Indonesian Forest Fire – A Quantitave Assessment

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Keywords: forest fires, fire potential, fire danger, fuels, NDVI, TOMS, Kalimantan Island, Indonesia

Abstract. The Indonesian forest fires have affected the environment since biomass burning has released aerosol, black carbon, and other particles to the atmosphere. In this research, an algorithm for assessing forest fire potential is tested for Kalimantan Island, Indonesia. It is based on a fuel model map modified from the US-National Fire Danger Rating System (US-NFDRS), Normalized Difference Vegetation Index (NDVI), and weather data. The Indonesian fuel model map was derived using the global 4-minute land cover data set consisting of 13 classes. The NDVI data was derived from the global 4-minute NOAA-AVHRR data. The output is presented as a monthly Fire Potential Index (FPI) from 1981 to 1993 and compared with trends in fire occurrences over the same time period. A case study illustrates correlation between the FPI and the hot-spot distribution derived from AVHRR data, as well as between the FPI and the Total Ozone Mapping Spectrometer (TOMS) Aerosol Index.

Introduction

Fire has become one of the greatest threats to tropical rainforests in the last two decades, especially in Indonesia. Dead biomass resulting from selective logging serves as fuel for fires: large-scale pulpwood companies and industrial crop plantations, as well as local farmers, use fire to clear the land and burn agricultural waste (Schweithelm 1998). Severe drought caused by El Niño has a major influence in creating conditions that lead to uncontrolled fire spread over large areas of tropical rainforest, grass and bushland. Due to the lack of comprehensive fire data in Kalimantan Island, however, the size and damage levels of burnt areas are uncertain. Potentially, remote sensing data can be used to efficiently obtain this information (Siegert and Hoffmann 1998). Another important aspect in which such data can contribute is development of methodologies for monitoring and predicting fire occurrence and assessing fire potential across the region.

Various methods have been implemented for forecasting fire danger on the basis of different assumptions. In general, meteorological factors play an essential role (Chandler 1983). The US National Fire Danger Rating System (NFDRS) is based on quantitative investigations as well as on laboratory experiments concerning the influence of various fuel, weather and topographic factors on fire behavior (Rothermel 1972). In the NFDRS, various parameters are used to describe fire danger (Wybo *et al*. 1995; Deeming *et al.* 1972). The NFDRS was first introduced in 1972 (Deeming *et al*. 1972), and has since been revised twice, in 1978 (Deeming *et al*. 1977) and in 1988 (Burgan 1988).

The fire potential index (FPI) was developed by Burgan (Burgan *et al.* 1998) to test whether satellite observations of vegetation greenness could be combined with moisture estimates of small dead fuel, as derived from surface weather data, to produce a useful measure of fire potential. This paper describes the first attempt to test the efficacy of the FPI in a tropical setting. We present the FPI model and utilize it at a resolution of 8 km. The results with the FPI are compared with the monthly hotspot data on September 1991, which was calculated from Global Area Coverage (GAC, 4-km resolution) NOAA SAA (Satellite Active Archive, htpp://www.saa.noaa.gov) data. The 1991 data were chosen for hotspot analysis, since only a few 1982-1983 (the most serious drought period) data were available in the archive.

The FPI features are compared also with the Aerosol Index (AI) observed by Total Ozone Mapping Spectrometer (TOMS). Both indexes are calculated for a time span of 13 years between 1981 and 1993.

Outline of the FPI Calculation

In this paper, forest fire events in Kalimantan Island are analyzed by means of monthly FPI values calculated using the method developed by Burgan. The input parameters required for the FPI calculation are summarized in Table 1.

The procedure for calculating the FPI is illustrated in Fig. 1. Because of the considerable differences in fuel types between the present tropical case and the US-NFDRS case, we develop a fuel model map on the basis of the vegetation types in Kalimantan. This map is used to assign dead fuel extinction moisture (DFEM) for the vegetation of Kalimantan.

Table 1. Input parameters used in the FPI calculation

Variable	Parameter	Value range	Period	Definition
NDVI	Normalized Difference Vegetation Index	-1 ~ 1	Monthly	Eq. (1)
RG	Relative Greenness	0~100(%)	Monthly	Eq. (2)
DFEM	Dead Fuel Extinction Moisture	25~40(%)	Table 2	Table 2
MLR	Maximum Live Ratio	35~80(%)	Single map	Eq. (3)
LR	Current Live Ratio	0~80(%)	Monthly	Eq. (4)
TTFMR	Rainfall-adjusted 10-hour Timelag Fuel Moisture	2~40(%)	Monthly	Eq. (5)
FPI	Fire Potential Index	1~100	Monthly	Eq. (8)

NDVI Data

We employ NDVI data obtained from the twenty-year, global, 4-minute (8-km resolution), AVHRR NDVI dataset (Tateishi 2000). The source of this dataset is the Pathfinder global, 4-minute, 10-day composites obtained by AVHRR on the National Oceanic and Atmospheric Administration’s (NOAA) TIROS-N series of polar-orbiting weather satellites. The NDVI is calculated from the visible and near infrared AVHRR channels as:

$$NDVI = (Ch_2 - Ch_1)/(Ch_2 + Ch_1), \qquad (1)$$

where Ch_1 is the reflectance in the visible wavelengths (0.58-0.68 μm), and Ch_2 is the reflectance in the infrared wavelengths (0.725-1.1 μm).

Relative Greenness (RG)

Relative greenness (RG) is derived from the NDVI and used to define seasonal changes in the proportion of live to dead vegetation. The values are scaled from 0 to 100(%), with low values indicating that the vegetation is at or near its minimum greenness. The basis for calculating RG is the historical minimum and maximum NDVI of each pixel (Burgan and Hartford 1993). We use all the available NDVI data from 1981 through 2000 as the source of the historical data. The relative greenness is calculated from the monthly and historical minimum and maximum NDVI values using the following relationship:

$$RG = \left(\frac{NDVI_o - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \right) \times 100, \qquad (2)$$

where $NDVI_o$ is the highest NDVI value of each pixel in a 10-day composite period for each month, $NDVI_{max}$ is the historical (1981-2000) maximum NDVI for that pixel, and $NDVI_{min}$ is the historical minimum NDVI for that pixel.

An example of the RG map for Kalimantan Island is shown in Fig. 2(a) (for September 1982). As seen from this figure, RG values are low in the southern and western parts of the Island due to the long drought in 1982, which resulted in severe forest fires in those areas. For comparison, the corresponding NDVI map scaled from 0-100% is shown in Fig. 2(b). It is seen that the two maps exhibit similar distributions, but RG map is more indicative of the fuel situation owing to the incorporation of the historical ranges of NDVI.

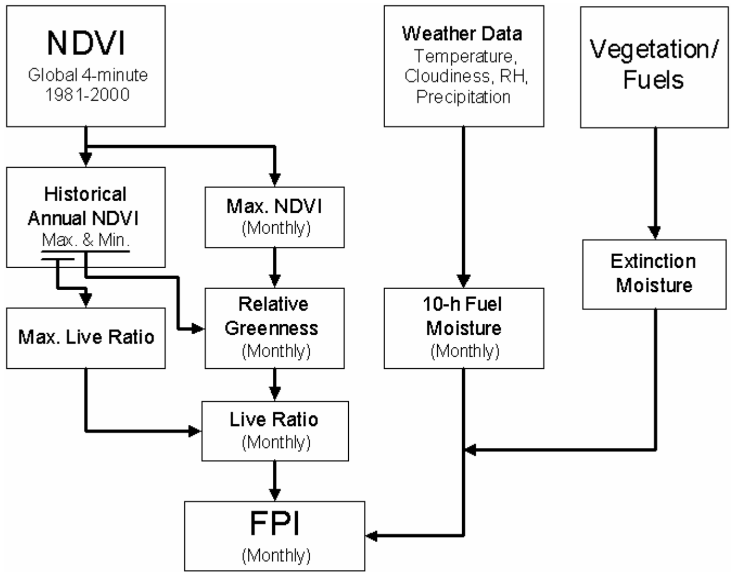

Fig. 1. Schematic diagram of the FPI Algorithm

Fuel Model Map

Numerous parameters define the US-NFDRS fuel models, such as fuel load by size class, surface area to volume ratios of the various size classes, heat content, dead fuel extinction moisture, wind reduction factors, and mineral damping coefficients (Burgan *et al*. 1998). The FPI algorithm, makes use the DFEM parameter to evaluate the relative dryness of dead vegetation.

We employ a vegetation map illustrated in Fig. 2(c), which is based on vegetation classes as derived from the 4-minute resolution Asian Association on Remote Sensing (AARS) Global Land Cover dataset. Originally, global, 8 km, 10-day composite AVHRR NDVI data from January 1, 1990 to December 31, 1990 were used for the development of this land cover dataset. These AVHRR data are part of the NOAA/NASA Pathfinder AVHRR Land Data Set (Agbu and James 1994). Table 2 lists the 13 vegetation classes assigned to the vegetation on Kalimantan Island, with the pixel count and DFEM value associated with each class. The assignments of DFEM values are based on values indicated for the US-NFDRS fuel models, but increased in an attempt to account for the tropical environment of Indonesia.

Table 2. Extinction moistures used for calculating the FPI

Class	AARS Category	DFEM (%)	Vegetation Represented	Number of Pixels
0	0	--	Waters, including Ocean and Inland Waters[1]	34164
1	10	40	Vegetation	3194
2	12	40	Forest or shrubland	13
3	14	40	Evergreen forest or shrubland	12986
4	18	40	Evergreen broadleaf forest	36
5	120	40	Mixed forest or shrubland	7
6	130	30	Grassland	55
7	132	30	Natural grassland/pastures	16
8	140	30	Grass crops	80
9	146	30	Wheat and rice	18
10	184	25	Dwarf vegetation	21
11	191	--	Bare ground[1]	29
12	222	--	Inland water[1]	6

[1] Fire Potential Index not calculated for this case

Maximum Live Ratio Map

In the original formulation of the FPI algorithm, maximum live ratios (MLR) were determined as a function of the live and dead loads assigned to each fuel model. However, this occasionally resulted in similar live ratios for fuel models of very different vegetation types. To avoid such a situation, our MLR map is derived from the maximum NDVI map of Kalimantan Island, under the assumption that these two parameters are directly related.

$$MLR = 35.0 + 45.0(ND_{max} - 62.4)/36.8, \quad (3)$$

where: $ND_{max} = NDVI_{max} \times 100$. The historical maximum NDVI map between 1981 and 2000 gives minimum and maximum values of 0.624 and 0.992, respectively. Thus, according to Eq. (3), the MLR value ranges from 35% for the driest areas, to 80% for the wettest areas. The MLR map for Kalimantan Island is shown in Fig. 2(d) where reddish parts in the northern, western and southern parts of the island exhibit the lowest maximum live ratios.

The current live ratio (*LR*) as denoted in percentage, is defined for any given date as

$$LR = 100(RG/100)(MLR/100). \quad (4)$$

This parameter defines the proportion of live vegetation to the maximum available live vegetation

Rainfall-adjusted, 10-hour-timelag dead fuel moisture (TTFMR)

The probability that a wildland fire spreads is strongly dependent on the moisture content of small dead vegetation. The US-NFDRS separates dead fuel moisture responses into timelag classes of 1, 10, 100, and 1000 hours (Deeming *et al.* 1977). A timelag period is defined as the time span in which the moisture content changes about 2/3 of the difference between initial and final conditions. We use the 10-hour-timelag dead fuel moisture. This parameter is calculated from temperature, relative humidity, state of weather (cloudiness), and precipitation amount obtained from the weather data as follows:

$$TTFMR = FM_{10} + (DFEM - FM_{10})R_f, \quad (5)$$

where *TTFMR* is the 10-hour-timelag dead fuel moisture adjusted for precipitation amount, FM_{10} is the 10-hour dead fuel moisture without any rain, and R_f is the rain fraction. This last parameter, R_f, is derived from an estimate of the amount of rain required to wet the small dead fuels to extinction moisture. Since $0 \le FM_{10} \le 40$, $0 \le R_f \le 1$, and $25 \le DFEM \le 40$(%), the value of *TTFMR* ranges between 2-40% (we impose a lower limit of $TTFMR \ge 2$; see also Eq.(7) below).

Weather Data

Global meteorological data, with the grid size of 0.5° latitude by 0.5° longitude, are available from the Climatic Research Unit (CRU), and are used for this analysis (CRU05 1998). There are 33 WMO stations on the Kalimantan Island, more or less uniformly covering low lands, but providing minimal coverage for the northern and central mountain areas on the island.

In the fire potential computation, mean temperature, precipitation, relative humidity, and cloud cover are used as input parameters. Additionally, to obtain the relative humidity (RH), we used the following empirical formula:

$$RH = \frac{e}{e_s} \times 100\%, \quad e_s = 6.39\exp(19.65 \times (T - 273)/T), \quad (6)$$

where e is the vapor pressure, and e_s is the saturation vapor pressure at a given temperature T.

FPI Computation

The FPI is calculated only for pixels of a valid fuel type, with agriculture land, barren land, etc. being excluded from the analysis. For each pixel, calculation of the FPI proceeds as follows:

1. Current live ratio (*LR*) is calculated by Eq. (4)
2. The fractional 10-hour fuel moisture, TN_f, is calculated from *TTFMR* and *DFEM*

   $$TN_f = (TTFMR - 2)/(DFEM - 2). \quad (7)$$

   The subtraction in the numerator ensures that the minimum value of TN_f is 0. In the FPI calculation (see below), “dryness” fraction is represented by (1-TN_f).
3. Finally, the value of FPI is calculated as

   $$FPI = 100(1 - TN_f)(1 - LR). \quad (8)$$

   Here (1-*LR*) stands for the “deadness” fraction.

TOMS Aerosol Index

Aerosol Index (*AI*) is determined using the 340 and 380 nm wavelength channels (which exhibit negligible dependence on ozone absorption) as follows:

$$AI = -100\left\{\log_{10}\left(\frac{I_{340}}{I_{380}}\right)_{\text{meas}} - \log_{10}\left(\frac{I_{340}}{I_{380}}\right)_{\text{calc}}\right\}, \quad (9)$$

where I_{meas} is the backscattered radiance measured by TOMS at the specified wavelength, and I_{calc} is the radiance calculated using a radiative transfer model for a pure Rayleigh atmosphere. As discussed by Torres *et al.* (1998), the AI is a measure of the wavelength-dependent reduction of Rayleigh-scattered radiance by aerosol extinction relative to a pure Rayleigh atmosphere. For a comparison with the FPI results, the AI data from NIMBUS 7 TOMS, uniformly gridded, level-3 data product (1° × 1.25°), are used. The AI parameter corresponds linearly to the aerosol optical depth (AOD) in the atmosphere. In this case, the monthly averaged AI shows the quantitative loading of aerosols not only from the fire, but also from other anthropogenic sources, as well as sea-salt from the ocean.

Results

Vegetation Distribution Maps

For this study, the area and time of interest is Kalimantan Island from 9.56°N, 105.6°E to 5.56°S, 120.6°E during July 1981 to December 1993. Fig. 2(b) illustrates the NDVI map for the island in September 1982. (Note that the scale is converted to 0-100% in this figure.) The original vegetation map for the area of interest is shown in Fig. 2(c). Most of the vegetation is categorized into evergreen forest or shrubland, while 19% of land pixels belong to class 1 (vegetation).

The DFEM map was constructed by assigning values to the various vegetation types. As explained above, the factor ($1\text{-}TN_f$) in Eq. (8) stands for the “dryness” of the fuel, and this value increases as the value of DFEM increases, as indicated by Eq. (7). It turns out that in most cases the assigned value of DFEM is close to 40%, the maximum value in the present analysis (see Table 1). Thus, as far as DFEM is concerned, a value of 40 characterizes the tropical rain forest.

Fire Potential Index

The algorithm is applied over a 13-year period (1981-1993) to assess conditions of forest fires on the Kalimantan Island. In particular, the most severe drought occurred in 1982-83, followed by slightly less severe droughts in 1987, 1991 and 1994. Figure 3(a), (b), and (c) depict the FPI maps calculated for August, September, and October, 1982, respectively. Comparison among these three plates indicates that the initial, spot-like increase of FPI in August (Fig. 3(a)) led to a conspicuous increase (FPI>40) in most of the southern island in September (Fig. 3(b)); then in October, substantial reduction was observed (down to $\text{FPI} \le 35$) in the western and eastern regions, while the southern region still exhibited high FPI values (Fig. 3(c)).

The AI distributions for the same time period are shown in Fig. 3(d)-(f). The temporal variation of the AI distributions is considered to represent the magnitude of the wildland fires, giving information on aerosols resulting primarily from biomass burning. It is seen that the aerosol distribution is denser in the southern part than in the western part, with aerosol transportation to the sea areas south of the Kalimantan Island.

The FPI features are also consistent with actual 1991 fire occurrence in the area, detected as hotspots from SAA NOAA data, as shown in Fig. 4(a)-(c). These are the composite data showing average values on September 1991. Hotspots are detected by empirically deriving thresholds for channel 3 temperatures and/or the temperature differences between channel 3 and 4 of AVHRR

(Kaufman *et al.* 1990). Figure 4(c) shows that hotspots are found mostly in the western, southern and eastern parts of the island, indicating major fire locations in this significant fire event. Comparison between the hotspot map and FPI map indicates that 89% hotspot pixels in Fig.4(c) correspond to pixels with FPI>60 in Fig.4(b), and 99% hotspot pixels to those with FPI>45.

Conclusions

Two cases of large forest fires (1982/83, 1991) have been treated in this work on the basis of the monthly potential fire index calculated between 1981 and 1993. It has been shown that both spatial and temporal distributions of the FPI exhibit good correlation with those of the TOMS Aerosol Index in the southern province of Kalimantan. It has also been shown that high FPI values were associated with actual fire occurrence in 1991. Thus, this work indicates that the FPI algorithm can be successfully applied to tropical fire warning systems, even though the relevant parameters such as dead fuel extinction moisture, temperature, precipitation, relative humidity and cloud coverage are remarkably different from the case of US-NFDRS.

Since this study was limited to monthly FPI calculations from historical data, additional research would be required to determine whether the FPI calculations could be more operatively useful for fire management if they were computed weekly or daily. Challenges in application of a daily FPI computation capability include obtaining timely satellite and weather data, distribution of the FPI maps to fire managers throughout Indonesia, and their ability to implement fire regulations.

Acknowledgements

The authors thank Prof. Ryutaro Tateishi of CEReS, Chiba University, for providing the Global NDVI and Land cover dataset.

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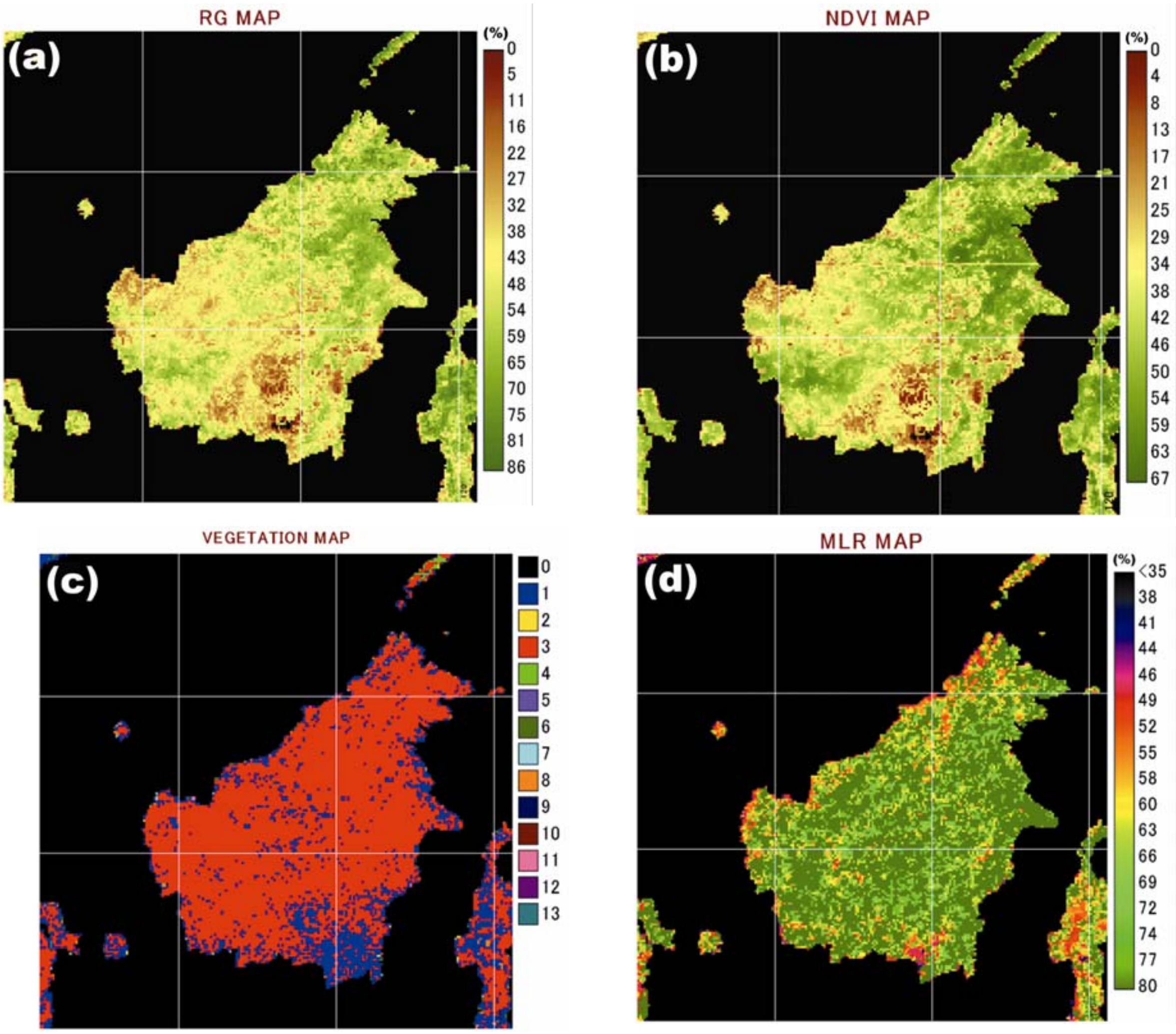

Fig. 2. (a) RG map and (b) NDVI map in September 1982; (c) Vegetation Map, and (d) Maximum Live Ratio Map.

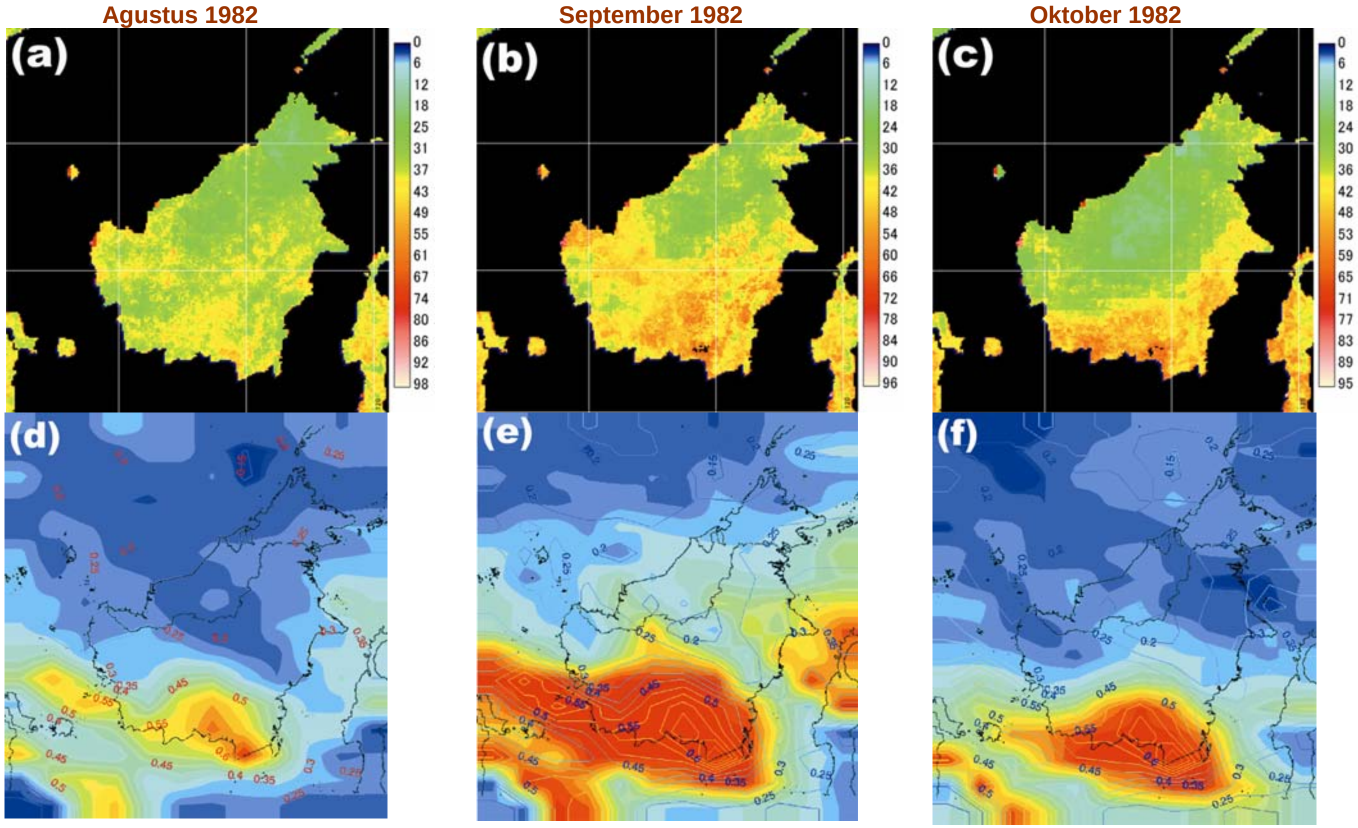

Fig. 3. Distributions of FPI ((a)-(c)) and TOMS AI ((d)-(f)) during the fire event in August, September, and October 1982.

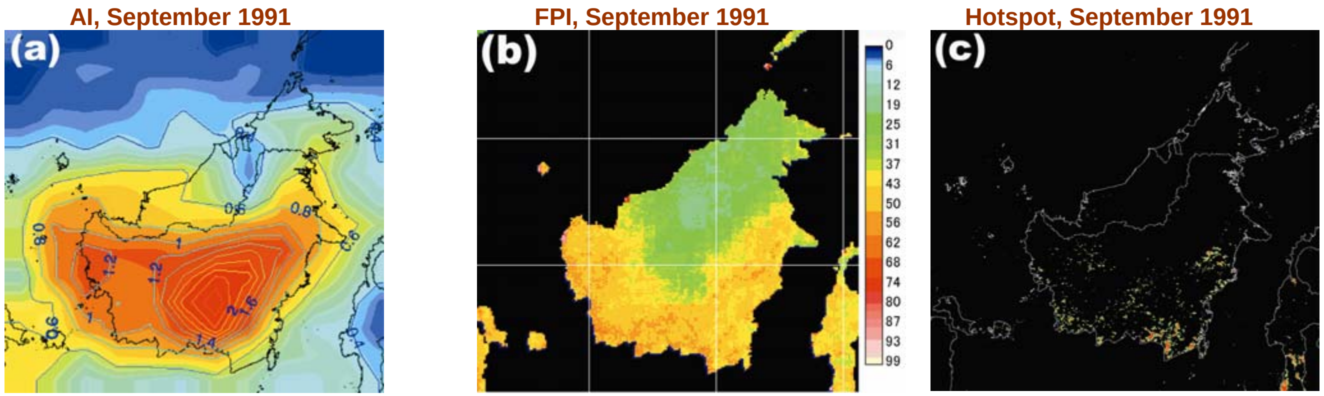

Fig. 4. Distributions of the AI, FPI and hotspots in September 1991