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IOP Publishing Environ. Res. Lett. 11 (2016) 075006 doi:10.1088/1748-9326/11/7/075006

Environmental Research Letters

OPEN ACCESS

RECEIVED
31 March 2016

REVISED
6 June 2016

ACCEPTED FOR PUBLICATION
11 July 2016

PUBLISHED
25 July 2016

LETTER

Objective identification of multiple large fire climatologies: an application to a Mediterranean ecosystem

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Keywords: fire regime, climate change, fire weather, large fires, Mediterranean France

Supplementary material for this article is available online

Abstract

There is growing evidence that the climatic conditions favorable to the occurrence of large fires (LFs) might not be unique within a homogeneous biogeographic area. But the identification of these coexistent multi-scalar climatologies often relies on empirical observations. Here we classify summer LFs ($>$120 ha) in Mediterranean France for the period 1973 to 2012, according to their local-scale weather conditions (i.e. temperature, relative humidity, wind speed and fuel moisture proxies). Three distinct climatologies were identified, and were referred as fire weather types (FWTs). (i) One of them is associated with near-normal atmospheric conditions. (ii) A heat-driven (HD) type is mostly discriminated by warm anomalies. (iii) A wind-driven (WD) type is mostly discriminated by faster winds, but cooler anomalies than usual. The frequency of WD and near-normal LFs sharply decreased in southern France over the last decades while the frequency of HD fires remained unchanged. In addition the current increase in HD potential fire days indicates a potential shift in the dominant FWT for this region. This approach offers a better understanding of the variations in fire activity and fire spread patterns in the context of contemporaneous global changes.

1. Introduction

Large fires (LFs) are responsible for the majority of burned area in most regions of the world (Stocks *et al* 2003, San-Miguel-Ayanz *et al* 2013) and are, as such, key drivers of vegetation dynamics (Bond and Keeley 2005), global carbon cycle (Van der Werf *et al* 2010), and generate most of socioeconomic fire costs (Gill *et al* 2013).

The analyses of historical meteorological data and fire records highlighted the prominent role of weather in driving the occurrence of these infrequent, but critical, LF events (Meyn *et al* 2007) through several processes intervening at different space-time scales (Swetnam and Betancourt 1990). At annual to seasonal scales, antecedent atmospheric conditions (i.e. years or seasons prior to the wildfire season) can limit or promote the growth of fine fuels. Prior and during the fire season, monthly to daily atmospheric variability controls the moisture content of vegetation. Then, short-term (hourly to daily) fluctuations in relative humidity, wind speed and temperature influence fire ignition and its propagation. Formal relationships between the incidence of LFs and these multi-scalar meteorological factors have been explored in a variety of locations (Abatzoglou and Kolden 2011, 2013, Barbero *et al* 2011, 2014, Stavros *et al* 2014, Ruffault and Mouillot 2015). Isolating the temporal scales and processes through which top-down atmospheric processes influence the spread of fires remains, however, a scientific challenge, due to a series of interacting biophysical and anthropogenic factors controlling this relationship.

First, vegetation is a strong mediator of the fire–weather relationship (Pausas and Paula 2012, Keeley and Syphard 2015). This phenomenon is typically, but non-exclusively, illustrated by the 'fuel limited versus drought limited' duality (Van der Werf *et al* 2008, Bradstock 2010, Krawchuck and Moritz 2011). This model supports that fire activity is associated with higher fuel abundance (driven by moisture availability during the growing season) in xeric regions, while moisture deficit during the fire season promotes fire spread in the more mesic landscapes. Second, human practices and activities also shape the fire–weather relationship, either directly through ignition patterns and fire suppression practices (Ruffault and Mouillot 2015) or indirectly through their impact on land use and land cover (Marlon *et al* 2008). Third, climate variables (e.g. temperature, humidity, wind speed) exhibit distinct local-scale patterns that arise from the coupling of large-scale atmospheric processes and regional-scale physiographic features, so that different climatic drivers of fire activity are sometimes observed between neighboring areas (Sousa *et al* 2015, Ruffault *et al* 2016). Fourth, this fire–weather relationship might not be unique, even within a homogeneous biogeographic area. That is, LF climatology may actually be composed of a number of distinct fire weather types (hereafter FWTs), each one being characterized by a certain combination of synergic weather conditions conducive to fire. For instance, wind-driven (WD) and heat-driven (HD) (convective) fires have both been identified as critical fire types in woody-fueled crown fires in Mediterranean forests and shrublands (Jin *et al* 2014, Ruffault *et al* 2016), although the atmospheric configurations and physical processes of fire spread behind these patterns may be fairly different.

There is a growing recognition that considering the multiplicity of FWTs is of considerable interest in fire-regime studies, not only for a deeper understanding of the fire–weather relationship (Hernandez *et al* 2015a, 2015b), but also to explain the patterns of fire severity (Lecina-Diaz *et al* 2014), to improve fire projections/predictions (Duane *et al* 2015, Jin *et al* 2015) and to adapt fire-fighting strategies (Lahaye *et al* 2014). Yet, despite these promising theoretical and practical developments, a conceptual framework for defining and identifying these FWTs is missing. That is, there have been few attempts to propose an objective and general method to distinguish the multiplicity of weather conditions associated with fires. In addition, this approach is still to be applied on an historical period, to test for the temporal variations of these FWTs in the context of current and future global warming.

In this study, we propose an objective definition of FWTs in Mediterranean France (see the location in figure 1), where different fire types have been previously described (Lahaye *et al* 2014, Ruffault *et al* 2016). Fire regime in this region is dominated by typical Mediterranean crown-fires (Keeley *et al* 2011), occurring in shrublands and in mixed oak-pine woodlands (Curt *et al* 2013, Fréjaville and Curt 2015), and usually lasting less than one day. Fire history over the last four decades shows a peculiar pattern in southern France compared to the other Euro-Mediterranean countries (see Moreira *et al* 2011), with a drop in fire activity (figures 1(c) and S1), generally attributed to new fire practices (Ruffault and Mouillot 2015), and this despite the climatic trends towards drier conditions observed over the same period (Ruffault *et al* 2013, see also figure S2). We used here both fire records and climatic datasets over a 40 year period (1973–2012) to examine the antecedent and synchronous local-scale weather conditions associated with LFs. We focused our analysis to the summer fire season, which concentrates most of the large and destructive fires in this region (Ruffault *et al* 2016). Our specific objectives are: (i) to determine the climatic factors and time-scales that distinguish summer LFs from other fires, (ii) to discriminate FWTs based on the analysis of the multi-scalar weather variables associated with LFs, (iii) and finally, to investigate whether the frequency of these FWTs, and the number of LFs belonging to each of these FWTs, were related to climate and human changes during the past decades.

2. Datasets and methods

2.1. Fire data

The location, date and final burnt area of wildfires during the summer fire season were obtained from the '*Prométhée*' database for between 1973 and 2012 (available at www.promethee.com). This database is managed by French forest services and covers the 15 administrative districts located in Southeastern France (80 500 km^2; figure 1(b)) since 1973. It provides consistent and relatively accurate fire statistics over time, except for a lack of homogeneity in the minimum size of reported fires (i.e. fires <1 ha; Ruffault and Mouillot 2015). Each fire in the database is characterized by its size, its day of occurrence and its ignition point on a 2 km × 2 km national reference grid. This grid was used as the basic spatial unit for our analyses. To reduce the uncertainty related to the fire size estimations, only fires larger than 1 ha were extracted and each fire was classified within four different classes according to its final fire size: burning at least 1, 30, 120 and 500 ha; which corresponds to the 1st, 85th, 95th and 98th percentiles of all fire sizes, respectively. From this dataset, only fires during the fire season (July and August-JA-) were extracted. It should be noted here that while only 40% of annual fires (fires >1 ha) occur during JA, this contribution rises to 65% for fires larger than 120 ha and 77% for fires larger than 500 ha.

2.2. Climate data and fuel moisture indices

Fire climatology (i.e. typical weather conditions associated with fires) was expressed as a function of a few daily variables known to play a key role in the occurrence, behavior and spread of wildfires (Pyne *et al* 1996): fuel moisture, temperature, precipitation, wind speed and relative humidity. Fuel moisture conditions were approximated through the drought (DC) and duff moisture codes (DMC) of the Canadian

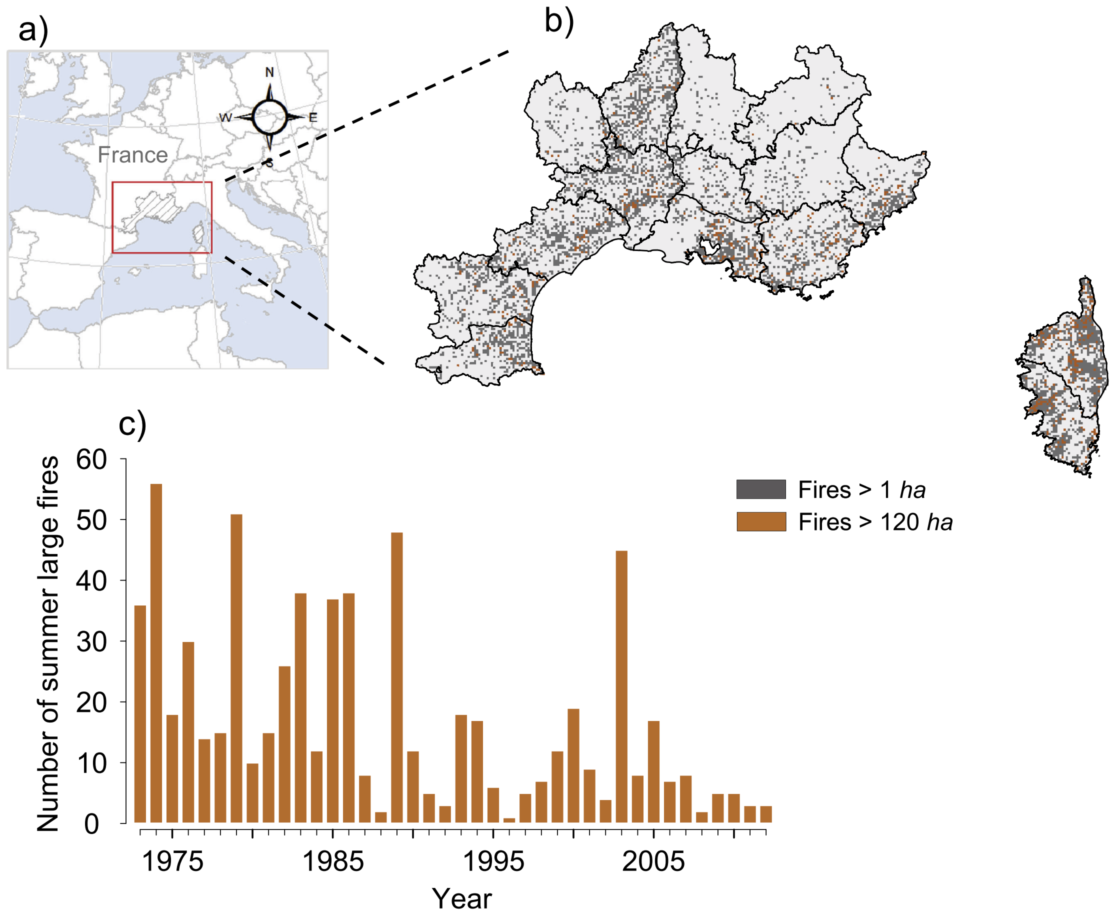

Figure 1. Spatial and temporal variations in summer (July–August) fires (>120 ha) occurrence in Mediterranean France over the period from 1973 to 2012. (a) Location of the studied area within the Euro-Mediterranean area. (b) Spatial distribution of all fires (>1 ha, gray) and large fires (>120 ha, orange) within the administrative units. (c) Interannual variations in the number of large fires (>120 ha). Additional historical fire statistics are reported in figure S1.

fire weather index (FWI; Van Wagner 1987). The DMC is computed from daily rainfall, relative air humidity and air temperature during and prior to the fire day. It represents moisture content of surface fuels and of loosely compacted organic layers of moderate soil depth. Similarly, the DC is computed from daily rainfall and air temperature during and prior to the fire day, representing moisture content of very slow drying fuels, typically the moisture content of living biomass. Both of these indices are good estimators of the variations in fuel moisture content for the Mediterranean-type ecosystems encountered in our study area (Viegas *et al* 2001, Pellizzaro *et al* 2007).

Daily historical observations of precipitation, wind speed, temperature and relative humidity variables were obtained from the SAFRAN dataset (Vidal *et al* 2010) for the same period as the fire database (1973–2012). SAFRAN is a reanalysis of surface observations on an 8 km resolution grid over France. Daily variables were previously re-interpolated to match the resolution of our spatial sampling unit (national reference grid, 2 × 2 km), using altitude-dependent methods described and validated over the region by Ruffault *et al* (2014). Climate variables and fuel moisture indices were then computed at the monthly and weekly time scale by summing (for precipitation) or averaging (for the other variables) daily values.

2.3. Analyses

We used composites analysis to investigate the multi-scalar local-scale climatic drivers associated with summer fires for the fire-size thresholds defined in section 2.1. The lead-lag composites anomalies of six key variables (see section 2.2) were examined at three distinct timescales in order to capture the inter-annual, sub-seasonal and synoptic variability associated with each fire. As fire duration is short within the Mediterranean area (generally less than one day), we mainly focused on the pre-ignition conditions. We compiled standardized climate anomalies on a 12-day window (from 10 days before to 2 days after each fire), a 5 week window (from 4 weeks before to 1 week after each fire) and an 8 month window (from 7 months before to 1 month after each fire). Weeks were defined here by the Julian day of the year; months were defined by the usual calendar months. Anomalies were computed versus the long-term local daily, weekly or monthly climatology (averaged over the studied period) and standard deviation of the basic spatial unit (4 km^2) where the fire occurred. This procedure was performed for two separate periods (before and after the introduction of a new fire policy in the region around 1990) to minimize the impact of the sharp decrease in fire activity (see figure 1(c)) that could affect the reported climate anomalies.

An objective and dynamical *k*-means clustering was applied to identify different FWTs from local-scale (i.e. the grid cell where the fire occurs) daily standardized anomalies of the six weather and fuel moisture variables associated with the day of LFs (fires >120 ha) and computed over the entire period (1973–2012). This method partitions *m* multivariate observations into *k* clusters by iteratively minimizing the sum, over all clusters, of the within-cluster sums of observation-to-centroid squared Euclidean distances. As in any other dynamical clustering, the value of *k* must be chosen *a priori*. The gap statistic (Tibshirani *et al* 2001) was used here to estimate the appropriate number of cluster, that is $k = 3$ (figure S3). This number also corresponded to a sound physical interpretation of obtained FWTs. The stability of the partition was checked by repeating the cluster analysis with different initial seeds. The overall similarity in the climatic anomalies related to the different partitions obtained gave confidence in the robustness of the clusters.

Historical LF activity was then studied by using the analytical framework built from the identification and the climatic characterization of FWTs. We computed the summer number of LFs classified according to their respective FWT. However, the temporal variations in LF activity are not likely to be only dependent from climate variations but are also the result of anthropogenic and land cover changes. Thus, to assess how climate dictates the temporal variations in fire weather conditions, we also computed the interannual variations in the potential fire conditions according to each FWT. To do that, we determined the yearly percentage of spatio-temporal units (known as voxels) that belonged to each FWT, regardless of the occurrence of fire within these voxels. To limit computational efforts, we randomly sampled 10 000 voxels per summer season (on a total of 1 249 176 voxels: 62 days × 20 148 4 km^2 gridcells). A voxel belonged to one FWT if the multi-scale centroid of its standardized anomalies falls within the FWT space, which was defined here as being the 90% confidence interval around each FWT centroid. Temporal trends in these variables were investigated with the Mann–Kendall test and their magnitude with the Theil–Sen coefficient (Sen 1968).

3. Results

No major differences in the nature of the fire–weather relationship were observed when comparing a range of final fire sizes (figure 2 for the 1973–1990 period; similar results were obtained on the period 1991–2012) but there were some modifications in the strength of these relationships, i.e. as fire size increases the standardized anomalies were stronger. Regardless of the final fire size, our results showed that fires were typically related to periods of low fuel moisture content and to days with specific anomalies in weather variables (figure 2). At a daily time scale, fires were associated with above-normal wind speed and below-normal relative air humidity (figure 2(b)). The influence of antecedent climatic anomalies on wildfire through their effect on fuel moisture (DC and DMC) was limited to 3–4 months before the fire season (figure 2(c)), and was the result of significantly below-normal precipitation and above-normal temperature for this same period ($p < 0.01$, all anomalies are reported in figure S4). It should be noted here that no significant long-term antecedent signals in DC and DMC were observed before 4 months before the fire. Taking into account the similitude of results obtained for different fire sizes, we considered only fires >120 ha (hereafter considered as large fires, LFs) in the following, as in Ruffault *et al* (2016).

The anomalies associated with each of the three FWTs provided further insights into the climatological processes involved in the occurrence of LFs (figure 3).

The first FWT cluster is named the HD type. It is mostly characterized by the largest anomaly in DC and DMC combined with a short and medium-term (i.e. starting at least 9 days before the fire) above-normal temperature and below-normal relative humidity (figure 3, in red). By contrast, the anomaly in daily wind speed is relatively weak, but still significant for the fire's day when compared to the mean climatology (figure 3(b), $p < 0.01$). The anomalies in drought conditions are significantly stronger than for other FWTs (figure 3(a)) and start, on average, 3–4 months before fire occurrence (figure 3(c)), as the consequence of both above-normal temperature and below-normal precipitation over this same period (all anomalies are reported in figure S5). Particularly important are the peaks in warm temperature and negative relative air humidity anomalies during the fire day, which are both significantly higher (respectively lower) than for other FWTs (figure 3(a)).

The second FWT cluster is named the WD type. It is mostly characterized by a moderate positive anomaly in DC and DMC coupled with short-term above-normal wind speed, below-normal relative humidity and below-normal temperature (figure 3, in blue). Significant anomalies in drought conditions start on average 3 months before the fire ($p < 0.01$, figure 3(c)), as a consequence of below-normal precipitations over this same period (figure S5). The peak in wind speed anomaly during the fire day is particularly strong and significantly higher than for other FWTs (figure 3(a)). Inversely, this FWT is also characterized by a significant drop in temperature

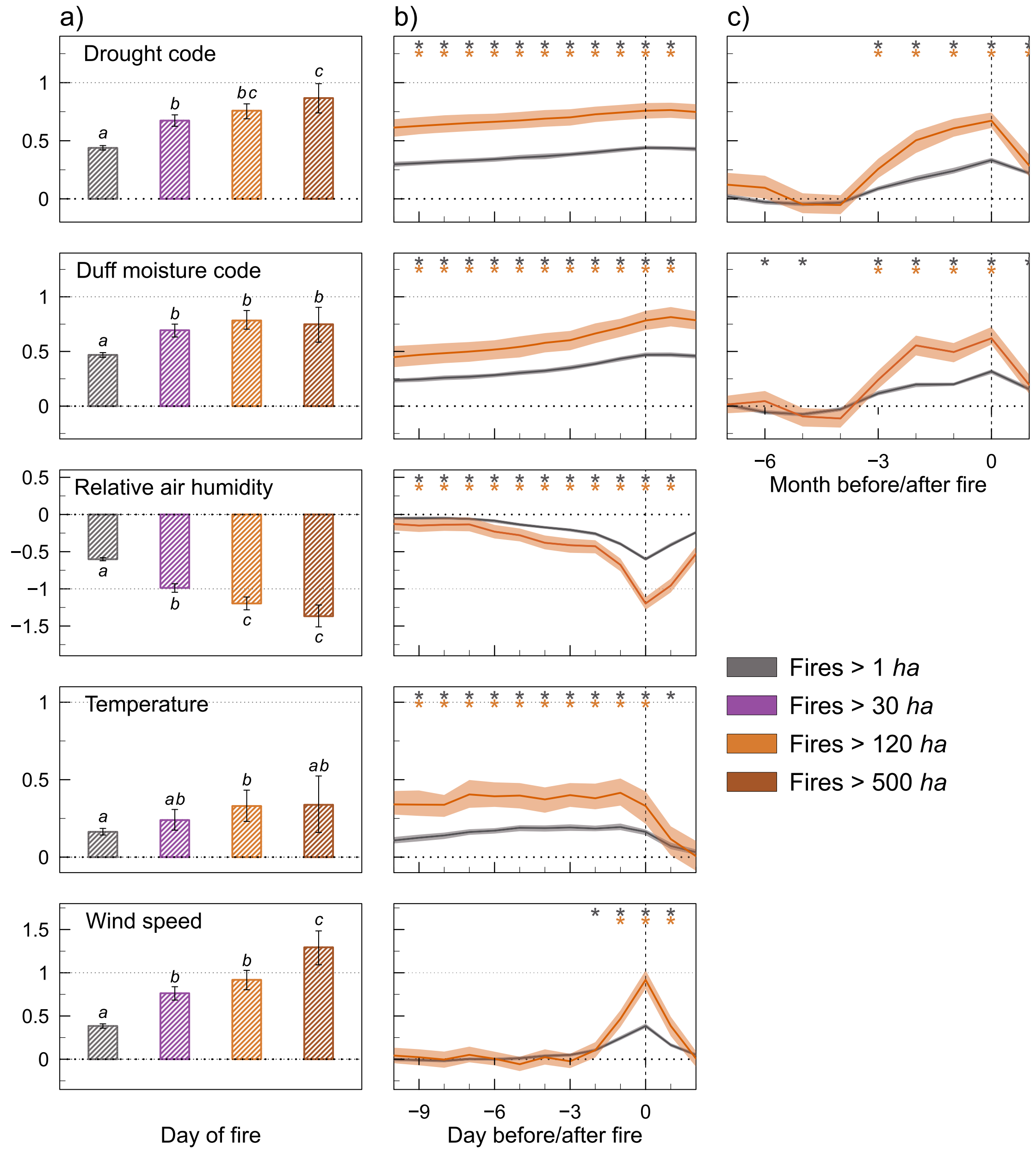

Figure 2. Composites of mean local-scale standardized climate anomalies associated with summer fire occurrence for four final fire sizes over the period from 1973 to 1990. Only a selected relevant time scales are displayed for each variable. (a) Comparison of climate standardized anomalies associated with the day of fire for four final fire sizes. Letters indicate distinct groupings based on pairwise t-test comparison among fire sizes ($p < 0.01$). (b) Standardized lagged anomalies at daily time scale for all fires (fires >1 ha) and large fires (>120 ha). (c) Standardized lagged anomalies at monthly time scale for all fires (fires >1 ha) and large fires (>120 ha). In (b) and (c) the 95% confidence intervals of the composite means (shaded areas) were computed using 1000 bootstrapped dataset. The significance between the anomalies and the mean climatology are indicated at the 0.01 level by colored stars. Standardized anomalies for all variables and all time scales are given in figure S4.

(figure 3(b)) during the day of fire while the thermal anomalies are weakly positive from 9 days to 3 days before the fire.

The third FWT is called the near-normal (NN). It is mostly characterized by a significant deviation in relative humidity (for the day before and the day of the fire), in DC (from 9 days before the fires) and DMC (from one day before the fire) (figure 3(b)), but the magnitude of these anomalies were significantly lower than those observed for the other two FWTs (figure 3(a)). Similarly, weak anomalous drought conditions start on average 3 months before the day of fire (see also figure S6).

The interannual variations in the number of LFs (>120 ha) and in the percentage of voxels associated with each FWT are presented in figure 4. The majority of voxels belonged to the NN type (63.4% in mean over the studied period, figure 4(a)), whereas the proportions of WD and HD voxels were relatively lower (9.4% and 9% respectively, figures 4(b) and (c)). It can also be inferred that, on average, 18.2% of voxels were not assigned to any FWT. These unassigned voxels are

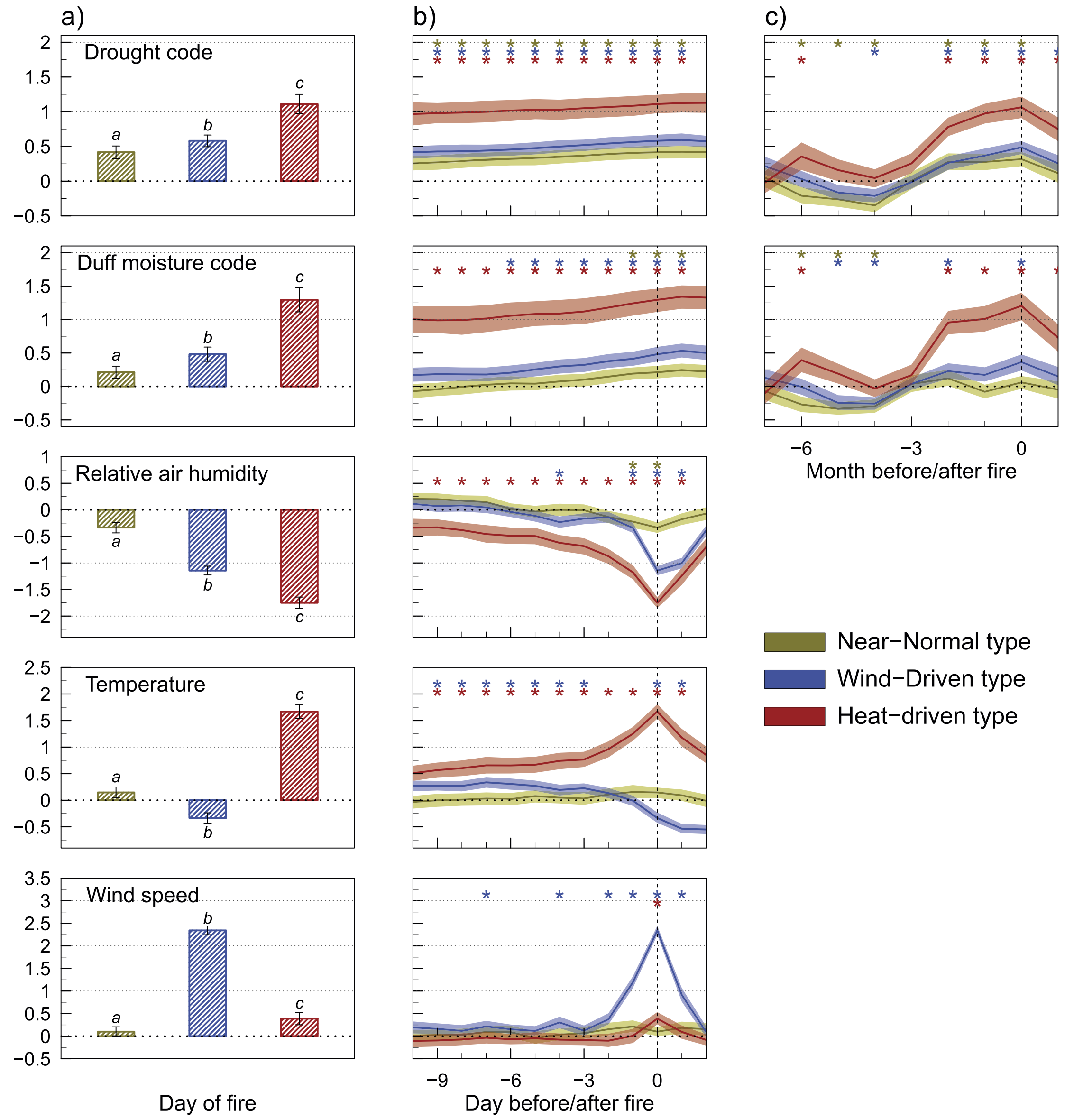

Figure 3. Composites of mean local-scale standardized climate anomalies associated with the different fire weather types (FWTs). FWTs were derived from the clustering of meteorological conditions associated with summer large fires (LF, >120 ha) over the period 1973–2012. (a) Comparison of climate standardized anomalies associated with the day of fire between FWTs. Letters indicate distinct groupings based on pairwise t-test comparison among fire sizes ($p < 0.01$). (b) Standardized lagged anomalies at daily time scale for each FWT. (c) Standardized lagged anomalies at monthly time scale for each FWT. In (b) and (c) the 95% confidence intervals of the composite means (shaded areas) were computed using 1000 bootstrapped dataset. The significance between the anomalies and the mean climatology are indicated at the 0.01 level by colored stars. Standardized anomalies for all variables and all time scales are given in figure S5.

due to the rule of considering the 90% confidence interval around each FWT. It is also likely that some of these voxels were not suitable for burning, such as during rainy days or when fuel is not dry enough to sustain the spread of fires. The number of fires according to each FWT was not related to this percentage of voxels. Over the 1973–2012 period, we observed more WD fires (287) than NN (223) and HD (165) fires. Interestingly, the temporal evolution of their frequency was different throughout the last decades. Thus, while the percentage of NN and WD voxels remained relatively unchanged ($p > 0.01$, MK test, figuress 4(a) and (b)), we observed a significant increase in the percentage of HD voxels (+0.29%/year, $p < 0.001$, figure 4(c)). Concurrently, the number of NN (−0.25 fires/year) and WD LFs (−0.22 fires/year) significantly decreased ($p < 0.001$) with a major shift around the year 1990. We should stress here the outstanding percentage of HD voxels and number of large HD fires during the summer 2003.

4. Discussion

There is considerable interest in identifying the meteorological factors that control the variations in wildfire activity in a global change context (e.g. Trigo *et al* 2016, Bedia *et al* 2015, Jolly *et al* 2015). In the present study, we provide evidence that the

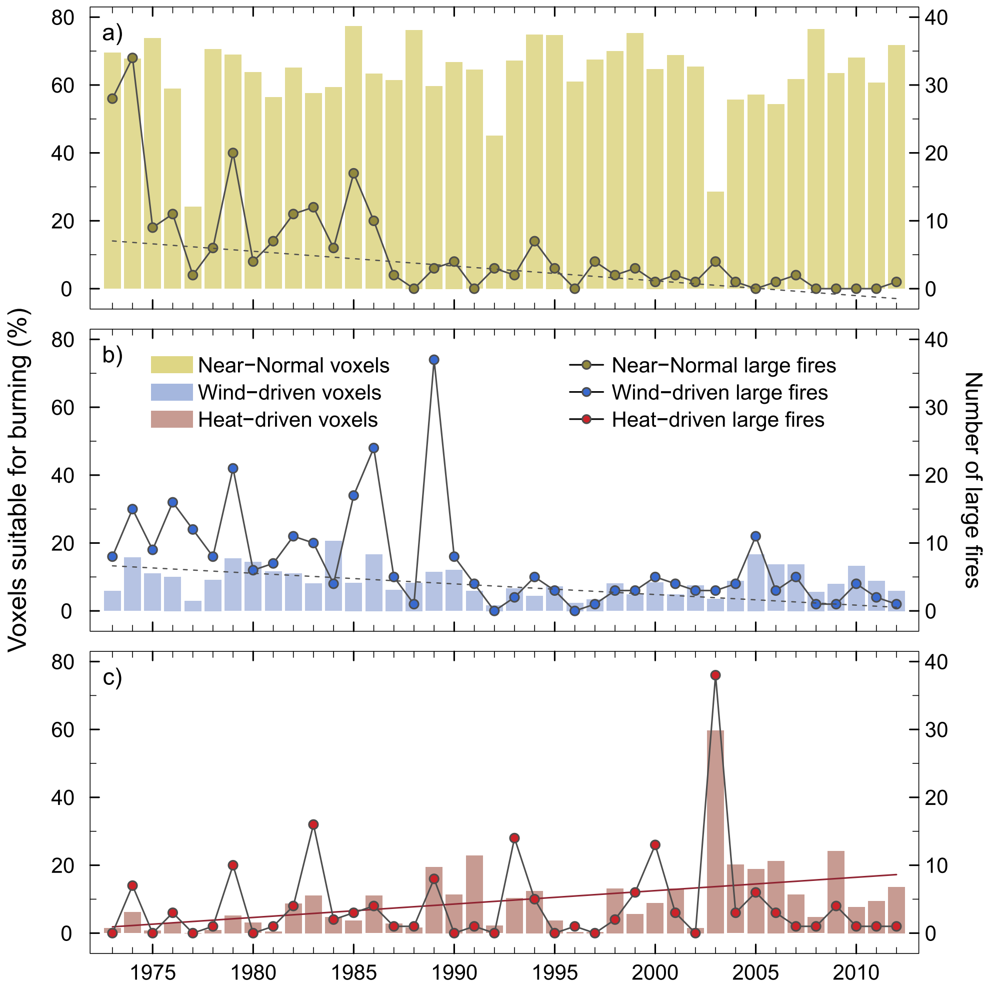

Figure 4. Historical reconstruction of the yearly number of summer large fires (LFs, >120 ha; right y-axis) and of the yearly percentage of summer voxels suitable for burning (left y-axis) according to each fire weather type (FWT): (a) near-normal type, (b) wind-driven type and (c) heat-driven type. Dotted lines in panels (a) and (b) indicate the significant decreasing trends in the number of near-normal and wind-driven LFs (Mann–Kendall test, $p < 0.01$), respectively. The plain red line in panel (c) indicates the significant trend in the number of heat-driven voxels suitable for burning (Mann–Kendall test, $p < 0.01$). The magnitude of trends was estimated with the Theil–Sen coefficient.

climatology of the large, typical Mediterranean crown-fires is actually composed of a limited number of distinct, (but coexistent) critical multi-scalar weather conditions called FWTs. This approach provides (i) a sound and mechanistic understanding of the weather drivers of fires, (ii) a robust conceptual framework for evaluating the impact of global changes on fire activity and (iii) opens new perspectives for climate-fire studies in fire-prone ecosystems. We elaborate these points in the following discussion.

Summer fires in Mediterranean France preferentially occur when two atmospheric-driven conditions are met (figures 2 and 3): vegetation drought (mostly controlled by seasonal-scale processes) and meteorological fire-prone days (mostly controlled by synoptic-scale processes). This indicates that fire activity is essentially 'drought-limited' in this area (*sensu* Krawchuk and Moritz 2011), in line with the conclusions drawn from local-scale (Koutsias *et al* 2013) and broad-scale (Gudmundsson *et al* 2014, Urbieta *et al* 2015) studies in Euro-Mediterranean countries.

Using here a 120 ha threshold for defining LFs, our results support the hypothesis of a non-uniqueness of the Mediterranean LF climatology (figure 3). While the existence of multiple FWTs in Mediterranean-type ecosystems has been already suggested in the Iberian Peninsula (Lecina-Diaz *et al* 2014, Duane *et al* 2015), in southern France (Lahaye *et al* 2014, Ruffault *et al* 2016) or in California (Jin *et al* 2014, 2015), we propose here an objective definition of these FWTs from the classification of local-scale antecedent and synchronous climatic anomalies associated with each fire. Three FWTs are identified in southern France (figure 3), each of those having very distinct meteorological anomalies at various time-scales, along with contrasting long-term temporal variations.

The WD FWT (figure 3, in blue) is a well-known climatology for being associated with large crown-fires (Rothermel 1991), such as those encountered in the Mediterranean basin (Ruffault *et al* 2016), in California (Jin *et al* 2014) or in circumboreal forests of Canada (Flannigan and Wotton 2001). WD fires pose particular risks owing to their speed and intensity. In southern France, these days are mostly related to local northerly continental dry and cool winds (Mistral and Tramontane) associated with a slow-down of the westerlies or blocking episodes over western Europe (Ruffault *et al* 2016), which partly disconnects here the co-occurrence of fast winds and warm anomalies. The frequency of these fires decreased over the last decades while its potential occurrence (i.e. fire and non-fire voxels belonging to this FWT) did not change (figure 4(b)), which implies a major role of non-climatic factors in this fire regime shift. As proposed by recent studies (Fox *et al* 2015, Fréjaville and Curt 2015, Ruffault and Mouillot 2015), the introduction of a new and efficient fire suppression policy in the late 80s might be responsible for this peculiar pattern.

The HD FWT (figure 3, in red) has been particularly related to the spread of fires in Mediterranean ecosystems (Jin *et al* 2014, Hernandez *et al* 2015a, 2015b, Ruffault *et al* 2016) and in some other crown-fire regimes worldwide (Rothermel 1991, Flannigan and Wotton 2001). Hot and dry episodes decrease the moisture content of living and dead vegetation and can even cause also mortality events (Allen *et al* 2015), both factors that increase fuel flammability. In addition, the peak of temperature during the day of fire exponentially increases the vapor pressure deficit of the atmosphere and therefore decreases the moisture content of fine fuels, such as shrubs leaves (Williams *et al* 2015). HD fires can reach very high intensities than renders suppression particularly difficult. Unlike most Euro-Mediterranean countries (e.g. Pereira *et al* 2005, Trigo *et al* 2016), this FWT is not the dominant type in southern France (figure 4(c)). But the increase in HD conditions (figure 4(c)), which is most likely due to current warming and drying in this region (figure S2), renders this FWT as the most potential candidate for driving fire activity in the next decades. In this regard, the outstanding number of HD fires observed during the summer 2003, when southern France experienced particularly dry and hot conditions (Trigo *et al* 2005) might occur more often in the mid-21st century (Barriopedro *et al* 2011, Ruffault *et al* 2014).

Contrasting with the two FWTs described above, the NN FWT is not related to specific daily atmospheric conditions, apart from significant positive drought anomalies. This negative anomaly in moisture content is a requirement to reach the 'moisture of extinction' in southern France i.e. the minimum water content that prevents fire spread (Chuvieco *et al* 2009). As for WD fires, the strong decrease in NN fires at the end of the 80s (figure 4(a)) suggests a major impact of suppression policies in this abrupt shift in fire activity.

Our study gives a better understanding of how global changes have impacted different types of fire-spread patterns in Mediterranean France. Being solely based on the objective classification of meteorological conditions associated with LFs, this approach opens similar perspectives for any other fire-prone ecosystems and could help to reconcile some long-standing debates about the different role of the fuel/ drought variables in driving fire regimes. It should be noted that the combination of several FWTs in the same wildfire might be common in some continents where fire usually burns during several days or even months. But in such cases, specific seasonal climatic patterns can also lead to the occurrence of some preferential FWTs.

It is likely that the number of FWTs, their climatic characteristics, their regional prevalence and probability of triggering LFs are all factors influenced by various human and biophysical constraints (e.g. fuel type, local-scale climatic patterns, suppression practices…). But it also appears from our analysis that similar FWTs could be identified between different biomes and regions. FWTs might be regarded as potential theoretical framework to derive, or describe, homogeneous fire units (or pyromes, *sensu* Archibald *et al* 2013). Additional efforts should be done to relate these different types of fires to some fire behaviors, intensity and severity fire patterns. In this regard, incorporating multiple fire climatologies into regional to global fire models could help to improve the simulation of the variability in these key fire-relevant parameters.

Acknowledgments

This work is a contribution to the Labex OT-Med (ANR-11-LABEX-0061) funded by the 'Investissements d'Avenir', French Government program of the French National Research Agency (ANR) through the A^*Midex project (ANR-11-IDEX-0001-02).

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