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Fire Weather Index (FWI) classification for fire danger assessment applied in Greece

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Abstract

The Fire Weather Index (FWI) has been studied by several researchers for a number of geographical areas in the world and has been proven to be an effective index for fire danger assessment. However, limited work has been done so far, for the calculation, the appropriate classification and mapping of FWI, at a higher spatial resolution that could be more efficient for operational use, at both national and local levels, for those countries with similar climatic and physical characteristics to Greece. A methodology is introduced in this paper for a straight-forward calculation, appropriate classification and mapping of the FWI in Greece. The methodology uses the Weather Research and Forecasting (WRF) mesoscale model to obtain high spatial resolution meteorological fields, while at the same time, the proposed classification takes into consideration the environmental variety of the country, which could highly influence the significance of FWI values and consequently their interpretation as reasonable and functional fire danger classes. The proposed approach of Percentile Indices provides suitably varying FWI boundaries of classes based on the specific physical characteristics of the study area. The new methodology of fire danger mapping has been validated using historical datasets of fire ignition location and burned areas of the country during the five-year fire period of study (2009-2013).

Key words: Fire weather, fire danger, Greece, FWI mapping, classification scheme

1 Introduction

Fire Danger is a general term used to express an assessment of fixed and variable factors of the fire environment that determine the ease of ignition, rate of spread rate, difficulty of control and fire impact (Merrill and Alexander, 1987). The Fire Weather Index (FWI) System is one of the two major subsystems of the Canadian Forest Fire Danger Rating System (CFFDRS) (Stocks et al., 1989). Van Wagner (1987) describes the structure and components of the FWI System. FWI represents the potential fireline intensity (Van Wagner, 1987) and it is a good indicator of fire danger (Stocks et al., 1989).

The FWI System, apart from Canada, has been adopted in other regions of the world, like the Mediterranean (Viegas et al., 1999; Dimitrakopoulos et al., 2011). Viegas et al. (1999) found that the FWI System components were well correlated with fire activity in southern Portugal, Spain, France and Italy, although the vegetation and dry Mediterranean climate were very different than those of Canada. Currently, the Joint Research Centre (JRC) of the European Commission uses FWI as a reference index to produce fire danger maps at a European level (Camia et al., 2008; San-Miguel-Ayanz et al., 2013).

The operational implementation of a fire danger rating system for an environment distinct from the original one (that of Canada), often requires an adjustment of its components. Several methods have been developed to allow the implementation and adjustment of fire danger rating systems to different conditions. Alexander (1994) revised the methodologies of calibration of the CFFDRS and proposed a fire-behaviour based criterion, where each fire danger class represents a distinct fire suppression difficulty, which is a

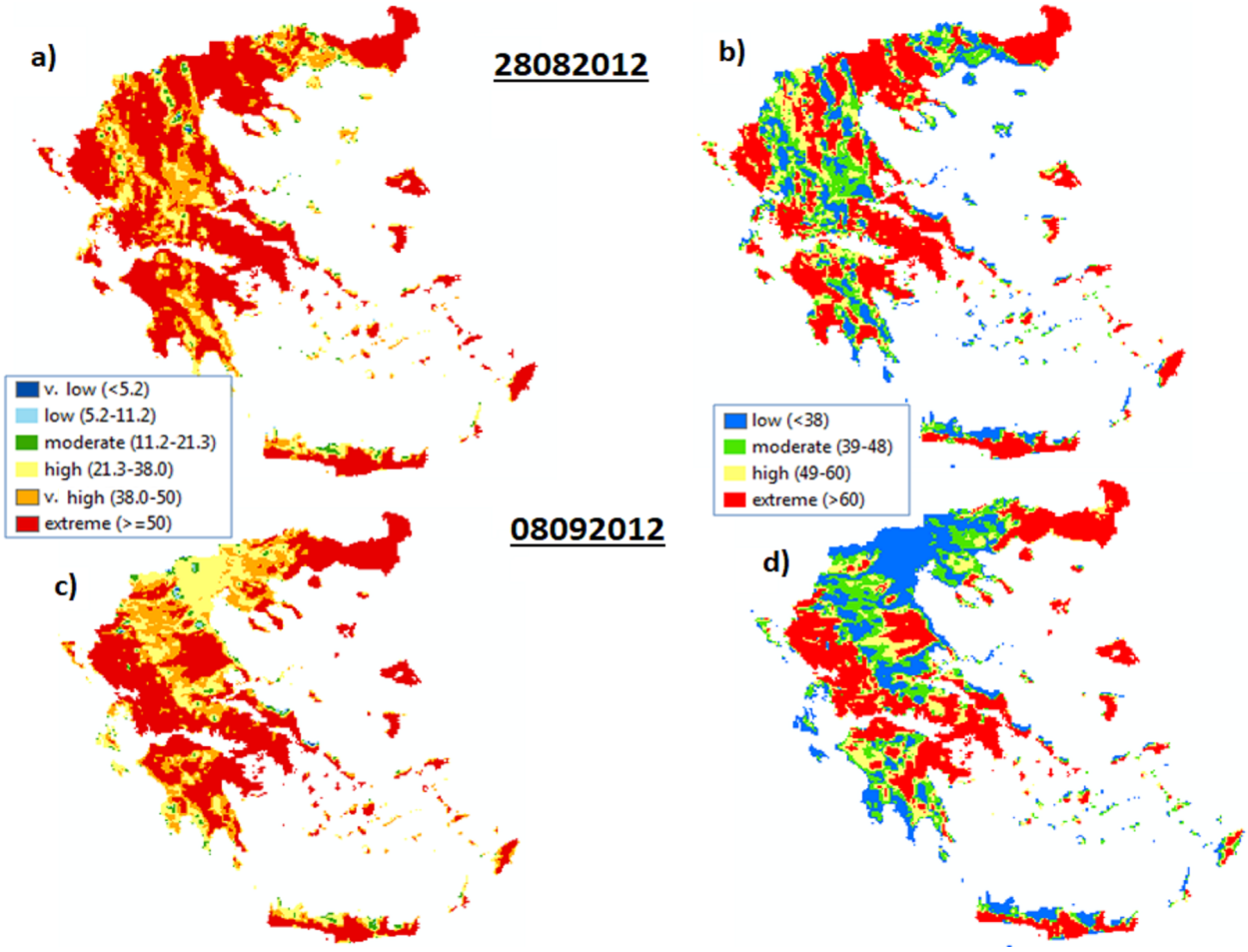

Figure 1: Classified FWI daily maps based on proposed classification by EFFIS (a, c) and Dimitrakopoulos et al. (2011) (b, d), for two selected dates, August 28, and September 8, 2012.

function of Byram's fireline intensity. Some authors (e.g. Haines et al. (1983); Van Wagner (1987); Viegas et al. (2004); Lynham and Stocks (1989)) adjusted fire danger classes by analysing fire weather history and temporal data series of the FWI system components. Those calibration methods could provide an estimation of the fire activity on a given day.

Understanding the links between weather and fires is important for implementing effective fire prevention policies (Karali et al., 2014). Xanthopoulos and Varela (1999) studied the forest fire danger distribution at the Forest Service Office (FSO) level in Greece, using fire data from the 1983–1993 period, suggesting the categorization of all Local Forest Service Offices (LFSO) based on the fire regime (fire frequency and pattern) prevailing in each LFSO area.

The FWI was evaluated by Dimitrakopoulos et al. (2011) and Karali et al. (2014) specifically for fire prone areas in Greece. Both studies proposed FWI value classes for association with fire danger. Giannakopoulos et al. (2009) and Good et al. (2008) studied the meteorological conditions associated with extreme fire danger (FWI>30) in Mediterranean areas and the relevance to climate change and climate models. Xanthopoulos et al. (2014) investigated the fire weather conditions leading to large forest fires in the broader area around Athens, Greece. That work was prompted by the operational need to tie the potential for such fires to FWI and provided some thresholds that could be useful for setting mobilization levels according to the predicted weather conditions and FWI, as well as for guiding pre-fire positioning of firefighting resources and supporting dispatching decisions in case of fire breaking out.

Ignition and burned areas depend on climate and meteorological features (Turco et al., 2017). Although anthropogenic ignition is dominant in Greece, as in most Mediterranean regions (Ganteaume et al., 2013; San-Miguel-Ayanz and Camia, 2010; Catry et al., 2010), the variations in the ease of ignition and in the burned area are governed by the presence, amount and connectivity of fuel (fuel structure) and by its moisture content (fuel flammability) (Pausas and Ribeiro, 2013). Daily and seasonal weather conditions that directly affect the moisture of fine, coarser fuel particles are very important factors for the estimation of the above fire parameters and consequently for the fire danger level estimation.

To date, the classification of the FWI values into Fire Danger Levels mapping for areas in Greece has been based either on existing classes of the European Forest Fire Information System (EFFIS), the Canadian one, or classes that have been derived from local and regional studies. However, such classes are considered inadequate for the Fire Danger mapping of Greece, since the interpretation of FWI values regarding Fire Danger Level, using the same classification boundaries for the whole country area, leads to systematic overestimation or underestimation of Fire Danger for certain regions according to the results of our preliminary study. Specifically, the application of other classification schemes for the qualitative comparison to fire history data on representative daily FWI value maps yielded the following results (see Fig. 1): a) an overall overestimation of the fire danger level of the EFFIS classification scheme as it proposed rather low threshold class values (six (6) classes: v. low [<5.2], low [5.2-11.2], moderate [11.2-21.3], high [21.3-38.0], v. high [38.0-50.0] and extreme [≥50.0]), particularly in the southern parts of Greece, where fire danger levels were reported as very high and extreme for most of the days of the fire period and b) a high diversity between the fire danger levels during the same day in adjacent areas based on Dimitrakopoulos et al. (2011) classification (four (4) classes: low [<38], moderate [39-48], high [49-60], extreme [>60]), frequently combined with a significant underestimation of the danger level, particularly in mountainous areas.

More particularly, the following important conclusions were drawn about existing schemes based on our preliminary investigation: i) when applied to the whole country, the classification scheme of Dimitrakopoulos et al. (2011) classifies the northern part of Greece systematically into the lower classes, despite the fact that there are days of significant fires in this region; ii) the classification scheme of EFFIS or Giannakopoulos et al. (2009) (based on the Canadian classes) classifies large areas of the country into the two higher classes (i.e. high and extreme) during most of the fire season. The above findings eliminate the operational usefulness of the fire danger level mapping according to those classification schemes in Greece. The country is characterized by an intense forest fire history as well as by a variety of climatic and vegetation conditions and the existing classification boundaries are inadequate for the definition of rational fire weather danger estimation and fire danger level mapping required for operational purposes at a local, regional or national level. Therefore, there is a great need to overcome such setbacks and introduce a different approach for the identification of a simple and effective classification scheme of FWI that can be applied in Greece for operational purposes. The methodology proposed here is built on sound, well-documented fire history databases and meteorological data that can be processed straightforwardly. This methodology can also be considered as an application case in a geographical area with a substantial diversity of environmental conditions and a history of significant forest fires in terms of spatial distribution, spread and frequency of occurrence. A classification scheme for FWI is therefore proposed, aiming at:

1. the effective mapping of the danger level for those regions within the envisaged area that are systematically under-represented.

2. the effective mapping of the danger level in such a way as to depict the appropriate classes in order to avoid gross spatial classification of FWI values to the highest classes, which leads to useless readiness alert (operational use).

2 Data and methods

2.1 Description of the application area

The Mediterranean climate and the vegetation of Greece are subject to a number of regional and local variations based on the country's physical diversity. Greece is characterized by a highly heterogeneous natural environment and a climate that varies from continental Mediterranean in the north to subtropical Mediterranean in the south, with rapidly decreasing continental characteristics from north to south and from the interior to the coastal regions and islands (e.g. Lolis et al. (1999)). The wide variety of Mediterranean climate subtypes encountered in several regions of Greece is mainly due to the influence of the topography on the air coming from the moisture sources of the central Mediterranean Sea. As a consequence, the western part of the Greek territory is generally wetter, while the eastern part is much drier and windier, mainly during the summer season.

Several studies support the hypothesis that in the Mediterranean type ecosystems, where the Greek ecosystems belong, the climate is the primary driver of the interannual variability of fires, controlling fuel flammability and fuel structure (e.g. Pausas and Ribeiro (2013); Pereira et al. (2005); Koutsias et al. (2013); Bedia et al. (2014). Increased fuel flammability, due to warmer and drier summer conditions (i.e. changes in fuel conditions), is considered to be one of the greatest fire responses to climate change. Fire activity is also favoured by the presence of fine fuel, which can be produced during antecedent periods (e.g. spring time) with favourable climatic conditions and reduced during warm and dry periods (changes in annual fuel loading due to dry and hot springs) (Turco et al., 2014).

One of the most important ecological problems that Greece faces every summer is the forest fires that burn trees and cause significant ecosystem damage. Greece suffers from significant forest fires, both in ecological and socioeconomic terms. The forest fires of the summers of 2007 and 2009 are tragic examples of a series of massive wildfires that broke out across several areas in Greece and burnt villages and areas of extreme natural beauty. Many other fires preceded and followed, such as the fires on

Parnitha Mountain (June 28, 2007), characterised as the last green area remaining close to Athens, in Evia island (August 2007) and other mainland regions.

Given the high physical diversity of the country, it is obvious that an appropriate classification of FWI is necessary for obtaining a reasonable FWI value interpretation of fire danger, useful for operational purposes, for the various sub-regions within the country. During the Greek fire period (May 1st - October 15th), the General Secretariat of Civil Protection of Greece provides a fire danger map daily at a national level, based on empirical estimations. According to this, the fire danger level is classified into five (5) classes, corresponding to each Forest Service area (LFSO boundaries).

In the current study, the same LFSO boundaries have been selected for the delineation of sub-areas, that can be considered as homogeneous in terms of physical characteristics (i.e. climate zone, ecosystem) and operational attributes (fire prevention, fighting resources). The country has 106 LFSO areas in total with an average area size of 1,250 km^2. Thus, in compliance with the operational protocol of the General Secretariat of Civil Protection, a five (5) classes scheme for the expression of fire danger level and the Greek LFSO areas as the geographical units of analyses are considered for the implementation of the proposed FWI methodology of classification.

2.2 FWI classification Methodology

The proposed classification methodology for FWI is built upon two basic aspects:

- the distinctive FWI spatial differentiation across the area of interest
- the relation between the forest fire history and the FWI behaviour in the study area.

FWI is comprised of six components: three fuel moisture codes and three fire behaviour indices. Calculation of the components is based on daily observations made at noon of air temperature, relative humidity, 10-m wind speed and 24-hour cumulative precipitation.

The calculation algorithm of FWI is quite complex (Van Wagner and Pickett, 1985). According to the literature, FWI values range from 0 to above 100 and are categorized, for operational purposes, into four (4) to six (6) classes, depending on the application area, corresponding to the different fire danger levels (Alexander, 1994; Dimitrakopoulos et al., 2011; Camia et al., 2010; Palheiro et al., 2006). In this study, a five- (5) class categorization has been adopted for the reasons previously discussed.

A software module of the Geographical Fire Management Information System G-FMIS (Varela et al., 1994; Eftichidis et al.), developed in C++ programming language, was used for calculating the FWI map series based on the meteorological fields provided by the meteorological model (see Section 2.3) for each day of the period of interest. The fire danger raster map (FWI map), at a spatial resolution of 3x3 km^2 has been calculated for every day of the fire seasons (May 1st - October 15th) for 2009-2013 for the geographical area of analysis (Greece, 106 LFSO).

2.3 Datasets used for Greece

The necessary meteorological variables (air temperature at 2 m, relative humidity, 10-m wind speed and 24-hour cumulative precipitation) for the FWI calculation were provided by the mesoscale, non-hydrostatic, compressible atmospheric model, Advanced Research Weather (ARW) - Weather Research and Forecasting (WRF) (version 3.4.1), (Skamarock et al., 2008). The WRF model was set-up and parameterized to simulate the three-dimensional meteorological fields for Greece (e.g. (Vlachogiannis et al., 2013; Emmanouil et al., 2015, 2016). Simulations were performed for the periods May 1st- October 15th 2009-2013, in two nested domains following a one-way nesting procedure. The outer domain, covering Europe, included 432 x 432 cells of 15 x 15 km^2 horizontal resolution and the inner domain, covering Greece, comprised 286 x 286 cells of 3 x 3 km^2 horizontal grid spacing. In the vertical, 28 unevenly spaced levels were used with the maximum resolution of 1.5 km at the top of the model (at approximately 50 mb).

The following physical parameterization schemes were selected for the case study: Thompson Graupel scheme for microphysics (Thompson et al., 2008); Rapid Radiative Transfer Model Longwave and Shortwave for longwave and shortwave radiation, respectively (Iacono et al., 2008); ETA similarity from Monin–Obukhov for surface layer (Janjic, 1996; Janić, 2001); Unified Noah land-surface model for land surface (Barlage et al., 2010); Mellor-Yamada-Janjic (Eta operational scheme) for planetary boundary layer (Janić, 2001); New Grell scheme for cumulus parameterization (Grell and Dévényi, 2002). The initial and boundary conditions for the WRF model simulations were obtained from the National Centres for Environmental Prediction (NCEP) FNL (Final) Operational Global Analysis data, available on 1°×1° grids valid at 00, 06, 12, and 18 UTC for the referenced simulation periods. After initialization of the model run, these data were only applied at the boundaries. An output temporal resolution of 1 hour was chosen for the calculated variables.

In addition to the calculated meteorological fields, a number of ancillary, but required, datasets were processed and used, including the following:

- USGS Land Use raster map for Greece, in raster format available at a spatial resolution of 3x3 km^2
- Arc Fuel type raster map for Greece, a product of Arc Fuel project (Arc FUEL - Mediterranean fuel maps geo-database for wild land forest fire safety LIFE10 ENV/GR/000617)

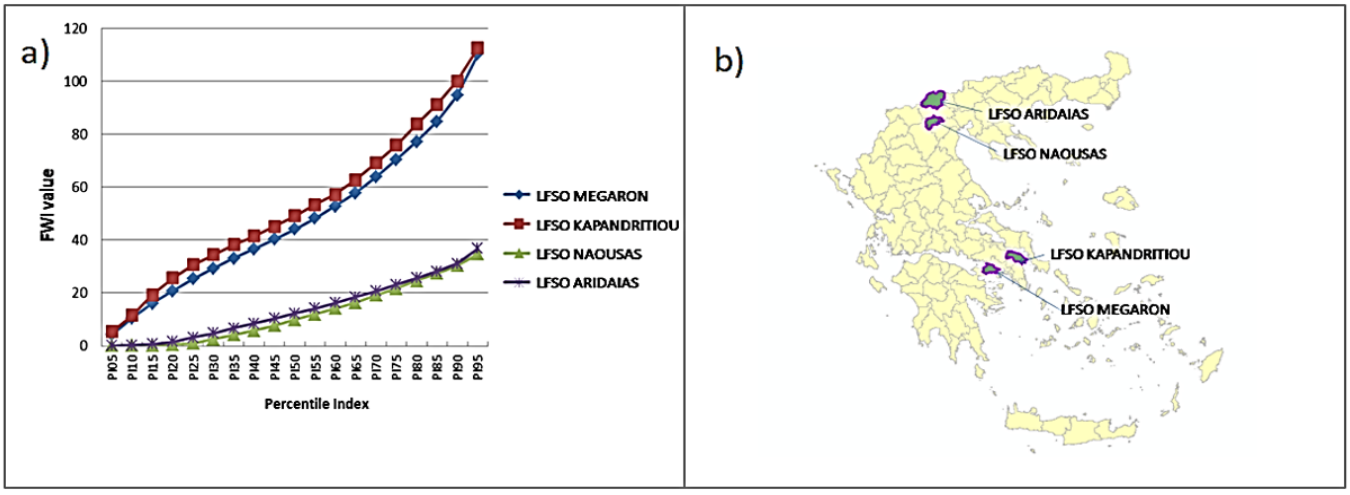

Figure 2: (a) Distribution of Percentile Indices of FWI for four LFSO areas with the highest and lowest PI values, (b) Map showing the 106 LSFO boundaries and the locations of the specific four LSFOs.

- Corine Land Cover v.2000, polygon map of Greece
- Boundaries of the Greek LFSO polygon map, provided by the Greek Forest Service
- EFFIS Fire archive for the years 2009-2013, provided by JRC (personal communication). The particular dataset included the burned areas and the date of ignition of the fires in Greece that burned areas larger than 10 ha.

2.4 Data processing and FWI classification for Greece

The FWI daily maps were processed according to the following steps:

- The cells occupied by fuels were selected for the analyses of the study. A fuel/no-fuel map was created, based on the Arc Fuel Forest Fuel map of Greece as a basic source of information, updated and completed by adding the 'permanent crops' categories (mostly olive trees) of the Corine Land Cover map.
- FWI values were then calculated for each day of the period of interest and for each spatial unit of high spatial resolution (3x3 km^2 cell) of the study area (Whole country, 106 LFSO areas in total).
- FWI Percentile indices (PI) were obtained from the FWI values corresponding to each LFSO area and a PI distribution diagram was created for the area. Thus, a total of 106 distribution diagrams were created, each corresponding to an LFSO.
- EFFIS Forest fires were studied for the 2009-2013 period and FWI values were attributed to each fire according to its date and position of ignition.
- Calculations were then performed on: a) the FWI attributed to each fire according to the ignition date and location and b) the FWI percentile indices of the corresponding LFSO.
- Distribution diagrams were created of the number of fires and burned areas per FWI percentile indices.

3 Results

In this section, the results of the applied methodology and the derivation of the boundaries of the five classes are described in detail.

Distributions of the PI for each LFSO were plotted (106 in total). The distribution lines of the PI show that there is a significant variety in their FWI PI range. Indicative distribution lines for four LFSO areas (Fig. 2(b)) with the lower and highest PI values are presented in Fig. 2(a). The figure shows that the range of FWI PI values in the distribution lines of the LFSO areas of Naousas and Aridaias (located in northern Greece) is found between 0 and below 40 while the respective one of the LFSO of Megaron (located in Attika) is found between 5 and above 100. The distribution lines of FWI PI for the rest of the LSFO areas were found between the curves of Naousa and Kapandritiou but they have not been plotted due to their great number (Fig. 2(a)).

The diagrams in Fig. 3 indicate that there is not a clear relation between the number of fires or the burned area and the calculated FWI values of the particular fires. Although a large number of fires occurred when the FWI corresponding to the date and position of the fire was extremely high, the majority of fires were found to occur at medium FWI values (30-45).

The picture is quite different when the FWI values of the fires are related to the FWI Percentile Indices that characterize the corresponding LFSO (Fig. 4). Both the

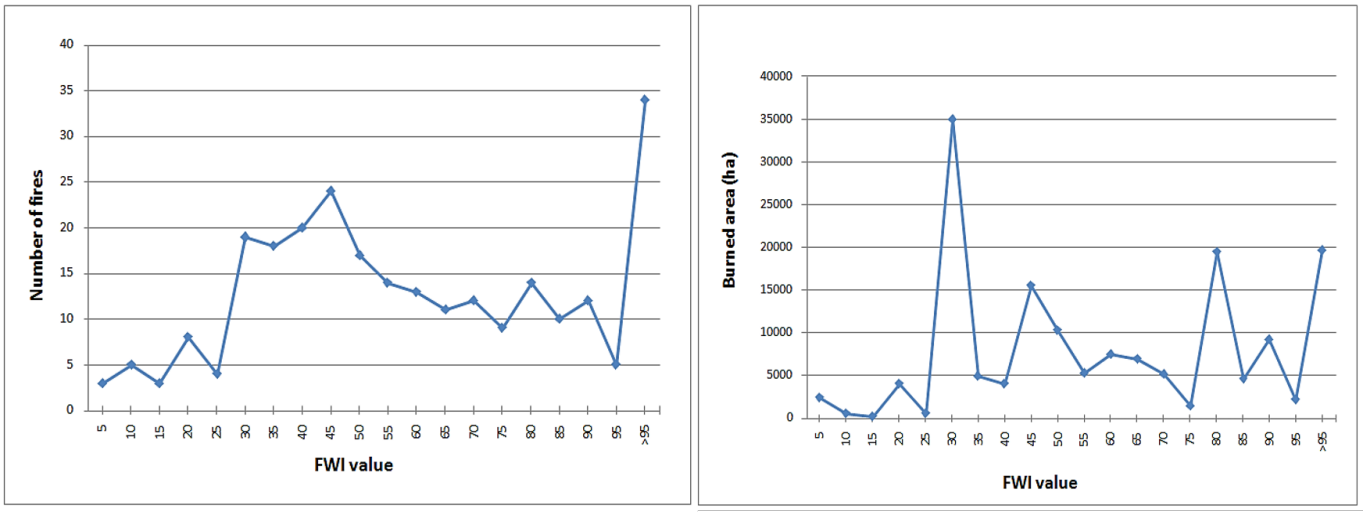

Figure 3: Distribution of number of fires (left) and burned area (in ha) (right) with respect to the corresponding FWI values calculated for the date and position of their ignition (for all LFSO areas).

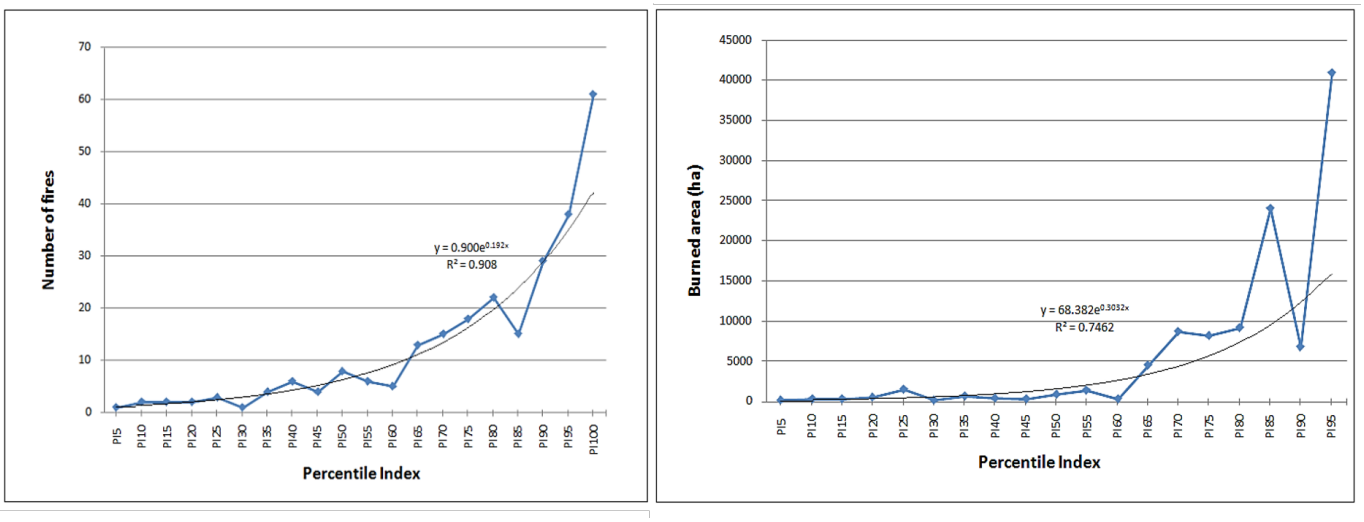

Figure 4: Distribution of the number of fires (left) and burned area (in ha) (right) per FWI Percentile Index (for all LFSO areas).

burned areas and the number of fires in this case show a strong relation with the FWI Percentile Indices. The line diagrams of Fig. 4 yield a strong exponential relation between the number of fires and burned area and the FWI PI values, respectively.

Fig. 5 depicts the percentage of the number of fires for FWI values greater than FWI PI of the corresponding LFSO. According to this diagram, about 40% of the fires occurred when FWI reached values greater than the 90th PI, 65% of the fires occurred when FWI values reached values greater than the 75th PI, while the majority of the fires (96%) were related to an FWI value greater than the 25th PI.

Based on the above results, the 25th, 50th, 75th and 90th Percentile Indices were selected as the most reasonable thresholds of five (5) danger level classes. For comparison reasons and for further evaluation of the proposed classification for operational use, maps of the number of extreme days during the five (5) year fire period were calculated according to the extreme class threshold values introduced by the four (4) different classification schemes, namely, i) EFFIS, ii) Giannakopoulos et al. (2009), hereafter GIAN, iii) Dimitrakopoulos et al. (2011), hereafter DIM and iv) the NCSR classification proposed in this paper (five (5) classes based on FWI PI). The resulting maps are shown in Fig. 6. Examination of these maps leads to the following: i) The number of extreme days according to EFFIS and DIM classification is very high for several regions in southern and south-eastern Greece (e.g. Attica, Crete, Evia, Lesvos, Rhodes), while there is a significant underestimation of the extreme days in the

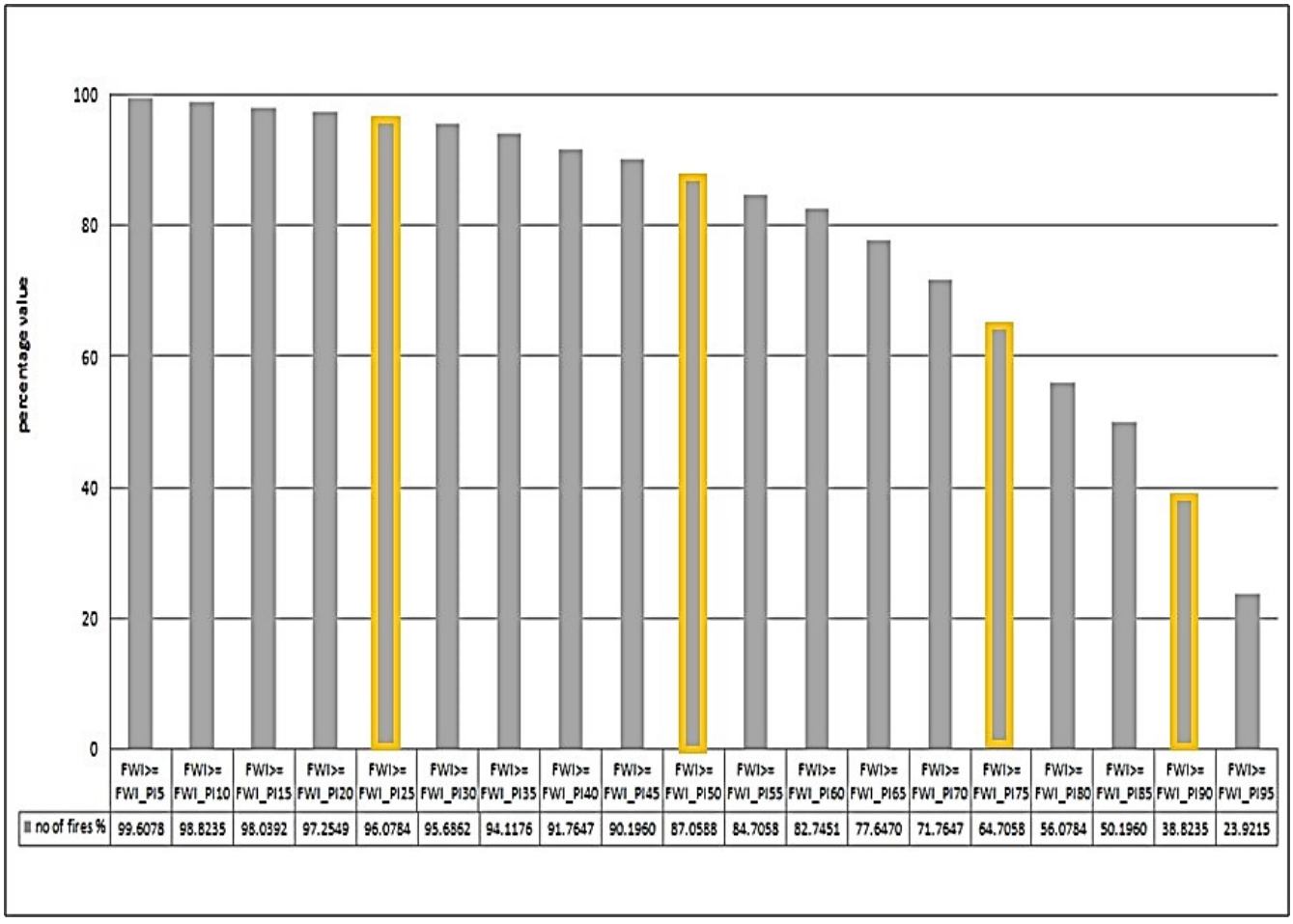

Figure 5: Percentage values of the number of fires for FWI values greater than FWI PI of the corresponding LFSO. The x-axis indicates the percentage value of the number of fires (all LFSO areas). The threshold percentiles (PI) are highlighted in yellow.

northern part of the country, especially according to DIM classification, contrary to the fact that large and significant fires occur in these areas according to the available statistical data; ii) GIAN classification leads to serious overestimation of the extreme days over the whole country; and iii) The distribution of the number of extreme days, which derives from FWI PI (NCSR) classification, is the most representative of the forest fire occurrence in Greece.

4 Discussion

The proposed classification scheme for Greece, which is based on FWI percentiles and provides flexibility in the values of class-boundaries that depend on the fire history and FWI behaviour of an area, effectively addresses and allows for the correction of the very commonly appearing inaccuracies of other applied classification schemes. Such drawbacks are caused by the fact that older schemes were not originally developed or calibrated for the particular area under consideration. As an example, a very common failure of the fire danger level mapping in Greece is the exaggeration of the total area under alert, in the windy part of Greece, during the days of favourable fire weather. At the same time, there is a systematic underestimation of the fire danger level in regions where FWI absolute values are constantly obtained at low to moderate level, while these FWI values are related to important fires in these regions of Greece, both in ecological and socioeconomic terms.

The proposed methodology can be applied to any region that encounters similar types of drawbacks, such as those mentioned before. In general, the use of the following types of datasets is required:

- A series of high spatial resolution meteorological fields (weather maps) of the meteorological parameters, which are necessary for the FWI calculation and mapping. A series of five fire season weather parameter maps is considered adequate for such a study.

- Fire history data of those fires that occurred and spread in forested areas at the same period (i.e. five-year period).

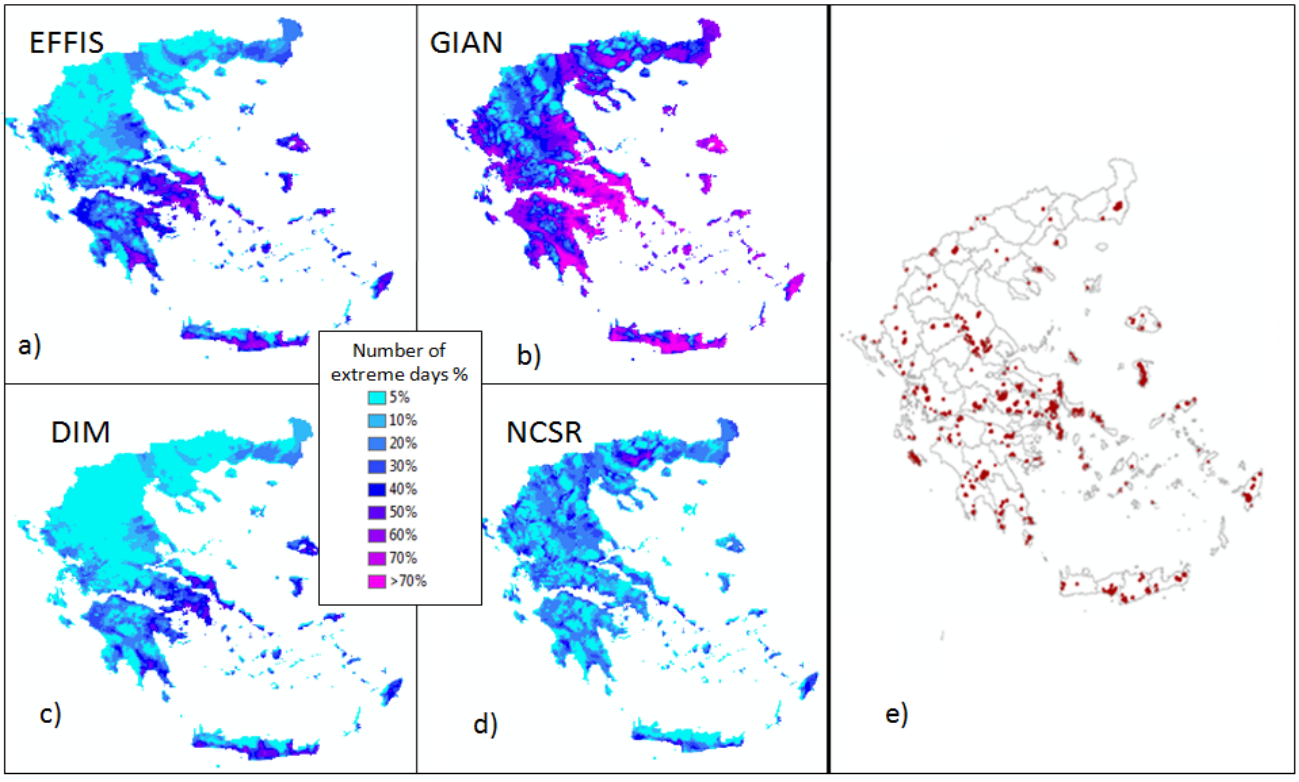

Figure 6: Number of extreme days % according to :a) EFFIS, b) Giannakopoulos et al. (2009) (GIAN), c) Dimitrakopoulos et al. (2011), (DIM), d) proposed FWI PI (NCSR) classification and (e) Forest fire distribution during the 2009-2013 period.

- Geographical boundaries, either administrative or physical for the delineation of homogeneous sub-areas/zones in terms of climatic and physical criteria (e.g. LFSO).

FWI values corresponding to the fire ignition and initial spread position and date are calculated and subsequently correlated to the FWI percentiles of the corresponding sub-area. The attainment of a strong exponential relation of the distribution of the number of fires and the FWI percentiles is the basis for the definition of the thresholds used to define the boundaries of the classes, for the study area. Based on the results of the applied methodology in Greece, the 25th, 50th, 75th and 90th percentiles are considered the most appropriate for the definition of the variable boundaries of FWI classes for expressing the fire danger level.

Another advantage of the proposed methodology is the appropriate correction of the FWI classification with higher values in areas of northern Greece, which have been, so far, systematically underestimated using other classification schemes although significant fires had occurred therein (Fig. 6 a), b), c) d) and e)).

The above qualitative assessment was also confirmed and strengthened by the results derived for the study area (Greece), based on quantitative results such as the calculation of the total number of days, during the envisaged period, categorized at the extreme FWI class, according to four (4) classification schemes, including the one proposed in the current paper (see Fig. 6). These results provide further evidence of the effectiveness and operational usefulness of fire danger mapping according to the proposed FWI percentile-based classification, since the achievement of the rational distribution of extreme fire danger, in accordance with the fire occurrence pattern all over the country, facilitates operational actions by eliminating an unnecessary increment in the preparedness level in some areas and/or significant underestimation of it in others.

5 Conclusions

The fire danger level expressed by FWI classes has been over- or under-estimated until now, using previous existing schemes, for geographical areas like Greece with diverse climatic conditions, where ranges of FWI values are highly variable during the fire season. Such areas could not be represented appropriately because the pre-defined threshold values of the FWI classes were originally determined for other geographical areas with different physical characteristics.

Therefore, the need for the calculation and appropriate classification and mapping of FWI at a high spatial resolution that could be useful for operational use in Greece, both at a national and/or local level directed the efforts to compile a new approach. The proposed FWI calculation takes into

account the climatic and environmental variety of Greece, which greatly affects the significance of the FWI values and consequently, their interpretation into reasonable and functional fire danger classes.

The proposed approach of Percentile Indices provides the capability of defining appropriately varying FWI boundaries of classes based on the specific physical characteristics of the study area. The new methodology of fire danger mapping using regionally adopted FWI classification has been applied in Greece and validated using historical datasets of fire ignition location and burned areas of the country during the five-year period of study.

Following the steps described above for a straightforward calculation and suitable classification of FWI, the new scheme could be used operationally and applied effortlessly by fire management agencies in Greece.

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