Universitat de Lleida

Ecology, meteorology and simulation of large wildland fires

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Ecología, meteorología y simulación de grandes incendios forestales

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DOCTORAL THESIS

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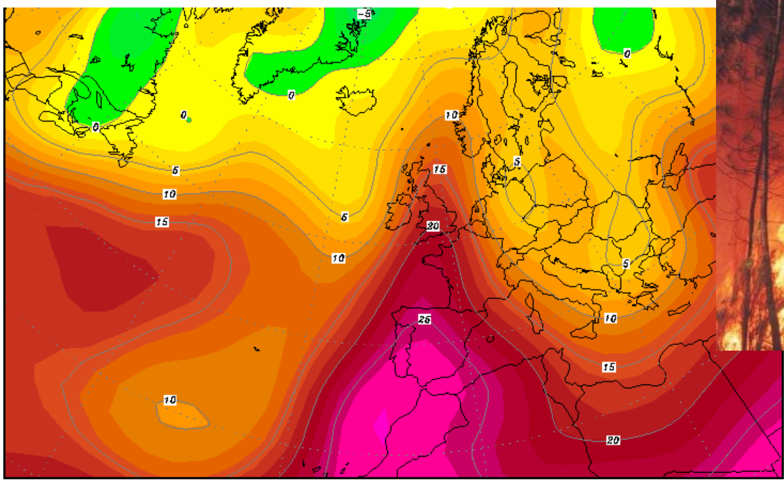

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Ecología, meteorología y simulación de grandes incendios forestales

Ecology, meteorology and simulation of large wildland fires

Tesis presentada por Adrián Cardil Forradellas para a optar al grado de Doctor de la Universidad de Lleida.

El trabajo ha sido realizado bajo la dirección del Dr. Domingo Miguel Molina Terrén (Universidad de Lleida).

Lleida, septiembre de 2015

ÍNDICE

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ABSTRACT

Extreme-temperature events are known to favor large wildland fires and have consequences for human health and mortality, forest disturbance patterns, agricultural productivity, and the economic repercussions of these consequences combined. To gain insight into whether extreme-temperature events are changing in light of global climate dynamics, the annual numbers of high-temperature days (those with temperatures higher than 20, 22.5, and 25 ºC at 850 hPa) were analyzed across southern Europe from the years 1978 to 2012. A significant increase in the frequency of these days was found in many areas over the time period analyzed, and patterns in the spatial distribution of these changes were identified. Additionally, this work analyzes the effects of high temperature days on medium and large fires from 1978 to 2010 in Spain and other areas (Sardinia, Italy). A high temperature day was defined as being when air temperature at 850 hPa was higher than the 95th percentile of air temperature at that elevation from June to September across the study period. Temperature at 850 hPa was chosen because it properly characterizes the state of the lower troposphere. The effects of high temperature on forest fires were remarkable and significant in terms of fire number (15 % of total large fires occurred under high temperature days), burned area (25 % of the total burned area occurred under high temperature days). Fire size was also significantly higher under 95th percentile air temperature at 850 hPa and a large part of the largest fires in the past 20 years were under these extreme conditions. Additionally, both burned area and fire number only decreased under non-high temperature days in the study period and not under high temperature conditions.

The worst consequence of wildland fires is the loss of human lives, a regular phenomenon over the last few decades worldwide. This work analyzes all recorded wildland fires in Spain with victims between 1980 and 2010. We classified causality causes during wildland fires to study the most frequent causes of fatalities and how they were related to regions, fire size, and extreme weather conditions (*i.e.*, high temperature days). Trends in number of both injured and killed individuals were analyzed. We observed that the annual number of victims did not decrease in the study period. Entrapment is the most frequent cause of death within the fire suppression employees. Fire size is a key factor in the occurrence of victims because 95% of fatalities in wildland fires (not counting aerial casualties) happened in fires larger than 100 ha. High temperature days also were important because 60% of entrapments were produced in this kind of days.

RESUMEN

Los eventos con temperaturas extremas favorecen la ocurrencia de grandes incendios forestales y tienen consecuencias en la salud y mortalidad humana, los patrones de perturbación forestal, la productividad agrícola y las repercusiones económicas de estas consecuencias combinadas. Para conocer si los eventos de temperaturas extremas están cambiando bajo la dinámica de cambio global, se analizaron las cifras anuales de días de alta temperatura (aquellos con temperaturas superiores a los 20, 22,5 y 25 ºC a 850 hPa) en el sur de Europa en el periodo 1978-2012. Un aumento significativo en la frecuencia de este tipo de días se encontró en muchas áreas durante el período de tiempo analizado, y se identificaron patrones en la distribución espacial de estos cambios. Además, este trabajo analiza los efectos de días de alta temperatura en incendios forestales medianos y grandes en España desde 1978, así como en otras áreas (Cerdeña, Italia). Un día de alta temperatura se define cuando la temperatura del aire a 850 hPa es mayor que el percentil 95 de la temperatura del aire a 850 hPa de junio a septiembre en todo el período de estudio. Elegí la temperatura a 850 hPa porque caracteriza adecuadamente el estado de la baja troposfera. Los efectos de las altas temperaturas sobre los incendios forestales fueron notables y significativos en términos de número de incendios (el 15% del total de los grandes incendios ocurrieron bajo días de alta temperatura) y área quemada (25% del total de área quemada se produjo bajo días de alta temperatura). El tamaño de los incendios también fue significativamente mayor en condiciones de alta temperatura y gran parte de los incendios más grandes en los últimos 20 años fueron en este tipo de condiciones extremas. Además, tanto el número de incendios como el área quemada solamente disminuyeron bajo días de no alta temperatura en el período de estudio.

La peor consecuencia de los incendios forestales es la pérdida de vidas humanas, un fenómeno que se ha producido con regularidad durante las últimas décadas en todo el mundo. Este trabajo analiza todos los incendios forestales en España con víctimas registradas entre 1980 y 2010. Los incendios se clasificaron por la causa que provocó la muerte de las víctimas durante los incendios forestales con el objetivo de estudiar las causas más frecuentes en accidentes mortales y cómo se relaciona con distintas regiones geográficas, el tamaño de los incendios, y las condiciones climáticas extremas (es decir, días de alta temperatura). Se analizaron tendencias temporales en el número de individuos heridos y muertos en el periodo de estudio. Se observa que el número anual de víctimas no disminuyó en el período de estudio. El atrapamiento es la causa más frecuente de muerte dentro de los empleados de extinción de incendios. El tamaño de los incendios es un factor clave en la aparición de las víctimas ya que el 95% de las muertes en incendios forestales (sin contar las bajas aéreas) ocurrió en incendios mayores de 100 ha. Los días de alta temperatura también fueron claves debido a que el 60% de atrapamientos se produjo en este tipo de días.

RESUM

Els esdeveniments amb temperatures extremes afavoreixen l'aparició de grans incendis forestals amb conseqüències en la salut i mortalitat humana, els patrons de pertorbació forestal, la productivitat agrícola i les repercussions econòmiques d'aquestes conseqüències combinades. Per conèixer si els esdeveniments de temperatures extremes estan canviant amb la dinàmica de canvi global, es van analitzar les xifres anuals de dies amb altes temperatures (aquells dies amb temperatures superiors als 20, 22.5 i 25ºC a 850hPa) al sud d'Europa en el període 1978-2012. Un augment significatiu en la freqüència d'aquest tipus de dies es va trobar en moltes àrees durant el període de temps analitzat, i es van identificar patrons en la distribució espacial d'aquests canvis. A més, aquest treball analitza els efectes de dies d'alta temperatura en incendis forestals mitjans i grans a Espanya des de 1978, així com en altres àrees (Cerdenya, Itàlia). Es defineix un dia d'alta temperatura quan la temperatura de l'aire a 850hPa és més gran que el percentil 95 de la temperatura de l'aire a 850hPa de juny a setembre en tot el període d'estudi. Vaig triar la temperatura a 850hPa perquè caracteritza adequadament l'estat de la baixa troposfera. Els efectes de les altes temperatures sobre els incendis forestals van ser notables i significatius en termes de nombre d'incendis (el 15% del total dels grans incendis es van produir en dies d'alta temperatura) i àrea cremada (el 25% del total d'àrea cremada es va produir en dies d'alta temperatura). Les dimensions dels incendis també van ser significativament més grans en condicions de temperatura i gran part dels incendis més grans en els últims 20 anys van ser en aquest tipus de condicions extremes. A més, tant el nombre d'incendis com l'àrea cremada només van disminuir en dies de no alta temperatura en el període d'estudi.

La pitjor conseqüència dels incendis forestals és la pèrdua d'éssers humans, un fenomen que s'ha produït amb regularitat durant les últimes dècades a tot el món. Aquest treball analitza tots els incendis forestals d'Espanya amb víctimes registrades entre els anys 1980 i 2010. Els incendis es van classificar per la causa que va provocar la mort de les víctimes durant els incendis forestals amb l'objectiu d'estudiar les causes més freqüents en accidents mortals i la seva relació amb les diferents regions geogràfiques, les dimensions dels incendis, i les condicions climàtiques extremes (és a dir, dies d'alta temperatura). Es van analitzar tendències temporals en el nombre d'individus ferits i morts en el període d'estudi. L'atrapament és la causa més freqüent de mort dins dels empleats d'extinció d'incendis. Les dimensions dels incendis són un factor clau en l'aparició de les víctimes, ja que el 95% de les morts en incendis forestals (sense tenir en compte les baixes aèries) es van produir en incendis que afectaven més de 100 ha. Els dies d'alta temperatura també van ser claus pel fet que el 60% d'atrapaments es van produir en aquest tipus de dies.

INTRODUCTION

Wildland fires are a growing hazard to human and environmental values worldwide, mainly in the fire prone areas as the Mediterranean Basin (Salis et al., 2012). Many biomes of this region have endured an increasing incidence of severe fire seasons (Mouillot and Field, 2005; Trigo et al., 2006). In the period 2000-2009, Southern European countries (Italy, France, Spain, Portugal and Greece) experienced ~57 000 wildfires year $^{-1}$, which burned ~430 000 ha year $^{-1}$ and 90% were human caused (JRC-IES, 2010).

Southern European countries have fire regimes that include large wildland fires (LWF) that might have an extreme fire behavior exceeding firefighting capabilities (Molina et al., 2010). Undesirable fires affect the forest landscape every year. In addition, when weather conditions facilitates fire propagation, fires can burn large areas in Spain with wildland fires larger than 20.000 ha as in 1994, 1998, 2003, 2007 and 2012. Other similar cases occurred in other countries as Greece (2007), Portugal (2003), Russia (2010), United States (2000) or Australia (2009, 2012).

Large wildland fires threaten social, economic and ecological resources (Alvarado et al., 1998; Salis et al., 2012), public and private properties (houses, infrastructures, roads, power lines and others) and the life of firefighters and people (Maselli et al., 2000, ciata el nuestro de víctimas y uno de los de Viegas). Therefore, wildfires cause environmental and socio-economic consequences. Fire suppression resources have to be designed to reduce fire damage caused by LWFs. Consequently, a large amount of money has been invested for this cause. The expenditure in fire suppression has grown a great deal and the Spanish Government were forced to create both the Emergency Military Unit (UME in Spanish in 2005) and the Attorney's Office of Environmental Crimes (within the Department of Justice, in 2006). Regional fire agencies have also reinforced in the last two decades. I have assessed whether fire agencies decreased burned area in Spain after this high investment in more resources.

LWF accounted for the majority of the total area burned despite their small percentage of the total number of fire (Stocks et al., 2003) and the most resulting damage is concentrated in them (Ganteaume and Jappiot, 2012; Alvarado et al., 1998). Much discussion is concentrated around if fire and forest policies and practices on fuel management are missing their original goal (Moreira et al., 2011). My thesis is focus on understanding LWFs and the interactions with extreme temperature conditions in South Europe, focusing on Spain.

Heat-wave events play a role in determining human health and episodic mortality patterns, and are also recognized as having marked impacts on agriculture, forestry, wildland fire, and socioeconomic activities (Poumadère et al., 2005; Mills, 2005; Trigo et al., 2006; Kuglitsch et al., 2010; Cardil et al., 2013). Multiple heat waves have been recorded in southern Europe in recent years, including in 2003, when summer temperatures across Europe were very likely warmer than any other summer looking back to 1500

(Luterbacher et al., 2004). Extreme-temperature days and heat waves were linked to above-average human mortality in the cities of Madrid and Lisbon (García-Herrera et al., 2005), and in France in 2003 (Poumadere et al., 2005). In addition, large wildland fires are more likely during heat-wave events, burning thousands of hectares across multiple ecosystems in the Mediterranean region (e.g., 1994 in Spain, 2003 in Portugal, 2007 in Greece). In Russia in 2010, unusual temperatures around 40 ºC were recorded and the resulting drought was linked to wildfires that were responsible for hundreds of human deaths, covering much of the region with toxic smog (Gobin et al., 2013). An unprecedented spring heat wave in the USA and Canada peaked in intensity during March of 2012 (Gobin et al., 2013), followed by a summer of destructive and even fatal wildfires in North American forests.

Extreme-temperature events can also exacerbate other effects of global climate change. For example, climate-change related increases in average temperatures have been linked to widespread insect outbreaks in North American forests (Safranyik, 2004), which, coupled with wildfires propagated by extreme temperature events, can have an multiplied effect on forest persistence. The synergistic effects of extreme temperatures and their repercussions have been identified as possible mechanisms for the development of a positive feedback cycle of global warming and continued loss of greenhouse gases to the atmosphere.

Climate-change projections for the Mediterranean Basin show a higher variability in weather conditions and an increase in extreme weather events, with longer, more frequent, and even more intense heat waves (Moriondo et al., 2006; Diffenbaugh et al., 2007; Giorgi and Lionello, 2008; Regato, 2008; Giannakopoulos et al., 2009; Barriopedro et al., 2011). The Mediterranean is widely considered a climate change “hot spot” (Giorgi, 2006), meaning that the region is a sensitive indicator of changes that have already occurred, and it is expected to be a sensitive responder to predicted changes due to its location at the intersection of tropical and mid latitude atmospheric and oceanographic processes. Although numerous authors have explored the relationships between predicted climate change and expected increases in temperatures (e.g., Giorgi and Lionello, 2008; Giannakopoulos et al., 2009), few have identified spatial patterns and differences in magnitude of recent changes in extreme-temperature-day frequencies.

Extreme high temperature conditions could be a key factor affecting fatalities because they provide extreme conditions for forest fire-fighters (fatigue, heat exhaustion, dehydration). Heat exhaustion is when a person experiences fatigue (extreme tiredness) as a result of a decrease in blood pressure and blood volume. It is caused by a loss of body fluids and salts after being exposed to heat for a prolonged period of time (NHS 2010). Fatigue is common in fire fighters working under extreme temperatures (Lorber 2006). Additionally, fire behavior is more extreme (Cardil et al. 2013) and can entrap firefighters and vehicles. Wind is another major environmental factor in extreme fire behavior but I do not have access to detailed local wind data for most of the earlier casualties of our study. Therefore, I recognize that I only address one of several environmental factors that create this extraordinary risk for fire fighters. These other factors are intense surface winds with gusts from changing directions and irregularities in relative air humidity at low tropospheric altitudes. All fatalities occurred in Spain in the 1980-2010 period were studied to learn the more frequent accident causes and to link extreme weather conditions and fatalities from different groups (i.e., paid fire fighters, volunteer fire fighters, individuals in airplanes/helicopters, citizen not related to fires suppression activities)).

The main purpose of the PhD thesis was to identify whether the number of heat waves increased in last 30 years and their effects on large wildland fires in terms of number of fires, burned area, fire size and victims (firefighters or population death in wildland fires). In order to explore trends in extreme-temperature events over time across southern Europe, I analyzed (i) annual number of high-temperature days and their spatial distribution, and (ii) temporal trends of extreme-temperature events to identify and quantify significant changes over the study period. I also related fires with extreme temperature conditions to assess their influence. Additionally, I tested fire suppression effectivity in extreme temperature days versus non-extreme temperature days.

Chapter 1. Extreme temperature days and their potential impacts on southern Europe

This chapter was published in Natural Hazards and Earth System Science (2014), 14, 3005–3014

A. Cardil, D. M. Molina, L. N. Kobziar

Abstract

Extreme-temperature events have consequences for human health and mortality, forest disturbance patterns, agricultural productivity, and the economic repercussions of these consequences combined. To gain insight into whether extreme-temperature events are changing in light of global climate dynamics, the annual numbers of high-temperature days (those with temperatures higher than 20, 22.5, and 25 ºC at 850 hPa) were analyzed across southern Europe from the years 1978 to 2012. A significant increase in the frequency of these days was found in many areas over the time period analyzed, and patterns in the spatial distribution of these changes were identified. We discuss the potential consequences of the increases in high-temperature days with regards to forest fire risk, human health, agriculture, energy demands, and some potential economic repercussions.

Introduction

Heat-wave events play a role in determining human health and episodic mortality patterns, and are also recognized as having marked impacts on agriculture, forestry, wildland fire, and socioeconomic activities (Poumadère et al., 2005; Mills, 2005; Trigo et al., 2006; Kuglitsch et al., 2010; Cardil et al., 2013). Multiple heat waves have been recorded in southern Europe in recent years, including in 2003, when summer temperatures across Europe were very likely warmer than any other summer looking back to 1500 (Luterbacher et al., 2004). Extreme-temperature days and heat waves were linked to above-average human mortality in the cities of Madrid and Lisbon (García-Herrera et al., 2005), and in France in 2003 (Poumadere et al., 2005). In addition, large wildland fires are more likely during heat-wave events, burning thousands of hectares across multiple ecosystems in the Mediterranean region (e.g., 1994 in Spain, 2003 in Portugal, 2007 in Greece). In Russia in 2010, unusual temperatures around 40 ºC were recorded and the resulting drought was linked to wildfires that were responsible for hundreds of human deaths, covering much of the region with toxic smog (Gobin et al., 2013). An unprecedented spring heat wave in the USA and Canada peaked in intensity during March of 2012 (Gobin et al., 2013), followed by a summer of destructive and even fatal wildfires in North American forests.

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Climate-change projections for the Mediterranean Basin show a higher variability in weather conditions and an increase in extreme weather events, with longer, more frequent, and even more intense heat waves (Moriondo et al., 2006; Diffenbaugh et al., 2007; Giorgi and Lionello, 2008; Regato, 2008; Giannakopoulos et al., 2009; Barriopedro et al., 2011). The Mediterranean is widely considered a climate change “hot spot” (Giorgi, 2006), meaning that the region is asensitive indicator of changes that have already occurred, and it is expected to be a sensitive responder to predicted changes due to its location at the intersection of tropical and midlatitude atmospheric and oceanographic processes. Although numerous authors have explored the relationships between predicted climate change and expected increases in temperatures (e.g., Giorgi and Lionello, 2008; Giannakopoulos et al., 2009), few have identified spatial patterns and differences in magnitude of recent changes in extreme-temperature-day frequencies. In order to explore trends in extreme-temperature events over time across southern Europe, we analyzed (i) annual number of high-temperature days and their spatial distribution, and (ii) temporal trends of extreme-temperature events to identify and quantify significant changes over the 1978–2012 period.

Although extreme events can be interpreted using a variety of metrics, we focused on air temperature at 850 hPa as a reference – the air temperature at approximately 1500ma.s.l. (above sea level) where pressure is 850 hPa – because it is used by many forecast agencies and is an indicator of heat waves or the evolution of temperatures in successive days (AEMET – Spanish Meteorological Agency; Trigo et al., 2006). In addition, some problems that affect near-surface reanalysis do not occur when using temperatures at this altitude (Ogi et al., 2005). We assessed trends in the number of high-temperature days (HTDs) with three different temperature thresholds: 20, 22.5, and 25 ºC. Because the 95th percentile weather, or the “hot tail”, has been identified as an important metric for predicting future heat stress and amplification by soil moisture loss in the Mediterranean Basin (Diffenbaugh et al., 2007), we also analyzed this variable using the summer period (June–September) from 1978 to 2012.

Methods

Study area

This work focused on southern Europe because it is expected to be the most susceptible European area to a significant increase in extreme-temperature events and to sustain some of the most significant impacts (Giorgi, 2006; Giannakopoulos et al., 2009). In all, 34 points were used for the analysis, distributed systematically across the region (Fig. 1). This region comprises Portugal, Spain (Mediterranean Coast, points 2, 3, 4, 8, 9, and 14; interior Spain, points 6, 7, and 13; northern Spain, points 10, 11, and 12) the south of France, Italy (Italian Peninsula, points 22, 23, 25, 26, 27, and 28; Italian islands, points 19, 20, and

21), and Greece. These points were chosen in order to capture a representation of trends for all of southern Europe below the 45th parallel.

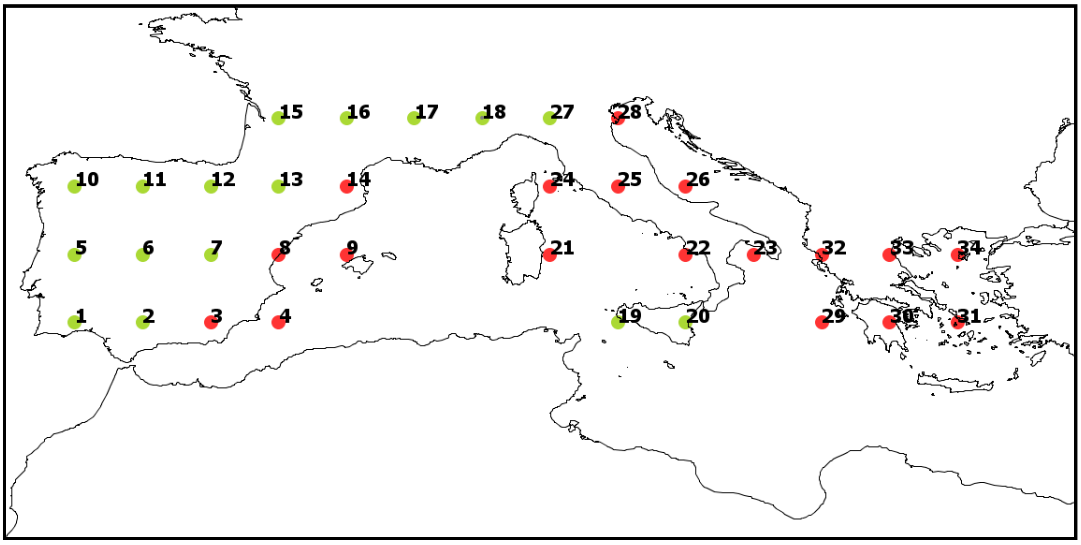

Figure 1. Identification of the NCEP reanalysis analyzed points (National Center for Environmental Prediction) in the study area (Portugal, Spain, South France, Italy and Greece). Red points mean a significant increase (p-value<0.05) in the annual number of days with an air temperature higher than 20 ºC at 850 hPa (HTD_{20}) in the June-September period from 1978 to 2012. Green points mean that there were no significant changes in terms of annual number of HTD_{20}.

High temperature days (HTD)

We used NCEP reanalysis data from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (Kalnay et al., 1996) to characterize the high temperature days on a synoptic scale. NCEP output data has a horizontal resolution of 2.5º latitude-longitude. We analyzed the 34 points distributed in the study area as shown in Figure 1. Daily air temperature data at 850 hPa pressure level at 00:00 UTC were analyzed from 1978 to 2012. We chose the air temperature at 850 hPa as reference because it is used by Meteorological Services to forecast and display heat-waves or the trend of temperatures in successive days (AEMET, Spanish Meteorological Agency). It is also used by different agencies across Southern Europe (i.e., Aragón Forest Service, Castilla-La-Mancha Forest Service, Catalonia Fire-Fighting Service, Valencia Fire-Fighting Service, CFVA in Sardinia- Italy) to analyze past fire weather events and to forecast daily potential fire occurrence and behavior (Trigo et al., 2006; Garcia-Ortega et al., 2011). In this manner, it provides adequate regional coverage and it is representative of the surface, avoiding some of the problems that affect near surface reanalysis (Ogi et al., 2005; Trigo et al., 2005; Trigo et al., 2006).

We used several HTD categories considering different temperature thresholds: (1) HTD_{20}, those days with an air temperature higher than 20 ºC at 850 hPa, (2) $HTD_{22.5,}$ those days with an air temperature higher than 22.5 ºC at 850 hPa and, (3) $HTD_{25,}$ those days with an air temperature higher than 25 ºC at 850 hPa, (4)

HTD_{p95}, 95th percentile of air temperature at 850 hPa in the June-September period from 1978 to 2012. The use of the 95% percentile helps capture the different implications for human health, energy systems, and natural vegetation and disturbances for temperature extremes in different locations. For example, in the northern section of the study area, where mean temperatures are generally lower, a temperature above 20 ºC would exceed the 95th percentile, while the same temperature would be nearly five degrees below the 95th percentile in the southern latitudes.

The limit of 20 ºC of air temperature at 850 hPa was chosen because it provides high temperatures in surface and typically low relative humidity in the territory, and is associated with heat waves in many zones in the study area (Montserrat, 1998; Cardil et al., 2013). We analyzed temporal trends in relation to the annual number of HTD in all four categories using least squares fitted linear regression models and tested whether slopes differed significantly from zero ($p < 0.05$). For those locations where significant temporal changes were found to exist, we further investigated spatial patterns of change. To determine whether significant differences in number and changes in high temperature days across latitudes and longitudes, we used one-way ANOVA followed by Tukey's HSD test.

Results

The annual number of HTD differed in relation to the different areas and countries. Generally, points with higher latitude had fewer HTD in all categories (Figure 2). The points with a higher annual number of HTD_{20}, $HTD_{22.5}$, HTD_{25} are located in Mediterranean Spanish Coast (points 2, 3 and 4) and in the South of Portugal (point 1; Figure 2). However, points located in Greece at the same latitude had a significantly lower number of these days. The island of Sardinia (point 21) and Balearic Islands (point 9) had higher numbers of extreme temperature days in relation to other locations at the same latitude. The same results were obtained in relation to the 95th percentile in terms of temperature during the June-September period from 1978 to 2012.

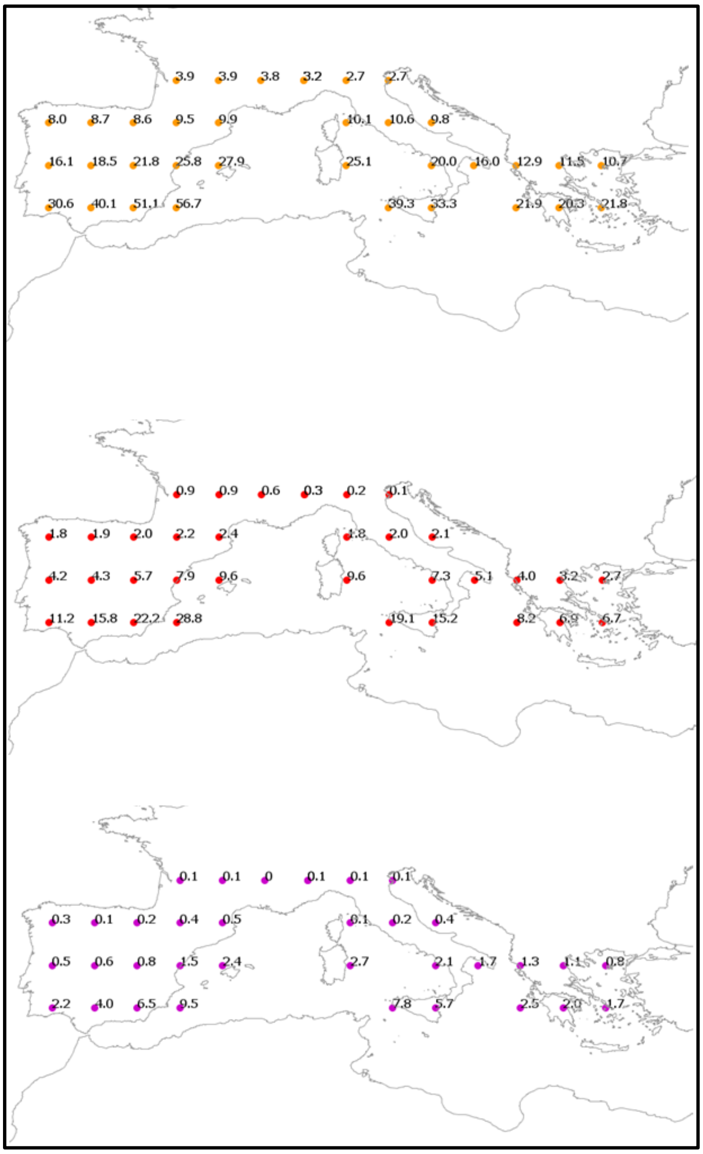

Figure 2. Mean annual number of days with an air temperature higher than 20 ºC (orange points), 22.5 ºC (red points) and 25 ºC (purple points) at 850 hPa in the June-September period from 1978 to 2012.

Temporal trends in terms of annual number of HTD_{p95}, HTD_{20}, $HTD_{22.5}$, and the 95^{th} percentile for all analyzed points are shown in Table 1 and Figure 3. Note that the HTD_{25} category is not in Table 1 because no significant trends were found at any point, mainly due to the low number of these days. A significant increase in the annual number of HTD_{20} was found in locations around the Mediterranean Spanish Coast (Figure 1 and Table 1). However, in other parts of Spain and in Portugal, the annual number of HTD did not change in any analyzed temperature threshold. In South France, no significant changes over the study time period analyzed were detected. However, significant increases of the annual number of HTD_{20} and/or the 95^{th} percentile were found in the majority of sites in Italy and Greece (except in Sicily). Extreme weather days are becoming more frequent in these areas. Additionally, the highest increases in terms of annual number of HTD_{20} were found in Greece and along the Mediterranean Spanish Coast (0.60

HTD_{20} more per year over the entire period). In Italy, significant increases were found but lower than in Greece or along the Mediterranean Spanish Coast (0.35 HTD_{20} more per year).

Table 1. Simple linear regression analysis of significant trends in annual number of HTD_{p95}, HTD_{20}, $HTD_{22.5}$, over time in the study area during the June-September period from 1978 to 2012. Point locations are mapped in Figure 1.

Point	Latitude/ Longitude	Country	(P values) and / slope coefficients		
			HTD_{20}	$HTD_{22.5}$	HTD_{p95}
1	37.5º / 352.5º	Portugal	n.s (0.480) / 0.111	n.s (0.090) / 0.156	n.s (0.370) / 0.057
2	37.5º / 355º	Spain	n.s (0.107) / 0.295	n.s (0.083) / 0.199	n.s (0.646) / 0.031
3	37.5º / 357.5º	Spain	+ (0.009) / 0.525	+ (0.029) / 0.344	n.s (0.182) / 0.103
4	37.5º / 0º	Spain	+ (0.008) / 0.531	+ (0.002) / 0.545	n.s (0.084) / 0.142
5	40º / 352.5º	Portugal	n.s (0.354) / 0.118	n.s (0.375) / 0.054	n.s (0.552) / 0.048
6	40º / 355º	Spain	n.s (0.296) / 0.115	n.s (0.836) / -0.012	n.s (0.651) / 0.028
7	40º / 357.5º	Spain	n.s (0.072) / 0.248	n.s (0.884) / 0.009	n.s (0.893) / 0.008
8	40º / 0º	Spain	+ (0.003) / 0.484	n.s (0.173) / 0.118	n.s (0.278) / 0.084
9	40º / 2.5º	Spain	+ (0.001) / 0.600	+ (0.018) / 0.222	n.s (0.238) / 0.094
10	42.5º / 352.5º	Spain	n.s (0.870) / 0.015	n.s (0.963) / 0.002	n.s (0.878) / 0.011
11	42.5º / 355º	Spain	n.s (0.710) / 0.032	n.s (0.805) / 0.011	n.s (0.684) / 0.032
12	42.5º / 357.5º	Spain	n.s (0.273) / 0.092	n.s (0.550) / 0.020	n.s (0.381) / 0.067
13	42.5º / 0º	Spain	n.s (0.078) / 0.147	n.s (0.251) / 0.038	+ (0.044) / 0.139
14	42.5º / 2.5º	Spain	+ (0.010) / 0.246	n.s (0.486) / 0.025	n.s (0.058) / 0.131
15	45º / 0º	France	n.s (0.305) / 0.051	n.s (0.301) / 0.031	n.s (0.319) / 0.077
16	45º / 2.5º	France	n.s (0.159) / 0.085	n.s (0.178) / 0.037	n.s (0.081) / 0.142
17	45º / 5º	France	n.s (0.108) / 0.115	n.s (0.297) / 0.022	n.s (0.114) / 0.135
18	45º / 7.5º	France	n.s (0.111) / 0.102	n.s (0.240) / 0.146	+ (0.044) / 0.167
19	37.5º / 12.5º	Italy	n.s (0.181) / 0.219	n.s (0.179) / 0.154	n.s (0.513) / 0.054
20	37.5º / 15º	Italy	n.s (0.166) / 0.222	n.s (0.051) / 0.186	n.s (0.369) / 0.073
21	40º / 10º	Italy	+ (0.022) / 0.371	+ (0.032) / 0.183	n.s (0.096) / 0.125
22	40º / 15º	Italy	+ (0.014) / 0.354	+ (0.014) / 0.182	+ (0.014) / 0.200
23	40º / 17.5º	Italy	+ (0.006) / 0.374	n.s (0.978) / -0.001	+ (0.019) / 0.190
24	42.5º / 10º	Italy	+ (0.011) / 0.278	n.s (0.459) / 0.023	+ (0.032) / 0.200
25	42.5º / 12.5º	Italy	+ (0.003) / 0.354	+ (0.047) / 0.090	+ (0.014) / 0.211
26	42.5º / 15º	Italy	+ (0.002) / 0.353	n.s (0.452) / -0.008	+ (0.005) / 0.213
27	45º / 10º	Italy	n.s (0.080) / 0.088	n.s (0.610) / -0.008	+ (0.013) / 0.240
28	45º / 12.5	Italy	+ (0.038) / 0.097	n.s (0.353) / -0.009	+ (0.023) / 0.198
29	37.5º / 20º	Greece	+ (0.011) / 0.362	n.s (0.065) / 0.160	n.s (0.169) / 0.097

30	37.5º / 22.5º	Greece	+ (0.003) / 0.447	n.s (0.060) / 0.130	n.s (0.052) / 0.125
31	37.5º / 25º	Greece	+ (<0.001) / 0.605	+ (0.025) / 0.168	+ (0.009) / 0.165
32	40º / 20º	Greece	+ (0.001) / 0.431	+ (0.032) / 0.153	+ (0.005) / 0.231
33	40º / 22.5º	Greece	+ (<0.001) / 0.449	n.s (0.081) / 0.108	+ (0.010) / 0.223
34	40º / 25º	Greece	+ (0.001) / 0.413	n.s (0.078) / 0.087	+ (0.012) / 0.218

+Significant increase over time (p-value<0.05), n.s not significant trend (p-value<0.05) and value in parenthesis means the p-value in the analyzed trend. The slope of the regression line is also shown in bold.

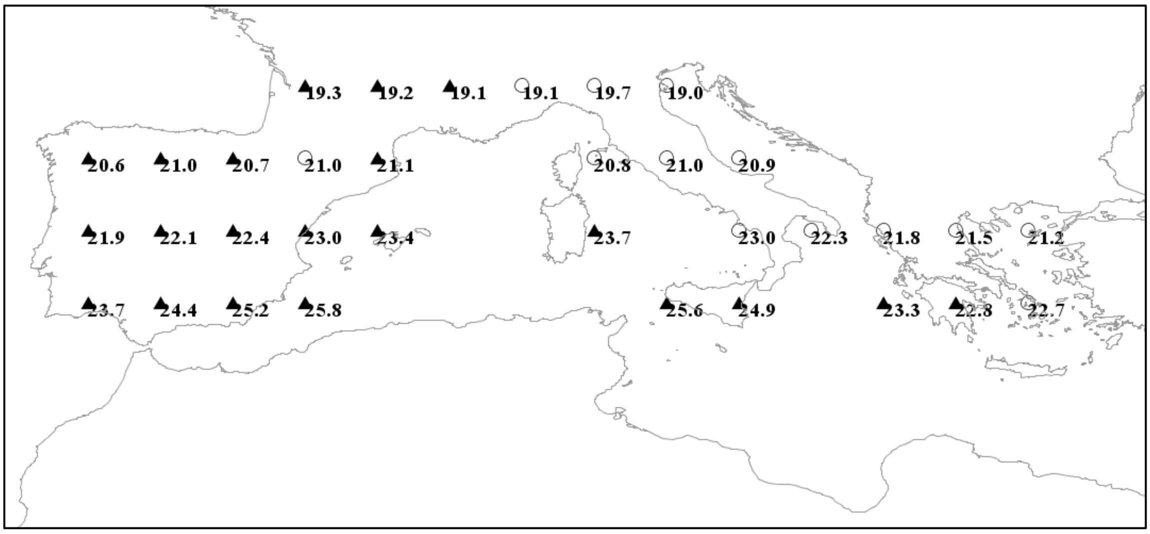

Figure 3. 95th percentile of maximum daily air temperature in degrees Celsius in the June-September period from 1978 to 2012. Circle points mean a significant increase (p-value<0.05) in the annual number of days with an air temperature higher than 95th percentile at 850 hPa in the June-September period from 1978 to 2012. Triangle points mean that there were no significant changes

When all sites were considered HTD_{20} was higher overall in coastal vs. inland locations (8.8 vs. 5.1 days increase in days over time, p = 0.005), Percent change in HTD_{25} differed between locations, being negative along the coast (-4.4%) and positive inland (+41.6%, p <0.05). Other differences associated with proximity to the Mediterranean coast were not detected. Although significant primarily for political planning, some overall differences among countries were detected. Italy had a higher change in HTD_{95} than Spain (4.1 vs. 2.3 days, p < 0.05), and Spain had a greater relative change in HTD_{25} than Italy (43.3% vs. -25.9%, p<0.05). Greece had more than three times the increase in HTD_{20} than France (9.6 vs. 2.3 days, p <0.05). Regarding $HTD_{22.5}$, there is a difference among Northern locations (points 14 and 28) versus Southern locations (3, 4, 22 and 23) in Spain and Italy. The Southern locations displayed a significant increase (0.3 $HTD_{22.5}$ more per year) in the number of $HTD_{22.5}$.

In higher latitudes, the increase in number of days with an air temperature at 850 hPa higher than 20 ºC and 22.5 ºC was less than in lower latitudes (Figure 4). However, the relative increase in HTD_{20} was significantly larger at higher latitudes (Figure 5), considering only sites where significant temporal changes were evidenced. However, considering 22.5 ºC and 25 ºC thresholds, the relative increase in HTD did not change consistently with latitude. In relation to those days that exceeded the 95th percentile, in higher latitudes there was an increase in both number of days and relative increase in number of days (Figure 4 and 5). In most points included within the study scope, there was an increase in both the number of days in HTD_{20}, $HTD_{22.5}$, and 95th percentile and the relative increase in these categories from 1978-1987 to 2002-2012. The highest relative increases were found in Italy and Greece with values higher than 100%; in other words, more than a doubling in the number of days (Table 2).

Table 2. Increase from 1978-1987 to 2002-2012 decades in both number of days and relative increase in number of days of HTD_{20}, $HTD_{22.5}$, and 95th percentile (June to September period).

Point	Latitude/Longitude	Country	Increase of days / relative increase (%) HTD_{20}	Increase of days / relative increase (%) $HTD_{22.5}$	Increase of days / relative increase (%) HTD 95th percentile
1	37.5º / 352.5º	Portugal	5.3 / 19.1	6.4 / 85.3	3.5 / 85.4
2	37.5º / 355º	Spain	9.2 / 25.5	7.1 / 61.7	1.9 / 40.4
3	37.5º / 357.5º	Spain	14.2 / 31.4	9.7 / 58.1	3.1 / 68.9
4	37.5º / 0º	Spain	13.0 / 25.6	13.3 / 58.6	2.9 / 58
5	40º / 352.5º	Portugal	4.8 / 35.8	3.4 / 178.9	12.8 / 108.8
6	40º / 355º	Spain	4.9 / 32.5	0.9 / 30.0	2.2 / 55
7	40º / 357.5º	Spain	7.5 / 42.9	1.1 / 22.5	1 / 18.9
8	40º / 0º	Spain	12.7 / 62.0	2.8 / 41.8	1.7 / 29.8
9	40º / 2.5º	Spain	14.9 / 68.7	5.1 / 68.9	1.7 / 30.9
10	42.5º / 352.5º	Spain	2.1 / 31.8	0.9 / 75.0	1.9 / 45.2
11	42.5º / 355º	Spain	1.9 / 27.5	1.0 / 71.4	1.8 / 40.9
12	42.5º / 357.5º	Spain	2.9 / 45.3	0.7 / 41.2	2.5 / 54.3
13	42.5º / 0º	Spain	4.0 / 53.3	0.7 / 33.3	3.8 / 84.4
14	42.5º / 2.5º	Spain	6.5 / 94.2	0.4 / 16.7	3.1 / 63.3
15	45º / 0º	France	1.6 / 51.6	0.8 / 88.9	2.4 / 47.1
16	45º / 2.5º	France	2.3 / 74.2	0.7 / 77.8	3.8 / 82.6
17	45º / 5º	France	2.9 / 93.5	0.5 / 83.3	3.7 / 74
18	45º / 7.5º	France	2.4 / 88.9	2.4 / 12.4	4.3 / 91.5
19	37.5º / 12.5º	Italy	4.3 / 10.9	3.0 / 19.6	0.6 / 9.8
20	37.5º / 15º	Italy	3.9 / 11.7	4.4 / 53.0	1.3 / 22.4
21	40º / 10º	Italy	8.3 / 36.7	4.1 / 66.1	2.9 / 53.7
22	40º / 15º	Italy	8.2 / 46.3	4.1 / 107.9	4.6 / 95.8
23	40º / 17.5º	Italy	8.2 / 59.0	-0.2 / -9.5	4.1 / 85.4
24	42.5º / 10º	Italy	7.6 / 97.4	0.5 / 22.7	5.5 / 107.8

25	42.5º / 12.5º	Italy	9.0 / 111.1	1.9 / 111.8	5.3 / 106
26	42.5º / 15º	Italy	8.9 / 127.1	-0.3 / -60	5.4 / 125.6
27	45º / 10º	Italy	1.8 / 66.7	-0.3 / -60	6.4 / 148.8
28	45º / 12.5	Italy	2.2 / 95.6	-0.3 / -75	5.2 / 108.3
29	37.5º / 20º	Greece	6.8 / 34.0	2.9 / 40.3	1.6 / 27.1
30	37.5º / 22.5º	Greece	9.3 / 54.4	2.2 / 34.9	2.2 / 39.3
31	37.5º / 25º	Greece	12.8 / 75.3	3.3 / 61.1	3.3 / 68.8
32	40º / 20º	Greece	9.4 / 94.9	3.0 / 107.1	4.6 / 102.2
33	40º / 22.5º	Greece	10.3 / 143.1	1.8 / 75.0	4.3 / 91.5
34	40º / 25º	Greece	9.1 / 128.2	1.5 / 75.0	4.6 / 97.9

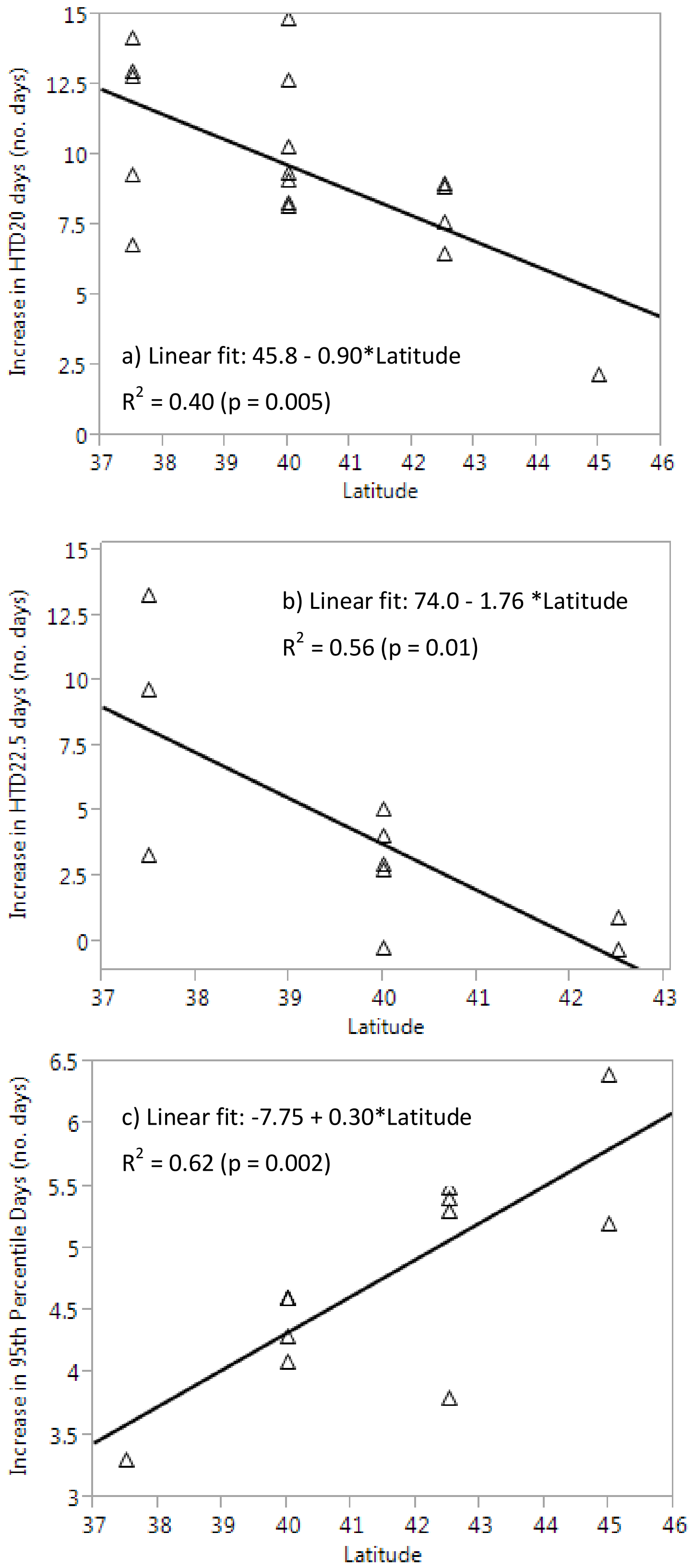

Figure 4. Linear regression showing the relationship between latitude and change in number of days with an air temperature at 850 hPa higher than a) 20 ºC (HTD_{20}), b) 22.5 ºC ($HTD_{22.5}$), and c) the 95th percentile at 850 hPa in the June-September period from 1978 to 2012. The analysis included only sites where significant temporal changes were identified.

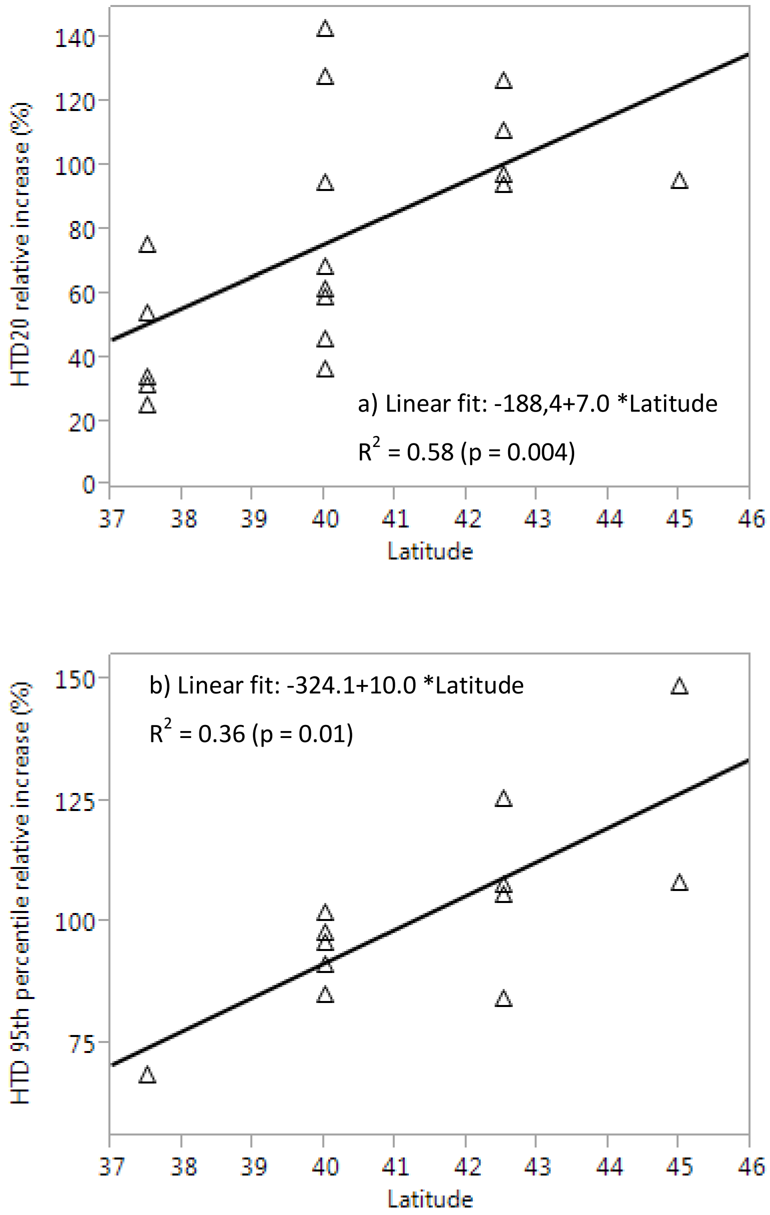

Figure 5. Linear regression testing relationship between latitude and percent change ("relative increase") in number of days with an air temperature at 850 hPa higher than a) 20 ºC (HTD_{20}), b) exceeding the 95th percentile at 850 hPa in the June-September period from 1978 to 2012. Only sites where significant temporal changes were identified were included in the analysis. $HTD_{22.5}$ did not change consistently with latitude.

Discussion

Mean, maximum and minimum temperatures have increased and will likely continue to increase in Southern Europe in the future (Moriondo et al., 2006; IPCC, 2007; Giorgi and Lionello, 2008; Giannakopoulos et al., 2009). Our study showed that there was also a trend towards more frequent HTD in summer (June to September) in Mediterranean coastal areas and in more southerly latitudes across the study area. This is in agreement with other studies on temperature trends, which have been shown to be correlated to wildfire size and occurrence (Cardil et al., 2013; Cardil et al., 2014). Overall, in Southern Europe, most high temperature days are related to the weather system that brings hot dry air masses from North Africa (Rodriguez-Puebla et al., 2010; Pereira et al., 2011). However, we did not find the same HTD trends in NW Iberia, where other reports have documented increased warming of surface temperatures from 1974-2006 (Gomez-Gesteira et al., 2011), or in Interior Spain. It is plausible that air fluxes from North Africa do not reach this area as frequently as in other regions, or that their influence is mitigated by other weather systems associated with Atlantic currents. Some HTD might simply be caused by summer heating in Central Spain (Spanish plateau, 800 m.a.s.l).

Areas with the highest increases in terms of annual number of HTD_{20} (June-September period) were found both in Greece and along the Mediterranean Spanish Coast. These areas are likely to be especially susceptible to the variety of impacts associated with heat-wave episodes, including ecological, social, and economic impacts. While higher latitudes (more northern) sites exhibited a smaller increase in the number of days with $HTD_{22.5}$ and HTD_{20} than lower latitudes, the number of days exceeding the 95th percentile increased with increasing latitude. This finding is corroborated by the higher *relative* increase in HTD 95 and HTD_{20} with latitude. It may be that the affected vegetative, social, and economic systems in the lower latitude sites have already experienced some of the pressures of adapting to, or mitigating, the repercussions of extreme temperatures. It is important to consider the relative increase in extreme temperature days in these higher latitudes, as a greater degree of change usually equates to a higher severity of challenge. Some authors suggest that the consequences of heat waves is closely tied to a culture's prior conditioning and adaptation to climate, including behavior (e.g. siesta on hot afternoons), characteristics of buildings (e.g. exterior sun shades) and communities (orientation of windows away from afternoon sun), and even social attitudes about health risks (Poumadere et al., 2005; deCastro et al., 2011). This suggests that although the absolute increase in extreme temperature days is less severe at the higher latitudes, the relevance of the effects of the change may be greater in more northern populations lacking prior conditioning and adaptation.

In all cases, where HTD 95 increased, additional synergistic repercussions are likely to already be occurring. For example, Diffenbaugh et al. (2007) use downscaled climate model predictions of heat stress in the Mediterranean region to show that increases in 95th percentile maximum temperatures are amplified by a reduction in soil moisture and 2 m relative humidity levels. These changes are relevant to human health, wildfire risk, energy demand, and perpetuity of existing ecological systems.

Implications and Recommendations

Implications of these results are far-ranging and diverse. Previous research shows that human mortality increases when maximum daily temperatures exceed a given threshold (García-Herrera et al., 2005; deCastro et al., 2011). In France alone in 2003, 15,000 excess deaths were attributed to an extreme heat wave (Poumadère et al., 2005). If the annual number of extreme temperature days continues to increase, as suggested by our data, mortality rates could respond similarly in the future. It may be necessary to take preventive measures to reduce these impacts on populations, preventing heat strokes and other heat-related illness. Such measures typically include increased cooling during these periods, which can also result in peak demands for energy consumption.

Energy demand is closely linked to climatic conditions (Giannakopoulos and Psiloglou, 2006). In the Mediterranean region, from mid-May onwards and during the summer period, an increase in air temperature aligns with a rise in energy consumption, mainly due to the wide use of air conditioning elements. It is during these early summer months that our data suggest increased number of HTD will have the greatest impact on energy demands, especially in coastal Mediterranean areas. Higher temperatures in summer are likely to cause a larger peak energy demand and not only an increase on net demand. This may require the development of additional, or more efficient, energy generating capacity.

Frequent heat waves in last decade or so (2000-2012) have also triggered the occurrence of large wildland fires (Mills, 2005; Trigo et al., 2006; Barriopedro et al., 2011; Cardil et al., 2013) in the Euro-Mediterranean region. On hot days, ignition probability is higher and wildland fire behavior is typically more extreme. As a result, fires may be difficult to contain as they exceed the firefighting capabilities (Riaño et al., 2007; Salis et al., 2012; Cardil and Molina, 2013). Recent analysis has shown that high temperatures days account for the majority of area burned in wildfires in some regions in Spain and Italy, where the average daily number of large fires and daily area burned was higher during HTDs than in non-HTDs (Cardil et al., 2013; Cardil et al., 2014). Therefore, if extreme conditions (HTD) are becoming more frequent, as our data suggests, forest fire risk and area burned will most likely increase.

The resilience of forests to disturbance may also be influenced by extreme temperatures. Touchan et al. (2014) analyzed long-term tree chronologies in the eastern Mediterranean to find that growth rates were sensitive to, and negatively related to, summer month temperatures. The trends reported here suggest that, in certain areas, forests have been increasingly stressed by extreme temperatures during the summer months over the last 34 years. Evidence of such stress has been documented in increased climate-linked mortality of forests across Europe (Allen et al., 2010). As summer temperatures continue to increase (Giorgi and Lionello, 2008), and soil moisture contents decrease (Diffenbaugh, 2007), the resilience of forests injured by wildfire may be reduced (e.g. van Mantgem et al., 2013), compounding wildfire impacts and costs to local economies.

Extreme temperature events will also have impacts on industrial sectors with close links to climate, such as agriculture and food security. A diversity of research publications since 2010 show that increased probability of extreme temperatures during the growing period has had deleterious impacts on agriculture

(Gobin et al., 2013). Our data provide quantification of these extreme temperatures, which can be informative for agricultural planning and decision making specifically in each location analyzed.

Risk management should be active in anticipating potential problems and planning to mitigate their consequences, rather than reacting to unfavorable events after they happen. Both structural and non-structural measures are vital to reducing the impact of climate unevenness including extreme weather events (Lobell, 2011). Structural actions include strategies, such as irrigation, water harvesting, creation of fuel breaks and improved wildfire suppression, while the non-structural measures include the practice of medium range weather forecasting and developing new protective infrastructure such as wildfire risk and crop insurance. We hope that the data presented here can be useful for planning for risk reduction across the multiple sectors affected by increases in high temperature days in Europe.

Conclusions

Even though we did not find significant increases in South France, Interior Spain and the Northwestern Iberian Peninsula, the annual number of HTD increased significantly in many areas across Southern Europe including the Spanish Mediterranean Coast, Italy, and Greece. The highest increases in terms of annual number of HTD were found in both Greece and along the Spanish Mediterranean Coast. In these areas, extreme temperature conditions are becoming more frequent now and could become more common in the future. In addition, in areas where temporal increases were detected, relative increases in 95^{th} percentile temperatures were larger at higher latitudes. Where social, infrastructure, and economic systems are not preconditioned to high temperature days and heat waves, the severity of increased temperature effects may be elevated. Heat wave days have been linked to negative impacts in terms of forest fire risk, human health, agriculture, energy demands, and economic repercussions. Adaptive measures should be taken for reducing the negative consequences for human populations and the environment.

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Chapter 2. Extreme temperature conditions and wildland fires in Spain

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Abstract

Extreme temperature events are known to favor large wildland fires. It is expected that fire activity will increase with changing climate. This work analyzes the effects of high temperature days on medium and large fires (those larger than 50 ha) from 1978 to 2010 in Spain. A high temperature day was defined as being when air temperature at 850 hPa was higher than the 95th percentile of air temperature at that elevation from June to September across the years 1978-2010. Temperature at 850 hPa was chosen because it properly characterizes the state of the lower troposphere. The effects of high temperature on forest fires were remarkable and significant in terms of fire number (15 % of total large fires occurred under high temperature days), burned area (25 % of the total burned area occurred under high temperature days). Fire size was also significantly higher under 95th percentile air temperature at 850 hPa and a large part of the largest fires in the past 20 years were under these extreme conditions. Additionally, both burned area and fire number only decreased under non-high temperature days in the study period and not under high temperature conditions.

Keywords: forest fire, temperature, climate change, Spain

Introduction

In the past decade, Europe has experienced a large number of wildland fires that have caused enormous losses in terms of human lives, environmental damage and economic disruptions. Most of the wildland fires in Europe take place in the Mediterranean region that accounts for over 95% in terms of burned area (JRC-IES 2010). Even though fire suppression resources have been enhanced in Spain as in other Mediterranean countries (including France, Italy, Greece and Portugal), the territory was affected by many large wildfires throughout the past 30 years (Marino et al. 2013). Cardil and Molina (2013) identified that neither the number of nor the area burned by large wildland fires decreased from 1995 to 2010 in any Spanish region, despite improved detection, response and suppression capabilities.

Although medium and large wildland fires (LWF, those larger than 50 ha) represent a small percentage of the total number of fires, they account for most of the area burned (Ganteaume and Jappiot 2012; Salis et al. 2013) and have more severe fire behavior (Molina et al. 2010). Fires occurring on days of extreme weather can be exceptionally difficult to suppress, and may surpass the capacities of available resources. This has been noted in several regions as reported by Barriopedro et al. 2011; Cardil et al. 2013;

Mills 2005; Salis et al. 2014 and Trigo et al. 2006 for the cases of Portugal (2003), Greece (2007), Russia (2010), USA (2000, 2006 and 2007), Canada (2004) and Australia (2005, 2006, 2009, 2011, 2012).

A wildland fire is a result of interactions between climate/weather, fuels and people (Flannigan et al. 2009; Trouet et al. 2009). Climate change projections for the Mediterranean Basin suggest an increase in extreme weather events, mainly in the summer season, when longer and more frequent heat waves are expected (Barriopedro et al. 2011; Moriondo et al. 2006). Extreme temperature events have caused negative impacts on forests, agriculture and economic activities (Kuglitsch et al. 2010; Mills, 2005; Trigo et al. 2005) and several heat waves also triggered the occurrence of large wildfires in the Euro-Mediterranean region and around the world (Barriopedro et al. 2011; Cardil et al. 2013; Mills 2005; Trigo et al. 2006). It is expected that fire activity would increase with a changing climate (IPCC 2007; Riaño et al. 2007; Eastaugh and Hasenauer 2014). Therefore, understanding the relationships between weather, climate and fires is important to implement effective fire prevention policies (Bedia et al. 2014), and to forecast fire behavior in the context of climate change.

The temperature of the lower troposphere (at that altitude where air pressure is 850 hectopascals) effectively integrates air temperatures across a broad region. This measure is used by Forest Service Agencies in Spain to analyze past fire weather and to forecast daily potential of fire occurrence and behavior (Cardil et al. 2013; Cardil et al. 2014; Garcia-Ortega et al. 2011; Trigo et al. 2006; Molina et al. 2010). Meteorological Services also use the air temperature at 850 hPa to forecast and show heat waves or the evolution of temperatures over successive days (AEMET, Spanish Meteorological Agency, 2011). Temperature at 850 hPa is sufficiently close to the surface to be representative of ground conditions over relatively large areas and some of the troubles that affect near surface reanalysis variables do not occur (Ogi et al. 2005; Trigo et al. 2004).

Days with high temperature in the lower troposphere (HTD) are usually associated with low moisture content in the fine (< 6mm diameter) components of the litter that makes up the fire fuel (i.e., this value could be lower than 4% in the Mediterranean Coast and lower than 7% in the North Spain). Under those days, ignition probability is higher and fire behavior could be extreme. Therefore, fires can burn rapidly and intensely and originate large and severe wildland fires that surpass firefighting capabilities and may be exceedingly difficult to extinguish (Molina et al. 2010). Cardil et al (2013, 2014) studied this phenomenon in Aragón (Northeastern region of Spain) and Sardinia (Italy) and found clear relationships between HTD and large wildland fires.

Temperature at 850hPa is reasonably predictable at synoptic scales (e.g. SánchezGómez and OrtizBeviá 2003) and so could be a useful means of predicting days of high fire danger at long lead times. This would permit a more efficient allocation of firefighting resources (Prestemon and Donovan 2008), aid in the development of hazard warning systems (Arpaci et al. 2013) and assist with long-term infrastructure planning (Eastaugh and Molina 2011; 2012).

To predict fire conditions under a climate change scenario, it is first necessary to evaluate historical climate and events. In this present work, we have analyzed the recent historical trends in the number of HTD in the whole of Spain to find i) where extreme temperature conditions increased in a significant way from 1978 to 2010 and ii) the areas with a higher number of these days. Also, we analyzed the historical trends of LWF in Spain and their relationships with HTDs and non-HTDs in terms of fire number, burned area, and fire size.

Data and Methods

Study area

Spain has 17 administrative regions (including the Canary and Balearic Islands). Most of the country has a Mediterranean climate with long hot summers and limited rainfall that contribute to increased wildland fire risk. Spain could be broadly divided into three different regions, considering the duration of summer, the intensity of oceanic influence on weather patterns, the intensity and frequency of extreme weather, population density, the amount of fire suppression resources and the annual number of fires (Cardil and Molina 2013; Bardají and Molina 1999). These three regions are (1) Mediterranean coast (Points 2, 3, 7, 8 and 13 in Figure 1), characterized by important sea influence, a long dry summer and high population density, (2) Mediterranean interior (Points 1, 4, 5, 6 and 12), in which the dry summer season is long, sea influence is minimal and air relative humidity is low during the summer without much day to day variability, and (3) North Spain (9, 10 and 11) in which there are more fires than in the other Spanish regions (Bardají and Molina 1999; Pereira et al. 2011) due to social reasons such as the traditional use of fire by farmers and rangeland users. The climate of this region is oceanic with a shorter dry season than other regions of Spain (Bardají and Molina 1999). The Canary Islands are not considered in this study because their location is very far to the south-west of continental Europe and the biogeographic conditions are very different to those of the Mediterranean Basin.

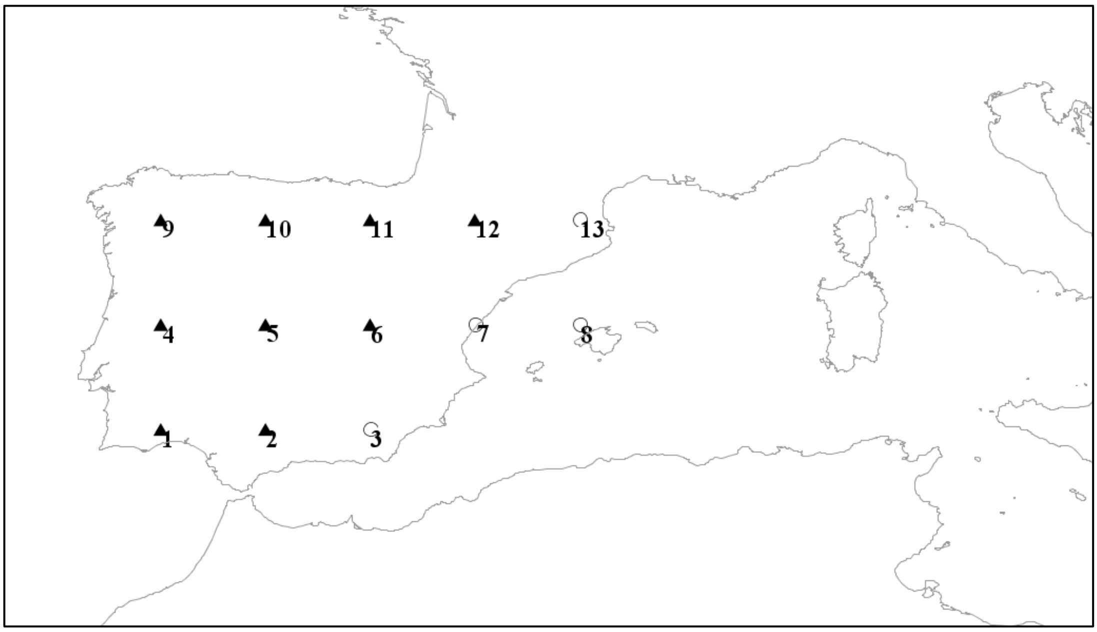

Figure 1. Identification of the NCEP reanalysis points (National Center for Enviormental Prediction) in Spain. Circle points mean a significant increase (p-value<0.05) in the annual number of days with an air temperature higher than 20 ºC at 850 hPa (HTD_{20}) in the June-September period from 1978 to 2010. Triangle points mean that there were no significant changes in terms of annual number of HTD_{20}.

High temperature days

NCEP/NCAR reanalysis data from the National Center for Environmental Prediction and the National Center for Atmospheric Research (Kalnay et al. 1996) were used to characterize high temperature days on a synoptic scale. NCEP outputs are available from 1948 to the present and the horizontal resolution of the data is 2.5º latitude/longitude (Figure 1). Daily air temperature data at the 850 hPa pressure level at midnight 00:00 UTC were analyzed to assess the influence of high lower troposphere temperatures on LWF throughout Spain from 1978 to 2010. We used here 13 reanalysis data points located across the Spanish landmass.

Medium and Large wildland fires

Historical wildland fire data from the Wildland Fire National Statistics (EGIF) of the Spanish Ministry of Environment and Rural and Marine Affairs were analyzed. This database includes the Wildland Fire Reports sent to the Ministry by both Fire-Fighting and Forest Services of the regions. It has an entry for each fire, regardless of size, and contains the same fields of information for each fire. We selected wildland fires larger than 50 ha (LWF) for the period of 1978-2010 because they were responsible for 85 to 95 % of the total area burned (depending on the region). Although the database includes fires smaller than 50ha and has records back to 1968 the comprehensiveness of the data for small fires is questionable for years before 1978 (Cardil and Molina 2013), as is common in historical natural disaster datasets (Eastaugh and Vacik 2012; Kron et al. 2012).

Analysis

We analyzed trends in relation to the annual number of HTD and their effects on LWF. We defined a high temperature day as one when air temperature at 850 hPa was higher or equal than the 95^{th} percentile of that temperature for each point individually in the June-September period from 1978 to 2010. The use of the 95% percentile helps capture the different implications of temperature extremes for human health, energy systems, natural vegetation and environmental disturbances in different locations. For example, in the northern section of the study area, where mean temperatures are generally lower, a temperature above 20 ºC would exceed the 95^{th} percentile, while the same temperature would be nearly five degrees below the 95^{th} percentile in the southern latitudes.

Additionally, we used several categories considering different levels of temperature to assess if warm and extreme temperature days increased in the study period: (1) HTD_{20}, those days with an air temperature higher than 20 ºC at 850 hPa, (2) $HTD_{22.5,}$ those days with an air temperature higher than 22.5 ºC at 850 hPa and, (3) $HTD_{25,}$ those days with an air temperature higher than 25 ºC at 850 hPa. The lower limit of 20 ºC of air temperature at 850 hPa was chosen because it can produce high temperatures at the surface and low relative humidity in the territory and is clearly associated with heat waves in many Spanish areas (Cardil et al. 2013; Montserrat 1998).

We analyzed the trends of the annual number of HTD, fire number and fire area burned and the differences in fire number, fire area burned and fire size under HTD and non-HTD for different areas in Spain, using a linear regression analysis. Results are tabulated showing the direction of significant trends, and a cumulative fraction plot is presented to compare fire size and frequency patterns for the periods 1978-1987 and 1988–2010 for both HTD and non-HTD.

Due to the lack of information on soil and fuel humidity on the EGIF database, they are not addressed explicitly. HTDs could influence wildland fires differently depending on the previous humidity content (sometimes related to seasonality, ie., early summer vs late summer).

Results

High temperature days

The number of HTD (sensu the 95^{th} percentile of air temperature at 850 hPa) was higher in the 2001-2010 period than in the 1978-1987 period across all study points. However, only in Point 12 was this increase statistically significant. 95^{th} percentile temperatures range from 20.57 ºC (Point 9) to 25.14 ºC (Point 3).

The annual number of HTD_{20}, $HTD_{22.5}$, HTD_{25} differed by region. The points with the most of these days are located along the Mediterranean Spanish Coast (Figure 2), in the South and South East (Points 2 and 3). The same results were obtained in relation to the 95th percentile in terms of temperature during the June-September period from 1978 to 2010.

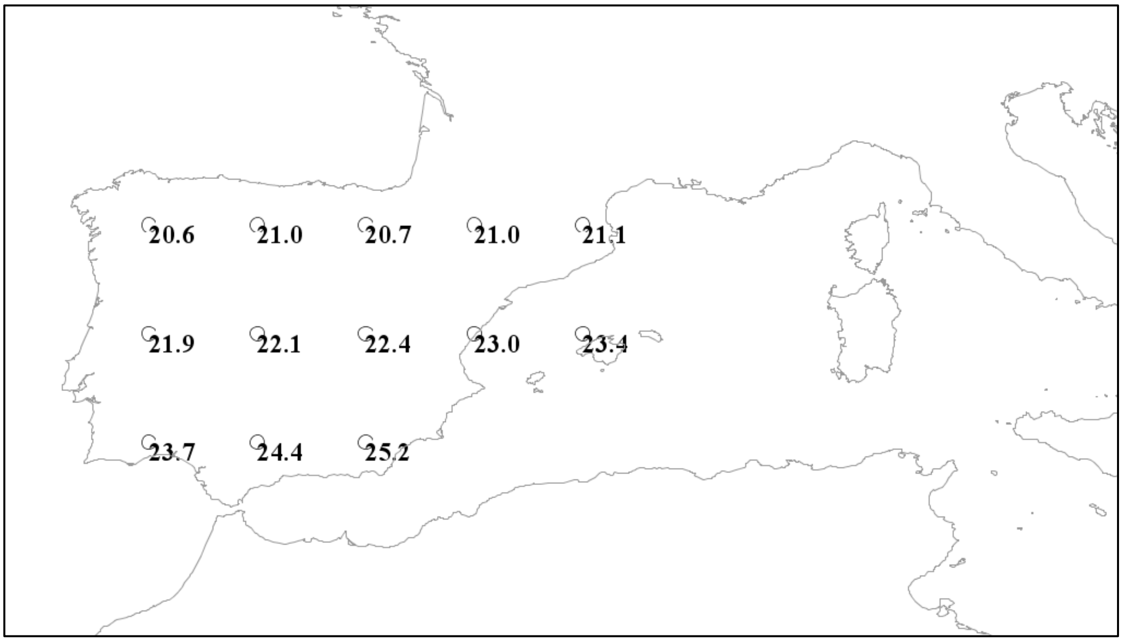

Figure 2. 95th percentile of daily air temperature data at the 850 hPa pressure level at midnight 00:00 UTC in degrees Celsius in the June-September period from 1978 to 2010.

Trends in terms of annual number of HTD_{p95}, HTD_{20}, $HTD_{22.5}$ are shown in Table 1 and the 95th percentile for all analyzed points is displayed in Figure 2. A significant increase in the annual number of HTD_{20} was found in locations around the Mediterranean Spanish Coast, for example from a mean of 6.3 in 1978-1987 to 10.6 in 2001-2010 for Point 13. However, in the other parts of Spain, the annual number of HTD did not change significantly at any analyzed temperature threshold. Regarding $HTD_{22.5}$, there is a difference between Northern locations (Point 13) with a mean of 2.4 to Southern locations (Point 3) with 7.6 hot days on average in the summer period. The Southern locations display a significant increase in the number of $HTD_{22.5}$ (0.3 more per year in the most extreme case, Point 3). The increase in terms of annual number of HTD_{20} in Mediterranean Spanish Coast was around 0.5 per year in the most extreme case, Point 3. No significant trends were found at any point in the HTD_{25} category mainly due to the low number of these days.

Table 1.Simple linear regression analysis of significant trends in annual number of HTD_{p95}, HTD_{20}, $HTD_{22.5}$, over time in the study area (Mediterranean coast, MC; Mediterranean interior, MI; North Spain, NS) during the June-September period from 1978 to 2010. Point locations are mapped in Figure 1.Only positive significant trends were found.

Point	Region	Latitude/Longitude	(P values) and / **slope coefficients**		
			HTD_{p95}	HTD_{20}	$HTD_{22.5}$
1	MI	37.5º / 352.5º	n.s (0.370) / **0.057**	n.s (0.480) / **0.111**	n.s (0.090) / **0.156**
2	MC	37.5º / 355º	n.s (0.646)/ **0.031**	n.s (0.107) / **0.295**	n.s (0.083) / **0.199**
3	MC	37.5º / 357.5º	n.s (0.182)/ **0.103**	+ (0.009)/ **0.525**	+ (0.029)/ **0.344**
4	MI	40º / 352.5º	n.s (0.552) / **0.048**	n.s (0.354) / **0.118**	n.s (0.375) / **0.054**
5	MI	40º / 355º	n.s (0.651) / **0.028**	n.s (0.296) / **0.115**	n.s (0.836) / **-0.012**
6	MI	40º / 357.5º	n.s (0.893) / **0.008**	n.s (0.072) / **0.248**	n.s (0.884) / **0.009**
7	MC	40º / 0º	n.s (0.278) / **0.084**	+ (0.003) / **0.484**	n.s (0.173) / **0.118**
8	MC	40º / 2.5º	n.s (0.238) / **0.094**	+ (0.001) / **0.600**	+ (0.018) / **0.222**
9	NS	42.5º / 352.5º	n.s (0.878) / **0.011**	n.s (0.870) / **0.015**	n.s (0.963) / **0.002**
10	NS	42.5º / 355º	n.s (0.684) / **0.032**	n.s (0.710) / **0.032**	n.s (0.805) / **0.011**
11	NS	42.5º / 357.5º	n.s (0.381) / **0.067**	n.s (0.273) / **0.092**	n.s (0.550) / **0.020**
12	MI	42.5º / 0º	+ (0.044) / **0.139**	n.s (0.078) / **0.147**	n.s (0.251) / **0.038**
13	MC	42.5º / 2.5º	n.s (0.058) / **0.131**	+ (0.010) / **0.246**	n.s (0.486) / **0.025**

+ significantly increased; - significantly decreased; n.s. not significant. Critical p-value:0.05; n.s.: not significant. Values in parenthesis are the P statistic

Large fires

LWF number

A significant decrease in the total number of LWF in the whole of Spain was found. Considering only LWF under non-HTDs, the number of LWF also decreased. However, under HTDs, we did not find a decrease (Figure 3).

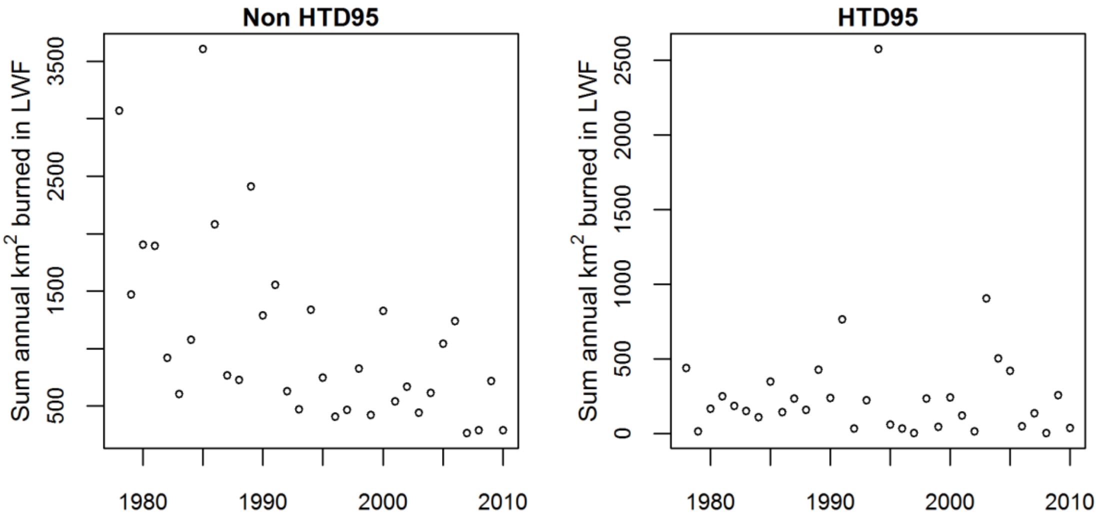

Figure 3. Pattern of annual area burned in Spain from 1978 to 2010 under high temperature days (HTD) and non-high temperature days (non-HTD).

Analyzing all chosen NCEP points in Spain individually, similar results were obtained (Table 2). Apart from Point 6, all points showed a significant decrease in the total number of LWF and those occurring under non-HTDs. However, the number of LWF under HTDs did not significantly decrease for any point, except Point 2.

The percentage of LWF events under HTD conditions in relation to the total number of LWF ranged from 6.1 to 17.5 %. Points located in Northern Spain had a lower percentage of LWF developed on HTDs (Points 9, 10 and 11). However, points located on the Mediterranean Coast had higher values (Points 3, 7 and 13). Additionally, the number of LWF per HTD is significantly higher than the number of LWF per non-HTD (Table 2). It is relevant to highlight that 45% of fires larger than 5,000 ha in the 1994-2010 period occurred in the Mediterranean Coast region where HTDs increased significantly (Figure 4).

Table 2. Trends in total number of fires (LWF), those under HTD and non-HTD in Spain from June to September in the 1978-2010period

Point	Region	(P values) and / **slope coefficients (number/year)**			LWF number under HTD as percentage of total fires (%)	LWF number per HTD	LWF number per non-HTD
		Total	HTD	Non-HTD			
1	MI	– (0.026) / **–0.49**	n.s (0.963)	– (0.009) / **–0.49**	13.7	0.32	0.11
2	MC	– (0.001) / **–1.70**	– (0.031) / **–0.23**	– (<0.001) / **–1.46**	11.4	0.70	0.29
3	MC	– (0.002) / **–0.90**	n.s (0.380)	– (0.002) / **–0.83**	14.0	0.46	0.15
4	MI	– (0.004) / **–1.15**	n.s (0.782)	– (0.002) / **–1.13**	12.6	0.53	0.20
5	MI	– (0.007) / **–1.54**	n.s (0.423)	– (0.003) / **–1.44**	13.3	0.97	0.35
6	MI	n.s(0.803)	n.s (0.468)	n.s(0.581)	17.5	0.39	0.10
7	MC	– (<0.001) / **–2.16**	n.s (0.494)	– (<0.001) / **–2.13**	8	0.36	0.23
8	MC	– (<0.001) / **–0.25**	n.s (0.210)	– (<0.001) / **–0.22**	10.3	0.07	0.03
9	NS	– (<0.001) / **–12.51**	n.s (0.065)	– (<0.001) / **–11.310.76**	10.0	4.32	2.13
10	NS	– (0.007) / **–2.13**	n.s (0.616)	– (<0.001) / **–2.08**	6.1	0.76	0.64
11	NS	– (0.007) / **–0.66**	n.s (0.885)	– (0.006) / **–0.65**	6.8	0.35	0.25
12	MI	– (0.020) / **–0.40**	n.s (0.855)	– (0.005) / **–0.41**	17.4	0.31	0.08
13	MC	– (0.006) / **–1.00**	n.s (0.243)	– (0.005) / **–0.89**	17.2	0.40	0.11

+ significantly increased; - significantly decreased; n.s. not significant. Critical p-value:0.05; n.s.: not significant. Values in parenthesis are the P statistic

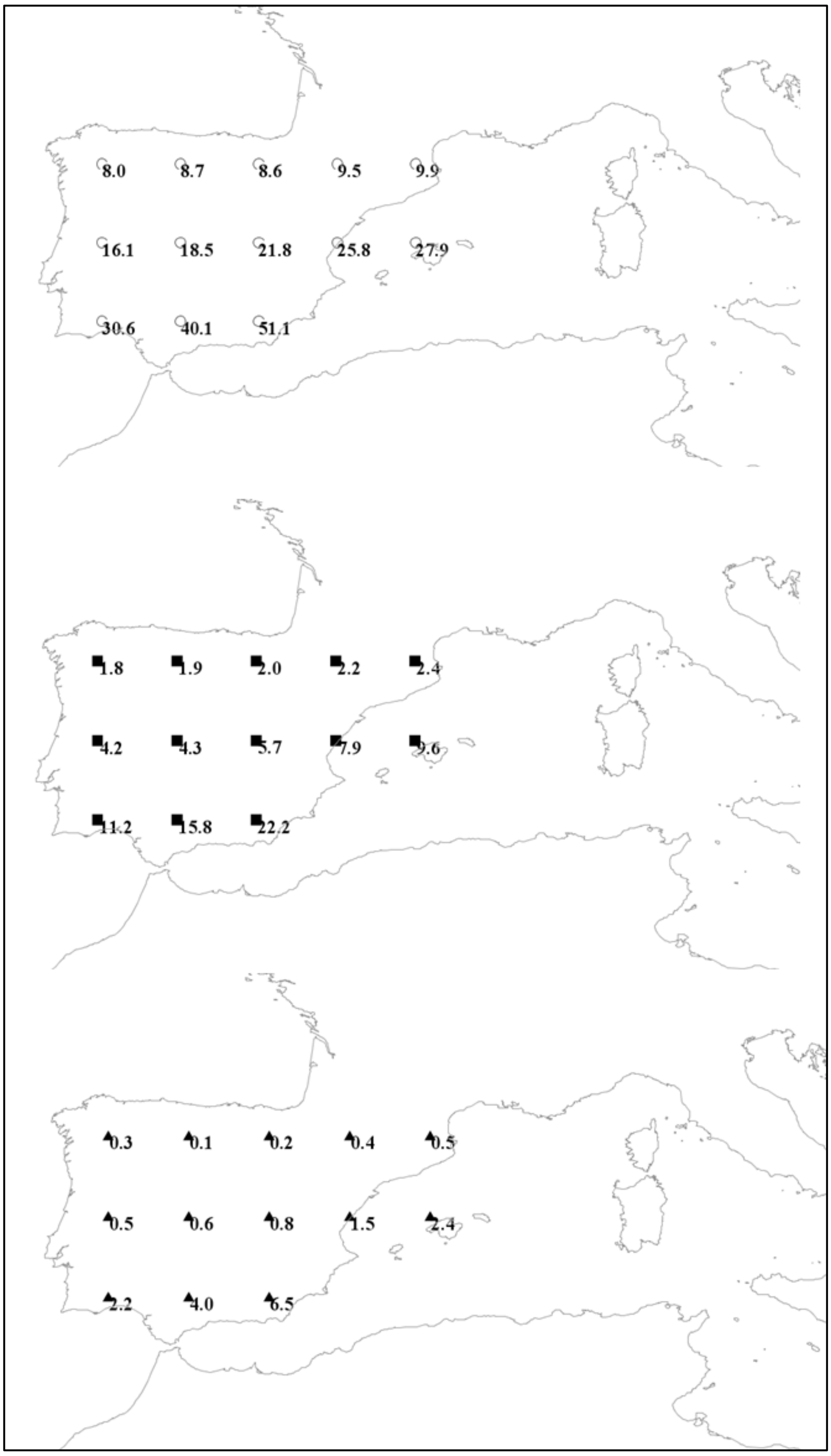

Figure 4. Mean annual number of days with an air temperature higher than 20 ºC (circle points), 22.5 ºC (square points) and 25 ºC (triangle points) at 850 hPa in the June-September period from 1978 to 2010.

LWF burned area

At the National scale we found a significant decrease in terms of burned area for all fires and also in those fires occurring under non-HTD conditions. Considering the burned area on HTDs, we did not find a significant decrease (Figure 3).

For most points on non-HTDs a significant decrease was found in terms of burned area (only points 1, 6 and 13 did not display a decrease). In all points except Point 2, no significant decreases were obtained under HTD conditions. Considering the total area burned in each point, we did not find a significant decrease (Table 3).

The percentage of LWF burned area under HTDs in relation to the total burned area of LWF varied between 7.8 and 38.2 %. Lower values are in Northern Spain (Points 9, 10 and 11) and higher values in the Mediterranean Coast (Points 2, 3, 7 and 13). LWF burned area per HTD is significantly higher than LWF burned area per non-HTD (Table 3).

Table 3. Trends in the total burned area by large wildland fires (LWF), those under HTD and non-HTD in Spain from June to September in 1978-2010 period

Point	Region	(P values) and / **slope coefficients (hectares/year)**			LWF burned area under HTD as percentage of total fires (%)	LWF burned area per HTD (ha)	LWF burned area per non-HTD (ha)
		Total	HTD	Non-HTD			
1	MI	n.s (0.777)	n.s (0.426)	n.s (0.069)	38.2	294.5	26.1
2	MC	– (<0.001) / **–537**	– (<0.005) / **–95**	– (<0.001) / **–441**	16.2	213.8	60.5
3	MC	n.s (0.333)	n.s (0.993)	– (0.012) / **–187**	37.1	409.9	38.2
4	MI	n.s (0.065)	n.s (0.589)	– (0.003) / **–388**	26.6	344.9	52.1
5	MI	n.s (0.066)	n.s (0.704)	– (0.011) / **–480**	20.9	396.3	82.3
6	MI	n.s (0.624)	n.s (0.511)	n.s (0.290)	25.8	181.2	28.5
7	MC	n.s (0.140)	n.s (0.945)	– (<0.001) / **–1096**	27.2	846.1	124.3
8	MC	– (0.003) / **–49**	n.s (0.370)	– (0.001) / **–43**	13.6	172	7.1
9	NS	– (0.019) / **–1702**	n.s (0.096)	– (0.017) / **–1489**	11.0	791.9	351.3
10	NS	– (0.002) / **–505**	n.s (0.229)	– (0.002) / **–465**	9.8	181.7	91.2

11	NS	– (0.008) / **–160**	n.s (0.916)	– (0.008) / **–159**	7.8	59.5	38.5
12	MI	n.s (0.316)	n.s (0.712)	– (0.043) / **–107**	35.1	196.9	19.9
13	MC	n.s (0.238)	n.s (0.705)	n.s (0.185)	31.0	384.5	48.9

+ significantly increased; - significantly decreased; n.s. not significant. Critical p-value:0.05; n.s.: not significant. Values in parenthesis are the P statistic

LWF size

HTDs influence fire size very significantly considering all LWF in the whole of Spain (p-value<0.001). Average fire size (of fires larger than 50 ha) was 441.3 ha under HTDs and 216.3 ha under non-HTDs. Considering wildland fires larger than 5000 ha, 63 % of the total burned area happened to occur under HTDs. For fires larger than 1,000 ha, this percentage was 35 %.

The number of fires larger than 5,000 ha increased in the study period under HTDs. These fires (under HTDs) were more frequent in the past 20 years (Figure 5). The largest fires (>5,000 ha) occurred under this type of condition, 29 of 44 fires occurred under HTDs in the 1990-2010 period.

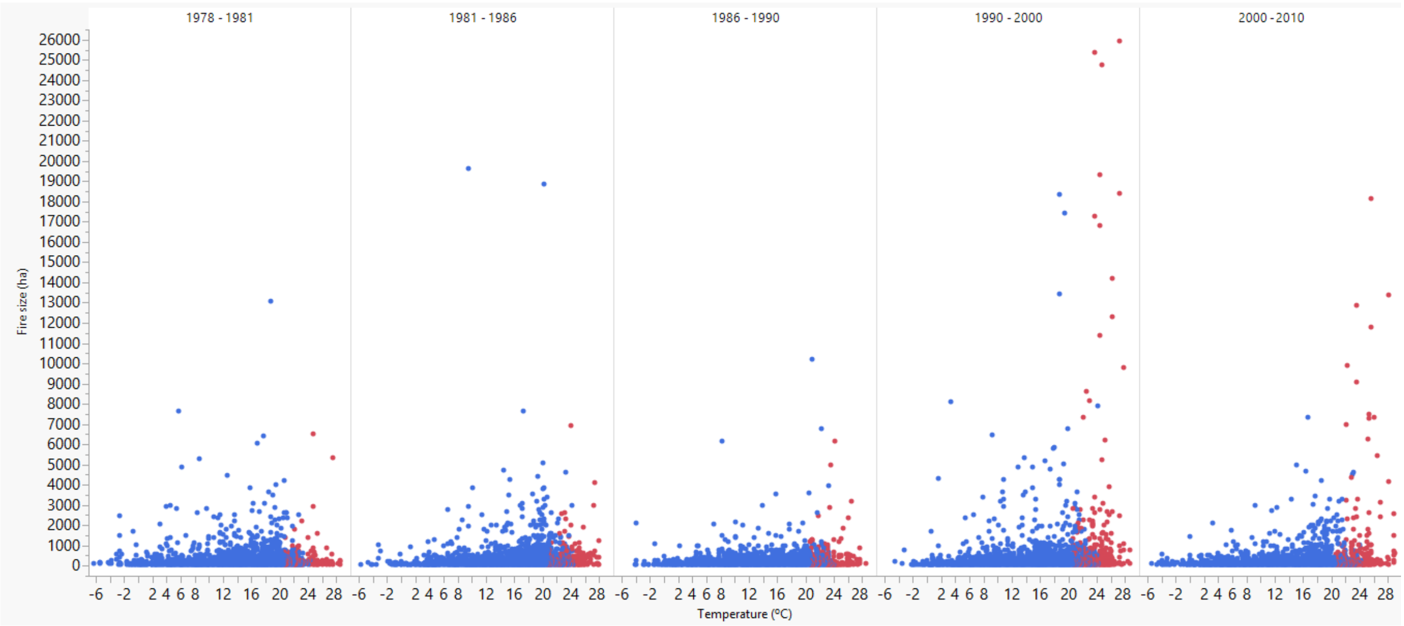

Figure 5 Relationship between fire size (ha) and temperature (ºC) in the study period. Blue points occurred under non-HTD. Red points mean fires under HTD

The difference between early fires (before 1988) and later fires (1988-2010) were analyzed, and also how HTDs / non HTDs affect them. We display fire size data as a cumulative fraction plot, with separate curves for 1978-1987 and 1988-2010 for HTDs and non-HTDs (Figure 6). There is no significant difference in the non-HTDs curves, but the difference on HTDs days is significant (Kolmogorov-Smirnov test).

Regarding HTDs, not much difference below about 300 hectares, but then the 1988-2010 line seems to lean over to the right, which means a higher likelihood of larger fires. In the period 1978-1987, only 4% of the fires were larger than 1000 hectares. However, from 1988 to 2010 they made up almost 10%. Regarding non-HTDs, 100% of the fires were below about 20,000 hectares, 80% below about 220, 40% below 100 hectares and so on. Both curves are graphically very similar (Figure 6).

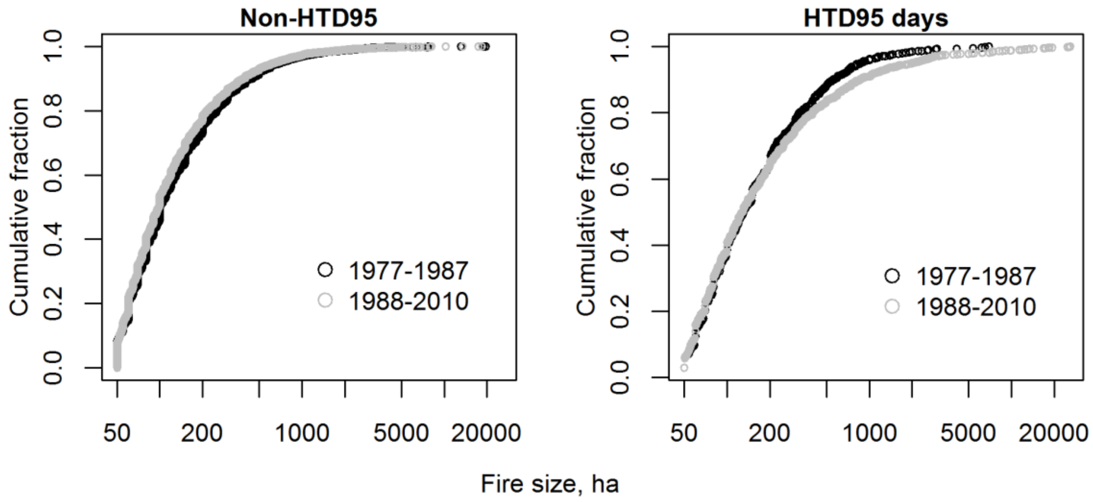

Figure 6. Cumulative fraction plot of number of fires, with separate curves for 1978-1987 and 1988-2010 under non-high temperature conditions (non-HTD) and high temperature conditions (HTD)

Discussion

Whereas it is accepted that the major determinants in fire weather forecasting are low humidity, high temperatures, and strong winds near the ground surface, meteorological indexes developed to evaluate temporal and spatial changes in meteorological conditions are not frequently used or available for all fire weather forecast agencies (Charney and Keyser 2010; Crimmins 2006). It is often not clear which surface-based indices may be most appropriate (Eastaugh et al. 2012) and it is difficult to find a single index that performs uniformly well across large heterogeneous areas (Padilla and Vega-Garcia 2011; Arpaci et al. 2013). For these reasons, we highlight the significance of discerning between HTD and non-HTD defined by the 850hPa synoptic conditions in developing pre-suppression efforts to prepare for large fires. It would be extremely useful to be able to distinguished the simply ‘bad’ and ‘very bad’ (extreme temperature) fire days with some reasonable lead time (i.e., 24 or 48 hours) to plan best strategies for suppression assets and to predict extreme fire behavior. We found in this work that this classification concerning HTD and non-HTD (at 850 hPa) can be used for that discrimination. The 850 hPa pressure level is representative of the Earth’s surface at broad spatial scales and has the potential to identify unusually severe fire weather events (Garcia-Ortega et al. 2011).

In our study, the number of HTD (number of days with an air temperature equal or higher than the 95th percentile air temperature in June-September period from 1978-2010) did not change significantly throughout the study period. However, we observed higher values in the number of HTD in the period 2001-2010 than 1978-1987. We also evaluated trends considering three air temperature thresholds (20, 22.5 and 25 ºC at 850 hPa) that provide warm and extreme temperature conditions. Significant increases were found on the Mediterranean Coast in the 20 ºC and 22.5 ºC classes. Many studies have recognized that mean, maximum and minimum temperatures have increased and will increase in the next years in Southern Europe (Arca et al. 2012; IPCC 2007; Moriondo et al. 2006; Regato 2008). Giannakopoulos et al. (2009) studied possible differences in two periods (from 1961-1990 to 2031-2060) in terms of number of hot days (days with T_{max}>30ºC on the surface) and heat-wave days (T_{max}>35ºC) in the Mediterranean basin. In some of those areas, (e.g. central Spain, Northern Italy) an increase in the occurrence of hot days and heat waves is expected, adding up to1-3 additional weeks per year. Therefore, HTD will become more frequent and they will determine a significant decrease in air humidity and fuel moisture (Cardil et al. 2013; Moreno 2005) and an increase in the potential for extreme fire behaviour. Most HTD in Spain are related to the weather regime that brings hot dry air masses from North Africa (Rodriguez-Puebla et al. 2010; Garcia-Ortega et al. 2011). Additionally, agricultural abandonment is the main cause of an increased fuel load, but wildland fuel homogeneity and continuity are also major facilitators of both a fast fire propagation and a higher fire line intensity (Vega-García and Chuvieco 2006). This could increase large wildland fire frequency and fire size.

The total annual number of LWF and the annual number of LWF occurring under non-HTD decreased for the majority of the analyzed points. Nevertheless, the annual number of LWF under HTD did not change in the same time span. Similar results were obtained in relation to the burned area. This circumstance could be explained through more efficient modern fire control activity due to significant investments in fire suppression technology and training in recent years. Fires occurring on HTDs however are difficult to contain even with modern methods, and hence no reduction in their number or severity was found. HTD also influenced mean fire size of LWF.

We highlight here a remarkable result of our analysis: the high proportion of area burned under HTD. On only 5 % of days in the summer season (June-September inclusive in 1978-2010 period) characterized by HTD conditions, in some regions fires burned around 40 % of the total burned area. This occurred mainly in the Mediterranean Coastal region. In North Spain, we did not find values so high. This could be related to the higher number of ignitions in the Northern Spain and suppression means cannot deal with all simultaneous ignitions in a single day being a HTD or non-HTD. This work shows that HTDs are critical for both fuel managers and firefighters because they could increase in the future and, most likely, fires spreading under HTD will propagate faster and further.

The majority of the largest historical fires (>5,000 ha) in Spain occurred under extreme HTD conditions, as for instance in 1994, 2006 and 2009 and they are more frequent in the most recent 20 years. Regarding HTD, in the period 1977-1987, only 4% of the fires were larger than 1000 hectares. However, from 1988 to 2010 they made up almost 10%. 45% of fires larger than 5,000 ha in the 1994-2010 period occurred in the Mediterranean Coast region where HTDs increased significantly. Additionally, both the number of LWF and LWF area burned per HTD are significantly higher than in non-HTDs (Table 2). This supports the statement that HTDs provide more extreme conditions for fire propagation and increase the difficulty of controlling those fires. This could be a challenge in the future.

Conclusions

Even though the sum of money invested in suppression assets increased across the studied period, neither the number of fires nor the area burned diminished under high temperature days, although a decrease of both indicators was detected under non-HTD. In the 4-month summer season 1978-2010, although only 5 % of days are characterized by HTD conditions, fires on these days account for around 25 % of the total burned area in Spain. They were 15 % of the total number of fires.

The classification of HTD and non-HTD (at 850 hPa) can be used for identifying those days that can cause more difficulties in fire suppression and to better distribute (spatially and temporally) the available resources. In addition to this, the number of HTD has been predicted to increase in future years in many studies. This could worsen the fire risk scenario. Therefore, forecasting HTD with reasonable lead time is critical for both fuel managers and firefighters in order to implement more efficient fire control strategies and tactics.

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Chapter 3. Trends in adverse weather patterns and large wildland fires in Aragón (NE Spain) from 1978 to 2010

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Abstract

This work analyzes the effects of high temperature days on large wildland fires during 1978–2010 in Aragón (NE Spain). A high temperature day was established when air temperature was higher than 20 ºC at 850 hPa. Temperature at 850 hPa was chosen because it properly characterizes the low troposphere state, and some of the problems that affect surface reanalysis do not occur. High temperature days were analyzed from April to October in the study period, and the number of these extreme days increased significantly. This temporal trend implied more frequent adverse weather conditions in later years that could facilitate extreme fire behavior. The effects of those high temperatures days in large wildland fire patterns have been increasingly important in the last years of the series.

Introduction

Mediterranean countries like Spain have numerous wildland fires each year (Pereira et al., 2011). Fire has always been part of the traditional Mediterranean agrarian land management, occasionally developing into unwanted fires (Millán et al., 1998). However, over the past 30 yr wildland fires have become more extreme, with fire behavior more and more often exceeding firefighting capabilities (Miralles et al., 2010; Molina et al., 2010), and fire agencies experience difficulties in suppressing extreme-behavior fires while providing safety for both firefighters and citizens, as reviewed in Werth et al. (2011). The social and physical/biological environment has changed dramatically, and wildfires constitute nowadays one of the problems that consistently obtain more attention from the media in summer. Agricultural abandonment is the main cause of an increased fuel load (Millán et al., 1998), but wildland fuel homogeneity and continuity are also major facilitators of both a fast fire propagation and a higher fire line intensity (Molina et al., 2010; Vega-García and Chuvieco, 2006). In addition, climate and weather are two of the main factors influencing fire regime (Trouet et al., 2009), and climate change could have an important impact on ecosystems due to increases in area burned and fire intensity/severity (Flannigan et al., 2000). Regato (2008) showed that climate change could provide an increase in the intensity and frequency of summer heat waves (short periods with very hot days, very low air humidity and frequently with strong winds) that increase the probability of large wildland fire (LWF).

Typically, just a few LWFs cause the majority of the damage (Alvarado et al., 1998; Ganteaume and Jappiot, 2012) because they account for a very high percentage of the total burned area (Stocks et al., 2003), and their severity is normally higher. In these LWF events fire behavior is often extreme, making suppression difficult. Therefore, LWFs affect our ecosystems, human safety and properties to the utmost (Alvarado et al., 1998) and also demand vast resources to suppress them.

It is essential to know what factors influence LWFs. We have focused on days with high temperatures (HTDs) to assess their potential impact on the development of LWFs. Previous works indicate that HTDs might provide more extreme weather conditions (Montserrat, 1998), which have an important role in forest fire behavior (Crimmins, 2006). Hot days decrease fuel moisture and increase the ignition probability and, as a result of that influence, other aspects such as longer flame length, most likely involving crown fire activity and spotting activity (long distance ignition by convection processes). Therefore, HTD has the potential to increase the probability of having a LWF. In a similar way, Mills (2005) indicates that unusually strong temperature gradients at 850 hPa (which usually stands for a level around 1500m up in the atmosphere) may have the potential to identify unusually severe fire weather events. It would be extremely profitable to be able to discriminate between the simply "bad" and the "disastrous" fire days with some reasonable lead time (i.e., 24 or 48 h).

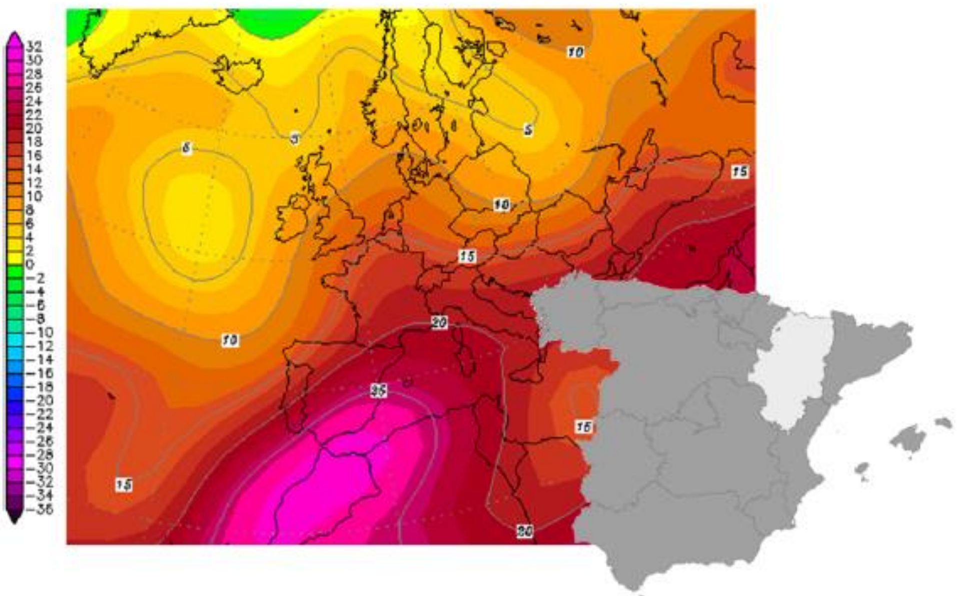

Fig. 1. Geographic location of Aragón and air temperature at 850 hPa (legend in ºC) for 2 July 1994. Source: www.wetterzentrale.de

The five largest LWFs on record in Aragón did develop under HTDs. In addition, those HTDs were extreme. The largest fire in Aragón affected 16 832 ha in Villarluengo (Teruel) on 2 July 1994, and air temperature at 850 hPa and at 00:00 UTC in the Aragón region was higher than 22.5 ºC (Fig. 1), during the day of the fire and also on the two previous days. In this case, the synoptic weather pattern that caused the HTD was a hot air mass inlet (south advection from the Sahara desert).

The exploration for underlying causes and visible patterns of LWFs is instrumental to plan best strategies for our suppression resources and to foresee extreme fire behavior. In this study, we have analyzed HTDs in the Spanish region of Aragón and their relationship to the LWF official records both in terms of amount and cumulative area burned and number of LWFs in HTDs versus non-HTDs.

Methods

Study area

Aragón is the fourth largest region in Spain (47, 719 km^2) and is located in the northeastern part of the country (Fig. 1). The region has 1.34 million inhabitants, comprises the provinces of Huesca, Teruel and Zaragoza, and it is politically divided in 33 counties. Aragón has a high altitudinal gradient that generates several ecosystems in the region. There is a major river (Ebro) bordered by two mountain chains: the Pyrenees (maximum altitude 3404 m, Aneto) and the Iberian System (maximum altitude 2314 m, Moncayo). The climate in Aragón can be generally regarded as a Mediterranean climate with continental nuances, but the irregular topography influences it and generates local climate variability. The environment varies from the high mountains of the north-central Pyrenees, with perpetual ice (glaciers) to the steppe or semidesert areas, such as Monegros, and intense continental climate in other areas. The mean annual temperature ranges from 22.5 ºC in the Ebro valley to 5 ºC in the highest areas of Pyrenees, and the average annual rainfalls also ranges from 1800mmin the highest mountains to 300mmin the valley (AEMET, 2012). The vegetation is conditioned by relief and climate. In upland forests there are several tree species (pine, fir, beech, oak), shrubs and meadows. In the Ebro valley, oak and juniper trees are the most common and there are degraded areas covered by shrubs and grasslands. Aragón has high ecological value with several protected wilderness areas.

High temperature days

In order to characterize the high temperature days, reanalysis data from the National Centers for Environmental Prediction (NCEP) were used (Kalnay et al., 1996). We analyzed daily air temperature maps (850 hPa at 00:00 UTC) to assess whether there was a HTD condition in the territory. Air temperature at 850 hPa is the air temperature at an altitude in the atmosphere where pressure is 850 hPa (around 1500m up in the atmosphere). The 850 hPa air temperature daily maps were available at Wetterzentrale (2013). We established that there was a HTD when air temperature at 850 hPa was equal to or higher than 20 ºC in at least two-thirds of the Aragón region. We chose the temperature at 850 hPa because it is generally used to analyze past fire weather and fire weather forecasts (Mill´an et al., 1998; Garcia-Ortega et al., 2011; Trigo et al., 2006). It provides a regional coverage as well because it is sufficiently close to the surface to be representative of the low troposphere state, and it avoids some of the problems that affect near-surface reanalysis variables (Trigo et al., 2005; Ogi et al., 2005). An air temperature at 850 hPa equal to or higher than 20 ºC is associated with heat waves, and this condition provides high temperatures in surface and low relative humidity in the territory (Montserrat, 1998).

Weather conditions were characterized every day from 1978 to 2010 in the fire season from April to October (included). We analyzed the number of HTDs and the duration and frequency of the high temperature (HT) phenomena as a proxy for potential fire behavior. We defined “HT periods” as the number of uninterrupted times that a HTD occurred.

Large wildland fires

Large wildland fires (LWFs) are defined in this work as those over 100 ha threshold (Moreno et al., 2011; De Zea Bermudez et al., 2009). In order to understand the interactions between HTD and LWF in the study period (1978–2010) in Aragón, we processed the historical fire data records from Spain’s EGIF database (General Statistics on Wildland Fires; see www.magrama.gob.es, accessed last time on 30 October 2012), which includes the wildland fire reports sent to the Ministry of the Environment by the firefighting and forest management services of all the Spanish regions. This database has an entry from each fire, regardless of size, and contains the same fields of information for each fire. The first years of the database (1968–1977) were not used in this study because the area burned on private properties were usually underreported in those years because the Forest Service mandate was to suppress only on state-owned or state-controlled forest but not privately owned lands (Antonio Muñoz, Forest Service, personal communication). Many fires smaller than 100 ha in the database most likely burned a larger area (maybe more than 100 ha) because foresters did not account for the area of burnt private land. Therefore, there are missing 100 ha+ fires prior to 1977. We have analyzed trends in the number of LWFs, LWF area burned and average LWF size under both HTDs and non-HTDs.

In the study period, there were 193 wildland fires in Aragón larger than 100 ha that burned 132 000 ha approximately. All of them affected forest and agricultural areas, roads and people. For instance, the four forest fires that occurred on 22 July 2009 in Teruel (the Aliaga, Alloza, Cedrillas and Corbal´an fires) burned about 10 000 ha in total.

Statistical analysis

The relationship between HTDs and LWFs was assessed in the period up to two days immediately before LWF occurrence date, and analyzed according to the following four HTD classes:

– Class A: LWFs that start on a HTD (day 0), HTD (day 1) and HTD (day 2), therefore, LWFs under a very strong HT period.

– Class B: LWFs that start on a HTD (day 0), HTD (day 1) and non-HTD (day 2), therefore, LWFs under a strong HT period.

– Class C: LWFs that start on a HTD (day 0), non-HTD (day 1) and HTD or non-HTD (day 2), therefore, LWFs under a weak HT period.

– Class D: LWFs that start on a non-HTD (day 0), HTD or non-HTD (day 1) and HTD or non-HTD (day 2). Therefore, they were fires with minor influence of HT conditions.

Only two days before all LWFs have been used in this analysis. Several days before each LWF were analyzed (5 days), but they did not influence the results, and previous days (day 3, day 4 and day 5) did not supply more information than HT classes used (above). We evaluated the influence of HTD on LWF on three consecutive days by using an ANOVA analysis and group comparison with the Fisher method with a 95% confidence interval.

We also quantified how many LWFs were conditioned by HTDs (only on the day that the fires started), and we summarized statistics in the studied period. We established the number of LWFs, burned area swept by them, the average size and percentage of LWFs under HTDs and non-HTDs.

We determined if there were significant changes (decrease, increase, no difference) in the studied variables (number of LWFs, area burned by LWFs and number of HTDs) from 1978 to 2010 with a linear regression analysis on annual raw data. The annual variability in fire occurrences is high, both in terms of large fire frequencies and their burned areas (Stocks et al., 2003). This variability is caused by diverse environmental factors, such as human influence (Mollicone et al., 2006) and climate (Gillett et al., 2004). For this reason, we added the evolution in time of the variables with the moving average method in order to obtain a better display in the figures. This smoothing technique was applied to mitigate the effect due to year to year random variation. This practice, when properly applied, reveals more clearly the underlyin trend (Legendre and Legendre, 1998). “The method calculates successive arithmetic averages over 2m+1 contiguous data as one moves along the data series” (Legendre and Legendre, 1998). In this study, we used simple moving average with seven-year periods (m=3).

Results

HTD trends

The annual number of HTDs increased in the study period significantly (p value= 0.020). It rose from 8 HTDs in 1981 to 15 in 2006 in terms of seven-year average values, as shown in Fig. 2. The number of HT periods also increased (p value= 0.022). Therefore, in recent years, we have more periods influenced by HTD phenomena. However, the average duration of HT periods did not change in the study period with an average duration of 2.2 days.

The majority of HTD events took place in mid-summer (July and August) with more than 80% of the total. June has 11.5% of days and September 5.8 %. In April, there were no HTDs; in October, there was only one HTD in the studied period. June had a significant increase in the number of HTDs from 0.7 days in 1981 to 2.7 in 2006 in terms of seven-year average. In July, August and September, no significant trends were observed.

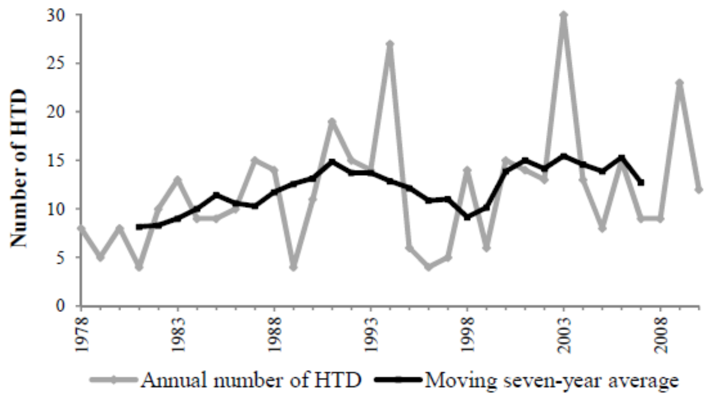

Fig. 2. Annual number of high temperature days (HTDs) (light grey line) in Aragón from 1978 to 2010 and moving seven-year average (black line) from 1981 to 2007.

Large wildland fires

A decrease in the total annual number of LWFs was observed in Aragón during the study period (p-value=0.003). It diminished from 12 LWFs in 1981 to 3 LWFs in 2007 in terms of seven-year average values. The annual number of LWFs under non-HTDs also decreased significantly (p-value<0.001). It diminished from 8 LWFs in 1981 to 2 LWFs in 2007 in terms of seven year average values. By contrast, the annual number of LWFs under HTDs did not decrease in the study period. Neither total annual area burned nor annual area burned under HTDs changed in the study period. Nevertheless, a significant decrease was found in the annual area burned under non-HTDs. It decreased from 2,204 ha in 1981 to 780 ha in 2007 in terms of seven-year average values.

Table 1. Trends in annual number of large wildland fires (LWFs), annual area burned, and annual number of high temperature days (HTDs) in Aragón from 1978 to 2010

Variable	Total	HTD	Non-HTD
Number of LWFs	– (0.003)	n.s (0.411)	– (<0.001)
Area burned	n.s (0.968)	n.s (0.590)	– (0.014)
HTD	+ (<0.020)		

+ significantly increased; - significantly decreased at P<0.05; n.s. not significant. Values in parenthesis are the P statistic

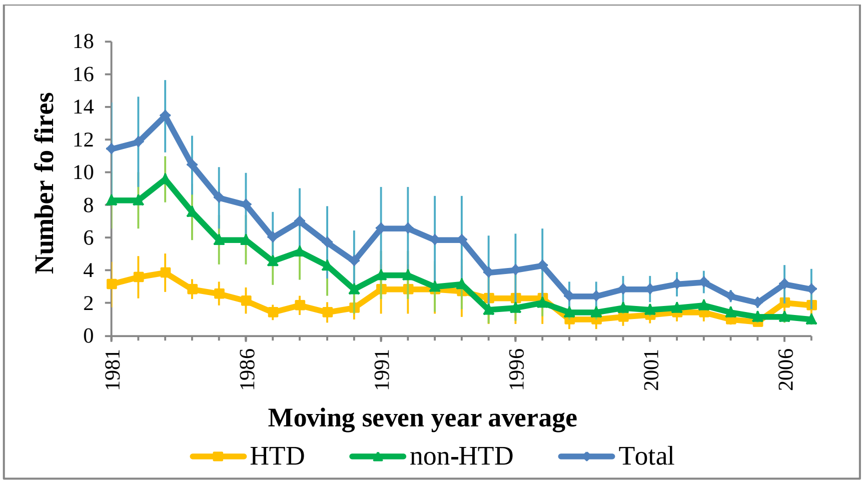

Fig 3. Number of large wildland fires in Aragón under high temperature days (HTDs), non high temperature days (non-HTDs) and total number of large wildland fires (LWFs) in Aragón from 1978 to 2010. Moving seven-year average from 1981 to 2007. Vertical lines are the annual standard error values.

HTDs also influence the average LWF size, and HTD classes explain the variable average size of the LWFs (p=0.003). Table 1 lists the number of LWFs, area burned and average size of LWFs in each HTD class (1978 – 2010). The HTD class comparison analysis shows that there was a significant difference between both A and B classes and D class. Average LWF size in D class was a third of those in both A and B classes (Table 2). No significant difference between class C and other classes can be established.

We split the study period in two intervals (1978 – 1993 and 1994 – 2010) because in 1994 there were LWFs with an extreme behavior under very strong HTD conditions. The average LWF size increased significantly between 1978 – 1993 and 1994 – 2010 periods (424 ha vs. 1275 ha) (p-value=0.001). Additionally, the average LWF size under HTDs is significantly larger in the 1994 – 2010 period (1923 ha) than in the 1978 – 1993 period (590 ha) (p-value=0.024). However, the average LWF size under non-HTDs did not change between two periods (389 ha). In the first interval (1978 – 1993), the majority of LWF were under D class with 5.59 LWF and 1,987 ha burned per year. In the second interval (1994 – 2010), the results changed significantly and the annual number of LWFs was 1.69 and the annual area burned was 858 ha (Table 2). By contrast, in HTD classes (A, B and C) neither annual number of LWFs nor annual area burned decrease between the two time intervals, and the annual area burned was higher in 1994 – 2010 interval in both A and B classes and the percentage of LWF number under HTD versus total LWF number was 54.2 % and the area burned was 81.7 %. Additionally, in the 1994 – 2010 period, most of the surface (76%) was burned by LWFs under A and B classes (in which HTD conditions were strong or very strong). The HTD influence in LWF increased in Aragón in the study period as shown in Fig. 4 with two ratios that indicate that most LWFs took place nowadays under HTDs and that was not the case in the 1980s and 1990s. The ratio of LWF number under HTDs versus total number of LWFs increased in the study period (Fig. 3) from 0.28 in 1981 to 0.65 in 2007. The ratio of LWF area burned under HTDs versus total area burned also increased from 0.45 in 1981 to 0.82 in 2007 (Fig. 4). The values of these ratios are in seven-year average.

Table 2. Number of large wildland fires (LWFs), area burned and average size in high temperature (HT) classes in Aragón from 1978 to 2010.

Classes	Number of fires[1]	Area burned[1] (ha)	Average size[2] (ha)	Annual number of fires[3] 1978 – 1993	Annual number of fires[3] 1994 – 2010	Annual area burned[3] (ha) 1978 – 1993	Annual area burned[3] (ha) 1994 – 2010
A	25	35,311	1,412 ± 699	0.82 ± 0.29	0.69 ± 0.25	462 ± 122	1,716 ± 1,087
B	26	34,388	1,323 ± 419	0.53 ± 0.22	1.06 ± 0.24	291± 182	1,840 ± 919
C	20	14,913	746 ± 423	0.94 ± 0.47	0.25 ± 0.06	604 ± 390	291 ± 66
D	122	47,502	389 ± 49	5.59 ± 1.21	1.69 ± 0.39	1,987 ± 437	858 ± 251
Total	193	132,114	685 ± 115	7.88 ± 1.67	3.69 ± 1.04	3,344 ± 756	4,704 ± 2,156

[1] Absolute values in the study period, [2] Mean and standard error (σ/√n) values over the period, [3] Annual mean and standard error (σ/√n) values

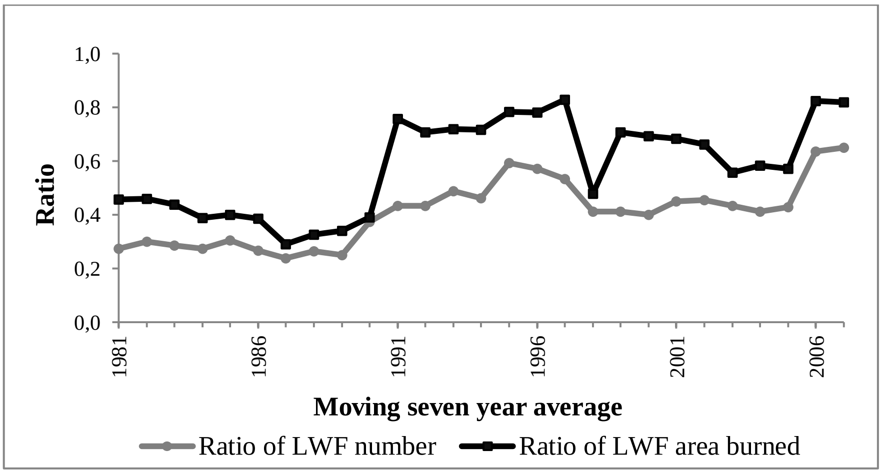

Fig 4. Ratio of LWF area burned under HTDs versus total area burned and ratio of LWF number under HTDs versus total number of LWFs in Aragón from 1978 to 2010. Moving seven-year average from 1981 to 2007.

In terms of area burned by LWFs, the worst years of the series were 1994 and 2009 with 32,600 ha and 21,925 ha respectively. More than 90 % of the total burned area (in these two years) was burned under HTD conditions. These years also have a very high annual number of HTDs, 27 HTDs in 1994 and 23 in 2009. Moreover, the largest fires in Aragón did spread in this HTD conditions.

Discussion

While it is recognized that the major elements for fire weather forecasts are low humidity, high temperatures, and strong winds near the ground, meteorological indexes planned to evaluate temporal and spatial dissimilarities in those elements are not frequently used or available by all fire weather forecast agencies (Charney and Keyser 2010; Crimmins 2006). For that very reason, we highlight the importance of discerning between HTD and non-HTD defined by 850 hPa synoptic conditions in planning pre-suppression efforts to stand up to large fires.

An increase was found in the number of HTDs in the study period, and this agrees with Rodriguez-Puebla et al. (2010). The main source of this increase might be related to the weather regime that brings hot dry air masses from the north of Africa (Rodriguez-Puebla et al. 2010). Different authors suggested that this increase might be linked to an increase of temperature in northeastern Spain due to climate change (Moreno, 2005, Giannakopoulos et al. 2009, and Kettunen et al. 2007). Giannakopoulos et al. (2009) suggested that the number of hot days (Tmax>30ºC) and heat wave days (Tmax>35ºC) will increase in Spain. Giannakopoulos et al. (2009) estimate that there will be 1 to 3 additional hot weeks per year. The mean annual temperature will increase, with greatest warm-up rate in Southern Europe (Moreno 2005; Castro, Martín-Vide and Alonso 2005; Kettunen et al. 2007). Van Wagner and Pickett (1985) remarked that the fire weather Index will increase in summer (i. e., increasing fire risk). Therefore, if HTD become more frequent and these conditions are able to decrease air humidity and fuel moisture and increase the fire behavior potential, we may be facing larger wildland fires in the future, and very likely extreme-behavior fires beyond suppression capacity (Molina et al. 2010). We also found that in the last years of the series there were more days under HT conditions in June. This may be translated as an increase in fire season length.

Both the total annual number of LWFs and the annual number of LWFs under non-HTDs decreased in Aragón from 1978 to 2010. Nevertheless, the annual number of LWFs under HTDs did not decrease in the same period. The total annual area burned did not decrease due to the area burned by LWF under HTD. However, a decrease in the annual area burned under non-HTD conditions was observed. Additionally the percentage of both LWF occurrence and area swept by LWFs under HTDs also increased. Three main reasons could explain this. First, the number of HTDs was greater at the end of the time series, and it is more likely to have a LWF under HTDs. Second, in the last years, fire suppression resources have improved in technology and training, and, therefore, LWF under non-HTD are suppressed more efficiently because the fuel moisture content is higher. Fires under HTDs have lower fuel moisture content and can propagate faster and with higher fire line intensity. Third, HTDs are more prone to have simultaneous fire events (LWFs or smaller fires) that split suppression resources.

The average LWF size in all fires increased in the study period (from 424 ha in 1978 – 1993 period to 1275 ha in 1994 – 2010 period), and this could be related to the major percentage of LWFs under HTDs in the last years of the series because the average LWF size in both A and B classes was larger than LWsF in non-HT conditions or weak HT conditions (class C and D). The fact that average LWF size increased under HTDs, when resources were better organized and trained than ever, reinforces the importance of these HT conditions and their influence on both total and average size per LWF in the period 1994 – 2010. The largest historical fires in Aragón happened under extreme HTDs in both 1994 and 2009. This supports the statement that HTDs provide more extreme conditions for fire propagation and more difficulties to suppress those fires. This has also occurred in other countries (Trigo et al., 2006; Mills, 2005), such as Russia (2010), Portugal (2003), Australia (different years), Greece (2007) and USA (2011, 2012).

Conclusions

There are significant effects of HTD conditions in the number of LWFs, total LWF area burned, and average LWF size in Aragón. As a result, if in the future the number of HTD conditions increases, fire suppression will be compromised. This is likely to happen because our study shows that the incidence of both the number of HTD and HT periods has increased significantly in the study period.

It would be extremely profitable to be able to discriminate between the simply “bad” and the “very bad” or “terrible” fire days with some reasonable lead time (i.e., 24 or 48 hours). We suggest that this classification regarding HTDs and non-HTDs (at 850 hPa) be used for that discrimination.

In terms of burned area, a decrease was observed only in annual area burned under non-HTDs. Total area burn is stable. This may indicate greater fire damage as more area is burned under HTDs.

Most HTD are in July and August (82% of total). However, June is becoming more active in HTDs lately. This indicates an earlier, longer fire season.

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Chapter 4. Large wildland fires and extreme temperatures in Sardinia (Italy)

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Abstract

Heat-wave events are commonly recognized as adverse impacts on agriculture, forests, and economic activities. Several studies showed that future climate changes in the western Mediterranean Basin will lead to an increase in extreme weather events, mainly in the summer season. For this reason, it is crucial to improve our knowledge and investigate the effects of extreme temperature events on wildland fire activity. This work analyses the relation between high temperature days (air temperature higher than 25ºC at 850hPa) and large wildland fires in Sardinia (Italy) during 1991-2009 period and the influence of high temperature days on large wildland fires was remarkable. The results showed that neither the number of fires nor the area burned decreased under high temperature days, although a decrease of both indicators was observed on the other days. Additionally, the average size of fires, the probability of large fire occurrence, the daily area burned and daily number of fires resulted higher in high temperature days.

Keywords: Wildfires, temperature, extreme, weather

Introduction

Heat-wave days cause adverse impacts on forests, and economic activities (Kuglitsch et al. 2010, Mills 2005, Trigo et al. 2006). In addition, they play a key role on human health and death (García-Herrera et al. 2005). The last 13 years (2000-2012) were characterized by frequent heat waves, which often triggered the occurrence of large wildfires (Barriopedro et al. 2011, Mills 2005, National Interagency Fire Center 2013, Trigo et al. 2006) in the Euro-Mediterranean region (Italy and Greece, 2007; Portugal, 2003 and 2005; Spain, 2006 and 2009) and overall the world (Australia, 1983 and 2009; Canada, 2004; Russia, 2010; USA, 2000, 2006 and 2007). In hot days, usually associated with very low fine dead fuel moisture content, the ignition probability is higher and wildland fire behavior could be extreme (i.e., increasing flame length, rate of spread, crown fire activity, and spotting activity). Therefore, fires can burn rapidly and intensely and originate large and severe wildland fires difficult to extinguish, exceeding the firefighting capabilities (Molina et al. 2010, Salis et al. 2012b).

Climate change projections for the western Mediterranean Basin show a greater variability in weather conditions and an increase in extreme weather events, mainly in the summer season, when longer and more frequent heat waves are expected to happen (Arca et al. 2012, Barriopedro et al. 2011, Moriondo et al. 2006, Regato 2008). This will result in an increase in wildfire activity (Arca et al. 2012, Flannigan et al. 2000, IPCC 2007, Riaño et al. 2007). For this reason, it is crucial to investigate the effects of temperature extreme events on fire activity and large wildland fires.

We chose the island of Sardinia, Italy, as case study for our analysis. Sardinia is a fire prone area that every year experiences thousands of wildfires (Arca et al. 2007, Pereira et al. 2011, Salis et al. 2012a) and some of them were very large fires as Bonorva's fire (23 July 2009, 9500 ha burned) and Nuoro's fire (23-25 July 2007, 9150 ha burned). Wildand fires larger than 100 ha (LWF) represent a small percentage of the total number of fires but account for most of the area burned and cause the most of damage (Ganteaume & Jappiot 2012, Salis et al. 2012a, Stocks et al. 2003) with more severe fire behavior (Molina et al. 2010).

In this work, we assessed the historical relationship between HTD and LWF in Sardinia, Italy. High temperature days were defined as those days in which the 850 hPa air temperature was equal or higher than 25ºC in at least two-thirds of North and South Sardinia. The 850 hPa pressure level is representative of the Earth surface and has the potential to identify unusually severe fire weather events (Mills 2005) and it is generally used by Forest Services to analyze past fire weather and to forecast daily potential fire occurrence and behavior (Garcia-Ortega et al. 2011, Trigo et al. 2006). We analyzed the historical trends of LWF and HTD in North and South Sardinia from 1991 to 2009 and their relationships in terms of fire number, burned area, and mean fire size. We also assessed the probability of having LWFs in HTD and the role of other factors (wind speed and number of ignitions) influencing LWF occurrence and burned area in HTD. Finally, we analyzed the differences between North and South Sardinia considering fire number, burned area and mean fire size.

Methods

Study area

Sardinia, Italy, is a large island in the Mediterranean Sea (Figure 1) (24,235 km2) located between 38º51´N and 41º15´N latitude and 8º8´E and 9º50´E longitude. The territory includes eight administrative provinces and a population of about 1.7 million inhabitants. In this work, we identified two reference areas (Figure 1): Northern Sardinia (including Sassari, Olbia-Tempo, and Nuoro provinces) and Southern Sardinia (including Oristano, Ogliastra, Cagliari, Medio-Campidano, and Carbonia-Iglesias provinces). In a preliminary analysis of fire size data (larger fires in the northern part) and the number of high temperature days (higher number in the southern part) showed a marked difference between north and south Sardinia and for these reasons, the island was divided in two parts.

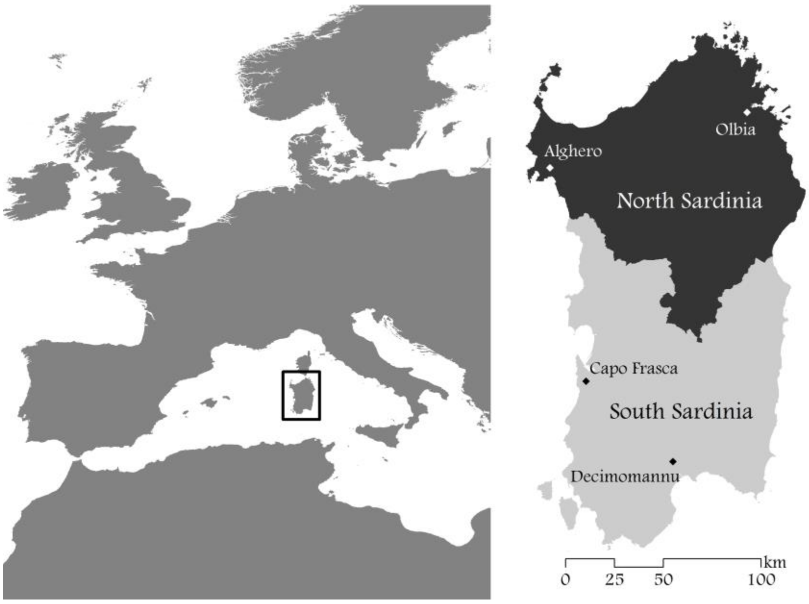

Figure 1. Geographic location of Sardinia (Italy) and northern and southern parts of the island

Overall, the island has a complex topography with hills and low mountains (Ricotta et al. 2012). The average elevation of the island is 338 m a.s.l. and the highest point is Punta la Marmora with1834 m a.s.l. in the center of the island.

The flora includes 2407 taxonomic species, with 10% of endemic species (De Angelis et al. 2012). Large areas of the island are covered by scrub and/or herbaceous vegetation associations (about 35% in the north and 36% in the south), comprised primarily of Pistacia lentiscus L., Arbutus unedo L., Erica arborea L., Myrtus communis L., Olea europea L., Phyllirea spp., Juniperus spp. and Cistus spp. (Salis et al. 2012a). Woodlands and forest area is approximately 23% in the north and 17% in the south of Sardinia with the main tree species being Quercus ilex L., Q. suber L., Q. pubescens Willd., and Q. congesta Presl. Pine plantations with Pinus pinea L. and P. halepensis Mill. only spread over 3% of the island and are mainly concentrated along the coast (Salis et al. 2012a). Pastures and agricultural lands represent about 36% in the north and 39% in the south while the urban areas cover 3% of the island.

The climate is classified as Mediterranean, with dry hot summers and an important water deficit from May to September (Chessa & Delitala 1997). The mean annual temperature ranges from 17.8 ºC in the Southern coast to 12.8 ºC in the mountainous areas. Maximum temperature peaks are higher than 30.8 ºC during the summer season. Average annual rainfall is 1300 mm in the mountains, but slightly less than 500 mm in the coast, and most of the annual rainfall occurs in fall and winter.

Fire data

We used the historical fire data records from the Sardinian Forest Service (CFVA - Corpo Forestale e di Vigilanza Ambientale) from 1991 to 2009 in North and South Sardinia. The CFVA database has an entry for each wildfire ignition and provides information on date, municipality and location of the ignition, and area burned. On average, in the last years (1995-2009) Sardinia experienced approximately 2,500 fires per year and about 17,000 ha burned per year. Wildfires are typically concentrated from June to September, with the maximum of both ignitions and area burned in July (Salis et al. 2012a). Therefore, this work was focused on the June-September period. Similar to elsewhere in Euro-Mediterranean ecosystems (Molina et al. 2010), a few large wildland fires account for most of the burned area (Salis et al. 2012a). For instance, in Sardinia, fires larger than 100 ha accounted approximately for 60% of the total area burned. In the studied period, fires larger than 100 hectares were 806 and the area burned about 290,000 ha. We analyzed large wildland fires considering three different size classes: wildland fires larger than 100 ha (LWF100), 500 ha (LWF500), and 1000 ha (LWF1000).

High temperature days (HTD)

Reanalysis data from the National Centers for Environmental Prediction (Kalnay et al. 1996) were used to characterize the high temperature days on a synoptic scale. Daily air temperature maps at 850 hPa pressure level were analyzed to assess the influence of high temperatures on LWF for both north and south Sardinia from 1991 to 2009. We defined high temperature days when the 850 hPa air temperature was equal or higher than 25ºC at 00:00 UTC in at least two-thirds of both parts of Sardinia. Reversely, we defined as non-HTD those days characterized by 850 hPa temperature lower than 25°C at 00Z in the period June-September. The 850 hPa air temperature was chosen as reference for several reasons. First, it is generally used by Forest Services to analyze past fire weather and to forecast daily potential fire occurrence and behavior (Garcia-Ortega et al. 2011, Trigo et al. 2006). Second, it is sufficiently close to the surface to be representative of it, while some of the problems that affect near surface reanalysis variables do not occur (Ogi et al. 2005, Trigo et al. 2006, Trigo et al. 2005). Third, it provides a regional coverage of air temperature. A temperature equal or higher than 25ºC at 850 hPa is commonly associated to heat waves (Montserrat 1998) and this condition is responsible of high temperatures at ground level in the territory, as occurred in Portugal in the summer of 2003 (Trigo et al. 2006) or in Russia (2010). Furthermore, we analyzed duration and frequency of HTD, and we used HTD as a proxy for the potential occurrence of fires larger than 100 ha.

Statistical analysis

We analyzed the number of HTD, LWF number and area burned for Northern and Southern parts of Sardinia using the ANOVA analysis and considering the normalized values of (1) annual area burned by LWF for 1 x 106 ha and (2) annual number of LWF for 1 x 106 ha.

We analyzed the trends of number of HTD, LWF number and area burned and the differences in LWF number, LWF area burned and LWF size under HTD and non-HTD.

To investigate the relationship between HTD and large fires, we defined the following indicators: (1) number of HTD with at least one LWF with respect to the total HTD (%), (2) normalized LWF average number per HTD with LWF, (3) normalized LWF average area burned per HTD with LWF, and (4) area burned by LWF under HTD with respect to the total area burned by LWF (%). To evaluate significantly differences between HTD and other days, we calculated the same indicators considering non-HTD. The number of days classified as HTD or non-HTD was calculated in the June-September time frame because the HTD were concentrated in these months, and about all LWF were observed in those four months (Salis et al. 2012, Trigo et al. 2006).

We also evaluated the influences of some explanatory variables on LWF. First, we calculated the number of fire ignitions for each HTD and the differences in ignition number considering days with and without LWF to understand how much the number of ignitions was associated to the occurrence of LWF in these extreme days. Second, we collected daily average wind speed data from several weather stations of the island to evaluate how wind velocity influenced HTD with or without LWF. We used four weather stations (Alghero and Olbia for north Sardinia, Capo Frasca and Decimomannu for south Sardinia). The weather data of these weather stations are available at www.tutiempo.net. Fire data were coupled with the closest weather station (among the above mentioned ones) to the fire ignition point.

Results

The average annual number of HTD in the Southern part of the island (3.73 HTD per year) was significant higher (p-value = 0.033) than in the Northern part (1.84 HTD per year). A not significant trend was observed in relation to the annual number of HTD in the study period in both north and south Sardinia (Table 1).

Table 1. Normalized average annual large wildland fire (LWF) number, normalized average LWF area burned, average LWF size and average annual number of high temperature days (HTD) and standard error in north and south Sardinia, from 1991 to 2009. The trend analysis for all variables in the time frame is also reported.

		North				South			
Indicator	LWF class	Normalized average annual LWF number	Normalized average annual LWF area burned (ha)	Average LWF size (ha)	Average annual HTD number	Normalized average annual LWF number	Normalized average annual LWF area burned (ha)	Average LWF size (ha)	Average annual HTD number
Average Value	LWF$_{100}$	16.2 ± 3.8	7,553 ± 1,977	465 ± 54	1.84	18.7 ± 3.5	5,121 ± 1093	273 ± 19	3.73
	LWF$_{500}$	3.1± 0.9	4,811± 1,492	1,551± 243		2.1 ± 0.5	1,924 ± 604	927± 135	
	LWF$_{1000}$	1.2± 0.5	3,426 ± 1,224	2,790± 541		0.42 ± 0.2	852 ± 439	2,013± 554	
Trends	LWF$_{100}$	- (0.035)	n.s (0.30)	n.s	n.s (0.865)	- (0.028)	n.s (0.08)	n.s	n.s (0.269)
	LWF$_{500}$	n.s (0.17)	n.s (0.61)	n.s		n.s (0.23)	n.s (0.32)	n.s	
	LWF$_{1000}$	n.s (0.24)	n.s (0.84)	n.s		n.s (0.45)	n.s (0.43)	n.s	

+ significantly increased at P<0.05; - significantly decreased at P<0.05; n.s. not significant. Values in parenthesis are the P statistic

The normalized annual number of LWF100 in Northern Sardinia was 16.2 fires per 106 ha of wildlands and the normalized average annual area burned was 7553 ha per 106 ha of wildlands, while in the south there were respectively 18.7 LWF100 and 5121 ha burned. However, there were not significant differences in both LWF100 number (p-value = 0.604) and area burned (p-value = 0.299) between the two areas. In north Sardinia, the total number of LWF100 calculated as five-year average decreased significantly along time from 38 to 10 fires (p-value=0.035) and in south Sardinia from 44 to 14 fires (p-value=0.028) (Table 1 and Figure 2). The number of LWF100 under non-HTD also decreased in both Northern and Southern parts of Sardinia, but the number of LWF100 under HTD did not decrease in the study period (Table 2). In terms of burned area, we observed a decrease in the burned area under non-HTD in the two parts of the island for LWF100 (Table 2). Figure 3 displays the LWF burned area in both north and south Sardinia.

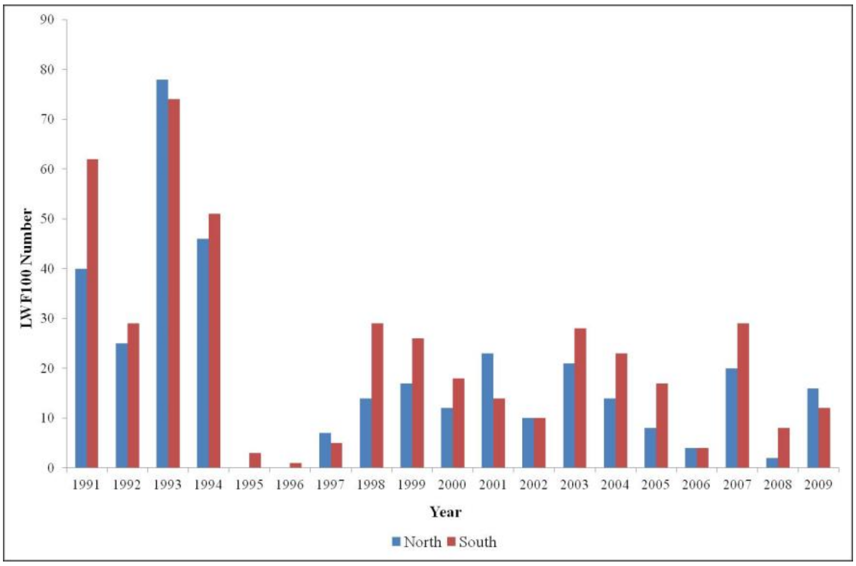

Figure 2. Large wildland fire number (100ha+) in north and south Sardinia from 1991 to 2009 (June-September)

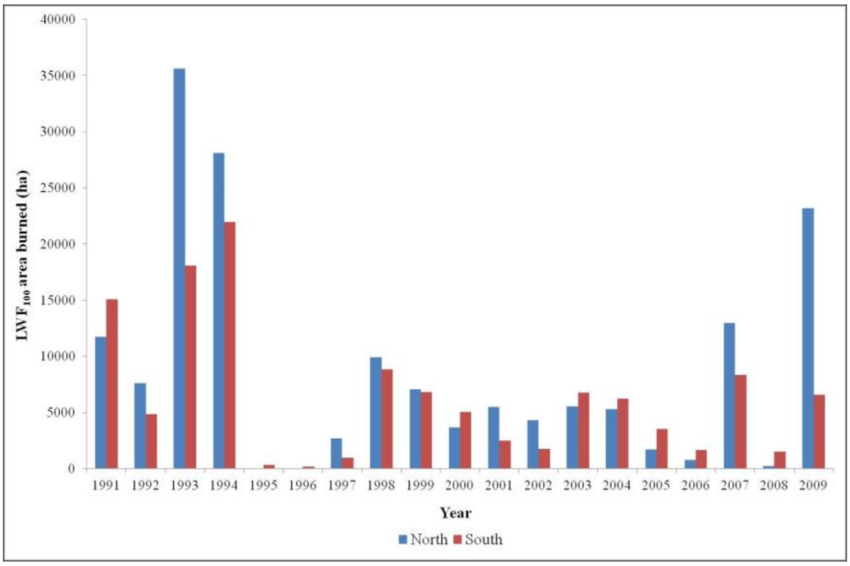

Figure 3. Large wildland area burned (100ha+) in north and south Sardinia from 1991 to 2009 (June-September)

Table 2. Trend analysis of normalized average annual large wildland fire (LWF) number, normalized average annual large wildland fire (LWF) area burned under high temperature days (HTD) and non-HTD in north and south Sardinia, from 1991 to 2009.

		North		South	
Trends	LWF class	Normalized average annual LWF number	Normalized average annual LWF area burned (ha)	Normalized average annual LWF number	Normalized average annual LWF area burned (ha)
HTD	LWF_{100}	n.s. (0.662)	n.s. (0.409)	n.s. (0.844)	n.s. (0.881)
	LWF_{500}	n.s. (0.709)	n.s. (0.314)	n.s. (0.217)	n.s. (0.896)
	LWF_{1000}	Insufficient values to test the trends			
Non-HTD	LWF_{100}	-(0.018)	-(0.049)	-(0.017)	-(0.028)
	LWF_{500}	-(0.027)	n.s. (0.119)	-(0.036)	-(0.047)
	LWF_{1000}	Insufficient values to test the trends			

+ significantly increased at $P<0.05$; - significantly decreased at $P<0.05$; n.s. not significant. Values in parenthesis are the P statistic

Focusing on fires larger than 500 ha and 1,000 ha, there were not significant differences between north and south Sardinia in both the normalized annual LWF number and the total area burned of LWF500 and LWF1000 (Table 1). Moreover, not significant trends were also observed for normalized annual LWF number and total area burned considering days with fires larger than 500 and 1000 ha. However, the number of LWF500 under non-HTD decreased significantly along time in both areas, and the normalized annual LWF500 burned area also decreased in south Sardinia in these conditions (Table 2). These variables were not analysed in LWF1000 due to the insufficient amount of data to perform a statistical analysis.

The normalized annual average values of LWF number and burned area were significantly different in north and south Sardinia in LWF100 and LWF500 under non-HTD (Table 3). However, not significant differences were observed between the two parts of the island in LWF occurred under HTD.

Table 3. Comparison between north and south Sardinia in terms of normalized average annual LWF number and normalized average annual large wildland fires (LWF) area burned from 1991 to 2009. *Values are the P statistic*

Indicator	LWF class	Normalized average annual LWF number		Normalized average annual LWF area burned		Average LWF size	
		HTD	Non-HTD	HTD	Non-HTD	HTD	Non-HTD
Comparison between north and south Sardinia	LWF_{100}	0.097	0.032	0.136	0.002	0.186	0.001
	LWF_{500}	0.238	0.005	0.293	0.028	0.468	0.065
	LWF_{1000}	0.294	0.077	0.598	0.180	0.478	0.215

Table 4 shows the relationships between HTD and non-HTD and LWF in both Northern and Southern Sardinia. There were differences between HTD and non-HTD in terms of LWF daily area burned and LWF daily number. In the north, the area burned by LWF100 under HTD equalled to 28.8 % of the total area burned and the normalized average daily area burned per HTD with LWF in LWF100 category significantly higher (2,503 ha day-1 in 1 x 106 ha of wildlands) than in non-HTD (541 ha day-1 in 1 x 106 ha of wildlands) (Table 4 and 5). Similar results were obtained considering the average daily number of LWF in HTD and non-HTD with values of 2.7 ha day-1 vs. 1.4 ha day-1, respectively (Table 4 and 5). The average size of LWF in north Sardinia was significantly different between HTD and non-HTD in LWF100 (944 ha vs. 396 ha). In the southern part, differences between HTD and non-HTD were also important, as shown in Tables 4 and 5.

Table 4. Summary of the relationship between large wildland fires (LWF) classes and days classified as high temperature days (HTD) or non-HTD, in the northern and southern part of Sardinia, from 1991 to 2009

<table>
<tr><td colspan="2"></td><td colspan="3">NORTH</td><td colspan="3">SOUTH</td></tr>
<tr><td rowspan="7">HTD</td><td></td><td>LWF_{100}</td><td>LWF_{500}</td><td>LWF_{1000}</td><td>LWF_{100}</td><td>LWF_{500}</td><td>LWF_{1000}</td></tr>
<tr><td>Number of days classified as HTD</td><td colspan="3">36</td><td colspan="3">72</td></tr>
<tr><td>HTD with LWF (%)</td><td>41.6</td><td>22.2</td><td>11.1</td><td>30.6</td><td>11.1</td><td>2.8</td></tr>
<tr><td>Normalized LWF average number per HTD with LWF</td><td>2.7 ± 0.69</td><td>2.1 ± 0.65</td><td>2.2 ± 0.75</td><td>1.6 ± 0.21</td><td>1.2 ± 0.21</td><td>0.8 ± 0</td></tr>
<tr><td>Normalized LWF average daily area burned per HTD with LWF (ha day-1)</td><td>2,503 ± 1,219</td><td>4,593 ± 2,325</td><td>6,423± 3,066</td><td>882 ± 295</td><td>1,638 ± 715</td><td>3,708 ± 1,735</td></tr>
<tr><td>Average LWF size (ha)</td><td>944 ± 244</td><td>1,934 ± 530</td><td>2,973 ± 901</td><td>536 ± 153</td><td>1,358 ± 513</td><td>4,612 ± 2,159</td></tr>
<tr><td>LWF area burned during HTD / LWF total area burned (%)</td><td>26.2</td><td>34.7</td><td>39.4</td><td>19.9</td><td>35.8</td><td>45.8</td></tr>
<tr><td rowspan="6">Non-HTD</td><td>Number of days classified as non-HTD</td><td colspan="3">2,283</td><td colspan="3">2,246</td></tr>
<tr><td>Non-HTD with LWF (%)</td><td>8.6</td><td>1.6</td><td>0.7</td><td>12</td><td>2.9</td><td>0.7</td></tr>
<tr><td>Normalized LWF average number per non-HTD with LWF</td><td>1.4 ± 0.10</td><td>1.2 ± 0.09</td><td>1.1 ± 0.10</td><td>1.2 ± 0.05</td><td>0.9 ± 0.06</td><td>0.80 ± 0</td></tr>
<tr><td>Normalized LWF average daily area burned per non-HTD with LWF (ha day-1)</td><td>541 ± 91</td><td>1,972 ± 487</td><td>2,815 ± 922</td><td>290 ± 23</td><td>711 ± 96</td><td>1097 ± 715</td></tr>
<tr><td>Average LWF size (ha)</td><td>396 ± 50</td><td>1,371 ± 268</td><td>2,682 ± 696</td><td>243 ± 11</td><td>788 ± 63</td><td>1364 ±129</td></tr>
<tr><td>LWF area burned during non-HTD / LWF total area burned (%)</td><td>73.8</td><td>65.3</td><td>60.6</td><td>80.1</td><td>64.2</td><td>54.2</td></tr>
</table>

Considering the LWF500 and LWF1000, there were significant differences between HTD and non-HTD in daily number of large fires, but not in relation to LWF daily burned area (Table 5) in north Sardinia. By contrast, in the Southern part of the island, significant differences were observed in LWF daily area burned in LWF500 and LWF1000, while in the case of the LWD daily number only LWF500 showed significant differences.

Table 5. Comparison between high temperature days (HTD) and non-HTD of the average large wildland fire (LWF) size and for those days with at least one LWF: i) average daily number of LWF, ii) average daily area burned per LWF for all LWF classes from 1991 to 2009

Indicator	LWF class	Normalized LWF average number per HTD/non-HTD with LWF	Normalized LWF average daily area burned per HTD/non-HTD with LWF	Average LWF size
North	LWF_{100}	Significant difference (<0.001)	Significant difference (<0.001)	Significant difference (0.001)
	LWF_{500}	Significant difference (0.029)	No significant difference (0.084)	No significant difference (0.312)
	LWF_{1000}	Significant difference (0.016)	No significant difference (0.139)	No significant difference (0.801)
South	LWF_{100}	Significant difference (0.008)	Significant difference (<0.001)	Significant difference (<0.001)
	LWF_{500}	No significant difference (0.069)	Significant difference (0.023)	No significant difference (0.069)
	LWF_{1000}	No significant difference (0.95)	Significant difference (0.008)	Significant difference (0.008)

Values in parenthesis are the P statistic

Our analysis highlighted that the annual number of HTD cannot significantly explain the annual LWF area burned and the annual number of LWF. However, in HTD the likelihood of having a LWF is higher than in other days. The percentage of HTD associated with LWF100 was 41.6% in the Northern part and 30.6% in Southern part of the island (Table 4). By contrast, under non-HTD, the LWF100 were 8.6% and 12.0% respectively. The same was observed in the other LWF classes, with high differences between HTD and non-HTD (Table 4). In addition to this, the ratio between LWF area burned under HTD and the total area burned by LWF was very high in north and south Sardinia as shown in Table 4. This percentage under HTD was 26.2% for LWF100, 34.7% for LWF500 and 39.4% for LWF1000 in the north. In the south, these values were 19.9% in LWF100, 35.8% in LWF500 and 45.8% in LWF1000.

We finally investigated if there was an influence of the daily number of ignitions and the average wind speed in the occurrence of LWF in days classified as HTD. HTD with LWF were characterised by a significantly higher number of fire ignitions than days without LWF, as showed in Table 6, with approximately the double of ignitions in all LWF categories for both Northern and Southern Sardinia. Additionally, the wind speed was higher in days with LWF500 and LWF1000 in the Northern part of the island, in particular considering the weather station of Alghero. On the other hand, we did not find significant influences of wind speed on LWF in the southern part of the island (Table 7).

Table 6. Normalized average number of fire ignitions and standard error in high temperature days (HTD) with and without large wildland fires (LWF), in north and south Sardinia, from 1991 to 2009

	North		South	
	Normalized average number of fire ignitions	p-value	Normalized number of fire ignitions	p-value
Days with LWF_{100}	14.4 ± 1.7	<0.001	23.0 ± 2.0	<0.001
Days without LWF_{100}	7.0 ± 0.6		12.8 ± 0.7	
Days with LWF_{500}	16.2 ± 2.0	<0.001	28.4 ± 4.0	<0.001
Days without LWF_{500}	8.3 ± 0.9		14.3 ± 0.8	
Days with LWF_{1000}	17.1 ± 3.7	0.011	41.8 ± 7.2	<0.001
Days without LWF_{1000}	9.2 ± 0.9		15.2 ± 0.8	

Table 7. Normalized average wind speed and standard error in high temperature days (HTD) with and without large wildland fires (LWF), in north and south Sardinia, from 1991 to 2009.

	North				South			
	Normalized average wind speed - Alghero	p-value	Normalized average wind speed - Olbia	p-value	Normalized average wind speed – Capo Frasca	p-value	Normalized average wind speed - Decimomanu	p-value
Days with LWF_{100}	14.6 ± 1.8	0.119	12.7 ± 1.7	0.546	18.6 ± 1.4	0.700	14.3 ± 1.5	0.936
Days without LWF_{100}	11.8 ± 0.7		11.7 ± 0.8		17.9 ± 1.1		14.4 ± 0.9	
Days with LWF_{500}	17.9 ± 2.5	0.002	12.7 ± 2.8	0.712	20.8 ± 1.8	0.270	15.7 ± 2.2	0.552
Days without LWF_{500}	11.6 ± 0.6		11.9 ± 0.8		17.7 ± 0.9		14.2 ± 0.8	
Days with LWF_{1000}	18.9 ± 4.5	0.015	9.1 ± 0.7	0.200	26.3 ± 5.1	0.107	21 ± 2.3	0.152

Days without LWF_{1000}	12.3 ± 0.8		12.5 ± 0.9		17.8 ± 7.2		14.2 ± 0.8	

Discussion

Whereas it is accepted that the major components for fire weather forecasts are low atmospheric humidity, high temperatures, and strong winds near the ground surface (Pyne et al. 1996), meteorological indexes developed to evaluate temporal and spatial variations in meteorological conditions are not frequently used or available for all fire weather forecast agencies (Charney & Keyser 2010, Crimmins 2006). For that reason, we highlight the significance of discerning between HTD and non-HTD defined by the 850hPa synoptic conditions in developing pre-suppression efforts to stand up to large fires. It would be extremely useful to be able to identify the simply ‘bad’ and the ‘very bad’ fire days with some reasonable lead time (i.e., 24 or 48 hours). We advise that this classification concerning HTD and non-HTD (at 850 hPa) can be used for that discrimination.

Some studies have established that mean, maximum and minimum temperatures have increased and will very likely increase in the next years in south Europe (Arca et al. 2012, Cane et al. 2012, IPCC 2007, Moriondo et al. 2006, Regato 2008). Giannakopoulos et al. (2009) studied possible differences between two reference periods (from 1961-1990 to 2031-2060) in terms of number of hot days (days with Tmax>30ºC on the surface) and heat-wave days (Tmax>35ºC) in the Mediterranean basin: in some of these areas, like for instance central Spain or north Italy, an increase in the occurrence of hot days and heat waves is expected, with 1-3 additional weeks per year. Therefore, in Mediterranean areas, HTDs are expected to become more frequent and to determine a decrease in air humidity and fuel moisture (Moreno 2005), along with an increase in the fire behaviour potential (Arca et al. 2012). Overall, in the Mediterranean Basin, the most of HTD are related to the weather regime that brings hot dry air masses from north Africa (Pereira et al. 2011; Rodriguez-Puebla et al. 2010).

There is evidence that, in recent years, an increase in the frequency of heat waves identified using the 850hPa synoptic conditions as indicator was observed in Northern Spain (Cardil et al. 2013). However, our work highlighted that the number of HTD did not change significantly from 1991 to 2009 in neither north nor south Sardinia. Furthermore, both the total normalized annual LWF number and area burned under non-HTD decreased in north and south Sardinia from 1991 to 2009 as in Northern Spain (Cardil et al. 2013). In particular, the normalized annual area burned decreased significantly under non-HTD conditions. Nevertheless, the normalized annual burned area and number of LWF under HTD did not change in the same period. In short, fire numbers and area burned have been reduced only on days of mild weather conditions in recent years. This fact could be explained with more efficient fire control activity due to important investments in fire suppression technology and training in the last years under non-HTD(http://www.sardegnaambiente.it/protezionecivile/).

Additionally, as expected, the normalized LWF average daily number with LWF, the normalized LWF average daily area burned with LWF, the percentage of days with LWF and the average LWF size were significantly higher under HTD than non-HTD conditions. Therefore, HTD influenced the occurrence of LWF and the area burned in those days. Moreover, this work suggested that HTD are critical for both fuel managers and firefighters, although the number of HTD did not increase in the study period. Probably, fires spreading under HTD can propagate faster and more intensely due to the low dead fuel moisture content and the water stress for live fuels.

Besides, this study shows that HTD with LWF had a higher number of ignitions than HTD without LWF. This could determinate a collapse in the efficiency of the fire suppression system during extreme weather conditions. Moreover, some fires remained smaller than 100ha due to the quick and effective efforts of the firefighting forces. This is to say, some fires might have not grown larger in recent years because of a larger suppression power, in particular in non-HTD conditions.

Our work also highlighted relevant differences between North and South Sardinia regarding the relationship between fires and HTD. In the northern part of the island, the average frequency of HTD was lower (1.84 vs 3.73 HTD per year) that in the South, but the incidence of large fires burning in those days was clearly larger in terms of LWF area burned, number and size, particularly as far as LWF500 and LWF1000 were concerned. This result suggested that the susceptibility to suffer large fires in the North of the island is higher than in the South, and that the use of 850 hPa synoptic conditions needs a careful evaluation and analysis to take into account other local phenomena (influence of topography, continentality effects, local winds, fuel types, etc.). From this point of view, for instance, wind speed was identified as a key factor to affect the occurrence of LWF500 and LWF1000 during HTD in Northern Sardinia.

In recent years, most of the largest wildfires in Sardinia happened in extreme HTD, as for instance in 2007, 2009 or 2012 (Salis et al. 2012b). This supports the statement that HTD provides more extreme conditions for fire propagation and more difficulties to suppress those fires. This also occurred in other countries as reported by Barriopedro et al. 2011, Mills 2005, National Interagency Fire Center (NIFC) 2013, Pereira et al. 2011, Trigo et al. 2006, for the severe wildfires that affected Portugal (2003, 2005), Greece (2007), Spain (1994, 2006, 2009), Russia (2010), USA (2000, 2006 and 2007), Canada (2004), Australia (2005, 2006, 2009, 2011, 2012).

Using fine scale simulation modelling considering the weather scenarios historically associated with large fires (i.e.: heat waves and strong winds) could help fire managers to be more effective in addressing fire management in the Mediterranean Basin, and to identify the priority areas in terms of extreme fire intensity or exposure of values of interest and assets (Ager and Finney 2009; Farris et al. 2000; Salis et al. 2012a; Thompson et al. 2012). It also allows for developing efficient methods and guidelines in a perspective of fire risk mitigation and budgetary planning (Ager et al. 2011; Thompson et al. 2012).

We are aware that in the future an important effort could be done in order to refine the division of the island in more pyro/climatic areas, but on the other hand this manuscript represents an important base for further investigations, and is so far the first study covering the complex relationship among temperatures at 850 hPa, large fires, and weather conditions in an Italian fire-prone area.

Conclusions

Results showed that neither the number of fires nor the area burned decreased under high temperature days, although a decrease of both indicators was observed on the other days. We tried to focus attention to high temperature days that represent most of the affected area by fires. Therefore, this is a proof of inefficient suppression efforts (we are not more efficient in the bad weather days).

The number of HTD did not increase from 1991 to 2009 significantly in Sardinia, Italy. However, we found a clear relationship between HTDs and both LWF occurrence and LWF area burned. Therefore, identifying HTD with reasonable lead time is critical for both fuel managers and firefighters to implement more efficient fire suppression tactics and strategies. The classification of HTD and non-HTD (at 850 hPa) could be used for discriminating and identifying those days that can cause difficulties in fire control and distribute (spatially and temporally) the available resources. This distribution of suppression resources could involve workers’ time sheets to fit the forecasted needs for tomorrow.

Even though the amount of money invested in suppression resources increased in the studied period, the total normalized annual area burned by LWF under HTD did not decrease in either Northern or Southern Sardinia. Additionally, the normalized LWF average daily area burned, the normalized LWF average daily number, the percentage of days with LWF and the average LWF size were significantly higher under HTD than non-HTD conditions. Therefore, it is very useful to forecast HTD conditions as indicators of possible severe wildland fires.

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Chapter 5. Large wildland fires in three diverse regions in Spain from 1978 to 2010

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Abstract

Aim of study: Large wildland fires (LWF) are major disturbance processes affecting many ecosystems each year. In last decades, socio-economic changes have contributed to major changes in land uses. This study assess trends in number, burned area and average size of large wildfires (> 100 ha) from 1978 to 2010 in Spain.

Area of study: This work analyzes three clearly different regions of Spain (Mediterranean coast, MC, Mediterranean Interior, MI, Northwestern Spain, NW).

Material and Methods: We studied historical wildland fire data from Spain's EGIF database (General Statistics on Wildland Fires). We selected only wildland fires larger than 100 ha. All LWF were analyzed to test trends in number of fires, burned area and mean fire size.

Main results: The number of LWF decreased in all regions but the burned area only decreased in MC and NW regions. However, both the number of LWF and the burned area did not decrease after 1995 in any region. The average size of LWF did not change in any of the three regions. Fires larger than 500 ha were very significant due to the high percentage of area burned in relation to the total area burned by fires larger than 100 ha (79.3 % in MC, 63.9 % in MI, and 35.7% in NW).

Research highlights: After 1995, the number of LWF and burned area did not decrease. Additional actions are required including learned lessons from past LWF spread, and better trained fire suppression workers and more fuel management.

Keywords: large wildland fires, trends, forest management, Spain

Introduction

Wildland fires are a growing hazard to human and environmental values worldwide, mainly in the fire-prone areas as the Mediterranean Basin (Salis *et al.*, 2012). Many biomes of this region have endured an increasing incidence of severe fire seasons (Mouillot and Field, 2005; Trigo *et al.*, 2006). In a analogous way, fire activity is expected to rise based on the predicted changes in climate and land use (Thonicke *et al.*, 2001; Moriondo *et al.*, 2006). In the period 2000–2009, Southern European countries (Italy, France, Spain, Portugal and Greece) experienced ~57 000 wildfires year $^{-1}$, which burned ~430 000 ha year $^{-1}$ and 90% were human caused (JRC–IES, 2010).

Spain like other Southern European countries (including France, Italy, Greece or Portugal) has a fire regime with large wildland fires (LWF) that have an extreme fire behavior exceeding firefighting capabilities (Miralles *et al*., 2010; Molina *et al*., 2010). Undesirable fires affect the forest landscape every year. In addition, when weather conditions facilitates fire propagation, fires can burn large areas as in 1994 in Spain with wildland fires larger than 20.000 ha. Other similar cases occurred in other countries as Greece (2008), Portugal (2003), Russia (2010), United States (2000) or Australia (2009).

Large wildland fires threaten social, economic and ecological resources (Alvarado *et al*., 1998; Salis *et al*., 2012), public and private properties (houses, infrastructures, roads, power lines and others) and the life of firefighters and people (Maselli *et al*., 2000). LWF accounted for the majority of the total area burned despite their small percentage of the total number of fire (Stocks *et al*., 2003; Molina *et al*., 2010) and the most resulting damage is concentrated in them (Ganteaume and Jappiot, 2012; Alvarado *et al*., 1998). Much discussion is concentrated around if fire and forest policies and practices on fuel management are missing their original goal (Moreira *et al.,* 2011). New approaches for reducing fire damage and improving fire suppression in terms of costs and effectiveness are available (Moreira *et al.,* 2011; Miralles *et al.,* 2010; Molina *et al.,* 2010).

Fire suppression resources have to be designed to reduce fire damage caused by LWF. Consequently, a large amount of money has been invested for this cause. The expenditure in fire suppression has grown a great deal and the Spanish Government were forced to create both the Emergency Military Unit (UME in Spanish in 2005) and the Attorney's Office of Environmental Crimes (within the Department of Justice, in 2006).

Numerous national authorities around the world gather datasets of wildland fire records. Examples of wildland fire databases are available from Spain (Bardaji and Molina, 1999; Spanish Environment Ministry, 2009) Switzerland (Conedera *et al.,* 1996), Austria (Eastaugh and Vacik, 2012), the USA (Brown *et al.,* 2002), Canada (Stocks *et al.,* 2003) and Europe (EC, 2008). Spain has compiled databases of forest and rangeland fire records since 1968, in a struggle to understand patterns, calculate risks and identify possible changes in wildland fire regimes. Such databases datasets, if valid and comprehensive, could be used for model validation, detection of trends and quantitative risk analyses (Eastaugh and Vacik, 2012). A growth in fire danger has been derived from historic wildland fire datasets (EC, 2008). However, others studies indicate that data quality issues can obstruct these findings (Podur *et al*., 2002).

Few studies on large fires (i.e., that focus only in large fires) are available for Southern Europe (Ganteaume and Jappiot, 2012) and the assessment of suppression means and other policies in them. In this paper, we research LWF from 1978 to 2010 in three different regions of Spain in terms of number of fires, burned area and fire size.

Data and methods

We studied historical wildland fire data from Spain's EGIF database (General Statistics on Wildland Fires) which includes the Wildland Fire Reports sent to the Ministry of the Environment by both Fire-Fighting Services and Forest Services of the regions. This database has an entry from each fire, regardless of size, and contains the same fields of information for each fire. We selected only wildland fires larger than 100 ha (100ha+ or LWF thereafter) for the period of 1978-2010. This is similar in other studies (De Zea Bermudez *et al*., 2009; Moreno *et al*., 2011). We did not use the first years of this database (1968-1977) because area burned in private properties were usually underreported in those years. We did not include burned agriculture lands or urban areas in this study.

All LWF from 1978 to 2010 were analyzed to test trends in number of fires, burned area and mean fire size. In the study, we set up three different regions using summer extent, intensity of sea influence in weather, intensity and frequency of extreme weather patterns, population density, amount of fire suppression resources and number of fires. This classification is an updated from Bardaji and Molina (1999) study. The Spanish Environment Ministry changed to this classification after Bardaji and Molina (1999) for their annual reports (Spanish Environment Ministry, 2009). These three regions are the following (Figure 1):

Northwestern Spain (NW). There are more fires than in the other regions in Spain (Pereira *et al*., 2005). The dry summer season is shorter than the other two regions. There is a more frequent traditional use of fire (traditional use of fire in range and agriculture). In this region, we included La Coruña, Lugo, Ourense, Pontevedra, León, Zamora, Asturias and Cantabria provinces.

Mediterranean Coast (MC). There is an important sea influence and a long dry summer season. In general, population density is high. In MC, we included Girona, Barcelona, Tarragona, Castellón, Valencia, Alicante, Murcia, Almería, Málaga, Cádiz, Huelva provinces.

Mediterranean Interior (MI): The dry summer season in the longest. Sea influence is minimal and air relative humidity is low during the summer without much day to day variability. Population density is the lowest. Land abandonment is very important. This region includes the following provinces: Guadalajara, Cuenca, Toledo, Ciudad Real, Albacete, Huesca, Zaragoza, Teruel, Cáceres, Badajoz, Salamanca, Valladolid, Palencia, Burgos, Soria, Segovia, Ávila, Jaén and Córdoba.

We excluded some provinces because of different causes:

Madrid: It is an interior province; however, its population density is much higher than other interior provinces and its suppression resources are stronger.

Lleida: In this province, suppression resources are much stronger than other interior provinces.

Navarra, Guipúzcoa, and Alava: They are small size provinces with strong suppression resources and / or very few wildland fires larger than 100ha per year.

Granada and Sevilla: These provinces have both an interior area and a coastal area. They do not fit to any of both conditions (Mediterranean Coast or Mediterranean Interior).

Canary Island and Balear Islands: They are particular provinces because they suffer only few large wildland fires.

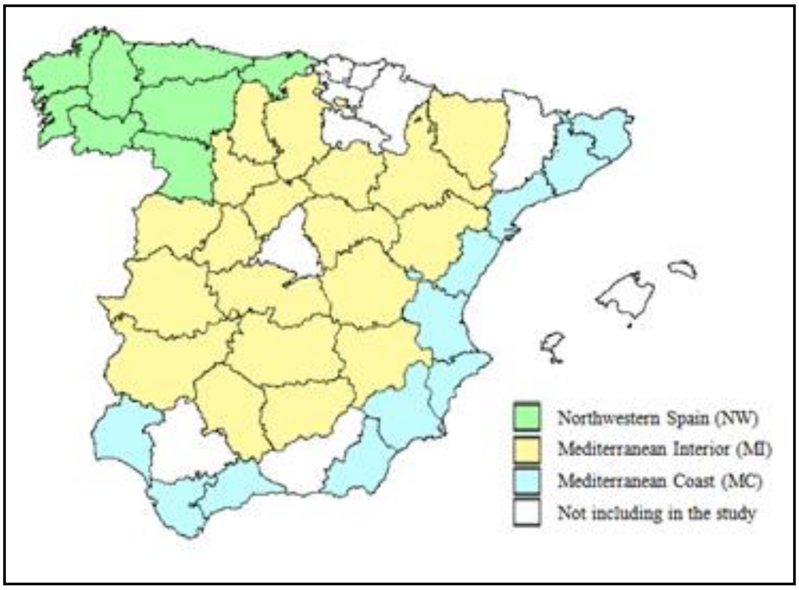

Figure 1. Regions in Spain to characterize large wildland fires. Canary Islands are neither displayed in this figure nor included in this study

Statistical data treatment

LWF were classified into three wildland fire categories: fires larger than 100 ha (100ha+), 250 ha (250ha+) and 500 ha (500ha+). Three normalized metrics were calculated and analyzed for three regions and fire categories: (1) annual ha burned for every 400.000 ha of forest and wildlands (relative burned area); (2) annual number of LWF for every 400.000 ha of forest and wildlands (relative total LWF); (3) average size of LWF. A base area of 400.000 ha was selected as in other studies (Stephens, 2005; Pyne, 1997). The wildland area was calculated using the Spanish National Forestry Inventory in all available editions, establishing linear interpolation to calculate the forest area in each year. The interpolation was performed only in the years between inventories. After the last available inventory for each province, the area was considered constant and before the first inventory, the forestry area also was considered constant for all previous years with the value of the first inventory.

The relative total LWF, relative burned area, and average size of LWF were analyzed in three regions and three wildland fire categories from 1978 to 2010 (27 time series). Analysis of these 27 time series showed that autocorrelations existed in some of them using Durbin-Watson Test. To reduce serial dependence, a 3-year average was calculated for each variable over 32 years (10 data points). This new condensed database was used in the analysis of variance (ANOVA) and linear regression analysis (Stephens, 2005).

We determined if there were significant changes (decrease, increase, no difference) in the three studied variables (relative burned area, relative total LWF and average size of LWF) from 1978 to 2010 in the three wildland fire categories with a linear regression analysis in a new condensed database (10 data points for each variable). The independent variable in the regression was the midpoint year of the average 3-year range and the dependent variable was the corresponding transformed 3-year averages of relative burned area, relative total LWF and average size of LWF.

An analysis of variance was performed using the series with 3-year average to determine significant differences ($P<0.05$) by regions in the studied variables from 1978 to 2010. If significant differences were detected, a Tukey Multiple Comparion Test was performed to determine these differences among regions (MI, MC and NW).

The annual variability in fire occurrences is high, both in terms of large fire frequencies and their burned areas as reported in Stocks *et al*. (2003). This variability is caused by diverse environmental factors (i.e., climate (Gillett *et al.*, 2004)) and human influence (Mollicone *et al*., 2006). All series were shown using the moving average method for a better display of the evolution of the variables in time. This smoothing technique was applied to mitigate the effect due to year to year random variation. This practice, when properly applied, reveals more clearly the underlying trend (Legendre and Legendre, 1998). The method calculates successive arithmetic averages over 2m+1 contiguous data as one moves along the data series (Legendre and Legendre, 1998). The interval (2m+1) is called window. In this study, we used simple moving average with five-year periods (m=1).

Results

In relation to ANOVA analysis, there were significant differences among regions in several variables. The results of the Tukey Multiple Comparion Test and the values of each variable by region and wildland fire categories are in table 1. The relative total LWF was significantly different from NW (14.97 in 100 ha+ category) to both MC and MI (3.76 and 2.14 respectively in 100 ha+ category) in 100ha+ and 250ha+ wildland fire categories. The relative total LWF was also significantly different from NW (1.47) to MI (0.43) in 500ha+ category. The region with lowest value in relative total LWF in all wildland fire categories was MI but significant differences with MC were not detected.

The relative burned area was not different significantly among regions in 250ha+ wildland fire category. However, there were clear differences in 100ha+ and 500ha+ categories. In the first, the maximum value occurred in NW with 4030.63 ha burned for every 400.000 ha of forest and wildlands. This value was significantly different from MI (1014.28 ha) but not from MC (2909.21 ha). No difference was found between MC and MI. By contrast, in 500ha+ category, the largest value was in MC (2307.51 ha) and it did differ from MI value (648.30 ha) significantly. No difference was found between MC and NW region (1441.51 ha).

The average size of LWF is less in NW than both MC and MI in 250ha+ and 500ha+ categories. In 100ha+ category, the LWF average size is larger in MC (651.72 ha) than NW (261.44 ha). There was no difference between MC and MI in any wildland fire category.

Table 1. Average of ha burned for every 400.000 ha by large wildland fires (LWF) (relative burned area), number of LWF for every 400.000 ha (relative total fires) and LWF average size from 1978 to 2010 in each region.

	Wildland fires categories	Relative total LWF	Relative burned area (ha)	LWF Average size (ha)
	100ha+	3.76[b]	2909.21[ab]	651.72[a]
Mediterranean	250ha+	1.89[b]	2617.56[a]	1103.72[a]
Coast (MC)	500ha+	1.03[ab]	2307.51[a]	1877.96[a]
	100ha+	2.14[b]	1014.38[b]	493.45[ab]
Mediterranean	250ha+	0.90[b]	820.28[a]	914.39[a]
Interior (MI)	500ha+	0.43[b]	648.30[b]	1472.81[a]
	100ha+	14.97[a]	4030.63[a]	261.44[b]
Northwestern	250ha+	4.30[a]	2432.17[a]	534.38[b]
Spain (NW)	500ha+	1.47[a]	1441.51[ab]	913.54[b]

Mean values in a column in each wildland fires categories followed by the same letter are not significantly different ($P < 0.05$)

Table 2 shows the trends in relative total LWF, relative burned area and average size of LWF in relation to wildland fire categories and regions in the studied period (1978-2010). In MC, we observed a significant decrease in relative total number of fires and relative burned area in all wildland fire categories. In MI, we did not find any significant trend in relative burned area and we only found a significant decrease in relative total number of LWF in 100ha+ category. In NW, the relative total number of LWF decreased in the studied period in 100ha+ and 250ha+ wildland fire categories and the relative burned area also decreased in 100ha+ category. Additionally, we observed and assessed that the relative total number of LWF did not decrease and this number was nearly constant from 1995 to 2010 in all regions (1.3 fires/yr in MC, 1.1

fires/yr in MI and 9.2 fires/yr in NW) as shown in Figure 2. We also observed that the burned area did not decrease in 1995-2010 period and remained almost constant (802 ha/yr in MC, 642 ha/yr in MI and 2755 ha/yr in NW) such as the number of LWF (Figure 3). Note that in MC, there is a peak in years close to 1994 and it is caused by mega-fires (i.e., 10,000ha+) occurred in 1994 and the moving average method moves this disturbance to neighboring years (Figure 3).

Table 2 Change of number of large wildland fires (LWF) for every 400.000 ha (relative total LWF), ha burned for every 400.000 ha by LWF (relative burned area) and average size of the LWF from 1978 to 2010 in each region. Coefficient of determination of linear regressions

	Wildland fire categories	**Relative total LWF**	**Relative burned area (ha)**	**Average size (ha)**
	100ha+	- (0.003)	- (0.014)	n.s (0.756)
Mediterranean	250ha+	- (0.007)	- (0.017)	n.s (0.868)
Coast (MC)	500ha+	- (0.017)	- (0.040)	n.s (0.518)
	100ha+	- (0.019)	n.s (0.160)	n.s (0.082)
Mediterranean	250ha+	n.s (0.062)	n.s (0.285)	n.s (0.211)
Interior (MI)	500ha+	n.s (0.209)	n.s (0.536)	n.s (0.255)
	100ha+	- (0.007)	- (0.049)	n.s (0.094)
Northwestern	250ha+	- (0.036)	n.s (0.179)	n.s (0.223)
Spain (NW)	500ha+	n.s (0.200)	n.s (0.493)	n.s (0.623)

+ significantly increased; - significantly decreased at P<0.05; n.s. not significant. Values in parenthesis are the P statistic. In MC, we did not consider 1994in relative burned area because it was an anomalous data in terms of burned area due to mega-fires that burned 279172 ha (100ha+)

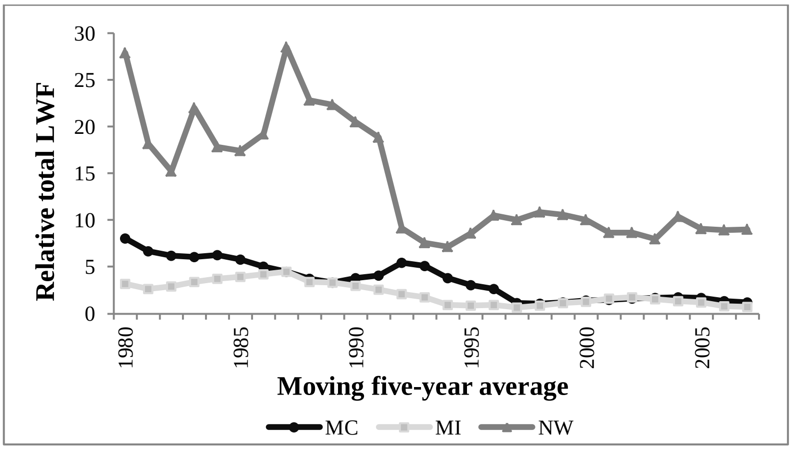

Figure 2 Relative total large wildland fires by regions. (MC: Meditarrenan Coast, MI: Mediterranean Interior, NW: Northwestern Spain)

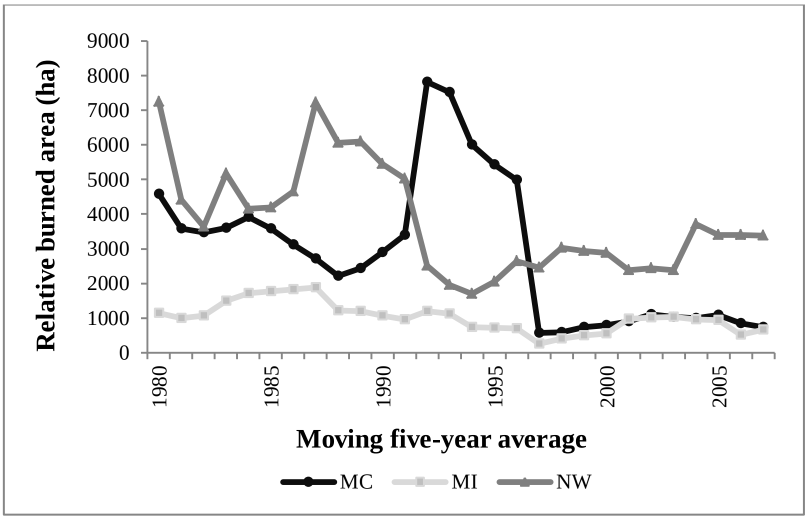

Figure 3 Relative burned area by regions (MC: Meditarrenan Coast, MI: Mediterranean Interior, NW: Northwestern Spain)

The average size of LWF did not change significantly in the studied period in three regions and three categories (651.72 ha in MC, 493.45 ha in MI and 261.44 ha in NW in 100ha+ category).

The importance of the largest forest fires is very high in terms of relative burned area and, particularly in MC region in which the burned area in 500ha+ wildland fire category account for 79.3 % of the total area burned by LWF. In MI, this value decreased to 63.9 % and in NW to 35.7%. In both MI and NW, we observed that these values do increase along the study period.

Discussion

After 1995, we observed that relative total LWF and the relative burned area did not decrease and was nearly constant from 1995 to 2010 in all regions. Therefore, it is clear from our results that we are unable to solve the wildland fire problem through allocating more resources to fire suppression.

For the whole time period studied, the relative number of LWF (100ha+) decreased in all regions (MC, MI and NW). Zavala *et al.*, (2011) studied trends in all fires (small and large fires) in several regions in Spain in a similar time period. Note that we used provinces as independent units and Zavala *et al.*, (2011) employed 10 regions, taking into account regional administrative borders and bio-geographical characteristics. We excluded from our analysis those provinces that do not fit easily in either region as we have defined them (NW, MC and MI). Zavala *et al.*, (2011) found an increase in number of fires in MI provinces series. Spanish Environment Ministry (2006) also perceived this trend in MI from 1996 to 2005. This is mostly due to the small size fires; however, this did not happen in our study about LWF in MI provinces. In MC, we found a significant decrease in the number of LWF and burned area in all wildland fire categories. Zavala *et al.*, (2011) also found this decreasing trend in the number of all fires (small and large fires).

The relative burned area decreased in MC and NW regions in 100ha+ wildland fire category and only in MC in 250ha+ and 500ha+ categories in the study period. However, observing the data in more detail and highlighting the underlying trends in MC and in the other two regions, we detected that after 1995, the decrease in both the number of LWF and the burned area did stop despite the additional investments in technology, roads, water reservoirs, material and human resources in the last 15 years. The mean size did not decrease in any region and the significance of LWF larger than 500 ha is higher in all regions in the recent years. Therefore, fire suppression effectiveness to reduce the effects from LWF is not improving in recent years and, for this reason, Castellnou *et al.*, (2010) suggested needed actions to improve fire suppression. These actions may involve learned lessons from past LWF spread; in particular, identifying synoptic weather patterns and critical areas to fire spread. Molina *et al*., (2010) also suggested a need for much better trained fire suppression workers; i.e, improving fire management success through fire behaviour specialists.

Under the actual fire suppression policies and practices in Spain, our data shows that we are unable to further reduce the effects of LWF by spending more money in suppression means (in a reasonable figures) because in last 15 years, the area burned did not decrease in any region. Molina *et al*., (2010) explained that more suppression resources are needed when biomass depletion and the mosaic arrangement of the landscape have collapsed. This is due, in part, to **a**gricultural abandonment and land cover changes that has increased fuel load (Millán *et al*., 1998) and the fuel homogeneity and continuity that are facilitators for both a faster fire propagation and a higher fireline intensity (Pausas *et al.*, 2012; Molina *et al*., 2010; Vega-García and Chuvieco, 2006)**.** Climate change issues are also instrumental and they could be already playing a significant role (Moreira *et al.*, 2011) due to the increase in the number of years with adverse fire weather; i.e., an increase in the length of the fire season and / or more frequent extreme events (Cardil *et al.*,2013; Moriondo *et al*., 2006). In a similar way, Pausas *et al.*, (2012) tested the hypothesis that fire regime changed in western Mediterranean Basin during the last century. They compiled a 130-year fire history for the Valencia province (Spain) to assess the role of climate and human-driven fuel variations on the fire regime change. The outcome suggested that there was a major fire regime alteration about the early 1970s in such a way that fires augmented in annual frequency (doubled) and area burned (an order of magnitude). The key driver of this modification was the increment in fuel amount and continuity due to countryside abandonment.

NW is the region more affected in terms of relative total fires and relative burned area in our studied period. This agrees with De Zea Bermudez *et al*., (2009)**.** In MI, these indexes had lower values than in NW. In MC, suppression means reduced the relative total LWF and burned area in our studied period because of strong resources in suppression tasks. However, the decrease in the number of fires and burned area did stop and, therefore, a further decrease in the last years was not able to be produced by the suppression resources.

Suppression expenditure increases with fire size (Liang *et al*., 2012). In SW USA, large fires are 2 percent of the total number of fires but 84 percent of suppression expenses (Gebert and Schuster, 2008). Therefore, limiting fire potential (in terms of area to burn), we can reduce the costs of the fire suppression (Miralles *et al*., 2010). Fire potential can be limited using fire prevention measures, including strategic fuel management actions and resource management plans and limiting human-caused fire occurrences. In Spain, the majority of the fires are human-caused (Padilla and Vega-García, 2011; Ministry of Enviorment, 2009). In Spain, we need more resources allocated to vegetation and fuel management, and should not focus only on increasing wildland fire suppression means. A revisited approach to vegetation and fuel management should include dealing with agriculture field abandonment (limiting shrub encroachment), and addressing the needed thinning in our forest stands (Costafreda-Aumedes *et al*., 2013). Moreover, surface fuel treatments including broadcast prescribed burning are desirable (Moreira *et al.*, 2011**;** Stephens *et al*., 2009**)**. Lastly, we need to understand that bio-energy (fire wood, wood chips, and pellets) is an opportunity for our forests in Spain, particularly those less profitable as timber sites.

Within Europe, an inter-agency approach must be implemented towards harmonizing the international efforts in reducing the negative consequences of wildfires (Goldammer, 2008, Miralles *et al*., 2010). A better cooperation among regions and countries would be an enormous improvement in the firefighting system. By intensifying material and human resource sharing among all fire agencies (and therefore distributing the suppression means adequately depending on fire risk map or other specific necessities of each moment), we could significantly reduce the suppression expenditure. Additionally, this could improve the training of both professional firefighters and volunteer. In this way, while decreasing the suppression spending, we will be able to allocate more funds for prevention measures to diminish the vulnerability of the forests and wildlands against LWF. This would be a pro-active approach (reducing fire potential by fuel management) instead of trusting only re-active actions (fire suppression).

Conclusions

In all regions (MC, MI and NW), the relative number of LWF (100ha+) decreased in the study period but the relative burned area only lessened in MC and NW regions. However, **a**fter 1995, the number of LWF and burned area remained constant despite the added investments in roads, water reservoirs, technology, material and human resources in all regions. The mean fire size did not decline in any region and the importance of LWF larger than 500 ha was higher in all regions in the recent years. Therefore, fire suppression effectiveness to reduce the effects from LWF is not improving in recent years. Additional actions are required including learned lessons from past LWF spread, and better trained fire suppression workers.

In recent years, land abandonment have provided fuel load and fuel continuity that enable a more dramatic fire propagation and, similarly climate change have made available some more heat waves and longer fire risk seasons. We have to change our fire management programs and strategies if we want less area burned in the future. We suggest that a change is required in both forest policies and practices to accomplish a more powerfully fuel management. An enhanced implementation of suppression capabilities is also needed. Better inter-agency cooperation agreements are essential to distribute the resources efficiently in the territory to improve the fire suppression systems in three regions in this study.

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Chapter 6. Factors Causing Victims of Wildland Fires in Spain (1980–2010)

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Abstract

The worst consequence of wildland fires is the loss of human lives, a regular phenomenon over the last few decades worldwide. This work analyzes all recorded wildland fires in Spain with victims between 1980 and 2010. We classified causality causes during wildland fires to study the most frequent causes of fatalities and how they were related to regions, fire size, and extreme weather conditions (*i.e.*, high temperature days). Trends in number of both injured and killed individuals were analyzed. We observed that the annual number of victims did not decrease in the study period. Entrapment is the most frequent cause of death within the fire suppression employees. Fire size is a key factor in the occurrence of victims because 95% of fatalities in wildland fires (not counting aerial casualties) happened in fires larger than 100 ha. High temperature days also were important because 60% of entrapments were produced in this kind of days.

Key Words**:** victims, wildland fire, fatalities, entrapments, causality causes.

Introduction

Wildland fires are a growing threat to environmental, social, economic, and human values worldwide, mainly in fire-prone areas (Salis *et al*. 2012; Pereira *et al*. 2011). Mediterranean countries in Southern Europe (Spain, Portugal, France, Italy, and Greece) present the largest number of fires on the continent (García-Ortega *et al*. 2011) and the number and area burned by large wildland fires did not diminish significantly since 1994 in any region of Spain (Cardil and Molina 2013). Increases of wildland fuel loads and fuel complex continuities across the landscape are increasing the probability of developing large wildland fires with extreme fire behavior (Molina *et al*. 2010; Vega-García and Chuvieco 2006) due to changes in land uses and rural abandonment (Millán *et al*. 1998). Additionally, because fire regime is influenced by climate and weather (Trouet *et al*. 2009), climate change is providing extreme conditions in terms of high temperature days that contribute to high fire intensity and large wildland fires (Cardil *et al*. 2013; Flanningan *et al*. 2000). Wildland urban interface areas have increased in Spain and many other countries in the last years, exposing larger populations to wildland fires (Liang *et al*. 2008). Both rural and coastal areas have been populated by secondary homes, which have contributed to the increase of wildland urban interface areas.

The loss of human lives is the worst outcome of wildland fires and populated areas have a higher exposure to large wildland fires (LWF) than ever (Viegas 2009). A large amount of resources have been invested in fire suppression resources to reduce the negative consequences of fires and to provide safety to the population. However, firefighters sometimes are found in a high-risk environment without the best training and safety protocols. Individuals involved in all aspects of fire management are subject to the dangers of burnovers, vehicle and aircraft casualties, and medical emergencies (Mangan 2007). Therefore, both citizens and firefighters are at risk and many people were involved in several wildland fire casualties in Spain. Many catastrophic cases were recorded in the last years in Spain: Horta de San Joan (Tarragona, 21 July 2009, 5 fatalities, all firefighters), Riba de Saelices (Guadalajara, 17 July 2005, 11 fatalities, all firefighters) or La Gomera (Canary Islands, 11 September 1984, 20 fatalities, 4 politicians and authorities, and 16 non-firefighters). In a similar way, there were many terrible cases in other regions of the world as in the United States, Australia, Chile, or Europe (Mangan 2007; Viegas 2009; Cabbidu *et al*. 2011). For instance, in the United States 133 firefighters died on 94 separate events in the 1990–1998 period (Mangan 2007). In Chile, 62 forest firefighters died on duty from 1978 to 2012 (Haltenhoff 2003; Ackerknecht and Mendoza 2007; Claudio Concha pers. comm.). The last large fatality in the USA involved the Granite Mountain Hotshots where 19 crew members lost their lives on June 30, 2013, on the Yarnell Hill Fire in Arizona. In 2007, in Greece, 78 people died. In Portugal, in 2007, 22 people died. In Sardinia (Italy), in 1983, there were 9 fatalities (Curraggia's wildfire).

As a result of those large number of fatalities, some Foundations and activities are active today as the following ones. WFF Wildland Firefighter Foundation's main focus is to assist families of firefighters killed in the USA in the line of duty, to support wounded firefighters and their families, and to bring recognition to wildland firefighters (http://www.wffoundation.org/). We believe that a Foundation like that is needed in Spain and maybe in other countries. Another excellent initiative is Always Remember (http://www.wlfalwaysremember.org/), which provides a permanent location to collect, organize, maintain, preserve, and share current and historical incidents in which wildland firefighters lost their lives. This group helps people to remember fallen firefighters, their contributions, and the lessons learned from their lives or in their passing.

High quality training on safety protocols such as LACES or Dead Man Zone (Gleason 1991; Thorburn and Alexander; 2001) should be critical to pursue a lower causality rate (Molina *et al*. 2010). However, even though the efforts to apply them, many fatalities occurred in Spain in the last years and we face a very different emergency category when there is an causality. A wildland fire with victims escalates to a more dramatic emergency level (Molina *et al*. 2010). First, a new emergency (*i.e.*, an causality) occurs during the propagation of the wildland fire, involving lots of resources in the causality. Second, when people lose their life in a wildland fire, social pressure increases quickly (Xanthopoulos 2008) and fire suppression resources are less efficient in these situations (*i.e.*, thinking about affected teammates, suffering uncertainty).

Extreme high temperature conditions could be a key factor affecting fatalities because they provide extreme conditions for workers (fatigue, exhaustion, dehydration). Heat exhaustion is when a person experiences fatigue (extreme tiredness) as a result of a decrease in blood pressure and blood volume. It is caused by a loss of body fluids and salts after being exposed to heat for a prolonged period of time (NHS 2010). Fatigue is common in firefighters working under extreme temperatures (Lorber 2006). Additionally, fire behavior is more extreme (Cardil *et al*. 2013) and can entrap firefighters and vehicles. Wind is another major environmental factor in extreme fire behavior but we do not have access to detailed local wind data for most of the earlier casualties of our study. Therefore, we understand that we only address one of several environmental factors that create an extraordinary risk for firefighters. These other factors include intense surface winds with gusts from changing directions and irregularities in relative air humidity at low tropospheric altitudes.

It is necessary to learn more about wildland fire fatalities in order to reduce them. Victims can be caused by a variety of factors (Desmond 2011; Beaver 2002) such as air vehicle engine failure, radiation, entrapment, heart attack, or traffic causality. In Canada and the USA, there are some remarkable analyses of firefighters' injury/fatality data. Beaver (2002) addressed human behavior in risk taken actions and Karter (2012) examined the causes in firefighters' injures. The aim of this work is to assess all recorded wildland fires in Spain from 1980 to 2010 in which firefighters were killed and to evaluate the factors of the causality and the people involved. We address which factors caused most of the fatalities. We also compare the influence of high temperature days and fire size in fatalities and evaluate trends in terms of number of fatalities and injured people.

Methods and materials

Study Area and Suppression Fire Organizations

Spain has 17 administrative regions including the Canary and Balearic Islands. Most of the country has a Mediterranean climate with long summers of high temperatures and limited rainfall that contributes to increase wildland fire risk. However, even in the northwestern part of Spain, which has an Atlantic climate with a dry season shorter than other regions of Spain, forest fire incidence is high (Pereira *et al*. 2011) due to the traditional use of fire.

The fire suppression varies by region in terms of leadership, volunteer/professional, and quality of training of forest firefighters. In some regions, the leadership in fire suppression actions is under unified emergency agencies (*i.e.,* Catalonia, Madrid, C. Navarra, Valencia, Asturias) while in others fire suppression is led by the forest service (*i.e.*, Aragón, Andalucia, Galicia, Castilla La Mancha, Murcia, Castilla y León, Canary islands, Balearic islands, Basque provinces, Cantabria, Extremadura, La Rioja) under different degrees of interagency cooperation.

Fire Data

Historical fire data records on firefighter fatalities and casualties from Spain's EGIF database (General Statistics on Wildland Fires, see www.magrama.gob.es) were analyzed for the period 1980–2010. This database includes the Wildland Fire Reports sent to the Ministry of the Agriculture, Food and Environment (2013) by the Fire-Fighting and Forest Management Services from all the Spanish regions. This database has an entry from each fire and contains the information about the burned area, fire date, injuries and fatalities, causes of death, and other variables. In addition to this, we used the wildfire official yearbooks of the Environment Ministry of Agriculture, Food and Environment to complement casualties with injuries and fatalities not found in the EGIF database.

All people who worked for the fire suppression system were in the analyzed databases. However, many civilians, shepherds, or farmers who lost their lives while they were burning their farmland and pastures were not recorded in the databases. Many official yearbooks said that some people unrelated to the fire suppression system died in some years, especially in northwestern Spain, but neither the number nor the fire date were reported. Therefore, we found few data on victims who were not working in the fire suppression system. However, firefighters' fatalities were recorded in the databases and we verified the data through interviews with senior managers in the different regions and by analyzing documents of the casualties and news in newspapers. Therefore, data about fatalities in wildland fires in fire suppression systems are accurate.

The number and trend of injured firefighters were also analyzed. However, in this case, we found a remarkable lack of data, with injured people underreported especially in the first years of the series. In the official yearbooks, there are references to injured people but in the majority of the cases the records did not clarify the number of affected people, the date or the location of the causality. Additionally, the damage level in affected people was not always reported. We used all the clear records of the database to analyze trends in injured people, but analysis of causes was impossible due to the lack of information of the database. Karter (2012) accomplished a remarkable analysis of firefighter injury data from the U.S. Fire Administration's National Fire Incident Reporting System (NFIRS). This analysis was undertaken to examine the causes in those injures. Data in Spain do not allow addressing injury causes.

Statistical Analysis

All fatalities were analyzed and classified in relation to the cause of death and the job duties of the victims in the fire suppression system. The categories used to describe the involvement of the victim in the wildland fire were the following: a) Firefighters: forest rangers, fuel and forest managers or supervisors, fire crew members, and people who worked in the fire suppression system; b) Aircraft personnel: pilots, aircraft engineer, fire crew members when flying; c) Volunteer firefighters: mainly people of forestry defense associations; d) Elected officials: town mayors, councilman or councilwoman, government delegates; e) Non-firefighters: local residents, hikers, shepherds, peasants; f) Others or unknown.

In the case of fatalities, we evaluated the cause of the death in all wildland fires using EGIF notes, the available information of the wildfire official yearbooks and several notices in newspapers. We classified all victims according to the following causes: a) Physical cause: this category includes different medical causes (heart attack, dizziness, *etc*); b) Entrapment: either when a wildland fire reaches the victim or death by hot gases; c) Aerial causality: flying, landing, or taking off; d) Terrestrial causality: including a person stepping on a power line, casualties while driving vehicles, falling down with injures; e) Unknown.

We determined if there were significant changes in the number of fatalities and injured people in Spain from 1980 to 2010 with a linear regression analysis of annual raw data. The annual variability in victim occurrences was high. For this reason, we added the evolution in time of the variables with the moving average method in order to mitigate the effect due to year-to-year random variation and reveal more clearly the underlying trend (Legendre and Legendre 1998). “The method calculates successive arithmetic averages over 2m+1 contiguous data as one moves along the data series” (*ibid.*). In this study, we used simple moving average with 5-year periods.

All fatalities in entrapments, terrestrial casualties, or physical causes were classified in relation to high temperature days (HTD) and fire size classes to understand if there were any relationships between victims and extreme fire weather and fire size. High temperature days provide extreme weather conditions and influence fire occurrence, fire size, and fire behaviour (Cardil *et al*. 2013) so they may increase the risk of entrapments or terrestrial casualties. Additionally, an air temperature of 20ºC at 850 hPa (equivalent to some 1500 m of altitude) provides high temperatures on the surface that may increase the risk of suppression personnel (less effectiveness, tiredness, exhaustion, dehydration). A HTD was defined when air temperature was equal or higher than 20ºC at 850 hPa (Cardil *et al*. 2013). Reanalysis data from the National Centers for Environmental Prediction (Kalnay *et al*. 1996) were used to characterize the high temperature days.

We assessed the relation between fatalities and fire size, segregating all wildland fires with victims in five size classes: (1) Forest fires smaller than 100 ha (<100 ha), (2) those between 100 and 250 ha (100–250 ha), (3) those between 250 and 500 ha (250–500 ha) and, (4) those larger than 500 ha (500 ha+). We have also used a combined class (5) those larger than 100 ha (100 ha+). We assessed if the fire size was associated with the number of victims and if the largest fires might have the highest percentage of victims.

Results

In the period 1980–2010, 241 people died in wildland fires in Spain (Table 1), of which 169 worked for the fire suppression systems. Therefore, 72 civilian people (without relation to the fire suppression systems or unknown) died in wildland fires in the study period. However, many external victims to the fire agencies were not included in the fire data records or it was impossible to get all information about the incident (number of victims, date, geographic location, and others). According to official yearbooks this value should be higher but we cannot evaluate it because quantitative data is not available. Therefore, surely, the number of people who died in a wildland fire external to the fire suppression system was higher.

In the study period, the number of injured people was 1670. In most cases, it was impossible to know if the victims were workers of a fire suppression system or not. In a similar way, the cause of the causality was mostly unreported.

Table 1. Number of fatalities according to the cause of death for victims in Spain (1980–2010).

Cause of Death	Suppression system	Non-suppression system	Total number
Physical cause	12	0	12
Entrapment	78	37	115
Aerial causality	46	0	46
Terrestrial causality	33	1	34
Unknown	0	34	34
Total number	169	72	241

Trends

No significant trend in the number of total fatalities was found during the study period (p-value = 0.198, n = 30) with a mean of 7.8 and a median of 6 fatalities per year. This value is an underestimate because of unreported fatalities of civilians, peasants and other people that did not belong to the fire suppression system. Shown in Figure 1 are the number of fatalities in wildland fires in Spain (1980–2010). The number of fatalities who worked in fire suppression did not decrease (5.5 fatalities per year, p = 0.344, n = 30) nor did the number of fatalities in entrapments, terrestrial and aerial casualties, and physical causes.

The worst years were 1984 due to the La Gomera's Fire with 20 fatalities in an entrapment, 1994 with 32 fatalities, and 2005 with 17 fatalities, 11 of them in the Riba de Saelices' fire (Guadalajara).

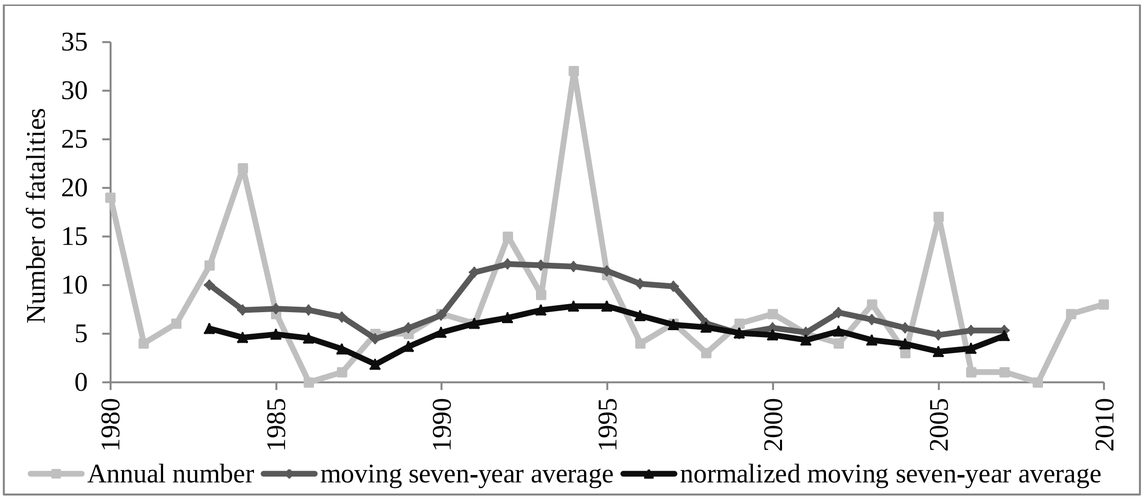

Figure 1. Annual number of total fatalities in wildland fires in Spain (1980–2010), light grey line. Moving seven year average (1983-2007) of fatalities, dark grey line, and normalized moving seven-year average, black line (number of fatalities per 100,000 burned ha).

The number of injured people in Spain did not change significantly in the study period with a mean value of 53.8 and a median of 46 injured people per year. The worst year of the series was 1994 with 217 affected people (Figure 2). If we normalize the number of injured people considering the area burned each year for all registered wildland fires in the official database (number of injured firefighters per 10,000 ha), it can be observed a significant increase in the normalized number of injured people (Figure 2). Note that it is unknown if victims were firefighters, civilians, elected officials, or others.

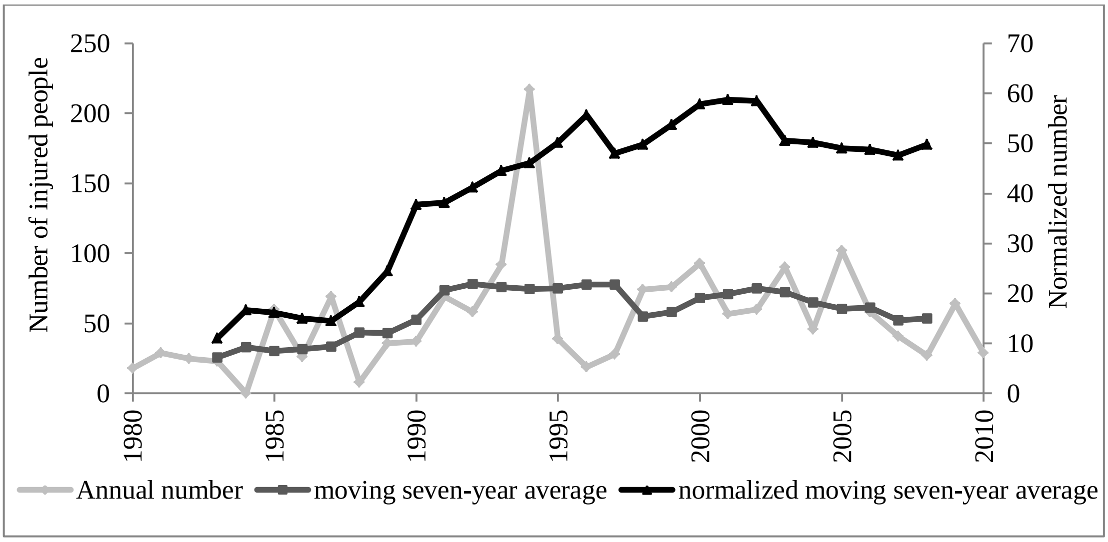

Figure 2. Number of injured people in wildland fires in Spain (1980–2010), light grey line. Moving seven year average (1983-2007) of injured people, dark grey line, and normalized moving seven-year average, black line (number of injured people per 100,000 burned ha).

Causes

In relation to the fatalities of the suppression system, entrapment was the most frequent cause with 46.2% of the total of fatalities. Aerial casualties comprised 27.2%, terrestrial casualties 19.5%, and physical causes 7.1% (Table 1). However, for people who did not work in a suppression system, the 50% of the death causes remain unknown and almost 50% of the victims were entrapments. Shown in Table 2 are the number of fatalities in relation to the cause of death and belonging to the fire service. However, in relation to the injured people, we could not assess the causes.

Table 2. Number of fatalities in relation to the death cause and the involvement of the victim in the incident in Spain (1980–2010).

Role/Cause	Physical cause	Entrapment	Terrestrial causality	Aerial causality	Unknown	Total
Firefighters	8	71	30	-	0	109
Aircraft personnel	-	-	-	46	-	46
Volunteer firefighters	1	3	3	-	0	7
Elected politician	3	4	0	-	0	7
Non firefighters	0	37	1	-	8	44
Unknown	0	0	0	-	26	26
Total	12	115	34	46	26	241

Fire Size

We observed significant differences in the leading cause of mortality across different fire sizes. For fires larger than 100 ha (100 ha+), the percentage of fatalities in entrapments was 94% of the total of fatalities in entrapments (Table 3). Only 41.2% of the total fatalities in terrestrial casualties occurred in this 100 ha+ fire size category. Additionally, 57% of total fatalities in entrapments occurred in wildland fires larger than 500 ha (Table 3).

Table 3. Number of fatalities in entrapments in wildland fires and percentage of them in relation to the wildfire size classes in Spain (1980–2010).

Wildfire class (ha)	Number of fatalities	Percentage of fatalities
<100	4	5.6
>100	64	90.1
[100-250]	14	19.7
[250-500]	9	12.7
>500	41	57.7
Unknown	3	4.2
Total	71	100

The results for aerial casualties were different. Most of the fatalities in this kind of causality (56.5%) took place in fires smaller than 100 ha and 26% were not assigned to any fire size. In the case of physical causes, half of the fatalities occurred in large wildland fires (100 ha+) and the other half in small fires.

Extreme Weather Conditions

Under high temperature days, 69 firefighters (60% of the total) died in an entrapment. Additionally, the fires with a larger number of fatalities occurred under these conditions (La Gomera fire or Riba de Saelices fire). The same results (60%) were found for terrestrial casualties and physical causes. However, the percentage of fatalities in aerial casualties under HTD was only 25%.

Different Regions in Spain

A higher percentage of firefighters' fatalities was presented in the "Cataluña and C. Valenciana" regions. We observed that these two regions account for 34.9% of the total number of firefighters' fatalities while they represent only 13.0% of the total wildland surface and 15.8% of the total burned wildland surface in Spain. These two regions are the northeastern Mediterranean Coast area of Spain. When we enlarged that area to the entire Mediterranean Coast area of Spain, we found similar results (although not that intense). that the Mediterranean Coast area of "Andalucia, Murcia, C. Valenciana and Cataluña" represent 48.5% of the total number of fatalities while they represent only 25.0% of the total wildland surface and 27.4% of the total burned wildland surface in Spain (Table 4).

Table 4. Percentage of fatalities that belonged to the fire suppression system, burned area and forestry area in each Autonomous Community.

Regions	Percentage of fatalities	Percentage of burned area	Percentage of forestry area
Andalucía	13.6	11.0	10.0
Aragón	8.9	2.9	10.0
Canary Islands	3.0	1.6	2.0
Cantabria	0.0	2.4	1.0
Castilla La Mancha	12.4	5.1	14.0
Castilla y León	7.7	20.5	19.0
Cataluña	13.0	6.9	8.0
Comunidad de Madrid	3.6	0.8	2.0
Comunidad Foral de Navarra	1.8	0.5	2.0
Comunidad Valenciana	21.9	8.8	5.0
Extremadura	1.2	8.7	9.0
Galicia	9.5	22.2	8.0
Islas Baleares	1.2	0.5	1.0
La Rioja	0.0	0.4	1.0
País Vasco	0.6	0.7	2.0
Principado de Asturias	1.2	6.3	3.0
Región de Murcia	0.0	0.7	2.0

Different Emergency Systems in Spain

A higher percentage of fatalities were found in “all-in-one” emergency regions (unified emergency agencies that care about all issues including wildland fires, residential fires, and industrial fires) versus “Forest Service” emergency regions. “All-in-one” emergency regions include Cataluña, C. Valenciana, C. Madrid, P. Asturias, and C. Navarra. We observed that aggregating “All-in-one” emergency regions, they account for 41.5% of the total number of fatalities while they represent only 20.0% of the total wildland surface and 23.3% of the total burned wildland surface in Spain (Table 4).

Discussion

In the period 1980–2010 there were 241 fatalities and 1670 injured people in wildland fires in Spain recorded in official databases. However, there is evidence that many more victims were affected by the wildland fires but they could not be accounted for in this study due to a lack of data. Data about fatalities of people who worked in the fire suppression system are reliable. However, in the civilian victim’s dataset, some cases were not reported but as general numbers are adequate for the analysis that we present here. We assume that there is an underestimation in this case.

Fire suppression is a high-risk profession (Mangan 2007; Viegas 2009). Society and all involved agencies have to be informed about the job hazard situations and all available protocols to try to reduce victims in wildland fires. However, even though the new safety measures, protocols, and investments in fire suppression such as LACES or Dead Man Zone (Gleason 1991; Thorburn and Alexander 2001; Molina *et al*. 2010), the number of victims (injuries and fatalities) in wildland fires did not decrease from 1980 to 2010 in Spain. There are some remarkable analyses of firefighter injury/fatality data. Beaver (2002) addresses human behavior in risk taken actions and Karter (2012) examined the causes of firefighter injures. Beaver (2002) highlight training in the human behavior factor, and Karter (2012) does not see a significant decrease in injures in the USA in the last years.

The normalized fatal causality rate (fatalities per 100,000 burned ha) in Spain is higher than in other countries. The normalized fatal causality rate in Spain was 4.5. By contrast, in the United States, this value was 0.91 (Mangan 2007, 2009). Therefore this rate in Spain was approximately 4 times higher. It is true that in the U.S. large burning areas are dealt with minimum intervention. Data from some other European countries could be interested to compare but were not yet available to us. However, this is consistent with other working environments such as building and civil engineering works. Spain is a country with high levels of casualties in the work place (Tejedor 2006).

The entrapment is the most frequent cause of death in wildland fires with almost 50% of fatalities in Spain. In contrast, this percentage was 14% in the United States (Mangan 2007). In addition to this, the normalized fatal causality rate in entrapments in Spain was 2.15. By contrast, in the United States, this value was 0.19 Mangan (2007, 2009).This may indicate that our LACES and Dead Man Zone protocols are not working well enough. Therefore, we could improve our figures by trying to reduce the entrapments by working harder in safety protocols during fire suppression.

Considering the normalized fatal causality rate in aerial casualties, we show that in Spain is also higher than the United States (0.86 vs. 0.22). This could be related to the higher use of aerial resources in Spain, relative to that in the US. The Spanish fire suppression system uses aerial resources are even in small fires, therefore increasing the probability of aerial casualties. Indeed, most aerial fatalities (56.5%) occurred in fires smaller than 100ha. Terrestrial casualties might also be reduced and fatalities due to physical causes too but the percentages are similar to EEUU. Many agencies might control firefighter health better with adequate training and medical inspections during the fire working season; this is not done as intensively in all regions in Spain. Aerial casualties require an aeronautical review of the causality causes, and this is not in the database, and therefore, we cannot go further in this review regarding sub-causes.

As seen in Molina and Cardil (2013), Mediterranean Coast provinces have a worse scenario in terms of average size of large wildland fires. This is consistent with having more firefighter fatalities in those regions. Note that "Cataluña and C. Valenciana, the two regions with worse dead-firefighters' ratio, are "all-in-one" emergency regions. Having a worse scenario of large wildland fires has been one of the main causes to shift from Forest Service to all-in-one emergency service. Although this is a descriptive study, shifting to "all-in-one" emergency service has not been enough to reduce firefighters' mortality in action. It would have been interesting to compare temporal changes in firefighters' fatalities in "all-in-one" emergency regions versus "Forest Service" emergency regions, but many regions changed the system recently and the data are not sufficient to perform a rigorous temporal statistical analysis.

In the case of people that did not work in the fire suppression system, the majority of the death causes was unknown. Probably, the entrapment is the most important cause in this group because it is the most frequent cause in the known victims and there are many references to farmers who were entrapped while burning their farm. In addition, some people died in wildland urban interface areas as a consequence of fire or smoke. In Catalonia (NE Spain), 19 civilians died in Lloret de Mar (1978), 6 in Bages fire complex (4-6/July/1994), 5 in Vespella-Gaia (July/1995, 1000 ha), 1 in Solsones (20/July/1998), 5 in Sant Llorenç Savall (10/Augost/2003, 4500 ha), 1 in Doncell (17/July/2009) and 4 in Junquera-Portbou (22/July/2012, 12000 ha) (Bombers and Castellnou, personal communication).

Except for aerial casualties, fire size is a key factor in the victim occurrence as shown in our results. This could be related to two factors. First, in large wildland fires, fire behavior is normally more adverse and the probability of entrapment could be higher. Second, when an causality occurs in a wildland fire, an additional emergency starts. Therefore, many resources become diverted to try to mitigate the consequences of the causality, allowing the fire to propagate more freely and thus increasing the fire size. Implementing suitable forest management could reduce the fire behavior and diminish the fire potential, eventually decreasing the burned areas and the probability of casualties (Cardil and Molina 2013).

Extreme weather conditions could also influence the victim occurrence because 60% of the fatalities in entrapments in wildland fires occurred under high temperature days. However, this high concentration is not showing up in aerial casualties (only 25% under high temperature days). Therefore, we have to focus the safety protocols to avoid entrapments under high temperature days. Additionally, the annual average number of these days in Spain increased from 10 to 20 in the period 1980–2010 depending on the region of Spain (Cardil *et al*. 2013). Climate change projections (IPCC 2007) indicate that we will experience more extreme temperatures that could influence new casualties in years to come. Extreme weather conditions influence fire behavior and, therefore, increase the probability of entrapment. In addition, these conditions could affect firefighters and people due to dehydration, stress, and worse working conditions.

Conclusions

The number of both injured and killed people did not decrease since 1980 and the causality rate is very high. Therefore, new approaches are needed to reduce the number of victims in wildland fires in Spain. The entrapment is the most frequent cause of death and its share has to be reduced in the future as a measure of success in safety.

Fire size is a key factor in the occurrence of injuries and fatalities; 95% of fatalities in wildland fires (if aerial casualties are excluded) happened in fires larger than 100 ha. Extreme weather conditions are also related to victim occurrence because 60% of entrapments occurred under extreme weather days that represent only a small percentage (5–15%) of the total days in the fire season (June–September).

High quality training on safety protocols and safety practices are critical in order to pursue a lower causality rate. Lessons learned, and shared among different agencies, in this causality topic should encourage agencies to opt for high quality training on safety protocols and measures.

We recommend establishing new approaches to reduce the number of victims, increasing the safety of the fire suppression system personnel and civil population. Training with fire in prescribed burns could be an option to train personnel in real fire scenarios and communication difficulties due to the noise coming from the burning of vegetation and including additional communication difficulties to simulate a large fire scenario. The larger the prescribed burn sizes could be the better to get closer to real wildfire situations. These training actions (with prescribed burning) could be useful for citizens to understand a fire situation, how suppression agencies work, and how they should behave in a real emergency. It is remarkable to note that most entrapments are close to roads. Not all roads are safe. Eastaugh and Molina (2012) have shown how to decide which roads are safer using extensive simulations with FlamMap (Finney 2002).

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GENERAL DISCUSSION

Both population and politicians want to decrease burned areas in Spain as other countries and society have made an effort investing money in resources and training in fire agencies. However, under the actual fire suppression policies and practices in Spain, my data shows that we are unable to further reduce the effects of LWF by spending more money in suppression means in reasonable figures (Cardil and Molina, 2013). The relative burned area decreased in MC and NW regions in 100 ha+ wildland fire category and only in MC in 250 ha+ and 500 ha+ categories from 1978 to 2010. However, observing the data in more detail and highlighting the underlying trends in all Spanish regions, we detected that after 1995, the decrease in both the number of LWF and the burned area did stop despite the additional investments in technology, roads, water reservoirs, material and human resources. The mean size did not decrease in any region and the significance of LWF larger than 500 ha with extreme fire behavior is higher in all regions in the recent years. Additionally, some of the largest fires in South Europe occurred in last 20 years (Portugal 2003, Greece 2007, Spain 2012 and 1994, France 2003). Therefore, fire suppression effectiveness to reduce the effects from LWF is not improving in recent years.

The reason so what we are not reducing burned areas could be related to agricultural abandonment and land cover changes that has increased fuel load (Millán et al., 1998) and the fuel homogeneity and continuity that are facilitators for both a faster fire propagation and a higher fireline intensity (Pausas et al., 2012; Molina et al., 2010; Vega-García and Chuvieco, 2006). Climate change issues are also instrumental and they could be already playing a significant role (Moreira et al., 2011) due to the increase in the number of years with adverse fire weather; i.e., an increase in the length of the fire season and/or more frequent extreme events (Cardil et al.,2013; Moriondo et al., 2006). In a similar way, Pausas et al. (2012) tested the hypothesis that fire regime changed in western Mediterranean Basin during the last century. They compiled a 130-year fire history for the Valencia province (Spain) to assess the role of climate and human-driven fuel variations on the fire regime change. The outcome suggested that there was a major fire regime alteration about the early 1970s in such a way that fires augmented in annual frequency (doubled) and area burned (an order of magnitude).

My thesis focuses on heat wave days and their effects on large wildland fires in South Europe. Mean, maximum, and minimum temperatures have increased and will likely continue to increase in southern Europe in the future (Moriondo et al., 2006; IPCC, 2007; Giorgi and Lionello, 2008; Giannakopoulos et al., 2009). My thesis shows that there was also a trend towards more frequent HTDs in the summer (June to September) in Mediterranean coastal areas and at more southerly latitudes across the South Europe. Areas with the highest increases in terms of the annual number of HTD_{20} (June–September period) were found both in Greece and along the Spanish Mediterranean Coast. These areas are likely to be especially susceptible to the variety of impacts associated with heat-wave episodes, including ecological, social, and economic impacts. While higher-latitude (more northern) sites exhibited a smaller increase in the number of days with $HTD_{22.5}$ and HTD_{20} than lower latitudes, the number of days exceeding the 95th percentile increased with increasing latitude. This finding is corroborated by the higher relative increase in HTD_{95} and HTD_{20} with latitude. It may be that the affected vegetative, social, and economic systems at the lower-latitude sites have already experienced some of the pressures of adapting to, or mitigating.

Overall, in southern Europe, most high-temperature days are related to the weather system that brings hot, dry air masses from North Africa (Rodriguez-Puebla et al., 2010; Pereira et al., 2011). However, we did not find the same HTD trends in NW Iberia, where other reports have documented increased warming of surface temperatures from 1974 to 2006 (Gómez-Gesteira et al., 2011), or in interior Spain. It is plausible that air fluxes from North Africa do not reach this area as frequently as they do in other regions, or that their influence is mitigated by other weather systems associated with Atlantic currents. Some HTDs might simply be caused by summer heating in central Spain (Spanish Plateau, 800ma.s.l.).

Frequent heat waves in the last decade or so (2000–2012) have also triggered the occurrence of large wildland fires (Trigo et al., 2006; Barriopedro et al., 2011; Cardil et al., 2013) in the Euro-Mediterranean region. On hot days, ignition probability is higher and wildland fire behavior is typically more extreme. As a result, fires may be difficult to contain as they exceed the firefighting capabilities (Riaño et al., 2007; Salis et al., 2012; Cardil and Molina-Terren, 2013). My works have shown that high-temperatures days account for the majority of area burned in wildfires in some regions in Spain and Italy (Cardil et al., 2013, Cardil et al., 2014a; Cardil et al., 2014b), where the average daily number of large fires and daily area burned was higher during HTDs than in non-HTDs (Cardil et al., 2013; Cardil et al., 2014a; Cardil et al., 2014b). Therefore, if extreme conditions (i.e., HTDs) are becoming more frequent, as my data suggests, forest fire risk and area burned will most likely increase.

In the case of the whole Spain and Sardinia, the total annual number of LWF and the annual number of LWF occurring under non-HTD decreased for the majority of the analyzed points. Nevertheless, the annual number of LWF under HTD did not change in the same time span. Similar results were obtained in relation to the burned area. This circumstance could be explained through more efficient modern fire control activity due to significant investments in fire suppression technology and training in recent years. Fires occurring on HTDs however are difficult to contain even with modern methods, and hence, no reduction in their number or severity was found. HTD also influenced mean fire size of LWF. Similar results were obtained considering Aragon and Sardinia studies.

We highlight here a remarkable result of our analysis: the high proportion of area burned under HTD. On only 5 % of days in the summer season (June–September inclusive in the 1978–2010 period) characterized by HTD conditions, in some regions, fires burned around 40 % of the total burned area. This occurred mainly in the Spanish Mediterranean Coastal region. In North Spain, we did not find values so high. This could be related to the higher number of ignitions in the Northern Spain and suppression means cannot deal with all simultaneous ignitions in a single day being a HTD or non-HTD. This work shows that HTDs are critical for both fuel managers and firefighters because they could increase in the future and, most likely, fires spreading under HTD will propagate faster and further.

The majority of the largest historical fires (>5000 ha) in Spain occurred under extreme HTD conditions, as for instance in 1994, 2006, and 2009, and they are more frequent in the most recent 20 years. Regarding HTD, in the period 1977–1987, only 4%of the fires were larger than 1000 ha. However, from 1988 to 2010 they made up almost 10 %. Forty-five percent of fires larger than 5000 ha in the 1994–2010 period occurred in the Mediterranean Coast region where HTDs increased significantly. This supports the statement that HTDs provide more extreme conditions for fire propagation and increase the difficulty of controlling those fires. This could be a challenge in the future.

Extreme weather conditions could also influence the victim occurrence because 60% of the fatalities in entrapments in wildland fires occurred under high temperature days. However, this high concentration is not showing up in aerial casualties (only 25% under high temperature days). Therefore, we have to focus the safety protocols to avoid entrapments under high temperature days. Additionally, the annual average number of these days in Spain increased from 10 to 20 in the period 1980–2010 depending on the region of Spain (Cardil et al. 2013). Climate change projections (IPCC 2007) indicate that we will experience more extreme temperatures that could influence new casualties in years to come. Extreme weather conditions influence fire behavior and, therefore, increase the probability of entrapment. In addition, these conditions could affect firefighters and people due to dehydration, stress, and worse working conditions.

Whereas it is accepted that the major determinants in fire weather forecasting are low humidity, high temperatures, and strong winds near the ground surface, meteorological indexes developed to evaluate temporal and spatial changes in meteorological conditions are not frequently used or available for all fire weather forecast agencies (Charney and Keyser 2010; Crimmins 2006). It is often not clear which surface-based indices may be most appropriate (Eastaugh et al. 2012), and it is difficult to find a single index that performs uniformly well across large heterogeneous areas (Padilla and Vega-García 2011; Arpaci et al. 2013). For these reasons, we highlight the significance of discerning between HTD and non-HTD defined by the 850 hPa synoptic conditions in developing pre-suppression efforts to prepare for large fires. It would be extremely useful to be able to distinguish the simply "bad" and "very bad" (extreme temperature) fire days with some reasonable lead time (i.e., 24 or 48 h) to plan the best strategies for suppression assets and to predict extreme fire behavior. We found in this work that this classification concerning HTD and non-HTD (at 850 hPa) can be used for that discrimination. The 850 hPa pressure level is representative of the Earth's surface at broad spatial scales and has the potential to identify unusually severe fire weather events (García-Ortega et al. 2011).

CONCLUSIONS

The annual number of HTDs increased significantly in many areas across southern Europe, including the Spanish Mediterranean Coast, Italy, and Greece. However, we did not find significant increases in the south of France, interior Spain and the northwestern Iberian Peninsula, Higher increases in terms of annual number of HTDs were found in both Greece and along the Spanish Mediterranean Coast. In these areas, extreme-temperature conditions are becoming more frequent now and could become more common in the future. In addition, where temporal increases were detected, the relative increase in 95th percentile temperature was larger at higher latitudes. Where social, infrastructure, and economic systems are not preconditioned to high-temperature days and heat waves, the severity of increased temperature effects may be more dramatic.

Even though money invested in suppression efforts increased across the studied period, neither the number of fires nor the area burned diminished under high-temperature days, although a decrease of both indicators was detected under non-HTD. There are significant effects of HTD conditions in the number of LWFs, total LWF area burned, and average LWF size in Spain. As a result, if the number of HTD conditions increases in the future, fire suppression will be compromised. In the 4-month summer season, although only 5% of days are characterized by HTD conditions, fires on these days account for around 25% of the total burned area in Spain. They were 15% of the total number of fires larger than 100ha. The classification of HTD and non-HTD (at 850 hPa) can be used for identifying those days , with a reasonable lead time, that can cause more difficulties in fire suppression and to better distribute (spatially and temporally) the available resources.

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