https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

Natural Hazards and Earth System Sciences
Discussions

Seasonal fire danger forecasts for supporting fire prevention management in an eastern Mediterranean environment: the case study of Attica, Greece

Anna Karali[1,2], Konstantinos V. Varotsos[1], Christos Giannakopoulos[1], Panagiotis P. Nastos[2], Maria Hatzaki[2]

[1]Institute for Environmental Research and Sustainable Development, National Observatory of Athens, Athens, 15236, Greece
[2] Laboratory of Climatology and Atmospheric Environment, Sector of Geography and Climatology, Department of Geology and Environment, National and Kapodistrian University of Athens, Athens, 15784, Greece

Correspondence to: Anna Karali (akarali@noa.gr)

Abstract. Forest fires constitute a major environmental and socioeconomic hazard in the Mediterranean. Weather and climate are among the main factors influencing forest fire potential. As fire danger is expected to increase under changing climate, seasonal forecasting of weather conditions conductive to fires is of paramount importance for implementing effective fire prevention policies. The aim of the current study is to provide high resolution (~9km) probabilistic seasonal fire danger forecasts, utilizing the Canadian Fire Weather Index (FWI) for Attica region, one of the most fire prone regions in Greece and the Mediterranean, employing the fifth generation ECMWF seasonal forecasting system (SEAS5). Results indicate that FWI and its Initial Spread Index (ISI) sub-component, present statistically significant high discrimination scores and are proven respectively, marginally useful, and perfectly reliable in predicting above normal fire danger conditions. When comparing year-by-year the fire danger predictions with the historical fire occurrence obtained by the Hellenic Fire Service database, both seasonal FWI and ISI forecasts indicate a skill in identifying years with high fire occurrences. Overall, fire danger and its subcomponents can potentially be exploited by regional authorities in fire prevention management regarding preparedness and resources allocation in the Attica region.

1 Introduction

The Mediterranean region includes more than 25 million hectares of forests and about 50 million hectares of other wooded lands that make vital contributions to rural development, poverty alleviation and food security, as well as to the agriculture, water, tourism, and energy sectors (FAO and Plan Bleu, 2018). The Mediterranean is considered a high fire risk region where fires cause severe environmental and economic losses and even losses of human lives (MedECC, 2020). Severe forest fires have consistently affected Europe since the beginning of the century, especially as regards the five European Mediterranean countries of Portugal, Spain, Italy, Greece, and France which on average collectively account for approximately 85% of the total burnt area in Europe per year (Costa et al. 2020).

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

Weather and climate, vegetation conditions and composition, as well as human activities play an essential role in fire regimes (Costa et al., 2020). According to Rogers et al. (2020), climate highly affects fuel properties and short-term weather patterns determine fuel moisture and physical conditions necessary for fire spread. Regarding the Mediterranean, the combination of extreme drought with extreme winds or heatwaves has been identified as crucial factor for the occurrence of wildfires (Ruffault et al., 2020). Under changing climatic conditions, future fire danger as well as the frequency and the extent of large wildfires are expected to increase throughout the Mediterranean basin (Dupuy et al., 2020; Ruffault et al., 2020; Turco et al., 2018). According to Moreira et al. (2020) burnt areas may be further amplified by land use and management changes that increase fuel load and continuity.

Fire management strategies in the Mediterranean Europe place emphasis on fire suppression which can indeed lead to higher fuel load and fuel connectivity as encapsulated in the term 'firefighting trap' which culminates in hindering suppression under extreme fire weather, ultimately leading to more severe and usually larger fires (Moreira et al., 2020). Fire management should be enriched, also comprising prevention and adaptation measures (Alcasena et al., 2019; Fernandes et al., 2013). This holistic point of view has been included in the new EU Forest Strategy for 2030 (European Commission, 2021) that explicitly considers fire prevention as an integral component for maintaining and enhancing the resilience of European forests. Further underlining this, in the recent report on wildfires of the United Nations Environmental Program (2022), a radical change in Governments spending on wildfires was called for, with the aim to rebalance government investment from reaction and response to prevention and preparedness.

Seasonal forecasting of weather conditions conductive to fires (fire weather), is of paramount importance for implementing effective fire prevention. The prediction of unfavourable conditions prior to each fire season may support policymakers and civil protection agencies to implement adequate fuel management policies in vulnerable regions, along with optimising fire-fighting resources to mitigate the adverse effects of forest fires (Turco et al., 2019).

For the relationship between meteorological conditions and fire danger, different indices are used worldwide that assess fire danger for research and operational purposes with the Canadian Fire Weather Index (FWI) being one of the most widely used systems (Field et al., 2015). FWI has been shown to correlate well with fire activity globally (Abatzoglou et al., 2018; Bedia et al., 2015) and regionally, including parts of Europe (e.g., Dupuy et al., 2020; Karali et al., 2014; Ruffault et al., 2020). Since 2007, the FWI has been adopted at the EU level by the European Forest Fire Information System (EFFIS), component of the Copernicus Emergency Management Service (CEMS), to assess fire danger level in a harmonized way throughout Europe after several tests on its validity and robustness for the European domain (San-Miguel-Ayanz, 2012). EFFIS provides short term FWI forecasts, as well as monthly and seasonal forecasts of temperature and rainfall anomalies that are expected to prevail over European and Mediterranean areas for a time window of seven months. To the best of our knowledge, the only study so far, assessing seasonal fire danger predictions for Europe is by Bedia et al. (2018) where the authors provided seasonal probabilistic predictions of FWI for Mediterranean Europe by utilizing the ECMWF System-4, focusing on the calibration of model outputs prior to forecast verification, as well as on the analysis of FWI forecast quality compared to reference observed values.

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

The current study aims to provide high resolution probabilistic FWI seasonal forecasts for Attica, Greece employing the methodology of Bedia et al. (2018) and further expanding it through statistical downscaling. Moreover, it aims to assess the ability of these forecasts to provide robust information and support fire management decisions in the Attica region. Attica encompasses the entire metropolitan area of Athens, the country's capital and largest city with approximately 3.8 million inhabitants (census of 2011). It is one of the country's most vulnerable regions to rural and peri-urban forest fires due to its complex topography, flammable vegetation, high concentration of population and activities as well as its extensive Wildland-Urban Interface (WUI) (Mitsopoulos et al., 2020; Salvati and Ranalli, 2015).

The catastrophic fires that took place in Attica during the summer of 2021 that burnt more than 150,000 ha (Evelpidou et al., 2022) of forests and arable land underpinned the timeliness and need for this study. These fires broke out during the most severe and the longest heatwave (maximum daily temperature reached 43.9°C, while heatwave conditions prevailed for 10 days) occurred in Attica in the last decades according to the meteorological records of the National Observatory of Athens. Our assessment includes the verification of the FWI forecasts against gridded observational data using a probabilistic tercile based approach and a qualitative comparison of predicted years with above normal fire danger conditions using historical fire occurrence data.

The paper is organized as follows. In the next section, the data and methods are introduced. In Sec. 3, the results of forecast verification for Attica region are presented together with the results of the qualitative evaluation of above normal fire danger conditions against historical fire occurrence. Finally, in Sec. 4, a summary of our results together with the main conclusions and suggestions for future work are provided.

2 Materials and methods

2.1 Fire Weather Index (FWI)

FWI is a daily meteorologically based system used worldwide to estimate fire danger in a generalized fuel type (mature pine forest). According to Wotton (2009), fire danger refers to the assessment of both the static and dynamic factors of the fire environment which determine the ease of ignition, rate of spread, difficulty of control and impact of a fire. The meteorological inputs to the system are daily noon values of air temperature, relative humidity, wind speed and 24-h precipitation. The FWI system consists of six components each measuring a different aspect of fire danger. The first three primary sub-indices are fuel moisture codes and are numerical ratings of the moisture content of litter and other fine fuels (FFMC sub-index) indicating the relative ease of ignition and flammability of fine fuel, the average moisture content of loosely compacted organic layers of moderate depth (DMC sub-index) and the average moisture content of deep, compact organic layers (DC sub-index).

The two intermediate sub-indices, ISI and BUI, are fire behaviour indices. The Initial Spread Index (ISI) is a numerical rating of the expected fire rate of spread. It combines the effect of wind and FFMC on rate of spread without the influence of variable quantities of fuel. The Buildup Index (BUI) is a numerical rating of the total amount of fuel available for combustion that combines the DMC and the DC. The resulting index is the Fire Weather Index (FWI), which combines ISI and BUI. FWI

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

represents the frontal fire intensity and can be used as a general index of fire danger in forested areas. Each component of the FWI System has its own scale, but for all of them a higher value indicates more severe burning conditions (de Groot, 1987). A more analytical description of the FWI system and its subcomponents can be found in van Wagner (1987) and Wotton (2009). The structure of the index and the meteorological variables needed for its calculation are presented in Figure 1.

2.2 Seasonal forecast data and reference observations

2.2.1 ECMWF SEAS5 dataset

In the framework of the current study, the fifth generation ECMWF seasonal forecasting system (SEAS5) (Johnson et al., 2019) available in the C3S Climate Data Store (CDS) (DOI: 10.24381/cds.181d637e) is utilized. SEAS5 has been operational since November 2017, replacing System 4. The system includes updated versions of the atmospheric (IFS) and ocean (NEMO) models with the addition of the interactive sea ice model LIM2 (Johnson et al., 2019). The set of re-forecasts (hindcasts) available in the CDS starts on the 1st of every month for the years 1993-2016 and contains 25 ensemble members. The data from these re-forecasts are used to verify the system and calibrate real-time forecast products. Real time forecasts (from 2017 onwards) consist of a 51-member ensemble initialised every month and integrated for 7 months. The seasonal forecasts are initialised with atmospheric conditions from ERA-Interim (Dee at al., 2011) until 2016 and the ECMWF Operational Analysis since 2017. Re-forecast and forecast data are available at a global 1x1 degree grid.

For the daily FWI values calculations, the SEAS5 instantaneous outputs at 12 UTC for 2-m air temperature, northward and eastward 10-m wind components, 2-m dewpoint temperature, and daily accumulated precipitation are used. The 12 UTC is used as a proxy for local noon values required as input to FWI. Moreover, relative humidity needed for FWI calculations was computed from air and dew-point temperature. Concerning precipitation, data correspond to the accumulated values since the initialization time, therefore differences with the previous day's values are computed (de-accumulation) to obtain daily accumulated values for each grid point.

A fire season spanning from May to September is considered and two different experimental setups for FWI calculations are performed. In particular, SEAS5 forecasts initialized in April (one month in advance of the target fire season, i.e., 1-month lead) and May (0-month lead) are considered, LM1 and LM0, respectively and henceforth. It should be noted that a spin-up period is required in order to minimize the effect of errors in the initial conditions used in FWI calculations. According to Bedia et al. (2018), this period is less than a month for the examined fire season and study region. In LM1 a spin-up of one month has been performed, while in LM0 no spin-up has been considered, which according to Bedia et al. (2018), can insert a limited degree of error due to the relatively fast stabilization of the index along with its seasonal averaging.

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

2.2.2 ERA5-Land reanalysis dataset

As a reference observational dataset, the state-of-the-art global reanalysis dataset ERA5-Land (Muñoz-Sabater, 2019) of Copernicus CDS (DOI: 10.24381/cds.e2161bac) is used. ERA5-Land comes with a series of improvements compared to ERA5 making it more accurate for all types of land applications. The dataset provides a total of 50 variables describing the water and energy cycles over land, globally, hourly, and at a spatial resolution of 9 km from 1950 to present (Muñoz-Sabater et al., 2021). To be consistent with the SEAS5 data, 2-m air temperature, 2-m dewpoint temperature, 10-m northward and eastward wind components at 12UTC, and daily accumulated precipitation are used for the calculation of daily FWI values.

2.3 Statistical downscaling of seasonal forecasts

To statistically downscale the seasonal forecasts at the ERA5-Land horizontal resolution a two-step approach is followed. In particular, the seasonal forecast meteorological variables used to calculate FWI are initially regridded to the ERA5-Land grid by means of bilinear interpolation, while in a second step of bias correction is applied using the empirical quantile mapping (EQM). This two-step approach is the reversed order of the bias correction and spatial disaggregation framework, which has been previously used to statistically downscale global models for both climate change and seasonal forecast studies (Abatzoglou and Brown, 2012; Lorenz et al., 2021; Markos et at., 2018). Regarding the bias correction method, EQM works by adjusting the 1-99 percentiles of the predicted empirical probability density function (PDF) based on the observed empirical PDF, while for lower or higher values falling outside this range, a constant extrapolation is applied using the correction obtained for the 1st or 99th percentile respectively. For more information on how EQM works the reader may refer to the studies of Manzanas et al. (2018, 2019), Manzanas (2020) and Bedia et al. (2018).

In this study bias correction is applied using daily data for the period May to September using a moving window width of 31-days to adjust the intra-seasonal biases originating from the models' behaviour (i.e., model drift, refer to Manzanas (2020) and references therein). Following Bedia et al. (2018), FWI is bias corrected after its calculation from the regridded fields of temperature, relative humidity, wind speed and precipitation to avoid unrealistic FWI trends that could occur by calculating FWI from the bias corrected meteorological variables. Nevertheless, for the purposes of the analysis, results of the statistically downscaled temperature, relative humidity, wind speed and precipitation are also presented in the following sections.

2.4 Metrics and methodology of fire danger forecast verification

According to WMO (2020), measures of historical predictive skill are an essential component of seasonal forecasts as they provide the users an indication of the trustworthiness of the real-time forecasts. There are many different skill measures describing the quality of specific forecast attributes that are estimated by calculating the corresponding properties of the set of hindcasts paired with reference observations (WMO, 2020). In the framework of the current study, the probabilistic Relative Operating Characteristic (ROC) skill score, measuring forecast discrimination, together with the reliability diagrams are used, to assess the potential skill and usefulness of fire danger seasonal forecasts after spatial disaggregation and bias adjustment.

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

2.4.1 ROC skill score (ROCSS)

ROC skill measures the frequency of occasions when the system correctly distinguished between events occurring and not occurring (Jolliffe and Stephenson, 2003). ROC is based on the ratio between the hit rate and the false alarm rate and is evaluated separately for each category (above normal, normal, or below normal). ROC Skill Score (ROCSS) ranges from -1 (perfectly bad discrimination) to 1 (perfectly good discrimination). A value of zero indicates no skill compared to a random prediction or the climatological value.

As in previous studies (e.g., Bedia et al., 2018; Manzanas et al., 2014; Mercado-Bettín et al., 2021), a tercile-based probabilistic approach for forecast verification has been applied. In order to assess fire-danger forecast performance, the easyVerification (MeteoSwiss, 2017), SpecsVerification (Siegert, 2020), and VisualizeR (Frias et al., 2018) R packages, are used for skill calculation and visualization. The ROCSS at each grid-point for the different tercile categories depending on the examined parameter, e.g., the upper tercile for FWI, temperature and wind speed or the lower tercile for relative humidity and precipitation, averaged over the verification period are calculated and maps depicting the geographical variations in their skill scores for the different initialization times are constructed (Fig. 2-6).

Moreover, tercile plots for FWI (and its sub-components) for Attica were built (Fig. 7) to complement the spatial analysis provided by the ROCSS maps, presenting the performance of the seasonal forecast along the hindcast period. In order to build a tercile plot for a given variable, the observations as well as the bias corrected multi-member ensemble predictions are categorised into three tercile categories, considering values above (upper tercile), between (middle tercile) or below (lower tercile) the respective climatological values within the period 1993-2016. Subsequently, a probabilistic forecast is computed year by year considering the number of members falling within each category. Moreover, the observed category according to the ERA5-Land dataset is provided in the plot, to facilitate a visual comparison of hits and misses of the forecast system along the hindcast period.

2.4.2 Reliability diagrams

Reliability diagrams are diagnostic tools measuring how closely the forecast probabilities of a specific event (for instance a particular tercile category) correspond to the observed frequency of that event (Weisheimer and Palmer, 2014). According to WMO (2020), in the context of decision-making, forecast reliability plays an important role in making a prior assessment of the benefits of using seasonal forecast information. A construction of a reliability diagram involves binning forecasts by probability category and plotting these values against the observed frequencies (WMO, 2020). For a perfectly reliable forecasting system, the line obtained would match the diagonal (perfect reliability line) (Figures 8-9). The reliability line that best fits the points in the diagram is calculated applying least squares regression weighted by the number of forecasts in each probability bin. Based on the slope of the reliability line and the uncertainty associated with it, six easy-to-interpret categories can be defined: perfect, still very useful, marginally useful+, marginally useful, not useful, and dangerously useless (Manzanas et al., 2018). The marginally useful+ category differentiated those cases for which the reliability line lies within the skill region

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

(Brier Skill Score>0, shaded in grey). The reader can refer to Frias et al. (2018) and Manzanas et al. (2018) for more information on the construction of the reliability diagrams.

It should be noted that concerning FWI (and its subcomponents), both in the tercile maps/plots and the reliability diagrams, only the results of the above normal conditions (upper tercile category) are discussed in the main body of the paper, as high FWI (and its subcomponent) values are related to increased fire danger conditions and, hence, to increased wildfire activity (e.g., Urbieta et al., 2015).

2.5 Qualitative evaluation of above normal fire danger conditions against historical fire occurrence

A qualitative evaluation of the ability of FWI hindcasts to predict actual fire occurrence as obtained by historical fire records is performed. To this aim, records of national wildfire time series data for the period between 2000 and 2016 have been obtained from the Hellenic Fire Service online database (https://www.fireservice.gr/el_GR/synola-dedomenon). As these data concern both forest and urban fires, only fire events that burnt at least 1ha of forest or forested areas are extracted from the database.

Burnt areas less than 1ha were excluded from our analysis, to limit the uncertainties associated with the recording of small fires in fire databases as has already been reported in previous studies (Jiménez-Ruano et al., 2017; Turco et al., 2013). Regarding the number of fires and the respective burnt areas, these are constrained for the months covering the fire season as defined in the current study (i.e., from May to September). The fire data for the hindcast years between 1993-1999, was decided not to be included in our analysis as they are part of a different database of the Hellenic Forest Service's, which features major differences and is not compatible with the Fire Service's one.

Regarding the approach to the qualitative evaluation, the years between 2000 and 2016 are characterized as high fire activity years since the number of fire events for the entire Attica domain for each year is greater than the mean number of fire events observed for the whole period. Moreover, only the years with observed (based on ERA5-Land) fire danger in the upper tercile category (above normal conditions) are selected from the tercile plots for Attica and the relevant proportion of ensemble members predicting upper tercile values is recorded. Consequently, the number of fires per year are shown along with the abovementioned proportion.

3 Results and discussion

3.1 Fire danger forecast performance

The quality of the downscaled fire danger hindcasts for the whole Greek domain is initially assessed via the ROCSS. In Figure 2, the ROCSS for the upper tercile of FWI hindcast predictions for May to September for the entire Greek domain for both lead time experiments are presented. As can be seen, there is a consistent positive discrimination skill mainly in the southern continental part of Greece, the Aegean islands and Crete for two the different lead times. However, statistically significant high discrimination scores (α=0.05) are found mainly for Attica, while scattered skilful areas are found in Crete and the Aegean

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

islands in both LM0 and LM1 predictions. For LM1, fire danger forecasts sporadic skilful areas are calculated also for the northern-eastern part of the domain. Focusing on Attica, statistically significant ROCSS for LM0 fire danger predictions are found almost for the entire domain, ranging between 0.4 and 0.8, while for LM1 predictions, lower discrimination power is found.

Moreover, the ROCSS of the forecasted meteorological variables used in FWI calculations, resulting in high fire danger conditions, i.e., high air-temperature, low relative humidity, low total precipitation and high wind speed, are calculated for LM1 and LM0 predictions. Thus, the ROCSS for the upper tercile category of air temperature and wind speed, as well as the lower tercile category of relative humidity and total precipitation for the different lead times are presented in Figures 3 and 4, respectively. For Attica, relative humidity, and wind speed exhibit high discrimination skill for LM1 (Fig. 3), while for LM0, relative humidity and to a lesser degree air temperature exhibit high positive discrimination skill score (Fig. 4). The high discrimination power of relative humidity for Greece was also found in Bedia et al. (2018) utilizing ECMWF Sys4 LM1 predictions.

Given that relative humidity (both in LM0 and LM1) and wind speed (only in LM1) demonstrated some discrimination power (ROCSS>0.4), the ROC skill scores of the FWI subcomponents that directly depend on these variables are further investigated (Figure 1). In particular, the ROCSSs for Fine Fuel Moisture code (FFMC), Duff Moisture Code (DMC) that receive relative humidity as an input variable and describe the fuel moisture content in the surface and upper layers of forest floor, respectively, are calculated. Similarly, the ROCSS of the Initial Spread Index (ISI) which integrates fuel moisture for fine dead fuels (FFMC) and near-surface wind speed, characterizing spread potential, is assessed.

As seen in Figure 5, the ROCSS for the upper tercile of ISI for both LM0 and LM1 predictions exhibited positive statistically significant values for Attica, much improved throughout the entire domain compared to the respective above normal FWI conditions (Fig. 2). On the other hand, both FFMC and DMC presented poor discrimination scores for LM0 and LM1 predictions. For both sub-indices, non-statistically significant ROCSS (<0.5) are calculated, except for a few grid points for FFMC LM0 predictions, therefore they were excluded from further analysis (Fig. 6).

In Figure 7, the tercile plots of FWI and ISI averaged over Attica, for LM0 and LM1, are presented in order to complement the spatial analysis, providing a year-to-year visual comparison between hindcast tercile categories and the corresponding observed values as obtained by ERA5-Land. As shown in the figure, the spatially averaged forecast predictions for the upper tercile categories for both FWI and ISI, indicate statistically significant positive ROCSS. For FWI, the ROCSS are 0.45 and 0.62 for LM1 and LM0 predictions, respectively, while for ISI values of 0.58 and 0.85 for LM0 and LM1 are attained. Concerning FWI, LM0 predictions, most of the observed above normal (upper tercile) years are predicted by more than 40% of the ensemble members, with 2003 and 2008 to be predicted by 80% of the members. For LM1 predictions, half of the observed above normal years are captured by 30% of the members and only 2008 is captured by most ensemble members (80%). As far as ISI predictions are concerned, for both LM0 and LM1 experiments, more than 60% of the members are found to predict most of the above normal observed categories, thus, suggesting an overall better performance of ISI predictions compared to FWI. Moreover, the FWI and ISI forecast probabilities for 2021 fire season are additionally presented in Fig. 7.

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

Natural Hazards and Earth System Sciences
Discussions

Here, most of the ensemble members (>70%) predict above normal conditions for both FWI and ISI for a year with elevated fire activity, supporting the case of their usefulness for providing fire danger forecasts under operational usage.
To complement the analysis on fire danger forecast verification, the reliability diagrams are presented in Figure 8 and 9. ISI upper tercile predictions for both lead time experiments are classified to perfect reliability, as ISI reliability lines are very close to the diagonal and the uncertainty range clearly includes the perfect reliability slope of 1 (Fig. 8). On the other hand, FWI reliability lines above the no skill line having significantly positive slopes, thus, FWI upper tercile predictions fall in the marginally useful+ category for both LM0 and LM1 predictions (Fig. 9). Based on the aforementioned categories, FWI forecasts are considered reliable and can potentially be partially useful, while ISI forecasts are perfectly reliable and can potentially be very useful in decision making for Attica.

3.2 FWI and ISI predictions against fire statistics

The correlation between FWI and ISI hindcasts with burnt areas and the number of fires for the years 2000-2016, revealed moderate correlation between FWI and ISI with the number of fires (Pearson correlation coefficient r=0.55 and 0.52 respectively, p-value<0.05) and no statistically significant correlation with burnt areas. Similar results were reported in a recent study of Galizia et al. (2021) suggesting that fire-prone pyro-regions, with Greece and Attica categorized as such, present moderate (>0.4) and strong (>0.6) positive correlations of the number of fires with FWI and ISI, respectively. Thus, the number of fires was favoured instead of burnt area as the variable of choice for the qualitative evaluation of fire danger hindcasts.
Figure 10 depicts the number of fires (with burnt area greater than 1ha) per year, for the years between 2000 and 2016 of the hindcast period and the respective proportion of ensemble members predicting above normal FWI and ISI values as obtained by the tercile plots averaged over the entire Attica domain (Fig. 7). Concerning FWI, the prediction of years with increased fire activity (i.e., the years with total number of fires greater than the 2000-2016 mean value based on the fire records), is highly dependent on the lead time of the forecasts. As seen in Fig. 10, most of the years with increased fire activity are predicted by more than half of the members either by LM0 or LM1 FWI forecasts. As far as ISI is concerned, the high activity of 2003 fire season is missed entirely, while two false alarms for 2013 and 2016 fire seasons are recorded. For 2013, more than 50% of the ensemble members for both LM0 and LM1 predicted above normal ISI predictions, while for 2016, 60% of the ensemble members for LM1 predicted above normal ISI values, however, fire activity was not that high during these years.
The rest of the observed years of high activity are well captured by both LM0 and LM1 ISI predictions. Moreover, 2009 and 2010 high fire activity years are missed by both FWI and ISI forecasts. These years fall in the middle and lower terciles, respectively, according to the ERA5-Land observations (Fig. 7), meaning that during the respective fire seasons normal and below normal fire danger conditions prevailed. This miss may be due to the fact that fire activity is not only driven by climate but rather by interactions among climate, vegetation and human activities as stated in Galizia et al. (2021), thus, a climate-only approach may be insufficient for particular years. It also highlights the sensitivity of the results to the ERA5-Land dataset which is used to statistically downscale and evaluate the seasonal forecasts output (Herrera et al., 2019; Mavromatis and Voulanas, 2021).

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

4. Conclusions

As climate plays an important role in fire dynamics and climate change is increasing the frequency and severity of fire weather, the ability to forecast fire danger conditions prior to the beginning of the fire season can enhance preparedness and support decision making in fire management in fire-prone areas. Moreover, the resilience of the forestry sector may be enhanced by developing dedicated climate services, such as fire danger seasonal forecasts, in order to reduce risks and offer opportunities for long-term reduction of wildfire disasters.

The aim of this study is to provide high resolution probabilistic seasonal fire danger forecasts, utilizing Fire Weather Index (FWI) for Attica Greece and verify these forecasts using probabilistic verification measures for skill assessment (ROC skill score, reliability diagrams). The analysis is focused on the predictability of above-normal (upper tercile) FWI years which have been associated in several studies with increased fire occurrence. Moreover, the study tried to assess the ability of fire danger forecasts to capture years with increased fire activity, by comparing hindcast years of above normal fire danger conditions with historical fire occurrence data obtained by the Hellenic Fire Service.

Our results suggest that FWI exhibits statistically significant positive discrimination scores mainly for LM0 predictions almost for the entire Attica domain. By analysing the discrimination power of the meteorological variables' predictions used in FWI calculations, both wind speed (only in LM1) and relative humidity attained high ROCSS. The ROCSS for the upper tercile of ISI for both LM0 and LM1 predictions exhibited positive statistically significant values for Attica, much improved compared to the respective above normal FWI conditions, while FFMC and DMC proved to have no discrimination power.

The tercile plots for Attica show an overall better performance of ISI predictions compared to FWI, as more than 60% of the ensemble members, for both LM0 and LM1 experiments, were found to predict most of the above normal observed categories. For 2021 fire season, most of the ensemble members (>70%) predicted above normal conditions for both FWI and ISI (in both LM0 and LM1), adding to the usefulness of such forecasts for operational purposes. According to the constructed reliability diagrams, FWI upper tercile predictions fell in the marginal useful+ category, so it could potentially be partially useful in decision making, while ISI predictions were perfectly reliable, thus, it could potentially be very useful in decision making for the Attica region. Additionally, according to the qualitative evaluation of FWI and ISI forecasts to capture high fire activity years in Attica, almost all years were captured either by LM0 or LM1 FWI predictions. ISI on the other hand, had one miss and two false alarms in 17 years, compared to FWI forecasts.

Bearing the above in mind, as well as the inherent interplays of fire related variables, from climate to human activity, ISI and at a lesser extent FWI seasonal forecast predictions, may be viewed as valuable climate related alarms of increased fire danger and fire occurrence and may be further exploited by regional authorities in fire management regarding prevention, preparedness and resources allocation in the Attica region and other fire prone regions and sub-regions in the Mediterranean.

Future work should focus on the assessment of large ensemble approaches utilizing different forecasting systems available in Copernicus CDS, as well as alternative pathways to enhance the skill of seasonal fire danger predictions to be applicable to

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

the whole Greek or even Mediterranean wide domain. Finally, the impact of the selected reference dataset, here ERA5-Land, on the statistically downscaled forecasts should also be explored.

References

Abatzoglou, J. T. and Brown, T. J.: A comparison of statistical downscaling methods suited for wildfire applications, 32, 772–780, https://doi.org/10.1002/joc.2312, 2012.

Abatzoglou, J. T., Williams, A. P., Boschetti, L., Zubkova, M., and Kolden, C. A.: Global patterns of interannual climate–fire relationships, 24, 5164–5175, https://doi.org/10.1111/gcb.14405, 2018.

Alcasena, F. J., Ager, A. A., Bailey, J. D., Pineda, N., and Vega-García, C.: Towards a comprehensive wildfire management strategy for Mediterranean areas: Framework development and implementation in Catalonia, Spain, Journal of Environmental Management, 231, 303–320, https://doi.org/10.1016/j.jenvman.2018.10.027, 2019.

Bedia, J., Herrera, S., Gutiérrez, J. M., Benali, A., Brands, S., Mota, B., and Moreno, J. M.: Global patterns in the sensitivity of burned area to fire-weather: Implications for climate change, Agricultural and Forest Meteorology, 214–215, 369–379, https://doi.org/10.1016/j.agrformet.2015.09.002, 2015.

Bedia, J., Golding, N., Casanueva, A., Iturbide, M., Buontempo, C., and Gutiérrez, J. M.: Seasonal predictions of Fire Weather Index: Paving the way for their operational applicability in Mediterranean Europe, Climate Services, 9, 101–110, https://doi.org/10.1016/j.cliser.2017.04.001, 2018.

Canadian Forestry Service: Tables for the Canadian Forest Fire Weather Index System, Environ. Can., Can. For. Serv., For. Tech. Rep 25 (4th ed.), 1984.

Costa, H., Rigo, D., Libertà, G., Houston Durrant, T., San-Miguel-Ayanz, J.: European wildfire danger and vulnerability in a changing climate: towards integrating risk dimensions, Technical report by the Joint Research Centre: JRC PESETA IV project: Task 9 forest fires, Publications Office of the European Union, Luxembourg, https://data.europa.eu/doi/10.2760/46951, 2020.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, 137, 553–597, https://doi.org/10.1002/qj.828, 2011.

de Groot, W.J.: Interpreting the Canadian forest fire weather index (FWI) system, in: Proceedings of the Fourth Central Regional Fire Weather Committee Scientific and Technical Seminar; Canadian Forest Service, Edmonton, Alberta, Canada, 3–14 pp., 1987.

Dupuy, J., Fargeon, H., Martin-StPaul, N., Pimont, F., Ruffault, J., Guijarro, M., Hernando, C., Madrigal, J., and Fernandes, P.: Climate change impact on future wildfire danger and activity in southern Europe: a review, Annals of Forest Science, 77, 35, https://doi.org/10.1007/s13595-020-00933-5, 2020.

European Commission: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions-New EU Forest Strategy for 2030, 2021.

Evelpidou, N., Tzouxanioti, M., Gavalas, T., Spyrou, E., Saitis, G., Petropoulos, A., and Karkani, A.: Assessment of Fire Effects on Surface Runoff Erosion Susceptibility: The Case of the Summer 2021 Forest Fires in Greece, 11, 21, https://doi.org/10.3390/land11010021, 2022.

FAO and Plan Bleu: State of Mediterranean Forests 2018, FAO & Plan Bleu, Rome, Italy, 308 pp., 2018.

Fernandes, P. M.: Fire-smart management of forest landscapes in the Mediterranean basin under global change, Landscape and Urban Planning, 110, 175–182, https://doi.org/10.1016/j.landurbplan.2012.10.014, 2013.

Field, R. D., Spessa, A. C., Aziz, N. A., Camia, A., Cantin, A., Carr, R., de Groot, W. J., Dowdy, A. J., Flannigan, M. D., Manomaiphiboon, K., Pappenberger, F., Tanpipat, V., and Wang, X.: Development of a Global Fire Weather Database, 15, 1407–1423, https://doi.org/10.5194/nhess-15-1407-2015, 2015.

Frías, M. D., Iturbide, M., Manzanas, R., Bedia, J., Fernández, J., Herrera, S., Cofiño, A. S., and Gutiérrez, J. M.: An R package to visualize and communicate uncertainty in seasonal climate prediction, Environmental Modelling & Software, 99, 101–110, https://doi.org/10.1016/j.envsoft.2017.09.008, 2018.

Galizia, L. F., Curt, T., Barbero, R., Rodrigues, M., Galizia, L. F., Curt, T., Barbero, R., and Rodrigues, M.: Understanding fire regimes in Europe, Int. J. Wildland Fire, 31, 56–66, https://doi.org/10.1071/WF21081, 2021.

de Groot, W. J.: Interpreting the Canadian Forest Fire Weather Index (FWI) System, 1987.

Herrera, S., Kotlarski, S., Soares, P. M. M., Cardoso, R. M., Jaczewski, A., Gutiérrez, J. M., and Maraun, D.: Uncertainty in gridded precipitation products: Influence of station density, interpolation method and grid resolution, 39, 3717–3729, https://doi.org/10.1002/joc.5878, 2019.

Jiménez-Ruano, A., Rodrigues Mimbrero, M., and de la Riva Fernández, J.: Exploring spatial–temporal dynamics of fire regime features in mainland Spain, 17, 1697–1711, https://doi.org/10.5194/nhess-17-1697-2017, 2017.

Johnson, S. J., Stockdale, T. N., Ferranti, L., Balmaseda, M. A., Molteni, F., Magnusson, L., Tietsche, S., Decremer, D., Weisheimer, A., Balsamo, G., Keeley, S. P. E., Mogensen, K., Zuo, H., and Monge-Sanz, B. M.: SEAS5: the new ECMWF seasonal forecast system, Geosci. Model Dev., 12, 1087–1117, https://doi.org/10.5194/gmd-12-1087-2019 , 2019.

Jolliffe, I.T., Stephenson, D.B.: Forecast Verification: A Practitioner's Guide in Atmospheric Science, John Wiley & Son, 126 pp., 2003.

Karali, A., Hatzaki, M., Giannakopoulos, C., Roussos, A., Xanthopoulos, G., and Tenentes, V.: Sensitivity and evaluation of current fire risk and future projections due to climate change: the case study of Greece, 14, 143–153, https://doi.org/10.5194/nhess-14-143-2014, 2014.

Lorenz, C., Portele, T. C., Laux, P., and Kunstmann, H.: Bias-corrected and spatially disaggregated seasonal forecasts: a long-term reference forecast product for the water sector in semi-arid regions, 13, 2701–2722, https://doi.org/10.5194/essd-13-2701-2021, 2021.

Manzanas, R.: Assessment of Model Drifts in Seasonal Forecasting: Sensitivity to Ensemble Size and Implications for Bias Correction, 12, e2019MS001751, https://doi.org/10.1029/2019MS001751, 2020.

Manzanas, R., Frías, M. D., Cofiño, A. S., and Gutiérrez, J. M.: Validation of 40 year multimodel seasonal precipitation forecasts: The role of ENSO on the global skill, 119, 1708–1719, https://doi.org/10.1002/2013JD020680, 2014.

Manzanas, R., Lucero, A., Weisheimer, A., and Gutiérrez, J. M.: Can bias correction and statistical downscaling methods improve the skill of seasonal precipitation forecasts?, Clim Dyn, 50, 1161–1176, https://doi.org/10.1007/s00382-017-3668-z, 2018.

Manzanas, R., Gutiérrez, J. M., Bhend, J., Hemri, S., Doblas-Reyes, F. J., Torralba, V., Penabad, E., and Brookshaw, A.: Bias adjustment and ensemble recalibration methods for seasonal forecasting: a comprehensive intercomparison using the C3S dataset, Clim Dyn, 53, 1287–1305, https://doi.org/10.1007/s00382-019-04640-4, 2019.

Marcos, R., Llasat, M. C., Quintana-Seguí, P., and Turco, M.: Use of bias correction techniques to improve seasonal forecasts for reservoirs — A case-study in northwestern Mediterranean, Science of The Total Environment, 610–611, 64–74, https://doi.org/10.1016/j.scitotenv.2017.08.010, 2018.

Mavromatis, T. and Voulanas, D.: Evaluating ERA-Interim, Agri4Cast, and E-OBS gridded products in reproducing spatiotemporal characteristics of precipitation and drought over a data poor region: The Case of Greece, 41, 2118–2136, https://doi.org/10.1002/joc.6950, 2021.

MedECC: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future, First Mediterranean Assessment Report [Cramer, W., Guiot, J., Marini, K. (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, 632 pp. ISBN: 978-2-9577416-0-1, DOI: 10.5281/zenodo.4768833, 2020.

Mercado-Bettín, D., Clayer, F., Shikhani, M., Moore, T. N., Frías, M. D., Jackson-Blake, L., Sample, J., Iturbide, M., Herrera, S., French, A. S., Norling, M. D., Rinke, K., and Marcé, R.: Forecasting water temperature in lakes and reservoirs using seasonal climate prediction, Water Research, 201, 117286, https://doi.org/10.1016/j.watres.2021.117286, 2021.

MeteoSwiss, Bhend, J., Ripoldi, J., Mignani, C., Mahlstein, I., Hiller, R., Spirig, C., Liniger, M., Weigel, A., Jimenez, J. B., Felice, M. D., Siegert, S., and Sedlmeier, K.: easyVerification: Ensemble Forecast Verification for Large Data Sets, 2017.

Mitsopoulos, I., Mallinis, G., Dimitrakopoulos, A., Xanthopoulos, G., Eftychidis, G., and Goldammer, J. G.: Vulnerability of peri-urban and residential areas to landscape fires in Greece: Evidence by wildland-urban interface data, Data in Brief, 31, 106025, https://doi.org/10.1016/j.dib.2020.106025, 2020.

Moreira, F., Ascoli, D., Safford, H., Adams, M. A., Moreno, J. M., Pereira, J. M. C., Catry, F. X., Armesto, J., Bond, W., González, M. E., Curt, T., Koutsias, N., McCaw, L., Price, O., Pausas, J. G., Rigolot, E., Stephens, S., Tavsanoglu, C., Vallejo, V. R., Wilgen, B. W. V., Xanthopoulos, G., and Fernandes, P. M.: Wildfire management in Mediterranean-type regions: paradigm change needed, Environ. Res. Lett., 15, 011001, https://doi.org/10.1088/1748-9326/ab541e, 2020.

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., and Thépaut, J.-N.: ERA5-Land: a state-of-the-art global reanalysis dataset for land applications, 13, 4349–4383, https://doi.org/10.5194/essd-13-4349-2021, 2021.

Rogers, B. M., Balch, J. K., Goetz, S. J., Lehmann, C. E. R., and Turetsky, M.: Focus on changing fire regimes: interactions with climate, ecosystems, and society, Environ. Res. Lett., 15, 030201, https://doi.org/10.1088/1748-9326/ab6d3a, 2020.

Ruffault, J., Curt, T., Moron, V., Trigo, R. M., Mouillot, F., Koutsias, N., Pimont, F., Martin-StPaul, N., Barbero, R., Dupuy, J.-L., Russo, A., and Belhadj-Khedher, C.: Increased likelihood of heat-induced large wildfires in the Mediterranean Basin, Sci Rep, 10, 13790, https://doi.org/10.1038/s41598-020-70069-z, 2020.

Salvati, L. and Ranalli, F.: 'Land of Fires': Urban Growth, Economic Crisis, and Forest Fires in Attica, Greece, 53, 68–80, https://doi.org/10.1111/1745-5871.12093, 2015.

Siegert, S., Bhend, J., Kroener, I., and Felice, M. D.: SpecsVerification: Forecast Verification Routines for Ensemble Forecasts of Weather and Climate, 2020.

Turco, M., Llasat, M. C., Tudela, A., Castro, X., and Provenzale, A.: Brief communication Decreasing fires in a Mediterranean region (1970–2010, NE Spain), Nat. Hazards Earth Syst. Sci., 13, 649–652, https://doi.org/10.5194/nhess-13-649-2013, 2013.

Turco, M., Rosa-Cánovas, J. J., Bedia, J., Jerez, S., Montávez, J. P., Llasat, M. C., and Provenzale, A.: Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models, Nat Commun, 9, 3821, https://doi.org/10.1038/s41467-018-06358-z , 2018.

Turco, M., Marcos-Matamoros, R., Castro, X., Canyameras, E., and Llasat, M. C.: Seasonal prediction of climate-driven fire risk for decision-making and operational applications in a Mediterranean region, Science of The Total Environment, 676, 577–583, https://doi.org/10.1016/j.scitotenv.2019.04.296, 2019.

United Nations Environment Programme: Spreading like Wildfire – The Rising Threat of Extraordinary Landscape Fires, A UNEP Rapid Response Assessment, Nairobi, 2022.

Urbieta, I. R., Zavala, G., Bedia, J., Gutiérrez, J. M., Miguel-Ayanz, J. S., Camia, A., Keeley, J. E., and Moreno, J. M.: Fire activity as a function of fire–weather seasonal severity and antecedent climate across spatial scales in southern Europe and Pacific western USA, Environ. Res. Lett., 10, 114013, https://doi.org/10.1088/1748-9326/10/11/114013, 2015.

van Wagner, C. E.: Development and structure of a Canadian forest fire weather index system, Forestry Tech. Rep. 35, Canadian Forestry Service, Ottawa, 1987.

Weisheimer, A. and Palmer, T. N.: On the reliability of seasonal climate forecasts, 11, 20131162, https://doi.org/10.1098/rsif.2013.1162, 2014.

WMO: Guidance on Operational Practices for Objective Seasonal Forecasting (WMO-No. 1246), Geneva, 2020.

Wotton, B. M.: Interpreting and using outputs from the Canadian Forest Fire Danger Rating System in research applications, Environ Ecol Stat, 16, 107–131, https://doi.org/10.1007/s10651-007-0084-2, 2009.

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

Natural Hazards and Earth System Sciences
Open Access
Discussions

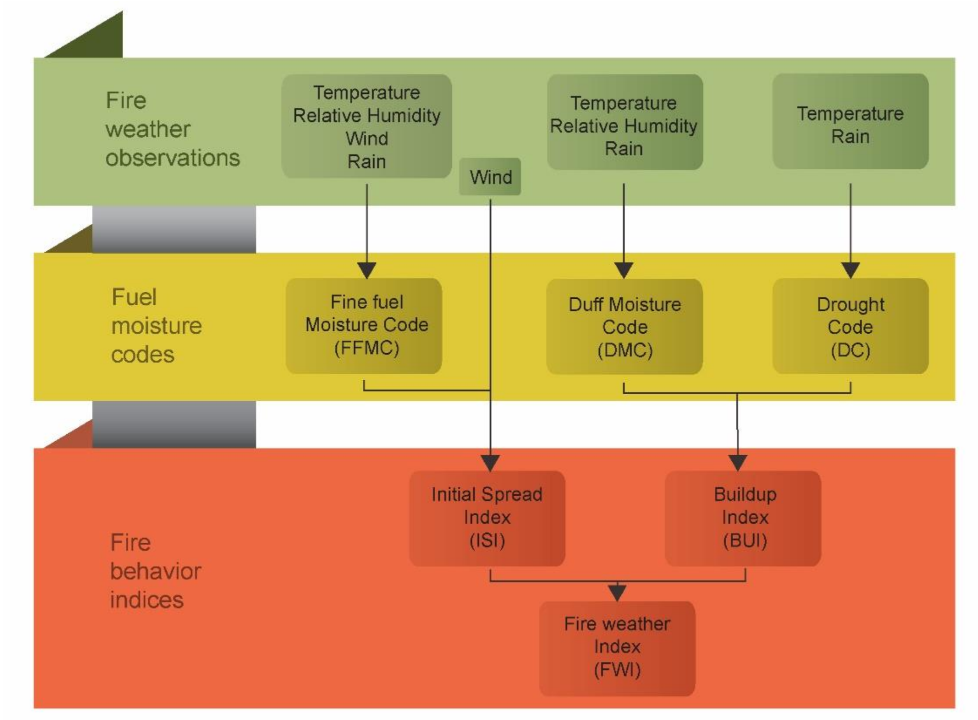


Figure 1: Structure of the Fire Weather Index (FWI) System (adapted from Canadian Forestry Service, 1984).

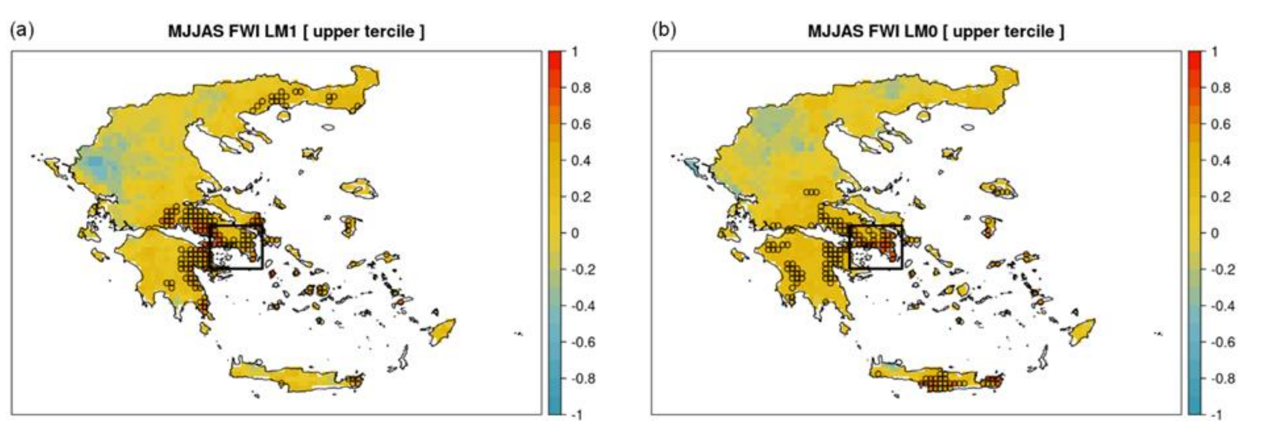
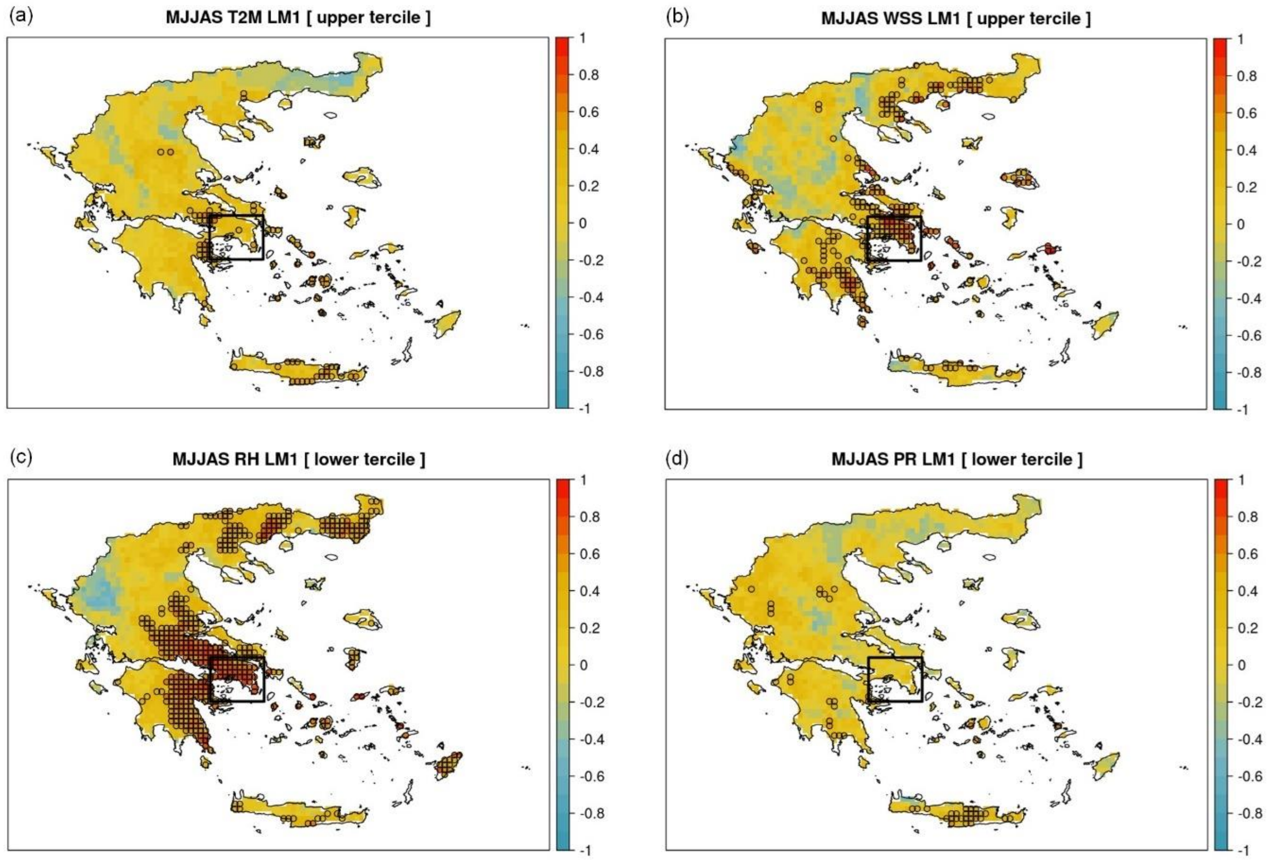


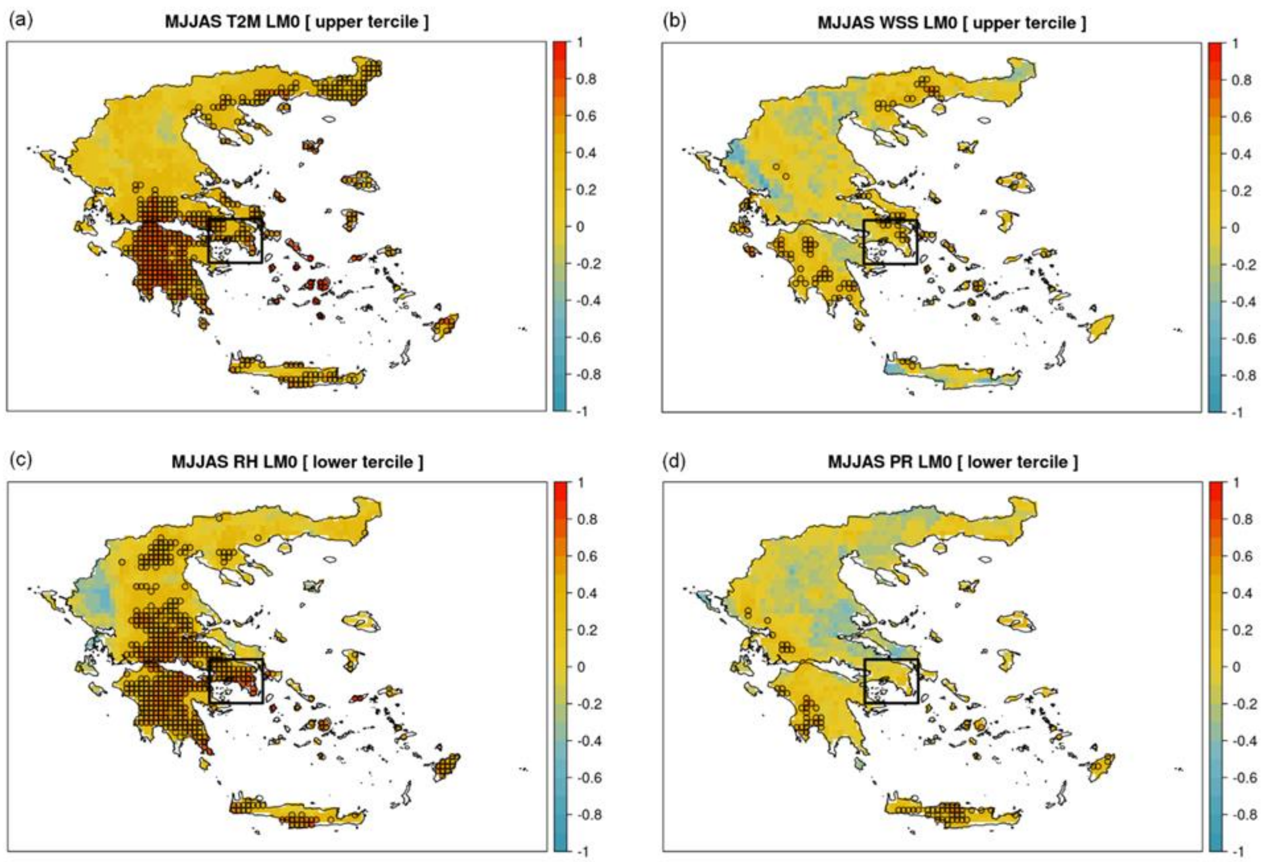
Figure 2: ROC Skill Scores (ROCSS) of the upper tercile SEAS5 FWI predictions initialized in (a) April (LM1) and (b) May (LM0), validated against ERA5-Land. The grid points with significant ROCSS values are indicated by circles (α=0.05). The rectangular black box indicates the Attica case study.



460 **Figure 3: ROC Skill Scores of the FWI input variables for LM1 forecasts that correspond to high fire danger values. (a) upper tercile of air temperature (T2M), (b) upper tercile of wind speed (WSS), (c) lower tercile of air relative humidity (RH) and (d) lower tercile of total precipitation (PR). The grid points with significant ROCSS values are indicated by circles (α=0.05). The rectangular black box indicates the Attica case study.**

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

Natural Hazards and Earth System Sciences
Open Access
Discussions



465

Figure 4: ROC Skill Scores of the FWI input variables for LM0 forecasts that correspond to high fire danger values. (a) upper tercile of air temperature (T2M), (b) upper tercile of wind speed (WSS), (c) lower tercile of air relative humidity (RH) and (d) lower tercile of total precipitation (PR). The grid points with significant ROCSS values are indicated by circles (α=0.05). The rectangular black box indicates the Attica case study.

470

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

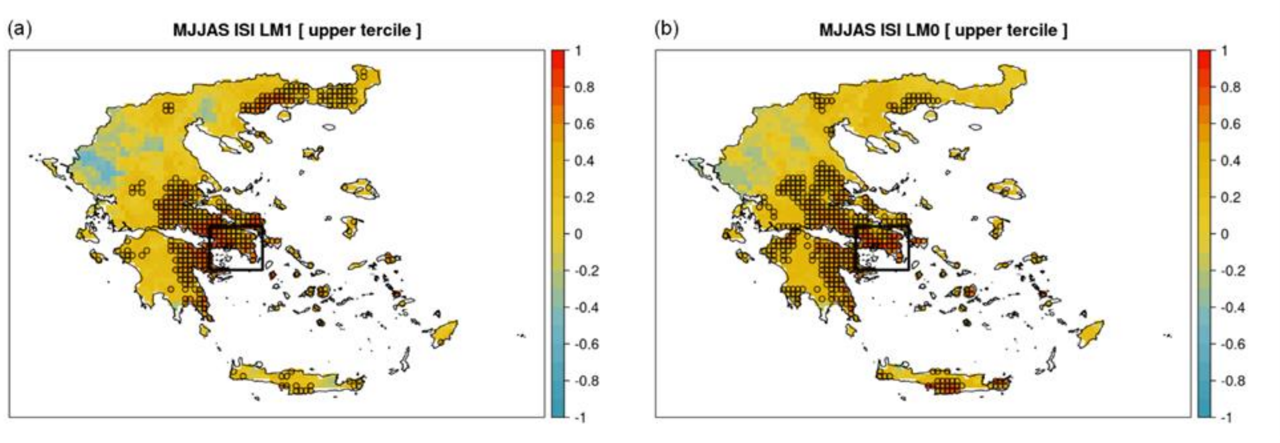
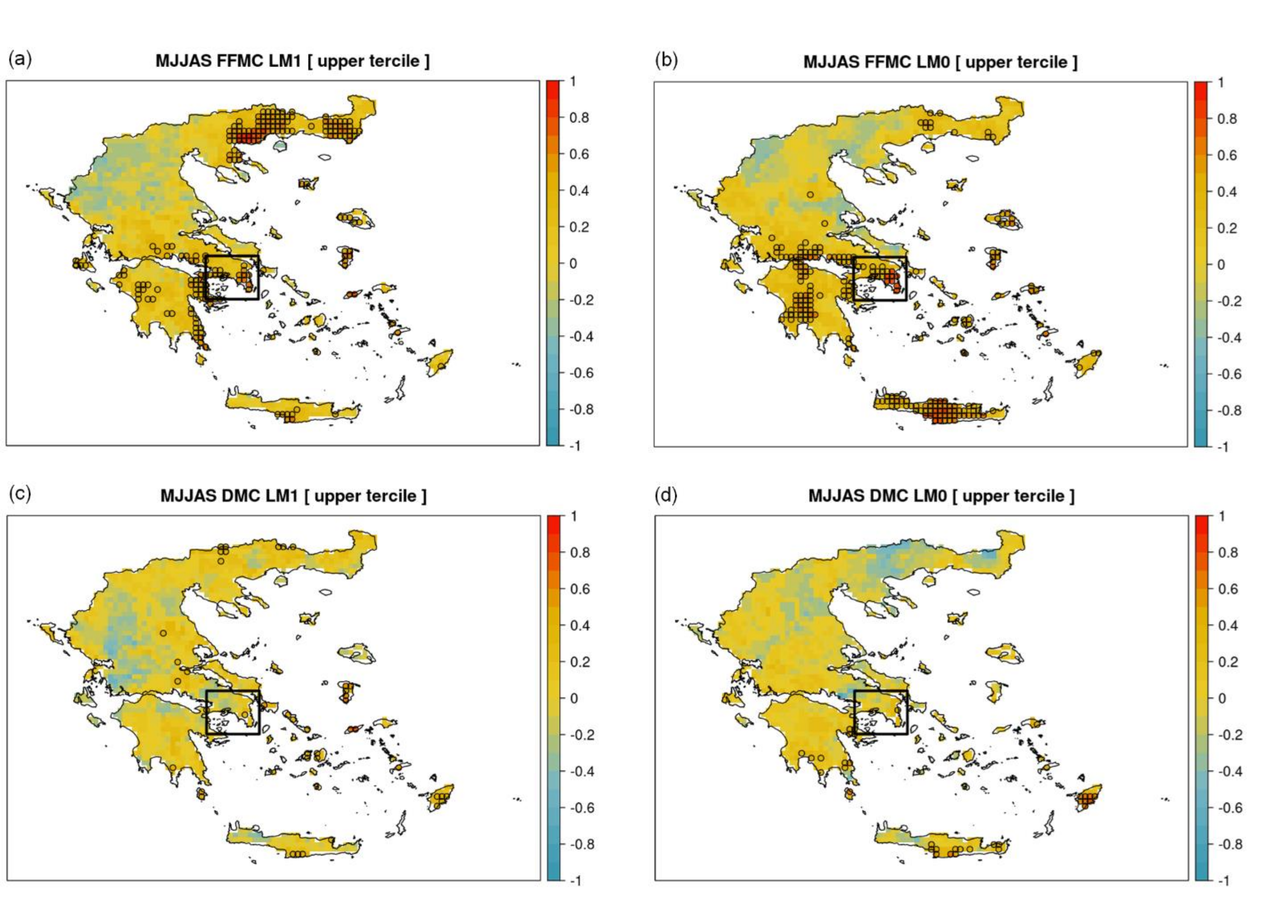


Figure 5: ROC Skill Scores of the upper tercile SEAS5 ISI predictions initialized in (a) April (LM1) and (b) May (LM0), validated against ERA5-Land. The grid points with significant ROCSS values are indicated by circles (α=0.05). The rectangular black box indicates the Attica case study.



https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

Natural Hazards and Earth System Sciences
Discussions

Figure 6: ROC Skill Score of the upper tercile SEAS5 FFMC and DMC predictions initialized in (a),(c) April (LM1) and (b),(d) May (LM0),respectively, validated against ERA5-Land. The grid points with significant ROCSS values are indicated by circles (α=0.05). The rectangular black box indicates the Attica case study.

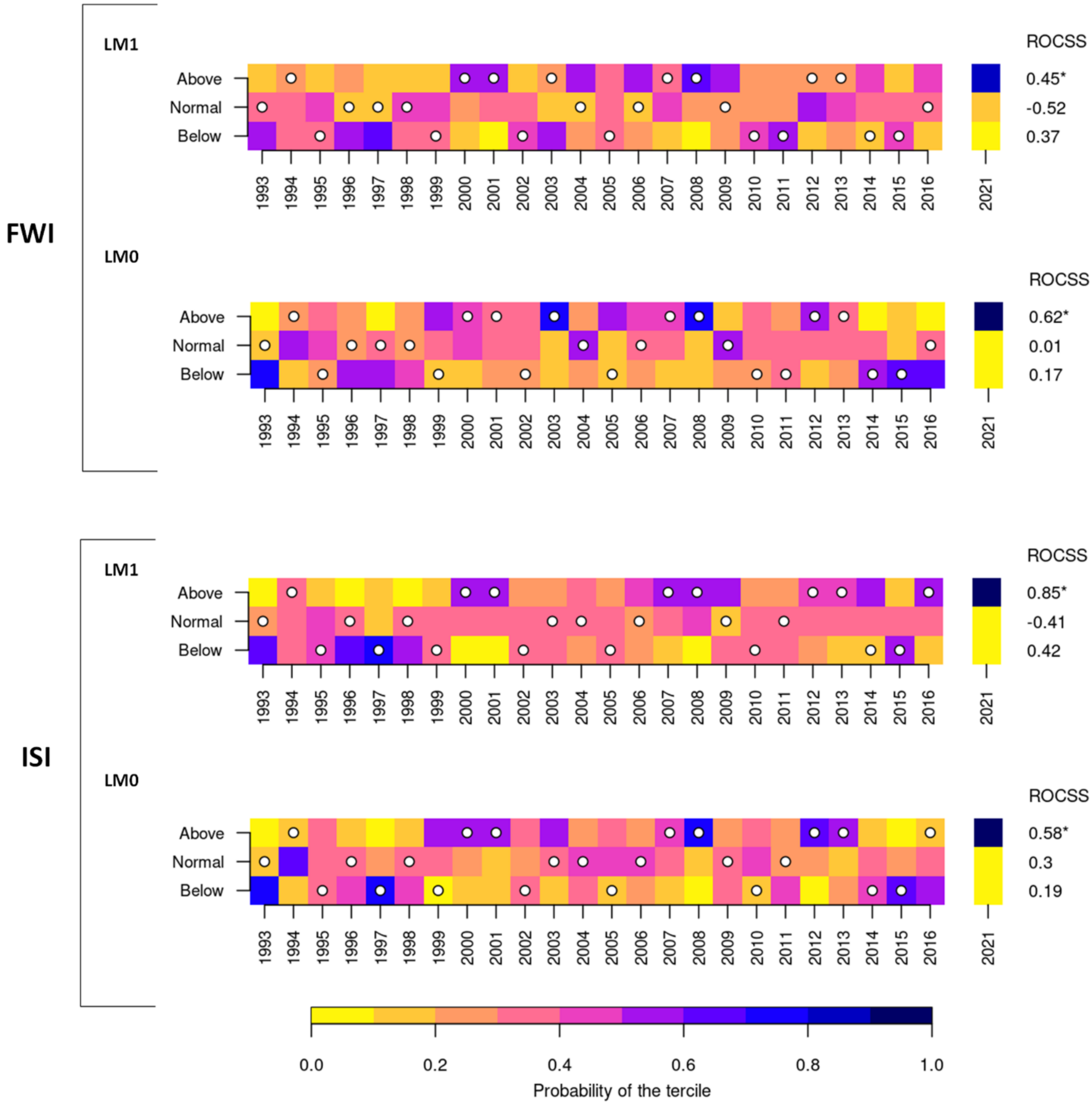


Figure 7: Tercile plots for May to September FWI and ISI sub-component for LM0 and LM1 predictions covering the hindcast period (1993-2016) and the forecast year (2021) for the Attica case study. Forecast probabilities for the three tercile categories are codified in a yellow (0, no member forecasts in one category) to blue (1, all the members in the same category) scale. The white

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

bullets represent the observed category according to the ERA5-Land dataset. ROCSS values obtained from the hindcast period are shown on the right side of each category and the asterisk indicates significant values (α=0.05).

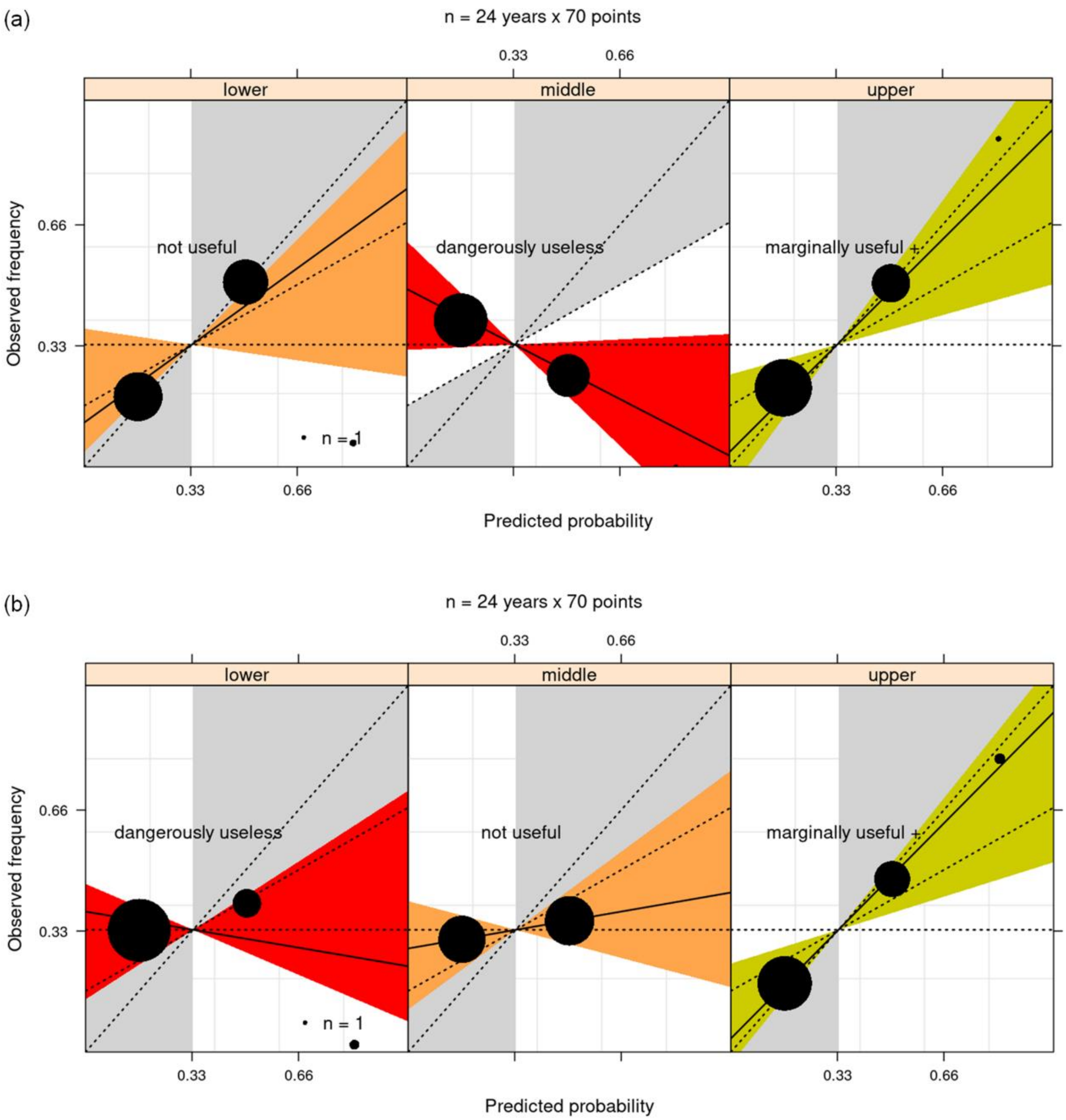
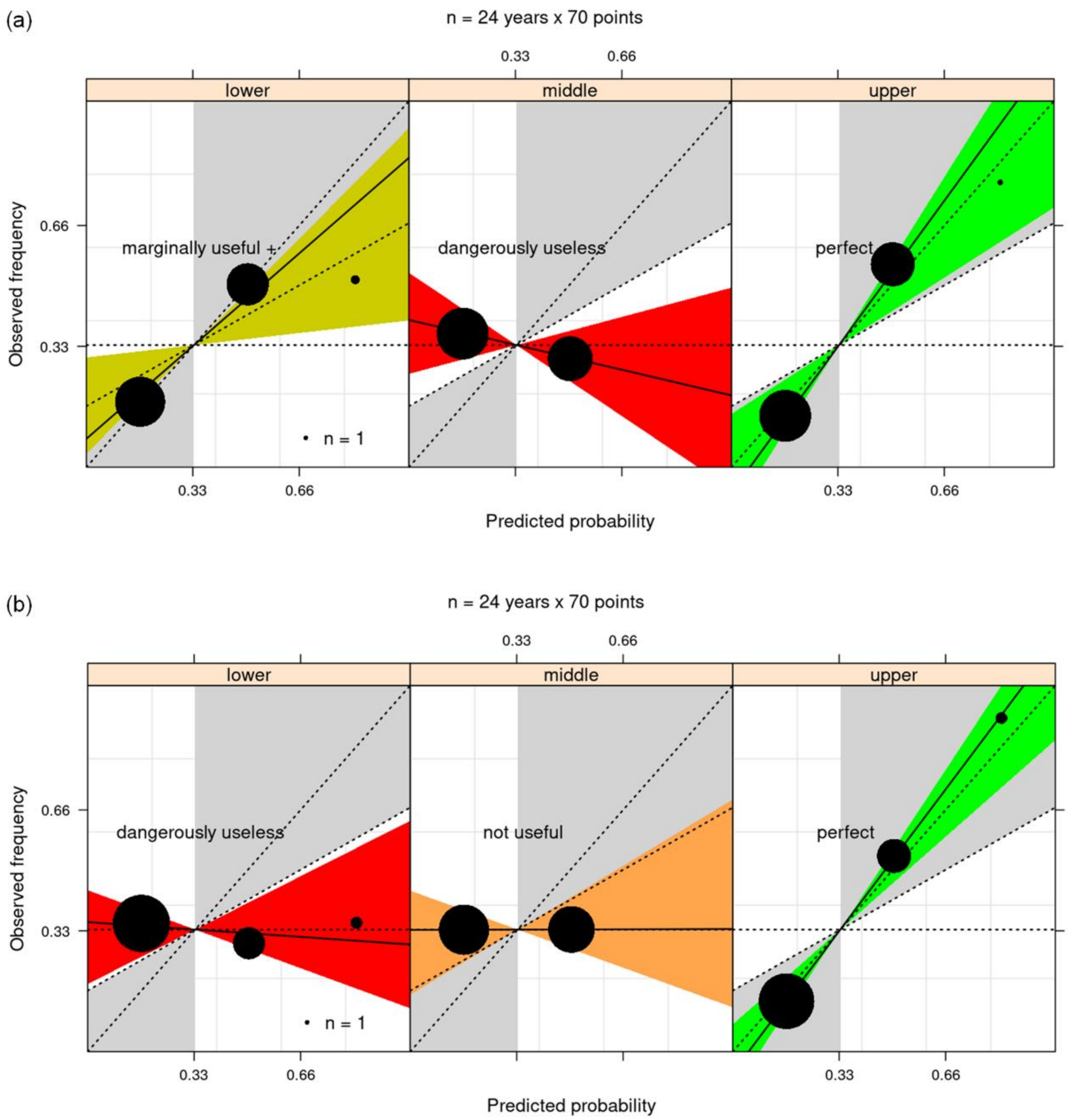


Figure 8: Reliability diagrams for each one of the FWI terciles (lower, middle, upper) for (a) LM1 and (b) LM0 predictions. The different colours correspond to the reliability categories proposed by Weisheimer and Palmer (2014) and further updated by

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

Manzanas et al. (2018). The perfect reliability (dashed diagonal line), no resolution (horizontal dashed line) and no skill (dashed line between the no-resolution line and the diagonal) lines and the skill region (in grey) are also indicated.



495

Figure 9: The same as Fig. 8 but for ISI predictions.

https://doi.org/10.5194/nhess-2022-140
Preprint. Discussion started: 7 June 2022

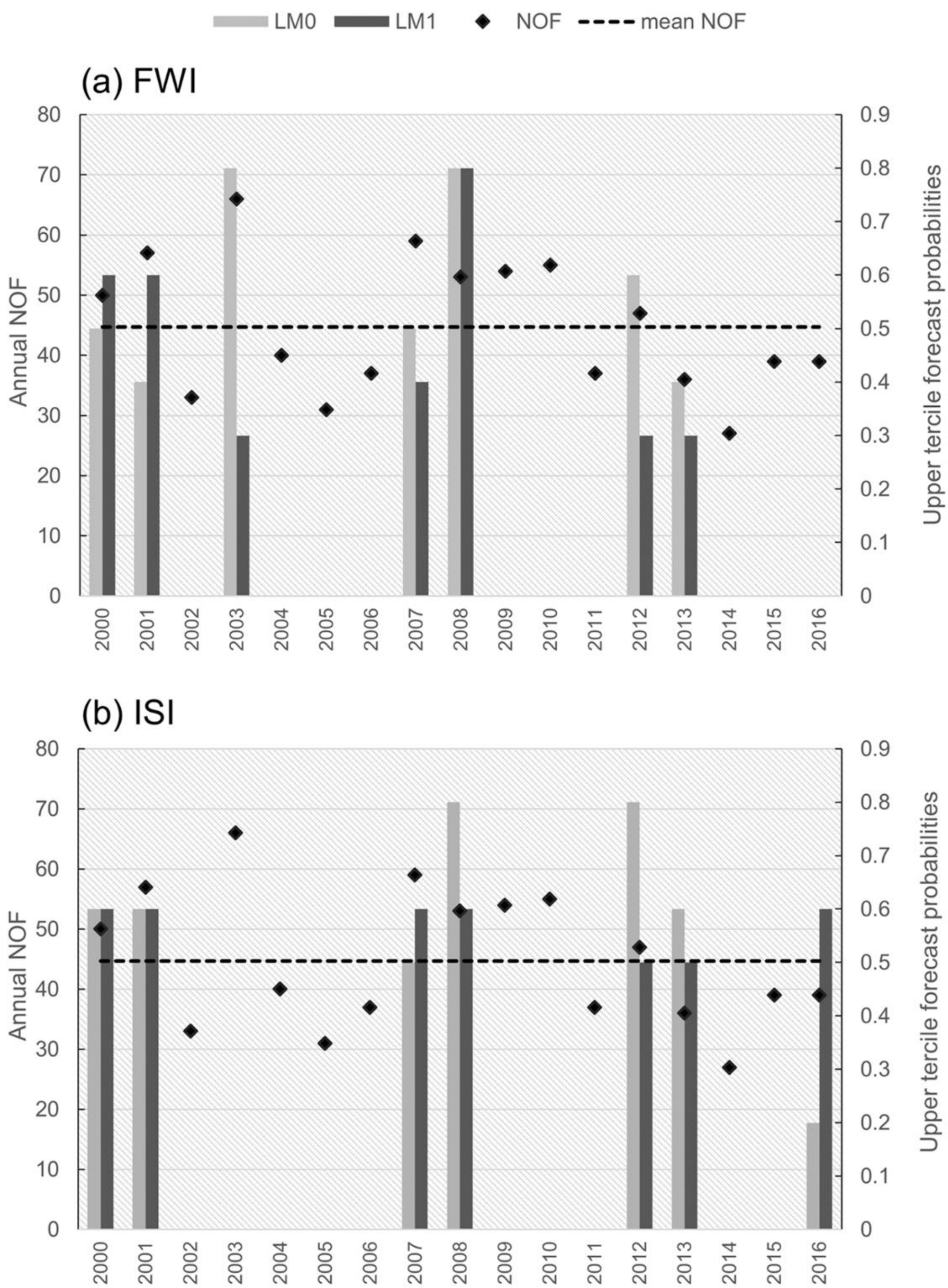


Figure 10: Annual number of fires (NOF) in Attica per year (black diamonds), mean number of fires for 2000-2016 (black dashed line) and forecast probabilities for the upper tercile categories of (a) FWI and (b) ISI for LM0 (grey columns) and LM1 (black columns) predictions.