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An extreme CO pollution event over Indonesia measured by the MOPITT instrument

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Abstract

In the fall of 2006, the Measurements Of Pollution In The Troposphere (MOPITT) instrument on the Terra satellite observed an extremely high Carbon monoxide (CO) concentration over Indonesia. This extreme event was caused by huge fire activity during the 2006 El Nino event. From our comparison with other high CO pollution events over Indonesia during similar and moderate El Nino events, we conclude that the 2006 fire activity, which caused large-scale pollution in this region, was probably amplified by an increase in frequency and/or intensity of lightning activity in a feedback mechanism. We also observed that after the fire episodes in El Nino years, the "lightning rate" was less than during the fire episode but displayed an increasing trend across the three events observed that might have been be caused by interactions with fire smoke plumes.

1 Introduction

Extreme weather events are important due to their large and possibly irreversible impact on our environment and on human life in general. The analysis of extreme events can be relevant to understanding long-term variability and trends in climate including the crucial issue of anthropogenically induced climate change (see Easterling et al., 2000 and references therein). An extreme event was recently observed in the level of CO over the equatorial region. The measurements by the MOPITT (Measurement Of Pollutions In The Troposphere) instrument (Drummond, 1992; Drummond and Mand, 1996; Drummond et al., 2008) on board the NASA Terra Spacecraft show a high concentration of CO at the beginning of November 2006 over the Indonesian region as a result of high fire activity. This major pollution event over Indonesia was confirmed locally and commented on by mass-media (see for example Nasa news NASA, 2004 and NASA, 2007).

It is known that the warm temperatures and reduced rainfall during the El Nino episodes are the main pre-conditions for biomass burning and widespread fires. In the last decade, 2002, 2004 and 2006 were moderate El Nino years. The El Nino year 2004 was the weakest one and as expected, so was the fire activity. The question that we address in this paper is why the Indonesian fire activity of 2006 was much larger than 2002, when, according to the standard measures, the 2006 El Nino was similar or even slightly weaker than 2002.

2 Event description and data sources

Figure 1 a shows the time series of daily average MOPITT-CO Total Column over Indonesia as well as over another equatorial region ("Africa") where very high CO levels can be observed. The regions selected are rectangular and of the same area covering latitudes ±10° and longitudes 60° E–150° E for "Indonesia" and 40° W–50° E for "Africa". Up to the fall of 2006, the highest CO total column values were over African region, a region where there is always high seasonal fire activity. Around 3 November 2006 (Fig. 1b), the CO total column over Indonesia reached the highest value ever observed by MOPITT for either region. This extreme CO pollution event is almost 35% higher than the normal high levels recorded in the previous seven years of the MOPITT measurements. It is bigger than any "African" maximum and is much more impressive due to the fact that the Indonesian land area (where the fires occur) is much less than the African land area.

It is interesting to note that due to the seasonal variations, the correlation between the CO Total Column over Indonesia and the African regions is well defined, except during the fall of El Nino years (see Fig. 2). The high CO values over Indonesia during the last three El Nino events are uncorrelated with the African region and appear to be independent of the general equatorial trend.

There are two main satellite-based data sources for estimating the extent of fire – usually designated by "hot spots" (HSs) or areas of high thermal emission: the ERS-2 and ENVISAT missions (ATSR, 2007) and the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on Terra satellite (GFEDv2). The ATSR World Fire Atlas (ATSR, 2007) extends from 1995 to present (ERS-2 and ENVISAT). All HSs (including gas flares) with a high temperature at night are precisely located using a 3.7 μm channel. The Global Fire Emission Database version 2 (GFEDv2) contains monthly burned area, total carbon emissions, trace gas emissions and aerosols (van der Werf et al., 2006; GFEDv2). It uses MODIS HSs as input data (Giglio et al., 2003).

These two data sources produce a consistent picture of the fire activity. For example, for the Indonesian region in 2006 the monthly CO emission of GFEDv2 based on MODIS fire observations is very well correlated (correlation coefficient >0.92) with the monthly number of HSs produced by ENVISAT night observations. For the time interval from 2000 to 2007, we found that the two databases over Indonesia agree very well.

Comparing the two similar El Nino years 2002 and 2006, we found for this region two main fire seasons per year roughly co-incident with the equinoxes. The March season is small with only a few fires located in the north, mainly in the north of Sumatra. The second, the Fall season, has higher activity with fires the in south of Indonesia (south of Sumatra and Borneo). The spatial distribution is similar for both years. In 2002 the fires peak in September (with a width of ~1.5 month) and in 2006 in October (with a width ~0.5 month). The total number of HSs observed over this region is a maximum (almost 4× more fires than average) for October 2006.

A good correlation between the variations of the CO total column as measured by MOPITT and the estimate of CO emissions from GFED (GFEDv2) can be observed during years with severe biomass burning, other years being dominated by transport of CO from different places (see Fig. 3a). This very intense fire activity is confirmed by aerosol measurements. MODIS on Aqua and MODIS on Terra monthly average of Aerosol Optical Depth at 0.55 μm (MODIS, 2007) show a very high maximum over Indonesia at the same time (~35% excess) – well correlated with the MOPITT observations (see Fig. 3b). Thus, the extreme CO pollution event over Indonesia in fall-2006 seen by MOPITT appears to be caused by a huge biomass burning activity – substantially bigger than that in 2002 and 2004.

3 The El Nino connection

A common way to understand such an extreme pollution event is with reference to the El Nino phenomenon (El-Nino-Southern Oscillation (ENSO) phenomenon) (Murdiyarso and Adiningsih, 2007). El Nino is an anomalous warming of the sea surface in the eastern and central Pacific, which begins early in the year and reaches a peak in late in the year. It has impacts on temperatures, humidity and precipitation patterns. El Nino can be responsible for hot and very dry atmospheric conditions in the Indonesian region. In such conditions the bio-mass burning can be of very high intensity. The most common indices for El Nino are the Multivariate ENSO Index (MEI) (Wolter, 2007; Wolter and Timlin, 1998) and the Southern Oscillation Index (SOI). All El Nino indices are fairly well correlated, so any index can be used to investigate possible cause-effect relationships for this event. The worst Indonesian pollution event in recent years was in 1997/1998 which was also the year of the largest El Nino in the last 30 years. The number of HSs in September 1997 reached a maximum number ~6500, almost 13× the normal annual mean level of 500. From this event and similar ones, a correlation between Fires and El Nino index is apparent and a major factor in pollution over Indonesia is the fire proliferation during the warm and dry phase of El Nino.

In the past seven years, MOPITT observed three high CO events over Indonesia (2002, 2004 and 2006 see Fig. 1a) and all three during the El Nino warm phase when the rainfall decreased (and the fires spread) (NASA, 2004 and NASA, 2007). Figure 4 compares the MEI index time series with the time series of HS from the region. As seen in this figure, there are two El Nino events (2002 and 2006) that are similar in MEI index, but with very different fire activity

An analysis (not shown here) of the surface temperatures for these two periods shows usual seasonal variations and no obvious trend. The monthly estimate of Accumulated Rainfall (mm) over Indonesian region (from the Tropical Rainfall Measuring Mission satellite – (TRMM) as well as from Global Precipitation Climatology Project, GPCP) shows similar dry periods (Fig. 5) for both 2002 and 2006 and even for 2004.

From both rainfall evaluations, the accumulated rainfall over Indonesia during the dry period (July to October) was ~130±40 mm. We conclude that from the point of view of temperature and rainfall all the last three El Nino events are similar and of moderate intensity. The recent El Nino event (2006) seems to be a moderate one from the point of view of MEI, temperature and rainfall, but with a much larger number of fires than other El Nino years (Fig. 4) and, as a consequence, a very high level of CO over the region, (Fig. 1).

4 Pollution caused by fires ignited by lightning – a feedback loop

It seems unlikely that the sharp spike in pollution and fire activity in 2006 was solely due to fires of anthropogenic origin. It is more probable that what was observed was caused by some special condition superimposed on the dry conditions created by the 2006 El Nino event. During "dry" conditions (El Nino) the fire will spread locally and the "fire activity" will increase mainly due to the increased burn area. On the other hand, a very large number of HSs observed from space (as in fall of 2006) is a signal for a probable additional (new) fire source, which increased the fire abundance. Even if humans caused a lot of fires, (as in the case of Alaska Fires analyzed in a recent study; McGuiney et al., 2004), fires caused by thunderstorm lightning seem to be more effective in burning a bigger area than anthropogenic fires – we can say they are "wilder" and these fires often occur in remote regions.

So, a possible explanation for the big fire activity in the fall of 2006 is the proliferation of anthropogenic fires due to the meteorological conditions (dry and hot), supplemented by fires produced by natural causes, for example by lightning. Lightning ignition requires the simultaneous occurrence of dry fuel and a dry atmosphere (dry lightning) that occur during storms without significant concurrent rainfall. A dry season during an El Nino warm period is a dry lightning season with a lot of fires. Increased lightning activity directly attributed to the 1997–1998 El Nino event, was observed and analyzed for the Southeastern US by Goodman et al. (2000) and over the Indonesian region by Hamid et al. (2001). The results of the Hamid analysis indicate that convective storms can be more intense during El Nino warm phases and this increases the lighting activity.

Biomass burning releases a large amount of aerosol into the atmosphere, which in turn reduces the solar radiation absorbed at the Earth's surface and can reduce the rainfall over a large area. For urban and industrial areas, there is evidence that air pollution can suppress rain and snow (Rosenfeld, 2000; Givati and Rosenfeld, 2004). The aerosol (smoke) entrained in a cloud may modify its development by increasing the number of, and depressing the size of, ice crystals within them (Sherwood, 2002; Sherwood et al., 2006; Jiang et al., 2008). This will suppress precipitation in the cloud and also change the electrical properties of the cloud.

It is known that the highest measured lightning currents with the largest charge transfers are associated with positive lightning. These positive cloud-to-ground (+CG) lightning strikes, even though a small percentage (10%–12%) of the total, are the most efficient for fire ignition. Some recent examples are given in McGuiney et al. (2004); Wotton and Martell (2005).

Another possible important factor for fire and pollution enhancement is the fact that smoke plumes from fires can result in pyro-convection that increases the number and intensity of positive CG lightning strikes (Latham, 1991; Lyons et al., 1998; Kochtubjada et al., 2002). An interpretation of the relation between fires and frequency of positive lightning is given by Jungwirth et al. (2005) who propose a new charge separation mechanism based on molecular dynamics simulations of particle surfaces and collisions. In this study they suggest the possibility that a lack of sulfate anions in the fresh smoke modifies the thundercloud electrification and produces an increase in positive charging. The fact that the current and the rate of positive (negative) flashes increases (decreases) in thunderstorms injected with smoke has recently been confirmed by a study of cloud-to-ground lightning characteristics in the Amazon region (Fernandes et al., 2006).

Thus it is possible that increased +CG induced by smoke and intense pollution in presence of an already dry atmosphere will ignite new fires that will emit more smoke and pollution and so on in a positive feedback loop. Such possible links and correlations are illustrated in Fig. 6. Feedbacks involving the suppression of precipitation and influence of the fire products on the charging characteristics of the clouds could, when proper conditions exist, be the precursor of a very high pollution event.

To further investigate these issues we used lightning data from the Lightning Imaging Sensor (LIS) on the [TRMM] satellite. Lightning activity observed by LIS on TRMM is in the range 35 N–35 S and from January 1998–December 2006. Because in August 2001 the satellite orbit changed from 350 Km to 402.5 Km (S. Harrison, University of Alabama in Huntsville, (Global Hydrology Resource Center), personal communication), we avoided any corrections by starting our analysis with January 2002. Here we used the data from TRMM-LIS named *“flashes”* and *“areas”*. A lightning *“flash”* consists of one or a few optical pulses observed in the same storm and clustered within a specified time and distance. The data type definition used in LIS algorithm is believed to generally correspond to the accepted definition of a conventional lightning flash. An *“area”* is defined as a near contiguous region on the Earth’s surface that produced a set of flashes separated by no more than 16.5 Km. *“area”* serves as a proxy for a single thunderstorm.

Since the LIS detects optical emissions from thunderstorm lightning discharges, there is no distinction between cloud-to-cloud (CC) and cloud-to-ground (CG) flashes or between negative and positive lightning. TRMM passes near the Indonesian region 2–6 times a day and therefore LIS data are not continuous. As others have reported (see for example Williams et al., 2000 and Hamid et al., 2001), the different lightning parameters peak in early afternoon and decline in the late evening and into the early morning hours. There is a maximum between 12:00 and 17:00–18:00 and a deep minimum in the morning between 09:00 and 12:00, a result of the fact that most thunderstorms are generated by convection from surface heating.

The MOPITT equator crossings are at ~10:30 and ~22:30 local time, so the CO measurements over the Indonesian region are during low thunderstorm activity (which also means that CO measurements are made preferentially under clearer conditions). The diurnal variation of CO is expected to be small due to its comparatively long lifetime.

Because storms are complex, probably the best parameter to indicate the "potential for wildfire" would be the storm-flash density, or in other words, the number of flashes per storm (FPS). A high FPS indicates a storm in which the clouds are highly charged (possibly with additional charging due to smoke and aerosol interactions) and therefore having more Cloud-Ground flashes.

In Fig. 7 we show the diurnal variation of lightning using a three-hour average of FPS for the year 2006. The general trend is similar to the distribution of flashes and storms with a minimum in the morning and a maximum in the afternoon. Comparing the FPS before the fire activity (before 16 September, green curve in Fig. 7) with FPS during (16 September–16 November, red curve) and after (16 November–31 December, blue curve) fire activity, we observe that during and after the fire peak there are more FPS in the early to late afternoon (12:00 to 22:00 local time) and weaker storms in the morning.

Using the full Indonesian region, we have examined the average FPS during the local afternoon maximum (12:00–22:00). This average FPS has been calculated for the period 8 August to 26 November of each year, the period of high fire activity and CO pollution during the El Nino years, as well as, during the post-fire month (December) – a rain period all over the Indonesian region. Under the El Nino conditions and during the fire period, the lightning FPS ratio is ~3.25, almost constant for 2002, 2004 and 2006 and slightly higher than the FPS ratio calculated for non-El Nino years (~3.1). During the post-fire period, the FPS ratio of the wet lightning under El Nino conditions has an increasing trend with time: from ~2.75 in 2002, ~2.85 in 2004 and ~3.2 in 2006, the big FPS value in 2006 is probably being caused by the huge amount of smoke produced by the fires. Even if there is a connection between the fires and lightning, this possible feedback connection is not strong as represented by these numbers due to the fact that during the fall, over Indonesia, the lightning activity is in fact concentrated over the northern part of the archipelago where a low fire activity and high precipitation rate prevail.

In order to investigate the possible connection between lightning and fires, we calculate the monthly average of HS (fires) and FPS over a reduced region where the main fire activities take place (Lat: 0 to −6; Long: 100 W to 120 W) – a region with high density of HS. The autumn is characterized by a high HS number and also by a number of thunderstorms with dry lightning. However, even a small number of thunderstorms can potentially lead to strong lightning activity during El Nino years (Hamid et al., 2001). In November 2006 there was a large number of thunderstorms over the areas with fire activity in Java and Borneo and the corresponding very high CO levels could be attributed to the lightning activity (not shown). However a similar increase in thunderstorms was also seen in November 2002, yet the CO levels were much less as compared to 2006. Of course, mainly due to variable time delay between possible CG lightning strike and proliferation of fire into a hot spot, pinpointing a physical coincidence between one flash and a hot spot location seems an impossible task and a statistical approach is the best way possible.

A collection of FPS (monthly average) for months with a big number of Hot Spots (>300) over this limited Indonesian region is shown in Fig. 8a. The points collected over 2002–2006 interval show that FPS increases with increasing HS counts in a non-linear fashion with some evidence of saturation at high levels. This saturation effect may explain why 2006 and 2002 are similar despite the increased fire activity in 2006. Normally, November is a transition month, the month of the end of the fire activity and the beginning of rainy season, and December is the month with a lot of rain and thunderstorms undisturbed by the presence of fires. The lightning activity in this month, not affected by the “fresh” fires, is characterized by lower values of FPS than during months with fires. But as presented in Fig. 8b, after the big fire activity, the thunderstorm (lightning) activity is still affected by pollution resulting in increased FPS for 2006, the year when autumn fires produced a record smoke and pollution.

All these facts suggest that the feedback mechanism involving lightning and smoke as proposed here might be contributing to the proliferation of fires even if it is not possible to attribute the difference between the events of 2002 and 2006 to this mechanism.

The large amount of lightning after the fire activity has consequences for the concentration of some gases such as NO_2 or O_3. For example The Tropospheric Emission Spectrometer instrument aboard the Earth Observing System's Aura satellite (TES) observed that the O_3 anomaly over Indonesian region persisted longer than the CO anomaly probably because of NO_x production by lightning (Logan et al., 2006).

The extreme Indonesian CO pollution event from fall 2006 is coincident with high lightning activity during, as well as after, the massive biomass burning. The high FPS during this period indicates a higher probability of more Cloud to Ground flashes that may ignite fires, pointing to a possible mechanism like that proposed in Fig. 6. In other words, the very high level of CO observed by MOPITT over the Indonesian region is probably maintained and amplified by an increase of thunderstorm lightning activity in a feedback loop (Fig. 6).

5 Conclusions

We have compared three recent high CO pollution events over the Indonesia region. These events took place during similar and moderate El Nino phases, but the pollution event from October–November 2006 was much higher than those from 2002 and 2004. We have presented evidence that suggests that a “fire-pollution-lightning” feedback loop could have had an important contribution to the October 2006 event over Indonesia and also that the “post-fire” lightning activity is possibly enhanced due to an increase in cloud electrification caused by entrainment of smoke and aerosol.

An interesting result from a model study of a possible impact of a doubled CO_2 Climate on fires caused by lightning (Price and Rind, 1994a) concerns a possible future large increase in tropical lightning induced fires and consequent changes in lightning frequency and/or their intensity. The extreme CO pollution event over Indonesia seen by MOPITT, and the increases of lightning after the storm could be the first sign of one of Price and Rind conclusions: “the situation in the future could become highly explosive" (Price and Rind, 1994b, c).

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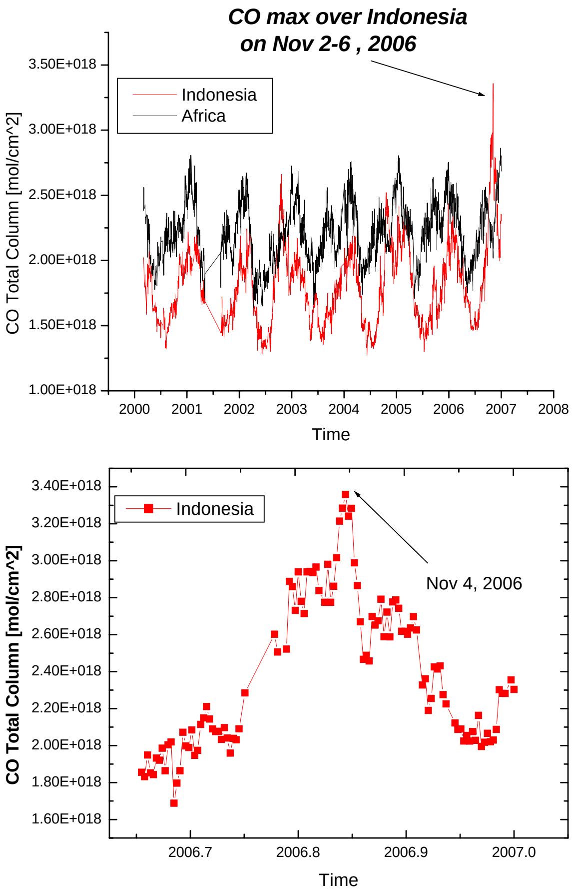

Fig. 1. **(a)** Time series of daily average MOPITT-CO Total Column over Indonesia and over another equatorial region ("Africa"), where very high CO levels can usually be observed.
(b) The time series of daily average MOPITT-CO Total Column over Indonesia during fall 2006.

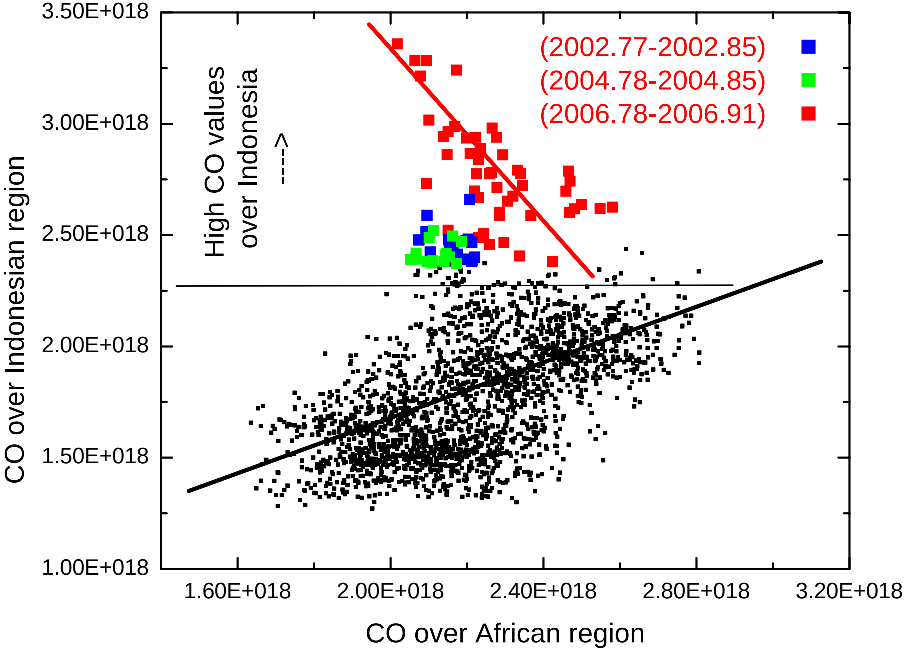

Fig. 2. The correlation between the CO Total Column over Indonesia and the African regions. El Nino data is defined by the solid (colored) squares.

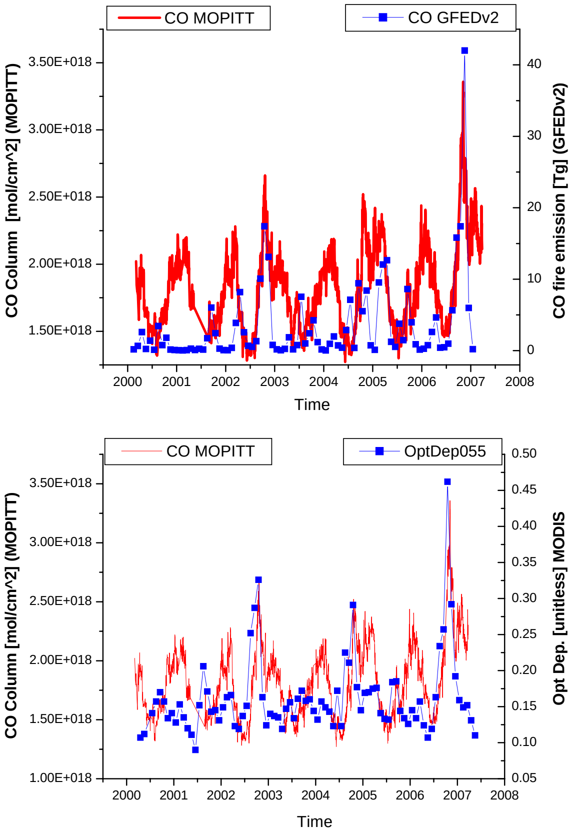

Fig. 3. The correlation between MOPITT CO Total Column (solid red line) and **(a)** CO emission [Tg] from GFED (Global Fire Emission Database is based on MODIS fire observations), **(b)** Aerosol Optical Depth at 0.55 microns (MODIS) (blue line).

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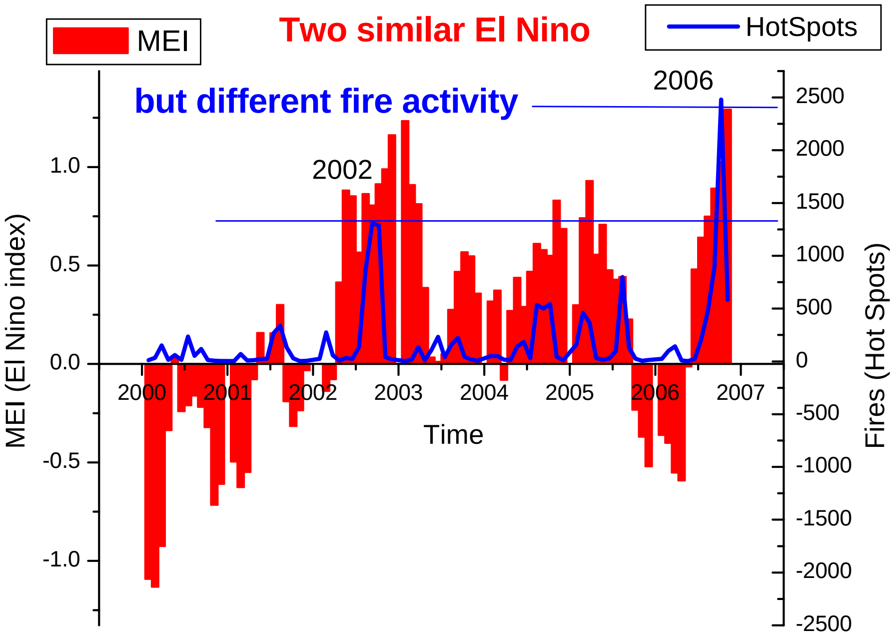

Fig. 4. El Nino MEI index and Fires (Hot Spots) over Indonesia from 2000 onwards. There are two similar El Nino events (2002 and 2006) but with very different fire activity.

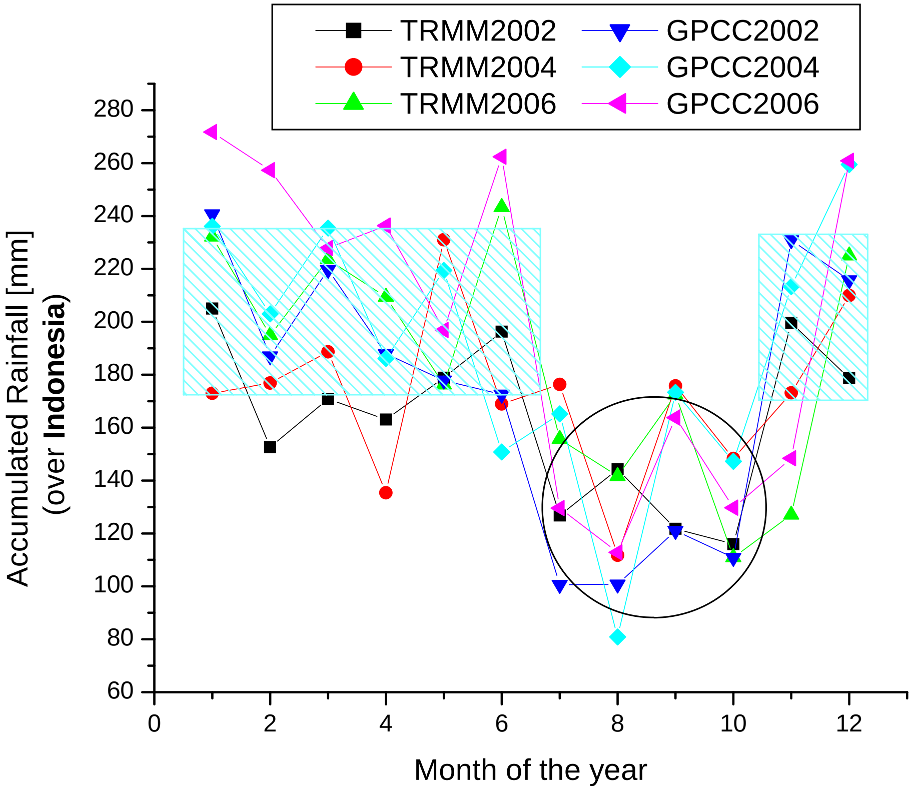

Fig. 5. Monthly estimate of Accumulated Rainfall (mm) over Indonesian region from the Tropical Rainfall Measuring Mission satellite – [TRMM] and from [GPCP] for the last three El Nino events.

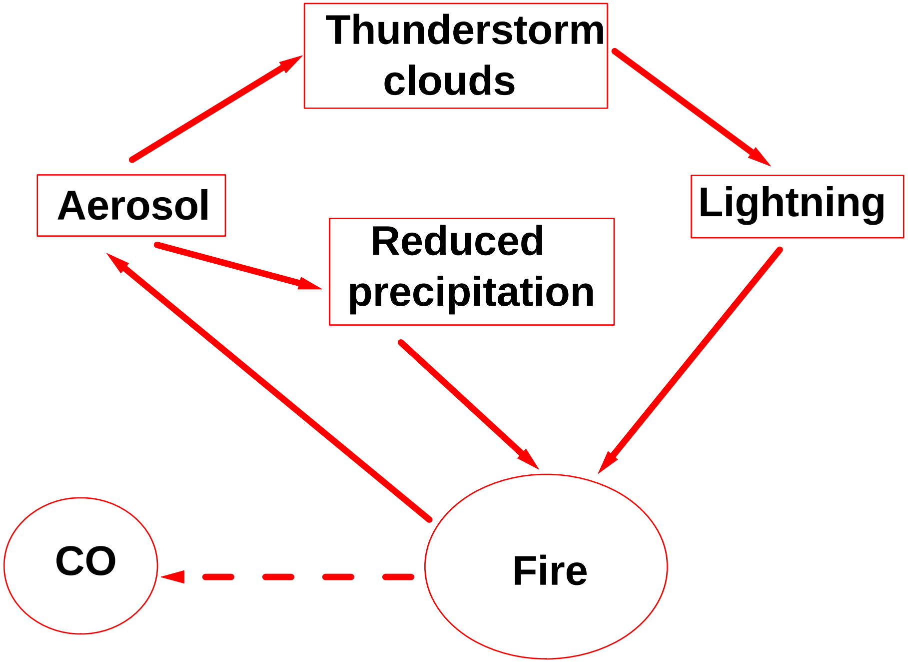

Fig. 6. Possible relationships between tropical biomass burning, aerosol, clouds and lightning. CO observations provide an indication of the intensity of the activity.

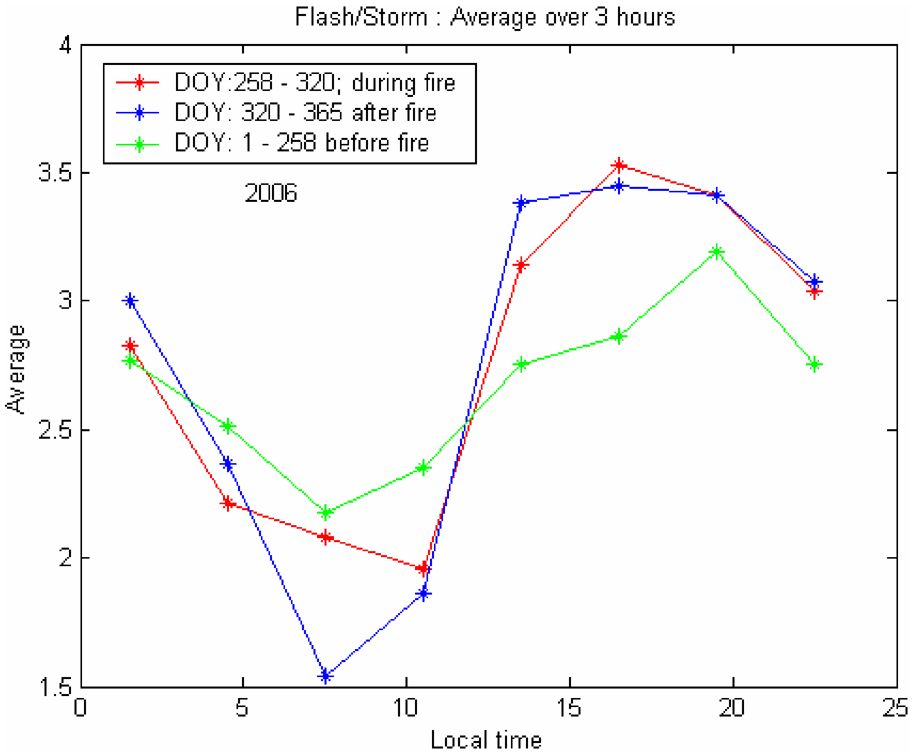

Fig. 7. Lightning diurnal variations in 2006 (DOY=258: 15 September; DOY=320: 16 November).

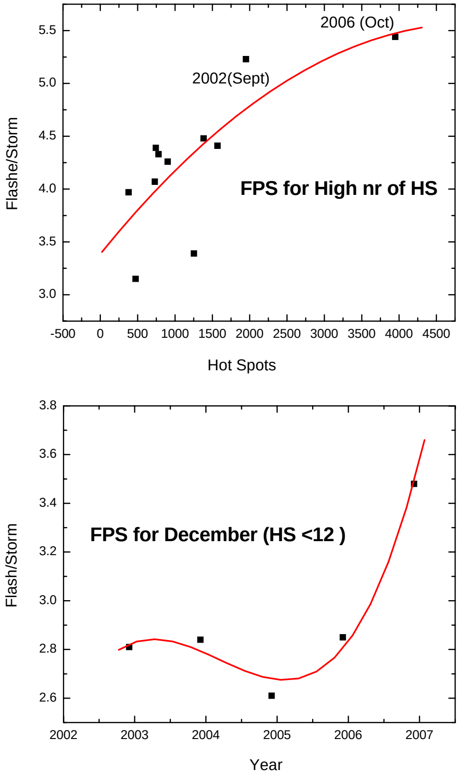

Fig. 8. **(a)** FPS versus the number of hot spot (fires) for those months (during 2002 to 2006) affected by big fires. **(b)** FPS for December (2002 to 2006), the month not affected by "fresh" fires (number of HS not more than 12). The data are selected over the small Indonesian region (Lat: 0 to −6; long: 100 W to 120 W), region strongest affected by the autumn fires. Curves are polynomials to guide the eye.