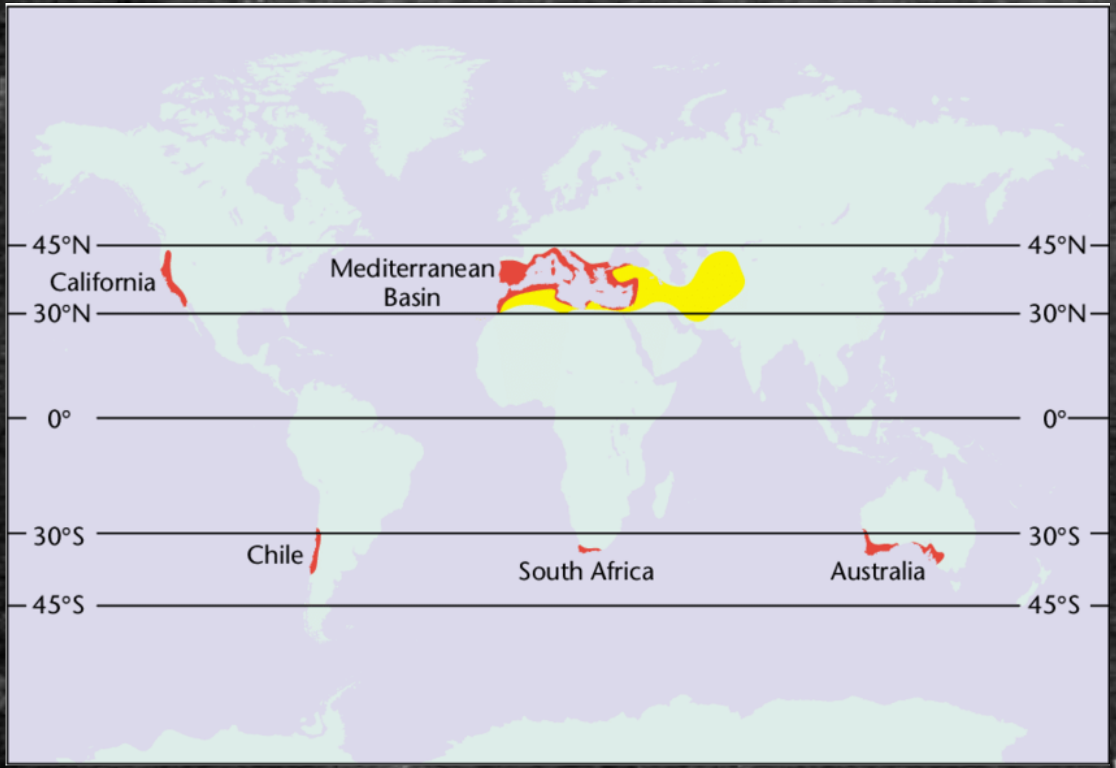
# CLIMATE, WEATHER, AND FIRE

# Mediterranean-type climates




"The mediterranean-type climate (MTC) is characterized by ***winter rains and summer drought***. Both winter growing conditions and summer drought contribute to making these landscapes ***some of the most fire-prone in the world***.

Coastal influence moderates winter temperatures so that ***rains coincide with suitable growing temperatures***. Due to this extended winter–spring growing season, ***primary productivity is moderately high for semi-arid regions*** and vegetation forms dense, sometimes impenetrable thickets that, when dry, contribute to fire spread."

"***The annual summer drought reduces fuel moisture to levels conducive to rapid ignition***. This MTC is the result of global circulation patterns that generate a ***summer high pressure cell of dry sinking air that blocks incoming summer storms on the western sides of continents*** concentrated between 32° and 38° N or S latitude." (pg. 5)

Keeley, J. E., Bond, W. J., Bradstock, R. A., Pausas, J. G., & Rundel, P. W. (2011). *Fire in Mediterranean ecosystems: ecology, evolution and management*. Cambridge University Press.

# Mediterranean-type climates

In ***Köppen's climate classification***, MTC are ***Temperate climates***:

- coldest month averaging between 0 °C and 18 °C
- at least one month averaging above 10 °C.
- wet summer (Cw) when more precipitation falls within the summer months than the winter months,
- ***dry summer (Cs)*** when more precipitation falls within the winter months.

There are three Temperate (***C***), dry summer (***s***) climates:

***Csa*** = ***Hot-summer Mediterranean climate***; coldest month averaging above 0 °C, at least one month's average temperature above 22 °C, and at least four months averaging above 10 °C.

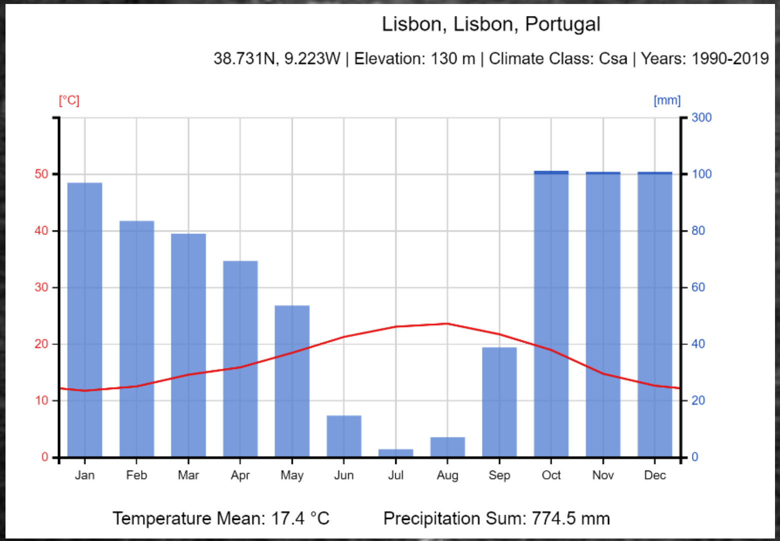
***Csb*** = ***Warm-summer Mediterranean climate***; coldest month averaging above 0 °C, all months with average temperatures below 22 °C, and at least four months averaging above 10 °C.

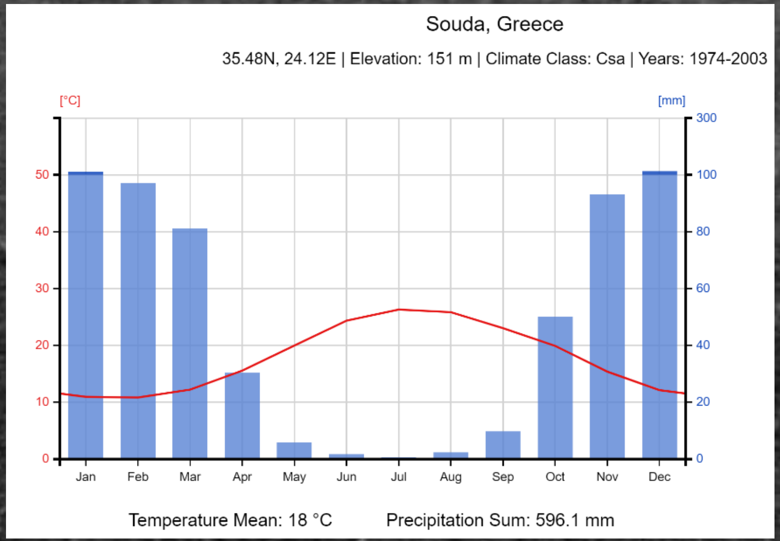
***Csc*** = ***Cold-summer Mediterranean climate***; coldest month averaging above 0 °C and 1–3 months averaging above 10 °C.

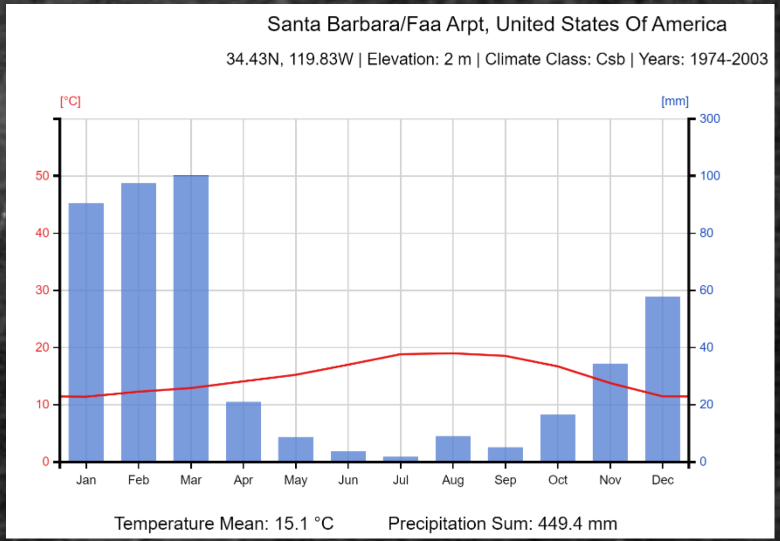
In all ***Cs*** climate types, there is at least three times as much precipitation in the wettest month of winter as in the driest month of summer, and the driest month of summer receives less than 40 mm.

# Mediterranean-type climates

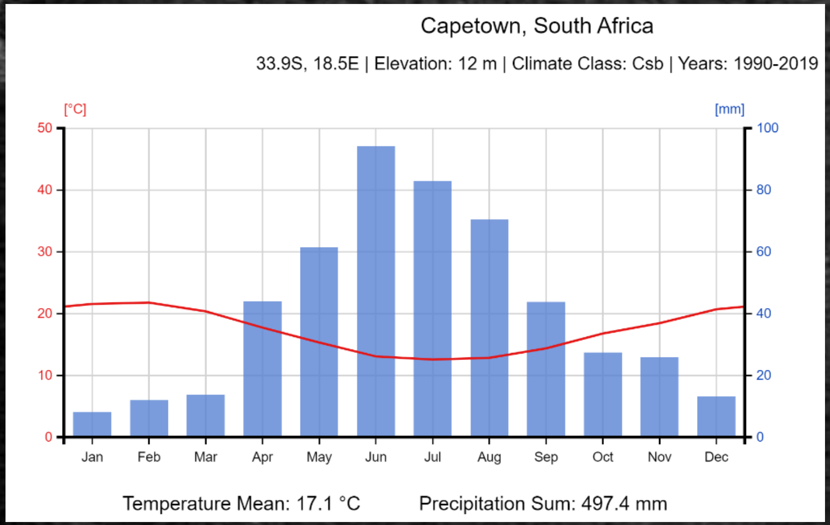
NH

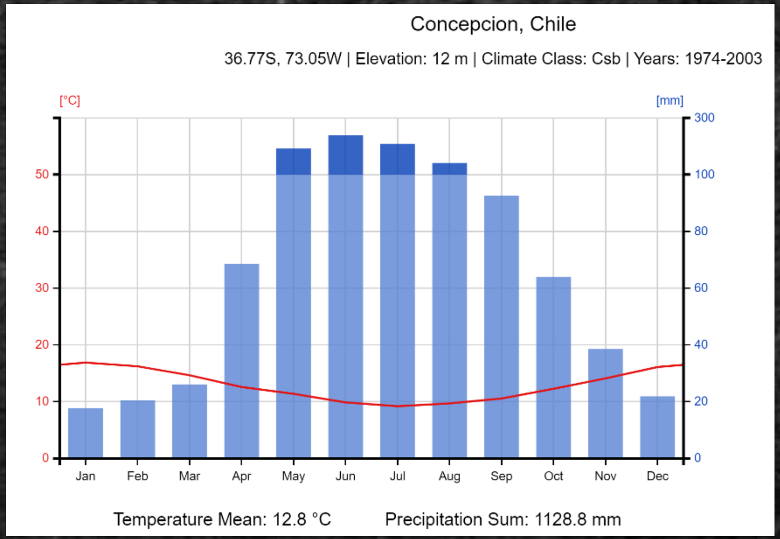


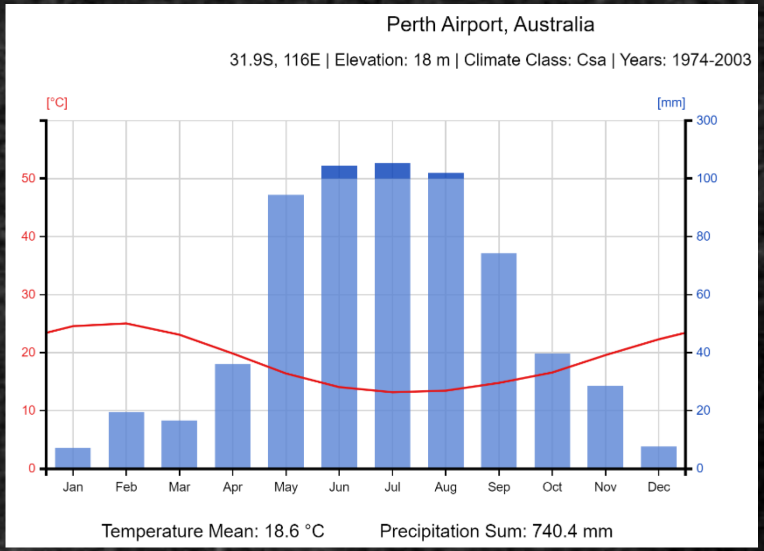




SH



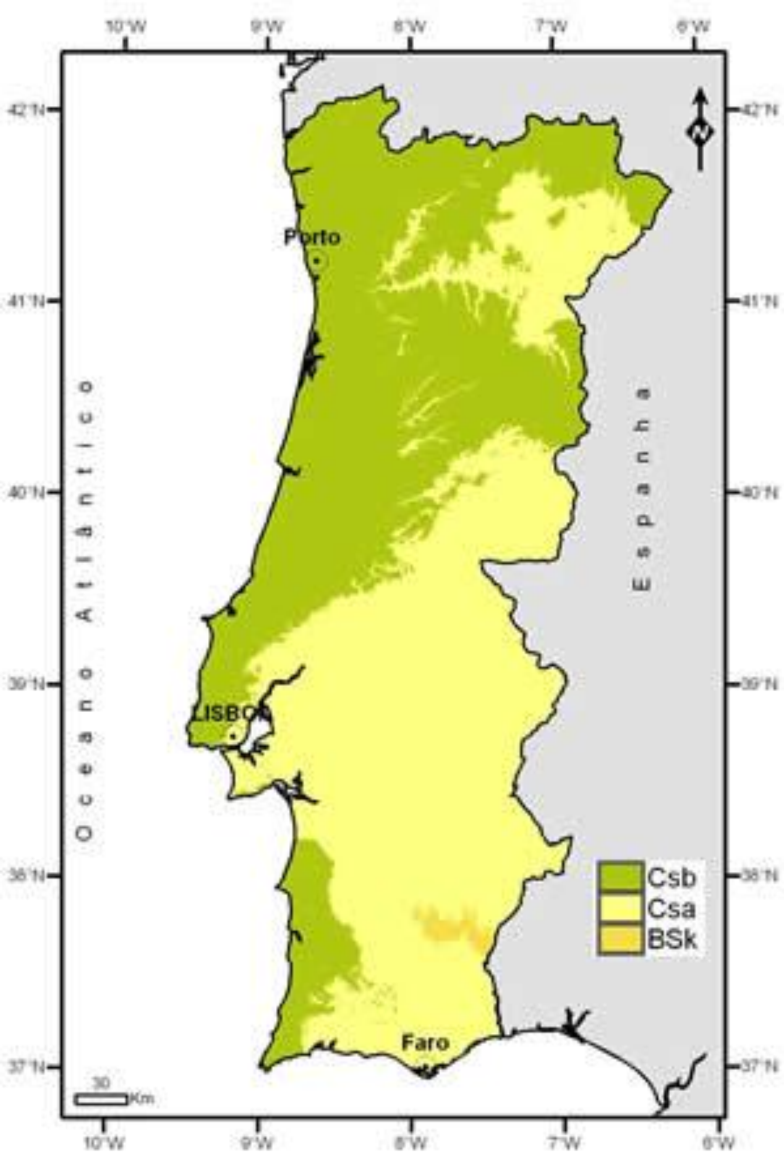



# Mediterranean-type climates

The climate of Portugal is dominated by Köppen climate sub-types ***Csa*** and ***Csb***. ***BSk*** is a cold, semi-arid climate and occurs over a small area of SE Portugal.

Köppen climate map of Portugal



# Mediterranean-type climates, NPP, and fire

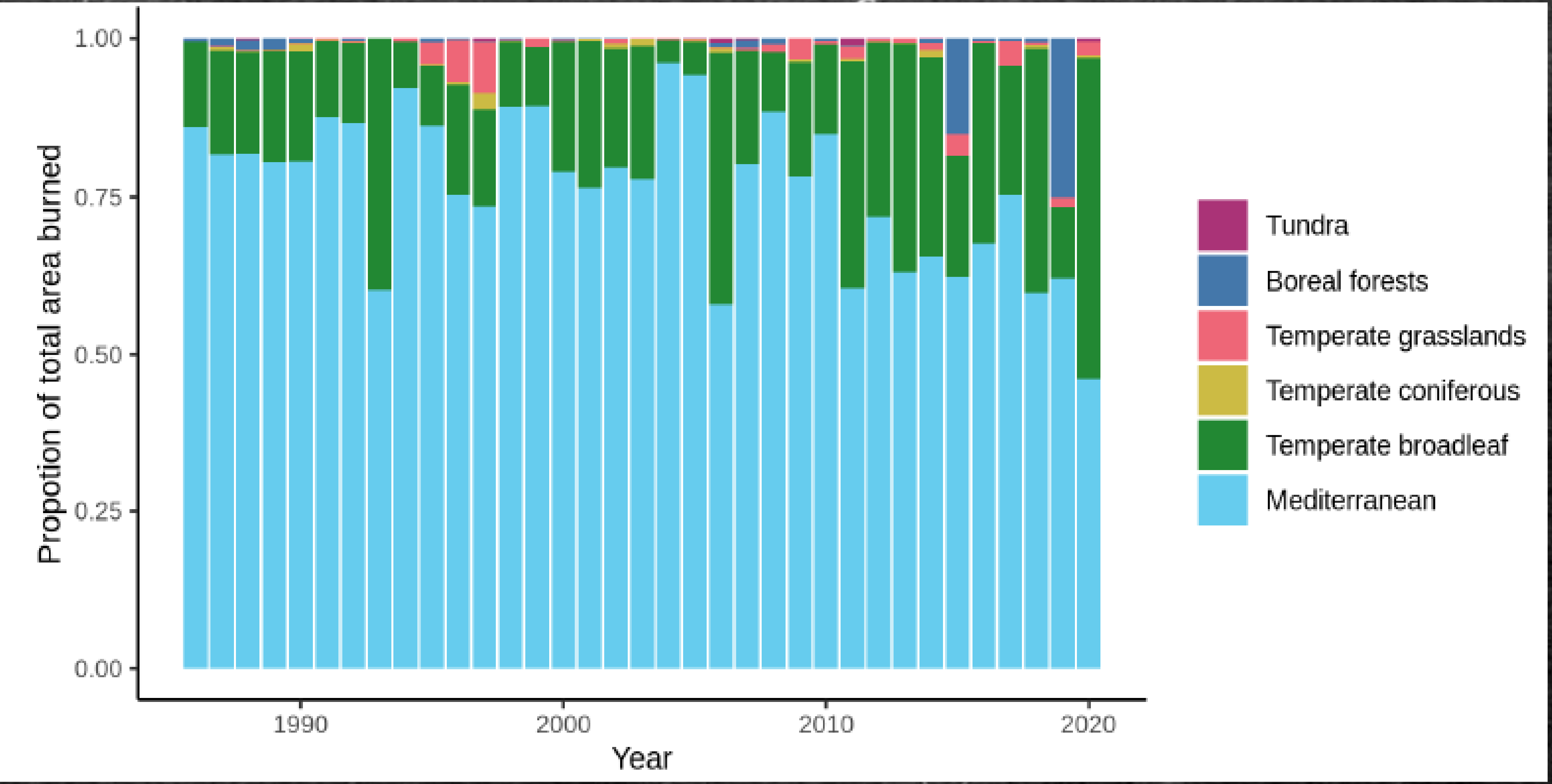



Figure 2. Proportion of total area burned in Europe by biome between 1986 and 2020.

Grünig, M., Seidl, R., & Senf, C. (2022). Increasing aridity causes larger and more severe forest fires across Europe. *Global Change Biology*, 2022;00:1–12.

# Mediterranean-type climates, NPP, and fire

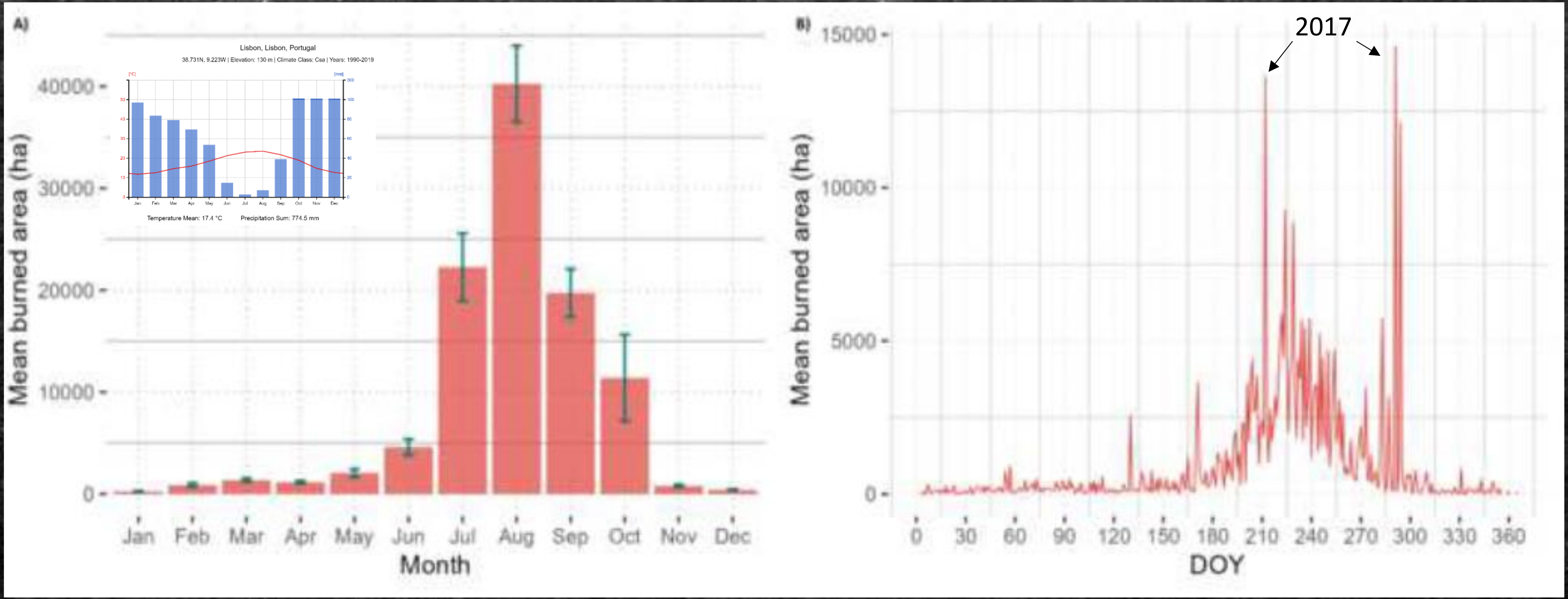



Figure 12. Monthly (A) and daily (B) mean burned area (ha), **1984 to 2021**. Error bars (in blue) represent the standard deviation divided by 10.


Neves, A.K., M.L. Campagnolo, J.M.N. Silva, and J.M.C. Pereira (2023). A Landsat-based atlas of monthly burned area for Portugal, 1984 – 2021. *Int. J. Applied Earth Observation and Geoinformation*

# Mediterranean-type climates, NPP, and fire

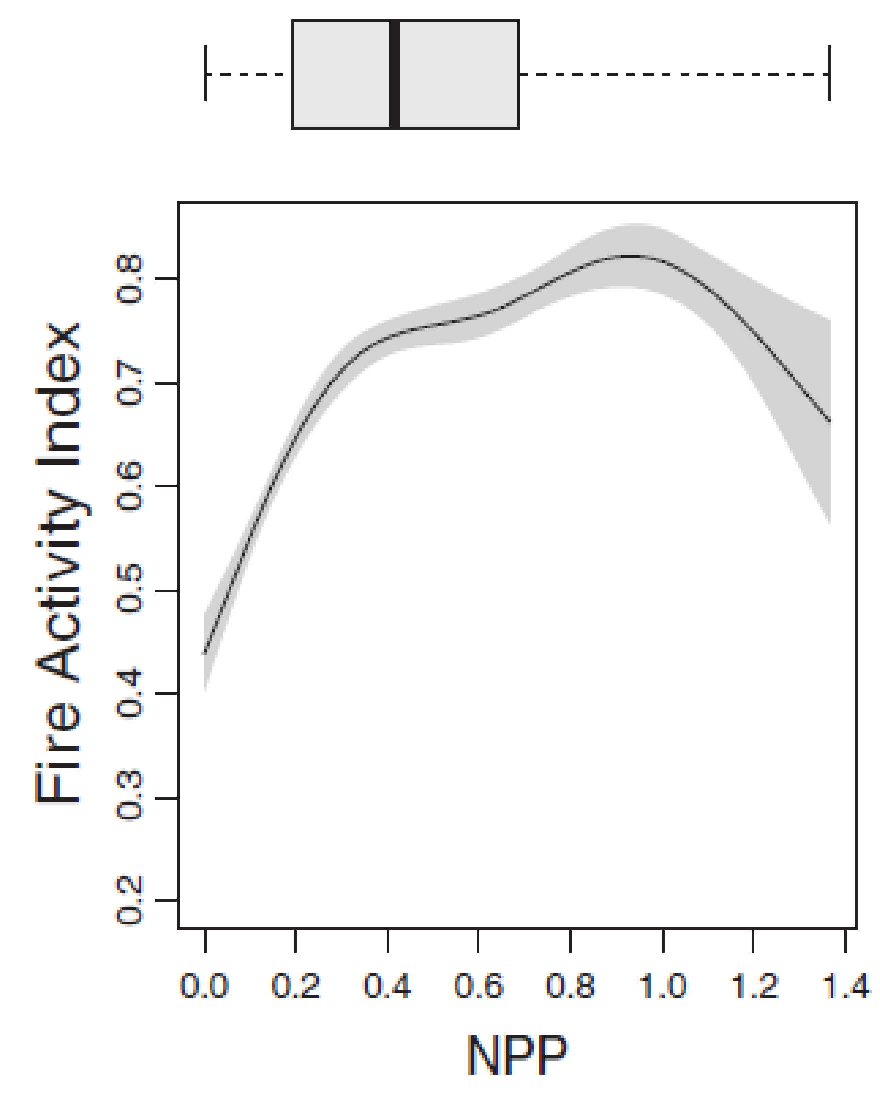



Figure 3. Generalized additive model (GAM) fit of the ***fire activity index against net primary productivity*** (NPP) (Gg km–2). […] Tukey's boxplots are shown at the top of each figure summarizing the NPP variability among ecoregions […].

The fire activity index is based on the MODIS active fire counts in each global ecoregion.

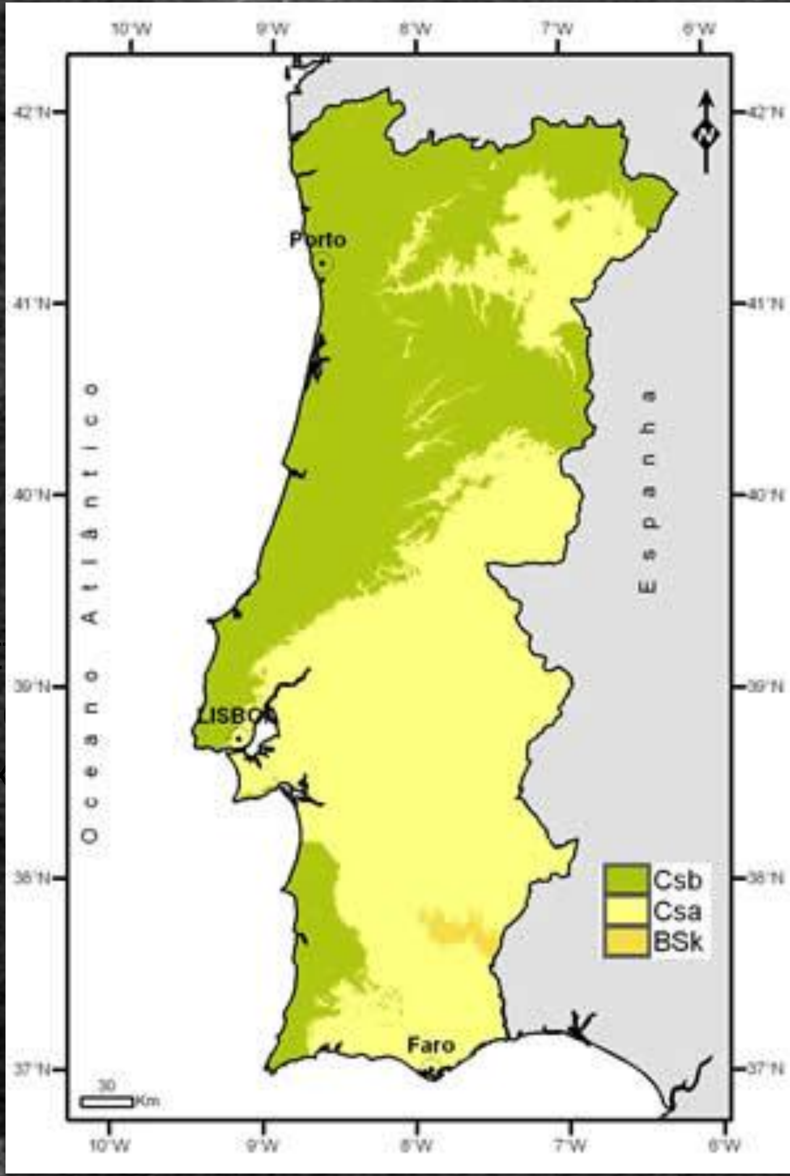
This global scale pattern also occurs at the scale of Portugal, along NW – SE climate and NPP gradients.

***THE IMPORTANT THING IS THAT FIRE INCIDENCE PEAKS AT INTERMEDIATE LEVELS OF NPP***.

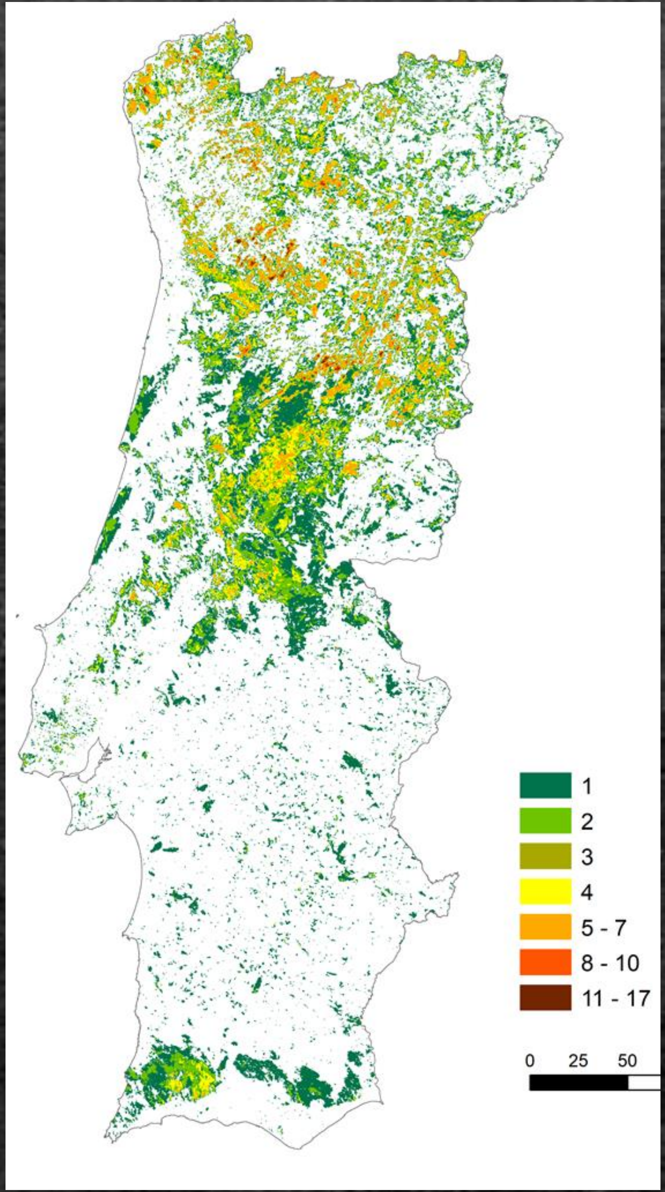
Pausas, J. G., & Ribeiro, E. (2013). The global fire–productivity relationship. *Global Ecology and Biogeography*, *22*(6), 728-736.

# Mediterranean-type climates, NPP, and fire

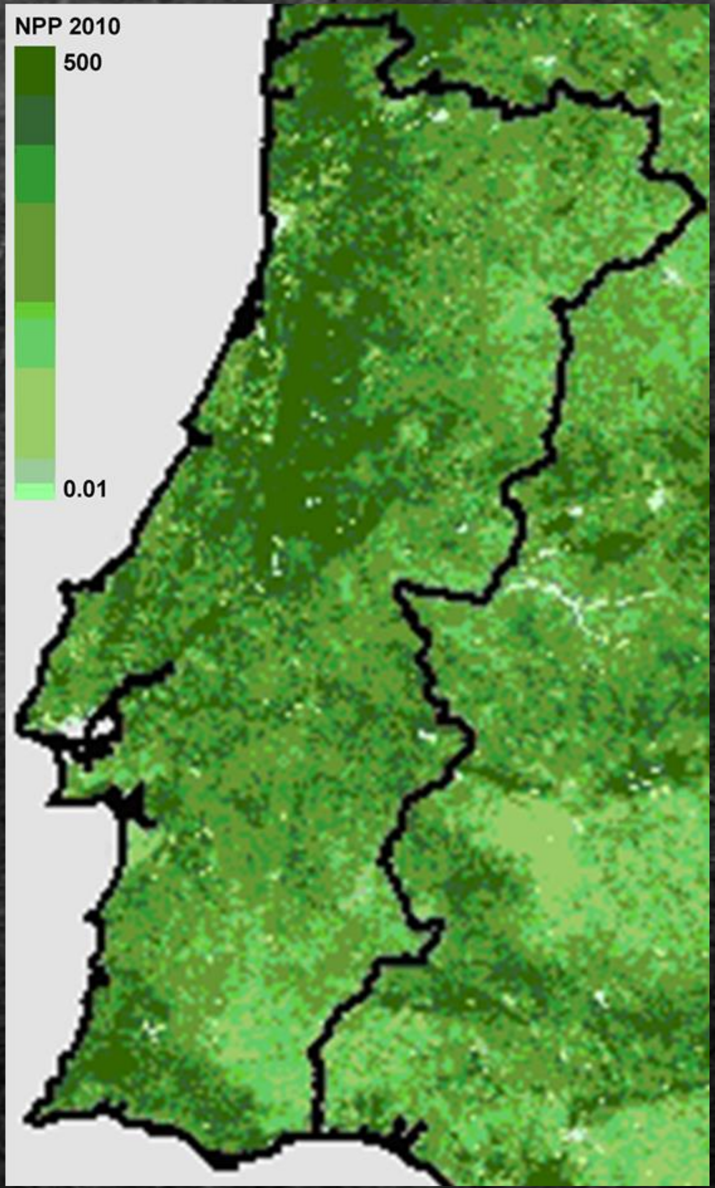
Köppen climate map of Portugal



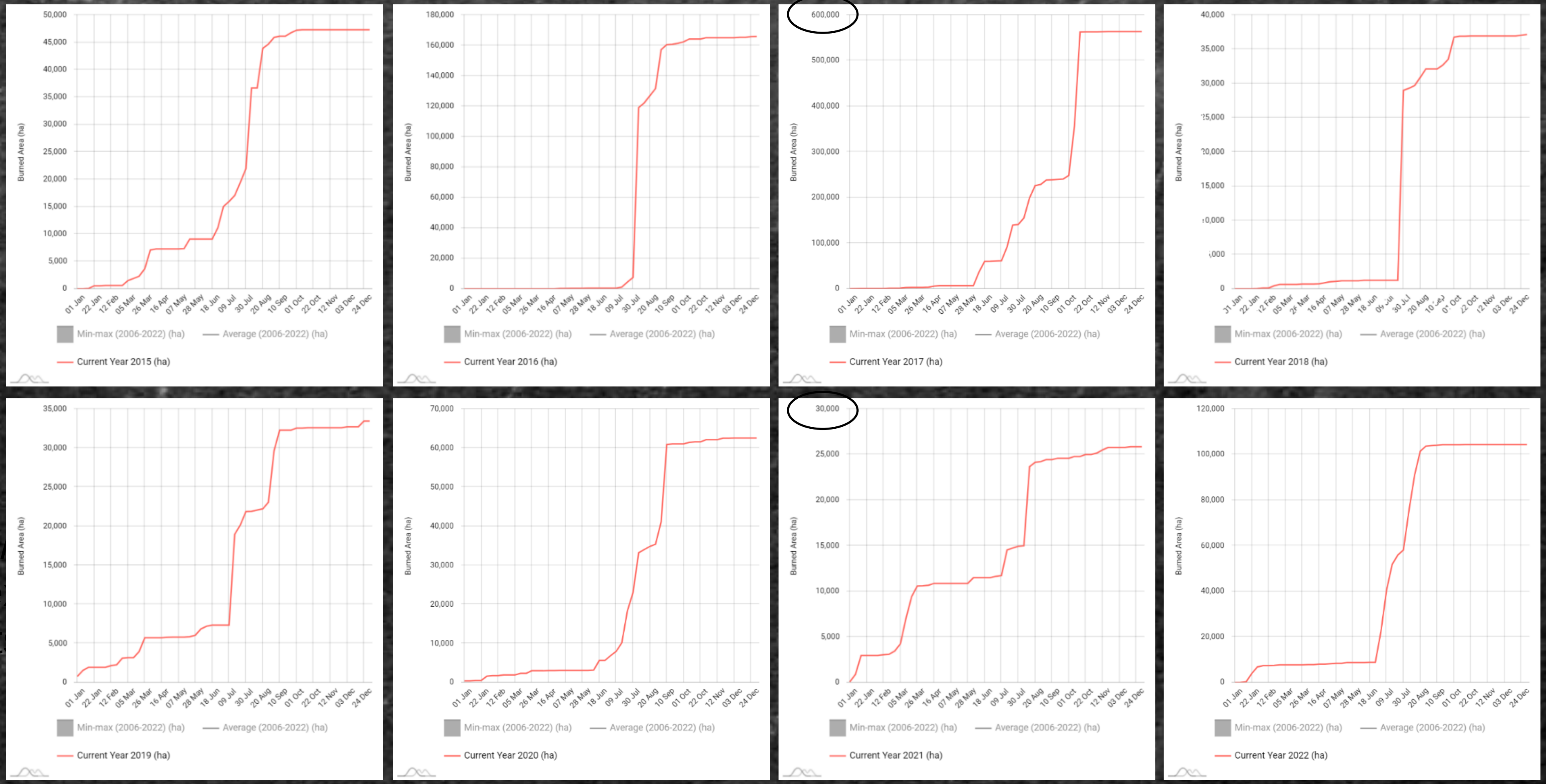

Number of times burned, 1975 - 2018




Annual NPP Portugal, 2010 ($Tg.km^{-2}.yr^{-1}$)



# Weather types and fire

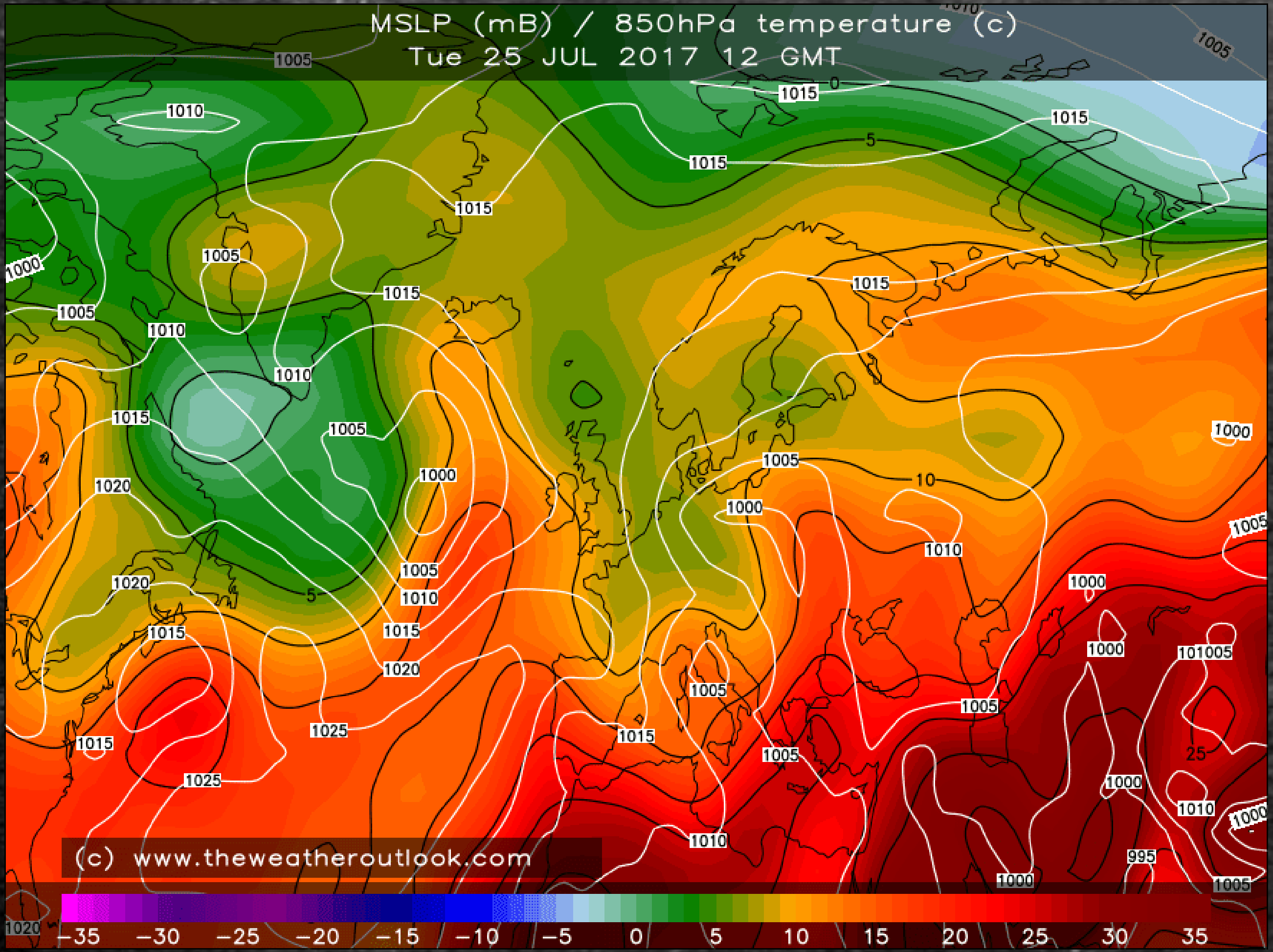



Notice y-axes vary over a 20-fold range.

Most of the annual burned area occurs in a small number of days (jumps in cumulative BA charts). What is so special about those days? The underlying processes occur at the ***synoptic scale***.

https://effis.jrc.ec.europa.eu/apps/effis.statistics/seasonaltrend

# Weather types and fire




***Synoptic*** (*seen together*) ***scale*** is a horizontal length scale of the order of 1000 to 2500 kilometers. This view corresponds to a horizontal scale typical of mid-latitude depressions. Weather analyses at synoptic scale may cover periods from 1 to 5-6 days.

The synoptic chart on the left shows USA E seabord, N Atlantic Ocean, and Europe, including European Russia (>> 2500 km).

The 850 hPa height corresponds to an altitude of about 1500 m. It is representative of surface conditions, without suffering local effects. The 850 hPa temperature is used to locate and identify warm fronts and cold fronts.

https://www.theweatheroutlook.com/twodata/reanalysis.aspx

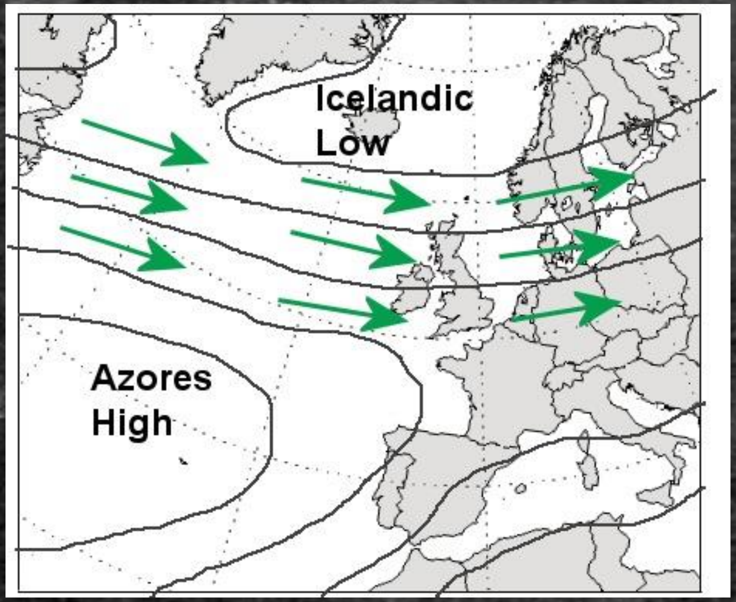
# Weather types and fire

Daily patterns of atmospheric dynamics, or ***circulation weather types (CWT)***, can be grouped on the basis various synoptic features of the pressure and circulation fields, such as ***atmospheric pressure gradient***, ***vorticity*** (the vertical rotation of air parcels, cyclonic or anticyclonic), and ***wind flow direction***.

Such groups, or clusters, are created using multivariate statistical techniques and then analyzed for their relationships with e.g., extreme temperatures or precipitation levels, area burned, etc.

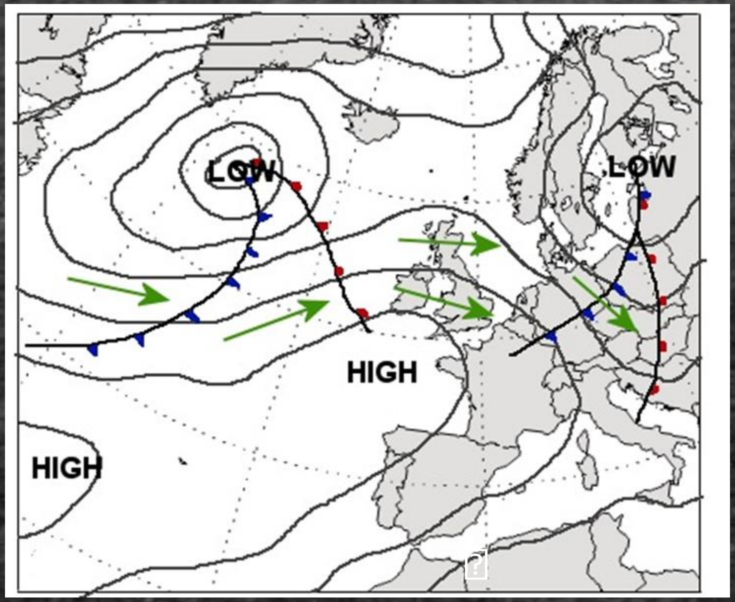
Averages ("***composites***") of all the synoptic charts belonging in each cluster characterize the ***typical synoptic configurations driving the main surface wind flow and heat advection*** that predominate during periods with e.g., high extents of area burned.

## The standard summer synoptic setup



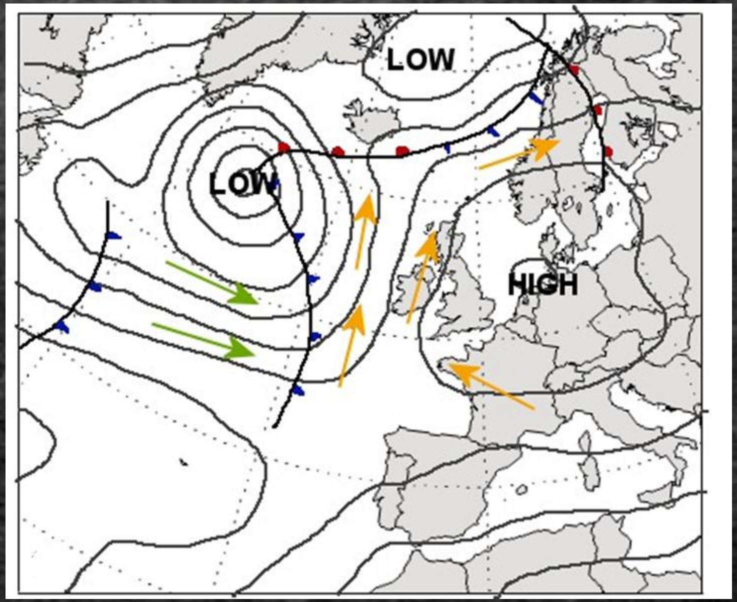

Low pressure systems moving from west to east reach W Europe cool and moist, after having crossed the Atlantic Ocean.

## Azores High ridging over W Europe




An elongated region of warm air aloft shows up on an isobaric map at higher heights and a ridge (an elongated area of high atmospheric pressure).

## Blocking High

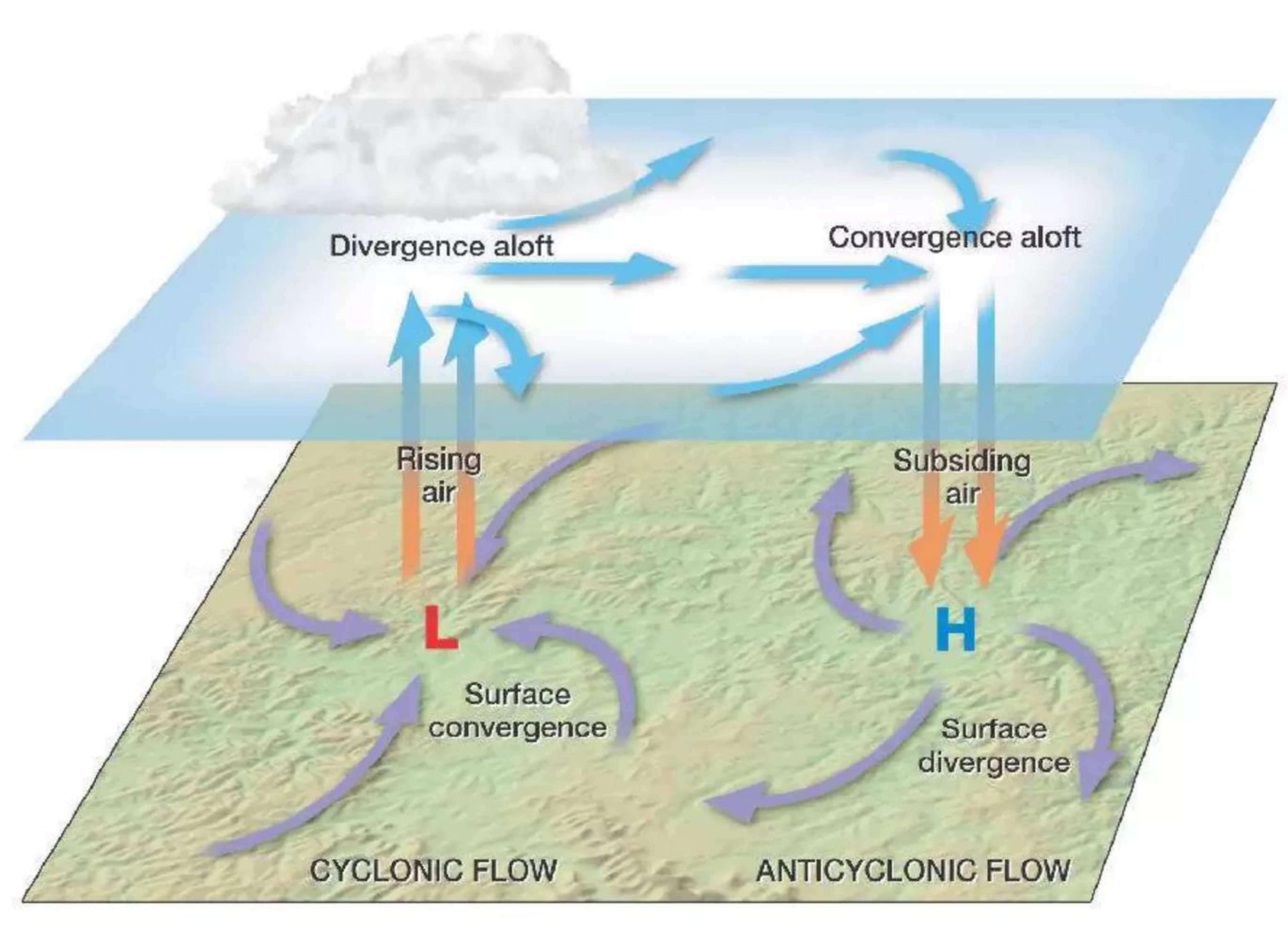



Blocking highs are high-pressure areas that tend to remain nearly stationary for several days, thus “blocking” the west-to-east movement of mid-latitude cyclonic storms.

https://community.netweather.tv/learning/basics/summer-synoptic-setups-r10/

***Cyclone***: An area of low pressure around which the winds blow counterclockwise
in the Northern Hemisphere and clockwise in the Southern Hemisphere.

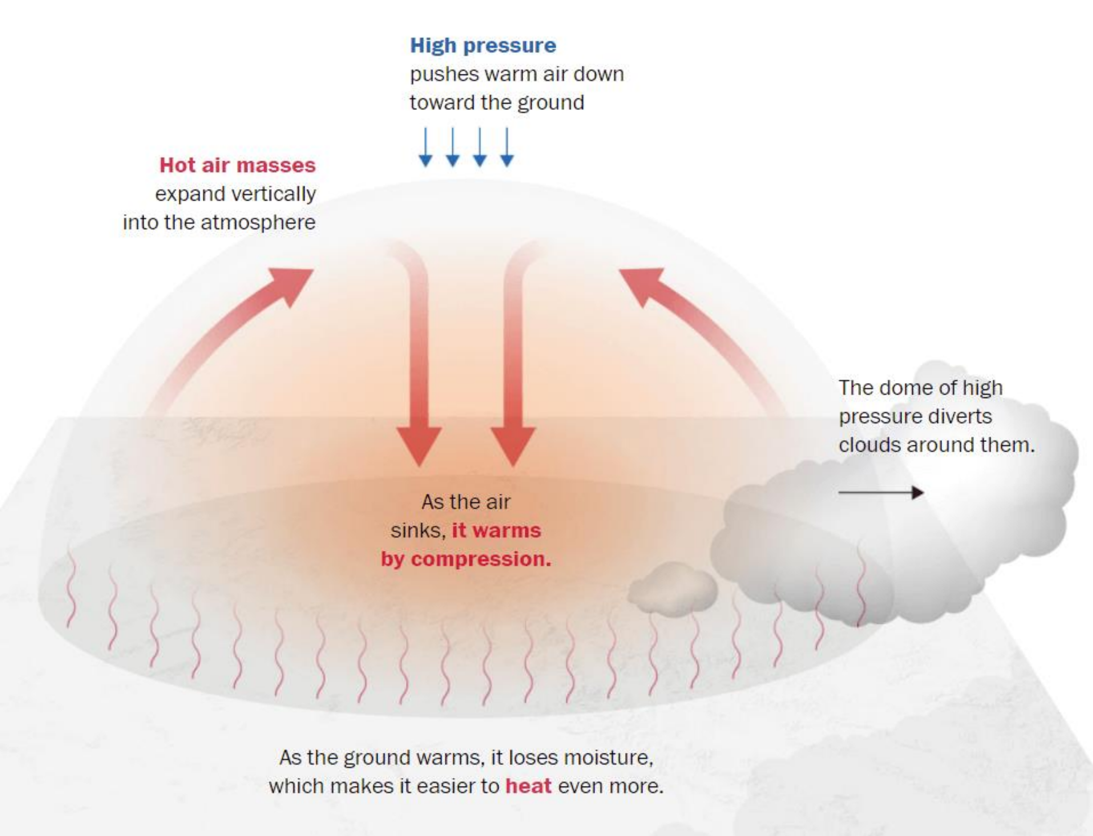
***Anticyclone***: An area of high atmospheric pressure around which the wind blows clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. Also called a high.



One of the most frequent ***interruptions to the westerly flow over Europe*** results from ***blocking high-pressure patterns*** developing either upstream in the mid-North Atlantic or over Europe.

The presence of a ***large anticyclone, persisting on average for 2 weeks***, causes disruption of and breakdown in the mid-level flow. This blocking may be dominant in some years (such as 2003) or only weakly developed in most other years.

Blocking highs are a main cause of ***heat waves*** and ***drought*** episodes over W Europe, which ***facilitate the occurrence of extreme burning periods***.




Kautz, L. A., Martius, O., Pfahl, S., Pinto, J. G., Ramos, A. M., Sousa, P. M., & Woollings, T. (2022). Atmospheric blocking and weather extremes over the Euro-Atlantic sector – a review. *Weather and Climate Dynamics*, *3*(1), 305-336.
Oliver, J. E. (Ed.). (2008). *Encyclopedia of World Climatology*. Springer Science.
https://www.severe-weather.eu/global-weather/heat-dome-heatwave-europe-june-2022-forecast-mk/

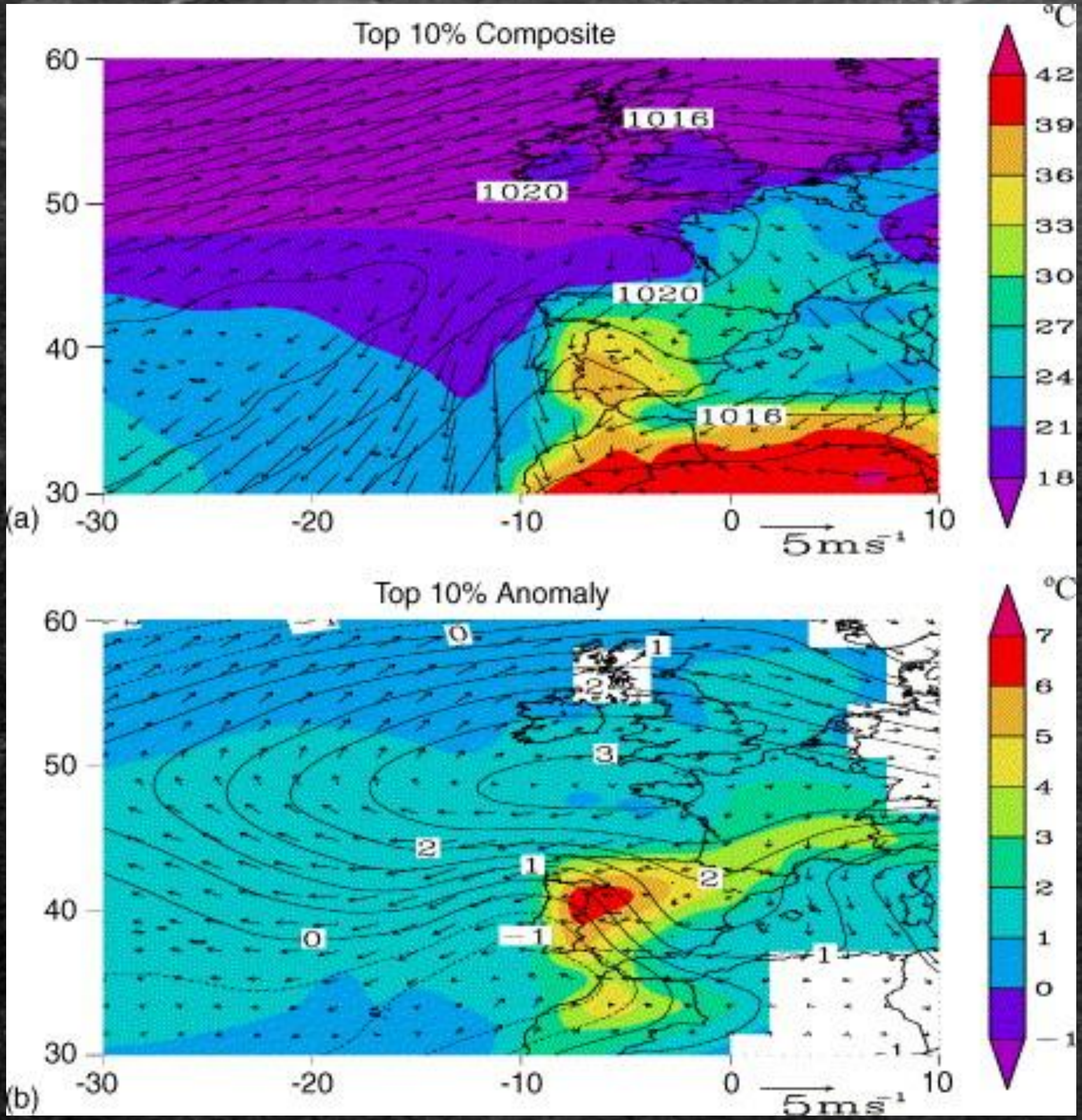
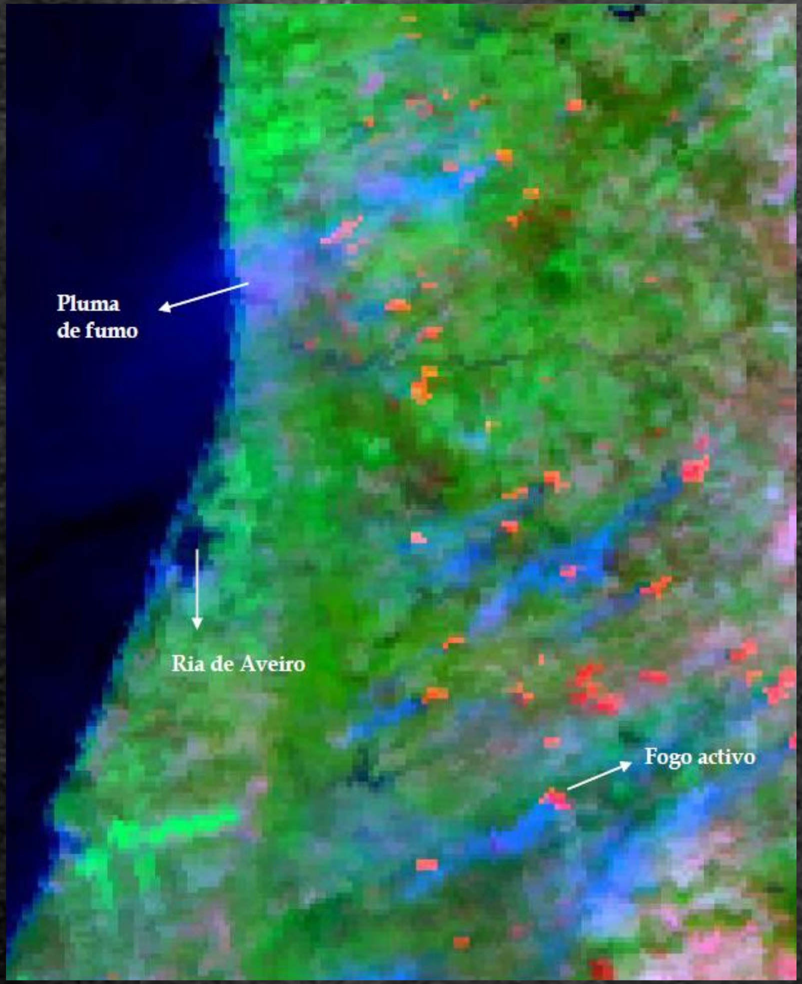


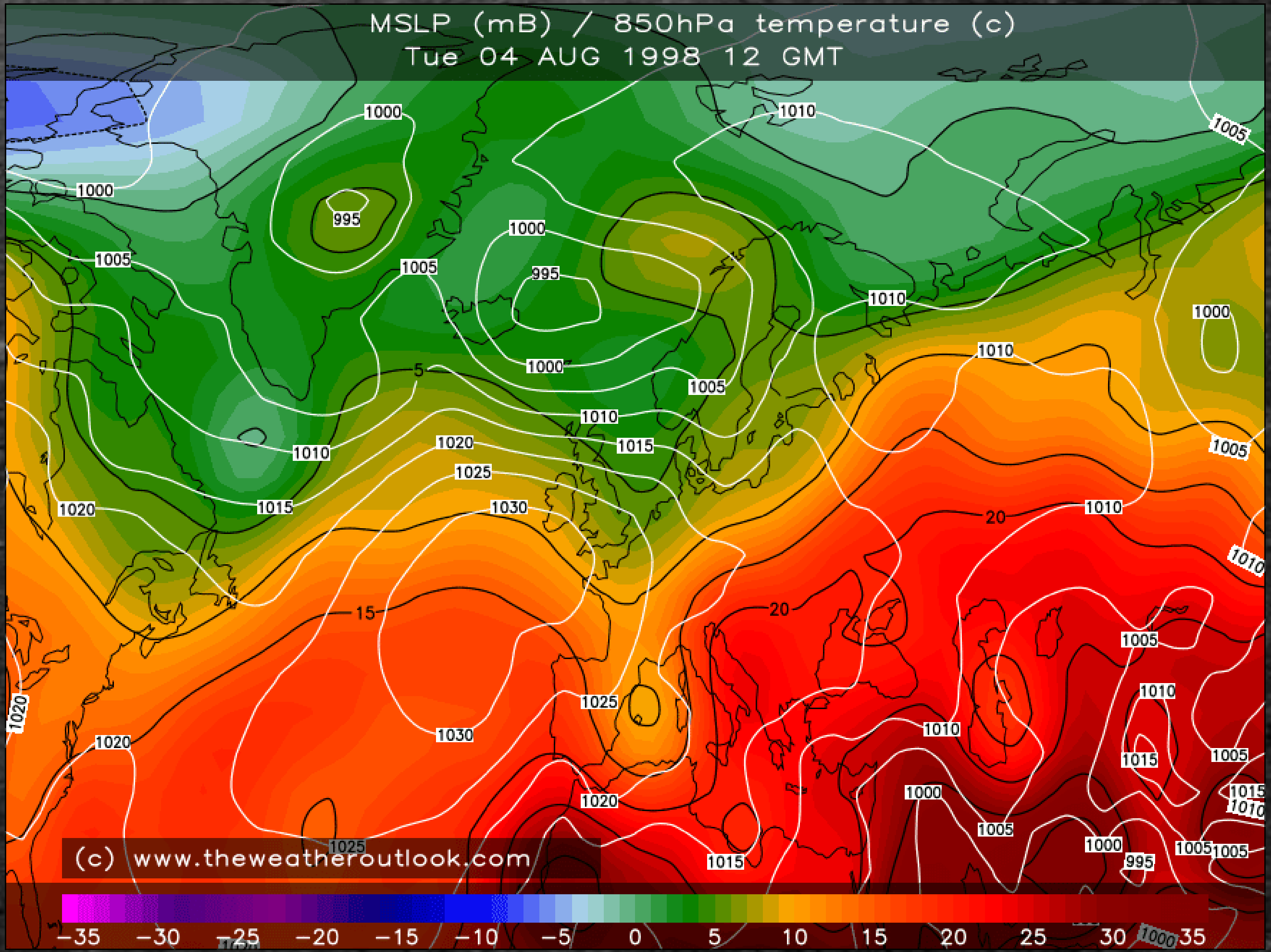

Fig. 6. Maximum temperature (°C), at 2 m height (Tx,2) for (a) composite for the 10% highest burnt area days in Portugal and (b) the corresponding 10% anomaly. Contour lines and arrows show, respectively, the corresponding sea level pressure (mb) and 10 m height wind fields (m s−1). Climate anomaly field (Tx,2) is represented only in those areas where such anomaly is significant at the 1% level (or 99% confidence level) computed with a two-tailed t-test.

Pereira, M. G., Trigo, R. M., da Camara, C. C., Pereira, J. M., & Leite, S. M. (2005). Synoptic patterns associated with large summer forest fires in Portugal. *Agricultural and Forest Meteorology*, 129(1-2), 11-25.

# Weather types and fire




NOAA-AVHRR image, Aug. 4, 1998.
Green – vegetation
Orange – burning fires
Blue – smoke plumes




Synoptic chart for Aug. 4, 1998. The Azores High is displaced to the NE of its more usual position and forms a ridge over W Europe, inducing NE / E wind flow over the Iberian Peninsula.

# Weather types and fire

The composites of atmospheric circulation types associated with days when extensive vegetation burning occurs, reveal ***anti-cyclonic circulation*** patterns usually associated with ***stable and dry conditions***.

Prevailing winds are ***warm and dry, from inland***, rather than moist and cool air advection from the sea, either from the Atlantic Ocean or the Mediterranean, in the case of the Iberian Peninsula.

Equivalent patterns occur over the other Mediterranean-type climate regions of the world.


California, Dec. 2017.


Chile, Feb. 2023.

# Canadian Fire Weather Index (FWI)

Fire managers must make decisions each day on how many resources they will need and where those resources should be positioned. They may also want to estimate the number of fires expected to occur in their regions each day.

***Fire danger*** describes 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 ***severity*** of fire effects.

The Canadian FWI provides a means of evaluating the severity of fire weather conditions in a common standardized forest type.

It provides ***numerical ratings of fuel moisture in important fuel layers*** and several relative ***indices of fire behavior***.

# Canadian Fire Weather Index (FWI)

The FWI System was built to ***integrate weather information into fuel moisture and fire danger indices***, without regard to differences in forest type.

It relies on ***once a day measurements*** (taken at 13:00 h) of ***air temperature*** and ***relative humidity***, 10m open ***wind speed***, and 24 h accumulated ***precipitation***.

The FWI system contains ***three moisture "codes" (i.e. indices)*** that track moisture in different levels of the forest floor and/or different dead, downed fuel size classes.

Calculations of each moisture code rely on a simple moisture exchange model. In the absence of rain, moisture change in each fuel layer follows an ***exponential curve towards an equilibrium moisture value***. The ***response time*** of moisture exchange and the equilibrium moisture content value can depend on the fire weather conditions measured for the day. When rain has occurred, the existing moisture is added to the moisture in the fuel layer and then moisture exchange with the atmosphere begins.

# Canadian Fire Weather Index (FWI)

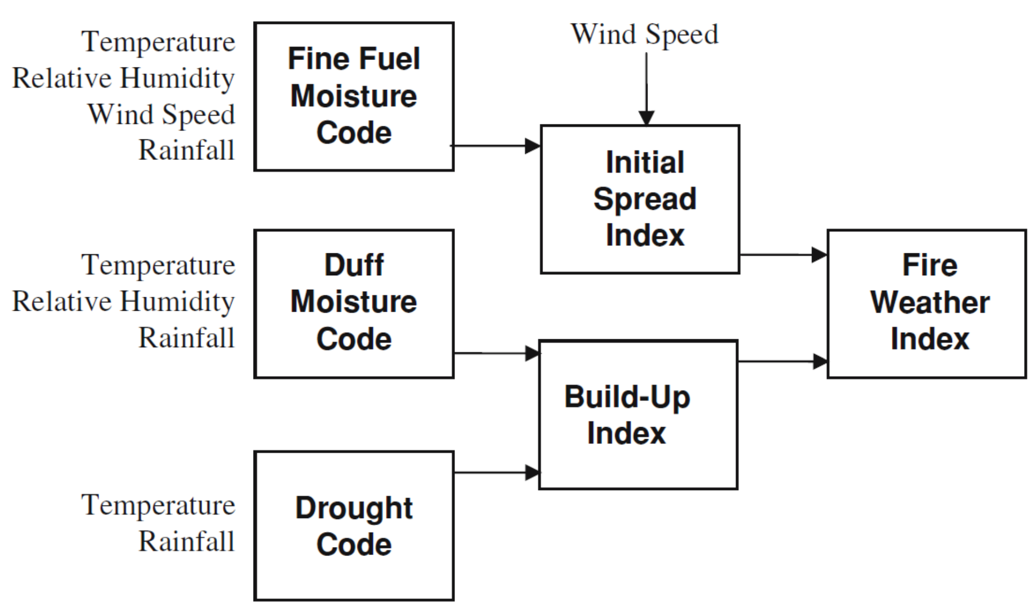



**Fig. 2** The structure of the Canadian Forest Fire Weather Index System

The remaining three fire behaviour codes are created from the moisture codes and represent relative ratings of ***fire behaviour potential***, capturing ***fire spread rate***, ***fuel consumption*** and ***fireline intensity***.

A 4$^{th}$ fire behaviour index, the ***Daily Severity Rating (DSR)*** is simply a transformation of the Fire Weather Index (FWI) and is generally used for averaging daily fire danger into monthly or seasonal values.

# Canadian Fire Weather Index (FWI)

**Fine Fuel Moisture Code**

When fire begins to spread in a forested stand as a surface fire it is strongly influenced by the ***moisture in the small, readily consumed fuels*** on the surface of the forest floor.

The moisture content in fine surface fuels is described by the Fine Fuel Moisture Code (FFMC). Fine surface fuels are considered as a ***1.2cm thick layer of pine litter*** with a fuel weight of ***0.25 kg/m²***, or ***dead woody fuels*** with a ***diameter of 0.6 - 2.5 cm***.

Central in the FFMC is a simple ***exponential model of moisture exchange***. At the start of its calculation each day, the previous days' ***FFMC is converted back to moisture content (mc)*** via the equation:

$$\mathrm{mc} = 147.2 \cdot \frac{101 - \mathrm{FFMC}}{59.5 + \mathrm{FFMC}}$$

# Canadian Fire Weather Index (FWI)

**Fine Fuel Moisture Code**

This exponential model for drying is based on a physical understanding of how cellulose materials lose or gain moisture in reaction with atmospheric conditions. The rate at which the fuel layer moves toward equilibrium in this exponential model is called the ***response time*** and is dependent on temperature, relative humidity and wind speed.

For conditions of 25°C, relative humidity of 30% and wind speed of 10 km/h the ***response time*** of the ***FFMC*** in the FWI System is approximately ***0.5 days***.

The FFMC is also reflective of litter moisture in small twigs, fuels which would also be consumed in flame front passage and contribute to the spread and intensity of a surface fire.

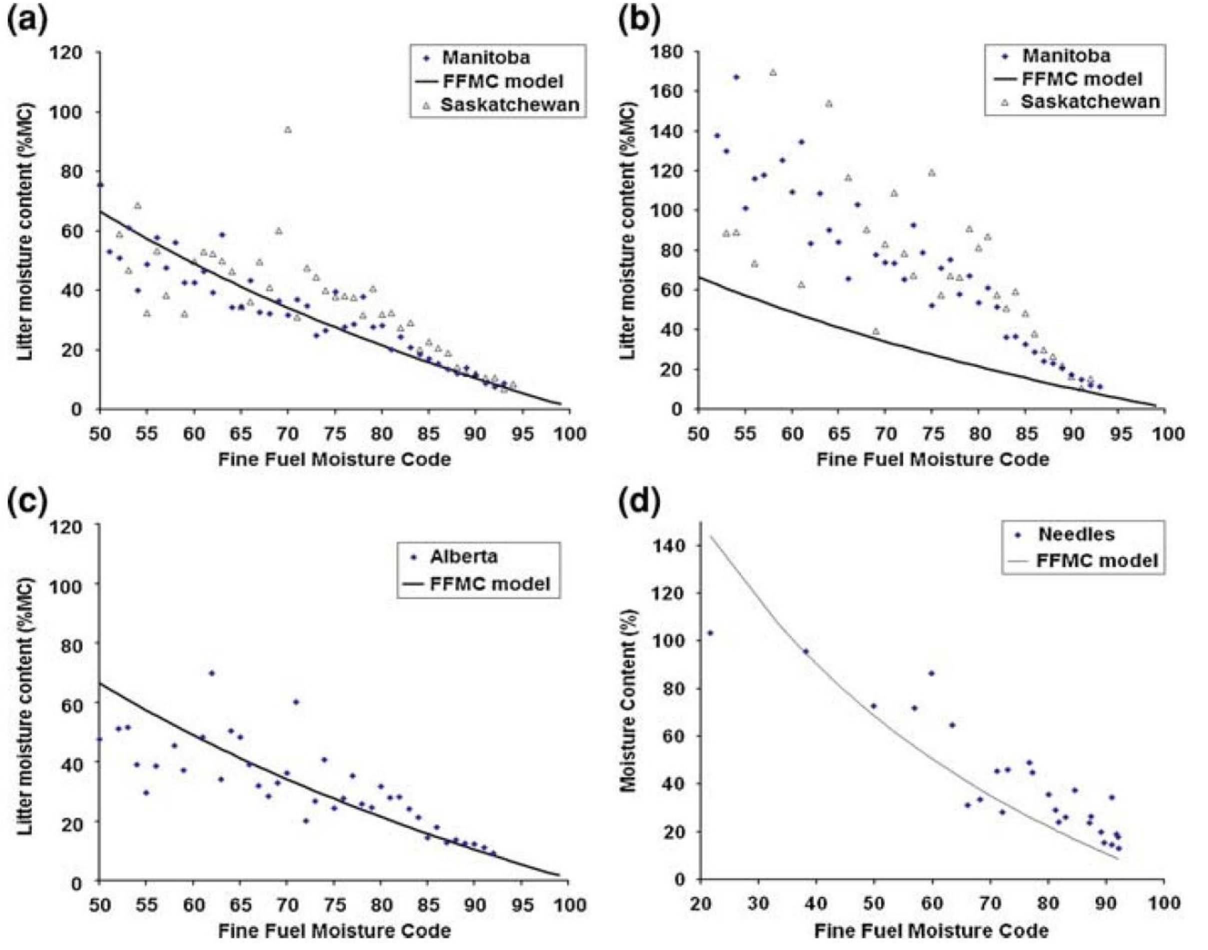



**Fig. 3** Observed litter moisture in relation to FFMC for (**a**) pine stands in Manitoba and Saskatchewan, (**b**) aspen stands in Manitoba and Saskatchewan, (**c**) spruce stands in Alberta, and (**d**) a pine stand in north-eastern Ontario with continuous feathermoss forest floor. The standard FWI System relationship between moisture content and FFMC (Eq. 1) is shown as a solid line

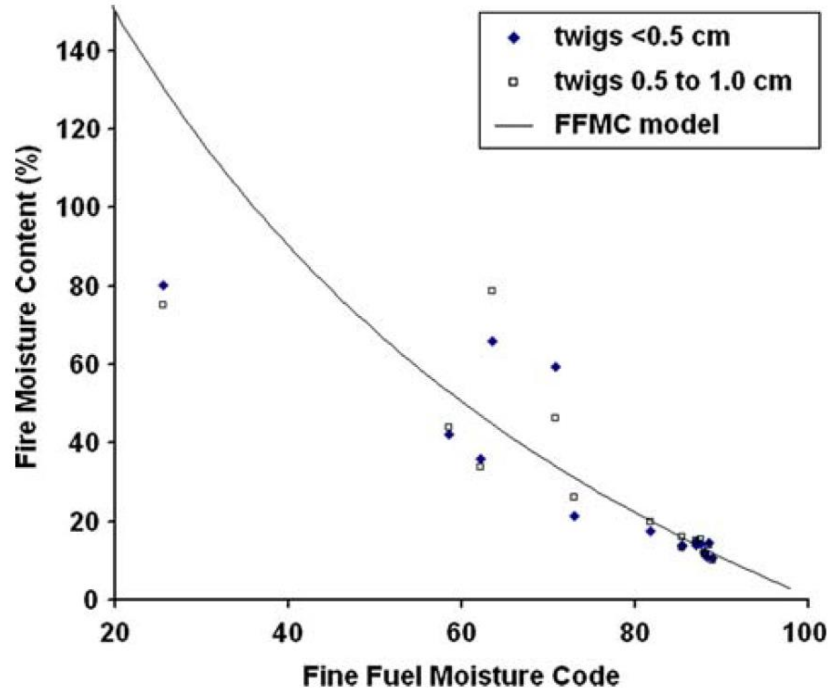



**Fig. 4** An example of moisture in small twigs on the surface of the forest floor in relation to FFMC calculated at a nearby weather station

The two size classes shown in Fig. 4 represent twigs that would likely be completely consumed in the passage of the flaming front of a fire.

# Canadian Fire Weather Index (FWI)

**Duff Moisture Code**

The Duff Moisture Code (DMC) describes the moisture content of the upper layers of the forest floor where litter is beginning to decay. It nominally tracks moisture in the ***top 7 cm of the forest floor*** in a mature jack or lodge pole pine stand and represents a ***fuel load of 5 kg/m²***.

***Moisture content can be found from the code value*** through the equation:

$$\mathrm{mc} = 20 + \ln\left(\frac{\mathrm{DMC} - 244.73}{-43.43}\right)$$

The DMC layer gains moisture directly only from rainfall and dries to a constant ***equilibrium moisture content of 20%***. The rate at which drying occurs (which corresponds to *the **time lag coefficient*** in the exponential drying model) depends on both relative humidity and temperature. For a July day with a temperature of 25°C and a relative humidity of 30%, the drying rate is approximately ***10 days***.

# Canadian Fire Weather Index (FWI)

## Duff Moisture Code

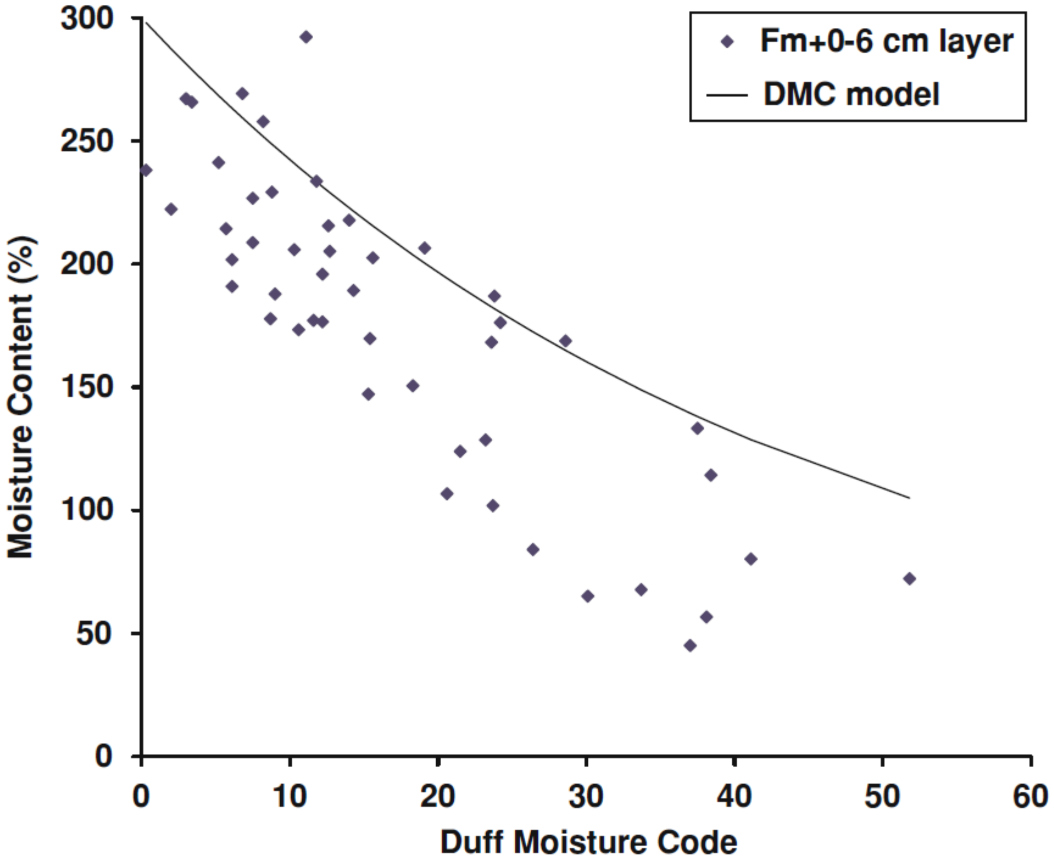



**Fig. 5** Observed duff moisture content in a mature jack pine stand in north eastern Ontario related to DMC calculated at a nearby weather station. The standard FWI System relationship (Eq. 2) is shown as a solid line

# Canadian Fire Weather Index (FWI)

**Drought Code**

The Drought Code (DC) accounts for the influence of ***long term drying on the fuels on the forest floor***. It is often used as an indicator of the moisture content of ***deep layers of the forest floor*** and the moisture content of large down and dead woody debris on the forest floor.

The DC nominally tracks moisture in a ***18 cm thick organic layer*** with a fuel load of ***25 kg/m²***.

This layer dries through the same exponential drying mechanism used in the FFMC and DMC models; however the ***DC dries toward a constant equilibrium moisture content of 0%***. Its drying rate is dependent on temperature alone. For a day in July with a temperature of 25°C the DC's ***response time*** is approximately ***50 days***.

# Canadian Fire Weather Index (FWI)

**Drought Code**

The conversion between DC and moisture content takes the form:

$$MC = 400 \cdot e^{\frac{-DC}{400}}$$

Understanding the level of drought influencing the forest is important because it gives an indication of the ***amount of fuel that will be consumed in fires***, both on the surface and within the forest floor.

It is also used by fire managers as an indicator of the ***difficulty of mop-up of a fire***, that is, the difficulty in finally extinguishing all areas where the fire is smouldering.

# Canadian Fire Weather Index (FWI)

**Initial Spread index**

The Initial Spread Index (ISI) integrates the ***moisture content of surface fuels*** (through the FFMC) and the ***observed wind speed***, to give a unitless indicator of the ***potential rate of spread of a fire***. **Appropriate to assess the need for prompt initial attack**

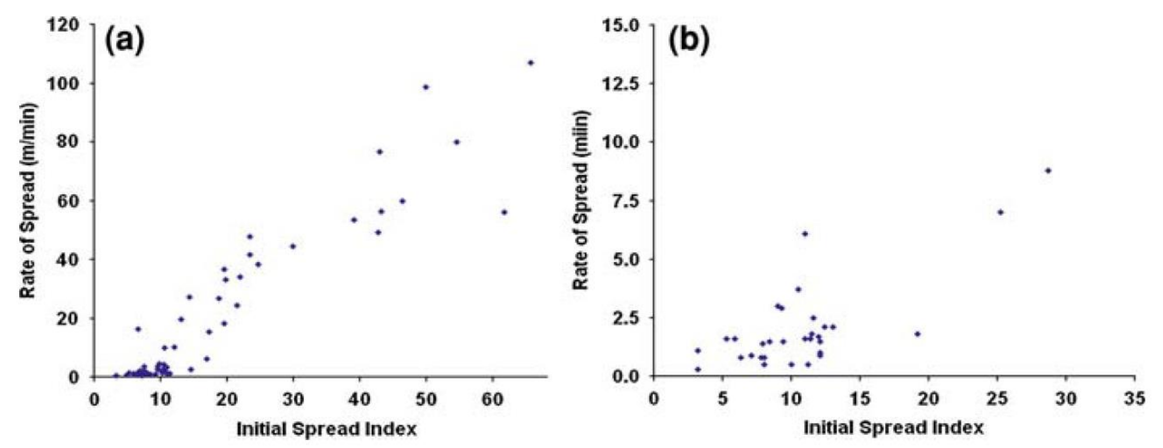



**Fig. 7** Rate of spread as function of ISI for (**a**) jack pine and lodge pole pine forests and (**b**) aspen forests (data is from experimental fires and well-documented wildfires)

While both plots show an increasing rate of spread with increasing ISI, the difference in the magnitude of the rate of spreads is large. At an ISI value about 30 the plot for the jack pine/lodgepole pine fuel type indicates an expected rate of spread of just over 40m/min while the plot for the aspen fuel type indicates a rate of spread of approximately 8m/min.

# Canadian Fire Weather Index (FWI)

**Build-Up index**

The Build-Up Index (BUI) accounts for ***moisture levels in the fuels tracked by the DMC and the DC***, under the form of a ***weighted mean*** of those two codes.

The BUI is a unitless index used as a relative indicator of ***potential fuel available for surface fuel consumption*** (consumption of material on and in the forest floor by the passing fire front).

The BUI is often used by forest fire management agencies as an indicator of the ***potential difficulty in extinguishing smouldering fire***, or the tendency of a fire to remain smouldering deep in the ground or in large woody material. **Need for involving heavy aircraft.**

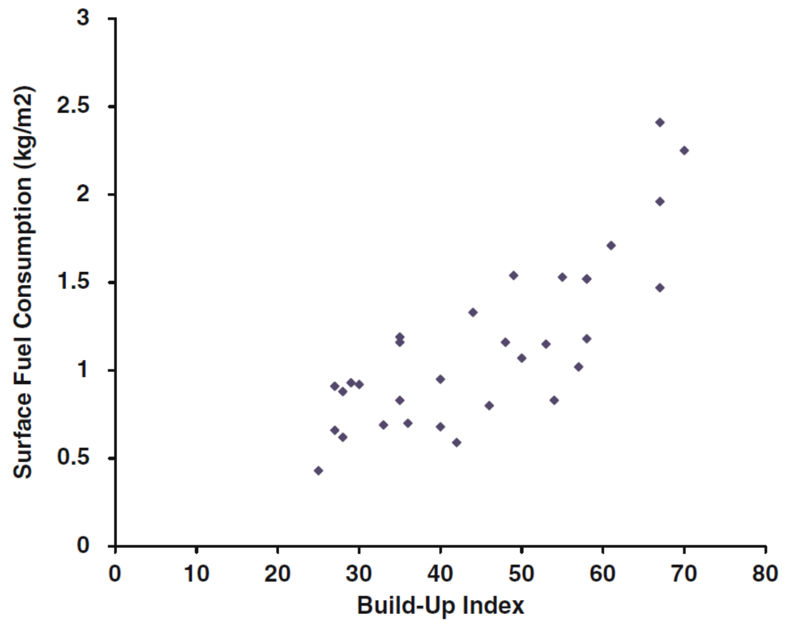



**Fig. 6** Total surface fuel consumption (surface litter, down and dead wood and forest floor consumption) for experimental fires in jack pine as a function of BUI

# Canadian Fire Weather Index (FWI)

**Fire Weather index**

The Fire Weather Index (FWI) is the final index of the FWI System and is ***multiplies the BUI*** (the fuel consumption indicator) ***by the ISI*** (the rate of spread indicator) and is a unitless indicator of ***expected fire intensity***.

The FWI provides a general ***summary of fire weather and fuel moisture in a region*** and can be useful when a single indicator of general fire potential is needed, for instance when communicating fire danger to the public.

Fire management agencies rely on the more basic elements of the FWI System (such as BUI, ISI and FFMC) in their daily operational planning.

The ***Daily Severity Rating (DSR)*** is a monotonic, non-linear transformation of FWI that more accurately reflects the expected effort required for fire suppression:

$$DSR = 0.0272 * FWI^{1.77}$$

# Canadian Fire Weather Index (FWI)

**Applications** - Occurrence of human-caused fires

The ***FFMC*** is used by fire managers as an indicator of the ***receptivity of surface fuels to ignition*** and has a strong influence on the ***vigour of spread of a surface fire***; thus it is an important element in ***predicting fire occurrence on the landscape***.

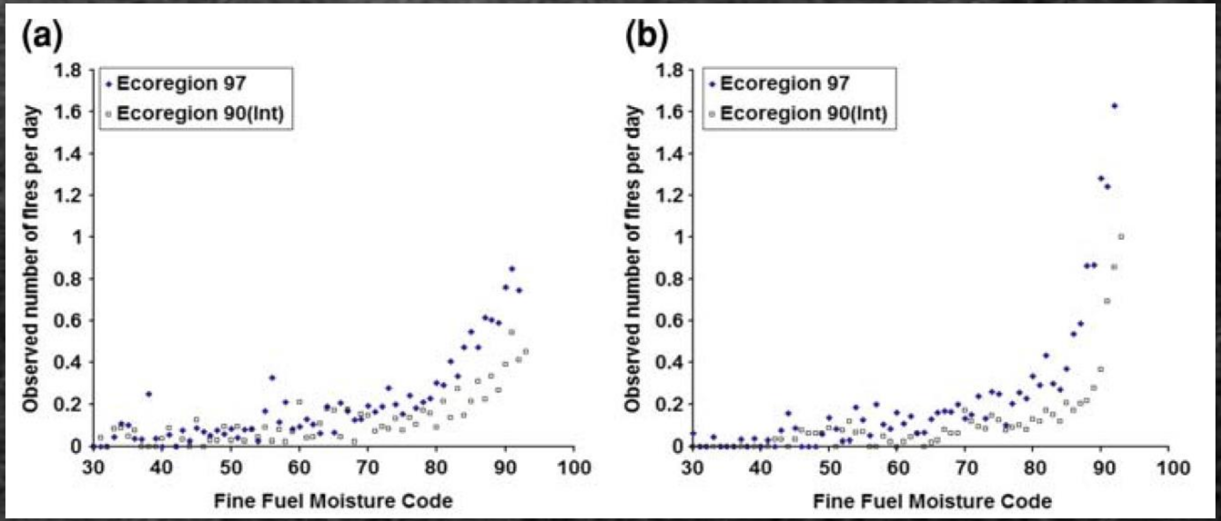



**Fig. 9** Observed number of human-caused fires per day in each integer FFMC class for two Ontario eco-regions (the $y$-axis has been adjusted for differences in the total number of days in each FFMC class). Fires have been seperated into two cause groups, (**a**) Recreational, Industrial, and miscellaneous cause type fires that have a peak in the mid-summer and (**b**) residential, railway and incendary which have a peak in spring.

Expected human-caused fire occurrence in an area depends on the receptivity of forest fuels to ignition and sustainable spread (e.g., moisture content of surface fuels) as well as the number of ignition sources in the forest: without ignition sources receptive forest fuels are unimportant.

# Canadian Fire Weather Index (FWI)

**Applications –** Area burned

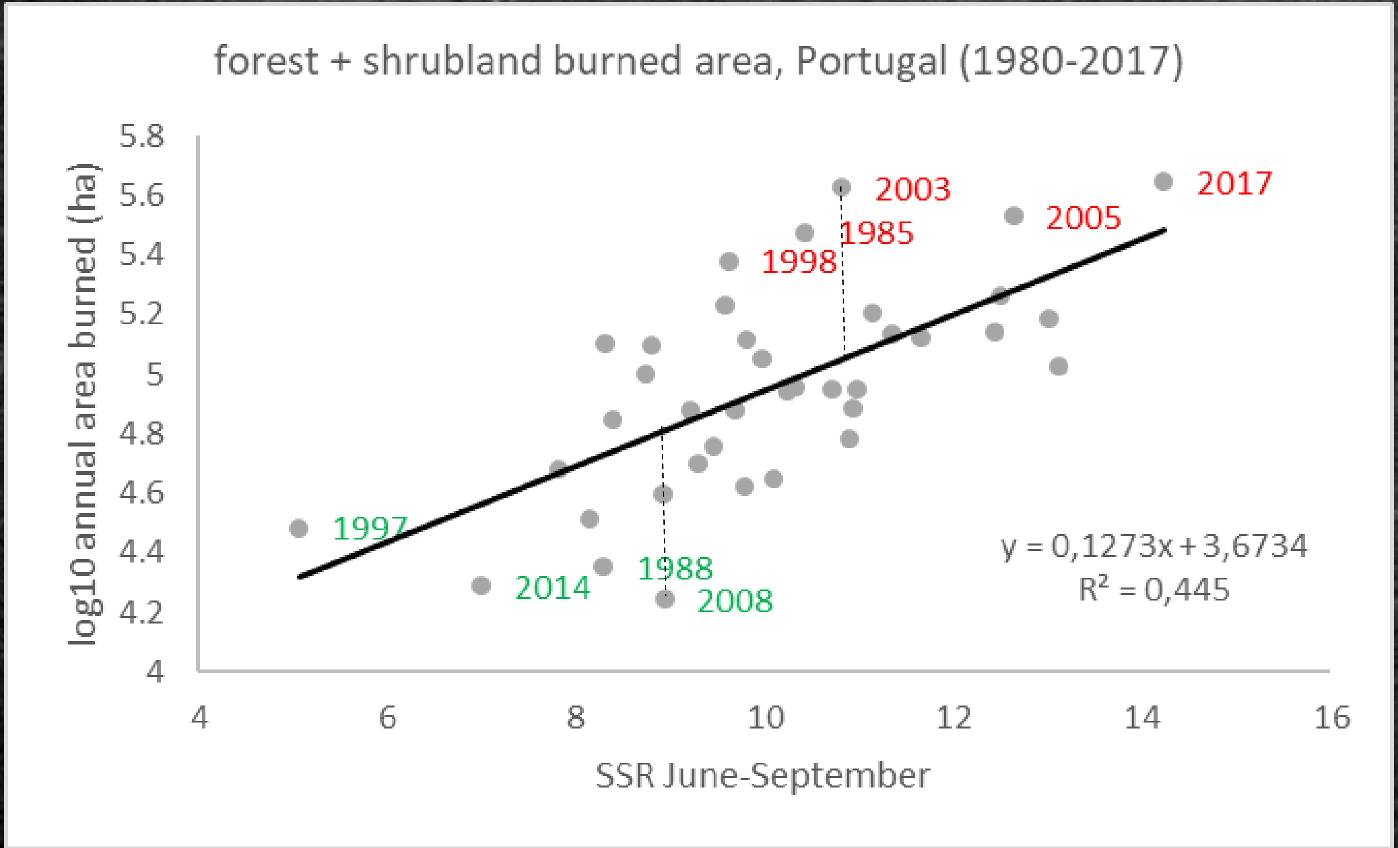
***Monthly means and maxima of the DMC and the daily severity rating (DSR***, an exponentially scaled version of the FWI) are ***good predictors of area burned***.

**Table 1** Correlation of annual area burned (1976–2004, $n = 28$) with annual mean and 99th percentile of several FWI System outputs and the number of fires occurring in the region

| Fire weather variable | Ecoregion 90 Correlation ($P$-value) | | Ecoregion 97 Correlation ($P$-value) | |
|---|---|---|---|---|
| | Mean | 99th %ile | Mean | 99th %ile |
| FFMC | 0.249 (0.202) | −0.004 (0.98) | 0.158 (0.423) | 0.176 (0.370) |
| DMC | 0.247 (0.206) | 0.338 (0.08) | 0.303 (0.117) | 0.332 (0.084) |
| ISI | 0.372 (0.051) | 0.578 (0.0013) | 0.340 (0.077) | 0.475 (0.011) |
| FWI | 0.0354 (0.065) | 0.562 (0.0019) | 0.334 (0.082) | 0.524 (0.0042) |
| Number of fires | 0.382 (0.045) | | 0.258 (0.186) | |
| Number of escape fires[a] | 0.504 (0.0063) | | 0.527 (0.0039) | |

[a] Number of escape fires is defined as fires over 4 ha in size occurring in a year

# Canadian Fire Weather Index (FWI)




***Seasonal Severity Rating (SSR)*** is the ***mean DSR*** over the extended summer (JJAS).

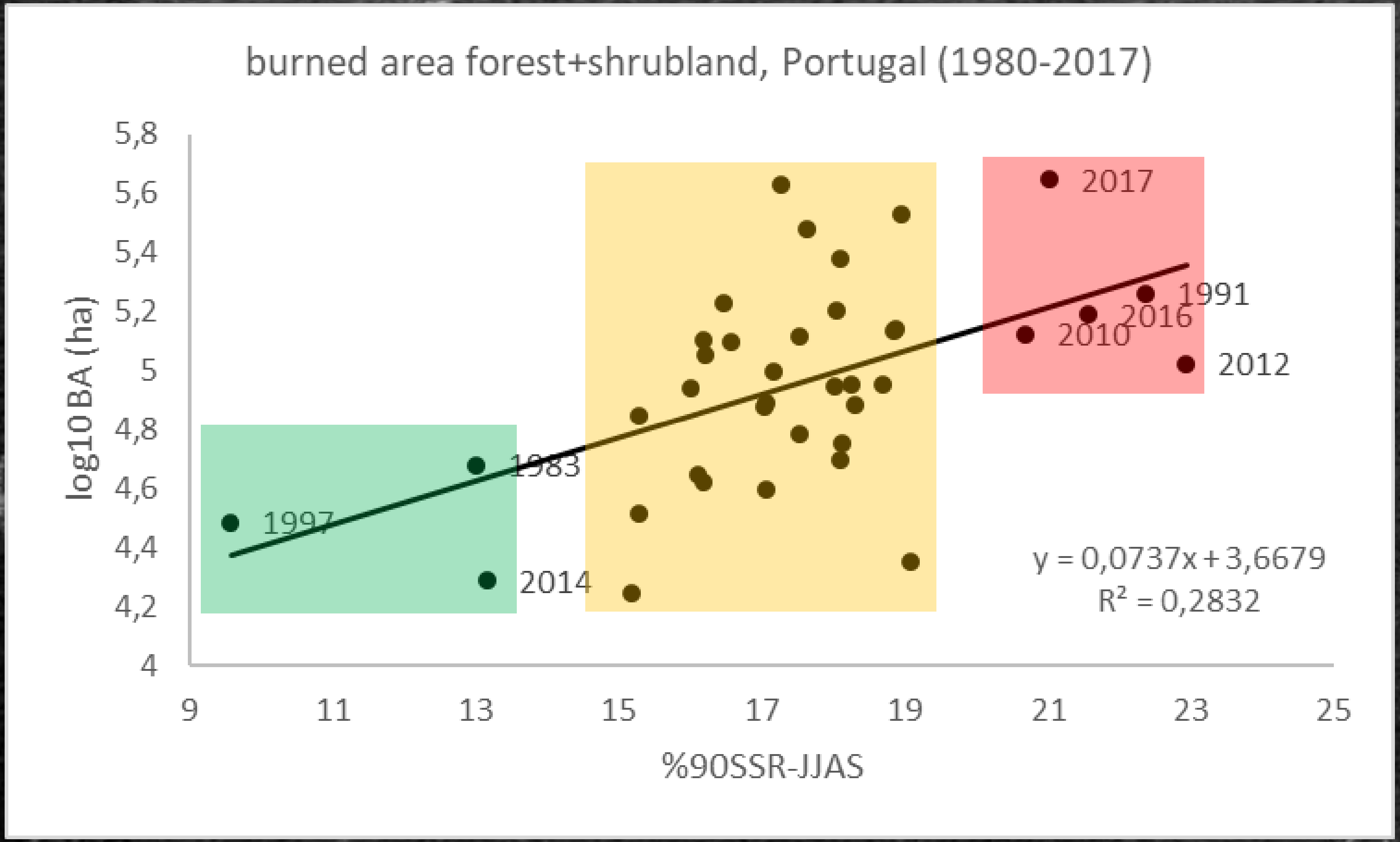
The extended summer (JJAS) ***SSR explains 45% of the interannual variance in area burned*** in Portugal.

2003 and 2008 are the years with the largest positive and negative regression residuals, respectively. Thus, 2003 (2008) had much more (less) area burned than predicted from their respective SSR values.

These large differences between observed and predicted values mean that variables other than mean summer SSR played an important role. ***Extreme DSR values over short periods*** and ***area burned in previous few years*** may be such variables.

# Canadian Fire Weather Index (FWI)

## **Applications** – Area burned




%90SSR is the ***90th percentile*** of DSR over the extended summer (JJAS).

With ***low %90SSR*** (<≈13, cool, humid summer), ***burned area is never high***.

With ***high %90SSR*** (>≈20, hot, dry summer), ***burned area is never low***.

With ***intermediate %90SSR*** (≈13<SSR<≈20, moderate summer), ***burned area varies widely***.

Under intermediate %90SSR values, factors other than meteorology gain importance. For example, the accumulated burned area of the previous ≈5 years, i.e. the availability of large stretches of land with heavy fuel loadings.

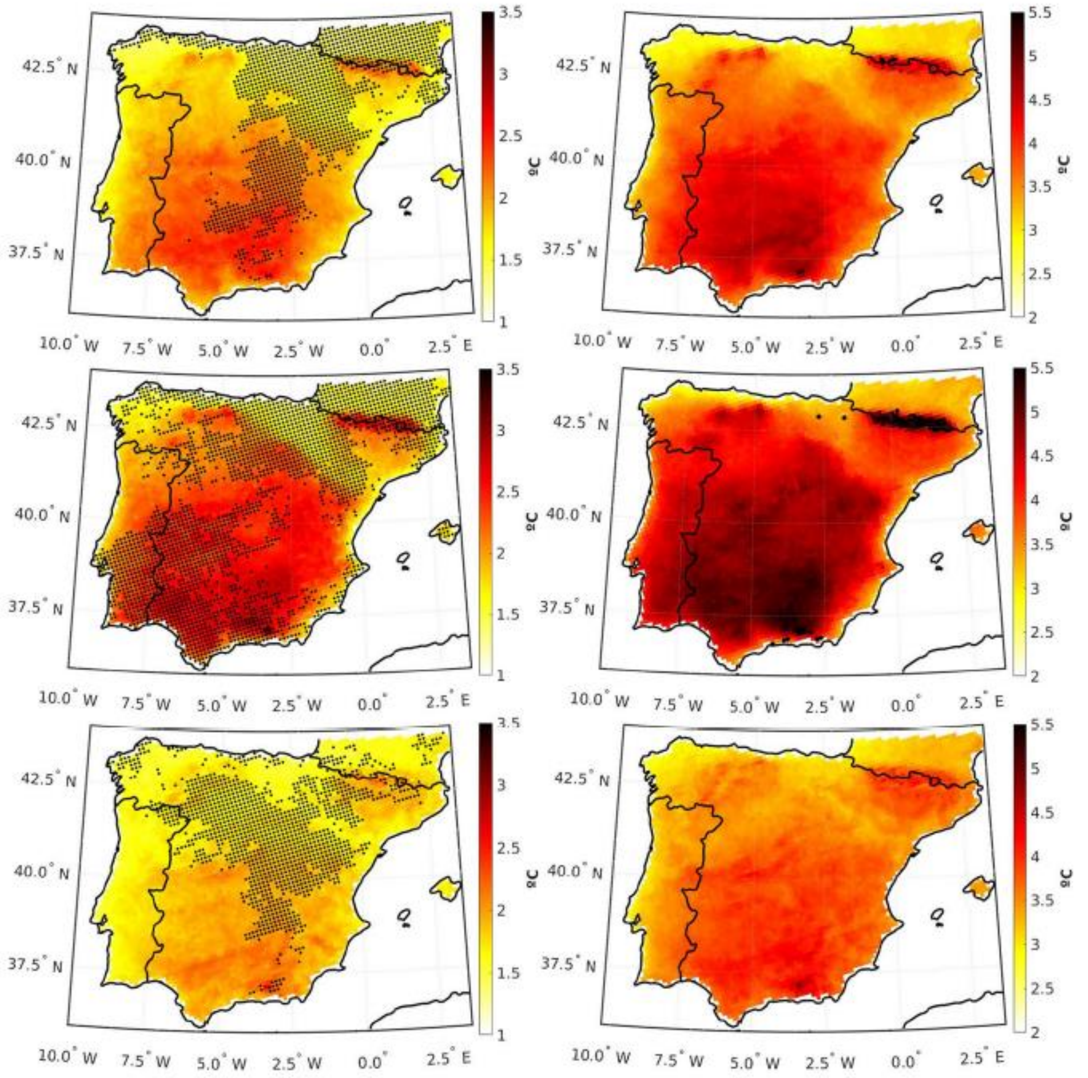
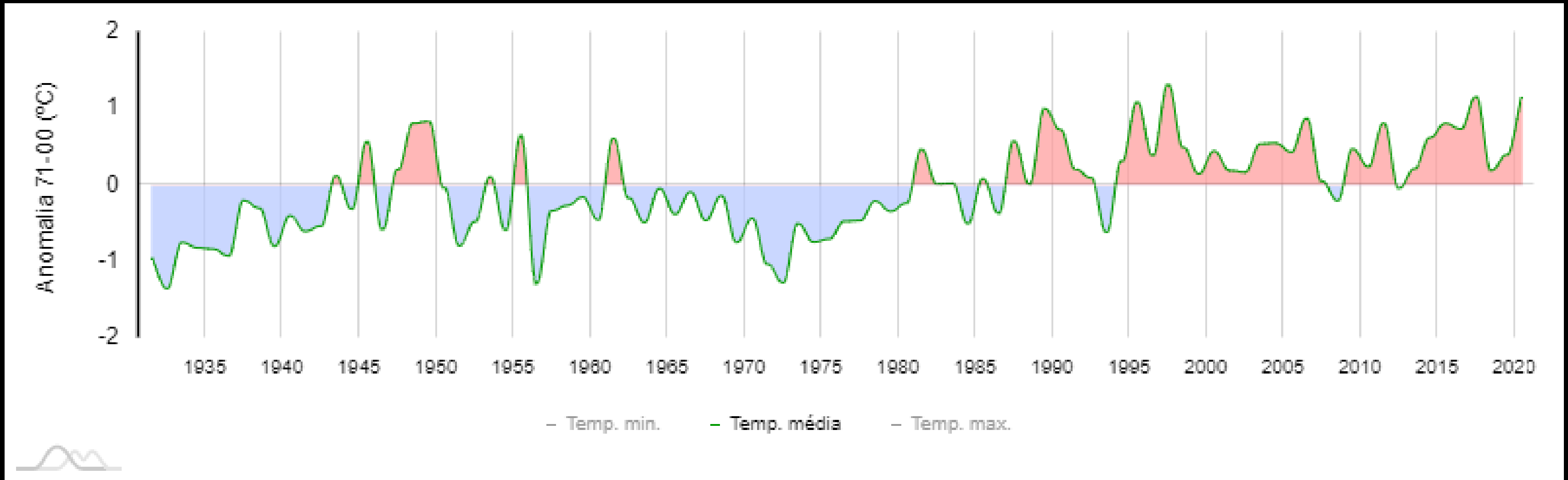



**Fig. 3** Spatial map of the median of the differences between the historical and 2046–2065 (left panels) and 2081–2100 (right panels) for the daily mean (top panels), maximum (center panels) and minimum (bottom panels) temperature. Stippling indicates areas with uncertainty in the differences

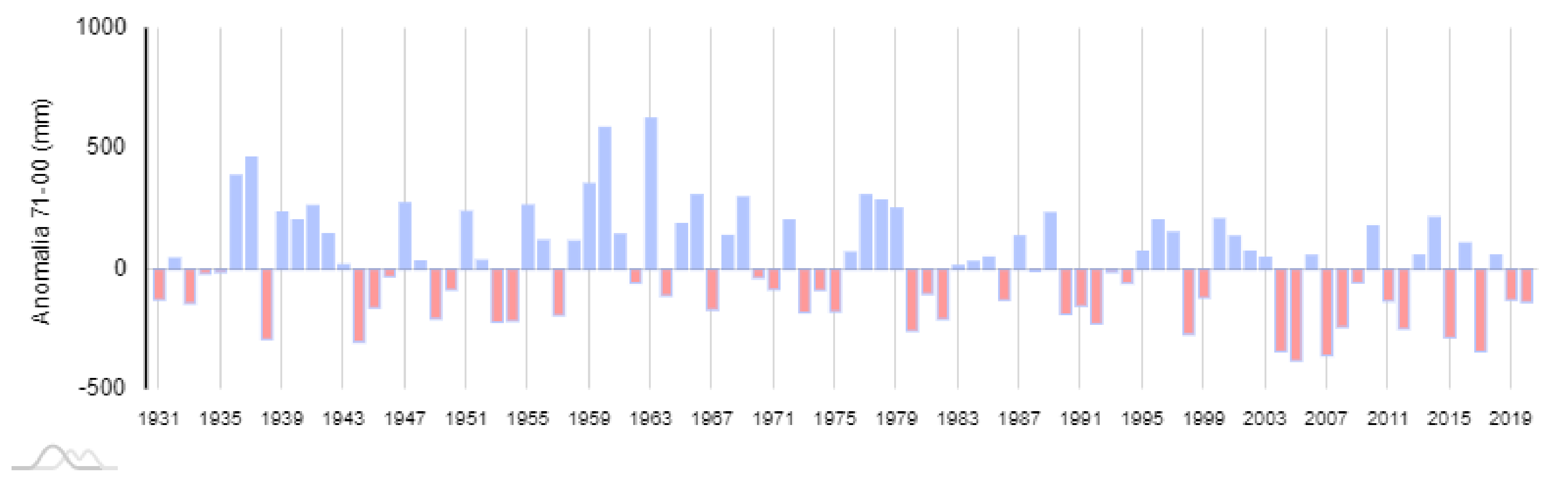
Carvalho, D., Cardoso Pereira, S., & Rocha, A. (2021). Future surface temperature changes for the Iberian Peninsula according to EURO-CORDEX climate projections. *Climate Dynamics*, 56(1), 123-138.

# Climate change and fire

**Temperature anomaly mainland Portugal, 1971-2000 baseline**

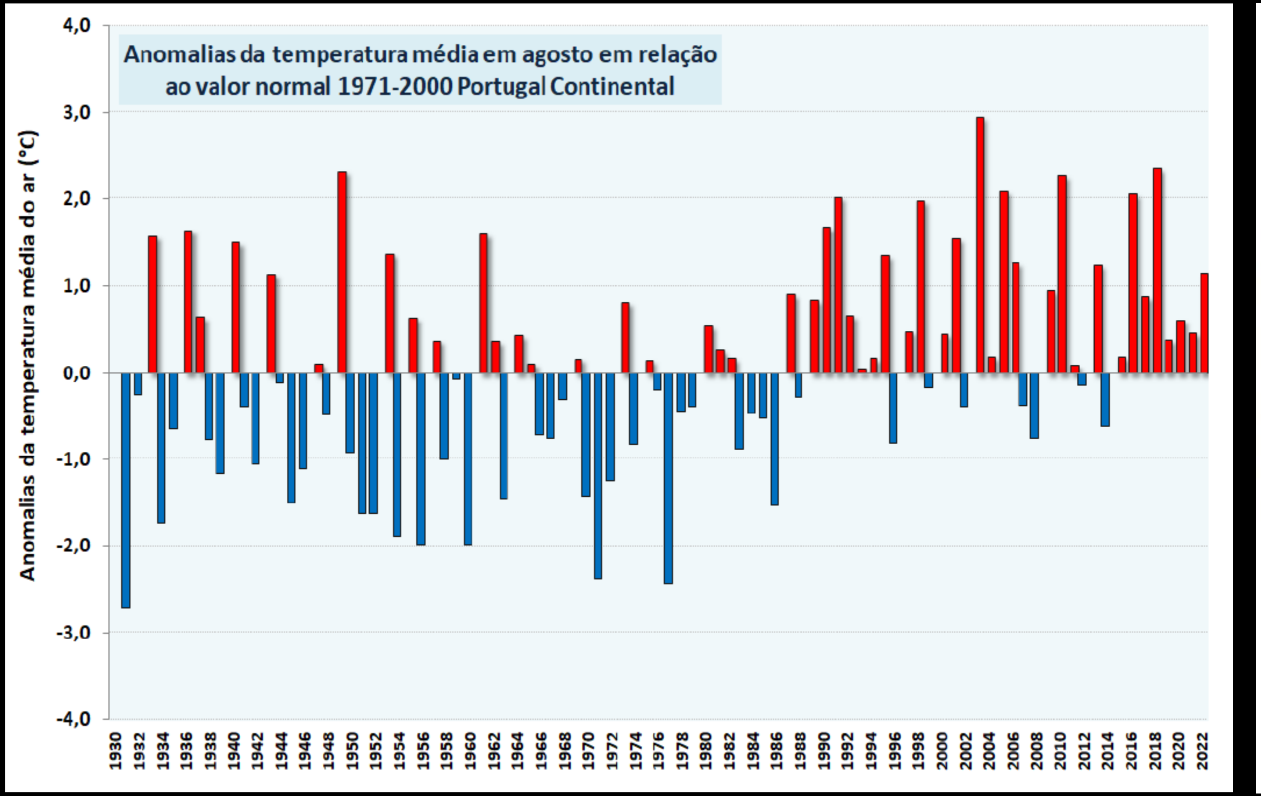



**Precipitation anomaly mainland Portugal, 1971-2000 baseline**

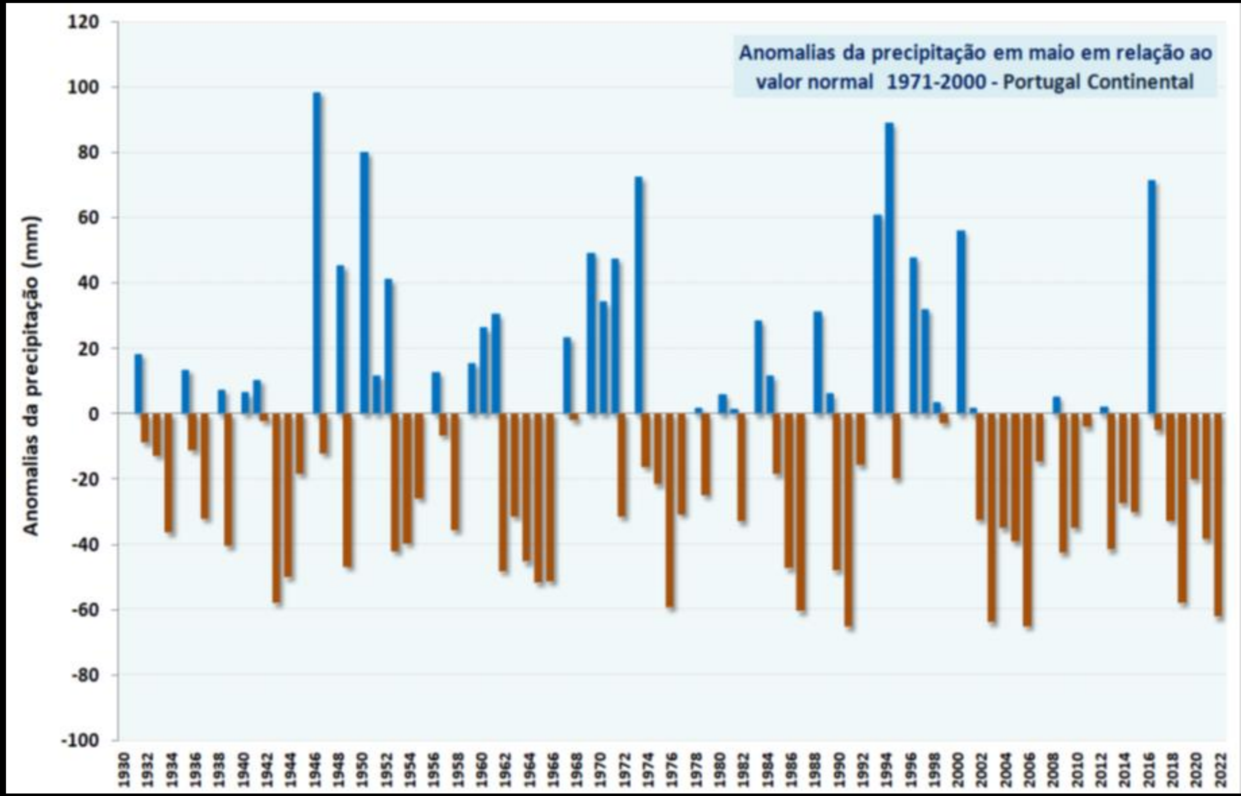



https://www.ipma.pt/pt/oclima/series.longas/?loc=Continente&type=raw

# Climate change and fire



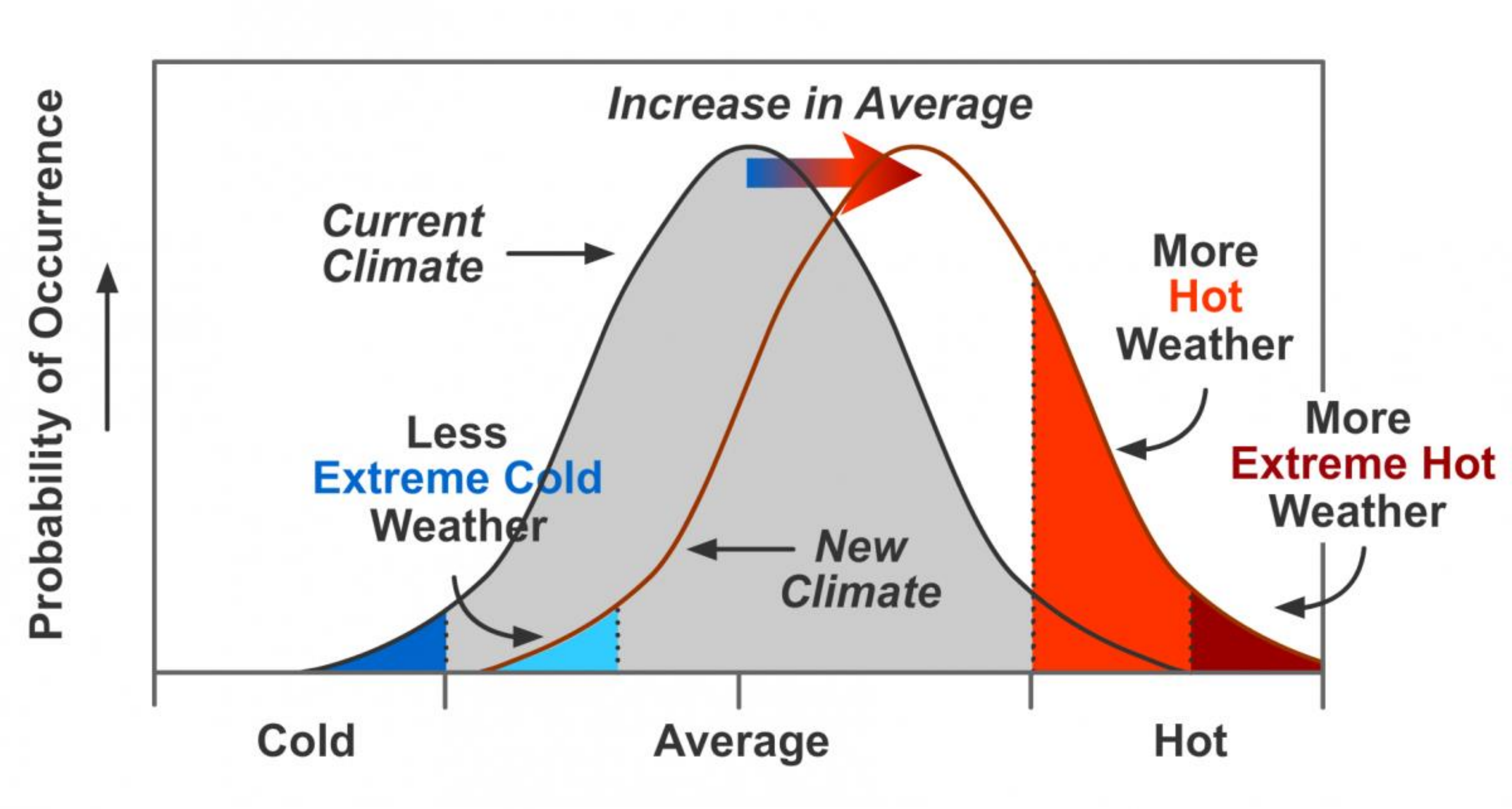

Mean montlhy ***air temperature anomalies*** for the month of ***August*** in mainland Portugal, relatively to the mean values in the period 1971-2000.

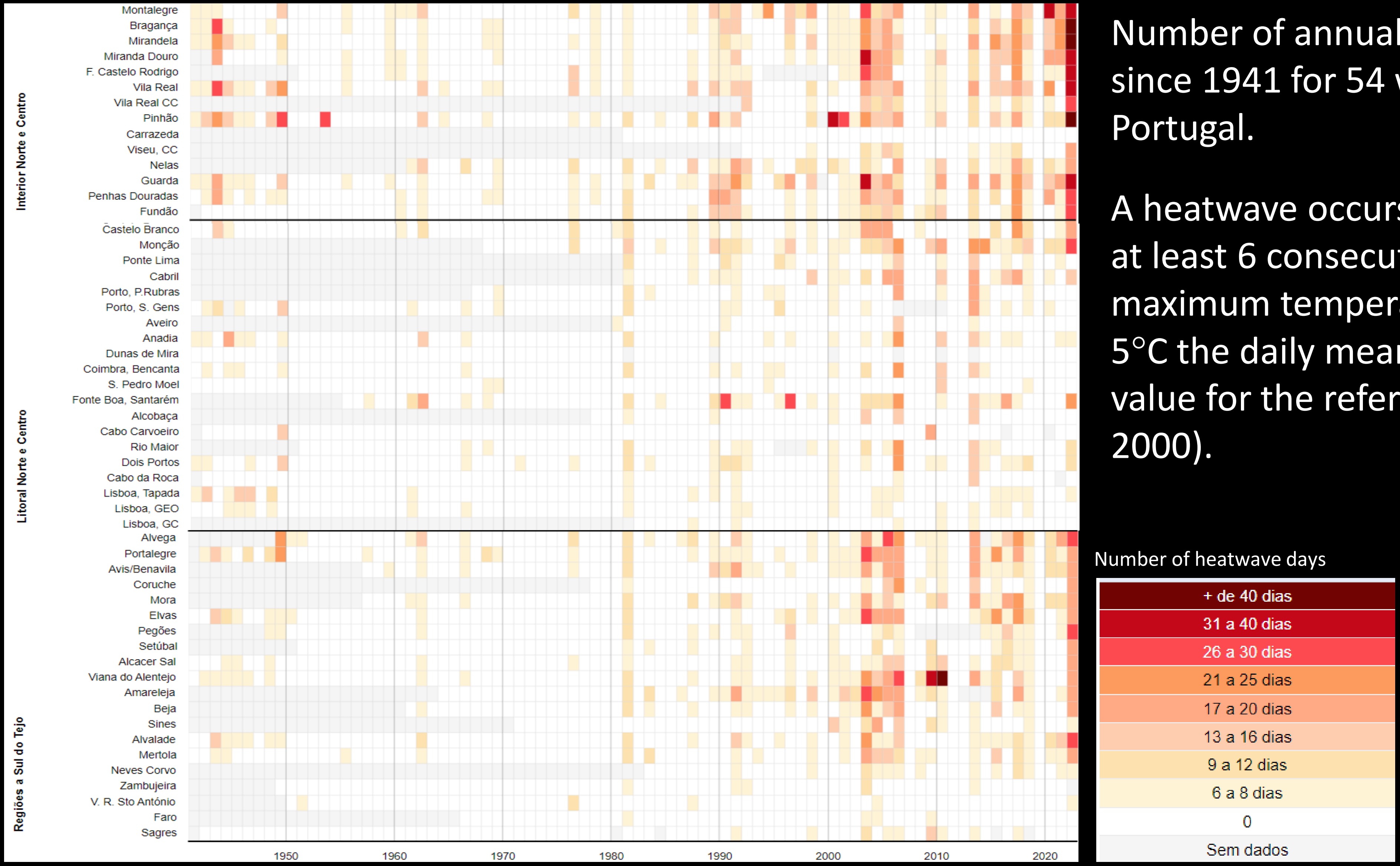



***Precipitation anomalies*** for the month of ***May*** in mainland Portugal, relatively to the mean values over the period 1971-2000.

Boletins climáticos do IPMA, Maio e Agosto 2022

# Climate change and fire



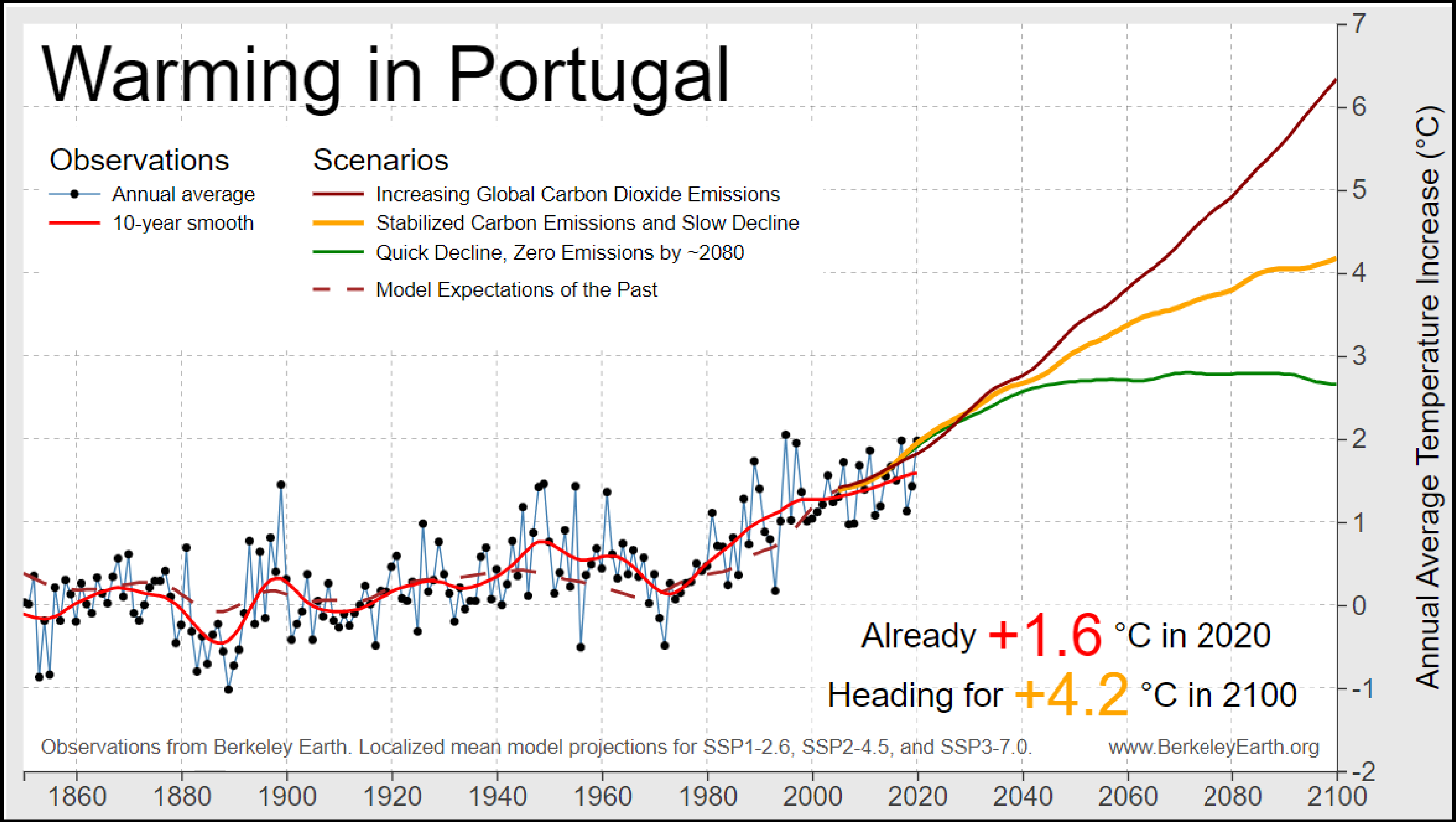



Number of annual summer heatwave days since 1941 for 54 weather stations in Portugal.

A heatwave occurs when over an interval of at least 6 consecutive days, the daily maximum temperature exceeds by at least 5°C the daily mean maximum temperature value for the reference period (1970 – 2000).

https://www.ipma.pt/pt/oclima/ondascalor/

# Climate change and fire




https://berkeleyearth.org/policy-insights/#