# Mapping combined wildfire and heat stress hazards to improve evidence-based decision making

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# Mapping combined wildfire and heat stress hazards to improve evidence-based decision making

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## ARTICLE INFO

## ABSTRACT

Heat stress and forest fires are often considered highly correlated hazards as extreme temperatures play a key role in both occurrences. This commonality can influence how civil protection and local responders deploy resources on the ground and could lead to an underestimation of potential impacts, as people could be less resilient when exposed to multiple hazards. In this work, we provide a simple methodology to identify areas prone to concurrent hazards, exemplified with, but not limited to, heat stress and fire danger. We use the combined heat and forest fire event that affected Europe in June 2017 to demonstrate that the methodology can be used for analysing past events as well as making predictions, by using reanalysis and medium-range weather forecasts, respectively. We present new spatial layers that map the combined danger and make suggestions on how these could be used in the context of a Multi-Hazard Early Warning System. These products could be particularly valuable in disaster risk reduction and emergency response management, particularly for civil protection, humanitarian agencies and other first responders whose role is to identify priorities during pre-interventions and emergencies.

## 1. Introduction

The frequency and length of high-temperature driven hazards such as wildfires and heat stress is likely to worsen under a changing climate (Running, 2006; Westerling et al., 2006; Diffenbaugh et al., 2007; Forzieri et al., 2016; Kurnik et al., 2017). According to the EM-DAT International Disaster Database (https://www.emdat.be/), between 1966 and 2017 approximately 167 major fires and heat events occurred in Europe, causing about 140,000 deaths. In 2017 alone, the 6 largest wildfire events spanning Spain, Portugal, Croatia and Montenegro resulted in 732 Million USD in total damages (data from EM-DAT). The summer period of 2017 also witnessed two major heat-related events, one in June and one in August, which led to unprecedented high temperatures across Europe (Di Giuseppe et al., 2017; Sánchez-Benítez et al., 2018). An increase in mortality was correspondingly observed by national health services in Belgium, France, Italy and Spain (Gil Bellosta et al., 2017; Ministero della Salute, 2017; Bustos Sierra and Asikainen, 2018; Beaudeau et al., 2018).

Extremely high temperatures are the common denominator for both heat stress and wildfires. According to Gill and Malamud (2014), the occurrence of a heat event, i.e. a heatwave, can trigger dangerous fire weather conditions. In turn, the emissions from wildfires can exacerbate the effects of heat stress on human body, especially on the cardiovascular and respiratory systems (Finlay et al., 2012). Although there is a wealth of research on mapping and analysing wildfires and heat events individually, the analysis of their simultaneous occurrences is relatively less explored. This is because the analysis and visualisation of multiple-hazards is considered a rather challenging task (Kappes et al., 2012). Relevant contributions include: monitoring wildfires during major heatwaves (Bondur, 2011; Gouveia et al., 2016), combined assessment of multi-hazard indicators under climate change scenarios (Lung et al., 2013; Forzieri et al., 2016), quantification of emissions and the combined long-term effects of wildfires and heatwaves on mortality (Tressol et al., 2008; Shaposhnikov et al., 2015), and assessment of weather driven disasters in the context of protection for the environment and citizens (Lavalle et al., 2006).

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In this work, as we contribute to the goal to develop a European Multi Hazard - Early Warning System (MH-EWS) platform, we focus on the last aspect, specifically on enhancing emergency management and response to extreme weather and climate events. Marzocchi et al. (2009) state that the "assumption of independence of the risk sources leads to neglect possible interactions […] a potential 'multi-risk' index could be higher than the simple aggregation of single risk indexes". In this context, analysing the historical occurrence of multiple hazards and applying that knowledge to future scenarios is paramount because the simultaneous occurrence of multiple hazards can potentially lead to substantial impacts, as the impacts of one hazardous event are often exacerbated by interaction with another (Marzocchi et al., 2009).

Here we propose a general framework to locate and predict the simultaneous occurrence of two high-temperature driven hazards: wildfires and heat stress. This type of information could be used within an operational MH-EWS as a reference layer to provide timely information with which decision makers could allocate resources and prioritise interventions. The framework is general and can be expanded to include other natural hazards.

## 2. Data and methods

First responders, emergency managers, decision makers and other stakeholders could make use of a MH-EWS by simply browsing individual hazard layers and extrapolating the consequences of concurring hazards on the basis of their experience and expertise. However, forecasters and forecast users are keen for innovation in the visualisation of information that can concisely and quickly highlight the possibility of upcoming natural hazards (Pappenberger et al., 2018), and this is particularly important for concurrent hazards. Here we propose four information layers for MH-EWS users: (1) maps of climatological thresholds for single hazards, (2) maps of hotspots for concurrent hazards, (3) maps of related probability of occurrence of future events and (4) a monthly summary of forecasted combined danger. In order to produce these information layers, we make use of a pan-European reanalysis database and medium-range (3–15 days) forecasts of heat stress and wildfire danger indices available from the European Centre for Medium-range Weather Forecasts (ECMWF). Below is a description of the hazard indices and datasets considered in the study, as well as a brief explanation of the three steps followed in the modelling workflow: (i) the calculation of daily climatology to define warning levels; (ii) the mapping of multi-hazard hotspots for past and future dates using reanalysis and high resolution medium range forecasts, respectively; and (iii) the mapping of the probability of occurrence of future simultaneous hazards using ensemble medium-range forecasts. The workflow is also illustrated in the infographics in Fig. 1.

### 2.1. Weather forcings

The models calculating fire danger and heat stress are driven by atmospheric forcings. Two types of forcings are used: a historical database, the ECMWF Re-Analysis (ERA-Interim, Dee et al., 2011) and the medium-range forecasts both generated by the Integrated Forecasting System (IFS) and produced by ECMWF. A reanalysis dataset is generated using a data assimilation scheme and a physical model that ingests quality controlled observations and produces a dynamically consistent estimate of the state of the atmosphere. ERA-Interim has a spatial resolution of approximately 80 km and a temporal extent from 1979 to the present day. In addition to this dataset, ECMWF provides weather forecasts using different configurations of its dynamical model, amongst which are: the high resolution configuration (also called HRES or deterministic forecast), a single run with a horizontal resolution of ~9 km and 10 days time horizon; and the ensemble configuration (called ENS or probabilistic forecast) comprising 51 realizations of the same forecast from slightly perturbed initial conditions and different model configurations. The spread in the ENS forecasts provides
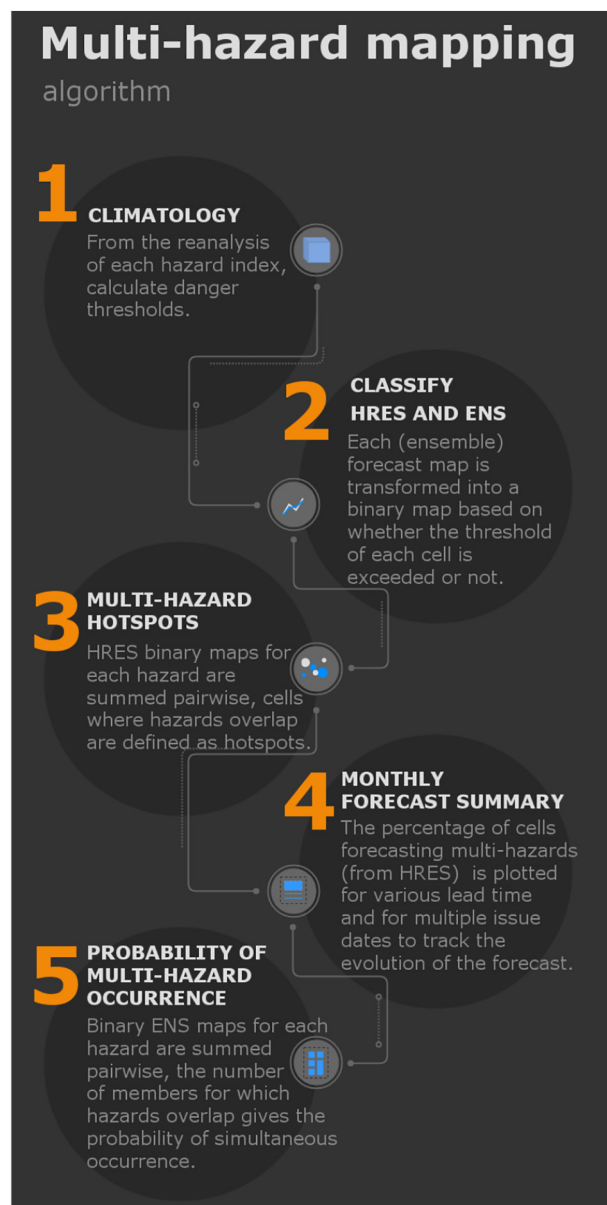


**Fig. 1.** Workflow illustrating the algorithm for multi-hazard mapping. Image made using https://www.draw.io/.

information about the accuracy and confidence of the forecast as similar outcomes are regarded as a proof of enhanced predictability for a given field. ECMWF ENS forecast has a spatial resolution of ~18 km and 15 days horizon.

### 2.2. Wildfire danger

Wildfires are natural phenomena and are controlled by fuel availability, weather and ignition agents. As ignition is a highly unpredictable factor, fire Early Warning Systems are based on the estimation of fire danger rather than on potential ignition. Most fire authorities in Europe rely on weather measurements from meteorological observations at point locations, which are then extrapolated to the surrounding areas. Examples of fire danger rating systems are the US Forest Service National Fire Danger Rating System (Deeming et al., 1977), the Canadian forest service Fire Weather Index (Van Wagner, 1974, 1987; De Groot, 1998) and the Australian McArthur rating systems (McArthur, 1966). All these systems provide estimates of fire danger in terms of indices that measure fire behavior, energy release

and rate of spread if a fire were to start (San-Miguel-Ayanz et al., 2003a).

The Fire Weather Index (FWI), is a simple model that provides good performance worldwide and has become the backbone model of the European Forest Fire Information System (EFFIS, http://effis.jrc.ec.europa.eu/) and the Global Wildfire Information System (GWIS, http://gwis.jrc.ec.europa.eu/), respectively the European and Global platforms for fire danger information in the framework of the Copernicus program (Di Giuseppe et al., 2016). The FWI is used here as a metric to quantify fire danger at the European scale. The system contains three soil moisture codes which represent fuel beds of different consistency and depths. They are therefore characterised by different time lag responses to the atmospheric forcings. From these codes, the model calculates the expected rate of spread immediately after ignition and a build-up component related to the fuel availability for combustion. The FWI combines the rate of spread and fuel availability to provide a generic numeric rating of potential fire intensity. The higher the numerical value, the more uncontrollable the fire is expected to be.

Forestry agencies usually estimate daily FWI from observations, therefore with uneven spatial coverage. Under the umbrella of Copernicus Emergency Management Services, ECMWF produces a historical dataset of FWI values using the atmospheric reanalysis dataset as forcings (Vitolo et al., 2019) with an even spatial coverage at global scale. In this dataset, FWI varies in the range [0, +inf[. However, in practical applications such as EFFIS and GWIS, values are usually binned into danger classes (e.g. very low, low, moderate, high, very high and extreme). These classes can be estimated on the basis of the local distribution of historical quantiles (Vitolo et al., 2017, 2018). ECMWF also provides daily forecasts of FWI using both the high resolution (HRES) and ensemble (ENS) configurations of the Integrated Forecasting System (Di Giuseppe et al., 2016, under review). The reader should note that the current FWI ensembles have shorter time horizon compared to the IFS ENS: 10 rather than 15 days.

## 2.3. Heat stress

Heat stress is the physiological heat load enforced by the outdoor environment on the human body which correspondingly reacts via different physiological responses, such as sweating, to maintain its core temperature within certain boundaries, even when the surrounding temperature is very different (McGregor and Vanos, 2018). A measure of heat stress is provided by the Universal Thermal Climate Index (UTCI), a bioclimate index that well reflects health hazards attributable to extreme high temperatures both at the European and global level (Pappenberger et al., 2015; Di Napoli et al., 2018; under review). The UTCI is defined as the isothermal temperature, expressed in degrees Celsius, of a reference condition that, following the human energy balance model, would elicit the same dynamic physiological response of the real condition (Jendritzky et al., 2012; Błażejczyk et al., 2013). Whereas other indices are based exclusively on meteorological parameters such as air temperature and humidity (e.g., humidex; Masterton and Richardson, 1979), the UTCI is based on a human energy balance model that considers heat and mass transfer within the body, thermoregulatory reactions of the central nervous system, perceptual responses and a temperature-adaptive clothing insulation for outdoor climates (Fiala et al., 2012). The UTCI is computed via a six-order polynomial equation in four environmental parameters (Bröde et al., 2012), namely 2 m air temperature, the mean radiant temperature (i.e., solar and thermal radiation), wind speed and humidity. While the UTCI is a continuous variable it is, like the FWI, categorised using the corresponding reanalysis database. ECMWF ENS and HRES forecasts of 2 m air temperature, humidity, radiation and wind speed are then used to calculate UTCI forecasts.

## 2.4. Daily climatology for warning levels

In this section we demonstrate how to define warning levels knowing the range of possible values for both the FWI and UTCI indices. There are two methodologies that are usually adopted to derive warning levels for the FWI: one is based on the number of events that occurred during fire seasons, and the other is based on the analysis of the probability distribution (i.e. using representative percentiles) of the historical record of the FWI values. In this work, we employ the latter method. Warning levels (or danger thresholds) are usually calculated as an average over large regions and/or at country level (Di Giuseppe et al., 2019). However, Vitolo et al. (2018) tested the same approach on European Nomenclature of Territorial Units for Statistics (NUTS) 1–2 levels and found that averaging fire danger over an area reduces the probability of detection of an event as the information on high danger levels is lost. Therefore, a better approach is to rely on statistics calculated cell-by-cell, even though this is more computationally demanding.

With regards to heat thresholds, Błażejczyk et al. (2013) suggested that the UTCI should be categorised in a ten thermal stress levels scale: extreme cold stress (UTCI < −40 °C); very strong cold stress (−40 °C ≤ UTCI < −27 °C); strong cold stress (−27 °C ≤ UTCI < −13 °C); moderate cold stress (−13 °C ≤ UTCI < 0 °C); slight cold stress (0 °C ≤ UTCI < 9 °C); no thermal stress (9 °C ≤ UTCI < 26 °C); moderate heat stress (26 °C ≤ UTCI < 32 °C); strong heat stress (32 °C ≤ UTCI < 38 °C); very strong heat stress (38 °C ≤ UTCI < 46 °C); and extreme heat stress (UTCI ≥ 46 °C). Each level corresponds to specific physiological responses from the human body. Although physiological responses are common across humans, populations across Europe have adapted to different heat stress levels, resulting in a variability in heat acclimatisation in both time and space. Southern Europe generally experiences higher heat stress than northern Europe, and summer thermal stress is usually higher in July/August than in June (Di Napoli et al., 2018). To take into consideration these aspects, in this work, the UTCI warning levels are not fixed levels but are defined, consistently with the FWI, using the probability distribution of reanalysis records.

For both hazards, a collection of maps of warning levels is generated, one for every day of the year and danger level. Every map corresponds to a predefined percentile and summarises the distribution of the values across the years. Although this procedure is more laborious and resource consuming than those adopted in previous studies, it provides a number of important advantages: it does not depend on the definition of the fire/heat stress season (often subjective and generally changing year on year) and the result is not smoothed because there is no spatial averaging. We generate the climatology of a given hazard index from historical reanalysis records over the period 1980–2016 extracting the following percentiles: 50th, 75th, 85th, 90th, 95th, 98th (corresponding to very low, low, moderate, high, very high and extreme danger, respectively). These percentiles are widely used to assess danger due to wildfire and heat stress in Europe (San-Miguel-Ayanz et al., 2003b; Di Napoli et al., 2019). We calculate these percentiles taking into account 333 days: the period that spans 4 days before and after a given date (total of 9 days) for the full record of 37 years. Values are evaluated cell-by-cell and provide thresholds of increasing danger. These thresholds are used as cut-off points to assess daily conditions from 2017 onwards.

The procedure can be applied to other hazard indices for which a long historical record is available. By *historical record* we mean either a reanalysis or a long record of in-situ observations, generating a gridded or point-based map respectively. In order to limit processing time, we only generated thresholds for the months that are most likely to be affected by fire and heat stress hazards in Europe: June, July and August (referred to as JJA season hereafter).

**Table 1**

Examples of media reports of heat and fire occurrences during June 2017 in Europe. Locations of fires in Italy are approximate as media only reported the region of interest. Locations of heat events are not explicitly mentioned, as the phenomenon invests large areas.

| Source | Statement | Dates and locations of interest (fires only) |
|---|---|---|
| El País (2017) | A warm air mass settled over the Iberian peninsula on Saturday, bringing unusually hot weather for this time of the year. [...] Six provinces – **Córdoba**, **Jaén**, **Seville**, **Toledo**, **Badajoz** and **Cáceres** – are on orange alert (signifying "important risk") for temperatures expected to top out at 41 °C. | 12 June 2017 |
| The Local (2017) | **Italy** sizzles in mid-June heatwave. | 13 June 2017 |
| Le Dauphine (2017) (in French) | Gros incendie à **Martigues**: 200 pompiers mobilisés. | 17 June 2017, Martigues (France) |
| ANSAmed (2017) | Three massive forest fires have been blazing since last Saturday on Croatia's Dalmatian Coast [...] The fires have been stoked by strong winds and have devoured acres of forest and coastal foliage around the tourist cities of **Podgora**, **Tucepi**, and **Makarska**. | 17 June 2017, Podgora - Tučepi - Makarska (Croatia) |
| BBC (2017) | Portugal fire [...] The week's highest temperatures in the area are expected to reach around 38 °C. [...] The government has declared a state of emergency in the **forested region around Pedrógao Grande**, north-east of the capital, Lisbon. | 17–18 June 2017, Castanheira de Pera - Pedrógão Grande (Portugal) |
| Phys.org (2017) | The Iberian peninsula encompassing **Portugal** and **Spain** is experiencing a warmer, drier June than usual. | |
| The Guardian (2017b) | **UK** heatwave brings hottest June day for 40 years.UK heatwave brings hottest June day for 40 years. | 21 June 2017 |
| CN24 (2017) (in Italian) | La protezione civile fa sapere che oggi sono state 16 le richieste di concorso aereo ricevute dal centro operativo aereo unificato del dipartimento per incendi boschivi: una dalla **Toscana**, un'altra dal **Lazio**, nove dalla **Sicilia** e due dalla **Calabria**. | 28 June 2017, Tuscany - Lazio - Sicily and Calabria) |
| El Mundo (2017) (in Spanish) | El incendio en la **Sierra Calderona** arrasa casi 1.000 hectáreas y avanza sin control. | 30 June 2017, Serra Calderona - Huelva (Spain) |
| The Guardian (2017a) | Spain forest fire forces > 1500 from homes and campsites. Emergency services fight to contain major blaze in **Huelva**, Andalucía, which has been on high alert due to heat wave. | |
| Greek Reporter (2017) | Large wildfires are raging in Attica and Messinia [...] With temperatures soaring to 43 degrees Celsius in parts of Greece, firefighters are battling the flames near **Krioneri**, north of Athens and **Koroni** in south Messinia. | 30 June 2017, Krioneri - Koroni (Greece) |

## 2.5. Maps of hotspots

Once a database of threshold maps is generated, we have a means of comparison and can assess on any given day whether a hazard index falls in a concerning range (e.g. above very high danger threshold). Then, the spatial overlap of multiple hazard maps can reveal areas of particular concern.

First responders, forecasters and other stakeholders might find it particularly useful to have access to an operational product that delivers a daily overview of where, in Europe, there is a chance of occurrence of one or multiple hazards. We call this daily overview a *map of hotspots*, to build upon work on mapping the observed occurrence of multiple weather driven disasters in the same location (Dilley et al., 2005).

A map of hotspots is generated by analysing the spatial overlap of the high resolution forecasts of multiple hazard indices and the relevant climatology on a given day. The methodology follows three steps:

1. Warning level maps, defined in the previous section, are resampled to match the resolution of the forecasts using the nearest neighbour technique.
2. Binary maps are generated, with 1 (resp. 2) in the cells where the fire (resp. heat) forecasted value is above a given threshold, and 0 otherwise. There will be a map for every hazard, danger threshold and day in the forecast horizon.
3. The binary maps of different hazards are summed pairwise. The result is a four-value encoded map (per danger threshold and day) in which cells are encoded as follows:
   ○ 0 = no hazard
   ○ 1 = only fire hazard
   ○ 2 = only heat stress hazard
   ○ 3 = fire and heat stress hazard

The same procedure can be employed to map hotspots during past dates, using daily reanalysis as input rather than high resolution forecasts. In this case, the computation is much faster as only 1 map is produced, per date of interest, and there is no need of resampling the layers as there is no change in the spatial resolution. In this work we focus on predicting hotspots and leave to future work the analysis of patterns of past co-occurrences.

## 2.6. Mapping probability of occurrence of simultaneous hazards

If a combined fire and heat stress hazard is detected in the previously described map of hotspots, it is important to inform decision makers of the confidence/uncertainty that accompanies this prediction, especially if this information is to be used for issuing alerts and warnings. The procedure described for the high resolution forecasts can be repeated for every member of the ensemble forecasts, generating a four-value encoded map per ensemble member, danger threshold and day in the forecast horizon. At each cell, the percentage of the ensemble members for which the fire and heat thresholds are both exceeded will return the probability of simultaneous occurrence of the two hazards. As ensemble members in the ECMWF forecasts can be treated as being equally likely, we can estimate the average statistics by comparing fire danger and heat stress forecasts deriving from the same weather realisation (fire danger forecast ensemble member 1 with heat stress forecast ensemble member 1, and so forth).

## 2.7. Monthly summary of forecasted simultaneous hazards

Local authorities may also benefit from visualisation tools to track the progress of forecasts over time and be able to compare today's information with what was forecasted over the past few days. In light of these needs, we have designed a 1-month forecast summary, in which successive forecasts are plotted one on top of the other to help contextualize the current forecast and gain an appreciation of how these complex dynamics evolve over time. The plot can be generated for different types of information and be used to track the persistency and/ or the fluctuation of a signal over time. For instance, when visualising a single danger index, such as fire danger, the plot can be used to identify the start/end of the fire season. In the results section we will show how to use this plot to track the expansion of the area characterised by very high combined danger, according to the forecasted maps of hotspots.
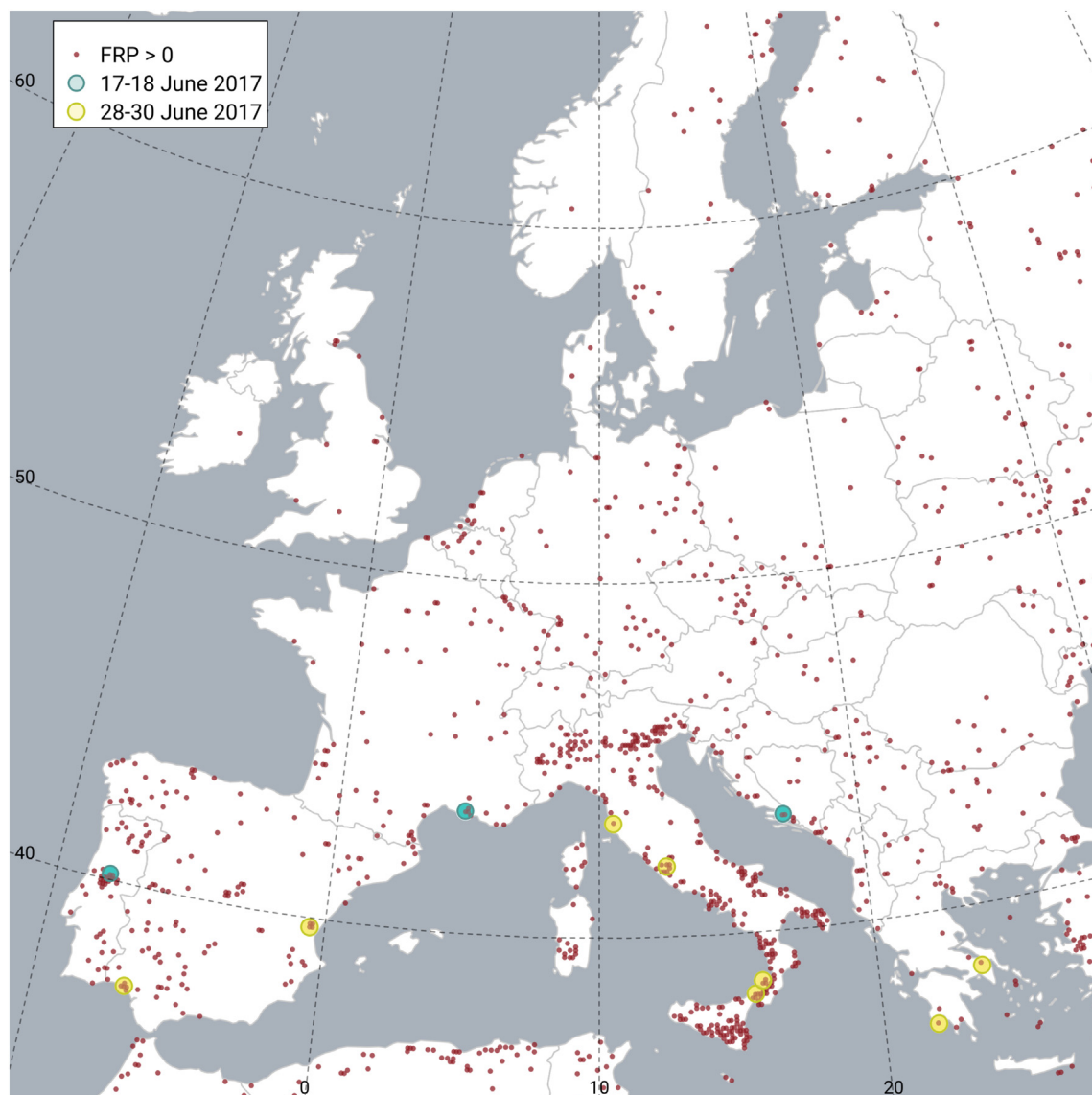
**Fig. 2.** The red dots show the location of Fire Radiative Power detected by satellites during June 2017. The major fire outbreaks reported by media on 17–18 June 2017 are highlighted by blue circles, while the ones occurred on 28–30 June by yellow circles (see also Table 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 3. Results

In order to illustrate the results of the above methodology, we analyse the summer 2017 in relation to its climatological values at the European scale. As points of reference, we will use the locations mentioned by media articles reporting outbreaks of extreme heat and wildfires during June (see Table 1 and Fig. 2). We use media reports to distinguish major fire outbreaks (blue and yellow circles in Fig. 2) from the numerous sources of Fire Radiative Power (FRP, generated using CAMS-GFAS (2019) information, red dots in Fig. 2) detected by satellites. The two major fires in Portugal were also checked against the Copernicus Emergency Management Service activation points (Copernicus EMS, 2017a, 2017b).

### 3.1. Wildfire and heat stress climatology

Fig. 3 shows the average FWI (top row) and UTCI (bottom row) very high danger values (95th percentile) for the months of June (left column), July (centre column) and August (right column). The climatology of wildfire and heat stress danger have different spatial distributions. The UTCI thresholds span the range [9, 44]°C and are more homogeneously distributed over Europe than FWI thresholds. FWI's spatial distribution presents a more pronounced difference between Mediterranean countries, central Europe and Nordic countries with values spanning a much larger range [2, 96]. This shows that, while moderate or stronger heat stress (UTCI > 26 °C) is above human acclimatisation capability for most of the European population, the interpretation of fire ratings varies greatly in space. For example, an FWI of 30 can signal very unusual fire weather in Scandinavia, while representing the norm in Mediterranean countries.

Climatological maps are very powerful tools that allow the re-classification of danger indices based on past decades of weather observations, on a cell-by-cell basis. Binning the data into categories defined by the historical percentiles allows expected biases in the reanalysis and forecasts to be accounted for. It is, in fact, when danger indices are reclassified that clearer patterns are revealed and multiple hazards can be compared.
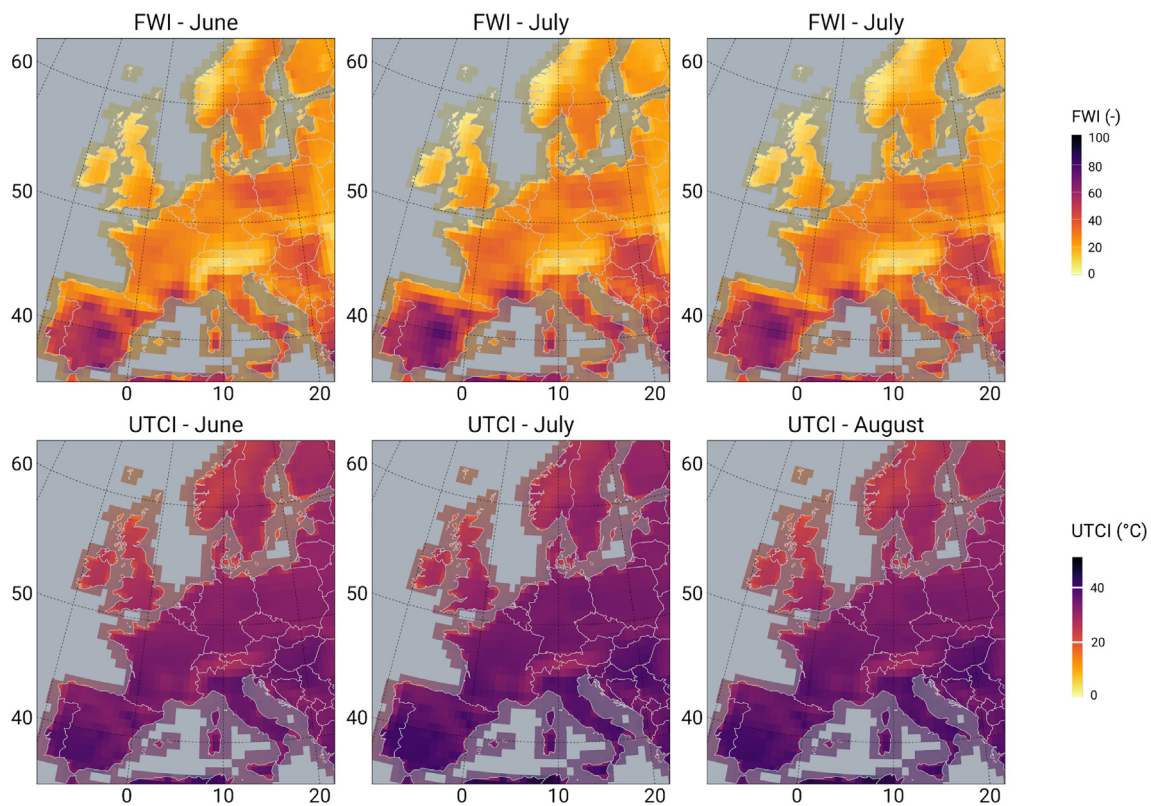
**Fig. 3.** Spatial distribution of FWI (top row) and UTCI (bottom row) very high danger thresholds (above the 95th percentile), based on the climatology (1980–2016). The maps on the left show the averages over June, while July averages are shown in the center and August averages on the right.

### 3.2. A case study: June 2017 in Europe

Fig. 4 shows the reclassified reanalysis layers corresponding to 17th June 2017, the day in which the major fire event in Pedrógão Grande, Portugal was ignited. On that day, high to extreme fire weather and heat stress were observed in various locations in Europe, e.g. Spain (El Mundo, 2017; The Guardian (2017b)), Portugal (BBC, 2017), France (Le Dauphine, 2017), Italy (CN24, 2017). A heatwave combined with numerous wildfires spreading across Europe caused evacuation of thousands of people (Copernicus EMS, 2017a, 2017b). The reanalysis of UTCI shows that the entire Portugal was under extreme heat stress, without clear spatial variation of danger. Fire danger, instead, was higher in the north and south of the country. In this particular case, combining the two danger maps means borrowing the spatial gradient of fire danger and applying it to both hazards, which would allow more targeted preparedness actions and prioritisation of interventions.

Fig. 5 shows what the map of forecasted hotspots would have looked like for 17th June 2017, taking 'very high danger' as the hazard level of reference for both indices. Numerous areas appear under combined danger: Spain, Portugal and France (1–3 days horizon), then moving also to Italy, Greece and the Balkans. The spatial distribution of the events is confirmed by the FRP detected from satellites as well as by news articles (Table 1). Some of the information in Fig. 5 could be considered a little surprising because it shows that wildfires and heat stress are not very spatially and temporally correlated for this case. Unusually high temperatures are certainly the common denominator but, the (high) relative humidity is likely to also have an important role in mitigating wildfire danger and exacerbating heat stress. Conversely, low relative humidity, drying out vegetation, can increase wildfire risk but mitigate heat stress. The key to predict combined danger is, therefore, being able to detect dangerous trade-offs in time and space.

The probability of occurrence of both hazards is explored by re-classifying and combining all the ensemble members of the probabilistic forecasts, as we have done for the single member of the deterministic forecasts. The percentage of the members reporting combined hazard is a measure of the confidence in the multi-hazard forecasts. Fig. 6 shows the 10-day ensemble forecasts for the combined danger that could have been issued on 17th June 2017. The highest probability of occurrence of both hazards was expected to move from West Europe (Spain, Portugal) to Central-East Europe (France, Italy, Greece, Croatia) which accurately reflects what was subsequently reported by the Copernicus Emergency Management Service (2017a, 2017b) and media (Table 1). With regard to the Iberian peninsula, where numerous media reported extreme heat (BBC, 2017; El País, 2017; Phys.org, 2017), Fig. 7 shows the areas affected by the Pedrógão Grande/Castanheira de Pera (Portugal) fires had a forecasted probability of occurrence between 6% and 40%. In Spain, instead, the probability raises to approximately 50% in Huelva and 74% in Serra Calderona.

Lastly, we use the monthly summary plot, in Fig. 8, to track the expansion of areas characterised by very high combined danger during June 2017 in Portugal. On the x-axis is the forecasted day and on the y-axis the issuing date of each forecast. Cells are color-coded based on the percentage of total area classified as hotspot. The bottom-left cell corresponds to the first day of the forecast issued on 1st June 2017. The forecasts for day 2 to day 10 are on the same row. The forecasts issued on the following day are one row above and so forth. The purpose of this plot is two-fold: on the one hand it provides an immediate estimate of the area under very high danger conditions and, on the other hand, it shows how the extent of this area evolves over time. The area of interest can be as small as a single pixel in the high resolution forecast or as large as a province/region/country. However, as the total area increases, the plot on its own becomes less informative because it does not provide the spatial distribution of the area at risk. When assessing large areas, therefore, the plot should be used in conjunction with maps of hotspots.
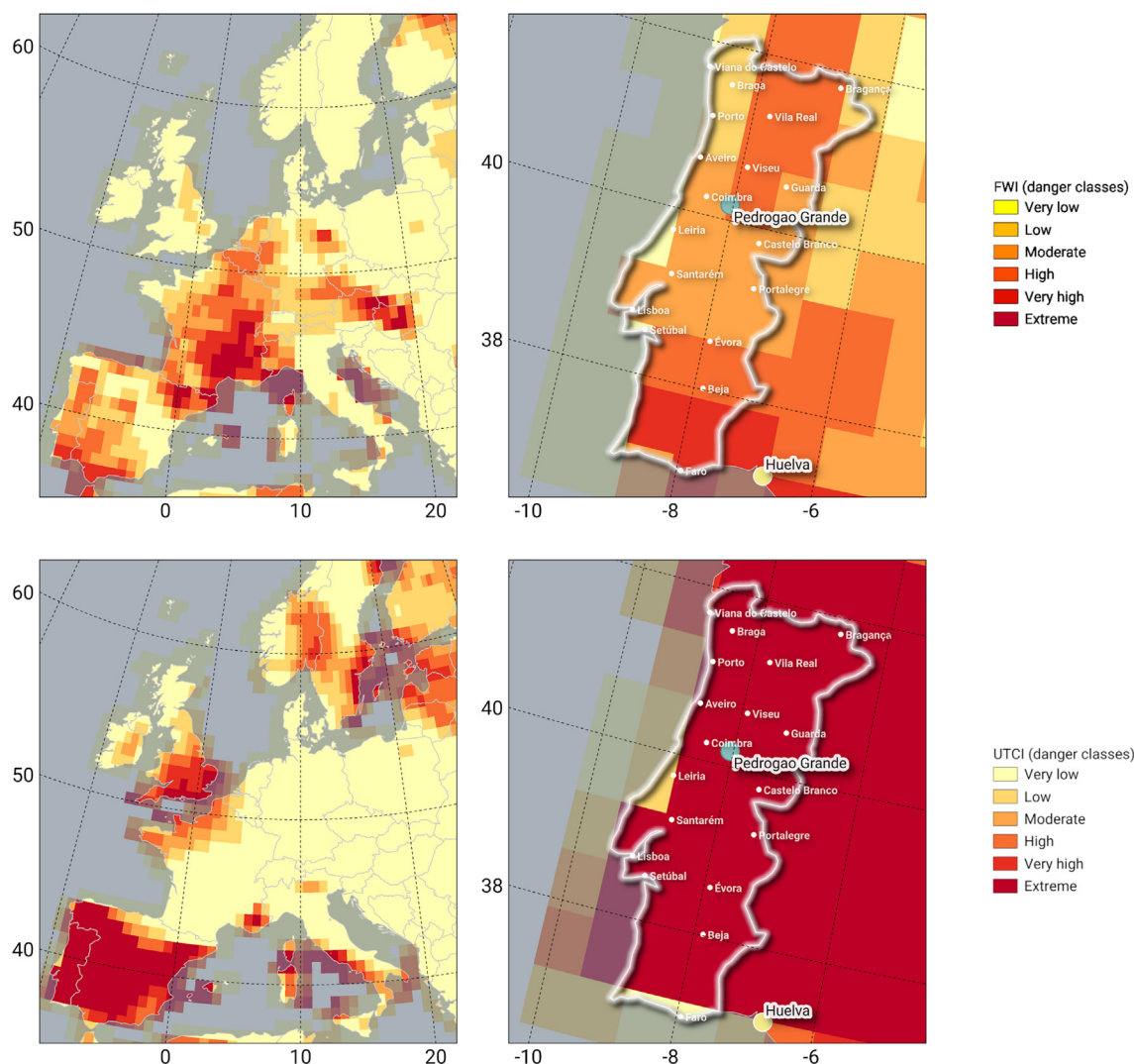
**Fig. 4.** Average FWI (top row) and UTCI (bottom row) in Europe (left) and Portugal (right) on 17th June 2017 from reanalysis, classified based on the climatology (1980–2016). The UTCI map shows no spatial variability of heat stress danger, while fire danger is higher in the north and south of the country. The blue dot in the right panels show the location of Pedrógão Grande fire, at the edge of the high fire danger area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Forecasts issued on 7th June started showing that > 50% of the country would have been affected by very high combined danger starting from 16th June. This information would have warned authorities 10 days before the major fire event in Pedrógão Grande, and give them time for pre-emergency planning and allocation of resources. In the future, collaborations with first responders and decision makers could clarify how these new layers could be best used operationally. Ideally, such a collaboration could lead to the co-production of forecasting and early warning products. This can be achieved by creating a collaborative eco-system in which all parties interested in designing new data products will build, test and deploy them through sequential iterations and regular feedbacks.

### 3.3. Uncertainty and robustness

Assessing the uncertainty and robustness of the newly generated combined danger maps is particularly complex because they are forecasted maps of hazard. The quantification of the risk to the population and environment would require information on exposure and vulnerability. This means any actual occurrence of fire requires the appropriate conditions (expressed by the fire danger index), an ignition source as well as populated areas, presence of fuel, lack of access to

transport/means of self-evacuation, no insurance, amongst others. Heat stress is conditional to people being outdoors or not using air conditioning systems indoors as well as the environmental conditions expressed by the index. Nevertheless, uncertainty for a past event can be assessed in terms of spatial accuracy of hotspot location and temporal span in which a dangerous signal can be predicted.

A preliminary assessment of the utility of these new layers was made in collaboration with various stakeholders (see Table 2 for the full list), amongst them is the Instituto Português do Mar e da Atmosfera (IPMA) who collaborated with decision makers in the 2017 event in Pedrógão Grande. Positive feedback was recorded, with the Portuguese Institute stating: "we liked the new layers, they identify well areas at risk, [...] they would have been useful during the event" [IPMA, Lourdes Bugalho, personal communication]. This statement highlights the importance, for stakeholder, to correctly identify hotspots of danger. It is also important that forecasts provide enough notice to allow preparedness and, in case of emergency, efficient allocation of resources.

In January 2019, a workshop for the ARISTOTLE-2 project (http://aristotle.ingv.it/tiki-index.php) was held at ECMWF headquarters and focused on delivering effective "consensus advice" to the Emergency Response Coordination Centre in Europe. One of the main feedbacks
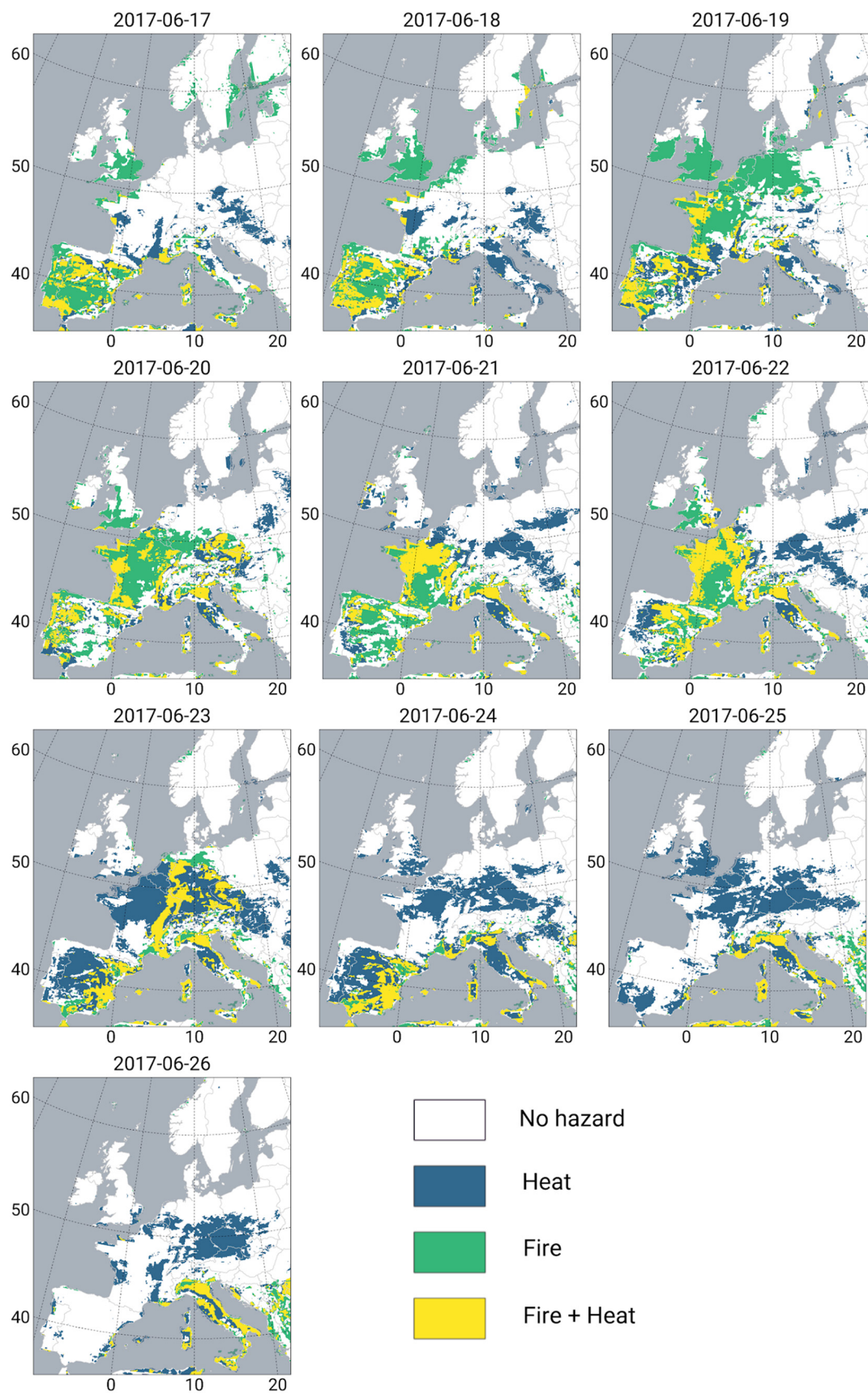
**Fig. 5.** Multi-hazards hotspots forecast maps at pan-European scale. The maps are generated on 17th June 2017 and with a 10-day horizon.
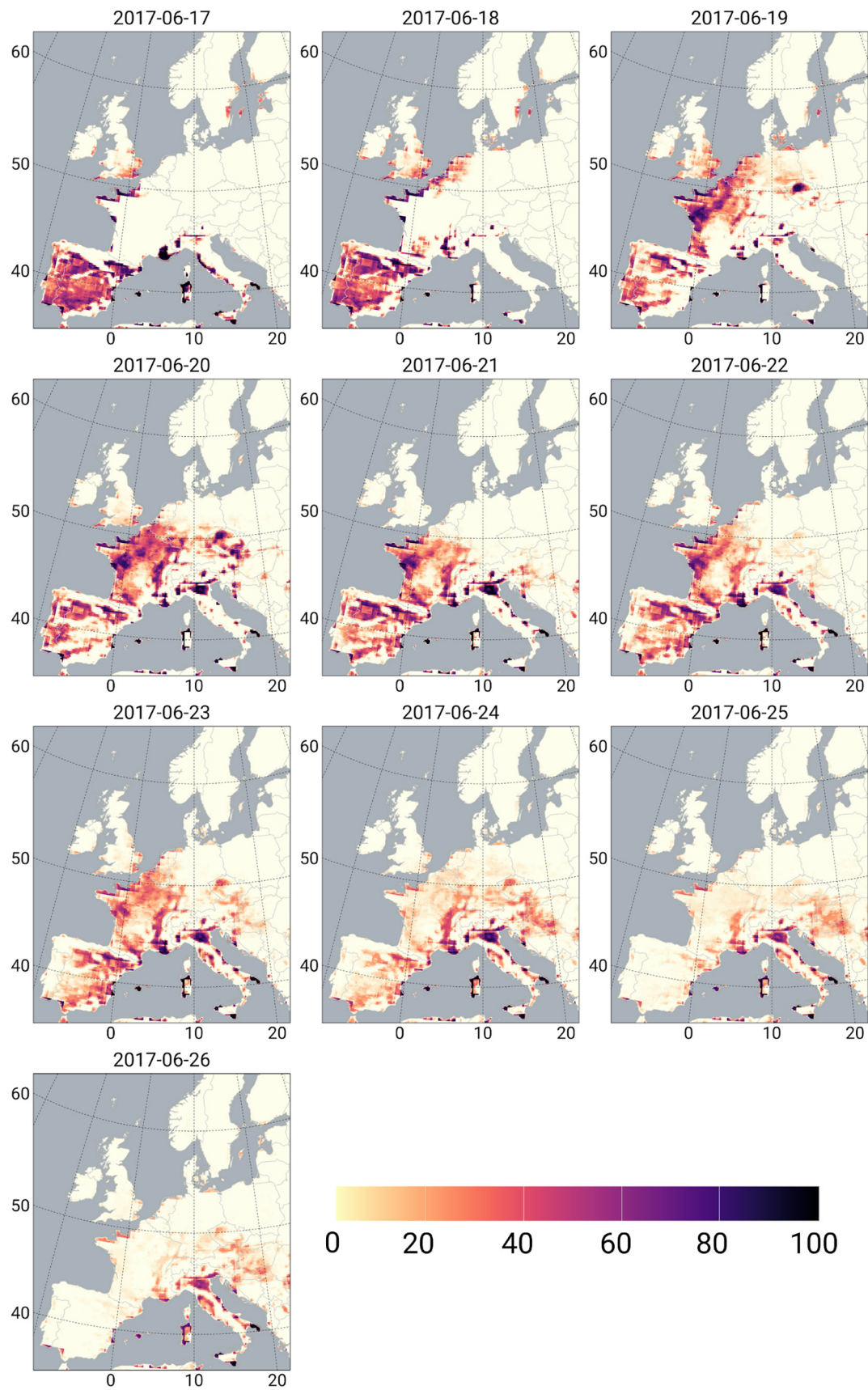
**Fig. 6.** Map of probability of occurrence of very high multi-hazard danger at the pan-European scale. The maps are generated on17th June 2017 with a 10-day horizon.
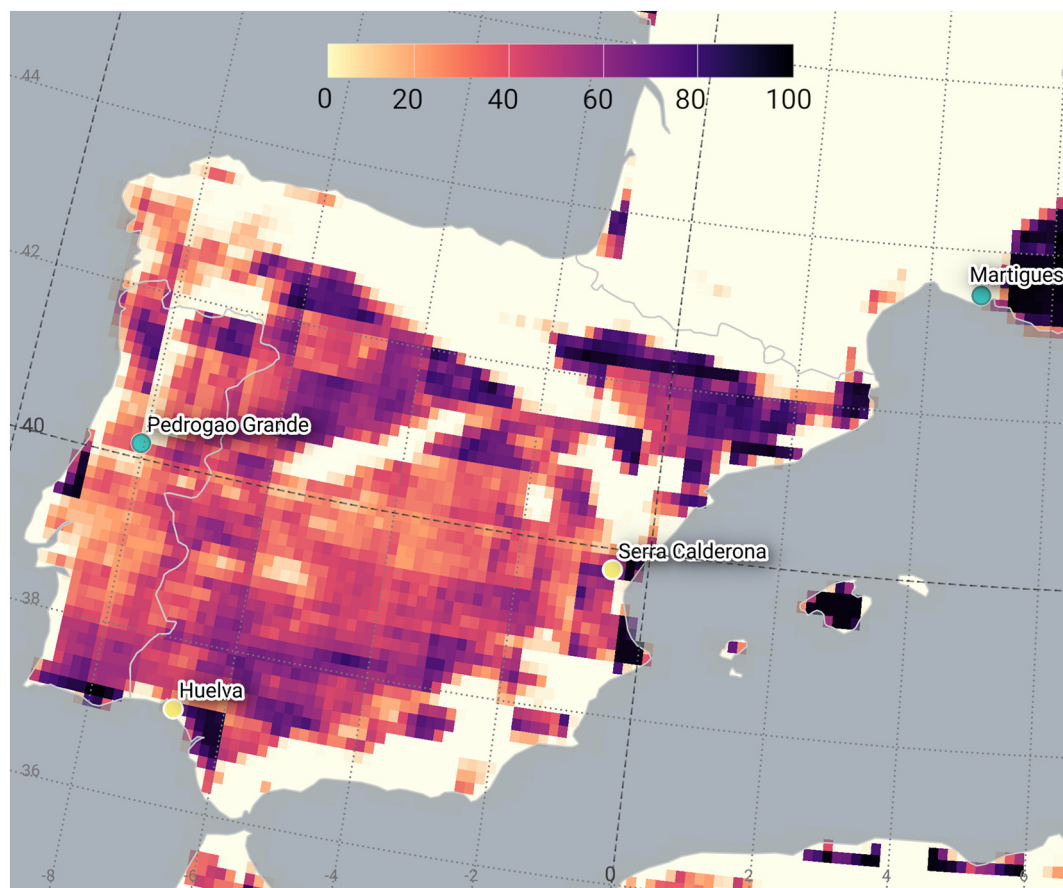
**Fig. 7.** Map of probability of occurrence of very high multi-hazard danger over the Iberian peninsula, generated on 17th June 2017.

from the workshop was about the timing of the issued forecasts. Fire emergency responders from IPMA and CIMA Research Foundation agreed they would benefit from reliable forecasts 3 days ahead but 5-day notice would be ideal (see list of feedbacks in Table 2, extract from the minutes of the workshop). These feedbacks are important to set baseline product expectations that will be discussed in the next section.

It must be noted that, in the previous section, maps are generated assuming that a significant combined hazard occurs where/when both indices exceed the very high danger threshold. This is, however, a simplification due to the need to generate static maps for this publication. In the context of a MH-EWS, an interactive map would be, by far, more suitable. A basic example of web application using interactive maps was developed for testing purposes and made publicly available at the following URL: http://rpubs.com/clavitolo/fire_heat (see also screenshot in Fig. 9). This application was particularly useful when requesting IPMA's feedback as officers were able to zoom into particular regions and check against their event records.

Ideally, a MH-EWS platform is envisaged to provide user-controlled tools, like radio buttons and sliders, for the interactive maps to allow users to switch between and explore different hazard combinations and days in the forecast horizon. Another option would be to generate animations of all the possible combinations so that users have an overview of the sensitivity of the tool to the tuning of the combined hazard thresholds.

## 4. Discussion

Wildfires and heat stress are commonly occurring natural hazards that lead to loss of lives and livelihoods and which are increasingly impacting upon our society. They are routinely monitored as individual hazards and rely on forecasters and civil protection authorities to detect

any potential spatio-temporal overlaps. When simultaneously affecting the same region, wildfires and heat stress can generate substantial impacts "as the impacts of one hazardous event are often exacerbated by interaction with another" (Marzocchi et al. 2009). There is therefore the need for spatio-temporal information layers that are tailored to identify the concurrence of multiple hazards, especially in the context of Early Warning Systems. In this work we demonstrate a methodology to generate various multi-hazard information layers based on the re-analysis, high resolution and probabilistic medium-range forecasts of two hazard indices: FWI representing fire danger and UTCI representing heat stress. The procedure is, to some extent, hazard-agnostic in the sense that any hazard index could potentially be integrated. The only prerequisite is that the indices should be binnable into the same categories of danger. This categorization is a very important step as it ensures that the different danger types become comparable to each other. We suggest defining categories of danger based on climatological percentiles (in the case study we used 37 years of reanalysis data) and generating maps of danger thresholds that could inform users which danger index values to consider unusual for a particular area and time of the year. Based on these thresholds, calculated at each pixel, we are able to assess whether the danger measured or forecasted on a given date is low, moderate, high, or extreme. This binning can be applied to both reanalysis and forecast data. Based on feedbacks from stakeholders, it seems the definition of danger thresholds is a rather controversial matter. Some stakeholders value the climatological information and prefer a statistical approach (consistent with what is presented in this work), others prefer to use a fixed set of thresholds at the pan-European scale and rely on forecasters experience and expertise to interpret them in the context of the local fire regime (consistent with the EFFIS approach). Motivations to opt for one approach or the other are deeply ingrained in the stakeholder's best practise, therefore the
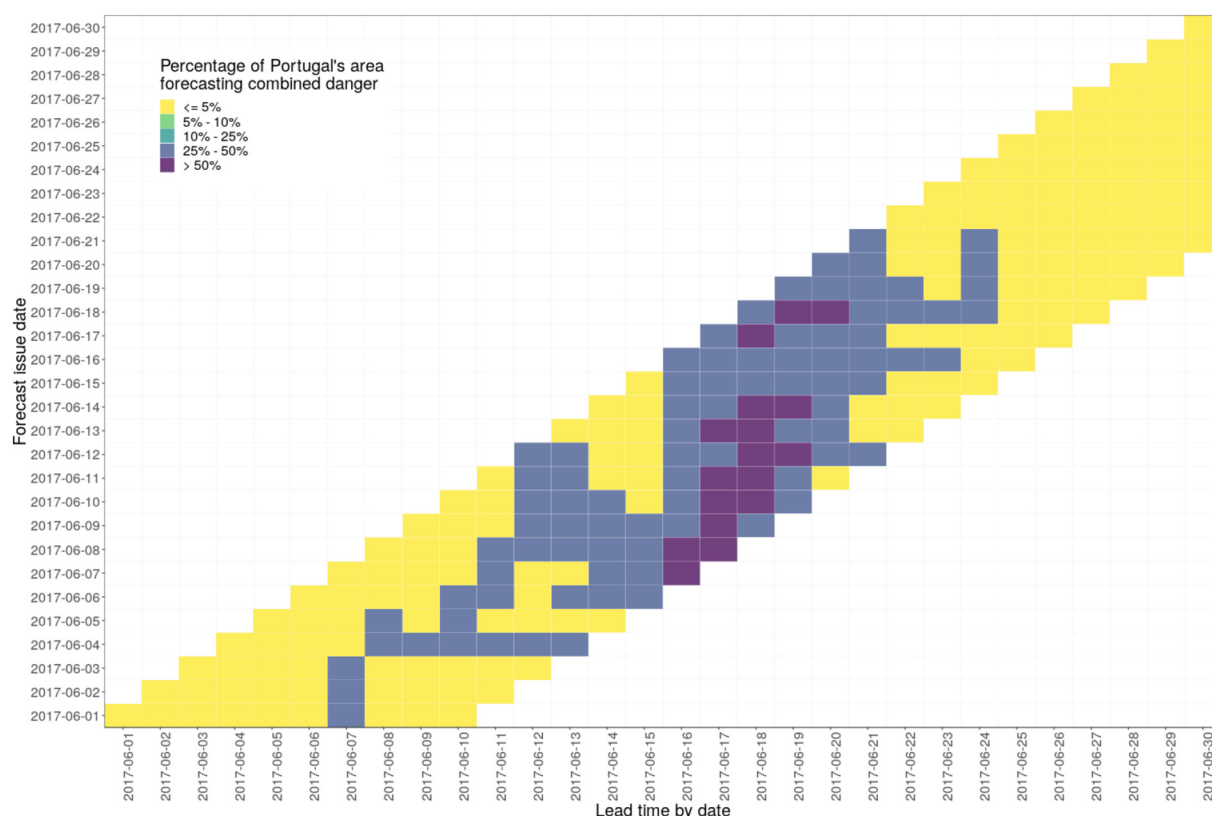
**Fig. 8.** The 1-month forecast summary plot, representing the percentage of Portugal's area forecasting combined fire and heat danger. The very high combined danger that characterised the event on 17th June 2018 in Pedrógão Grande could have been forecasted 10 days in advance.

consensus is to have access to both information. Problems may arise if the two sources provide diverging information. How to consistently interpret the two approaches remains an open question.

The second layer we presented is a map of hotspots of combined danger. This is obtained by spatial overlap of binned danger maps that

have been converted into binary maps based on whether they exceeded a given threshold or not. A map of hotspots of combined danger can be used to analyse the extent of a past event and its spatial correlation with other observed variables (working in retrospect, this makes use of re-analysis data) or to make a prediction for the future (using forecast

**Table 2**
Some feedbacks from European stakeholders on their needs for forecasts and data products.

| Stakeholder | Statement |
|---|---|
| Lourdes Bugalho | "we liked the new layers, they identify well areas at risk, […] they would have been useful during the event" |
| Divisão de Previsão Meteorológica, Vigilância e Serviços Espaciais Divisão de Meteorologia e Geofísica | (The comment above refers to the multi-hazard layers presented in this work) |
| Instituto Português do Mar e da Atmosfera (Portugal) | |
| Célia Gouveia and Rita Durao | "Forecasts products anticipating dangerous conditions 3-day ahead would already be useful, but 5-day notice would be ideal to allow efficient allocation of resources, plan evacuations, etc." |
| Núcleo de Observação da Terra Divisão de Meteorologia e Geofísica | "The monthly forecast summary was very informative to track the spatio-temporal evolution of the forecasts and can also be very useful as managing tool." |
| Instituto Português do Mar e da Atmosfera (Portugal) | "We like the approach to define danger thresholds by looking at spatio-temporal variability of danger indices using a statistical approach. We consider this a valid approach to assess the fire danger risk in Portugal but also in the entire Pan European region, where many different fire regimes exist." |
| | (The comments above refer to fire danger layers only) |
| Paolo Fiorucci | "3 days are usually enough for efficient allocation of resources" |
| CIMA Research Foundation (Italy) | "A fixed set of fire danger thresholds for the whole Europe would probably be more convenient that thresholds based on the local climatology" |
| | "Caliver's products such as forecast summary and firegrams, calculated for a region of interest, could be very useful operationally and also during emergencies" |
| | (The comments above refer to fire danger layers only) |
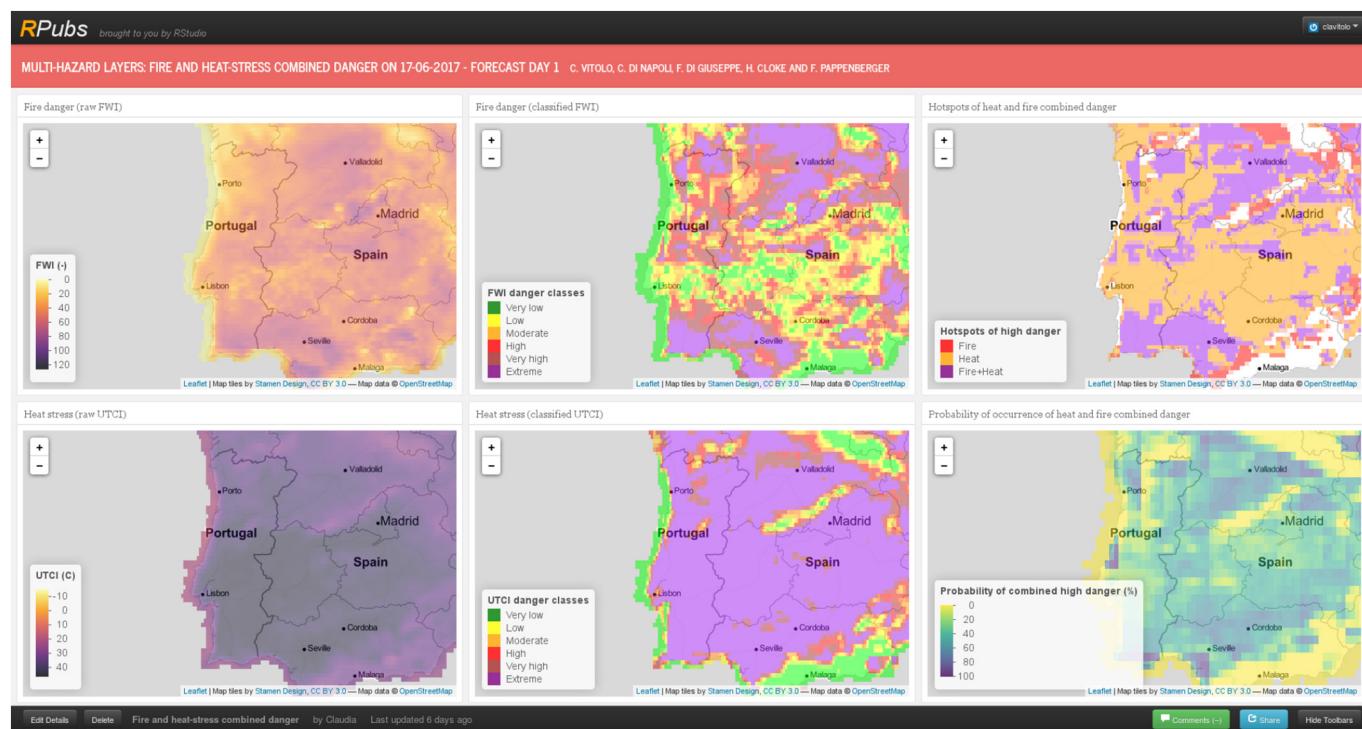
**Fig. 9.** Web-application to explore sample multi-hazard layers: raw FWI rating (top left panel), raw UTCI (bottom left), reclassified FWI (top center) and UTCI (bottom center), map of forecasted hotspots (top right) and map of probability of occurrence of two concurring hazards (bottom right). The layers have been computed at pan-European scale, although the panels above zoom in to show Portugal and part of Spain.

data). The confidence in the identification of combined danger in a given area is provided by a third layer: a map of probability of occurrence that is generated by spatial overlap of fire danger and heat stress ensemble forecasts. Lastly, an overview of the evolution of the forecasts is provided by the monthly forecast summary plot. Although the above mentioned layers have been designed with users' needs in mind, the optimal use and visualisation of multi-hazard layers would require significant co-production: through collaboration with stakeholders, developers can identify strengths and weaknesses and improve the products by incorporating feedback. Amongst the feedbacks received during the January workshop and with regards to fire danger forecast, IPMA stated that "the monthly forecast summary was very informative to track the spatio-temporal evolution of the forecasts and can also be very useful as managing tool" (see Table 2).

Despite fire danger and heat stress being highly correlated (temperature and wind speed are common precursors/predictors), we found there is scope combining them for the benefit of decision makers. An increase in relative humidity can play a mitigating role for fire danger, while has an exacerbating effect on heat stress (Climate Communication - Science and Outreach, 2012). In the future, therefore, it could be interesting to investigate humid and dry heat waves separately and their occurrence in relation to droughts and wildfires. This would also imply the definition of a threshold on the value of relative humidity, which would not be a trivial task.

With regards to June 2017 in Europe, the signal of an important combined danger was detectable 10 days before the major wildfire in Pedrógão Grande (Portugal) started, demonstrating the usefulness to local responders (who need 3–5 days notice to efficiently allocate resources) while being relevant on a pan-European scale. Collaboration with stakeholders was extremely useful to set their expectations and assess our data products accordingly. Collaborations are currently ongoing and we plan to have more workshops and opportunities to exchange experiences in the future.

This study is limited to the combination of two hazards which are expected to occur simultaneously. Further work is needed to

understand how to best use this type of information in the context of Multi-Hazard Early Warning Systems and support first responders and decision makers. In the future, the dynamic update of this multi-hazard zonal classification combined with the integration of other concurrent or lagged hazards could permit the identification of the most impacted and/or multi-hazard prone areas and shape environmental policies in Europe. It is also important to point out that this study focuses on a multi-hazard framework, while decision makers and first responders have to operate within a multi-risk setting. The latter would require an extension of the analysis including cross-correlation of risk factors and components (such as population density), which would lead to an improvement of the system. This is particularly important as projected changes in the climate will lead to a significant increase in the variability of temporal and spatial patterns of extremes which are linked to rising temperatures (such as the two hazards presented in this study) as well as a potential increase in the magnitude and frequency of these hazards (Forzieri et al., 2016). An increasing use of multi-hazard and multi-risk frameworks is an essential component of an efficient and effective adaptation strategy to a changing climate.

The scientific advances of this study aim to support operational programs such as Copernicus. Copernicus is the European Programme for the establishment of a European capacity for Earth Observations with a strong focus on services to exploit satellite and in-situ data. It is currently divided into six separate services (Atmosphere, Land, Climate, Marine, Emergency, Security) which span multiple hazards. For example, fire hazard is part of the atmosphere service as fires impact air quality, part of the land service as it requires information about vegetation cover, integral to the climate service as it is driven by reanalysis and seasonal forecasts, and an important component of the emergency service in terms of forecasting. A similar argument can be made for the heat stress used in this study. We demonstrated that not only are the different services interconnected through hazards but also that the individual hazards are correlated and connected. Thus a future Copernicus service needs to be structured not only from the point of view of the earth observation provider but also should be strongly led

from the emergency responder perspective and thus have a stronger focus on cross-cutting, user perspective elements.

## 5. Conclusions

When multiple hazards affect the same region simultaneously, they can generate substantial impacts, as impacts of one hazardous event are often exacerbated by interaction with another. This suggests the need for spatio-temporal information layers that identify hotspots of combined danger. We suggest a methodology to generate such layers based on the reanalysis, high resolution and probabilistic medium-range forecasts of two hazard indices: FWI representing fire danger and UTCI representing heat stress. The maps of hotspots created for June 2017 highlighted that despite fire danger and heat stress being highly correlated, an increase in relative humidity can play a mitigating role for fire danger, while having an exacerbating effect on heat stress. Therefore the key to identify areas prone to combined danger is to understand these dangerous trade-offs. Probabilistic medium-range forecasts are used to quantify the uncertainties related to the spatial and temporal occurrence of these events. We also introduced the monthly forecast summary plot to track the temporal evolution of the forecast and ease comparison with past forecasts. The summary plot for June 2017 over Portugal showed the signal of an important combined danger in Portugal was detectable 10 days before the major wildfire in Pedrógão Grande (Portugal) started. According to stakeholders, 5 day notice or more would allow sufficient time for planning and allocating resources. This work can be used within a Multi-Hazard Early Warning System to provide improved early warning information on concurrent natural hazards, which will support operational programs such as Copernicus.

## Acknowledgements

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