central and Eastern Europe is shown through the 7-day anomaly composites of air temperature at 850 hPa (T850) and 500 hPa geopotential height (Z500) for July 2007 (Fig. 5a). The low-tropospheric air temperature anomaly field shows the onset and development over central Europe of an intense positive anomaly, which on 16 July was higher than 6 °C. On the following days it is further intensified while being displaced to the south-east, achieving a maximum on 20 July (>8 °C), when it extended over some regions of Greece, Romania, Bulgaria and Turkey. The excessive heat persisted until 28 July, although mostly over Turkey. Concurrently, the Z500 anomaly field changed from negative values on the first 2 weeks of July (days 8 and 12 corresponding to the period 5–15 July), being dominated, on 16 July, by a marked positive anomaly maximum (>100 gpm) also located over Central Europe, coinciding with the location of the maximum temperature anomaly (Fig. 5a). This large-scale feature is usually associated with fewer clouds

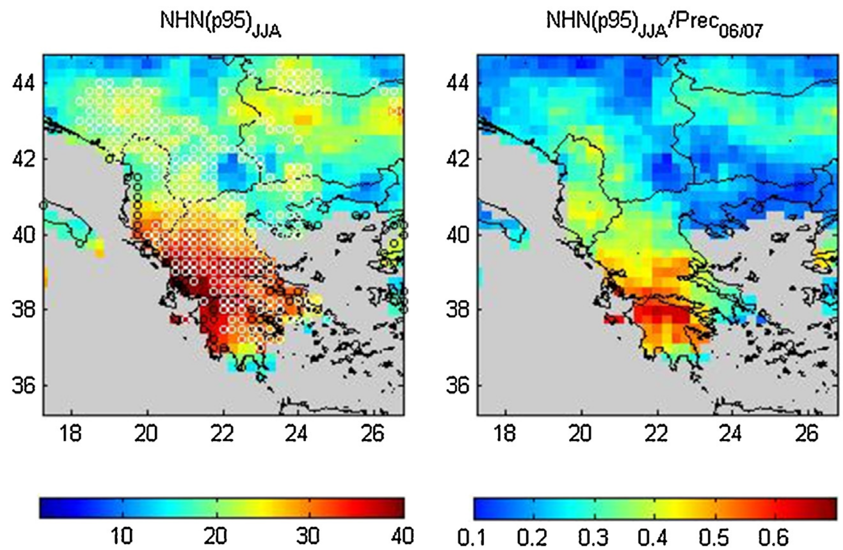

Fig. 4. Left: Spatial distribution of accumulated number of hot nights (NHN: t_{min} > 95th percentile) during summer of 2007 (June to August). White circles represented grid points where 2007 present the highest accumulated value of NHN and black circles the grid point values obtained by interpolation. Right: Spatial distribution of the ratio between NHN and accumulated precipitation in the hydrological year 2006/2007.

than normal (i.e. subject to increased solar heating) and with an enhancement of the subsidence of air into the troposphere, and thus a reinforced increase of air temperature through adiabatic heating at lower levels (Xoplaki et al., 2003; Trigo et al., 2005; Amraoui et al., 2013).

Correspondingly, Fig. 5b shows the 7-day anomaly composites of the T850 and Z500 for August 2007. The first days of August (days 8 and 12, corresponding to the period 5–15 August) reveal a negative T850 anomaly over Italy, Croatia and Greece together with the associated negative geopotential height departures (<60 gpm). From 20 August, the synoptic conditions are characterized by a Rex-type blocking over the Eastern Atlantic, which evolved into an omega pattern (Amraoui et al., 2013). The flow at the 500 hPa level was dominated by a pronounced trough over Eastern Mediterranean, with the axis oriented from SW to NE. Positive departures of Z500 (Fig. 5b, on day 24 August), as large as 80 gpm, which delimit a region over southern Italy and Greece, were thus characterized by a strong enhancement of the subsidence of air into the troposphere, leading also to an increase of air temperature through adiabatic heating at lower levels (Trigo et al., 2005). This feature persisted on the region until the end of August, albeit with a smaller amplitude.

In order to better understand how the large-scale atmospheric conditions associated with the two heatwaves affected specifically each fire event on the Peloponnese Peninsula during the summer 2007, the spatial distribution of surface and lower tropospheric meteorological fields is shown in more detail for 12 UTC of each day from 18 to 21 July 2007 (Fig. 6a) and from 22 to 25 August 2007 (Fig. 6b). For each day of the July heatwave, Fig. 6a shows, on the top panel, the air temperature at 2 m (T2) as well as the wind vectors at 10 m (U10) and on the lower panel, the relative humidity (RH850) with the wind vectors (U850), both at the 850 hPa pressure level. The top panels confirm that the surface temperature remained around 35 °C, increasing slightly on the Peloponnese Peninsula from 18 to 21 July. The shaded fields on the lower panels, representing the RH850, clearly show that the dry air mass over the Peloponnese Peninsula became even drier from 18 to 21 July, from values below 40% to values around 25% on 21 July. On all panels it is evident that the circulation at the surface (U10) and lower troposphere (U850) is dominated by an intense northerly (at the surface) and north-easterly (at 850 hPa) advection of continental hot and dry air. These intense northerlies correspond to the well-known etesian winds, which dominate the Adriatic, Ionian, and Aegean Seas and the adjacent countries from about mid-May to mid-September (Lionello et al., 2006). A similar analysis was undertaken for the August heatwave (Fig. 6b) showing that from 22 to 25 August 2007 the Peloponnese Peninsula had even higher values of surface air temperatures (above 40 °C, top panels) and low values of relative humidity (below 40%), while the intense northerly advection of continental hot and dry air continued (Fig. 6).

3.4. Drought impact on pre-fire vegetation

We identify seven main phenological types over Peloponnese with a cluster analysis on the monthly means of NDVI for the entire period (Fig. 7, left top panel). These seven clusters correspond approximately to the main vegetation communities over Peloponnese (Table 1). Shrubland occupies around 2/3 of area of clusters C1 and C2, being the other 1/3 distributed more or less equally by needle leaved evergreen forest and cultivated and managed areas. Clusters C6 and C7 are mainly associated to shrubland (around 75%) with about 20% of the area occupied by cultivated and managed areas. Cluster C3 are mainly occupied by needle leaved evergreen forest (62%) with 22% of shrubs. On the other hand cluster C5 are mainly distributed by shrubland and cultivated areas. It should be noted that there is some topography influence on these vegetation distribution. Thus, clusters C4 and C7 correspond mainly to mountainous areas, while C1, C4 and C5 are representative of lowland regions, being C2, C3 and C6 associated with intermediate areas. These results bear a close resemblance to the bioclimatic zones obtained using pluviometric quotient and thermic variables shown by Koutsias et al. (2012). The annual cycle of the monthly mean of NDVI relative to each community is a useful tool to understand their distinctive fingerprint in vegetation activity, in both absolute and relative terms, by considering simultaneously their amplitude and seasonal cycle evolution, respectively (Fig. 7, bottom panel). Clusters C2, C3 and C7 present a relative minimum of vegetation activity in late winter/early spring, presenting the cluster C2/C7 the highest/lowest vegetation activity, as obtained by the highest/lowest annual mean NDVI value. The high value of NDVI for cluster C3 throughout the entire year is compatible with the vegetative cycle of needle leaved evergreen forest of intermediate altitudes, whereas the accentuated minimum of vegetation activity in late winter for clusters C2 and C7 are compatible with the predominance of shrubs and crops. The lower value of annual

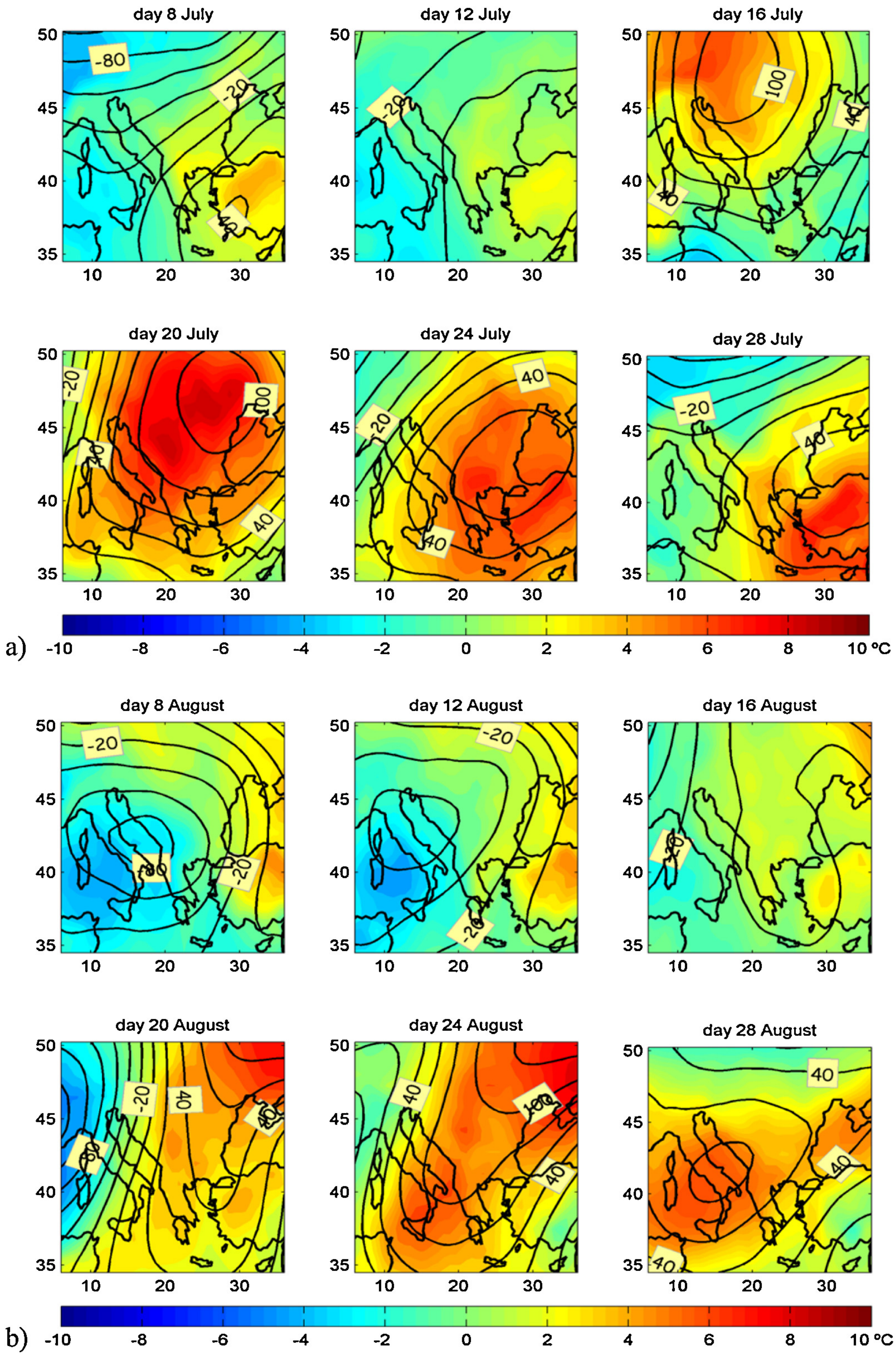

Fig. 5. Anomaly fields of 7 days composites of air temperature at 850 mb (T850, shaded, °C) with 500 hPa geopotential height (Z500, contour, gpm) for July 2007 (a) and for August 2007 (b) (using ERA-Interim reanalysis data for the period 1981–2010).

mean NDVI in C7 also reflects the predominance of high altitude location, being C2 associated with intermediate altitudes. Cluster C4 presents low vegetation activity throughout the entire year, a typical feature of areas occupied by shrubs and managed areas in mountainous areas (Fig. 8c from Koutsias et al., 2012) characterized also by a low number of biological dry days (Fig. 8e from Koutsias et al., 2012). Cluster C5 presents the most accentuated vegetative cycle, with a minimum in summer and a maximum in spring, a typical vegetative cycle of shrubs and crops over semi-arid regions with a dry summer and extremely dependent of winter and spring precipitation. Effectively cluster C5 matches fairly well the drier zones, classified as semi-arid in the bioclimatic classification used

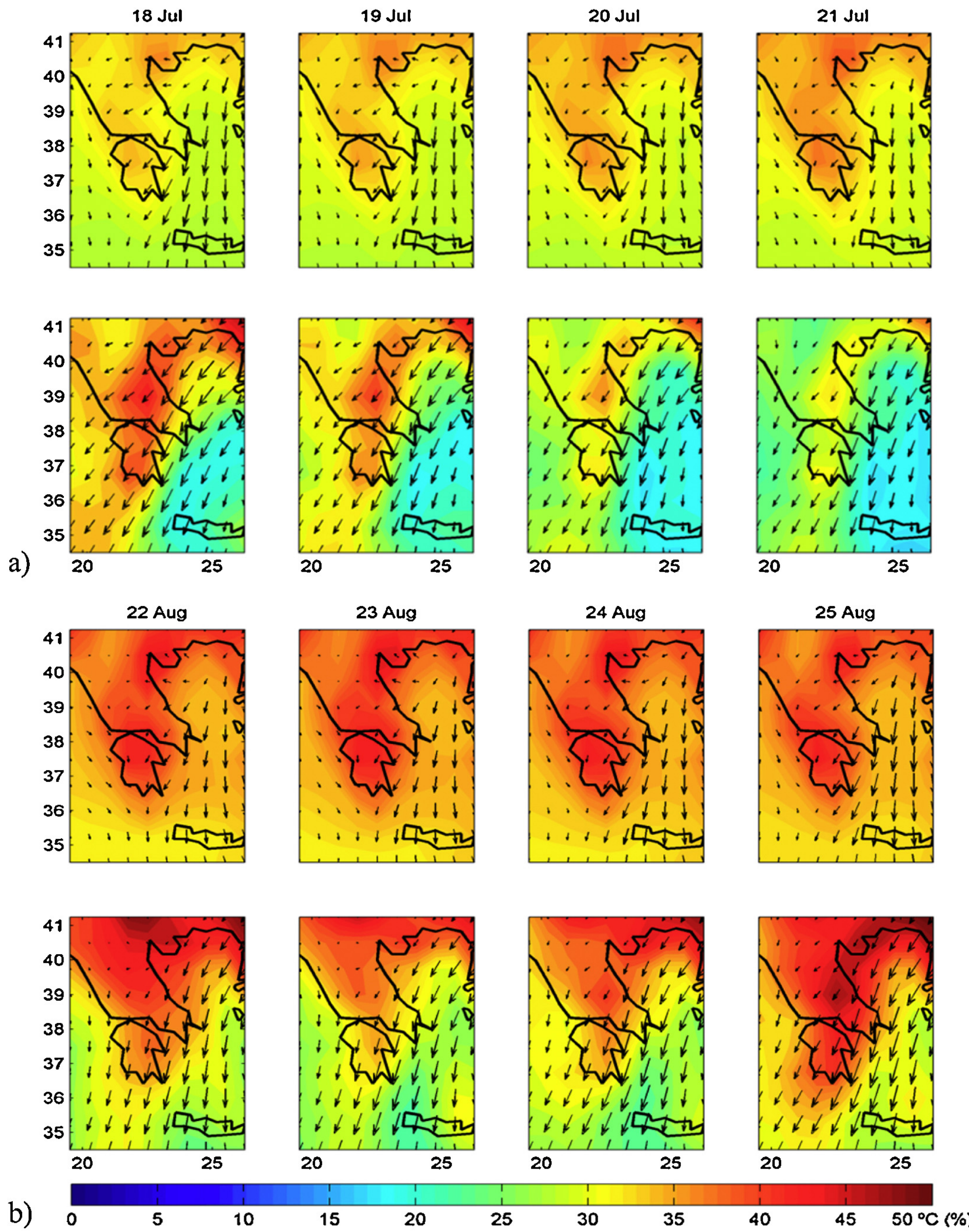

Fig. 6. Spatial distribution of air temperature at 2 m (T2, shaded, °C – top panel) with wind vectors at 10 m (U10, m s^{-1}) and relative humidity (RH850, shaded, % – bottom panel) with wind vectors (U850, m s^{-1}) both at 850 hPa, for the period of July, 18–21 (four figs) (a) and for August, 22–25 (four figs) (b) 2007 (using ERA-Interim reanalysis data).

Table 1
Percentage of pixels within each cluster belonging to needle-leaved evergreen, shrub closed-open and cultivated/managed accordingly with Global Land Cover 2000 (GLC2000).

Cluster	Needle-leaved evergreen	Shrub closed-open	Cultivated/managed	Others
C1	11	68	19	2
C2	17	63	14	6
C3	62	22	3	13
C4	6	38	54	2
C5	5	51	43	1
C6	2	82	15	1
C7	2	71	21	6

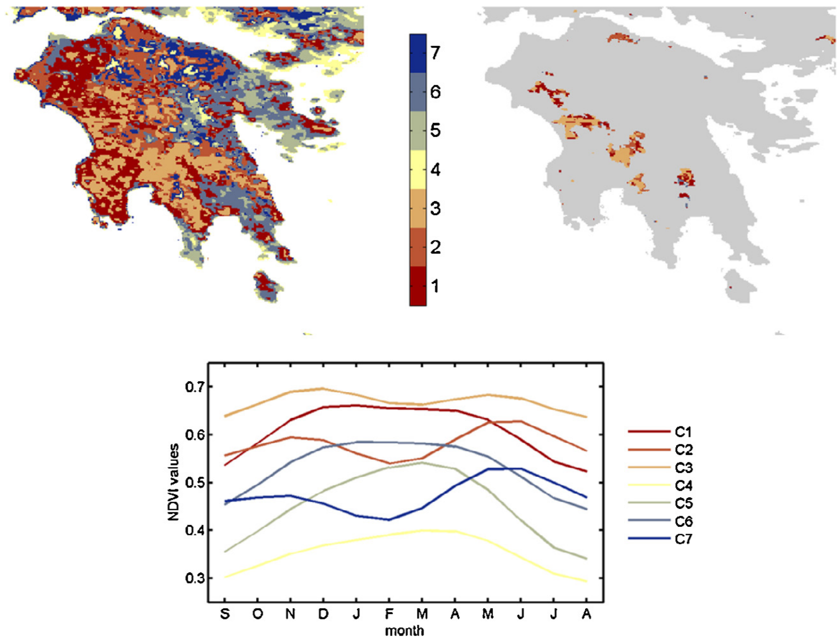

Fig. 7. Top left panel: Spatial distribution of the seven clusters of NDVI obtained for the period 1998–2009. Top left panel: The same but for the considered burnt areas. Bottom panel: annual cycles of monthly NDVI that characterize the centroids of the seven identified clusters.

by Koutsias et al. (Fig. 8f, Koutsias et al., 2012). Clusters C1 and C6 present a maximum of vegetation activity during late winter/early spring, presenting the Cluster C1 the highest annual mean NDVI value that is related with the higher water availability characteristic of humid zones (Fig. 8f from Koutsias et al., 2012).

The results of the persistence of vegetative stress through the analysis of NDVI anomalies (Fig. 8) revealed that 20% of Peloponnese was under vegetative stress conditions for more than 4 months before the fire season. Some pixels present even 8 months of negative NDVI anomaly in south and north-eastern Peloponnese. The main burnt areas of the 2007 fire season are located over sectors that were not particularly affected by vegetation stress (Table 2). While burn scars A2 to A4 showed around 85% of pixels with no vegetative stress, areas A1 and A6 showed around 70%. However, these last two burned areas show respectively 19% and 14% of pixels presenting more than 1 month with negative NDVI anomalies. It should be noted the complete absence of pixels presenting more than 4 months of negative NDVI anomalies inside the studied burn areas, which seems indicate that the vegetation over the burnt scares was not suffering a strong dryness in the months preceding the fire.

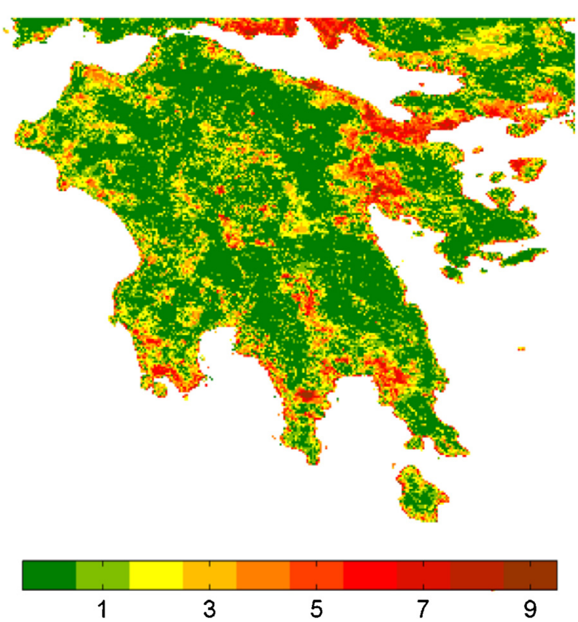

Fig. 8. Drought persistence was evaluated by adding up (for each pixel) the number of months between November 2006 and July 2007 with NDVI anomalies lower than −0.010.

Table 2
Percentage of pixels within each bunt areas with 0 to 6 months of negative anomalies of NDVI.

	0	1	2	3	4	5	6
A1	64.2	16.1	15.4	3.7	0.4	0	0
A2	87.4	7.3	4.0	0.8	0	0	0
A3	90.4	3.7	5.2	0	1	0	0
A4	88.6	6.0	4.2	1.2	0	0	0
A5	83.7	11.3	4.5	0.5	0	0	0
A6	75.5	10.2	9.2	4.1	1.0	0	0

The pixels of the selected burnt areas belong mainly almost entirely (>98%) to clusters C1, C2 and C3 and a residual number of pixels belonging to cluster C6 (Fig. 7, right top panel). Table 3 shows the percentage of each cluster type in the total amount of pixels burnt (regions A1 to A6) and in each burnt scar. Table 3 indicates that the burnt area resulting from fires occurring in July (A6) is mainly occupied by cluster C2 (more than 80%). In the fires occurring in August, A5 has more than 60% of pixels belonging to cluster

Table 3
Percentage of each cluster type in the total amount of burnt pixels and in each of the selected burnt scars in Greece.

	C1	C2	C3	C4	C5	C6	C7
Total	27.5	21.1	49.8	0	0	1.6	0
A1	28.9	6.7	63.8	0	0	0.6	0
A2	11.1	29.6	59.0	0	0	0.3	0
A3	4.0	32.4	63.2	0	0	0.0	0
A4	48.2	9.1	32.5	0	0	10.2	0
A5	62.0	8.6	29.4	0	0	0.0	0
A6	11.2	81.6	5.1	0	0	2.1	0

Table 4
Cumulative effect of drought conditions for each cluster during the drought episode of winter 2006/2007.

No. of months	C1	C2	C3	C4	C5	C6	C7	Total
≥4	13.9	3.8	6.7	19.3	18.4	23.8	14.1	4885
≥5	12.8	2.1	5.8	20.7	20.7	23.2	14.9	2908
≥6	13.2	1.5	5.8	21.0	21.0	23.0	14.6	1645
≥7	10.6	1.8	7.4	23.4	19.0	22.1	15.7	700
≥8	13.1	3.6	14.4	20.3	9.9	20.7	18.0	222

C1, whereas in areas A1, A2 and A3 around 60% of the pixels belong to cluster C3 (Table 4).

4. Discussion and conclusions

The study attempts to quantify the drought event of 2007, to present a synoptic view of the two heatwaves in July and August and to assess the impact of these two extreme climate events in vegetation dynamics of different vegetation communities during the whole phenological cycle. We show that the extreme fire season of 2007 was driven by two complementary climatic extreme drivers including a major drought in preceding months and two major heatwaves in July and August. During the hydrological year of 2007, Greece was stricken by a severe winter drought that corresponds to the second lowest annual accumulated value ever since 1951. That dryness extended to the months of March and April although the subsequent month of May was very wet and partially attenuated the effect of the previous drought. Moreover the accumulated number of hot nights associated with the heatwaves during the summer of 2007 was particularly outstanding over much of Greece and the Balkan Peninsula. The use of the ratio between the accumulated number of hot nights and winter precipitation shows spatially coherent patterns in the Peloponnese peninsula. Thus this index seems to be particularly suitable to take into account pre-fire season effects (drought) and be combined with the extreme heat indicator from the fire season. In particular, the index explains the selectivity of wildfire and consequently the location of the main burnt scars, which is related with the cumulative impact of both drought and heatwave extreme events. We confirm previous results that mention the role that the two independent heatwave events played during July and August 2007. They were both associated with drier and warmer air masses over the Peloponnese Peninsula in addition to an intense northerly advection of continental hot and dry air during the same period of the onset of the fire events. These results are in agreement with the findings of Amraoui et al. (2013). These authors have performed a fire-risk analysis for the same two episodes and showed how the region of high values and of high positive anomalies of FWI is more concentrated in the August episode than in the July event, mainly located over the Peloponnese and Attica peninsulas (their Figs. 8c and 11c). The extremely severe fires in the Peloponnese, particularly in August, are located in the area of higher values and stronger positive anomalies of FWI.

Despite the severe drought in 2007 and the second lowest amount of total precipitation, vegetation activity was not severely affected. The cumulative effect of drought conditions for each cluster during the drought is provided in Table 3, and shows the amount of pixels of each cluster that present more than four months with negative anomalies of NDVI. The clusters more severely affected by drought are C4 to C7, being responsible for around 3/4 of the total amount of stressed pixels (Table 3) that correspond to semi-arid zones. This feature is related with the fact that the 2007 drought episode was essentially a winter short drought event that ended with a month (May) with higher than usual precipitation. In more humid regions, drought impacts are most probably related to damages in plant tissues due to the poor tolerance of plants to water stress, but the growth rates characteristic of plants of humid regions could allow vegetation to recover its prior state in a short period as soon as the drought ends (Vicente-Serrano et al., 2013). On the other hand, recurrent droughts in semi-arid regions can produce a progressive loss of resilience that disturbs adversely the ability of recovering the initial state (Lloret et al., 2004). Our results show around 20% of Peloponnese vegetation was in vegetative stress conditions for more than four months during the pre-fire period. However, the areas presenting high intensity of vegetative stress are located in south and north-eastern Peloponnese, whereas the larger burnt areas are located in sectors (south-eastern Peloponnese) that were not particularly affected by vegetation stress.

The predominance of clusters C1 to C3 inside the larger burned areas in Peloponnese during 2007 confirms higher fire incidence in regions with higher vegetation activity and density. In fact, these three clusters present the highest NDVI values in the beginning of summer and correspond to high vegetation activity and density, confirming the sensitivity of fire activity to dry conditions increases with productivity, i.e., the higher fuel availability (Pausas and Paula, 2012).

The location of burned areas in regions with less vegetation stress, is indicative that burnt areas of 2007 fire season in less productive regions, such as the Peloponnese Peninsula are more sensitive to fuel availability and vegetation density than to vegetation dryness, similarly to other regions of the Mediterranean (Pausas and Paula, 2012). The assessment of the main phenological types over Peloponnese highlights the predominance of large burned areas in humid regions and confirms the preference of fires for regions with higher vegetation activity and density. In fact, vegetation in these regions does not present evidence of vegetative stress, as they show high NDVI values in the beginning of summer, i.e. high vegetation activity and density, and thus higher fuel availability. Large burnt areas of 2007 fires season in Peloponnese Peninsula reinforced the relative contribution of climate and fuel as drivers of fire activity (Pausas and Ribeiro, 2013). The fuel dependence is common in other Mediterranean regions, observed for instance during the 2003 and 2005 fire seasons in Iberian Peninsula (Gouveia et al., 2012). In this regard, our results are in good agreement with previous works for the region (Koutsias et al., 2012; Sarris and Koutsias, 2014; Xystrakis et al., 2014). Koutsias et al. (2012) showed that the fires of 2007 fire season over Peloponnese occurred essentially in relatively humid zones, while the fires during the 2000–2006 fire seasons tended to occur in more arid environments. According to Koutsias et al. (2013), Sarris and Koutsias (2014) and Xystrakis et al. (2014) findings, late spring precipitation increases biomass accumulation as result of wet conditions during the growing season. In this situation fuel is no more a limiting factor, being the fire activity driven by the extreme climate event (heatwave) that increase flammability (Pausas and Ribeiro, 2013), leading to an increase of ignition probability and fire spread (Sarris and Koutsias, 2014; Xystrakis et al., 2014). All the above-mentioned works pointed out the synergistic effect between fuel availability and weather conditions, which could explain the unusually large fires in Peloponnese.

Several studies attempted to assess the main driving factors of this exceptional event (Founda and Giannakopoulos, 2009; Koutsias et al., 2012; Amraoui et al., 2013; Sarris and Koutsias, 2014). These studies highlighted climate factors and a synergy of land use changes and climate. This extreme fire season was preceded by (or contemporaneous with) two different extreme weather events, specifically the occurrence of a drought event during winter, and two exceptional heatwaves in July and August.

To the best of our knowledge, this complementary and interdisciplinary approach brings new insights about the impacts of the two extreme weather events in vegetation activity. However, fire regimes are also influenced by drivers beyond those directly related to weather conditions, such as socio-economic, land use changes and other, less direct, human activities (Koutsias et al., 2012). Likewise the works of Costa et al. (2010) or Pausas and Fernández-Muñoz (2012) also evaluate the human role on both fuel availability and landscape and how these two factors have been producing shifts in fire regimes amongst the Mediterranean environment.

The last assessment report by the IPCC (AR5, IPCC, 2014) confirms that most Global and Regional Climate Models project an important warming in the Mediterranean basin leading to an increased fire danger potential (e.g. Bedia et al., 2013; Sousa et al., 2015). While changes in the precipitation regime are less clear cut than those expected for temperature, it is also expected less precipitation outside the winter season, as well as a tendency towards more extreme events (AR5, IPCC, 2014). The fact that heatwaves and droughts are expected to become more frequent and intense in the Mediterranean under future climate warming scenarios (Fischer and Schär, 2009) may reinforce these patterns and lead to forest decline due to frequent large fires as shown recently for the Iberian Peninsula (Sousa et al., 2015). These results highlight the role of biomass accumulation during spring and dryness in summer, as consequence of spring precipitation and summer heatwaves that increase ignition probability and fire spread (Sarris and Koutsias, 2014; Xystrakis et al., 2014), which may be useful to guide better land management practices.

Acknowledgments

This work was partly supported by the EU 7th Framework Program (FUME) contract number 243888. This work was also partially supported by Project QSECA (PTDC/AAG-GLO/4155/2012) funded by the Portuguese Foundation for Science and Technology (FCT). Ana Bastos was funded by Portuguese Foundation for Science and Technology (SFRH/BD/78068/2011). NDVI dataset was kindly supplied by VITO database (http://free.vgt.vito.be). We acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://www.ecad.eu).

References

Amraoui, M., Liberato, M.R., Calado, T.J., DaCamara, C.C., Pinto-Coelho, L., Trigo, R.M., Gouveia, C.M., 2013. Fire activity over Mediterranean Europe based on information from Meteosat-8. For. Ecol. Manage. 294, 62–75.

Bastos, A., Gouveia, C., DaCamara, C.C., Trigo, R.M., 2011. Modelling post-fire vegetation recovery in Portugal. Biogeosciences 8, 4559–4601.

Bedia, J., Herrera, S., Martín, D.S., Koutsias, N., Gutiérrez, J.M., 2013. Robust projections of Fire Weather Index in the Mediterranean using statistical downscaling. Clim. Change 120, 229–247, http://dx.doi.org/10.1007/s10584-013-0787-3.

Berrisford, P., Dick, D., Fielding, K., Fuentes, M., Kallberg, P., Kobayashi, S., Uppala, S. The ERA-Interim Archive, ERA Report Series, European Centre for Medium Range Weather Forecasts, ERA Report Series No. 1., 2009.

Besson, C.K., Lobo Vale, R., Siegwolf, R., Rodrigues, L., Almeida, P., Herd, A., Grant, O.M., David, T.S., Schimidt, M., Otieno, D., Keenan, T., Siegwolf, R., Gouveia, C., Meriaux, Chaves, M.M., Pereira, J.S., 2014. Impact of precipitation change on Cork oak physiological traits: results of a rainfall manipulation experiment. J. Agric. For. Meteorol. 184, 230–242.

Boschetti, L., Roy, D., Barbosa, P., Boca, R., Justice, C., 2008. A MODIS assessment of the summer 2007 extent burned in Greece. Int. J. Rem. Sens. 29 (8), 2433–2436.

Costa, L., Thonicke, K., Poulter, B., Badek, F.W., 2010. Sensitivity of Portuguese forest fires to climatic, human, and landscape variables: subnational differences between fire drivers in extreme fire years and decadal averages. Reg. Environ. Change 11 (3), 543–551, http://dx.doi.org/10.1007/s10113-010-0169-6.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., Vitart, F., 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc. 137, 553–597, http://dx.doi.org/10.1002/qj.828.

Dimitrakopoulos, A.P., Vlahou, M., Anagnostopoulou, C.G., Mitsopoulos, I.D., 2011. Impact of drought on wildland fires in Greece: implications of climatic change? Climatic Change 109, 331–347, http://dx.doi.org/10.1007/s10584-011-0026-8.

Fischer, E.M., Schär, C., 2009. Future changes in daily summer temperature variability: driving processes and role for temperature extremes. Clim. Dynam., http://dx.doi.org/10.1007/s00382-008-0473-8.

Founda, D., Giannakopoulos, C., 2009. The exceptionally hot summer of 2007 in Athens, Greece – a typical summer in the future climate. Global Planet. Change 67, 227–236, http://dx.doi.org/10.1016/j.gloplacha.2009.03.013.

Fried, S.J., Torn, S.M., Mills, E., 2004. The impact of climate change on wildfire severity: a regional forecast for Northern California. Climatic Change 64, 169–191.

Gitas, I.Z., Polychronaki, A., Katagis, T., Mallinis, G., 2008. Contribution of remote sensing to disaster management activities: a case study of the large fires in the Peloponnese, Greece. Int. J. Rem. Sens. 29 (6), 1847–1853.

Gobron, N., Pinty, B., Mélin, F., Taberner, M., Verstraete, M.M., Belward, A., Lavergne, T., Widlowski, J.-L., 2005. The state of vegetation in Europe following the 2003 drought. Int. J. Rem. Sens. Let. 26, 2013–2020.

Good, P., Moriondo, M., Giannakopoulos, C., Bindi, M., 2008. The meteorological conditions associated with extreme fire risk in Italy and Greece: relevance to climate model studies. Int. J. Wildland Fire 17, 155–165, http://dx.doi.org/10.1071/WF07001.

Gouveia, C., Trigo, R.M., DaCamara, C.C., Libonati, R., Pereira, J.M.C., 2008. The north Atlantic oscillation and European vegetation dynamics. Int. J. Climatol. 28, 1835–1847.

Gouveia, C.M., Bastos, A., Trigo, R.M., DaCamara, C.C., 2012. Drought impacts on vegetation in the pre and post-fire events over Iberian Peninsula. Nat. Hazard. Earth Syst. Sci. 12, 3123–3137.

Gouveia, C., DaCamara, C.C., Trigo, R.M., 2010. Post fire vegetation recovery in Portugal based on SPOT-VEGETATION data. Nat. Hazard. Earth Syst. Sci. 10, 673–684.

Gouveia, C., Trigo, R.M., DaCamara, C.C., 2009. Drought and vegetation stress monitoring in Portugal using satellite data. Nat. Hazard. Earth Syst. Sci. 9, 185–195.

Hagolle, O., Lobo, A., Maisongrande, P., Duchemin, B., De Pereira, A., 2005. Quality assessment and improvement of SPOT/VEGETATION level temporally composited products of remotely sensed imagery by combination of VEGETATION 1 and 2 images. Rem. Sens. Environ. 94, 172–186.

Haylock, M.R., Hofstra, N., Klein Tank, A.M.G., Klok, E.J., Jones, P.D., New., M., 2008. A European daily high-resolution gridded dataset of surface temperature and precipitation. J. Geophys. Res. (Atmos.) 113, D20119, http://dx.doi.org/10.1029/2008JD10201.

Holben, B.N., 1986. Characteristics of maximum-value composite images from temporal AVHRR data. Int. J. Rem. Sens. 7, 1417–1434.

IPCC, 2014. Climate Change, 2014. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jentsch, A., Kreyling, J., Elmer, M., Gellesch, E., Glaser, B., Grant, K., Hein, R., Lara, M., Mirzae, H., Nadler, S.E., Nagy, L., Otieno, D., Pritsch, K., Rascher, U., Schädler, M., Schloter, M., Singh, B.K., Stadler, J., Walter, J., Wellstein, C., Wöllecke, J., Beierkuhn- lein, C., 2011. Climate extremes initiate ecosystem-regulating functions while maintaining productivity. J. Ecol. 99, 689–702.

Julien, Y., Sobrino, J.A., Verhoef, W., 2006. Changes in land surface temperatures and NDVI values over Europe between 1982 and 1999. Rem. Sens. Environ. 103, 43–55, http://dx.doi.org/10.1016/j.rse.2006.03.011.

Kogan, F.N., 1997. Global drought watch from space. Am. Meteorol. Soc. 78, 621–636.

Koutsias, N., Arianoutsou, M., Kallimanis, A.S., Mallinis, G., Halley, J.M., Dimopoulos, P., 2012. Where did the fires burn in Peloponnese, Greece the summer of 2007? Evidence for a synergy of fuel and weather. Agric. For. Meteorol. 156, 41–53.

Koutsias, N., Xanthopoulos, G., Founda, D., Xystrakis, F., Nioti, F., Pleniou, M., Mallinis, G., Arianoutsou, M., 2013. On the relationships between forest fires and weather conditions in Greece from long-term national observations (1894–2010). Int. J. Wildland Fire 22 (4), 493–507.

Kreyling, J., Wenigmann, M., Beierkuhnlein, C., Jentsch, A., 2008. Effects of extreme weather events on plant productivity and tissue die-back are modified by community composition. Ecosystems 11, 752–763.

Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, D., Corona, P., Kolstro, M., Lexer, M.J., Marchetti, M., 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For. Ecol. Manage. 259 (4), 698–709.

Lionello, P., Bhend, J., Buzzi, A., Della-Marta, P.M., Krichack, S., JansÃ, A., Maheras, P., Sanna, A., Trigo, I.F., Trigo, R., 2006. Cyclones in the Mediterranean region: climatology and effects on the environment. In: Lionello, P., Malanotte-Rizzoli, P., Boscolo, R. (Eds.), The Mediterranean Climate: An Overview of the Main Characteristics and Issues. Elsevier, pp. 324–372 (Chapter 6).

Lloret, F., Siscart, D., Dalmases, C., 2004. Canopy recovery after drought dieback in holmoak Mediterranean forests of Catalonia (NE Spain). Global Change Biol. 10 (12), 2092–2099.

Lobo, A., Maisongrande, P., Coret, L. The impact of the heat wave of summer 2003 in SW Europe as observed from satellite imagery. Phys. Chem. Earth 35 (1), 19–24.

Luterbacher, J., Liniger, M.A., Menzel, A., Estrella, N., Della-Marta, P.M., Pfister, C., Rutishauser, T., Xoplaki, E., 2007. Exceptional European warmth of autumn 2006 and winter 2007: historical context, the underlying dynamics, and its phenological impacts. Geophys. Res. Lett. 34, L12704, http://dx.doi.org/10.1029/2007GL029951.

Maisongrande, P., Duchemin, B., Dedieu, G., 2004. VEGETATION/SPOT – an operational mission for the earth monitoring: presentation of new standard products. Int. J. Rem. Sens. 25, 9–14.

Orlowsky, B., Seneviratne, S.I., 2012. Global changes in extreme events: regional and seasonal dimension. Climate Change 110, 669–696.

Pausas, J.G., Fernández-Muñoz, S., 2012. Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. Climate Change 110 (1–2), 215–226, http://dx.doi.org/10.1007/s10584-011-0060-6.

Pausas, J.G., Paula, S., 2012. Fuel shapes the fire–climate relationship: evidence from Mediterranean ecosystems. Global Ecol. Biogeogr. 21, 1074–1082.

Pausas, J.G., Ribeiro, E., 2013. The global fire–productivity relationship. Global Ecol. Biogeogr. 22, 728–736.

Pellizzaro, G., Cesaraccio, C., Duce, P., Ventura, A., Zara, P., 2007. Relationships between seasonal patterns of live fuel moisture and meteorological drought indices for Mediterranean shrubland species. Int. J. Wildland Fire 16 (2), 232–241.

Rodriíguez-Puebla, C., Ayuso, S.M., Friías, M.D., Garciía-Casado, L.A., 2007. Effects of climate variation on winter cereal production in Spain. Climate Res. 34 (3), 223–232.

Rudolf, B., Schneider, U., 2005. Calculation of gridded precipitation data for the global land-surface using in-situ gauge observations. In: Proceedings of the 2nd Workshop of the International Precipitation Working Group IPWG, EUMETSAT, Monterey October 2004, ISBN: 92-9110-070-6, ISBN: 1727-432X, 231-247.

Sarris, D., Koutsias, N., 2014. Ecological adaptations of plants to drought influencing the recent fireregime in the Mediterranean. Agric. For. Meteorol. 184, 158–169.

Sarris, D., Christopoulou, A., Angelonidi, E., Koutsias, N., Fulé, P.Z., Arianoutsou, M., 2013. Increasing extremes of heat and drought associated with recent severe wildfires in southern Greece. Reg. Environ. Change, http://dx.doi.org/10.1007/s10113-013-0568-6.

Schillinger, W.F., Schofstoll, S.E., Alldredge, J.R., 2008. Available water and wheat grain yield relations in a Mediterranean climate. Field Crops Res. 109 (1–3), 45–49.

Smith, M.D., 2011. An ecological perspective on extreme climatic events: a synthetic definition and framework to guide future research. J. Ecol. 99, 656–663.

Sousa, P., Trigo, R.M., Pereira, M., Bedia, J., Gutierrez, J.M., 2015. Different approaches to model future burnt area in the Iberian Peninsula. Agric. For. Meteorol. 202, 11–25, http://dx.doi.org/10.1016/j.agrformet.2014.11.018.

Stöckli, R., Vidale, P.L., 2004. European plant phenology and climate as seen in a 20-year AVHRR land-surface parameter dataset. Int. J. Rem. Sens. 25, 3303–3330.

Tolika, K., Maheras, P., Tegoulias, I., 2009. Extreme temperatures in Greece during 2007: could this be a “return to the future”? Geophys. Res. Lett. 36, L10813, http://dx.doi.org/10.1029/2009GL038538.

Trigo, R.M., García-Herrera, R., Díaz, J., Trigo, I.F., Valente, A., 2005. How exceptional was the early August 2003 heatwave in France? Geophys. Res. Lett. 32, L10701, http://dx.doi.org/10.1029/2005GL022410.

Trigo, R.M., Gouveia, C., Barriopedro, D., 2010. The intense 2007–2009 drought in the Fertile Crescent: Impacts and associated atmospheric circulation. Agric. For. Meteorol. 150, 1245–1257.

Trigo, R.M., Ramos, A., Nogueira, P., Santos, F.D., Garcia-Herrera, R., Gouveia, C., Santo, F.E., 2009. Evaluating the impact of extreme temperature based indices in the 2003 heatwave excessive mortality in Portugal. Environ. Sci. Policy 12, 844–854.

Udelhoven, T., Stellmes, M., del Barrio, G., Hill, J., 2009. Assessment of rainfall and NDVI anomalies in Spain (1989–1999) using distributed lag models. Int. J. Rem. Sens. 30 (8), 1961–1976.

Vicente Serrano, S.M., Beguería, S., 2003. Estimating extreme dry-spell risk in the middle Ebro valley (Northeastern Spain): a comparative analysis of partial duration series with a General Pareto distribution and Annual maxima series with a Gumbel distribution. Int. J. Climatol. 23, 1103–1118.

Vicente Serrano, S.M., Lasanta, T., Gracia, C., 2010. Aridification determines changes in forest growth in *Pinus halepensis* forests under semiarid Mediterranean climate conditions. Agric. For. Meteorol. 150, 614–628.

Vicente Serrano, S.M., 2007. Evaluating the impact of drought using remote sensing in a Mediterranean, semi-arid region. Nat. Hazard. 40, 173–208.

Vicente-Serrano, S.M., Gouveia, C., Camarero, J.J., Beguería, S., Trigo, R., López-Moreno, J.I., Azorín-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Morán-Tejeda, E., Sanchez-Lorenzo, A., 2013. The response of vegetation to drought time-scales across global land biomes”. Proc. Natl. Acad. Sci. U.S.A. 110, 52–57, http://dx.doi.org/10.1007/s10113-012-0387-1.

Xoplaki, E., González-Rouco, J.F., Gyalistras, D., Luterbacher, J., Rickli, R., Wanner, H., 2003. Interannual summer air temperature variability over Greece and its connection to the large-scale atmospheric circulation and Mediterranean SSTs 1950–1999. Clim. Dyn. 20, 537–554, http://dx.doi.org/10.1007/s00382-002-0291-3.

Xystrakis, F., Kallimanis, A.S., Dimopoulos, P., Halley, J.M., Koutsias, N., 2014. Precipitation dominates fire occurrence in Greece (1900–2010): its dual role in fuel build-up and dryness. Nat. Hazard. Earth Syst. Sci. 14, 21–32.

Zhang, X., et al., 2011. Indices for monitoring changes in extremes based on daily temperature and precipitation data. WIREs Climate Change 2, 851–870.