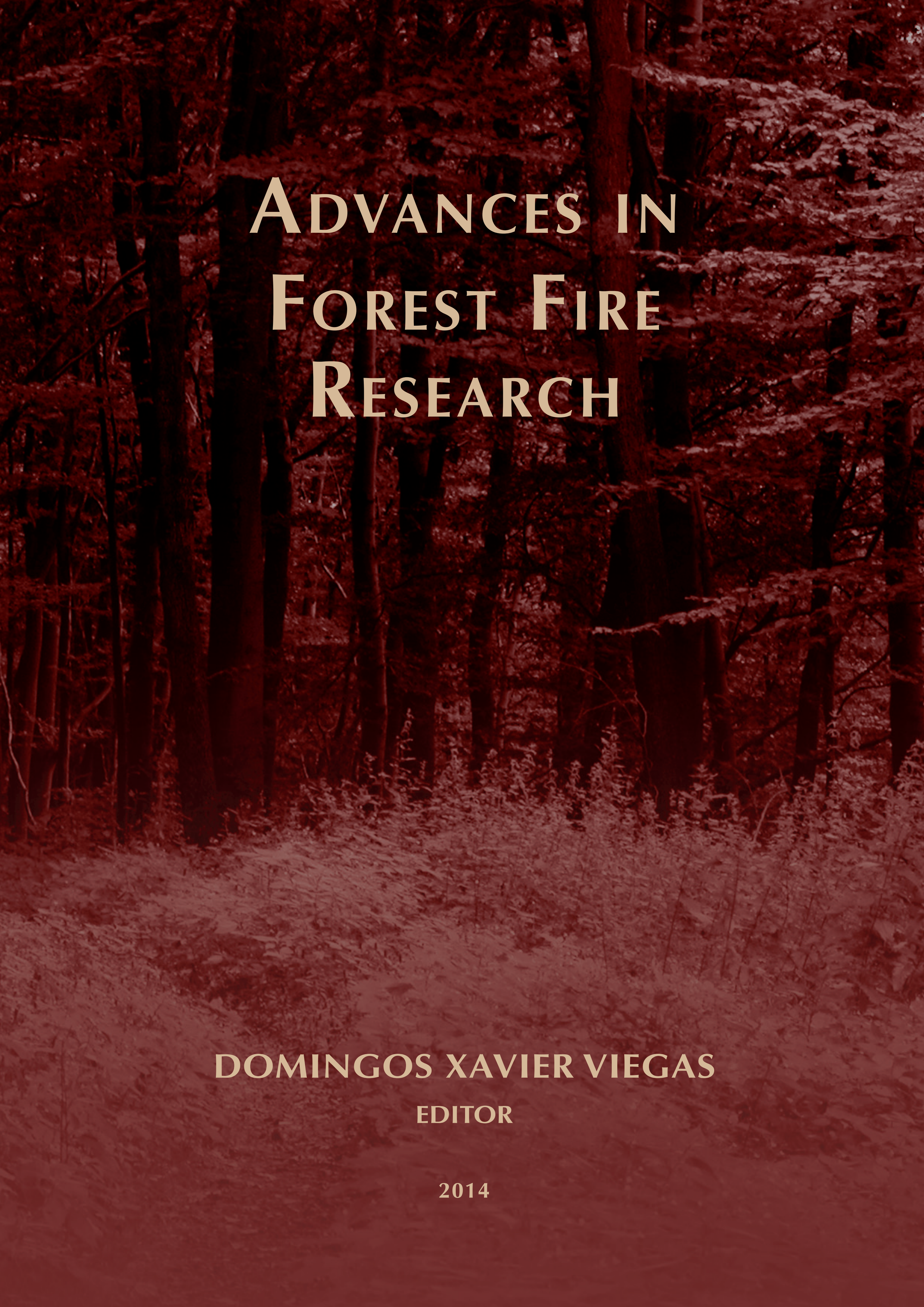

Advances in Forest Fire Research

Domingos Xavier Viegas

Editor

2014

Use of weather generators for assessing local scale impact of climate change on dead fuel moisture

Grazia Pellizzaro[a], Martin Dubrovsky[b], Sara Bortolu[a], Bachisio Arca[a], Andrea Ventura[a], Pierpaolo Duce[a]

[a] *National Research Council, Institute of Biometeorology (CNR-IBIMET), Traversa La Crucca 3 Sassari Italy, g.pellizzaro@ibimet.cnr.it*
[b] *Institute of Atmospheric Physics, Praha, Czech Republic, madu1110@gmail.com*

Abstract
The main aims of this work are to identify useful tools to determine potential impacts of expected climate change on dead fuel status in Mediterranean shrubland and, in particular, to estimate the effect of climate changes on the number of days characterized by critical values of dead fuel moisture. Measurements of dead fuel moisture content in Mediterranean shrubland were performed in North Western Sardinia (Italy) for six years by using humidity sensors. Meteorological variables were also recorded. Data were used to determine the accuracy of the Canadian Fine Fuel Moisture Code (FFM code) in modelling moisture dynamics of dead fuel in Mediterranean vegetation. Critical threshold values of FFM code for Mediterranean climate were identified by percentile analysis, and new fuel moisture code classes were also defined.
A stochastic weather generator (M&Rfi), linked to climate change scenarios derived from 17 available General Circulation Models (GCMs), was used to produce synthetic weather series, representing present and future climates, for the selected site located in North Western Sardinia, Italy. The number of days with critical FFM code values for present and future climate were calculated and the potential impact of future climate change was analysed.

Keywords: *Forest fires, Mediterranean shrubs, Fine fuel moisture code, Downscaling techniques*

1. Introduction

The moisture content of dead fuel (FMC) is an important variable in fire ignition and fire propagation and is strongly affected by changes in atmospheric conditions. According to projections of future climate in Southern Europe, changes in temperature, precipitation and extreme events are expected (Christensen *et al*. 2007; Giannakopoulos *et al*. 2009; Giorgi *et al*. 2004). More prolonged drought seasons could influence fuel moisture content and, consequently, the number of days characterized by high ignition danger in Mediterranean ecosystems (Flannigan *et al*. 2009; Flannigan *et al*. 2013; Liu *et al*. 2013; Matthews *et al*. 2012; Westerling *et al*. 2006).
The low resolution of the climate data provided by the general circulation models (GCMs) represents a limitation for evaluating climate change impacts at local scale. For this reason, the climate research community has called to develop appropriate downscaling techniques. One of the downscaling approaches, which transforms the raw outputs from the climate models (GCMs or RCMs) into data with more realistic structure, is based on linking a stochastic weather generator with the climate model outputs. Weather generators linked to climate change scenarios can therefore be used to create synthetic weather series (air temperature and relative humidity, wind speed and precipitation) representing present and future climates at local scale.
Moisture exchange in dead materials is controlled by physical processes, and is clearly dependent on rapid atmospheric changes. Therefore, some meteorological danger indices can be used for modelling the moisture dynamics of dead fuel (Van Wagner 1977; Chandler *et al*. 1983; Van Wagner 1985; Wotton, 2009; Matthews, 2014).

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2. Materials and Methods

The study was carried out in in North Western Sardinia, Italy (40° 36' N; 8° 09' E, 30 m a.s.l.). Climate is Mediterranean with water deficit conditions occurring from May through September and precipitation mainly concentrated in autumn and winter. The mean annual rainfall is 640 mm and the mean annual air temperature is 16.8 °C. The experimental area is mainly covered by Mediterranean shrubs.

Figure 1. Experimental site location

The study was carried out in two different phases. In the first one, FMC values (1 hour and 10 hours fractions) were periodically determined during six consecutive years on three Mediterranean shrub species: *Cistus monspeliensis* L., *Pistacia lentiscus* L., and *Juniperus phoenicaea* L. During the same period meteorological variables and temporal patterns of moisture content, measured by using humidity sensors, were recorded. The relationships between direct field measurements and FMC values given by moisture sensor were analysed. Then, the Canadian Fine Fuel Moisture Code (FFM code) was calculated. Finally, FMC values obtained from fuel sensors were used to develop appropriate FFM code danger classes specific for Mediterranean climate.

In the second step the potential climate change impact on fuel status and ignition danger season in Mediterranean area was simulated. The weather generator M&Rfi (Dubrovsky *et al*. 2005, 2007) linked to climate change scenarios derived from 17 available General Circulation Models (GCMs), was used to produce synthetic weather series, representing present and future climate (2100) for the selected site (Table 1). The downscaling of future climate projections was made using three scenarios (A2, B1, and A1B) from the IPCC Special Report on Emission Scenarios (Nakicenovic *et al.* 2000) . The projected future climates were then used to calculate the FFM code of the Canadian Forest Fire Weather Index System (Van Wagner 1987) and to estimate possible impacts of climate change on dead fuel moisture content pattern.

Table 1. General Circulation Models (GCMs) used in conjunction with the M&Rfi weather generator to produce synthetic weather series representing present and future climates at four location in North Sardinia, Italy

BCM2	Bjerknes Centre for Climate Research, Norway
CGMR	Canadian Center for Climate Modelling and Analysis, Canada
CNCM3	Centre National de Recherches Meteorologiques, France
CSMK3	Commonwealth Scientific and Industrial Res. Organisation, Australia
ECHOG	Met. Inst. Univ. Bonn + Met. Res. Inst., Korea + Model and Data Groupe at MPI-M, Germany
GFCM20	Geophysical Fluid Dynamics Laboratory, USA
HADCM3	UK Met. Office, UK
HADGEM	UK Met. Office, UK
INCM3	Institute for Numerical Mathematics, Russia
MIMR	National Institute for Environmental Studies, Japan
MPEH5	Max Planck Institute for Meteorology, Germany
MRCGCM	Meteorological Research institute, Japan
NCCCSM	National Centre for Atmospheric Research, USA
NCPCM	National Centre for Atmospheric Research, USA
GFCM21	Geophysical Fluid Dynamics Laboratory, USA
GIER	Geophysical Fluid Dynamics Laboratory, USA. Model E20/Russel
IPCM4	Institute Pierre Simon Laplace, France

3. Results

A highly significant relationship (R^2=0.82; $p< 0.001$) between direct measurements of FMC and values given by fuel moisture sensor was observed. Therefore, we used FMC values by sensor measurements to calibrate FFM code for Mediterranean species.
The range of values of FFM code (from 10 to 95) was divided into 35 classes of equal width (2.5). The frequencies of number of days characterized by values lower than 20% and 15% for each FFM code class were calculated. Figure 2 shows that most of days with moisture content lower than 20% and 15% are included in the FFM classes 87.5 and 90, respectively, and corresponded to 85th and 95th percentile of FFM series, respectively. Therefore, threshold values equal to 85th and 95th percentile of FFM code values calculated by synthetic weather series representing present and future climates were selected to identify days characterized by high (85th percentile) and extreme (95th percentile) fire danger.

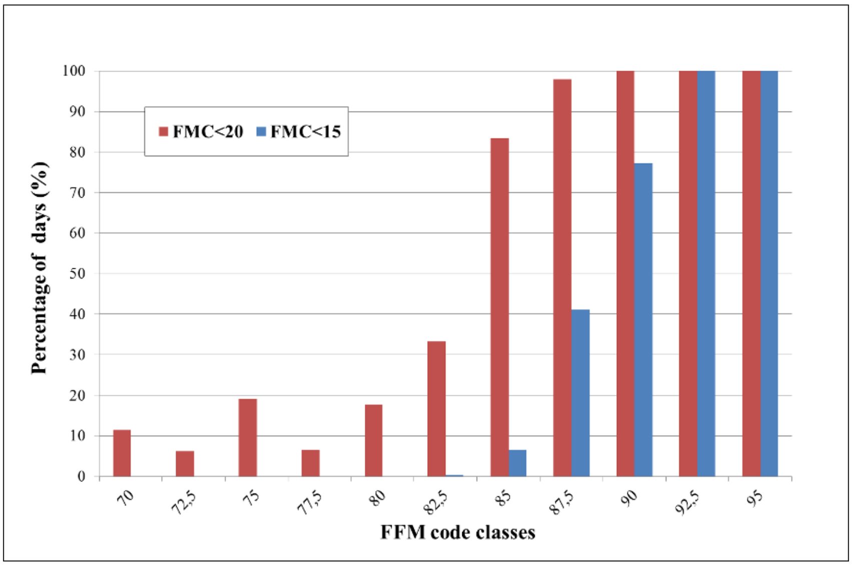

Figure 2. Frequency distribution (percentage) of days when dead fuel moisture content values (FMC) were less than 15% and 20% by FFM code classes (2007-2012)

Figures 3 and 4 show the forecasted total number of days characterized by high and extreme fire danger for each GCM and scenario (actual and 2100 projection) relative to April - October months.

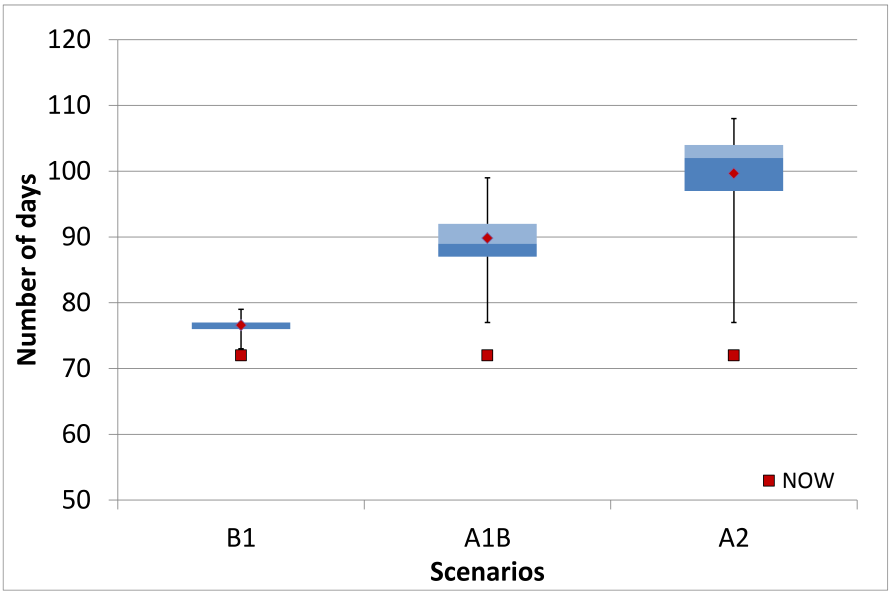

Figure 3. Boxplot of the actual and projected (blue) number of days characterized by high danger (85th percentile) relative to three climate change scenarios (B1, A1B, and A2). The chart shows the mean (red diamond), median, minimum and maximum values, and the lower and upper quartiles. The actual number of days characterized by high danger are indicated by the red squares (April - October period).

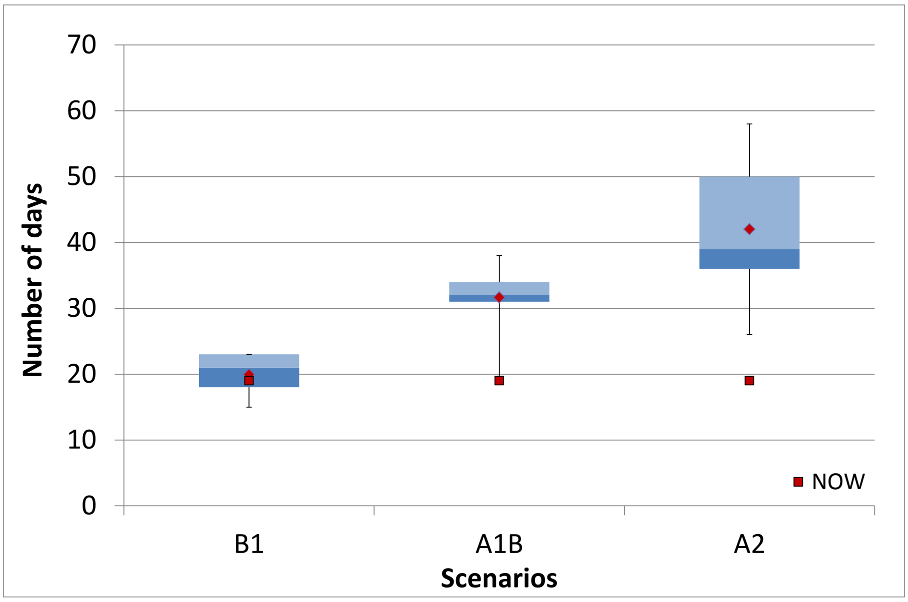

Figure 4. Boxplot of the actual and projected (blue) number of days characterized by extreme danger (95th percentile) relative to three climate change scenarios (B1, A1B, and A2). The chart show the mean (red diamond), median, minimum and maximum values, and the lower and upper quartiles. The actual number of days characterized by extreme danger are indicated by the red squares (April - October period).

No evident differences between baseline period and future were observed for B1 scenario especially regarding days characterized by extreme danger. More evident changes were observed for A1B and A2 scenarios. For A1B scenario the mean total number of high and extreme danger days is expected to increase by 18 and 12 days, respectively, compared to the present climate. The increase of high and extreme danger days reached 27 and 23 days in the case of A2 scenario.

Analysis of distribution of danger days throughout the April - October period shows that in general the increase of days characterized by high danger (85th percentile) is likely to occur during the second half of summer. For all three scenarios, in fact, the number of danger days increased in August and September. In addition, our results suggest that the fire season may end later than today (scenarios A1B and A2), although scenario A2 projections indicate a possible anticipation of the fire season.
With reference to extreme days (95th percentile), a general increase of number of critical days is likely to occur on the basis of A1B and A2 scenarios that are characterized by intermediate (A1B) and high (A2) anthropogenic greenhouse gas emissions.
In conclusion, this study confirms that an increase of number of days critical for fire occurrence and a longer fire season could be expected also in Mediterranean areas as a consequence of climate change projections.

4. Acknowledgements

This work was partly supported by the EU 7th Framework Program (FUME) contract number 243888. The authors are also grateful to Mr Angelo Arca and Mr Pierpaolo Masia for their valuable support in the field work

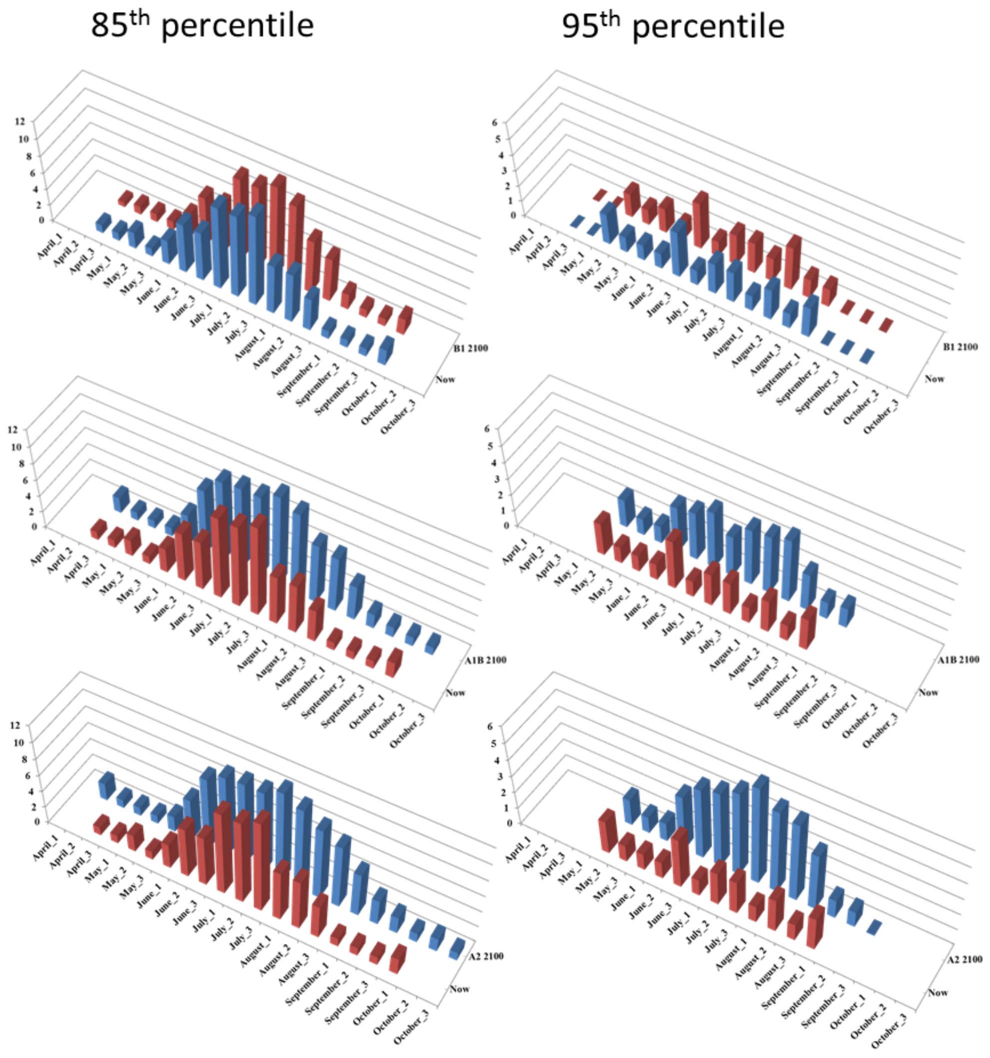

Figure 5. Mean total number of days with high (85th percentile) and extreme danger (95th percentile) at the end of the century during the period April 1st to October 30th. Mean values were calculated per ten-days periods and three climate change scenarios (B1, A1B, and A2) .

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