

CHARACTERISING FIRE HAZARD FROM TEMPORAL SEQUENCES OF THERMAL INFRARED MODIS MEASUREMENTS

Carmin Maffei¹, Silvia Alfieri², and Massimo Menenti¹

1. Delft University of Technology, Department of Geoscience and Remote Sensing, Delft, The Netherlands; e-mail: [c.maffei\(at\)tudelft.nl](mailto:c.maffei@tudelft.nl)
2. National Research Council, Institute for Agricultural and Forest Systems in the Mediterranean (CNR-ISAFoM), Ercolano, Italy; e-mail: [silvia.alfieri\(at\)isafom-cnr.it](mailto:silvia.alfieri@isafom-cnr.it)

ABSTRACT

The objective of the present research was the characterisation of fire hazard using temporal sequences of land surface temperature (*LST*) derived from Terra-MODIS measurements. The investigation was based on a complete sequence of MODIS *LST* data from 2000 to 2006 on Campania (Italy) and on a data set of fires officially recorded in the area in the same period.

Missing and/or cloudy *LST* data were reconstructed by means of the HANTS (Harmonic ANALYSIS of Time Series) algorithm applied to annual sequences of daily observations. The coefficients of the Fourier analysis were then assessed against spatial patterns of fire occurrence. The HANTS algorithm was also used on the complete *LST* data set to construct daily reference temperature maps against which to evaluate temperature anomalies and cumulated temperature anomalies.

Results show that fires tend to occur in areas characterised by specific values of several Fourier coefficients with high significance, and to avoid the other areas. The amplitude of the second harmonic is the only Fourier coefficient dictating mean fire size. The mean fire size and the proportion of large fires correlate with both daily and cumulated thermal anomalies. However, the dynamic range of the predictions from cumulated anomalies is much larger, and thus maps of the latter are more effective in predicting fire hazard.

INTRODUCTION

Forest fires are a major environmental threat in large areas of the Mediterranean. There is a widespread agreement on the prominent role that fire prevention should have over remediation activities, and a consequent demand for fast and reliable methodologies to monitor and forecast fire hazard.

Vegetation moisture and temperature are the most variable fuel properties determining fire hazard (1). Both parameters depend on meteorological forcing over time and on vegetation response to it. These factors are not independent of each other, and indeed prolonged heat and absence of rainfall drive vegetation into water stress conditions that lead to an increase of its temperature. Since stressed vegetation is more prone to fire, there might be a potential role for Earth observation technologies in mapping fire hazard (2), whereas it is proved that current orbiting instruments are able to detect anomalies in vegetation temperature that can be related to fire events.

The identification of temperature anomalies requires the prior definition of a reference temperature against which to compare the actual recorded temperature. By using long-time series of satellite data it is possible to identify expected temporal patterns on a pixel-by-pixel basis. The HANTS (Harmonic ANALYSIS of Time Series) algorithm accomplishes this task by means of a Fourier series (3,4). HANTS has been reported to successfully provide reference data for both vegetation spectral indexes and land surface temperature (5,6,7). However, its potential in determining fire hazard is still unexplored.

The objective of the present research was to develop and test a methodology for the characterisation of fire hazard from anomalies of daily land surface temperature (*LST*) maps, as derived from thermal infrared measurements of the Moderate Resolution Imaging Spectrometer (MODIS) on board Terra satellite, evaluated against a reference multi-annual mean temperature calculated with HANTS algorithm. Since maps of HANTS coefficients (mean value, plus amplitude and phase of each harmonic) provide a detailed characterisation of the spatial and temporal patterns of surface temperatures, their potential to explain spatial patterns of fire events was also investigated.

MATERIALS AND METHODS

Study area and available data

The research focussed on Campania, Italy (40°50'N, 14°08'E; Figure 1), a region that extends over about 13,600 km². The interest in this area is given by its position in the middle of the Mediterranean, by the diversity of the landscape and the land use/land cover it embraces, and by the high anthropic pressure that leads to almost all fires being triggered by human activities. Campania is among the most densely populated regions of Mediterranean Europe, and fire incidence is considered high (8).

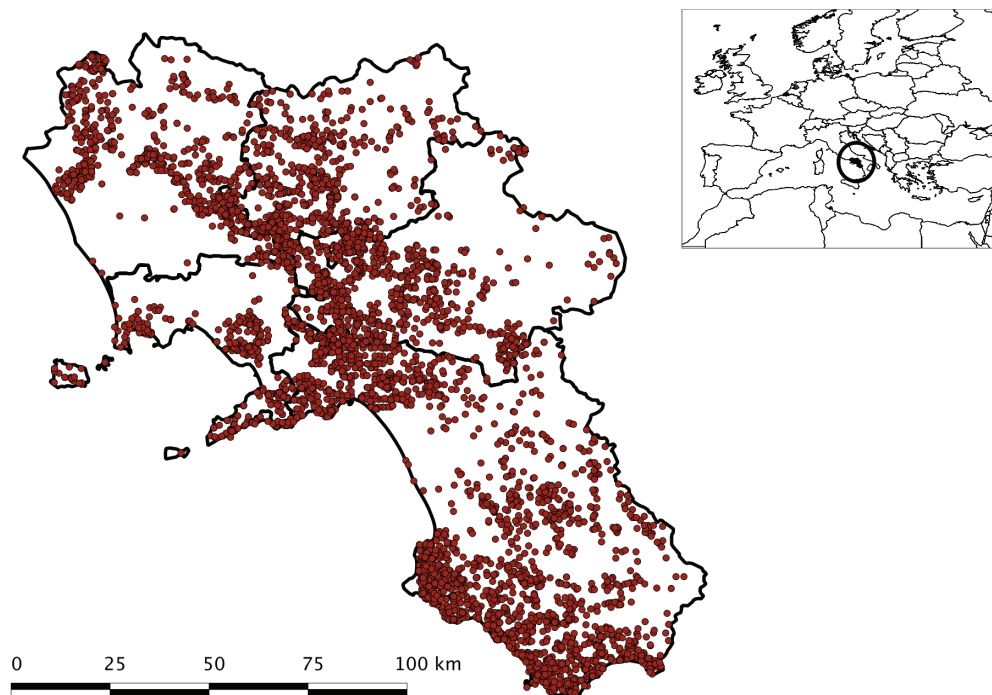


Figure 1: Study area. Red dots represent the fires officially recorded from 2000 to 2006.

For the purpose of the present research, the Italian Forest Corps (*Corpo Forestale dello Stato*, CFS) provided a data set of more than 4,400 fire records covering the years between 2000 and 2006. Data included date and time, coordinates, duration, extent and presumed causes of each event. About 99.7% of occurred fires are of human origin (unintentional or fraudulent). The data set covered a range of fire seasons that were considered safe (year 2002) to critical (2000 and 2003) in both number of fires and burnt area. On average, 750 fires are recorded each year, leading to the loss of more than 6,300 ha of natural areas including 4,100 ha of forests. Most fires (82%) occur in the summer season, i.e. June to September.

A collection of daily diurnal (approximately 9.30 am GMT) Terra-MODIS *LST* data (MOD11 product) from 2000 to 2006 was used for this research. These data are publicly available at the Land Processes Distributed Active Archive Center (LP DAAC) hosted by the United States Geological Survey (USGS) (9). In the years 2000-2006 a range of yearly averages of minimum

and maximum temperatures were observed in the region (10), allowing for the construction of reliable maps of reference *LST*.

Fourier analysis of *LST* data

To remove cloud-affected pixels from input data and to reconstruct missing *LST* values, the HANTS algorithm was used. This algorithm handles the Fourier analysis as a curve-fitting problem. Basing on an iterative approach, invalid observations are removed from the curve fitting process and the best fitting series is identified (3,4).

Series comprising three harmonics (365, 180 and 120 days) were fit to the data with two different methods, to achieve the diverse purposes of this research:

1. HANTS was executed on each yearly sequence of daily *LST* data separately to reconstruct missing or cloudy data. The retrieved yearly images of Fourier coefficients (mean *LST*, amplitude and phase of the three harmonics) were then compared against spatial patterns of fire occurrence.
2. The algorithm was executed on the whole 2000-2006 data set to construct daily maps of the reference temperature. These served as a basis for the calculation of thermal anomalies.

Spatial patterns of fire occurrence

Yearly Fourier coefficients of *LST* are related to the start and the length of the warm season and to the phenological cycle (11,12). Since fires exhibit specific spatial and temporal patterns dictated by the same factors (13), it may be questioned whether these are related to Fourier coefficients. To investigate this hypothesis, yearly maps of Fourier coefficients were first masked by a map of vegetated areas (extracted from CORINE land cover map, year 2000 update) and then classified by segmenting their values. Spatial patterns of fire occurrence were then assessed with respect to fire number and mean burnt area in terms of selectivity, i.e. by understanding whether in each class fire incidence is higher (preferred) or lower (avoided) than expected from a random null model (14).

Selectivity is calculated from Monte Carlo simulations where all fires in the data set are randomly re-assigned to the identified classes (interval of values of the Fourier coefficients) with probabilities that are proportional to the extent of each class in the study area (null model). The actual number of fires in each class is compared with the results of 1,000 of such random simulations, and the *P* value (two tails) is calculated as the proportion of the simulated number of occurrences that were lower (or higher) than the actual number of fires in that class. A similar approach was performed to evaluate selectivity in the mean burnt area.

Analysis of *LST* anomalies

Daily maps of thermal anomalies (TA) were computed by subtracting the daily reference temperature from MODIS *LST* for each pixel. Whenever in a pixel the anomaly was negative, it was set to zero. Forest fires are expected to occur in areas with a prolonged exposure to lack of rainfall and high air temperature. In these circumstances a temperature anomaly is observed over a number of consecutive days. For this reason cumulated anomalies (CTA) were calculated as well. Daily cumulated anomalies were computed as the sum of all thermal anomalies observed from the day when the thermal anomaly was first recorded in the pixel up to the current day; the cumulated anomaly is returned to zero each time a negative anomaly is observed.

Each fire was associated to the values of TA and CTA observed at the fire's location the day previous to the event. Anomalies and cumulated anomalies were then evaluated against fire size by first calculating the conditional mean fire size observed when the TA (CTA) was larger than the considered value, and then plotting the calculated means against the values of anomaly (cumulated anomaly) used in the calculation. In a similar manner, the conditional proportion of large fires was evaluated against anomaly and cumulated anomaly. A fire was considered large if its burnt extent exceeded the 95th percentile of all the fire sizes recorded in the study area in 2000-2006, i.e. 16 ha.

RESULTS

The analysis of the selectivity of fires towards Fourier coefficient maps showed that the annual mean *LST*, the amplitude of the three harmonics of the Fourier analysis, and the phase of the first harmonic correlate with the spatial patterns of fire occurrence. Fires tend to significantly occur in areas where the mean temperature and the amplitude of the first harmonic have higher values and tend to avoid low values. Fires also prefer areas where the amplitudes of the second and third harmonics are low, and where the phase of the first harmonic is high. Mean fire size shows significant and unambiguous selectivity only towards the amplitude of the second harmonic, with larger values occurring where the amplitude is larger. No significant selectivity was observed for the phase of the second and third harmonics. For the sake of brevity, only the tables reporting fire selectivity towards the amplitude of the second harmonic (Table 1) and the phase of the first harmonic (Table 2) are reported here.

From their definition, daily maps of thermal anomalies and cumulated thermal anomalies carry different information. This is clearly shown by the example in Figure 2, where vast areas with a high thermal anomaly have actually undergone a small cumulated anomaly.

Plots of conditional mean fire size vs. intensity of the thermal anomaly show a clear link among them (Figure 3). With increasing values of TA observed the day previous to the fire event at its location, the conditional mean fire size increases. A similar trend is observed with the conditional fraction of fires larger than 16 ha.

When cumulated thermal anomalies are considered instead, the same trend is observed, with increasing values of cumulated thermal anomaly leading to larger conditional mean fire size (Figure 4). As opposed to the case of thermal anomaly, the ranges of values of mean fire size that can be mapped from CTA are considerably larger. Moreover, when the cumulated anomaly is larger than about 60 K, a steep increase in mean fire size is observed. It must be observed that also the range of conditional fraction of large fires explained by cumulated thermal anomaly is larger.

DISCUSSION

The HANTS algorithm has been used in various applications involving multi-temporal remote sensing measurements of surface reflected and emitted radiance, to both fill missing/cloudy data and construct a reference basis against which anomalies can be identified. The results in this paper show that this approach can be successfully used to understand spatial patterns of fire occurrence and to predict expected fire size and fraction of large fires.

By analysing the selectivity of fires towards areas with different values of the Fourier series coefficients, it was found that mean annual temperature and the amplitudes of the three harmonics used in the analysis have a clear role in determining spatial patterns of fire occurrence. The amplitude of the second harmonic is the only factor dictating spatial patterns of mean fire size; here, a clear inverse relationship between number of fires and mean fire size is observed, with larger fires significantly preferring areas where the amplitude is larger (Table 1).

Table 1: Selectivity of number and mean size of fires for classes of amplitude (degree Kelvin, K) of the second harmonic. Symbol "+" means class preference, "-" class avoidance. One symbol: selectivity non significant. Two symbols: significant $P < 0.05$. Three symbols: significant $P < 0.01$.

Amplitude of the second harmonic				
Surface temperature range (K)	Number of fires		Mean fire size (ha)	
0-1	2,083	+++	3.52	---
1-2	1,723	-	6.01	++
2-3	570	---	7.24	++
>3	28	---	12.85	++

Table 2: Selectivity of fires' number and mean size for classes of phase (degrees) of the first harmonic. Symbol "+" means class preference, "-" class avoidance. One symbol: selectivity non significant. Two symbols: significant $P < 0.05$. Three symbols: significant $P < 0.01$.

Phase of the first harmonic				
Phase values (degrees)	Number of fires		Mean fire size (ha)	
<180	21	---	10.15	+
180-185	126	---	3.12	---
185-190	645	---	3.21	---
190-195	1,438	--	4.29	-
195-200	1,329	+++	6.63	+
200-205	623	++	5.28	++
205-210	193	+++	5.27	+
>210	29	-	6.9	+

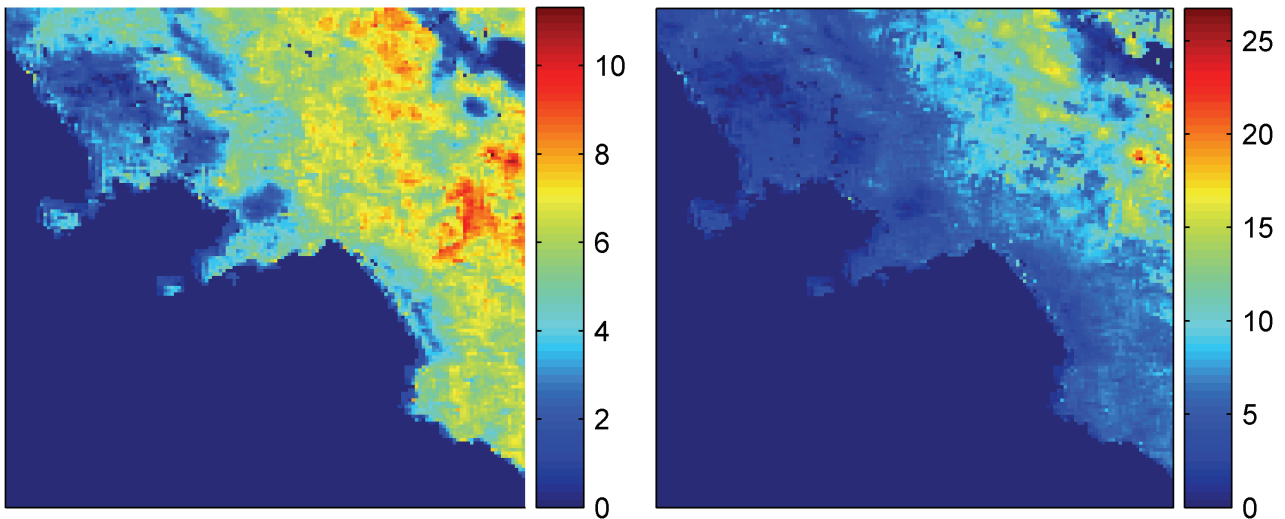


Figure 2: Maps of thermal anomaly (left) and cumulated thermal anomaly (right) in the study area as of 15 July 2001 (K).

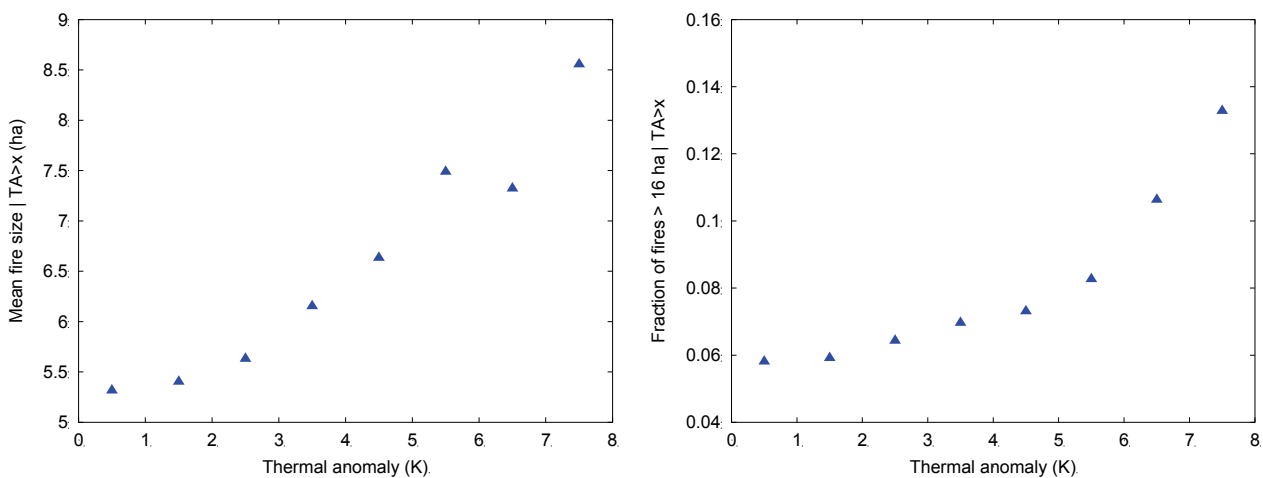


Figure 3: Relationship between conditional mean fire size (left) and conditional fraction of large fires (right) against values of thermal anomaly (TA) observed the day previous to the event at the fires' locations.

The only phase component of the Fourier analysis related to fire incidence is that of the first harmonic (Table 2); fires significantly prefer areas where this phase is higher. The phase carries information on the timing of fire events, and indeed a larger number of fires are observed where the phase is higher, i.e. when a prolonged warm season occurs.

The information carried by daily maps of anomalies of *LST* is quite different and more specifically related to the fire size that can be expected in a given area. Daily thermal anomalies are clearly related to fire size: with increasing values of the thermal anomaly, the conditional mean fire size increases (Figure 3). A similar pattern is observed with the conditional fraction of large fires. However, it must be noted that the range of values of both factors explained by the TA is quite limited.

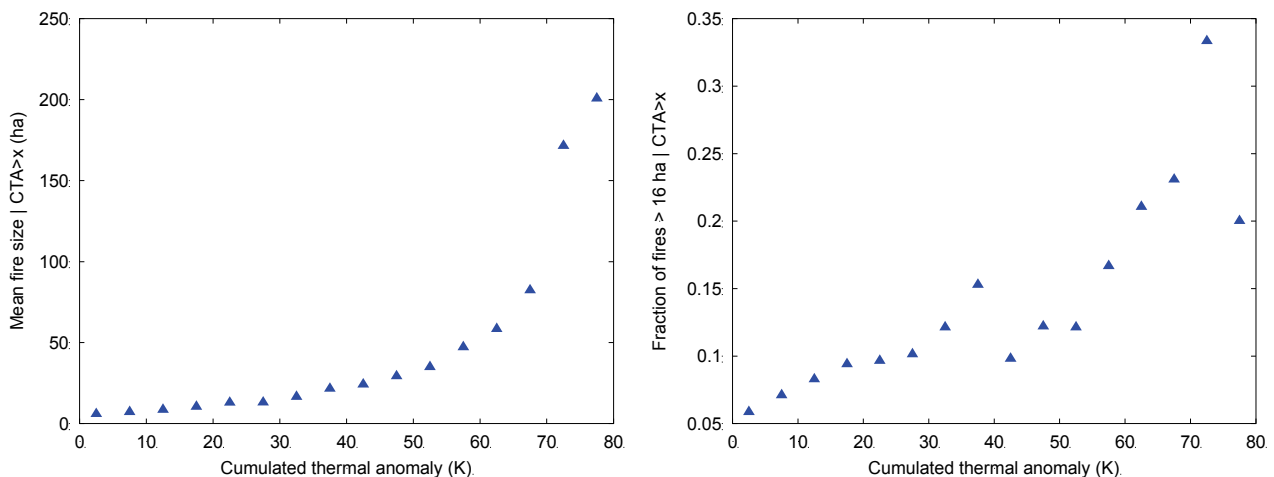


Figure 4: Relationship between conditional mean fire size (left) and conditional fraction of large fires (right) against values of cumulated thermal anomaly (CTA) observed the day previous to the event at the fires' locations.

From the point of view of fire size, cumulated thermal anomaly maps carry a stronger informative content. CTA is a measure of heat “accumulated” in a certain area, providing more direct information on the prolonged exposure of vegetation to stress conditions. This is reflected in the prediction of expected mean fire size over two orders of magnitude (Figure 4), allowing the production of more meaningful fire hazard maps as compared to TA. CTA is also able to predict a larger range of the proportion of large fires.

CONCLUSIONS

The objective of the present research was the use of temporal sequences of *LST* data derived from Terra-MODIS radiance measurements to characterise fire hazard. Results show that the HANTS algorithm plays an important role in both characterising spatial patterns of fire occurrence and in predicting mean fire size. The first of these results derives from the observed selectivity of fires towards areas exhibiting specific values of various Fourier components of the yearly harmonic analysis. The second derives from the clear relationship found between cumulated anomalies of *LST* and conditional mean fire size and proportion of large fires, where the HANTS algorithm was used to construct daily reference *LST* maps against which the cumulated thermal anomalies were evaluated.

The maps of Fourier coefficients exhibit significant yearly variations. Nevertheless, spatial variability might not be uncorrelated with other spatial attributes such as land cover and topography. Moreover, the definitions of anomaly and thermal anomaly adopted herein pose a serious constraint on the data set of fires. The “hard” zeroing of the cumulated anomaly as soon as a negative anomaly is detected has excluded from the analysis roughly 40% of the fires in the dataset. Both the understanding of the effect of landscape factors on the observed spatial patterns of Fourier coefficients and the identification of a more general and inclusive, yet effective, definition of cumulated thermal anomaly are the subject of our current research activities.

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