The Distribution in Time and Space of Savanna Fires in Burkina Faso as Determined from NOAA AVHRR Data

Thomas Theis Nielsen & Kjeld Rasmussen

Abstract

Fires have significant effects on both biological diversity, nutrient cycling and emission of greenhouse gasses in the savanna zones of Africa. The meaning and characterization of the fire regimes of such areas are briefly discussed, and it is demonstrated that time series of NOAA AVHRR satellite images may be used for identifying active fires in Burkina Faso, and thus contribute to the characterization of the fire regime. Most fire activity in Burkina Faso is shown to take place in a brief period after the beginning of the dry season, defined as the date of a sharp increase in surface temperature. Based on an analysis of a small area over a short period the possibility of identifying fire scars, rather than active fires, is demonstrated. Furthermore it is shown that the number of pixels detected as active fire pixels may only be a small fraction of all pixels affected by fire. This has important implications for the use of fire detection methods for assessing the total area affected and the biomass burnt, something which is necessary in studies of gas emissions at a national scale as well as other studies of the impact of fires on the ecosystem. Finally, the future development of fire identification methods using Earth Observation data is discussed, and it is argued that development of fire models, using both Earth Observation and other information as inputs, will be required.

Keywords

Fire, fire regime, savanna fires, Burkina Faso, Earth Observation, NOAA AVHRR.

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Savanna fires are becoming an increasingly important area of study due to the many different effects, both positive and negative. These include effects on biological diversity (Goldammer, 1993) and nutrient cycling (Jordan 1985; Jou & Kang 1989) as well as emission of paprticles and gases of global and local climatic significance (Seiler & Crutzen 1980; Robinson 1989). Fires affect large areas in semi-arid and sub-humid Africa, yet their extent, causes and effects are poorly known.

As a consequence, a cross-disciplinary research project, Fires in Tropical Ecosystems (FITES), was initiated in early 1996 with the aim of studying a range of closely interrelated subjects associated with bush or savanna fires in sub-Saharan Africa. The study areas of FITES encompass parts of Senegal, Ghana, Burkina Faso and Ethiopia, and were selected on the basis of representativity with respect to vegetation and climate within the (broadly defined) savanna zone. The project makes full utilization of well-established research links with local institutions. The present paper will focus on Burkina Faso.

Objectives

The aims of this paper will be to present and discuss results relevant for the characterisation of the fire regime of Burkina Faso, obtained through analysis of NOAA AVHRR satellite data. The discussion will concern both the fire regime as such and the methodologies used and required to characterize it. Furthermore, the suitability of the currently most widely used approach, that of detection of ongoing fires on the basis of their emittance of thermal radiation, for the characterization of the fire regime and for assessments of burnt area and biomass will be discussed.

The fire regime

The fire regime (of a certain location) is a statistical description of the spatial and temporal distribution of fires and their characteristics at that location. No complete list of fire characteristics may be produced, since this will depend on the topic studied, yet the description of the fire regime may include:

- Fire Probability. The probability that a certain small surface, represented by its centre coordinates (x,y), is affected by a fire within a certain time period $[t_1,t_2]$.
- Temporal Temperature Profile. The probability distribution of maximum surface- (or flame-) temperature of the fire front.
- Fire Size. The probability distribution of fire size, that is the contiguous area affected by one individual fire.
- Diurnal variation. The probability of a fire occurring as a function of the time of day.
- Multiple fire incidents. The probability of multiple burnings of the same location.

A full description of the fire regime, based on the above mentioned probabilities and probability distributions, is relatively complex, and obtaining the required information will be unrealistic at a large scale. Earth Observation (EO) satellite data may, however, provide part of the information required. In particular, the distribution in time and space of fires may be assessed, as well as other spatial properties. Derivation of other characteristics of fires, such as temperature and duration, will both require data from other sources and the use of modelling.

Methodologies for detection of active fires and fire scars by use of NOAA AVHRR data.

The rationale of using NOAA AVHRR satellite data for describing the fire regime is simple:

- The AVHRR sensor onboard the NOAA series of satellites measures electromagnetic radiation reflected or emitted by the Earth's surface in five wavelength intervals, relevant to the study of fires, fire scars and vegetation. The first AVHRR channel measures reflected radiation in the visible part of the spectrum (0.58-0.687 µm), the second in the near-infrared (0.72-1.1 µm), the third in the middle infrared (3.55-3.93 µm) and the fourth and fifth in the thermal infrared (10.3-11.3 µm and 11.5-12.5 µm). This allows identification of active fires (channels 3, 4 and 5), fire scars (mostly channels 2 and 4) and vegetation productivity (channels 1 and 2).
- Large areas, entire countries or even continents may be viewed with a high temporal resolution and a moderate spatial resolution of approximately 1 km^2.
- Data can be received free of charge locally using relatively inexpensive equipment and processing can be carried out on a PC.
- Data can be received and processed in near-real time.

Two approaches to the use of NOAA AVHRR data for describing the fire regime are in use:

- Active fires may be detected on the basis of the thermal radiation emitted.
- Fire scars may be identified on the basis of their spectral reflectance properties (and the variations of these in time and space).

In the following the principles and problems of these two approaches are briefly discussed.

Detection of active fires.
Planck's law and its derivatives, combined with Wiens displacement law, states that the maximum wavelength of the emittance of a blackbody with temperatures as those commonly reached by fires (600 to 1000 K), will be in the interval from 5 to 3 µm. In parts of this interval (usually termed atmospheric windows) the atmosphere is relatively transparent, allowing for remote sensing from space of the emittance from fires.

The AVHRR sensor onboard the NOAA series of satellites has a spectral band, channel 3, which is able to detect radiation in a wavelength interval centred around 3.7 µm and thus allows detection of active fires, provided that the fire is large enough to influence the emittance from a pixel significantly. For a number of practical reasons it is not generally possible to invert Planck's law in order to determine size and temperature of fires on the basis of the measured emittance of the pixels in channels 3 and in the thermal infrared part of the spectrum (channels 4 and 5 of AVHRR). Thus, an empirical/statistical classification approach is required in order to detect the presence of a fire in a pixel. Several classification algorithms have been suggested:

- A simple thresholding based on the channel 3 alone, implying that all pixels with a channel 3 brightness temperature higher than a threshold value, sometimes adjusted according to location and time, are classified as fire affected pixels (Kaufman et al, 1990; Kane, 1992).

- A 2-dimensional thresholding based on channel 3 and the difference between channel 3 and channel 4 (Kaufman et al, 1990). This can further be expanded to include a separate channel 4 threshold. The difference between channels 3 and 4 is included in order to compensate for the saturation of the channel 3 for high surface temperatures.
- Thresholding as above, but including an albedo threshold based on channel 2 to eliminate pixels with bright soils (Kennedy et al, 1994), since these may add considerably to the brightness temperature of channel 3.
- As above, but including also a brightness temperature threshold in channel 4 (Kaufman et al, 1990) (Kennedy et al, 1994).
- As above, except for the channel 4 threshold, yet combined with a contextual tresholding: Only pixels differing significantly from the majority of the neighbouring pixels will be accepted as fire pixels (Flasse & Ceccato, 1996; EOS, 1995). In order to be considered significantly different from the background, a candidate pixel has to be warmer than the average plus two standard deviations of the temperature of the pixels in a window around it. This may apply both to brightness temperatures in channel 3 as well as to the brightness temperature difference between channel 3 and 4.

In the present context, the latter algorithm has been used, based on the recommendations of EOS (1995). It includes the criteria of the three first mentioned, and in addition it accepts only pixels as fires, if they differ significantly from the local background, or immediate surrounding pixels. Thereby it solves the problem of, on one hand, establishing a generally applicable algorithm and, on the other hand, assuring that differences in reflectance and emittance of the background are taken into account.

Table 1: Three sets of threshold values, denoted 'Kaufman', 'EOS' and 'Kennedy', used in the classification of active fires. The units refer to respectively Top Of Atmosphere reflectance and Brightness Temperature of the preprocessed Mercator data set.

	EOS	*Kaufman*	*Kennedy*
CH3 Threshold (K)	311	316	320
CH3-CH4 Threshold (K)	8	10	15
CH2 Threshold (%)	20	NA	16

Various thresholds in channel 3, in the channel 3 and 4 difference and in channel 2 have been suggested, among these EOS (1995), Kaufman et al (1990) and Kennedy et al (1994). The thresholds used here are summarized in Table 1. All three sets of constants were combined with a contextual threshold of 3K, as suggested by EOS (1995).

With respect to the description of the fire regime, the problems associated with the use of the above mentioned classification algorithm for detection of active fires are the following:

- The active fires at the moment of image acquisition are only a fraction of the fires occurring during the period, which the image should be representative of. This fraction will depend on many factors, such as the time of day of the image acquisition, the typical duration of fires in that particular region, the time of year, the cloud cover (determining the frequency with which images may be acquired) etc.
- The overpass time of a NOAA satellite drifts through its lifetime, and thus the sample of fires detected will be taken at different times of the day.
- Only a fraction of the pixel affected by the fire may actually be burnt. This fraction will depend on many factors as well, such as the typical size of fires in the particular region and at that time of the year. The method does not allow determination of the fraction of the pixel burnt, nor of the fraction of the biomass of a pixel burnt.

Thus, this approach gives relatively crude descriptions of fire regimes, mostly useful at large, even continental scales, as exemplified by the work of the FIRE project (Koffi et al., 1996). For work at national and sub-national scales and for more comprehensive and quantitative descriptions of the fire regime, improved methods and/or other data sources will have to be brought into use. Some options are discussed in a later section.

Detection of fire scars

Identification of fire scars is important if a quantitative estimation of the total area affected by fires is required and/or if it turns out that the sample of fire pixels detected, using the active fire detection method, is seriously biased.

In addition, a method relying on identification of fire scars is less sensitive to the occurrence of long periods without NOAA AVHRR coverage of a certain location, due to cloud cover or malfunction of data acquisition systems. The period for which a fire scar may be detected has been discussed by Langaas (1995). Fire scars will normally be clearly visible on the ground for at least a few weeks, although this will depend on meteorological and biological conditions. Furthermore the exclusion of the AVHRR channel 3 from future daytime acquisitions imply that detection of active fires will be greatly hampered in the future.

No generally accepted methodology for fire scar identification presently exists, although research in various regions has led to a number of suggestions. Langaas (1995) proposed the use of a pre/post fire index based on the reflection in the red and the near infrared part of the spectrum. In a study of the mediterranean coast of Spain (Pilar Martin & Chuvieco, 1995) it was found that a multi temporal analysis of NDVI (normalized difference vegetation index) resulted in a high level of accuracy when the results were compared with high resolution data as well as fire reports. In a study in Central Africa, ATSR-1 (along-track scanning radiometer) data was used in mapping burned surfaces (Eva et al., 1995), using a multi-temporal analysis of shortwave infrared radiation and thermal infrared radiation. Here, a good agreement between the active fire detection by AVHRR and the area affected by burning derived from the ATSR scanner was found. Furthermore, it was found that the best estimates of burnt area was for the open savanna ecosystems, whereas the results were less reliable in the forest-savanna mosaics. These variations were found to be a function of fire size. Likewise, Barbosa & Gregoire (1995 and pers. comm.) suggests that combinations of GEMI (Global Environmental Monitoring Index), channel 2 and NDVI with surface temperature in a multi temporal and multi threshold analysis, give reasonable results for identification of areas affected by fire using AVHRR/GAC time series in most of the fire affected biomes in Africa. It is also mentioned that the use of other vegetation indices like VI3 and GEMI3 will improve these results as suggested in the work by Pereira (1996) applied to a mediterranean type zone.

Generally it is often possible to devise methods useful for limited areas, although problems are often encountered if the method or algorithm is applied to larger ecological zones.

In the present paper we will demonstrate that it is likely that fire scars in a certain region of Burkina Faso can be identified using NOAA AVHRR data on the basis of the temporal change in the ratio between the measured brightness temperature in channel 4 and the reflectance in channel 2.

The available data and data preprocessing methods

All satellite data was made available by the Mercator project at Space Applications Institute (SAI), Joint Research Centre, Ispra. This data set consists of 164 NOAA (11) AVHRR afternoon pass images, covering the period from June 1st 1990 to June 1st 1991. Originally, data was supplied as scenes measuring 1440 lines of 2048 samples, with an upper left corner offset of 20°N 9°W. Sub scenes measuring 550 lines of 800 samples with an upper left corner offset of approximately 15°N 6°W covering Burkina Faso were extracted for use in this study. The area is outlined in Figure 1. Also included in the data set was the preprocessed NDVI. As part of the preprocessing, channel 1 and 2 were calibrated into Top Of Atmosphere (TOA) reflectance and channels 3, 4 and 5 were calibrated into Brightness Temperature (BT) in K.

Separate cloudmasking was performed using the standard methodologies in SAI's NOAA AVHRR processing chain (EOS,1995).

Results

The temporal and spatial distribution of active fires.
In Figure 2 is shown the distribution in time of detected active fires in Burkina Faso as a whole. The three different sets of threshold values, given in Table 1, were used, and it is seen that results differ widely. One possible criterion for testing the adequacy of the applied thresholds is that fires should not be detected during the rainy season. The Kennedy set of constants is obviously most successful in meeting this criterion. It may, however, be argued that too few fires are detected using these threshold values. Here, the Kennedy set detects 3260 fires, in comparison to the Kaufman thresholds detecting 21273 fires and the EOS set 15797 fires. Even though this question can not be resolved on the basis of the available data, we must assume that

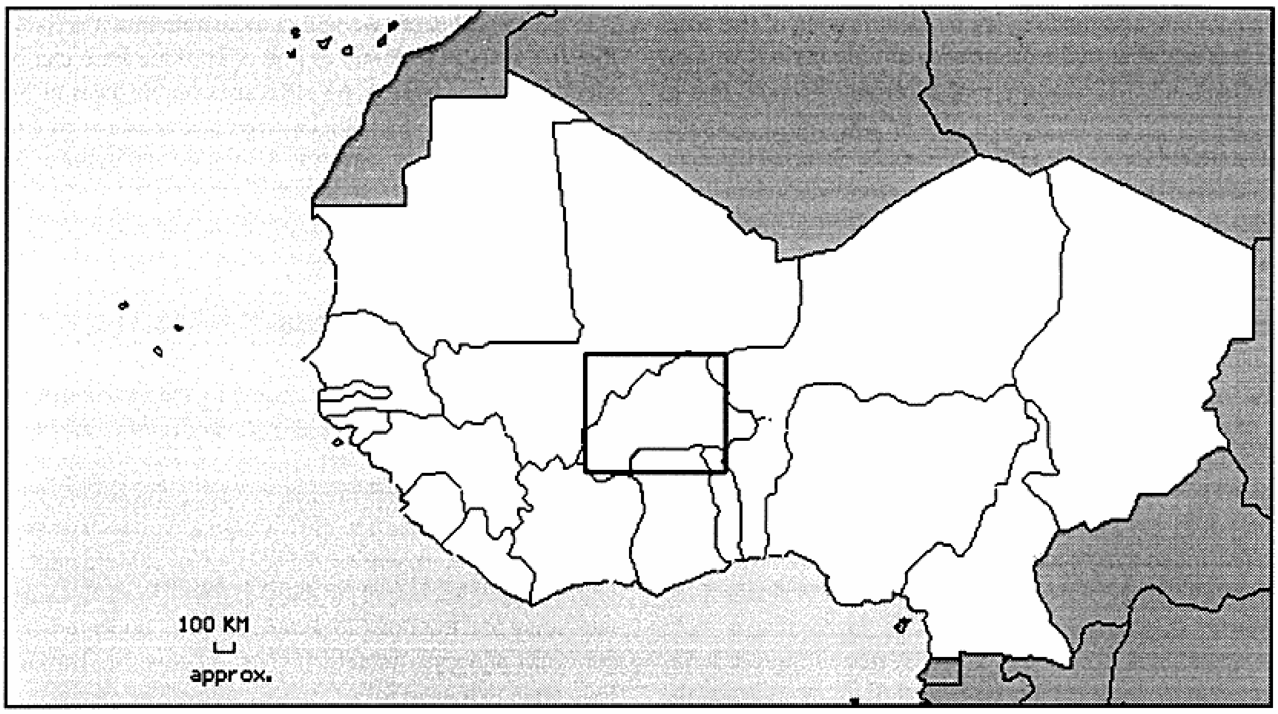

Figure 1: The location of Burkina Faso and the NOAA AVHRR window studied.

whereas the Kennedy set of constants is successful during the rainy season it seriously underestimates the number of fire affected pixels in the dry season. In the following we will assume that the sample of fires, detected using the Kennedy set of constants, is unbiased. In that case, the main objective of this paper - the establishment of the spatial and temporal patterns of fire occurrence - will not be affected by the size of the sample. Thus, the Kennedy set of constants will be preferred in the present context, and it will be used as a basis for the subsequent analyses.

It is obvious from the figure, that the fire season in Burkina Faso is largely confined to a 115 day interval from approximately day 135 (mid October) to day 250 (mid February). Within this interval, a period of one to two months from November to late December can be identified as the most intensive period of the fire season.

As shown in Figure 3, the fire frequency depends strongly on latitude. This is likely to be due mainly to the variation in combustible biomass. An estimate of the variation with latitude of the yearly (dry, above-ground) net primary production (NPP) is also shown in Figure 3, and it appears that fires are only widespread in areas with a yearly net primary production of more than 2000 kg/ha. However, NPP, as estimated using this method, levels out South of the 400 km coordinate, yet the fire frequency continues to rise. Thus there is no simple relationship between NPP and fire frequency. It should be stressed that no field data on NPP were available. The estimation is based on the approach of Prince (1991) and Andersen & Schultz-Rasmussen (1996), relating NPP to the time integral of the NDVI for the growing season. The coefficients used are those of Andersen & Schultz-Rasmussen (1996), determined on the basis of extensive field sampling of biomass by the Centre de Suivi Écologique in Senegal (Diallo et al., 1991). The absolute values may not be precise yet the variation with latitude is believed to be realistic.

It appears from Figure 2 that the great majority of fires occur within one to three months after the onset of the dry season (around mid-October). However, the start of the dry season can be identified as the time of a sharp increase in surface temperature, caused by a decrease in evapotranspiration leaving more of the incoming solar radiation for heating the surface.

Since NOAA AVHRR data can be used for estimation of surface temperatures using the split window method (Price, 1984), the onset of the dry season as a function of location can be identified. Different sets of coefficients can be applied for the split window method. In the present case those originally suggested by Price (1984) have been used. The resulting temperatures appear unrealistically low, although it is assumed that the temporal and spatial variations are realistic. The reason for the somewhat low temperatures may be sub-optimal cloud masking that does not exclude haze-affected pixels or thin, high clouds - a documented effect of the cloudmasking performed (EOS, 1995 p. 29). This will cause a general decrease in the detected average temperature. This decrease will be larger during the rainy season due to the generally higher cloud cover percentage. In Figure 4 average temperatures as a function of the daynumber and the latitude are shown, and overlaid on a 3-D representation of fire distribution in time and space. It is clearly seen from the figure that:

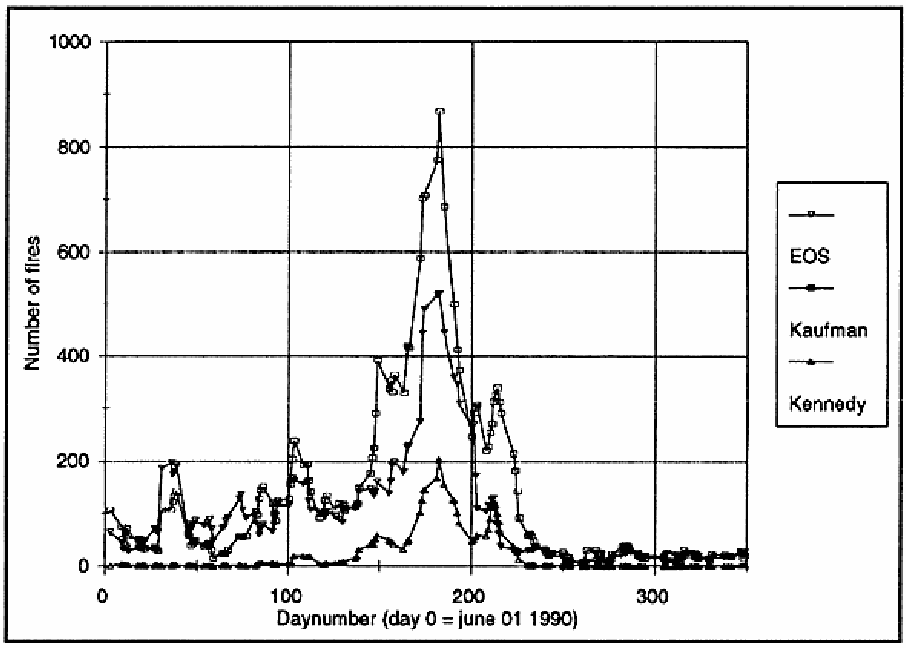

Figure 2: The number of active fires detected, using three different sets of threshold constants, as a function of the day number (June 1st 1990= day 0).

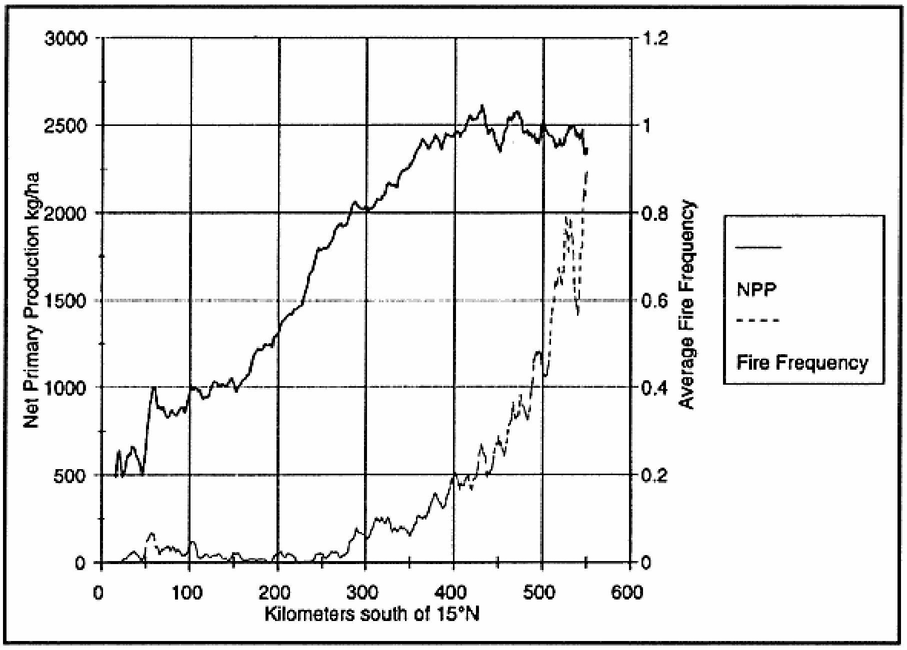

Figure 3: The latitudinal variation of (a) the average fire frequency, calculated as the sum over the year of the number of pixels with detected fires divided by the number of cloud-free pixels for a 1 km wide E-W strip of Burkina Faso, and (b) the yearly net primary production (dry, above-ground), estimated from the integrated normalized difference vegetation index.

- The start of the fires is earlier in the North than in the South.
- The onset of fires is closely related to the sharp increase in surface temperature.
- For each latitude, the great majority of fire occurs within a relatively brief period.
- The temporal span of the fire season is seen to increase from North to South.

In summary, the temporal and spatial distribution of active fires indicates a fire regime that is relative simple for Burkina Faso, although this approach does not allow a quantitative indication of the total extent of fires.

Detection of fire scars

As mentioned, a well-proven methodology for detecting fire scars does not presently exist, although some studies have shown promising results (Eva et al., 1995, Langaas, 1995). Thus, no comprehensive attempt to map fire scars in Burkina Faso has been made since this will require the availability of ground truth data that would allow validation of any methodology applied. In a specific case, the extent of detected active fires will, however, be compared to the extent of (areas appearing to be) fire scars in the NOAA AVHRR images. This is done in order to:

- provide inputs to the subsequent discussion of approaches for fire scar detection, and
- assess the size of the sample of burnt areas, which detection of active fires may provide.

For an area of 50*50 km centred around 12°N 3°30'W, where a substantial number of fire pixels have been identified within a 30-day period, 7 NOAA AVHRR sub-images from the relevant period have been extracted. Four out of these are shown in Figure 5, yet note that the active fires have been identified in all 7 images, and accumulated.

It appears from figure 5 that the locations of active fire pixels correspond to a spreading pattern of pixels with low reflection in NOAA AVHRR channel 2 (near-infrared), and it is safe to assume that this pattern represents fire-scars.

Using the extracted sub-images, the temporal development of the Top of Atmosphere reflectance in channel 2 (TOA_2) and Brightness Temperature in channel 4 (BT_4) and the ratio between them for a burnt (on day 166) and a non-burnt pixel is shown in Figure 6.

With respect to identification of fire scars, it can be seen

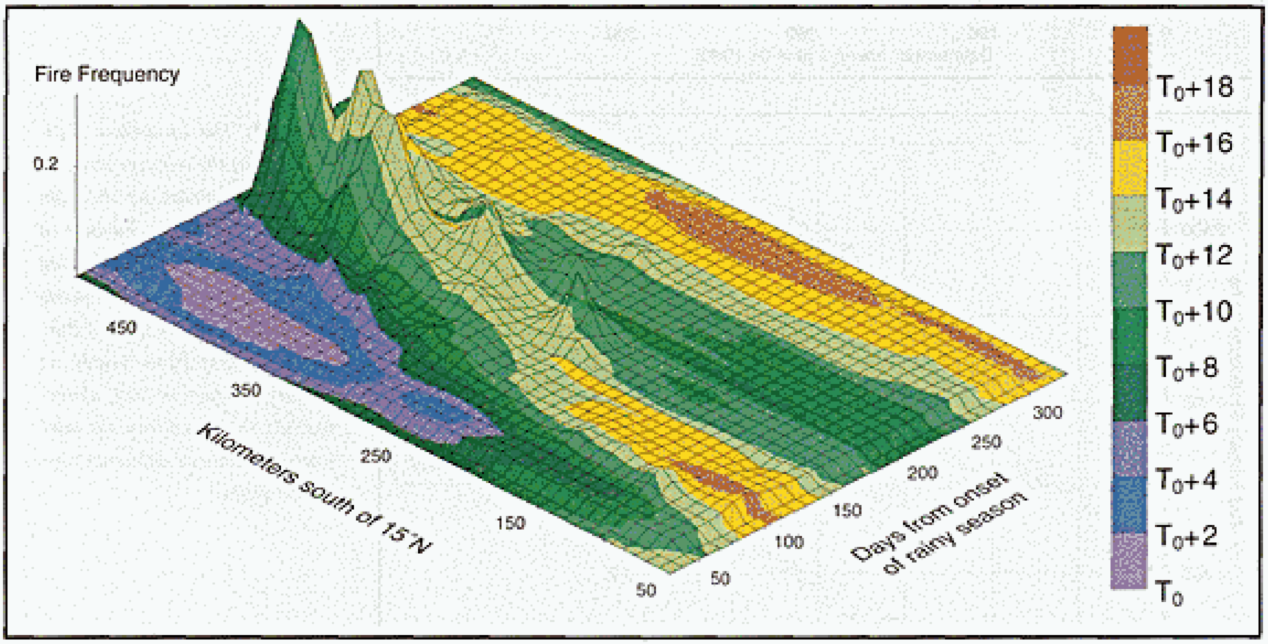

Figure 4: *3D plot of the fire frequency as a function of latitude and day number (day 0 = June 01 1990, the start of the rainy season). Overlayed on the 3D graph is the average surface temperature calculated from 1 km wide E-W strips on the basis of NOAA AVHRR channels 4 and 5, using the split window technique. Note that krieging was used to produce the illustrated results.*

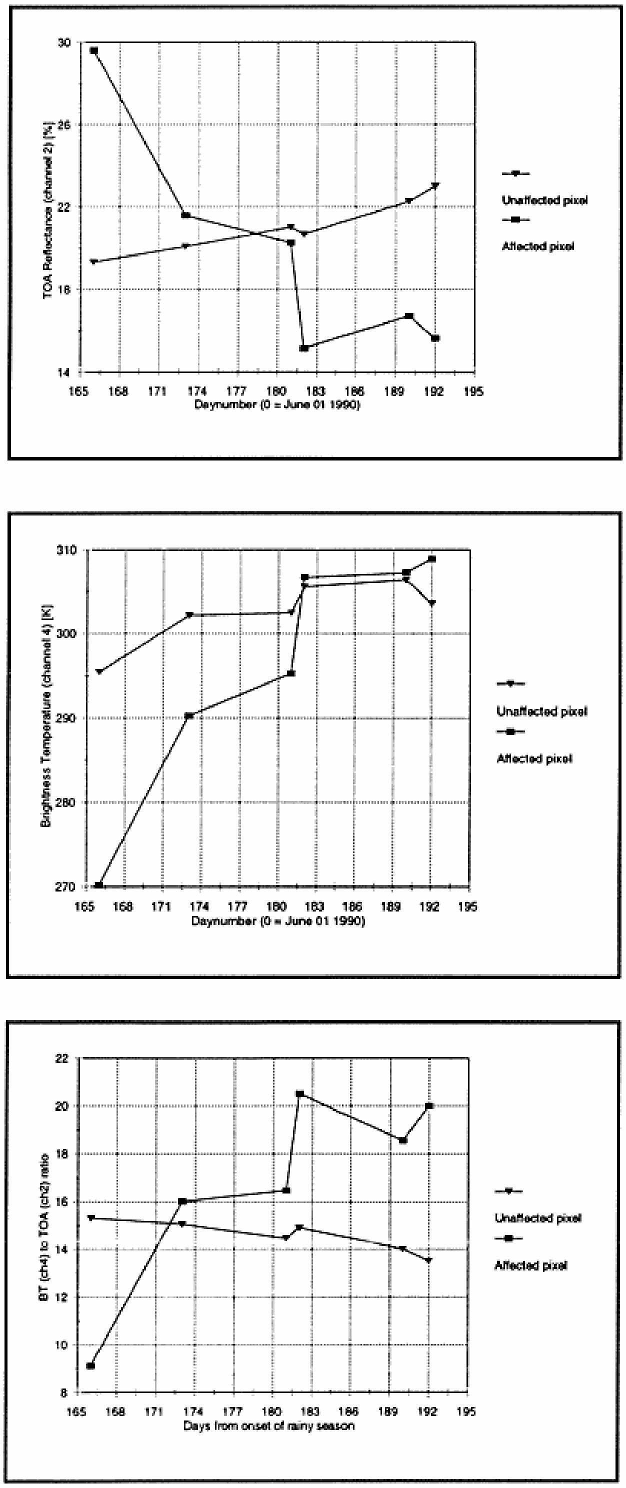

Figure 6: *The temporal variation in reflectance in (TOA) channel 2, brightness temperature in channel 4 and the BT_4 TOA_2 ratio of individual pixels, one burnt on day 166 and one not burnt.*

that in the present case the most marked changes are the drop in TOA_2 and the increase in BT_4. This corresponds to the approach followed by Eva et al. (1995) who classified firescars based on a sharp drop in the short wave infra-red reflectance and an increase in the brightness temperature in the thermal infra-red. It should be noted, however, that the short-wave infra-red channel of the ATSR is quite different from channel 2 of the AVHRR, and better suited for fire scar detection, according to Eva et al (1995). Irespectively of this, a ratio between the brightness temperature, as determined from BT_4 and the TOA_2, may be used as a basis for identifying fire scars.

Figure 5 shows all the pixels in the window experiencing a drop in the BT_4 to TOA_2 ratio of more than 10 percent from one image to the next. A visual/subjective and qualitative analysis indicates that all burnt pixels may well be detected in this way. Both validation of this method and assessment of its general applicability will, of course, require field work and/or analysis of high resolution satellite data.

The size of the sample of burnt pixels that were also detected as active fire pixels can be calculated on the basis of the above classifications.

In this specific case, only 2.6 percent of the burnt pixels, as identified using the fire scar methodology, were identified as actively burning (1363 and 35 pixels respectively). This number should only be seen as an indication since many factors will control this sampling fraction, including the constants used in the active fire detection algorithm, the interval between image acquisition, the cloud cover and the fire regime itself.

Discussion

The results presented here illustrate that a simple characterization of the fire regime of Burkina Faso may be achieved by applying the well-established methodologies for identification of active fires. The fires in the central and southern part of Burkina Faso start within few weeks after the beginning of the dry season. Among the different set of coefficients found in the literature, the Kennedy-set seems to be the most applicable to Burkina Faso, judged by its ability to produce a temporal distribution of fires that is in accordance with *a priori* knowledge. The threshold set is, however, conservative and leads to the detection of relatively few fires. The unavailability of validation data im-

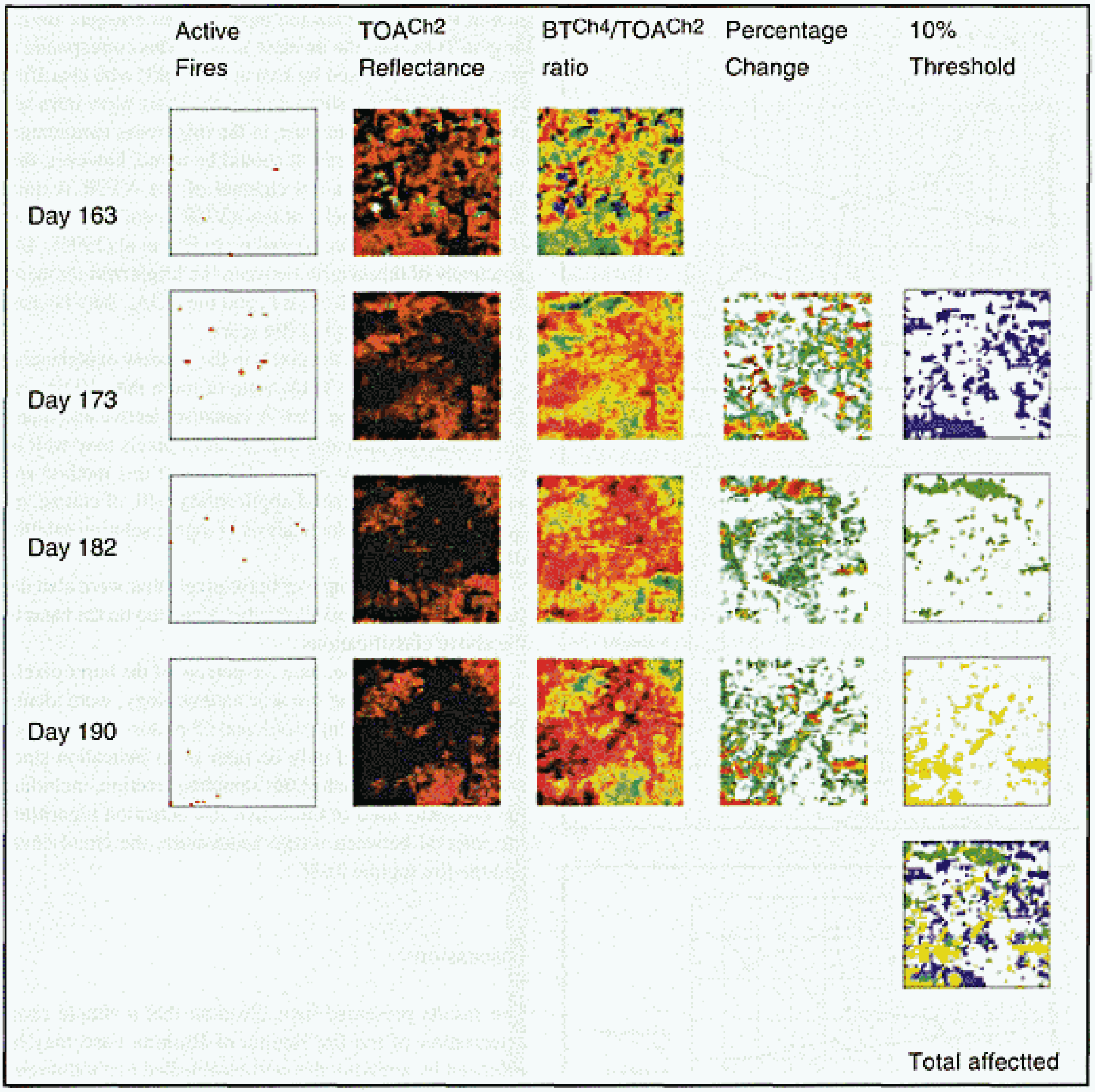

*Figure 8: The evolution of active fires and fire scars between day 163 and day 190 for a 50*50 km^2 area, centred around 12oN 3o30W. The figure illustrates:*

A the detected active fires in the periods between the four images shown,

B channel 2 of NOAA AVHRR, extremely high values are shown in green, high in red and low values in black,

C the BT_4 to TOA_2 ratio,

D the change in the BT_4 to TOA_2 ratio from one image to the next. Large negative changes are shown in red, smaller negative in green, no change and increase in white,

E the new fire scars, appearing in the period between two images, classified on the basis of an increase in the BT_4 to TOA_2 ratio of more than 10%.

plies that this conclusion, as well as the following, must be considered preliminary.

The variation of fire occurrence with latitude shows that few fires occur where the yearly net primary production is less than a given threshold value, which appears to be in the order of 2000 kg/ha as estimated using the integrated NDVI method with coefficients determined in a similar climatic zone in Senegal. If correct, this threshold may well be used as an input to predicting the extent and location of fires before the start of the dry season.

With respect to characterising the fire regime, as defined earlier, the results obtained demonstrate certain limitations: The active fire pixels detected constitute a sample of all burnt pixels. The size of the sample is probably small. The example given illustrates that the sample fraction may be less than 5 percent. Furthermore, it must be expected that this fraction varies considerably, is controlled by a range of factors, and is likely to be biased. Yet the present study does not provide evidence on the direction and magnitude of such possible bias. Thus, assessment of the absolute fire probability and its variation in time and space will not be realistic, whereas relative probabilities may be obtained. As a consequence, it is important to move towards the identification of fire scars and away from the detection of actively burning fires. This will be particularly important when quantitative assessments of burnt area and biomass are required, e.g. in relation to establishment of national budgets of greenhouse gases.

The example given illustrates that temporal changes in reflectance of near-infrared as well as in surface brightness temperature may constitute a good basis for identifying fire scars. Development and validation of a robust and widely applicable algorithm should be a research priority. Since the background, or surroundings, of fire scars differs - in reflectance and emittance properties - we expect that inclusion in the algorithms of neighbourhood constraints will be necessary, as in the case of active fire detection.

Future prospects.

In the present study, NOAA AVHRR data have been the basis for identifying active fires, thus forming the basis for characterizing the fire regime. In the future the AVHRR sensor will not have the middle infrared channel (channel 3) during the daytime and thus methods, such as those for detecting active fires used in the present study, based on day-time emittance from active fires will not be possible. Future work using EO data for fire studies will, therefore, have to rely on other methods and data sources. The following approaches and data sources should be considered:

- Use of NOAA AVHRR and future look-alikes for mapping fire scars, as discussed briefly above.
- Use of the Second Generation Meteosat (MSG) that is planned to be in orbit in year 2000. One advantage of MSG is that it will provide very frequent observations (one image per hour). In addition, data may be received in near real-time using simple and inexpensive equipment. The spatial resolution will, however, be low (~3 km).
- Limitations of present methods caused by the inadequate spatial resolution of the sensor (> 1 km) may be overcome by using data from medium resolution satellite-sensor systems, such as RESURS and SPOT Vegetation. In addition, the latter will be equipped with a channel in the short wave infra-red, suitable for detection of fire scars. The practical and large scale application of these data sources will, of course, depend very much upon pricing policies and efficiency of data distribution systems, and in particular on whether local reception is possible.
- Use of SAR-data may become an interesting area of study. Savanna fires can be expected to result in significant changes in surface roughness which should make it possible to detect them in SAR-images. However, the high resolution and small swath of most SAR-systems, and the associated high cost per square kilometre, indicate that they may not be useful in large-scale studies.
- High-resolution data (e.g. from SPOT HRV and Landsat TM) may be used to calibrate and validate operational methods, requiring less costly data, available at shorter intervals. Such work is already in progress.

Irrespective of what EO data will become available in the future, not all of the information required for a full characterization of the fire regime can be extracted from EO data. A useful direction to proceed may well be the integration of EO data into fire models that incorporates data from other sources, such as vegetation and geomorphological maps and meteorological observations. The development of such models is still in its infancy.

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