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Using cellular automata to assess the role played by wind direction in two large fire episodes in Portugal

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Abstract

Portugal is recurrently affected by severe wildfires, the fire season of 2017 representing the most tragic year with half a million of hectares burned and 115 deaths. The events that took place on October 15 deserve special attention, not only because the area burned on that day represents more than 50% of that burned during the entire year, but also because it resulted from the combination of very strong winds steered by the passage of hurricane Ophelia, very dry vegetation because of a prolonged drought affecting the country, very low atmospheric relative humidity and a record number of ignitions. Meteorological fire danger is usually rated using the Fire Weather Index (FWI) that is part of the Canadian Forest Fire Weather Index System. However, wind direction is not taken into account when defining FWI, and therefore it is worth investigating how this factor may affect the evolution of a given fire keeping all the remaining factor unaltered. The role played by wind direction is assessed using a cellular automata (CA) model to simulate two wind-driven wildfires that took place at Pataias-Burinhosa and Quiaios on October 15, 2017. The CA model is first calibrated using winds derived from a regional weather forecasting model and sensitivity studies are then performed by systematically rotating the forecasted winds keeping all the other parameters constant. Results indicate a progressive decrease in probability of burning from a 45º to a 90º counterclockwise rotation. These results suggest improving FWI by defining an FWI vector, whose direction is that of the wind and magnitude is that of FWI. This vector should then be compared against the prevailing vegetation patch orientation, and the closer the alignment between the two directions, the greater the meteorological fire danger.

1. Introduction

Portugal is recurrently affected by severe wildfires with strong adverse impacts at social, economic, ecologic and environmental levels (Costa et al., 2011; Pereira et al., 2011). A recent tragic case is the year of 2017 with the highest record of total burned area since 1980 (above half a million hectares), 115 deaths and an involvement of about 1.5 thousand firefighters (ICNF, 2017).

Information about the likelihood of a large fire event on a given day and in a given location is of vital importance for fire management and fire prevention. The likelihood of a fire event is usually rated by means of meteorological fire danger indices (Finney, 2005), and in this respect the Canadian Forest Fire Weather Index System (Stocks et al., 1989) has shown to be particularly useful for the ecosystems of Mediterranean Europe (San-Miguel-Ayanz et al., 2012). The Canadian System consists of six components that account for the effects of fuel moisture and wind on fire behaviour and all components are derived from surface weather observations at local 12 noon, namely air temperature, air relative humidity, wind speed and cumulated precipitation. Wind direction is not considered in the Canadian System but, especially in cases of wind-driven fires, it is expected that the total area burned will also depend on the relationship between wind direction and the orientation of major flammable vegetation patches, with fire propagating longer distances when wind direction is closer to patch orientation.

The large fire events that started on October 15, 2017 in Central Portugal are especially worth being studied from the point of view of the relationship between wind direction and vegetation patch orientation. That day was marked by strong and persistent southerly winds associated to the passage of hurricane Ophelia; around 500 ignitions started on October 15 that combined with the extremely dry state of the vegetation due to a persistent drought that had affected Portugal and with the very low values of atmospheric humidity resulted in a daily amount of burned area representing more than 50% of the total burned area of that year (Pinto et al. 2022). Two of the events, at Pataias-Burinhosa and at Quiaios, took place along two coastal elongated bands of forested terrain, with 94% of pine and 2% of eucalyptus forests in Pataias and 64% of pyne and 18% of eucalyptus forests in Quiaios (Guerreiro et al. 2018). The orientation of the two coastal bands was very close to the prevailing south-north wind direction of the winds, a situation that is not common in Portugal at that time of the year.

The aim of this work is to assess the role played by wind direction on total area burned in the events of Pataias and Quiaios. After calibrating a cellular automata model to fire propagation observed in the two events using winds as derived from a regional weather forecast model, the models are run with winds rotated by constant amounts and keeping the remaining parameters constant and, finally, a sensitivity study is performed on total burned area to wind rotation.

2. Methods and Data

2.1. The Alexandridis CA model of fire spread

Cellular automata (CA) models are built up on a set of rules defined at a local level that yield global complexity that can resemble fire propagation. Space is defined by a regular grid where each cell is found to be in one of a number of possible states. Cells can only interact with cells in a neighbourhood by means of evolution rules. For every time step, each cell's state is updated according to these rules and depending on the previous states of the cell as well as of its neighbours (Wolfram 2002). We will use a simplified version of the Alexandridis CA fire spread model (Alexandridis et al. 2008) to simulate fire spread. Fire modelling is probabilistic in the sense that a set of simulations is performed and the probability that a given cell will burn is derived from the fraction of simulations where the cell did burn.

In order to run the model first we need to identify the cell that is burning, then consider a squared-cell grid around it, the eight surrounding cells, called neighbours, translating the eight directions along which the fire can propagate. Each cell can be in one of four states: 1) void of fuel content (being assumed that it cannot be ignited at any future instant); 2) contains fuel (it can be ignited); 3) has been ignited (fire can propagate in the next time step to its neighbours); 4) the fire is extinguished (the cell remains in that burnt state until the end of the run).

The model considers three factors when evaluating the likelihood of fire propagating from a cell to another cell in its neighbourhood: wind, slope of the terrain, and type of vegetation. The three factors considered are included in the weight of the probability of a fire to spread to a cell (p_{burn}) in the neighbourhood of a cell classified as in fire, according to the expression:

$$p_{burn} = p_h\left(1 + p_{veg}\right)p_w p_s \qquad (1)$$

where p_s, p_{veg} and p_w are the slope, the vegetation type and the wind contributions, respectively, and where p_h corresponds to the value of p_{burn} for a certain cell with no slope or wind ($p_h = 0.58$ by optimisation).

Four transition rules are then applied:

1) If $state(i,j) = 1$ at t, $state(i,j) = 1$ at $t + \Delta t$.
2) If $state(i,j) =3$ at t, $state(i,j) = 4$ at $t + \Delta t$.
3) If $state(i,j) =4$ at t, $state(i,j) = 4$ at $t + \Delta t$.
4) If $state(i,j) = 2$ at t, $state(i \pm 1, j \pm 1) = 3$ at $t + \Delta t$ if the factor p_{burn} is higher than a value obtained by a random generator.

Following Freire and DaCamara (2019), a wind rule was added in order to simulate spotting. This rule allows fire to spread to a number of cells placed along the wind direction instead of only spreading to the direct neighbour as described in the baseline model. The number of cells to be burned when applying the wind rule was obtained from a step function of the wind speed. According to the rule, i) only cells whose p_{veg} value is greater than a certain threshold can be set on fire when applying this rule, and ii) fire can jump over cells with no fuel or with low values of p_{veg} so that spotting effect is captured.

2.2. Case studies

The model was used to simulate the two coastal wildfires of Pataias-Burinhosa and Quiaios, that started on October 15, 2017. As shown in Figure 1, the two fire events present an elongated shape which reflects the strong influence of the prevailing wind (from south to north). The Pataias-Burinhosa wildfire started with an ignition in Pataias at 2:01 pm, followed by a second ignition at 2:33 pm, in Burinhosa (northeast from the first ignition). Most of the 16,949.6 ha of burned area did occur on the first day. The Quiaios wildfire originated from a single ignition located at the most southern point of its fire perimeter. It was first reported at 2:36 pm. This wildfire was dominated at 11:16 pm on the following day. During that period, an area of 19,025.5 ha was consumed by fire.

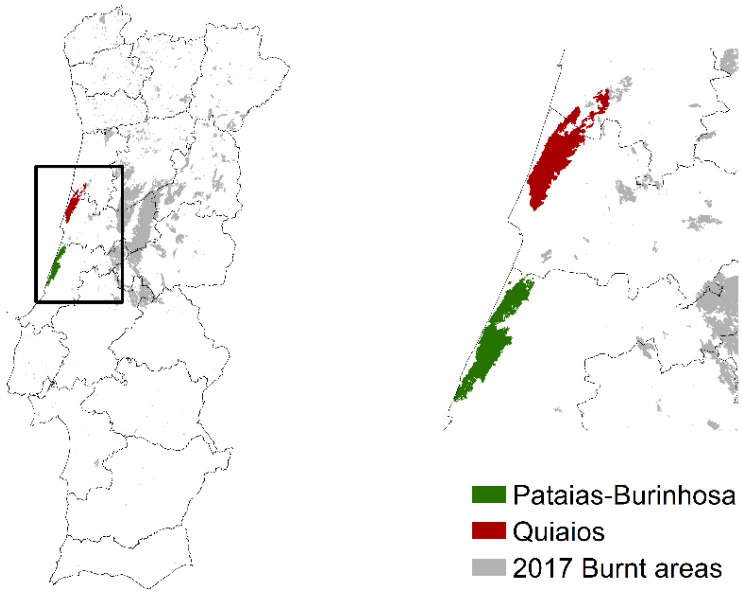

Figure 1- The burned areas of the Pataias-Burinhosa (in green) and the Quiaios (in red) fire events within the context of the burnt areas in 2017 (in grey).

2.3. Input data

Elevation profiles were provided by SRTM (Shuttle Radar Topography Mission) digital model (Farr et al., 2007). Land cover data were extracted from 100-m resolution CORINE land cover maps (CLC2012) to build the initial state and vegetation type matrices. The regional model WRF (Weather Research Forecast, version 4.0) (Skamarock et al., 2019) was run to obtain wind data which was subsequently corrected for wind interaction with topography with software WindNinja (version 3.4.1) (Forthofer et al., 2014). Wind information was updated every hour in the simulation. Information on starting ignitions and duration of fire events was provided by ICNF (Instituto da Conservação da Natureza e das Florestas) burned area maps (ICNF, 2022; ICNF, 2017). We also resorted to the official report (Guerreiro et al., 2018) to check the data.

Calibration of the model was performed by comparing the simulated burned area against shapefile maps provided by EFFIS (European Forest Fire Information System) (San-Miguel-Ayanz et al., 2012) in the case of the Pataias-Burinhosa event and, in the case of Quiaios, against a Sentinel-2 product of burned areas and implementing the methodology described in the RUS-Copernicus tutorial (RUS-Copernicus, 2017).

3. Results and discussion

Results presented in Figure 2 are the outcomes of ensembles of 100 simulations with time steps of $\Delta t = 4$ min covering a period of 21 hours for Pataias-Burinhosa and 35 hours for Quiaios, these values corresponding to the period where virtually all the area was burnt.

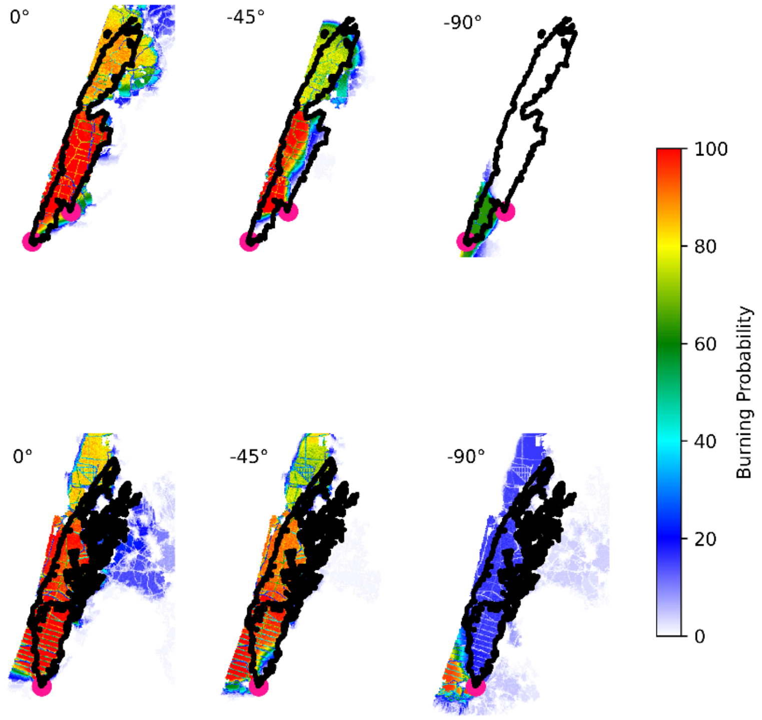

Figure 2- Maps of burning probability (%) as obtained for the simulations of the Pataias-Burinhosa (top panel) and the Quiaios (bottom panel) events. Left column shows the results from model calibration using winds derived from the regional weather forecast model, and the middle and right columns show the results from simulations when the winds are rotated counterclockwise of 45º and 90º, respectively. Black lines represent the real fire perimeters and the pink circles indicate locations of the ignition points.

Maps of probability of burning that resulted from the 100 simulations for model calibration, i.e. using winds derived from the regional weather forecast model (Fig. 2, left column) show an overall agreement with the observed fire perimeter (lines in black), and it is worth stressing that no barriers were defined representing actions of firefighting. Simulations using winds rotated counterclockwise show a progressive decrease in probability of burning from a 45º (Fig. 2, central column) to a 90º (Fig. 2, right column) rotation. In this latter case, simulations for the Pataias-Burinhosa event indicate that most of the area does not even burn, whereas for Quiaios most of the area presents values of probability lower than 20%.

Results obtained suggest that incorporation of wind direction in the Canadian System represents an added value when rating meteorological fire danger. For instance, this information could be incorporated in the Fire Weather Index (FWI), that rates fire intensity, leading, e.g. to the definition of an FWI vector, whose direction is that of the wind and magnitude is that of FWI. This vector should then be compared against the prevailing vegetation patch orientation, and the closer the alignment between the two directions, the greater the meteorological fire danger.

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