https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

Forest fire risk in Croatia under a changing climate

Mislav Anić[1], Ksenija Cindrić Kalin[2], Maša Zorana Ostrogović Sever[3], Doroteja Bitunjac[3], and Hrvoje Marjanović[3]

[1]Agrometeorology Department, Croatian Meteorological and Hydrological Service, Zagreb, 10000, Croatia
[2]Department of Geophysics, Faculty of Science, University of Zagreb, Zagreb, 10000, Croatia
[3]Department of Forest Management and Forestry Economics, Croatian Forest Research Institute, Jastrebarsko, 10450, Croatia,

Correspondence to: Mislav Anić (mislav.anic@dhz.hr)

Abstract. Forest fires in Croatia inflict substantial economic and ecological damage and frequently pose a threat to infrastructure and human lives. The southern part of the Croatian Adriatic, belonging to the Mediterranean basin, is the most severely affected region. To evaluate fire risk, the Canadian Fire Weather system was applied, and indices based on Fire Weather Index (FWI) – Seasonal Severity Rating (SSR), the number of days with FWI > 30 (FWI30), the 90-th percentile of FWI (FWIp90), and Length of Fire Season (LOFS) were derived. This study investigates the extent to which climate change has influenced the variability of latter indices across Croatia during June-September season. The analysis covers the period 1961–2020, revealing upward trends and predominantly positive anomalies in the evaluated indices. The most favourable fire weather conditions occur in the southern part of the Croatian Adriatic, which also exhibits the strongest increasing trends in SSR and FWI30. Although the continental parts of Croatia have historically been less susceptible to wildfires, the observed trends in the analysed indices suggest that conditions conducive to ignition and spread of wildfires are gradually emerging in these areas as well.

1 Introduction

The Mediterranean basin is a region known to be highly prone to wildfires (Moreira et al., 2011; Keeley et al., 2012). With the climate change, the large wildfires are becoming increasingly frequent not just in the Mediterranean part, but also in the continental Europe (Miller et al., 2025). Between 1980 and 2024, among all weather and climate related hazards, wildfires (together with heat waves, droughts, cold spells and frost) caused 26% of economic losses in Europe (EEA, 2025), whereas the total burned area in Greece, Italy, France, Spain, and Portugal amounted to 538,846 ha in 2022 and 354,244 ha in 2023 (San Miguel-Ayanz et al., 2022, 2023). Due to prolonged dry and hot periods during the warm part of the year, in combination with easily flammable Mediterranean vegetation, favourable conditions are created for the occurrence of wildfires that cause significant human, ecological, and economic losses (Ruffault et al., 2020; Eberle and Higuera, 2022). Climate change is leading to prolonged and more intense droughts and heatwaves, and the Mediterranean region stands out as a climate change hotspot (Giorgi, 2006). The frequency of concurrent hot, dry and fire-weather events has increased over the Mediterranean region

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

(Dosio et al., 2025) leading to the future risk of direct increase in the extent of burnt area due to wildfires (Tramblay et al., 2020).

Croatia lies at the intersection of three major natural regions: the Pannonian Plain, the Dinaric Alps, and the Mediterranean Sea. The northern part of the territory is continental lowland Croatia, which is separated by highland Croatia from the Adriatic coastal area belonging to the Mediterranean region. In Croatia, wildfires most frequently occur in the coastal counties (NUTS 3; CBS, 2019) of the central part of the Adriatic coast (Fig. 1a). According to VIIRS Active Fires Version 2 (375 m) data (Giglio, 2024), during the 2012–2024 period, the highest number of wildfires (3,445) was recorded in county HR033, followed by HR032, HR034, and HR035, with a total of 3,094, 3,069, and 2,859 wildfires, respectively. The total daily number of wildfires across Croatia in the same period indicates the existence of two peaks (Fig. 1b). The first occurs in late winter and early spring, most likely due to human negligence during the burning of agricultural waste. The second peak occurs in summer during the fire season, traditionally defined as lasting from June 1 to September 30. The year 2017 stands out with the highest total number of wildfires (5,066; Fig. 1c), followed by 2012 with 4,863 fires. The extreme fire season of 2017 (Posavec et al., 2023) is considered one of the worst in state history, and according to the European Forest Fire Information System (EFFIS), the total burned area during that season amounted to 67,666 ha. It is estimated that the total damage caused by wildfires during the 2010–2021 period amounted to approximately 249 million EUR (DRA-HR, 2024). In addition to destroying vegetation and causing major ecological and economic losses, wildfires in Croatia often threaten populated areas. A notable example is the Split wildfire of July 2017, which lasted for nine days, with the fire being put under control only 4 km from the city centre

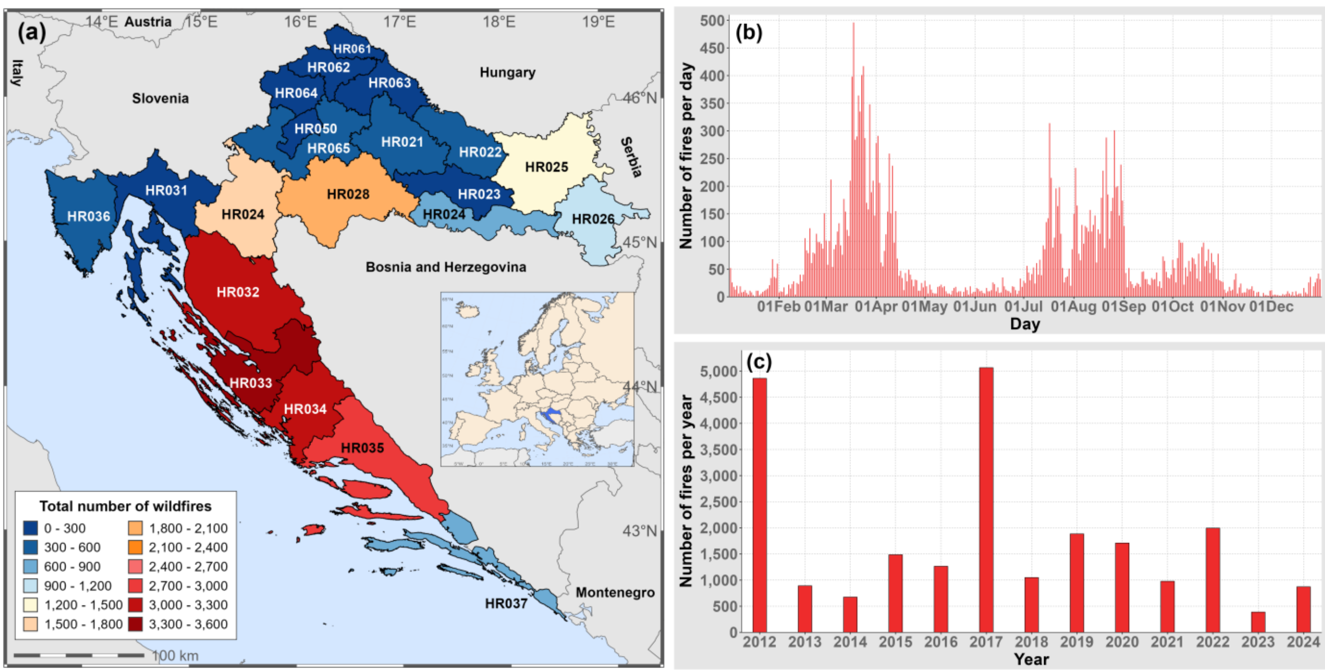


Figure 1. Total number of wildfires in Croatia during 2012 – 2024 per: **(a)** NUTS3 regions; **(b)** day; and **(c)** year (Data source VIIRS 375 m).

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

(Čavlina Tomašević et al., 2022). These impacts underline the importance of reliable forest-fire risk assessment for both prevention and operational fire management.

The Canadian Forest Fire Weather Index System (FWI) has been widely used in the assessment of forest fire danger (Van Wagner and Pickett, 1974; Van Wagner, 1987; Lawson and Armitage, 2008). Although originally calibrated for boreal pine forests in Canada, the model has proven successful when applied in other climates and environments (de Groot et al., 2007; Tian et al., 2011; de Jong et al., 2016; Mandal et al., 2022; Kudláčková et al., 2024), including the Mediterranean region (Viegas et al., 1999; Carvalho et al., 2008; Dimitrakopoulos et al., 2011; Bedia et al., 2012; Lahaye et al., 2018; Varela et al., 2018, Politi et al., 2023).

Consequences of climate change on fire risk have been studied at global and regional level using, in most cases, relatively coarse spatial resolution (Venäläinen et al. 2014, Jolly et al. 2015, Giannaros et al. 2020). However, for areas with a complex orography where, like in Croatia, the mountainous and coastal regions meet and altitude changes sharply within only a few kilometres, coarse resolution models are not adequate as they can underestimate extreme values. In such cases, modeling at the finer spatial resolution is needed.

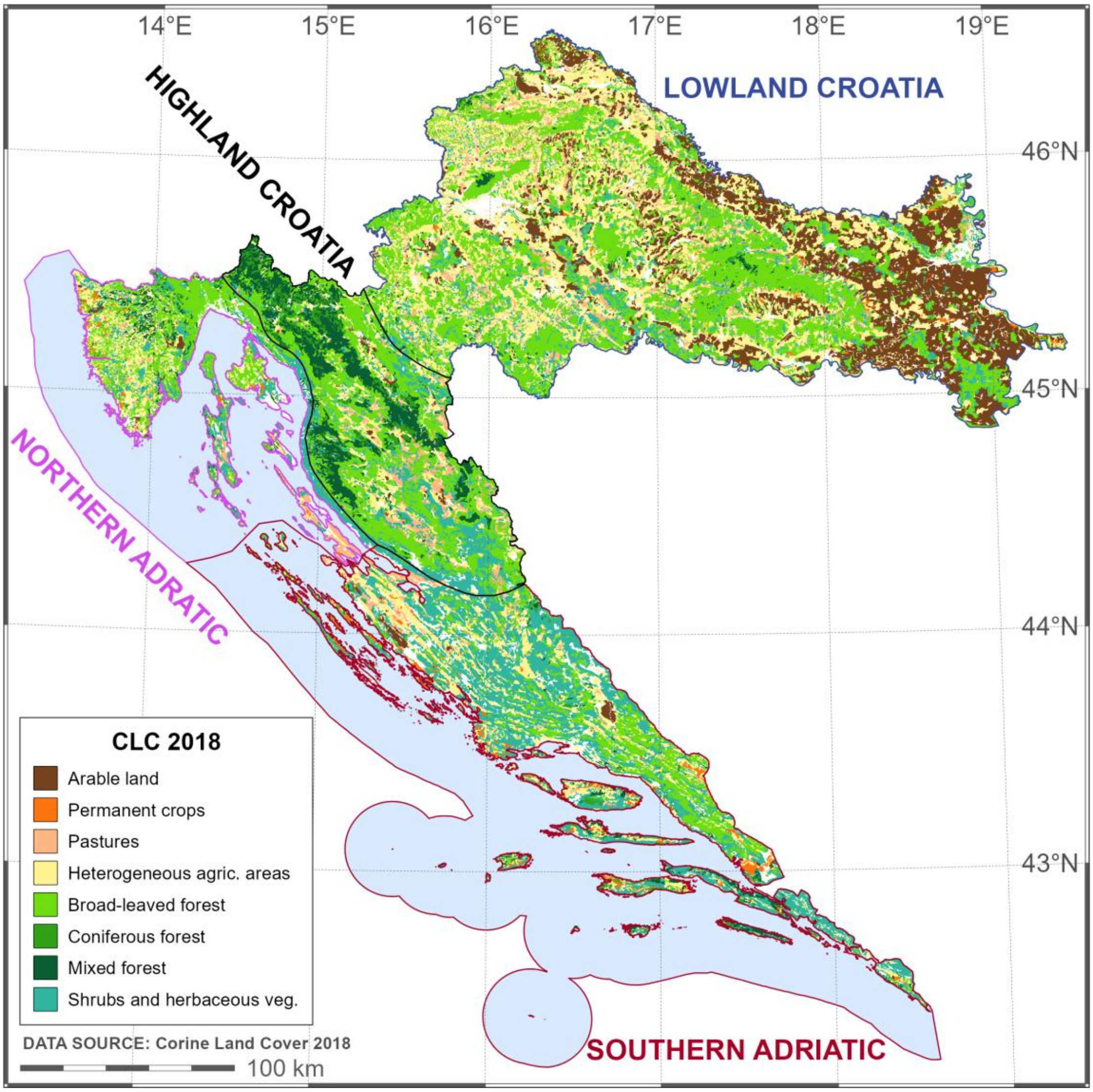
The aim of this study is to assess the trends of wildfire risk by analysing spatial and temporal variability in climate and FWI based indices in Croatia at 1 km spatial resolution during the period 1961–2020. Based on the FWI values, seasonal severity rating (SSR), length of fire season (LOFS), the number of days with FWI > 30 (FWI30), and the 90th percentile of FWI (FWIp90) were calculated to quantify changes in fire risk and identify vulnerable areas in support of fire prevention efforts.

2 Research area

According to the Köppen–Geiger climate classification, lowland Croatia is characterized by a humid subtropical climate (Cfa) (Beck et al., 2018). In the mountainous regions of Dinaric Alps, the climate is mostly classified as subtropical highland (Cfb), while at higher altitudes a humid continental climate with warm summers (Dfb) predominates. In the northern Adriatic, the climate is mostly humid subtropical (Cfa), whereas the southern Adriatic is characterized by a Mediterranean climate (Csa). In summer, the Adriatic region is strongly influenced by the Azores anticyclone maintaining long-term stable weather conditions with prolonged dry spells (Cindrić Kalin and Pasarić, 2022). The Adriatic coast is largely covered by shrublands and, to a lesser extent, by deciduous forests (Fig. 2), with the pubescent oak (*Quercus pubescens* Willd.) being the main species in the Submediterranean and holm oak (*Quercus ilex* L.) in the Eumediterranean part. From the coniferous species in the coastal part of Croatia predominates the Aleppo pine (*Pinus halepensis* Mill.) (Posavec et al., 2023). It is generally the most widespread pine species in the Mediterranean, with forests covering approximately 6.8 million hectares (Mauri et al., 2016). Lowland Croatia is characterized by a higher proportion of agricultural and arable land, particularly in Eastern Croatia. In terms of forest cover, deciduous forests dominate, with pedunculate oak (*Quercus robur* L.), narrow-leafed ash (*Fraxinus angustifolia* Vahl.) and common hornbeam (*Carpinus betulus* L.) as the most common species in the plains, while sessile oak (*Quercus petraea* L.) and European beech (*Fagus sylvatica* L.) predominate in the hills and low-lying mountains (highest

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

1,035 m). In the mountainous region, mixed forests of silver fir (*Abies alba* Mill.) and European beech prevail at higher elevations, while pure beech forests predominate at medium elevations.



85 **Figure 2.** Vegetation cover of Croatia (data source CORINE Land Cover 2018 (EEA, 2018)).

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

3 Methodology and data

3.1 Climate indices

To assess changes in thermal conditions in Croatia during the June–September (JJAS) season over the period 1961–2020, the maximum daily air temperature (Tmax), the total number of hot days with Tmax ≥ 30 °C (Nhot), and the duration of periods with consecutive hot days – hot spells (DHot) were analysed. To calculate seasonal values, daily Tmax values at 42 meteorological stations were averaged over the JJAS season. The total seasonal number of hot days was obtained by summing all hot days within the JJAS period, and the longest sequence of consecutive hot days was extracted. In the same manner, the total number of dry days (NDry) and the maximum duration of dry spells per season (DDry) were determined, where a dry day is defined as a day with precipitation ≤ 2.8 mm. It represents the precipitation threshold for calculating the drought code within the FWI system (see subsection 3.2) and it was found as the median daily accumulated precipitation associated with lightning-ignited wildfires (Kalashnikov et al., 2023). To assess drought intensity, the Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente Serrano, 2010) was used. Based on the distribution of the difference between precipitation (P) and potential evapotranspiration (ET_0), the SPEI index provides an assessment of dryness/wetness over a specific period, while the inclusion of potential evapotranspiration accounts for the influence of air temperature on drought. Lončar-Petrinjak et al. (2024) confirmed a generalized logistic distribution as the most suitable theoretical distribution for representing the water balance (P - ET_0) in Croatia. Negative values of the SPEI index indicate dry conditions, while positive values indicate wet conditions. In this study, the SPEI4 index for September was calculated, and for this purpose, potential (i.e., reference) evapotranspiration was estimated using the Penman–Monteith equation (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(\frac{900}{T+273})u(e_s - e_a)}{\Delta + \gamma(1 + 0.34u)} \quad (1)$$

where R_n denotes net radiation at surface [MJ m^{-2} d^{-1}], G soil heat flux density [MJ m^{-2} d^{-1}], T average daily air temperature [°C], u adjusted wind speed [m s^{-1}] at 2m height, e_s the vapour pressure of the air at saturation [kPa], e_a the actual vapour pressure [kPa], Δ the slope of the vapour pressure curve [kPa $°C^{-1}$] and γ psychrometric constant [kPa $°C^{-1}$].

3.2 FWI calculation

The Canadian Forest Fire Weather Index (FWI) system (Van Wagner, 1974, 1987; Lawson and Armitage 2008) requires measurements of air temperature, wind speed, and relative humidity at 12:00 local time, as well as the accumulated precipitation over the previous 24 hours. Since standard meteorological measurements in Croatia are taken at 07:00, 14:00, and 21:00, meteorological variables measured at 14:00 were used for the calculation, along with the 24-hour accumulated precipitation from 07:00 to 07:00. The system consists of six main components that are computed directly from meteorological variables. The first step is to estimate the moisture content in three types of fuel: fine fuel (Fine Fuel Moisture Code, FFMC), moderate duff layers and medium-sized downed woody material (Duff Moisture Code, DMC), and deep duff layers and large

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

logs (Drought Code, DC). Higher values of these fuel moisture codes indicate lower moisture content in the fuel, implying higher flammability. Depending on the amount of precipitation, two phases are distinguished: a wetting phase and a drying phase. If the accumulated 24-hour precipitation is less than the threshold value for a given fuel type, the drying phase begins. The precipitation thresholds for FFMC, DMC, and DC are 0.5, 1.5, and 2.8 mm, respectively. In the next step, two intermediate fire behaviour indices are calculated based on the fuel moisture codes: the Initial Spread Index (ISI) and the Buildup Index (BUI). The ISI is derived from FFMC and wind speed and represents a numerical estimate of the expected rate of fire spread. The BUI quantifies the dryness of the total fuel available for combustion. Based on the ISI and BUI, the final component of the system, Fire Weather Index (FWI), is calculated, representing a numerical value of fire intensity with larger FWI values indicating unfavourable fire weather and higher fire danger. In this study, the individual FWI system components were not analysed directly. Instead, indices derived from the FWI were considered. From daily FWI values, the Daily Severity Rating (DSR) was computed according to the formula:

$$DSR = 0.0272 \cdot FWI^{1.77} \tag{2}$$

and these values were averaged over the JJAS season to obtain the Seasonal Severity Rating (SSR). To assess fire weather extremes, the 90th percentile of FWI (FWIp90) and the number of days with FWI > 30 (FWI30) were calculated (Bedia et al., 2014). Additionally, the Length of Fire Season (LOFS) was determined as the period whose start and end were defined by two consecutive weeks with FWI > 15 and FWI < 15, respectively. In this case, FWI represents a 7-day moving average rather than the daily value (Moriondo et al., 2006). The calculations started on January 1, 1961, using standard initial values of the fuel moisture codes: $FFMC_0 = 85$, $DMC_0 = 6$, and $DC_0 = 15$ (Van Wagner, 1974). The entire procedure was implemented in R software (R Core Team, 2025), following the original equations presented in Van Wagner and Pickett (1985).

3.3 Spatial interpolation

For the spatial interpolation of climate and fire weather variables onto a regular grid, the method of regression kriging was applied. This is an advanced geostatistical mapping technique whose framework is presented in Hengl (2004, 2007, 2009) and was already applied for Croatia (Zaninović et al., 2008; Perčec Tadić, 2010; Perčec Tadić et al., 2023). In the first step of the method, the spatial trend is determined by performing a multiple linear regression of the observed variable against selected predictors. For the interpolation grid, a digital elevation model (DEM) with a horizontal resolution of 1 km was used, from which four predictors were derived: elevation [m], distance from the sea [m], latitude, and longitude. To account for local spatial variation, the next step involves performing ordinary kriging of the residuals, the differences between the measured values and those predicted by the regression model. Based on the defined model, predictions are then made for all grid points. The predictive performance of the model was evaluated using leave-one-out cross-validation (LOOCV). For all analysed variables, the mean error (ME), coefficient of determination (R^2), root mean square error (RMSE), and normalized root mean square error (RMSEr) (calculated by dividing RMSE by the standard deviation of observations) were determined. The ME represents the mean difference between observed and predicted values, and ME values close to zero indicate an unbiased estimate. The R^2 indicates how much of the variability is explained by the model, while RMSEr expresses prediction error relative to the variability of the data. Model predictions are considered successful if RMSEr < 0.4, in which case the model explains more than 84% of the variability (1 – $RMSEr^2$). Predictions are considered relatively satisfactory if RMSEr is between 0.4 and 0.75. If RMSEr > 0.75, the model explains less than 43% of the variability, meaning it does not adequately represent the spatial variation of the data (Perčec Tadić, 2010), and predictions are therefore considered unsatisfactory. When the data distribution was positively skewed, a log transformation was applied prior to spatial interpolation (Burrough and McDonnell, 2004; Hengl et al., 2004) to approximate a normal distribution. This transformation was used for the spatial interpolation of SSR, FWI30, and LOFS data. The described procedure was implemented in R software using the gstat package (Pebesma, 2004; Gräler et al., 2016), while the maps were produced using the ggplot2 package (Wickham, 2016).

In this study, climate normals, i.e. 30-year means of the analysed climate and fire weather variables were mapped for the climatological period 1991–2020. To determine changes in the analysed variables, trends were examined during the longer period, 1961–2020. For the trend calculation, 60 seasonal raster layers obtained via regression kriging were combined into a single multi-layer raster, after which the Theil–Sen slope (Sen, 1968) was computed for each pixel, a method chosen to reduce the influence of outliers. The statistical significance of the trend at the 95% level ($p \leq 0.05$) was tested using the Mann–Kendall test (Kendall, 1938; Mann, 1945). Given that the spatial interpolation of annual and seasonal values of LOFS and FWIp90 showed a high level of uncertainty, anomalies of these variables were calculated instead of trends, by subtracting the mean 1961–1990 values from the more recent 1991–2020 climatological mean.

3.4 Meteorological data

The study utilized data from 24 main meteorological stations, 18 climatological stations, and 105 rain gauge stations operated by the Croatian Meteorological and Hydrological Service (DHMZ), with their locations shown in Fig. 3. For the purposes of analysis, the following measurements were used from meteorological stations: air temperature [°C], relative humidity [%], wind speed [m s^{-1}], cloud cover, sunshine duration [h], and total daily precipitation [mm]. From rain gauge stations, only total daily precipitation data were available. The selected stations conducted continuous measurements during the 1961–2020 period. Although additional stations operated during this period, their data were excluded due to substantial gaps in the time series. The data coverage for most analysed stations exceeded 95%, while only four stations had coverage between 80% and 90%. Gaps in the time series of meteorological elements were interpolated using multiple linear regression (Hasanpour Kashani, 2012), based on data from neighbouring stations, in order to obtain a complete dataset for the 1961–2020 period. Since the digital elevation model (DEM) used in this study covers a large portion of Slovenia, to improve model prediction in the northern and western parts of Croatia, data from 11 Slovenian meteorological stations were also employed (ARSO, 2025), however these data were used solely for spatial interpolation purposes and are not displayed in the results.

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

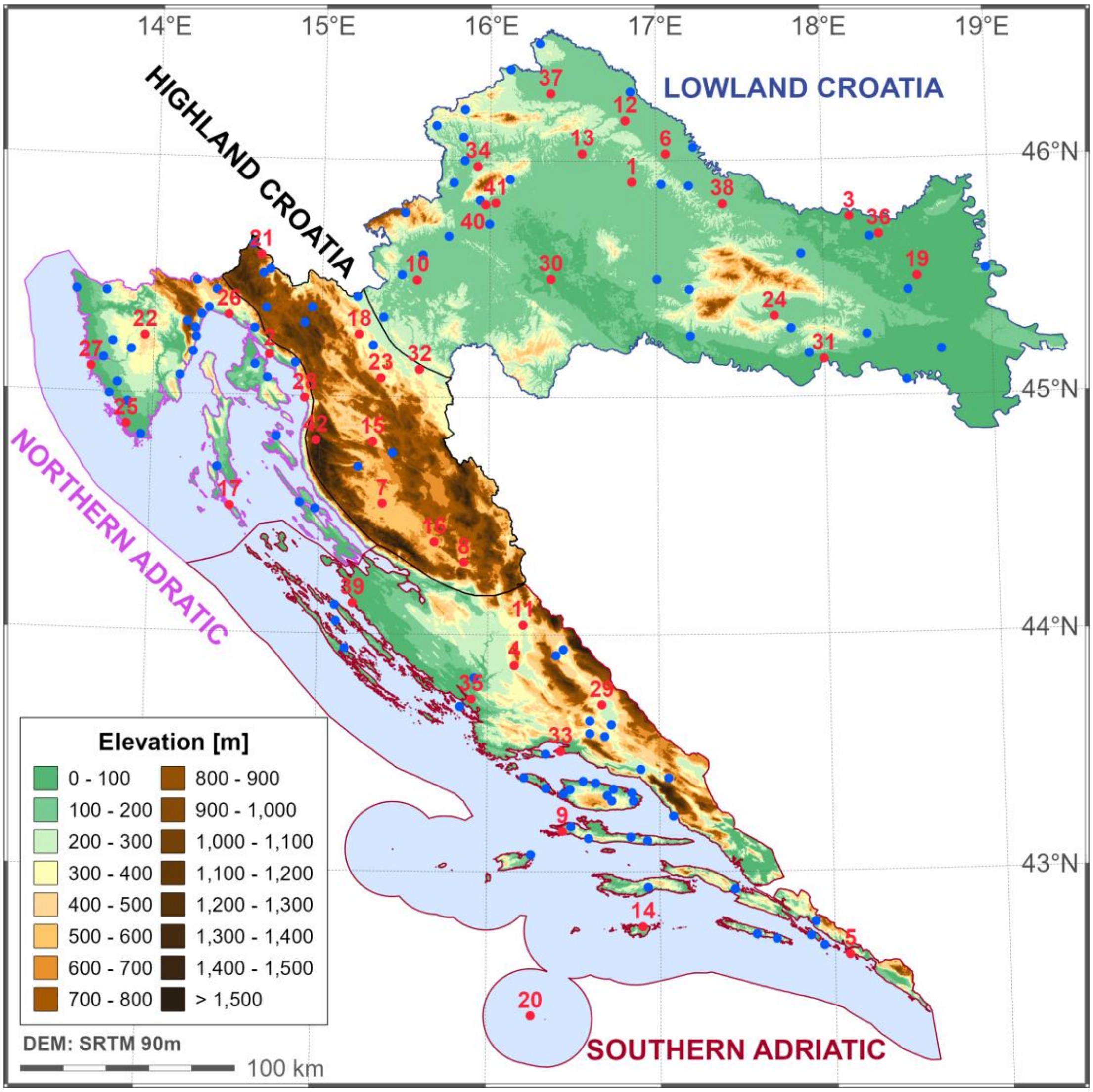


Figure 3. Topography of Croatia (data source NASA Shuttle Radar Topography Mission (2023)) with location of climatological (red colour) and raingauge stations (blue colour).

4 Results

4.1 Climatological conditions

According to the spatial analysis of Tmax during the JJAS season, the highest values occur in the coastal region, particularly in its central part and the adjacent continental hinterland, where the average Tmax for 1991–2020 ranges between 29 and 31°C

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

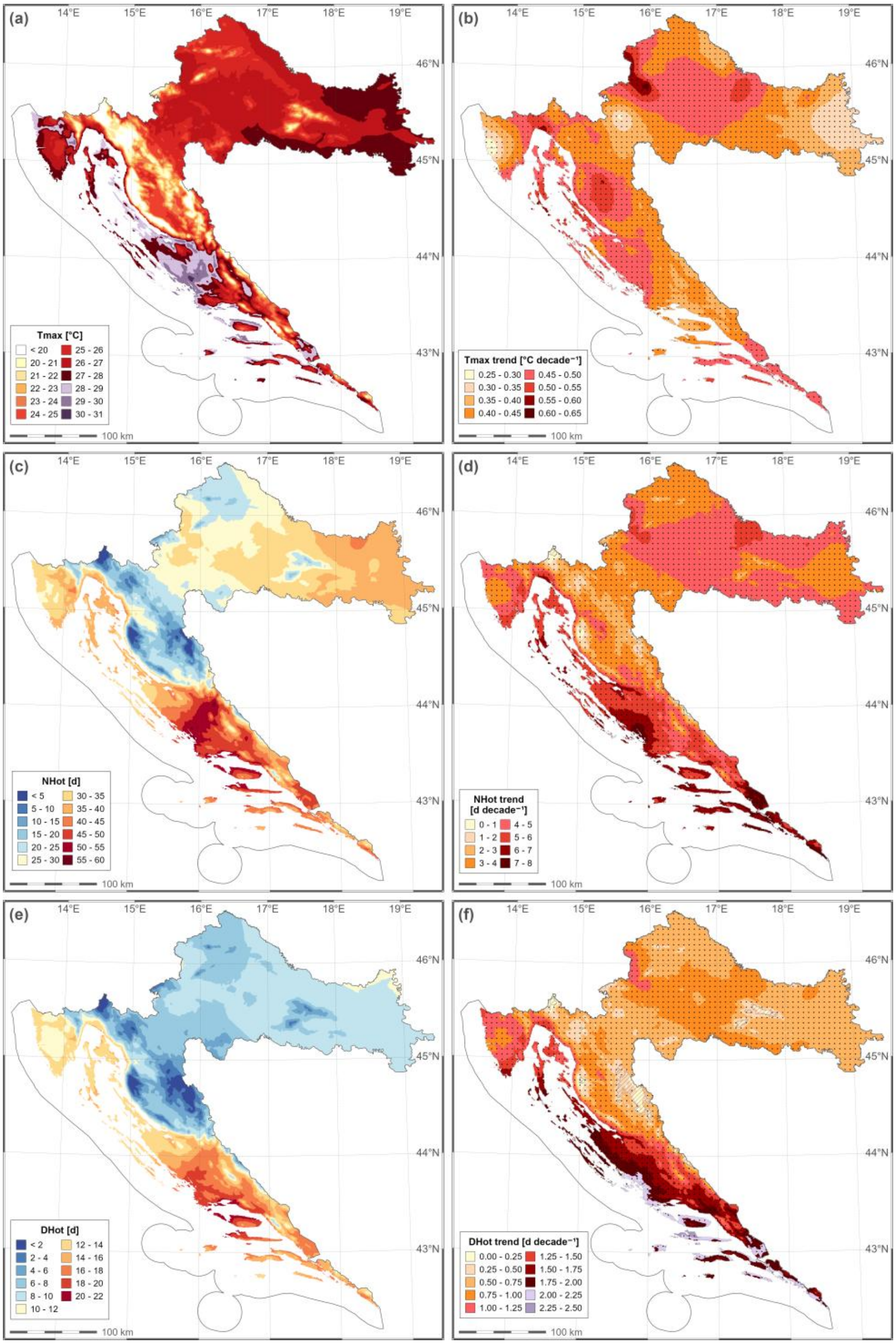


Figure 4. Average values of: maximum daily air temperature (Tmax) **(a)**, number of hot days (NHot) **(c)** and duration of period with consecutive hot days (DHot) **(e)** over June–September (JJAS) season during period 1991–2020; Trend of: Tmax **(b)**, NHot **(d)** and DHot **(f)** per decade for JJAS season over period 1961–2020; Areas with dots on the trend maps indicate statistically significant trends ($p \leq 0.05$),
195 while regions covered with diagonal hatching indicate non-significant trends.

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

(Fig. 4a). The second warmest regions are the eastern mainland and northern Adriatic coast with Tmax between 27 and 29 °C. The spatial distribution of NHot, closely follows the pattern of Tmax: the southern Adriatic exhibits the highest number of hot days ranging from 45 to 60 days, followed by the eastern mainland with 30 to 40 days (Fig. 4c). However, the longest hot spells, DHot, predominantly occur along the southern Adriatic (14–22 days) (Fig. 4e) followed by northern Adriatic with 10 to 14 days. In the rest of the country, hot spells generally do not exceed 10 days. The lowest Tmax values occur at higher elevations, where the fewest hot days and the shortest hot spells are observed. The Tmax trend analysis indicates a consistent and statistically significant ($p \leq 0.05$) warming across the entire country since 1960, with trend values ranging between 0.25 and 0.65 °C per decade (Fig. 4b). Moreover, a systematic increase in the number of hot days is observed, with the most pronounced increase in the southern Adriatic coastal area, amounting to 6–8 days per decade (Fig. 4d). In the rest of Croatia, the increase is somewhat lower, generally 3–6 days per decade. A consistent positive trend in the duration of hot spells across the country, with a gradual increase from continental mainland toward the northern Adriatic and the largest increase along the southern Adriatic (2 to 2.5 days per decade) (Fig. 4f). The observed trends in both the number of hot days and the duration of hot spells are statistically significant ($p \leq 0.05$) in almost the entire country.

The spatial distribution of dry indices shows a clear pattern with south-north gradient. The southern Adriatic records the highest number of dry days (100–112) and the longest dry spells lasting on average 31–40 days (Fig. 5a, c). Moving toward the hinterland and northern Adriatic, both the number and duration of dry spells decrease, with 88–104 dry days and dry spells of 19–28 days. In the lowland continental regions, mean dry conditions are further slightly reduced, with 80–100 dry days and typical dry spells lasting 10–22 days, while the fewest dry days occur at higher altitudes. The trend analysis revealed predominantly positive trends in both the number of dry days and duration of dry spells. However, the trend values are small and generally not statistically significant (Fig. 4b, d). The most prominent change is found in the southern Adriatic, where dry spells have lengthened by 0.5–2 days per decade, while elsewhere in the country the increase does not exceed 1 day per decade (Fig. 4d).

Based on the analysis of the SPEI4 index for September, an increased frequency of drought episodes was observed at the analysed stations during the most recent climatological period 1991–2020, compared to 1961–1990 (Fig. 6). Excluding the normal class, during the period 1961–1990, moderately wet and very wet JJAS seasons were more frequent. Among the dry seasons, those of 1961 in lowland Croatia and 1962 and 1985 in the coastal and highland regions stand out. In contrast, during 1991–2020, the frequency and intensity of very dry and extremely dry episodes increased, indicating more intensive drought events. The driest seasons during this period include 1991 in continental Croatia, and 2000, 2003, 2011, and 2012 across most of the country. Alongside the intensification of drought episodes, a growing frequency of opposite extremes, very wet and extremely wet seasons, was also detected during 1991–2020, with 2014 standing out as an extremely wet JJAS season.

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

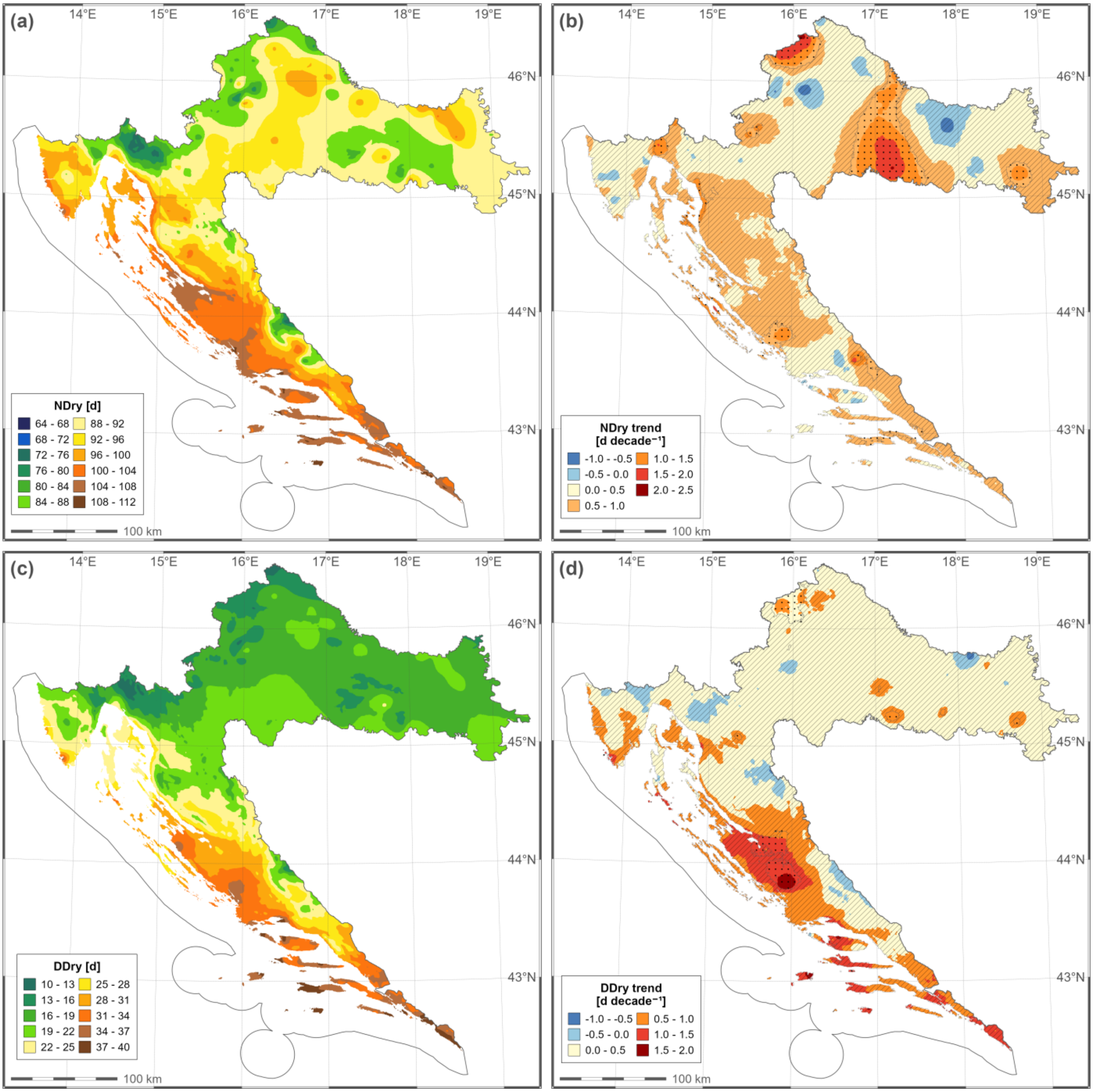


Figure 5. Average values of: number of dry days (NDry) **(a)**, duration of period with consecutive dry days (DDry) **(c)** over June–September (JJAS) season during period 1991–2020; Trend of: NDry **(b)**, DDry **(d)** per decade for JJAS season over period 1961–2020. Areas with dots on the trend maps indicate statistically significant trends ($p \leq 0.05$), while regions covered with diagonal hatching indicate non-significant trends.

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

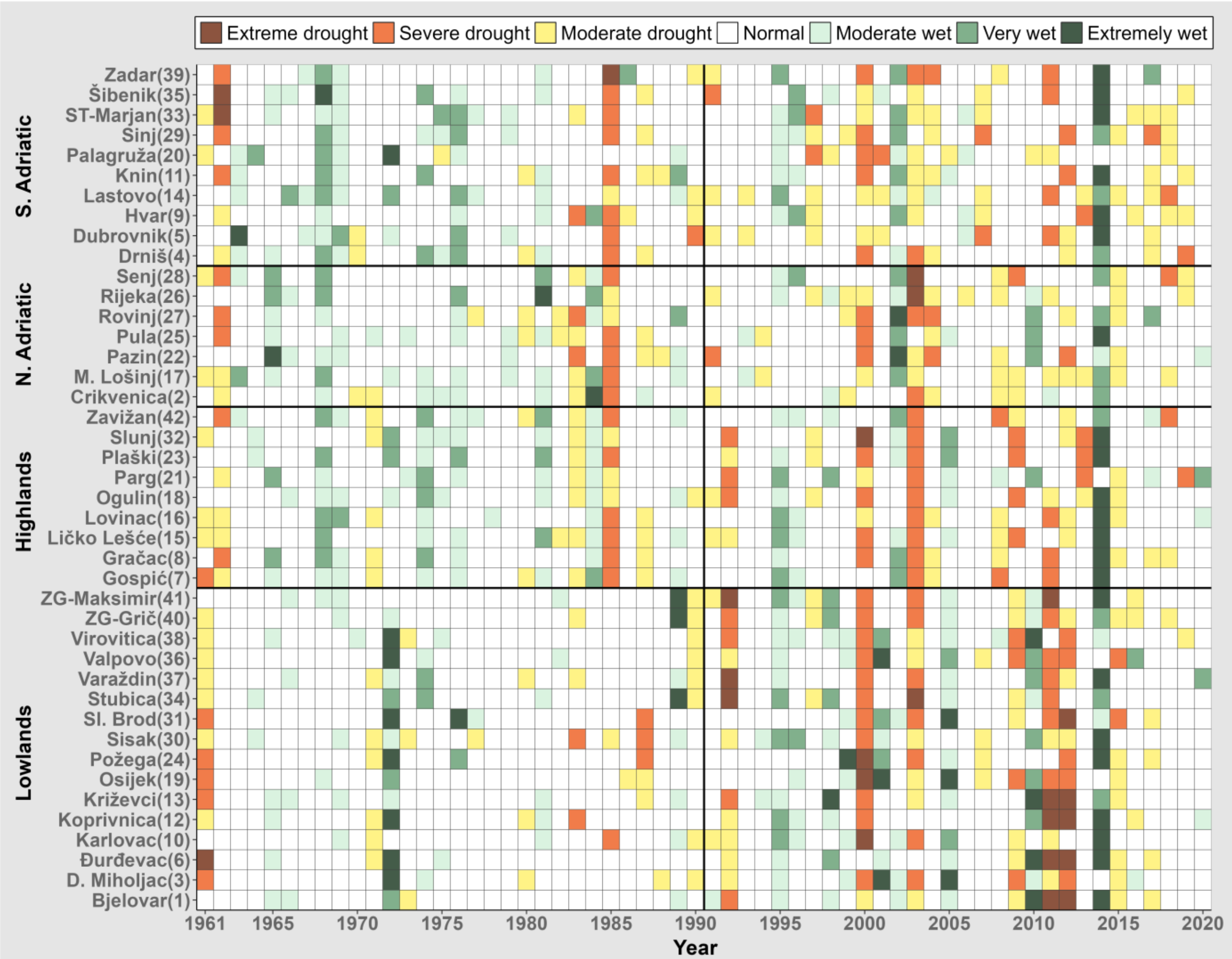


Figure 6. September SPEI4 values for each year during the 1961–2020 period at meteorological stations in Croatia. The stations are arranged per region and the number in brackets corresponds to the station number in Fig. 3.

4.2 Fire weather indices

The spatial analysis of the SSR shows that the highest values occur in the coastal area of the southern Adriatic, where the long-term average for the period 1991–2020 generally ranges between 11 and 16 (Fig. 7a). In the northern Adriatic, values are slightly lower, between 5 and 10, while in the continental part of the country, SSR reaches its lowest values in mountainous regions. In the eastern part of lowland Croatia, SSR values are somewhat higher, between 4 and 6, compared to other lowland areas. The trend analysis of SSR for the period 1961–2020 indicates a consistent rising trend, which is most pronounced in the continental hinterland of the southern Adriatic, where the trend reaches up to 1.4 per decade (Fig. 7b). In the coastal Adriatic

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

area, the SSR increase ranges mostly between 0.6 and 1.1 per decade, indicating a stable but slightly weaker rise compared to the hinterland. In continental Croatia, particularly in the karst fields of the mountainous region, the increase ranges between 0.4 and 0.9 per decade, which is somewhat higher than the trend observed in the lowland regions (0.1–0.7 per decade).

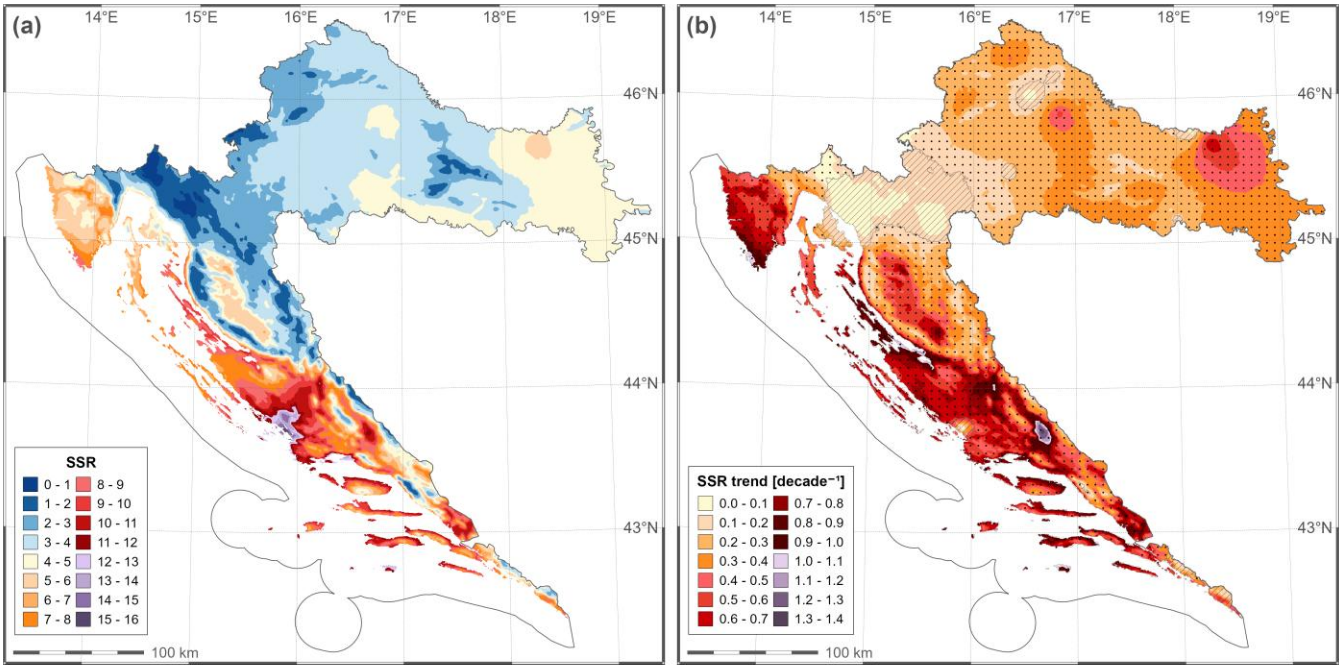


Figure 7. Average Seasonal Severity Rating (SSR) during period 1991–2020 **(a)**; SSR trend per decade over period 1961–2020 **(b)**; Areas with dots on the trend maps indicate statistically significant trends ($p \leq 0.05$), while regions covered with diagonal hatching indicate non-significant trends.

The extreme fire weather indices show a spatial pattern similar to that of SSR (Fig. 8a, c). The lowest FWI30 values are found in mountainous areas at the highest elevations, while the most unfavourable fire weather conditions are observed in the southern Adriatic, where FWI30 reaches up to 75 days (Fig. 8a). On average, in continental Croatia, the number of FWI30 days does not exceed 20 during the JJAS season. The frequency of such days is higher in the northern Adriatic but generally does not exceed 35 days on average. The trend in FWI30 indicates an increase in the number of such days across most of the country (Fig. 8b). In lowland Croatia, the recorded increase reaches up to 2.5 days per decade, and in the karst fields of mountainous regions up to 3.5 days per decade. The largest changes occur in the southern Adriatic, with a peak of 6.5 days per decade in the continental hinterland, while along the coast the trend generally ranges between 3 and 6 days per decade.

Values of FWIp90 are slightly lower in the western part of lowland Croatia compared to the eastern part, with the highest continental values recorded in the karst fields of mountainous areas (Fig. 8c). In the coastal region, higher FWIp90 values are found in the southern Adriatic, with the highest overall values observed in its continental hinterland. Predominantly positive FWIp90 anomalies indicate an increase in FWIp90 during the most recent climatological period (1991–2020) compared to the

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

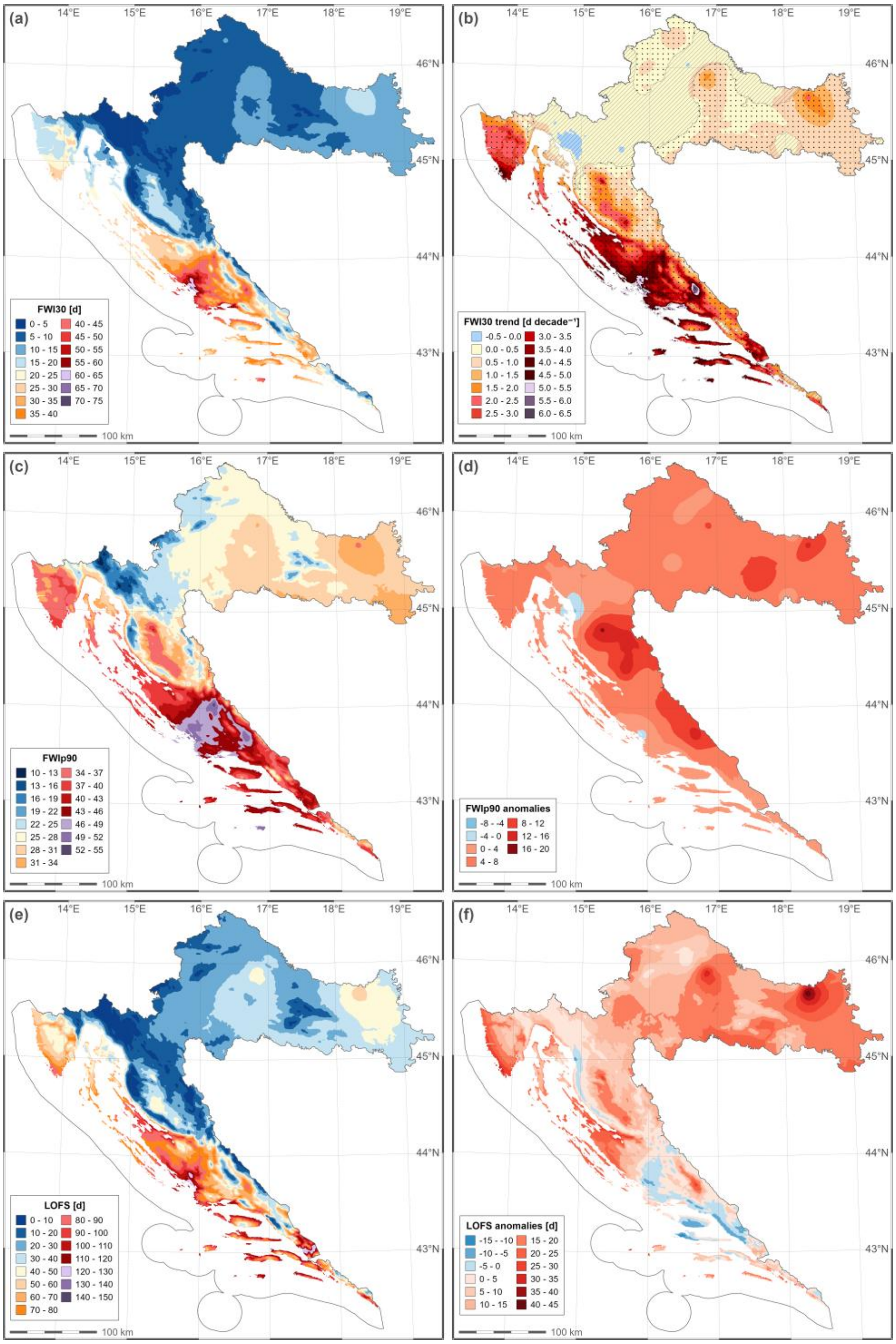


Figure 8. Average values of: the number of days with FWI > 30 (FWI30) **(a)**, length of fire season (LOFS) **(c)** and the 90-th percentile of FWI (FWIp90) **(e)** during period 1991–2020; Trend of FWI30 over period 1961–2020 **(b)**; Anomalies of: LOFS **(d)** and FWIp90 **(f)**; Areas with dots on the trend maps indicate statistically significant trends (p ≤ 0.05), while regions covered with diagonal hatching indicate non-significant trends

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

previous one (Fig. 8d). At higher elevations, the LOFS generally does not exceed 20 days (Fig. 8e), while the highest continental values (up to 60 days) occur in the eastern lowlands and karst fields of the mountainous regions. The longest LOFS values are found in the southern Adriatic, where the average length can reach up to 150 days. Predominantly positive LOFS anomalies across most of the country indicate a lengthening of the fire season during the recent climatological period compared to the previous one, with the greatest extension recorded in the eastern lowlands (Fig. 8f). Conversely, in parts of the southern and northern Adriatic coasts and their hinterlands, negative anomalies were locally observed, indicating a shortening of the fire season in those areas. Overall, the FWI30 and FWIp90 trend results indicate increasingly favourable meteorological conditions for fire ignition along the Adriatic coast, particularly in its southern part, which has already been identified as the most fire prone region in Croatia. However, the length of the fire season shows a tendency to increase in the eastern mainland and along the northern Adriatic coast.

4.3 Accuracy of spatial prediction

The results of the regression kriging prediction accuracy assessment using the LOOCV method are summarized in Table 1. In the case of spatial interpolation of climate normals for the analysed variables, the low ME values indicate an unbiased prediction. According to the R^2 and RMSEr indicators, the model achieved the highest predictive performance for maximum air temperature, whereas the poorest performance was observed for Ndry and FWIp90. The RMSEr values for the prediction

Table 1. Prediction performance measures of spatial interpolation using regression kriging: R^2 – coefficient of determination, ME – mean error, RMSEr – root mean square error normalized by the standard deviation. n denotes the number of stations used in the analysis

	Statistics/Element		Tmax	Nhot	Dhot	NDry	Ddry	SSR	FWI30	FWIp90	LOFS
Normals	n		53	53	53	157	157	50	50	50	50
	R^2		0.88	0.66	0.74	0.50	0.75	0.79	0.67	0.64	0.82
	ME		-0.07	-0.19	-0.07	0.21	0.11	-0.02	-0.01	0.02	0.00
	RMSEr		0.34	0.60	0.52	0.72	0.5	0.45	0.58	0.60	0.42
Seasonal values	R^2	Min	0.83	0.48	0.34	0.22	0.03	0.39	0.17	-	-
		Max	0.92	0.73	0.76	0.69	0.76	0.82	0.71	-	-
		Av	0.88	0.60	0.56	0.46	0.46	0.63	0.44	-	-
	ME	Min	-0.10	-0.68	-0.27	0.03	-0.06	-0.04	-0.05	-	-
		Max	-0.03	0.03	0.27	0.37	0.45	0.02	0.03	-	-
		Av	-0.06	-0.22	-0.07	-0.19	0.15	-0.01	0.00	-	-
	RMSEr	Min	0.28	0.54	0.49	0.56	0.49	0.42	0.54	-	-
		Max	0.41	0.75	0.85	0.93	1.02	0.78	0.94	-	-
		Av	0.34	0.65	0.67	0.75	0.74	0.60	0.76	-	-

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

of Tmax were below 0.4, suggesting that the model yielded a highly reliable prediction. For the remaining variables, RMSEr values ranged between 0.4 and 0.75, which may be interpreted as satisfactory predictive accuracy. The prediction of seasonal Tmax values retained a high level of precision; however, the predictive performance measures for the seasonal values of other variables were notably lower compared to those for the climate normals. This indicates an increase in uncertainty when predicting seasonal values. Such a reduction in predictive accuracy is expected, given that seasonal values exhibit substantially higher variability than climate normals. Nevertheless, only the mean RMSEr values for FWI30 exceeded the threshold of 0.75 indicating poor model performance regarding spatial variability. The prediction of seasonal Ndry and Ddry also exhibited relatively high average RMSEr values; however, in the prediction of these variables, data from a considerably larger number of stations, specifically 157, were employed. Given that the seasonal prediction of FWIp90 and LOFS generally showed a high level of uncertainty with RMSEr usually above 0.75, the anomalies of these elements were considered instead. Table 1 presents the prediction performance metrics for FWIp90 and LOFS only for the climatological period 1991–2020, with comparable results obtained for the period 1961–1990.

5 Discussion

The study examines the extent to which climate change has influenced fire weather conditions in Croatia during the JJAS season. For this purpose, the climatology of FWI-based indices accompanied with the corresponding climatological hot and dry indices were analysed. The driest fire seasons identified using SPEI4 correspond well with earlier drought assessments for Croatia (Cindrić et al., 2016). The spatial distribution of mean values of SSR, FWIp90, FWI30, and LOFS for the period 1991–2020 showed that the most favourable conditions for the occurrence of wildfires develop along the southern Adriatic, specifically in its northern and central sections, which is generally the driest and hottest region in the country and recorded the highest number of wildfires (Fig. 1). It is in line with the results obtained by Santos et al. (2024) who showed that months with higher fire activity are predominantly associated with extreme climatic conditions, revealing a substantial occurrence of compound events. In addition to highly flammable vegetation cover along the Adriatic, the area is characterised by complex orography and steep slopes, which significantly enhance fire danger under such conditions (Viegas and Paolo Pita, 2004). A good example of this is the Split wildfire, whose spread was significantly enhanced by bora (Čavlina Tomašević et al., 2022), a gusty downslope wind blowing across the Dinarides from the northeastern quadrant (Makjanić, 1978). Predominantly increasing trends in FWI-based indices, as well as their positive anomalies, indicate that conditions for the ignition and spread of wildfires have been becoming increasingly favourable since the mid-20th century, not only in coastal areas, but also in continental mainland. Highland Croatia is a highly forested area dominated by European beech, a species that produces large quantities of flammable material and has thin bark, making it vulnerable to fire (Leuschner, 2020). The lowland part of the country is a mosaic of forests and agricultural land, where crop residues can serve as a significant source of flammable fuel, increasing fire risk, especially during the hot season. Occasionally still present, although illegal, practice of agriculture residue burning, and fire incidents due to negligence from growing numbers of tourists also contribute to the fire risk.

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

Rising trends of FWI-based indices can be explained by consistent warming during the JJAS season since 1961, an increase in the number of hot days and the extension of periods with consecutive hot days, as well as more frequent and more intense dry periods. Analyses of dry days and the longest dry spells usually rely on more general precipitation thresholds commonly applied in climatology, e.g. 1, 5 or 10 mm (Cindrić Kalin and Pasarić, 2022), whereas in this study the precipitation threshold relevant for Drought Code was used. The southern Adriatic, which typically experiences the highest number of dry days and the longest dry spells, shows a continued drying trend, consistent with previous findings for this region (Gajić–Čapka et al., 2015). Combined with the warming trend, the southern Adriatic is aligning with broader Mediterranean patterns of increasing climatic aridity (Vicente-Serrano et al., 2025) with increase in frequency of fire weather events (Dosio et al., 2025). However, a substantial increase in the length of the fire season was found in the easternmost mainland which may be attributed to the stronger warming trends in July and August found in this region (Perčec Tadić et al., 2023). In addition, due to negative correlation between temperature and precipitation during warm season over land (Zscheischler and Seneviratne, 2017), reduced soil moisture content driven by concurrence of warm and dry summers may trigger a positive feedback land-atmosphere mechanism that further reinforces warm-dry conditions (de Luca et al., 2020). Negative LOFS anomalies found along the parts of Adriatic coast may be attributed to considerable increase in number of wet hours and length of wet spells particularly in autumn months (including September) (Starčević et al., 2025). Although climate change resulted with generally prolonged and more intense dry spells, climatic variability can also occasionally lead to extremely wet seasons. Such seasons increase moisture content in fuel, especially when precipitation is evenly distributed, resulting in lower fuel flammability and fewer wildfires. This is supported by satellite fire occurrence data showing that during the JJAS season of 2014 (Fig. 1c), which was classified as very or extremely wet according to the SPEI index, and the lowest number of fires (105) was recorded in Croatia compared with other years in the 2012–2024 period. On the other hand, when vegetation has sufficient water available, it grows vigorously and produces a large amount of fuel for subsequent fire seasons. A positive correlation between precipitation and fire occurrence with a time lag of two years has been identified, for example, in Pausas (2004), Turco et al. (2013), and Xystrakis and Koutsias (2013). Although 2016 did not record an exceptionally high number of wildfires or an exceptionally large burned area in Croatia, 2017 was record-breaking by both metrics.

Our results are consistent with simulations performed by Giannaros et al. (2020) using the WRF model for the period 1987–2016 over the European part of the Mediterranean. Their results indicated increasing trends in FWI30 and FWIp90 over territory of Croatia, with the strongest trend in the southern part of the Croatian Adriatic. Since in this study the period 1961–2020 was analysed, the trend values are not directly comparable. Furthermore, Venäläinen et al. (2014) conducted an analysis for Europe and reported a positive trend in the FWI during the March–September season, while Matteo et al. (2025) performed a global analysis and found an upward trend in the annual number of days with FWI exceeding the 95th percentile over the territory of Croatia, indicating an exacerbation of fire-weather conditions, which is consistent with our findings. Results from other studies conducted in Mediterranean countries likewise point to increasing trends in FWI or FWI-based indices, as well as a growing risk of wildfires. For example, Orgambides-García et al. (2024) documented an upward trend in the FWI index in the Mediterranean part of the Iberian Peninsula, with the strongest increase occurring during the summer season. According

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

to recent climate projections, an increase in the frequency and duration of heatwaves during extended summer periods across the Mediterranean, including Croatia, can be expected in the future (Sutanto et al., 2025.). The increase in single hazard events will lead to a corresponding increase in compound and cascading events. Moreover, warm extremes are projected to occur more frequently in combination with prolonged dry spells and more frequent droughts. Under these conditions, an increase in the favourability of environmental conditions for wildfire development and spread during summer months is anticipated, could potentially result in more frequent and more intense wildfire events across the country. Based on climate projections in the Mediterranean, Bedia et al. (2014) predicted increases in FWI, SSR, FWIp90, FWI30 and extension of the fire season over territory of Croatia. However, fire activity does not depend exclusively on weather and climate conditions, but also on other factors such as availability of fuel, ignition agents and human influence (Flanigan et al., 2005). Consequently, despite the increasingly favourable fire weather conditions, the burned area over the past few decades has not increased as dramatically as expected (Jones et al., 2022). Hetzer et al. (2024) conclude that in southern European countries the most likely explanation for this is the improvement of wildfire surveillance and early warning systems. Further enhancements in monitoring, together with the development of accurate early warning systems, timely response measures, and improved cooperation among responsible institutions, could substantially reduce fire-related damage.

6 Conclusion

A comprehensive, high-resolution assessment of changes in climate conditions and the corresponding June–September fire risk during the period 1961–2020 was made based on spatial interpolation of the observations from the national network of meteorological stations. The analysis reveals a clear and statistically significant ($p \leq 0.05$) increase in fire-favourable meteorological conditions which led to increase in fire risk.

Significant increasing trends in maximum air temperature (0.25–0.65 °C decade^{-1}), number of hot days (1–8 days decade^{-1}) and the duration of hot periods (0.25–2.50 days decade^{-1}) were found in all parts of Croatia. The strongest temperature trends were observed in central Croatia and along the Adriatic, with the coastal areas also exhibiting the highest trends in the number of hot days and duration of hot periods. The trends in the number of dry days and dry period duration were less univocal, with a significant drying trend manifesting only in some areas of both the continental and the coastal parts of Croatia.

Significant warming, accompanied with drying, has led to significant trend in FWI-based indices, pointing at noteworthy increase in fire risk, in particular for the hinterlands of the central Adriatic, but also for the northeast parts of the continental mainland. While the average length of the fire season for the period 1991–2020, compared to 1961–1990, generally increased by 10–25 days in most of the Adriatic part, it is worth observing that in parts of the central Adriatic it was shorter by 5–10 days. The biggest increase in the length of the fire season (15–45 days) was recorded in the continental northeast, indicating the emergence of fire-favourable conditions in areas which historically had not been prone to wildfires.

The use of high-resolution spatial modelling enabled taking into account pronounced topographic gradients and the resulting complexity in weather patterns, which would be missed at coarse spatial resolution. Although fire occurrence and spread are

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

affected by many factors, such as land use, fuel availability, human factor etc., the results obtained within this study enable more precise mapping of trends in fire risk indices and the identification of new hotspots. These results provide a scientific basis for improving fire prevention activities, as well as the re-evaluation of resource allocation. This is particularly relevant for regions where fire risk has been increasing but has not yet been fully recognized, where accumulated biomass in forests is high, water availability might be limited, and airborne fire-fighting support is restricted.

Data availability

Data used in this study are the property of the Croatian Meteorological and Hydrological Service. The data are available under the Creative Commons Attribution 4.0 International (CC BY 4.0) License.

Author contributions

Author contributions follow the CRediT authorship categories.
MA: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. KCK: Formal analysis, Writing – review & editing. MZOS: Writing – review & editing. DB: Writing – review & editing. HM: Conceptualization, Writing – review & editing.

Competing interests

The contact author has declared that none of the authors has any competing interests.

Disclaimer

Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors. Views expressed in the text are those of the authors and do not necessarily reflect the views of the publisher.

Acknowledgements

This research was supported by the by the Croatian Science Foundation under the project ADRIAirBURN (HRZZ-IP-2024-05-6224) and the Recovery and Resilience Plan for Croatia within the project Dendro-Carbon (No. 400-01/23-01/6-2).
The authors acknowledge the use of ChatGPT (OpenAI) for English language editing and grammar checking.

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

Financial support

This work was supported by the Croatian Science Foundation under the project ADRIAirBURN (HRZZ-IP-2024-05-6224).

References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration – guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper 56, FAO, Rome, Italy, ISBN 978-92-5-104219-9, 1998.

Environmental Agency of the Republic of Slovenia: Meteorological archive, available at: https://meteo.arso.gov.si/met/sl/archive/ (last access: 25 June 2023), 2025.

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., and Wood, E. F.: Present and future Köppen–Geiger climate classification maps at 1-km resolution, Sci. Data, 5, 180214, https://doi.org/10.1038/sdata.2018.214, 2018.

Bedia, J., Herrera, S., and Gutiérrez, J. M.: Sensitivity of Fire Weather Index to different reanalysis products in the Iberian Peninsula, Nat. hazards earth syst. sci., 12, doi: https://doi.org/10.5194/nhess-12-699-2012 , 2012.

Bedia, J., Herrera, S., Camia, A., Moreno, J. M., and Gutiérrez, J. M.: Forest fire danger projections in the Mediterranean using ENSEMBLES regional climate change scenarios, Clim. Change, 122, 185–199, DOI: 10.1007/s10584-013-1005-z, 2014.

Burrough, P. A. and McDonnell, R. A.: Principles of Geographical Information Systems, Oxford Univ. Press, Oxford, 2004.

Carvalho, A., Flannigan, M. D., Logan, K., Miranda, A. I., and Borrego, C.: Fire activity in Portugal and its relationship to weather and the Canadian Fire Weather Index System, Int. J. Wildland Fire, 17, 328–338, DOI: 10.1071/WF07014 , 2008.

Cindrić Kalin, K. and Pasarić, Z.: Regional patterns of dry spell durations in Croatia, Int. J. Climatol., 42, 5503–5519, https://doi.org/10.1002/joc.7545, 2022.

Cindrić, K., Telišman-Prtenjak, M., Herceg-Bulić, I., Mihajlović, D., and Pasarić, Z.: Analysis of the extraordinary 2011/2012 drought in Croatia, Theor. Appl. Climatol., 123, 503–522, https://doi.org/10.1007/s00704-014-1368-8, 2016.

Croatian Bureau of Statistics: Nacionalna klasifikacija statističkih regija 2021. (HR_NUTS 2021.). Narodne novine (in Croatian) (125/2019), 2019.

de Groot, W. J., Field, R. D., Brady, M. A., Roswintiarti, O., and Mohamad, M.: Development of the Indonesian and Malaysian Fire Danger Rating Systems, Mitig. Adapt. Strat. Gl., 12, 165–180, https://doi.org/10.1007/s11027-006-9043-8, 2007.

De Luca, P., Messori, G., Faranda, D., Ward, P. J., and Coumou, D.: Compound warm–dry and cold–wet events over the Mediterranean, Earth Syst. Dynam., 11, 793–805, https://doi.org/10.5194/esd-11-793-2020, 2020.

de Jong, M. C., Wooster, M. J., Kitchen, K., Manley, C., Gazzard, R., and McCall, F. F.: Calibration and evaluation of the Canadian Forest Fire Weather Index (FWI) System for improved wildland fire danger rating in the United Kingdom, Nat. hazards earth syst. sci., 16, 1217–1237, https://doi.org/10.5194/nhess-16-1217-2016, 2016

Dimitrakopoulos, A. P., Bemmerzouk, A. M., and Mitsopoulos, I. D.: Evaluation of the Canadian Fire Weather Index system in an eastern Mediterranean environment, Meteorol. Appl., 18, 83–93, https://doi.org/10.1002/met.214, 2011.

Dosio, A., Koronaci, K., Migliavacca, M., and Spinoni, J.: Increasing frequency and intensity of single, multiple and concurrent meteorological hazards in Europe from a high-resolution dataset (1961-2020), Environ. Res. Clim., DOI 10.1088/2752-5295/ae1ce0, 2025

Eberle, C. and Higuera Roa, O.: Technical Report: Mediterranean Wildfires, United Nations University–Institute for Environment and Human Security, Bonn, Germany, 2022.

European Environment Agency (EEA): Economic losses from weather- and climate-related extremes in Europe, Indicators, European Environment Agency, published 14 Oct 2025, available at: https://www.eea.europa.eu/en/analysis/indicators/economic-losses-from-climate-related (last access: 11 December 2025)

European Environment Agency (EEA): CORINE Land Cover 2018, version 20, Copernicus Land Monitoring Service, https://land.copernicus.eu/, https://doi.org/10.2909/71c95a07-e296-44fc-b22b-415d0fba1a93 (last access: 3 May 2025), 2018.

Flannigan, M. D., Logan, K., Amiro, B., Skinner, W., and Stocks, B.: Future area burned in Canada, Clim. Change, 72, 1–16, DOI: 10.1007/s10584-005-5935-y, 2005.

Gajić-Čapka, M., Cindrić, K., and Pasarić, Z.: Trends in precipitation indices in Croatia, 1961–2010, Theor. Appl. Climatol., 121, 167–177, https://doi.org/10.1007/s00704-014-1217-9, 2015.

Giannaros, T. M., Kotroni, V., and Lagouvardos, K.: Climatology and trend analysis (1987–2016) of fire weather in the Euro-Mediterranean, Int. J. Climatol., 41(S1), E491–E508, https://doi.org/10.1002/joc.6701, 2020.

Giglio, L.: VIIRS/NPP Active Fires 6-Min L2 Swath 375 m V002, NASA LP DAAC, https://doi.org/10.5067/VIIRS/VNP14IMG.002, 2024

Giorgi, F.: Climate change hot-spots, Geophys. Res. Lett., 33, https://doi.org/10.1029/2006GL025734, 2006.

Gräler, B., Pebesma, E., and Heuvelink, G.: Spatio-temporal interpolation using gstat, R J., 8, 204–218, 2016.

Hasanpour Kashani, M. and Dinpashoh, Y.: Evaluation of efficiency of different estimation methods for missing climatological data, Stoch. Env. Res. Risk A., 26, 59–71, https://doi.org/10.1007/s00477-011-0536-y, 2012

Hengl, T.: A practical guide to geostatistical mapping of environmental variables, University of Amsterdam, 2009.

Hengl, T., Heuvelink, G. B. M., and Stein, A.: A generic framework for spatial prediction of soil variables based on regression-kriging, Geoderma, 120, 75–93, https://doi.org/10.1016/j.geoderma.2003.08.018, 2004.

Hengl, T., Heuvelink, G. B. M., and Rossiter, D. G.: About regression-kriging: from equations to case studies, Comput. Geosci., 33, 1301–1315, https://doi.org/10.1016/j.cageo.2007.05.001, 2007.

Hetzer, J., Forrest, M., Ribalaygua, J., Prado-López, C., and Hickler, T.: The fire weather in Europe: large-scale trends towards higher danger, Environ. Res. Lett., 19, 084017, https://doi.org/10.1088/1748-9326/ad5b09, 2024.

Jolly, W. M., Cochrane, M. A., Freeborn, P. H., Holden, Z. A., Brown, T. J., Williamson, G. J., and Bowman, D. M. J. S.: Climate-induced variations in global wildfire danger from 1979 to 2013, Nat. Commun., 6, 7537, https://doi.org/10.1038/ncomms8537, 2015.

Jones, M. W., Abatzoglou, J. T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M., et al.: Global and regional trends and drivers of fire under climate change, Rev. Geophys., 60, e2020RG000726, https://doi.org/10.1029/2020RG000726, 2022.

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

Kalashnikov, D. A., Abatzoglou, J. T., Loikith, P. C., Nauslar, N. J., Bekris, Y., and Singh, D.: Lightning-ignited wildfires in the western United States: ignition precipitation and associated environmental conditions, Geophys. Res. Lett., 50, e2023GL103785, https://doi.org/10.1029/2023GL103785, 2023.

Keeley, J. E., Bond, W. J., Bradstock, R. A., Pausas, J. G., and Rundel, P. W.: Fire in Mediterranean Ecosystems: Ecology, Evolution and Management, Cambridge University Press, 522 pp., 2012.

Kendall, M. G.: Rank Correlation Methods, 4th ed., Charles Griffin, London, 1975.

Kudláčková, L., Bartošová, L., Linda, R., Bláhová, M, Poděbradská, M., Fischer, M., Balek, J., Žalud, Z., and Trnka, M.: Assessing fire danger classes and extreme thresholds of the Canadian Fire Weather Index across global environmental zones: a review, Environ. Res. Lett., 20, 013001, DOI 10.1088/1748-9326/ad97cf, 2024.

Lahaye, S., Curt, T., Fréjaville, T., Sharples, J., Paradis, L., and Hély, C.: What are the drivers of dangerous fires in Mediterranean France?, Int. J. Wildland Fire, https://doi.org/10.1071/WF17087, 2018

Lawson, B. D. and Armitage, O. B.: Weather Guide for the Canadian Forest Fire Danger Rating System, Natural Resources Canada, Northern Forestry Centre, Edmonton, 2008.

Leuschner, C.: Drought response of European beech (Fagus sylvatica L.) – a review, Perspect. Plant Ecol. Evol. Syst., 47, 125576, https://doi.org/10.1016/j.ppees.2020.125576, 2020.

Končar-Petrinjak, I., Pasarić, Z., and Cindrić Kalin, K.: Drought monitoring in Croatia using the standardized precipitation–evapotranspiration index, Geofizika, 41, 1–23, https://doi.org/10.15233/gfz.2024.41.2, 2024.

Mandal, A., Nykiel, G., Strzyzewski, T., Kochanski, A., Wronka, W., Gruszczynska, M., and Figurski, M.: High-resolution fire danger forecast for Poland based on the Weather Research and Forecasting Model, Int. J. Wildland Fire, 31, 149–162, https://doi.org/10.1071/WF21106, 2022.

Mann, H. B.: Non-parametric tests against trend, Econometrica, 13, 163–171, https://doi.org/10.2307/1907187, 1945.

Mauri, A., Di Leo, M., de Rigo, D., and Caudullo, G.: Pinus halepensis and Pinus brutia in Europe: distribution, habitat, usage and threats, in: European Atlas of Forest Tree Species, Publ. Off. EU, Luxembourg, e0166b8+, 2016.

Matteo, A., Garnés-Morales, G., Moreno, A., et al.: Challenges in assessing fire weather changes in a warming climate, npj Clim. Atmos. Sci., 8, 284, https://doi.org/10.1038/s41612-025-01163-0, 2025.

Miller, J., Touma, D., and Brunner, M. I.: Compounding preconditions of wildfires vary in time and space within Europe, Commun. Earth Environ., 6, 1005, https://doi.org/10.1038/s43247-025-02955-1, 2025.

Moreira, F., Viedma, O., Arianoutsou, M., Curt, T., Koutsias, N., Rigolot, E., Barbati, A., Corona, P., Vaz, P., Xanthopoulos, G., Mouillot, F., and Bilgili, E.: Landscape–wildfire interactions in southern Europe: implications for landscape management, J. Environ. Manag., 92, 2389–2402, 10.1016/j.jenvman.2011.06.028, 2011.

Moriondo, M., Good, P., Durao, R., Bindi, M., Giannakopoulos, C., and Corte-Real, J.: Potential impact of climate change on fire risk in the Mediterranean area, Clim. Res., 31, 85–95, https://doi.org/10.3354/cr031085, 2006.

NASA Shuttle Radar Topography Mission (SRTM): Shuttle Radar Topography Mission (SRTM) Global, distributed by OpenTopography, https://doi.org/10.5069/G9445JDF (last access: 15 February 2023), 2013.

Orgambides-García, D., Corell, D., Estrela, M. J., Barberà, M. J., and Miró, J.: Trend analysis and spatial behaviour of the Fire Weather Index in the Mediterranean Iberian Peninsula, 1971–2022, Int. J. Climatol., 44, 6065–6082, https://doi.org/10.1002/joc.8684, 2024.

Pausas, J. G.: Changes in fire and climate in the eastern Iberian Peninsula (Mediterranean Basin), Clim. Change, 63, 337–350, https://doi.org/10.1023/B:CLIM.0000018508.94901.9c, 2004.

Pebesma, E. J.: Multivariable geostatistics in S: the gstat package, Comput. Geosci., 30, 683–691, 2004.

Perčec Tadić, M.: Gridded Croatian climatology for 1961–1990, Theor. Appl. Climatol., 102, 87–103, https://doi.org/10.1007/s00704-009-0237-3, 2010.

Perčec Tadić, M., Pasarić, Z., and Guijarro, J. A.: Croatian high-resolution monthly gridded dataset of homogenised surface air temperature, Theor. Appl. Climatol., 151, 227–251, https://doi.org/10.1007/s00704-022-04241-y, 2023.

Politi, N., Vlachogiannis, D., Sfetsos, A., Gounaris, N., and Varela, V.: Investigation of fire weather danger under a changing climate at high resolution in Greece, Sustainability, 15, 2498, https://doi.org/10.3390/su15032498, 2023.

Posavec, S., Barčić, D., Vuletić, D., Vučetić, V., Čavlina Tomašević, I., and Pezdevšek Malovrh, Š.: Forest fires, stakeholders, activities and economic impact on state-level sustainable forest management, Sustainability, 15, 16080, https://doi.org/10.3390/su152216080, 2023.

R Core Team: R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, 2025.

Republic of Croatia: Procjena rizika od katastrofa za Republiku Hrvatsku (Disaster Risk Assessment for the Republic of Croatia) (in Croatian), https://civilna-zastita.gov.hr/UserDocsImages/CIVILNA%20ZA%C5%A0TITA/PDF_ZA%20WEB/Procjena%20rizika%20od%20katastrofa%20za%20Republiku%20Hrvatsku.pdf, 2024.

Ruffault, J., Curt, T., Moron, V., Trigo, R. M., Mouillot, F., Koutsias, N., Pimont, F., Martin-StPaul, N., Barbero, R., Dupuy, J.-L., and co-authors: 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.

San Miguel-Ayanz, J., Durrant, T., Boca, R., et al.: Forest Fires in Europe, Middle East and North Africa 2022, Publications Office of the European Union, Luxembourg, https://doi.org/10.2760/348120, 2023.

San Miguel-Ayanz, J., Durrant, T., Boca, R., et al.: Forest Fires in Europe, Middle East and North Africa 2023, Publications Office of the European Union, Luxembourg, https://doi.org/10.2760/8027062, 2024.

Santos, R., Russo, A., and Gouveia, C. M.: Co-occurrence of marine and atmospheric heatwaves with drought conditions and fire activity in the Mediterranean region, Sci. Rep., 14, 19233, https://doi.org/10.1038/s41598-024-69691-y, 2024.

Sen, P. K.: Estimates of the regression coefficient based on Kendall's tau, Journal of the American Statistical Association, 63, 1379–1389, https://doi.org/10.2307/2285891, 1968.

Starčević, A., Cindrić Kalin, K., and Pasarić, Z.: Climatology and trends of sub-daily indices of precipitation extremes in Croatia, Int. J. Climatol., under review, 2025.

https://doi.org/10.5194/egusphere-2025-6439
Preprint. Discussion started: 4 January 2026

Sutanto, S. J., Duku, C., Gülveren, M., Dankers, R., and Paparrizos, S.: Future intensification of compound and consecutive drought and heatwave risks in Europe, Nat. Hazards Earth Syst. Sci., 25, 3879–3895, https://doi.org/10.5194/nhess-25-3879-2025, 2025.

Tian, X. R., McRae, D. J., Jin, J. Z., Shu, L. F., Zhao, F. J., and Wang, M. Y.: Wildfires and the Canadian Forest Fire Weather Index system for the Daxing'anling region of China, Int. J. Wildland Fire, 20, 963–973, https://doi.org/10.1071/WF09120, 2011.

Tomašević, I., Cheung, K. W., Vučetić, V., Fox-Hughes, P., Horvath, K., Telišman Prtenjak, M., Beggs, P. J., Malečić, B., and Milić, V.: The 2017 Split wildfire in Croatia: evolution and the role of meteorological conditions, Nat. hazards earth syst. sci., 22, 3143–3165, https://doi.org/10.5194/nhess-22-3143-2022, 2022.

Tramblay, Y., Koutroulis, A., Samaniego, L., Vicente-Serrano, S. M., Volaire, F., Boone, A., et al.: Challenges for drought assessment in the Mediterranean region under future climate scenarios, Earth-Sci. Rev., 210, 103348, https://doi.org/10.1016/j.earscirev.2020.103348, 2020.

Turco, M., Llasat, M. C., von Hardenberg, J., and Provenzale, A.: Impact of climate variability on summer fires in a Mediterranean environment (northeastern Iberian Peninsula), Clim. Change, 116, 665–678, https://doi.org/10.1007/s10584-012-0505-6, 2013.

Van Wagner, C. E.: Structure of the Canadian Forest Fire Weather Index, Publication No. 1333, Canadian Forest Service, Information Canada, Ottawa, 1974.

Van Wagner, C. E. and Pickett, T. L.: Equations and Fortran program for the Canadian Forest Fire Weather Index System, Forestry Technical Report 33, Canadian Forestry Service, 18 pp., 1985.

Van Wagner, C. E.: Development and structure of a Canadian forest fire weather index system, Forestry Technical Report 35, Canadian Forestry Service, Ottawa, 1987.

Varela, V., Sfetsos, A., Vlachogiannis, D., and Gounaris, N.: Fire Weather Index (FWI) classification for fire danger assessment applied in Greece, Tethys, 15, 31–40, DOI:10.3369/tethys.2018.15.03, 2018.

Venäläinen, A., Korhonen, N., Hyvärinen, O., Koutsias, N., Xystrakis, F., Urbieta, I. R., and Moreno, J. M.: Temporal variations and change in forest fire danger in Europe for 1960–2012, Nat. hazards earth syst. sci., 14, 1477–1490, doi:10.5194/nhess-14-1477-2014, 2014.

Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index, J. Climate, 23, 1696–1718, https://doi.org/10.1175/2009JCLI2909.1, 2010.

Vicente-Serrano, S. M., Tramblay, Y., Reig, F., et al.: High temporal variability, not trend, dominates Mediterranean precipitation, Nat., 639, 658–666, https://doi.org/10.1038/s41586-024-08576-6, 2025.

Viegas, D. X. and Pita, L. P.: Fire spread in canyons, Int. J. Wildland Fire, 13, 253–263, https://doi.org/10.1071/WF03050, 2004.

Viegas, X. D., Bovio, G., Ferreira, A., Nosenzo, A., and Sol, B.: Comparative study of various methods of fire danger evaluation in southern Europe, Int. J. Wildland Fire, 9, 235–246, https://doi.org/10.1071/WF00015, 1999.

Wickham, H.: ggplot2: Elegant Graphics for Data Analysis, Springer, New York, 2016.

Xystrakis, F. and Koutsias, N.: Differences of fire activity and their underlying factors among vegetation formations in Greece, iForest, 6, 132–140, https://doi.org/10.3832/ifor0837-006, 2013.

Zaninović, K., Gajić-Čapka, M., Perčec Tadić, M., et al.: Klimatski atlas Hrvatske/Climate Atlas of Croatia 1961–1990, 1971–2000, Državni hidrometeorološki zavod, Zagreb, 2008.

Zscheischler, J. and Seneviratne, S. I.: Dependence of drivers affects risks associated with compound events, Sci. Adv., 3, e1700263, https://doi.org/10.1126/sciadv.1700263, 2017.