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Spatio-temporal trends in fire weather in the French Alps

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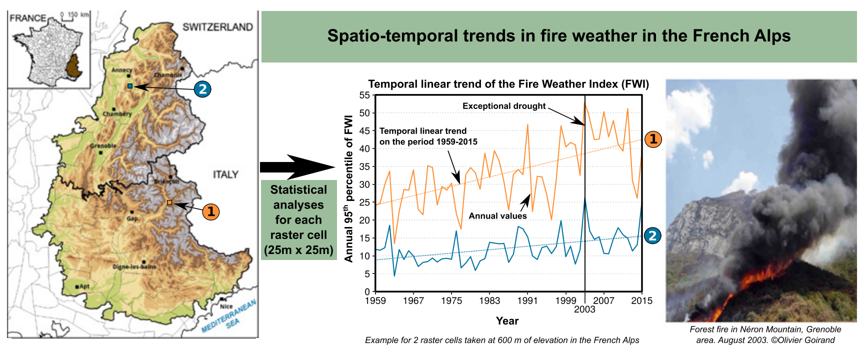
HIGHLIGHTS

- We investigated the changes in fire weather in the French Alps since 1959.
- Frequency, intensity, seasonality and window of opportunity of wildfires were analysed.
- A major contrast exists between North (low danger) and South (high danger) of the Alps.
- Ongoing climate changes induce an increase of fire weather danger in most of the area.
- High resolution maps were produced with direct applications in fire prevention policy.

GRAPHICAL ABSTRACT



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ABSTRACT

The Alpine area is particularly sensitive to climatic and environmental changes that might impact socio-ecosystems and modify the regime of natural hazards. Among them, wildfire is of major importance as it threatens both ecosystems and human lives and infrastructures. Wildfires result from complex interactions between available vegetation fuels, climate and weather, and humans who decide of the land use and are the main source of fire ignitions.

The changes in fire weather during the past decades are rather unknown in the French Alps especially due to their complex topography. Moreover, local institutions and managers wonder if the ongoing climate changes might increase fire risk and affect the environmental quality and the different ecosystem services provided by the mountain forests.

In this context, we used the national forest fires database together with daily meteorological observations from 1959 to 2015 to investigate the changes in wildfire danger in the French Alps. We analysed the spatial and temporal variations in terms of intensity, frequency, seasonality and window of opportunity of two fire weather indices: the fine fuel moisture code (FFMC) and the fire weather index (FWI) that measure the daily water content of vegetation and the potential intensity of fires, respectively.

Our results showed a major contrast between Southern Alps with a high fire weather danger on average and a significant increase in the past decades, and Northern Alps with low to moderate danger on average that increased only at low elevations. This study contributes to the understanding of the consequences of ongoings climate changes on wildfires in the French Alps. It produced high resolution results that account for the topographic and climatic variability of the area. Finally, the maps of the different fire weather components have practical implications for fire management and modelling and for preventing indirect effects of fires on ecosystems and human assets.

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1. Introduction

Mountains environments are especially sensitive to climatic changes (Pachauri et al., 2014; Kohler et al., 2010; Beniston, 2005). The ongoing changes have already resulted in many impacts on natural hazards in the Alps (Einhorn et al., 2015) including snow conditions and avalanches (Castebrunet et al., 2014; Le Meur et al., 2007), rockfalls (Ravanel and Deline, 2011) or debris flows (Jomelli et al., 2004). Forest fires might also be a major hazard and a threat for many mountain ecosystems and human assets in the next decades. Wildfires may disturb plant and fauna communities (Gibson et al., 2016; Moretti et al., 2002) and alter soil stability with implications on water resources (Cerdà, 1998), soil erosion (Pardini et al., 2017; Shakesby et al., 2016) and runoff (Ebel and Moody, 2017). They may also affect Alpine forests which ensure protection against natural hazards (Dupire et al., 2016a), thus reducing their effectiveness in protecting human stakes which are generally located down slope (Maringer et al., 2016).

Recent investigations have stated the main effects of climate changes in the Alps (Gobiet et al., 2014) and demonstrated an increase of temperature throughout the French Alps, especially since the 1980s (Dumas, 2013). Due to their extension and their topoclimatic complexity, the Alps experience many climatic influences and a strong regionalization of climate. In the French Alps (Fig. 1) the overall annual increase in temperature is about $+1\ ^{\circ}C$ on the period 1958–2002 (Durand et al., 2009). However, there are strong seasonal (Dumas, 2013) and spatial (Durand et al., 2009) variations. Mid elevations (1500–2000 m) and, in a lesser extent, low elevations, exhibited higher increases. Northern Alps showed a higher temperature increase than Southern Alps.

In the conceptual framework described by Bradstock (2010), climate is the only biogeographic factor that influences the four "switches" of fire regimes (e.g. biomass, availability to burn, fire spread and fire ignition). Thus, climate exerts a strong influence on fire activity in the Alps at different spatial and temporal scales. In the long term, it controls the vegetation composition and biomass (Blarquez and Carcaillet, 2010). In the short term, it controls vegetation moisture content that drives flammability (Fréjaville et al., 2016) and weather conditions that control fire behaviour (Valese et al., 2014). In the classification of Meyn et al. (2007), the Alpine environments would mostly fit the "biomass-rich and rarely dry ecosystems" with favourable conditions to fuel growth. Therefore, in the French Alps, the fire regimes are mostly driven by fuel moisture and fire ignition. Thus, surface fires of low-to-moderate intensity are the majority (Valese et al., 2014), while intense crown fires are rare and mostly located in the Southern Alps (Curt et al., 2016). Fire size distribution is very asymmetric with many very small fires (<1 ha) and few large fires, which generally develop during exceptional droughts like in 2003 (Poumadère et al., 2005; Luterbacher et al., 2004). Fires caused by lightning strikes are infrequent (only 15% of the fires) and mostly concentrated during the summer months (Arndt et al., 2013) at the highest altitudes where they primarily affect conifer forests, generally causing small to medium fires (Müller et al., 2013; Müller et al., 2015). In contrast, human-caused fires are prevailing and range from small to large fires. They mostly result from human activities (Reineking et al., 2010) and are predominant in winter and summer. In the last decades, new generation of intense wildfires are observed, they are linked to fuel accumulation due to both land abandonment, increase of the human stakes (Wildland-Urban Interfaces) and climate changes (Valese et al., 2014; Lahaye et al., 2014).

Climate-induced changes in wildfire activity and fire regime may affect Alpine territories and assets (Harris et al., 2016). The increase of temperature and droughts are hypothesized to increase fire frequency and intensity (Arpaci et al., 2013; Wastl et al., 2012), while exceptional droughts or heatwaves like in 2003 promote large and devastative wildfires (Gobron et al., 2005; Poumadère et al., 2005; Fink et al., 2004). Seasonal changes in weather conditions can also modify the fire regime in interaction with the use of fire by humans which are the main source of ignitions (Fréjaville and Curt, 2015).

Few studies exist concerning wildfire hazard in the Alpine region but none focused on the French Alps. Moriondo et al. (2006) included the Mediterranean Alps in their analysis and indicated that global warming would increase the length of the fire season and the probability of extreme meteorological events. In Switzerland, Reinhard et al. (2005) indicated that long episodes without rain and sunshine duration increased since 30 years, thus potentially decreasing the fuel moisture. Reineking et al. (2010) also depicted the increase in the severity and intensity of droughts and of lightning fires. In a study of 25 meteorological stations located throughout the Alps, Wastl et al. (2012) demonstrated that fire danger increased on average since 1951, but with high regional differences.

The overall aim of this study was to bridge the knowledge gaps on climate-fire relationships in the French Alps by jointly analysing fire weather and fire activity. Detecting hotspots of fire weather danger and spatial-temporal trends becoming more conducive to fire is of paramount importance for fire risk assessment and sustainable management of mountain socio-ecosystems. We investigated the climatic changes over the period 1959–2015 in order to determinate: (i) the fire weather hotspots with high fire weather frequency and intensity; (ii) the changes in fire weather along seasons; (iii) the hotspots where fire weather danger is increasing on average and for extreme conditions which promote large and destructive fires.

This approach has scientific and practical implications. First, it enhances knowledge of changing weather conditions on different components of fire weather at the regional scale which is a key scale for operational guidelines on the adaptation of forest management to ongoing climate changes and fire impacts. Second, it provides useful information and maps for a better prevention and suppression of fires.

2. Material and methods

2.1. Study area

The study area corresponds to the French Alpine area (Fig. 1) as defined by the French Institutions (Decree no. 2016–1208). Located at the South-East of France, it represents about 40,600 km^2 with an elevation ranging from 15 m to 4809 m (Mont-Blanc). This territory is divided into Northern and Southern Alps representing respectively 41% and 59% of the total area. Southern French Alps are marked by a mountain climate with a strong Mediterranean influence (dry summer and wet autumn and winter). Northern Alps are characterized by a mountain climate with degraded oceanic influences (rainfall distributed all the year with summer thunderstorm). Moreover, in both areas, the climate undergoes a strong continental component in the Eastern part (inner Alps) (Joly et al., 2010).

The threshold of 800 m of elevation was chosen in order to differentiate the ecosystems from the sub-montane elevation level (low elevation) with those from the montane and Alpine elevation levels (high elevation) (Ozenda and Wagner, 1975). It resulted in a sub-division of the Northern and Southern Alps with low elevation representing 36% of the total area and high elevations 64%.

2.2. Climatic data

The climatic data used in this study were taken from the Safran analysis system implemented by Météo France (Vidal et al., 2010). Safran had initially been designed to provide atmospheric forcing data in mountainous areas for avalanche hazard forecasting and was then used to develop a long-term meteorological reanalysis over the French Alps (Durand et al., 2009). A detailed description of Safran and its application over France is given by Quintana-Segui et al. (2008).