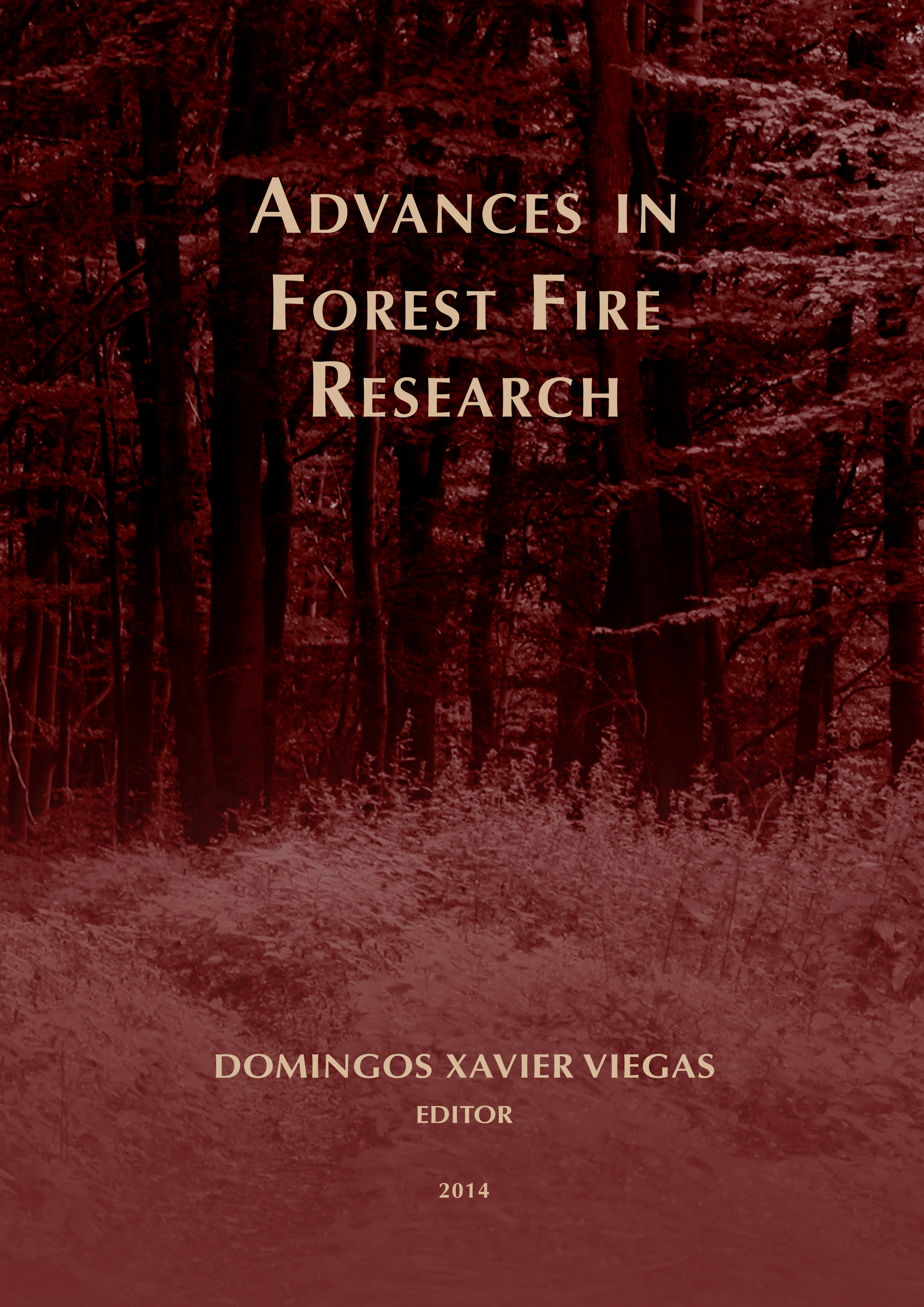

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Improving wildfire spread simulations using MODIS active fires: the FIRE-MODSAT project

Ana Sá[a], Akli Benali[a], Renata Pinto[a], Paulo Fernandes[b], Ana Russo[c], Fábio Santos[c], Ricardo Trigo[c], José Pereira[a], Sónia Jerez[d], Carlos da-Camara[c]

[a] *Centro de Estudos Florestais, Instituto Superior de Agronomia da Universidade de Lisboa, Tapada da Ajuda, 1349-017 Lisboa, Portugal, anasa30@gmail.com*
[b] *Centro de Investigação e de Tecnologias Agro-Ambientais e Biológicas, Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, Apartado 1013, 5001-801 Vila Real, Portugal*
[c] *Instituto Dom Luís, Faculdade de Ciências da Universidade de Lisboa, Campo Grande. Edifício C8, Piso 3, 1749-016 Lisboa, Portugal*
[d] *University of Murcia, Department of Physics-Physics of the Earth. Edificio CIOyN, Campus de Espinardo, 30100 Murcia, Spain*

Abstract

Wildfires are an important ecological disturbance in Mediterranean forests and have dramatic social, economic and environmental impacts. Portugal is already experiencing an increase in the number and extent of wildfires, with records of burnt extent exceeding 400,000ha and 300,000ha in 2003 and 2005, respectively. With the projected future increase in the frequency of large wildfires, those negative impacts and fire suppression difficulties will also likely increase.

Spatially explicit wildfire spread models (e.g. FARSITE) are one of the most effective tools to understand complex interactions among topography, vegetation fuel and weather conditions. These models can be used not only to study past fire events but also for forecasting fire spread and behavior. MODIS active fires have a large potential to provide relevant information regarding the spatio-temporal distribution of large wildfire events. When combined with fire spread models, they may provide crucial information to overcome the error propagation that arise when simulating large and long duration wildfire events, which is crucial for monitoring and forecasting fires in an operational fire-fighting context.

We investigated nine large wildfires (>=10,000ha) that occurred in Portugal between 2001 and 2012 in order to evaluate if combining fire growth simulations with active fire data improves the accuracy of fire spread predictions. To achieve this goal we propose to: 1) simulate fire growth using FARSITE model in combination with the time and spatial information of the MODIS active fires during the fire event propagation; and 2) assess the performance of fire spread simulations comparing them with the spatio-temporal distribution of the active fires. Additionally we performed a sensitivity analysis to evaluate the impact of key model parameters and variables on fire growth simulations, to understand the main sources of error and identify future work needed to improve the use of combined model-satellite approach in an operational context.

Results show that fire growth simulations are improved when satellite-derived active fires were used to reinitialize the simulation while the fires are occurring. Sørensen coefficients obtained for these simulations assisted by MODIS active fires were all above 0.5, showing a significant improvement over full fire growth event simulations. This innovative approach of combining satellite active fires data with fire spread simulations reduces the propagated errors of the large and long duration fire events and improves the forecasting ability of fire spread models.

***Keywords**: Fire growth simulations, satellite active-fires, FARSITE, FIRE-MODSAT.*

1. Introduction

Large wildfires while infrequent are responsible for severe environmental, ecological and socio-economic impacts. In Portugal, wildfires have consumed an average of 140,000ha/year during the last decade (Sá and Pereira 2011). Portugal has been experiencing significant increments of both maximum and minimum temperature at annual and seasonal scales (Ramos *et al*. 2011) and all regional climate models indicate an increased likelihood of future increases in the frequency and amplitude of summer heat waves (Barriopedro *et al*. 2011). Therefore, most climate change studies point to an increase in the number and extent of forest fires (Flannigan *et al*. 2013), thus the negative impacts of wildfires and fire suppression difficulties will also likely increase. Portugal is already experiencing this reality, with records of burnt extent exceeding 400,000ha and 350,000ha in 2003 and 2005, respectively (Oliveira *et al*. 2012), and several very large and catastrophic wildfires in the South and Centre of Portugal (Trigo *et al*. 2006).

The scientific community is becoming increasingly aware of the significance of large wildfires impacts, being essential to understand the complex interactions among the main drivers of wildfire spread and behaviour, such as topography, fuel and meteorology. Spatially explicit wildfire spread models are one of the most effective tools to understand such complex interactions and have been commonly used to simulate wildfire growth and behaviour (e.g. Arca *et al*. 2007). They can provide relevant descriptors directly related with fire suppression, such as the rate of spread and fireline intensity of the fire front (Finney 2004). However, fire spread models have been seldom used to monitor real wildfire events, particularly large wildfires (Arca *et al*. 2007, Kochanski *et al*. 2013).

Since large wildfires have extensive burn scars and are in general active for several days, some authors have recently explored the potential of using satellite data to monitor such events events in a quasi-continuous mode (Smith and Wooster 2005, Loboda and Csiszar 2007, Benali and Pereira 2013, Coen and Schroeder 2013). The MODerate Resolution Imaging Spectroradiometer (MODIS) detects active fires that are burning at the time of overpass up to four times per day (Giglio *et al*. 2003) and has been integrated in operational systems assisting fire managers to define strategic decisions regarding fire suppression resource allocation (e.g. Lee *et al*. 2002, USDA 2014).

Modelling and monitoring large wildfires is limited by the accuracy and availability of information about the spatio-temporal distribution of fire spread which is usually taken from subjective eye-witness interviews and limits the accuracy of model calibration and validation. The skill of forecasts in simulating future fire states is basically dependent on accurate weather forecasts, and therefore, both decrease significantly with time (Coen and Schroeder 2013, Lilly 1990). In this context, satellite active-fire data can provide detailed and objective information regarding the dynamics of those events improving the implementation of fire spread models. Both satellite data and fire spread models provide different types of information about the spatial and temporal distribution of large wildfires. However, they have not been combined in a manner that fully exploits their potential and minimizes their limitations. Remote sensing and modelling have been successfully combined to provide useful and accurate predictions in other earth sciences contexts, for instance in hydrological applications (Moradkhani 2008) but very few studies have explored this combination for wildfire applications (Lee *et al*. 2002). Combining active fires satellite data with fire-spread simulations may reduce error propagation during simulations of large, long duration wildfire events. To the best of our knowledge a single recent study moved towards this direction exploring the use of satellite active fires data to initialize and evaluate coupled weather-wildfire growth model simulations in a long lasting fire event (Coen and Schroeder 2013).

FIRE-MODSAT (Supporting FIRE-suppression strategies combining fire spread MODelling and SATellite data in an operational context in Portugal) is an one-year funded project by the Portuguese Foundation for the Science and Technology (FCT) that aims at providing crucial information to understand how large wildfire impacts can be minimized in the future, by combining fire spread simulations and satellite data to support fire management decisions in an operational context improving the efficiency of the fire suppression system.

The study presented here shows some preliminary results of the former project. We selected extreme wildfires (above 10,000ha) that occurred in Portugal between 2001 and 2012 to evaluate the potential of combining fire growth simulations with active fire data, and improve the accuracy of fire spread predictions. We propose to: 1) simulate fire growth using FARSITE (Fire Area Simulator, Finney 2004) model in combination with the temporal and spatial information of the MODIS active fires during the fire event; 2) assess the performance of fire spread simulations comparing them with the spatio-temporal distribution of the active fires. Additionally we carry out a sensitivity analysis to evaluate the impact of key model parameters and variables on fire growth simulations, to understand the main sources of error. This will contribute to identify future work needed to improve this new approach, producing valuable information to be integrated in a fire-fighting operational context.

2. Data and Methods

2.1. Data

2.1.1. *Case studies*

Nine unusually large wildfires (larger than 10,000ha) which took place in the centre and south of mainland of Portugal between 2001 and 2012 were selected for analysis (Figure 1). Corresponding burnt area perimeters were extracted from the annual 35-years fire atlas of Portugal (1975-2009) (Sá and Pereira 2011) and were used as reference data.

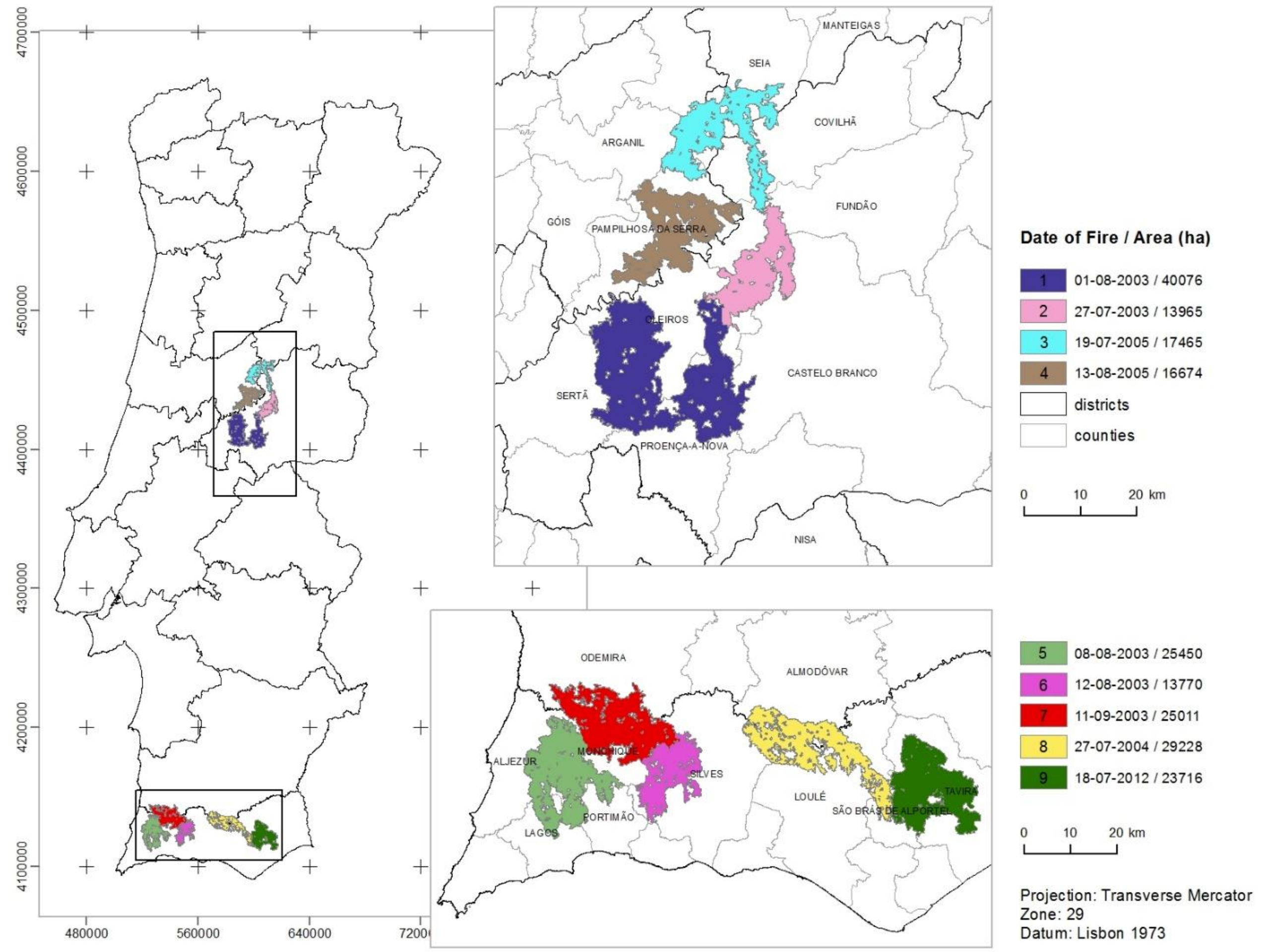

Figure 1. Case studies: nine very large fire events (larger than 10,000ha) that occurred in the mainland of Portugal between 2001 and 2012. Fire events are named as: (1) CasteloBranco1 (Cb1 2003); (2) CasteloBranco2 (Cb2 2003); (3) Covilhã1 (Cov1 2005); (4) Covilhã2 (Cov2 2005); (5) Monchique1 (Mcq1 2003); (6) Monchique2 (Mcq2 2003); (7) Monchique3 (Mcq3 2003); (8) Loulé (Lou 2004); and (9) Tavira (Tav 2012). In the legend we can see each fire date of ignition and the corresponding burnt area extent.

2.1.2. *Landscape and weather data*

Fire spread simulation requires spatial information of the landscapes, and on the weather conditions prevailing during the entire simulation period. Spatial data comprise fuels, weather, and topography. In the simulations, weather variables are input as streams of data, whereas fuels and topography are provided as GIS raster themes. Based on the input variables spatial resolution, and on the time-consuming resources of each simulation, the landscape cell-size spatial resolution was set equal to 100m, which provides an acceptable level of detail for heterogeneous landscapes.

Elevation was obtained from the Shuttle Radar Topography Mission (Farr *et al*. 2007). This dataset was also used to derive the slope and aspect variables.

Fuel maps as per the Northern Forest Fire Laboratory (NFFL) 13 fuel models (Anderson 1982) were provided by the Portuguese municipalities affected by the selected fire events. Some municipal fuels maps were not available for this study, so those maps were derived using a Classification Tree algorithm (Breiman *et al*. 1984) setting as predictor variable the Corine Land Cover (CLC, Caetano *et al*. 2009) class and the fuel class model as the response variable. Burnt areas up to two years before the date of the land cover map were updated to shrublands. The fires that occurred in the same fire season as the fire events were classified as non-burnable.

Tree cover was derived from the MODIS Vegetation Continuous Fields (MOD44B) at 250 m spatial resolution (DiMiceli *et al*. 2011). Stand and tree-based variables were set constant for the entire simulated landscapes (canopy height = 5m; crown base height = 2m and crown bulk density = 0.1 kg /m^{-3}).

FARSITE requires daily weather observations of minimum and maximum temperatures, humidity and precipitation at a specified elevation, and hourly observations of wind speed and direction. These data characterize the daily weather pattern and are used to calculate the dead fuel moisture contents. Spatially variable wind fields were modelled wind the WindNinja software to account for the effect of complex topography (Forthofer *et al*. 2009).

Weather (temperature, precipitation, insolation, relative humidity and wind speed and direction) hourly simulated data were derived from the 10km regional climate model (MM5), which is able to reproduce the main regional circulation patterns as well as the temporal variability of the wind series (Jerez *et al*. 2013a). This model was already applied to various applications that require reliable fine-scale meteorological fields (Jerez *et al*. 2013b, Jerez *et al*. 2010).

2.1.3. *MODIS active fires satellite data*

Satellite data has large potential to provide relevant and innovative information about the spread dynamics of large wildfire events, such as the direction and rate of fire spread (Benali and Pereira 2013). The MODIS active fire product detects fires in 1km pixels that are burning at the time of overpass under relatively cloud-free conditions up to four times per day (Giglio *et al*. 2003). MODIS active fires satellite data were aggregated in day and night time overpasses and, within each overpass, we identified the early and late active fires. Each overpass has a different viewing geometry and thus a different pixel size (Wolfe *et al*. 1998). The active fire *footprint* was defined based on the viewing zenith angle and on the azimuth of each MODIS overpass (Ichoku and Kaufman 2005).

MODIS active fires satellite data were coupled with fire growth models in four stages: 1) to initialize simulations from ignition points; 2) to define the start and end date of each wildfire event; 3) to restart fire spread simulations at each satellite overpass; and 4) to evaluate the accuracy of the simulated fire growth. Only the early overpass active fires were used to reinitialize the simulations to ensure a significant simulation time and capture the relevant fire spread periods. However, to evaluate model's performances both the late active fires of the previous overpass and the early active fires of the next overpass were used.

2.2. Wildfire simulation

We used FARSITE 4.0 (Fire Area Simulator, Finney 2004) fire growth model simulator, which incorporates existing models of surface fire spread, crown fire spread, spotting and fuel moisture. Fuel moisture (live and dead) has to be provided for each fuel model. Live fuel moistures (woody and herbaceous) were assumed constant during the simulations. Dead fuel moisture varies over time as a function of fuel particle size, weather conditions, and exposure to wind and sun (Finney 1998). Thus, FARSITE uses an initial fuel moisture condition and throughout the simulation it re-calculates dead fuel moisture contents for each time. Considering the weather conditions that usually prevail during the Portuguese fire season, fuel moisture contents were set based on the low scenarios (Table 1) of Scott and Burgan (2005).

Table 1. Dead (1-hr, 10-hr and 100-hr time-lag classes) and life (herbaceous and woody) fuel moisture contents (Scott and Burgan 2005).

Dead fuel moisture content (%)			Live fuel moisture content (%)	
1-hr	10-hr	100-hr	herbaceous	woody
6	7	8	60	90

The rate of spread adjustment factor is a fuel model specific parameter that adjusts the simulated rate of spread to match observed fire patterns. Thus, its value is dependent on the user expertise of fire behaviour in the local fuel complex. Changes in this parameter are based on limitations of the temporal/spatial scales of the simulations, or to adjust errors in fuel classification, inaccurate fuel moistures or improperly represented local winds (Finney 1998). We kept this parameter equal to 1 to keep the original fire spread rate.

Crown fires were simulated using the previously defined constant stand and tree-based variable values. Fire suppression activities were not considered during simulations. Fire growth simulations were performed for i) the full length of the wildfire event using as ignition points the first active fires detected within the reference burnt area perimeter (hereafter *Full simulation*) and, ii) the fire growth simulations were reinitialized at each MODIS overpass during the lifetime of each fire event (hereafter *Satellite simulation*). Thus, the satellite-assisted simulations used all the active fires derived from each satellite passage as ignition points to restart fire growth simulations until the next satellite passage.

2.3. Performance of the fire simulations

In order to assess the performance of fire growth simulations with and without combining actives fires detected from each satellite passage, we compared the simulated final burnt area perimeters with the respective reference burnt area perimeter extent. For this analysis of performance we used the Sørensen coefficient (SC, Sorensen 1948), which is widely used in ecology to compare the similarity of two samples (Eq. 1):

$$\boldsymbol{SC} = \frac{\boldsymbol{2a}}{(\boldsymbol{2a}+\boldsymbol{b}+\boldsymbol{c})} \qquad \text{(Eq. 1)}$$

where, a is the intersection of the simulated burnt area extent values (from the full or the satellite combined simulations) with the reference burnt area extent, b is the area burned exclusively by the simulation, and c the area exclusively burned in the reference data. It ranges from 0 to 1, with the former value corresponding to a completely failed simulation and the latter indicating a perfect agreement between the fire growth simulations and the reference burnt area perimeter.

Additionally, for both the *full* and *satellite* simulations for each MODIS overpass we calculated the distance between the active fire footprint and the position of the nearest correspondent simulated burnt area pixel. This provided a measure of the spatial displacement error between simulations and the position of the fire front observed by the MODIS satellites during the length of each fire event.

2.4. **Sensitivity analysis**

Sensitivity analysis was performed to evaluate the impact that small changes of selected variables/parameters had on the simulated final burned area extent. Given the model complexity, a large number of variables and parameters affect simulated fire growth and behaviour. Therefore we limited the sensitivity analysis to the variables wind speed and direction, the rate of spread adjustment factor and the position of the ignition point. In order to restrict this analysis to a common fire lifetime period, we set a common simulation period of three days for all case studies.

Wind speed has a strong influence on fire spread and can be one of the most important factors shaping fires (Beer 1993). Changes in wind direction are also considered important because of its interaction with the topography, and also because this information may be used to define fire-fighting strategies. The rate of spread adjustment factor is usually defined empirically based on user's expertise and impacts on the simulated burnt area extent. Additionally, we also evaluated the impact of the uncertainty in the position of active fires within their footprint. The MODIS active fire product can identify a fire as small as 10% of the pixel's footprint, however the correct position of the actual fire within the latter is unknown. Thus, we varied the position of the ignition point in each quadrant of its footprint and varied its distance to the centroid in intervals of 20, 40, 60, 80 and 100% of the maximum distance between the centroid and the footprint's boundaries.

Table 2 shows the sensitivity analysis for the range of values of the selected variables/parameters. For each variable we performed 21 simulations, which resulted in a total of 672 simulations comprising the nine case study fire events. Within the simulations for each variable there is one that is the reference. In the case of the wind speed and direction reference values were those observed during the three-day simulation period. For the rate of spread adjustment factor the reference value is 1, meaning no adjustment. Active fires centroids were used as the ignition reference points.

Table 2. Variables used in sensitivity analysis, with respective interval unit change, with a total number of simulations of 21 each. Dmax is the maximum distance between a centroid of an active fire and its footprint borderline.

Variable	Interval range / (step)
Wind speed (km/h)	(-10; +10) / (1 km/h)
Wind direction (º)	(-50; +50) / (5º)
Rate of spread adjustment factor (adim.)	(0.25; 1.75) / (0.075)
Active fire position (% dmax, m)	(0; dmax) / (0.2)

3. **Results and Discussion**

3.1. **Model performance**

For each case study the fire event simulations performance was assessed using the Sørensen coefficient (Figure 2). Based on the coefficient values there is clear evidence that fire simulations are improved when they are coupled with active fires to reinitialize the simulations at each satellite aggregated overpass (with only one exception). These simulations had Sørensen coefficients above 0.5 (often higher than 0.6) indicating an accuracy improvement when compared with a full event simulation.

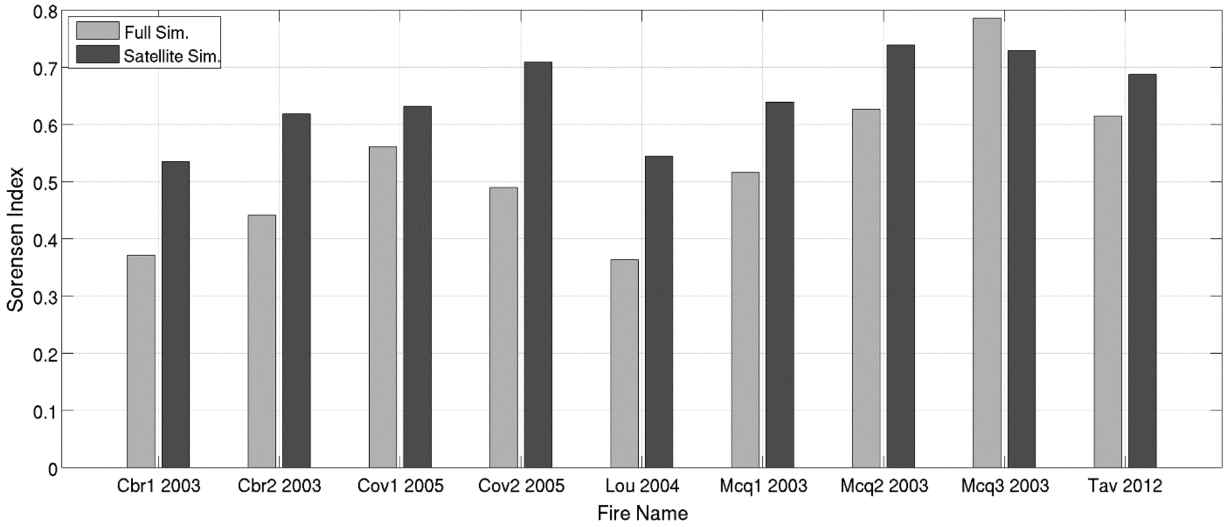

Figure 2. Assessment of the performance of the fire growth simulations using the Sørensen coefficient for: a) a full event lifetime simulation where the ignition points are derived from the first detected active fires satellite passage after the beginning of the event (grey bars); b) simulation of the fire event supported by the MODIS active fires satellite passages during the lifetime of the fire event (black bars).

Figure 3 shows the distribution of simulation accuracies along the duration of the fire events. Full simulations show that the error is almost always higher than the one derived from the satellite simulations and, propagates over time, with a maximum which is more than three times higher at 65% of the time of a fire event completed. The complex interactions between weather, fuels and topography are often difficult to reproduce with fire models producing inaccuracies on the fire spread that increase for long periods of simulations. Additionally, these errors have larger variance than the ones observed for the satellite simulations. Reinitializing simulations with the actual positions of the active fires reduces the propagation of these errors as well as its variability. For most of the time steps, the satellite-assisted simulations have a significantly lower error (around 1 km) than the full simulations.

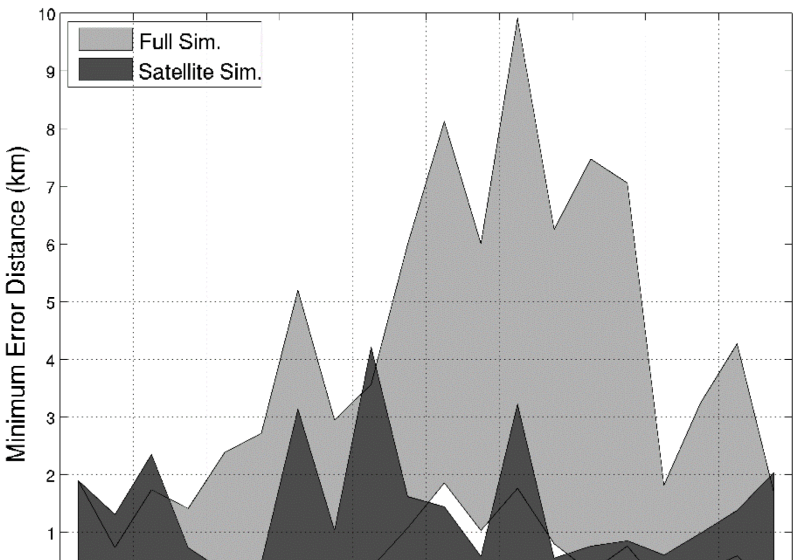

Figure 3. Interquartile range of the minimum error distance for the full and satellite simulations as a function of the fraction of the fire event completed.

3.2. Sensitivity analysis

Figure 4 shows the impact that wind speed and direction, rate of spread adjustment factor and the position of the ignition point have on the simulated burnt area (Figure 4, bottom left panel). As expected, wind speed has a large impact on the simulated burnt area extent. Positive wind speed increments produce more variation in the simulated burnt area extent than the negative increments. Two fire events cases are contributing to this wide variation: Lou 2004 and Mcq1 2003. The Loulé fire was more resilient to wind speed increments showing a simulated burnt area extent variation less than ~25% when compared with the simulation using the reference data. The reason for this may be the fact that prevailing wind speed during the simulation period was already quite high so additional increments did not have a significant impact on the new simulated burnt area extent (Figure 5). The length-to-breadth ratio of a fire increases with wind speed, implying that increasingly higher wind speeds will increase fire size at an increasingly lower rate (Alexander 1995). On the other hand, any small increase in wind speed in the Monchique1 fire event (which overall has a low length-to-breadth ratio) produced a large change on the burnt area extent because the reference wind speed values for this fire were low. Other reasons might be involved in the differences between fires, as fire spread rate as a non-linear function of wind speed varies with fuel characteristics (Rothermel 1972).

Changing the wind direction produces a lower extent of burnt area variations than introducing small changes on the wind speed (Figure 4, top right panel). The effect of wind direction increments over the variation of burnt area is more pronounced also on the Loulé fire event, but with an opposite response in terms of burnt area extent. This fire propagated under strong wind conditions with a prevailing direction (from North), thus any change from north to northeast direction will reduce the simulated burnt area extent. Negative increments (from north to northwest) have a smaller and positive effect on burnt area.

As expected, the impact of changing the rate of spread adjustment factor is also very high, with large positive values producing an increase in burnt area extent that can be four-fold larger than the no-adjustment reference value value (Figure 4, bottom left panel). Again, the Loulé fire showed more resilience in terms of burned area variation while CasteloBranco2 showed an opposite response. One explanation for this impact may be that ~40% of the fuels in this fire event are litter (NFFL fuel model 9) and they are concentrated around the area where the fire started. Fire propagation on this type of fuel bed is high and, increases in both wind speed and spread of rate, largely promote the increase in the simulated burnt area extent.

Another source of variation on fire growth simulations evaluated here is the location of the ignition point inside the footprint of MODIS active fire. Sensitivity analysis on this variable (Figure 4, bottom right panel) shows that increasing the distance of the ignition point from the centroid increases the variability on the output simulated burnt area extent. Several factors affect this measure namely the vegetation fuel map where the ignition point is located.

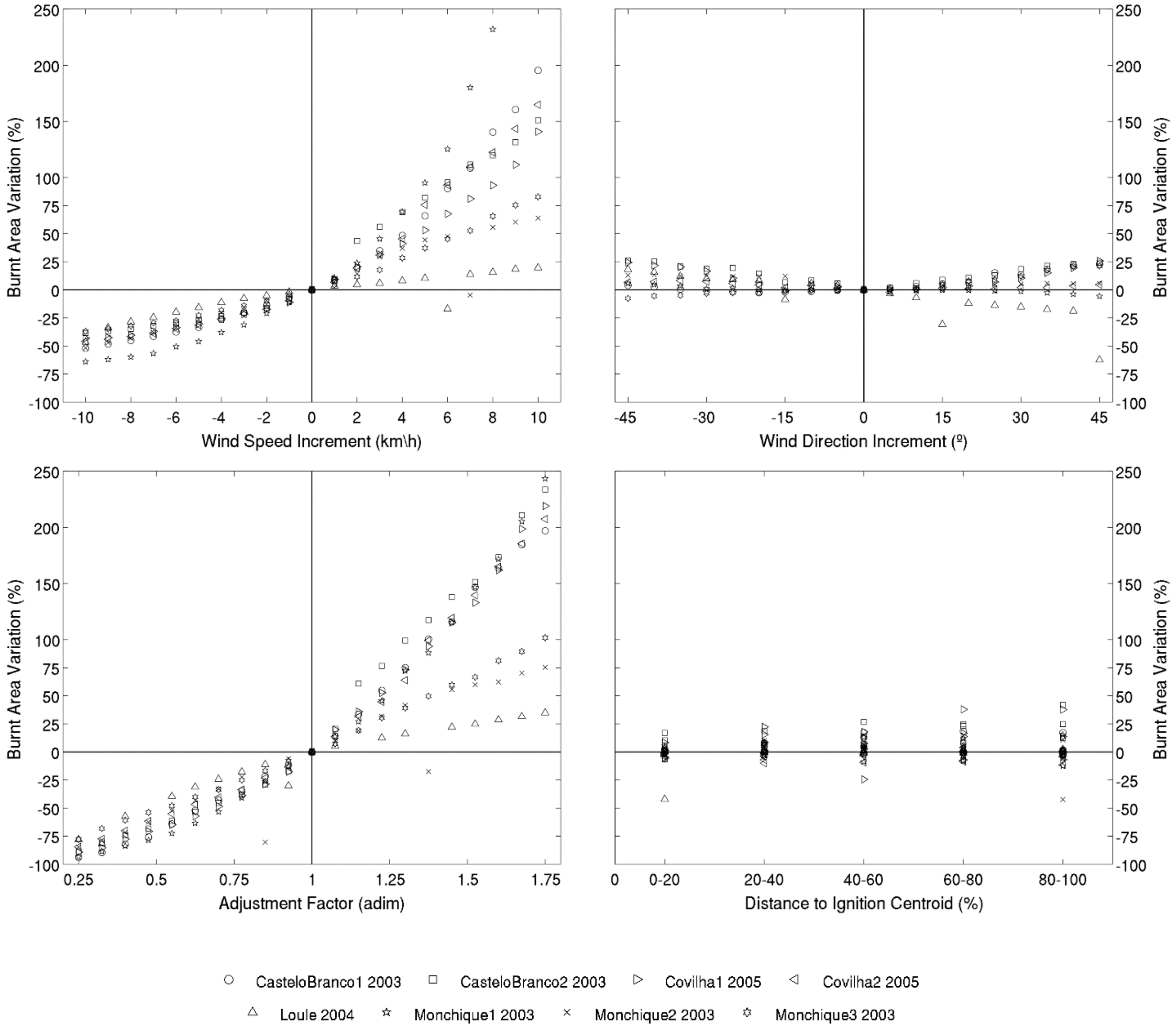

Figure 4. Sensitivity analysis for the wind speed and direction, rate of spread adjustment factor and distance to the ignition centroid variables. Analysis was based on the variation of the burnt area extent derived from introducing small increments of each variable and comparing it with the simulation derived using the corresponding variable reference values.

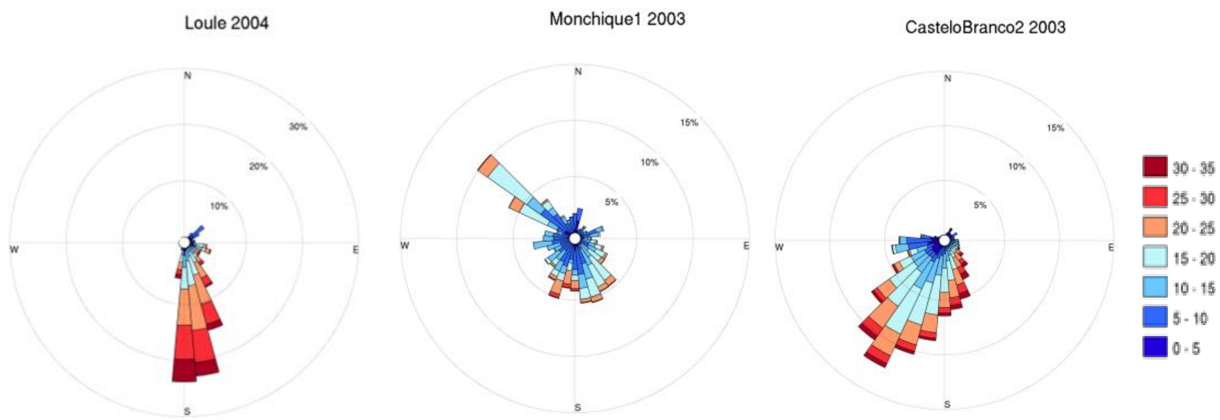

Figure 5. Wind speed (km/h) and direction (º)for the Loulé2004, Monchique1 and CasteloBranco2 fire events for the entire 3-day fire simulation period.

4. Conclusions

Fire-spread simulations can be improved using MODIS active fires satellite data for monitoring large and long duration wildfires. Estimated burnt area extent derived from fire growth simulations reinitialized with MODIS active fires detected at each overpass showed an improvement when compared with the single ignition point simulation for the entire fire duration.

We evaluated the impact of wind speed and direction, rate of spread adjustment factor and ignition point position, given the potential effect these variables have on fire propagation. As expected, small changes on the wind speed and on the rate of spread adjustment factor had a large impact on the simulated burnt area extent. This response enhances the importance of having accurate information on the wind variable when using fire spread models either for studying past fire events or for fire spread modelling in an operational context.

This innovative approach of combining satellite active fires data with fire spread simulations minimized the observed propagation error through the single fire event simulation. This improvement arises from reinitializing fire-spread simulations for each satellite aggregated overpass with updated maps of fire location for the next simulation.

Attempts to integrate fuel and weather data inaccuracies on the simulations may also improve the fire spread and behaviour simulations.

Future work will encompass uncertainties in fire spread and behaviour simulations using custom fuel models derived from other fuel classification systems (e.g.,Fernandes *et al*. 2009, Scott and Burgan 2005), changing some of its most influential parameters, namely live fuel moisture contents, weather-dependent variables, and stand level variables derived from the Portuguese National Forest Inventory. This information will be integrated in this innovative combination of fire spread and behaviour simulations assisted by MODIS active fires, in order to have a tool that will support decisions in a fire-fighting operational context.

5. References

Alexander M.E. (1985). Estimating the length-to-breadth ratio of elliptical forest fire patterns. In: Donoghue L.R. and Martin R.E. (Eds.), Proceedings of the 8th Conference on Fire and Forest Meteorology, April 29-May 2, Detroit, Michigan. SAF Publication 85-04. Society of American Foresters, Bethesda, Marylan.

Anderson H.E. 1982. Aids to determining fuel models for estimating fire behavior. General Technical Report INT-122, USDA Forest Service.

Arca B., Duce P., Laconi M., Pellizzaro G., Salis M. and Spano D. (2007). Evaluation of FARSITE simulator in Mediterranean maquis. International Journal of Wildland Fire, 16 (5), 563-572.

Barriopedro D., Fischer E.M., Luterbacher J.R., Trigo R.M. and Garcia-Herrera R. (2011). The hot summer of 2010: redrawing the temperature record map of Europe. Science, 332 (6026), 220-224.

Beer, T. (1993). The speed of a fire front and its dependence on wind speed. International Journal of Wildland Fire, 3, 193-202.

Benali A.A. and Pereira J.M.C. (2013) Monitoring and extracting relevant parameters of wild fire spread using remote sensing data. Anais XVI Simpósio Brasileiro de Sensoriamento Remoto - SBSR, Foz do Iguaçu, PR, Brasil, 13-18 April, INPE.

Breiman L., Friedman J.H., Olshen R.A. and Stone C.J. (1984). Classification and Regression Trees. Wadsworth and Brooks, Monterey, CA.

Caetano M., Nunes V. and Nunes A. (2009). CORINE Land Cover 2006 for Continental Portugal. Technical report, Instituto Geográfico Português.

Coen J. and Schroeder W. (2013). Use of spatially refined satellite remote sensing fire detection data to initialize and evaluate coupled weather-wildfire growth model simulations. Geophysical Research Letters, 40, 5536-5541, doi 10.1002/2013GL057868

DiMiceli C.M., Carroll M.L., Sohlberg R.A., Huang C., Hansen M.C. and Townshend J.R.G. (2011). Annual Global Automated MODIS Vegetation Continuous Fields (MOD44B) at 250 m Spatial Resolution for Data Years Beginning Day 65, 2000 - 2010, Collection 5 Percent Tree Cover, University of Maryland, College Park, MD, USA.

Farr T.G., Rosen P.A., Caro E., Crippen R., Duren R. et al. (2007). The Shuttle Radar Topography Mission, Reviews of Geophysics, 45, RG2004, doi:10.1029/2005RG000183.

Fernandes P., Gonçalves H., Loureiro C., Fernandes M., Costa T., Cruz M.G. and Botelho H. (2009). Modelos de Combustível Florestal para Portugal. In: Actas do VI Congresso Florestal Nacional, 348-354.

Finney M.A. (1998). FARSITE: Fire Area Simulator—model development and evaluation. Res. Pap. RMRS-RP-4. Fort Collins, CO. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47p.

Finney M.A. (2004). FARSITE, Fire Area Simulator--model development and evaluation. US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Flannigan M., Cantin A.S., de Groot W.J., Wotton M., Newbery A. and Gowman, L.M. (2013). Global wildland fire season severity in the 21 st century. Forest Ecology and Management, 294, 54-61.

Forthofer J., Shannon K. and Butler B. (2009) Simulating diurnally driven slope winds with WindNinja. In: Proceedings of 8th Symposium on Fire and Forest Meteorological Society; 2009 October 13-15; Kalispell, MT (2,037 KB; 13 pages).

Giglio L., Descloitres J., Justice C.O. and Kaufman Y.J. (2003). An enhanced contextual fire detection algorithm for MODIS. Remote Sensing of Environment, 87 (2), 273-282.

Ichoku C. and Kaufman Y.J. 2005. A method to derive smoke emission rates from MODIS fire radiative energy measurements. IEEE Transactions on Geoscience and Remote Sensing, 43, 2636-2649.

Jerez S., Montávez J.P., Gómez-Navarro J.J., Jiménez-Guerrero P., Jiménez P. and González-Rouco J.F. (2010). Temperature sensitivity to the land-surface model in MM5 climate simulations over the Iberian Peninsula. Meteorologische Zeitschrift, 19 (4), 363–374, doi:10.1127/0941-2948/2010/0473.

Jerez S., Trigo R.M., Vicente-Serrano S.M., Pozo-Vázquez D., Lorente-Plazas R., Lorenzo-Lacruz J., Santos-Alamillos F. and Montávez J.P. (2013a) The impact of the north atlantic oscillation on renewable energy resources in southwestern europe. Journal of Applied Meteorology and Climatology, 52(4), 2204–2225, doi: http://dx.doi.org/10.1175/JAMC-D-12-0257.1

Jerez S., Montávez J.P., Jiménez-Guerrero P., Gómez-Navarro J.J., Lorente-Plazas R. and E. Zorita (2013b). A multi-physics ensemble of present-day climate regional simulations over the Iberian Peninsula. Climate Dynamics, 40 (11-12), 3023–3046, doi:10.1007/s00382-012-1539-1.

Kochanski A.K., Jenkins M.A., Mandel J., Beezley J. and Krueger S. (2013). Real time simulation of 2007 Santa Ana fires. Forest Ecology and Management, 294, 136-149.

Lee B., Alexander, M., Hawkes B., Lynham T., Stocks B. and Englefield P. (2002). Information systems in support of wildland fire management decision making in Canada. Computers and Electronics in Agriculture, 37 (1-3), 185-198.

Lilly D.K. (1990). Numerical predictions of thunderstorms – Has its time come? Quarterly Journal of the Royal Meteorological Society, 116, 779-798.

Loboda T. and Csiszar I. (2007). Reconstruction of fire spread within wildland fire events in Northern Eurasia from the MODIS active fire product. Global and Planetary Change, 56 (3), 258-273.

Moradkhani H. (2008). Hydrologic remote sensing and land surface data assimilation. Sensors, 8 (5), 2986-3004.

Oliveira S.L., Pereira J.M. and Carreiras J.M. (2012). Fire frequency analysis in Portugal (1975-2005), using Landsat-based burnt area maps. International Journal of Wildland Fire, 21 (1), 48-60.

Ramos A.M., Trigo R.M. and Santo F.E. (2011). Evolution of extreme temperatures over Portugal: recent changes and future scenarios. Climate Research, 48 (2), 177.

Rothermel, R.C. (1972). A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-115, Intermt. For. and Range Exp. Stn., Ogden.

Sá A.C.L. and Pereira J.M.C. (2011). Cartografia de Áreas Queimadas em 2009 em Portugal Continental. Final Report. Protocol between the Portuguese Forestry Service and the Forest School of Agriculture. Lisbon.

Scott J.H. and Burgan R.E. (2005). Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. General Technical Report RMRS-GTR-153. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO. 80 p.

Smith A.M. and Wooster M.J. (2005). Remote classification of head and backfire types from MODIS fire radiative power and smoke plume observations. International Journal of Wildland Fire, 14 (3), 249-254.

Sørensen, T. (1948). A method of establishing groups of equal amplitude in plant sociology based on similarity of species and its application to analyses of the vegetation on Danish commons. Biologiske Skrifter /Kongelige Danske Videnskabernes Selskab, 5 (4), 1-34.

Trigo R.M., Pereira J.M.C, Pereira M.G., Mota B., Calado T.J., Dacamara C.C. and Santo F.E. (2006). Atmospheric conditions associated with the exceptional fire season of 2003 in Portugal. International Journal of Climatology, 26 (13), 1741-1757.

USDA Forest Service, Active Fire Mapping Program. URL: http://activefiremaps.fs.fed.us/ (last visited: 2014, 16 June).

Wolfe R.E., Roy D.P. Vermote E. (1998). MODIS Land Data Storage, Gridding, and Compositing Methodology: Level 2 Grid. IEEE Transactions on Geoscience and Remote Sensing, 36(4), 1324-1338.