The influence of precipitation patterns on recent peatland fires in Indonesia

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Introduction

Recently, Indonesia experienced severe peat and forest fire in 2002, 2004, 2006, and 2009 under low monthly precipitation in Kalimantan and Sumatra [1]. Mostly fires in Indonesia regions caused by human. Once these human-caused fires have started, the fire behavior is controlled by natural factors such as precipitation, wind and dryness of fuel. For most tropical areas in Southeast Asia, including Indonesia with its relatively high annual rainfall, precipitation is one of most effective factors against fire. Indeed, our earlier study [2] showed that more than 90% of peat fires in Central Kalimantan from 1997 to 2007 occurred in the dry season.

To evaluate the fire situation in Indonesia accurately, satellite monitoring is the best method. This study investigates MODIS (Moderate Resolution Imaging Spectroradiometer) hotspot data from 2002 to 2012 for Indonesia, Kalimantan, and Sumatra using several sizes of grid cells based on geographical latitude and longitude. To ascertain the relationships between fire activity and various weather conditions, this study obtained the weather data from several weather stations, where measured at the airports in Kalimantan and Sumatra. Mostly precipitation data in Kalimantan and Sumatra was available in recent twelve years (2001-2012), and not all the data was present. However, previous studies [3] have shown precipitation patterns in two Island of Indonesia and noted that the northern latitudes have a different weather pattern to the southern latitudes.

Main goal of this study is to enable an effective future fire prevention strategy in Indonesia. To achieve this, objectives of this study were as follows: (1) to understand typical spatial fire distribution and times of the most fires in recent years (MODIS era), (2) to clarify daily mean precipitation and typical dry season, (3) to investigate how the differences of dry season patterns can be influence the seasonal fire occurrence, and (4) to compare the relationship among precipitation patterns, El Niño events, and peatland fire trends between Kalimantan and Sumatra.

Methodology

Analysis is done for MODIS hotspots data for peatland of Indonesia, Kalimantan, and Sumatra using various grid sizes utilizing latitude and longitude angles from 1° × 1° to 0.01° × 0.01°, as shown in Fig. 1. Precipitation data was mainly analyzed to explain fire activities in several regions in Kalimantan and Sumatra, simply because precipitation was a common weather data for all the major weather stations in Indonesia. In this study, a 10-day period was used to evaluate the average daily precipitation and day number was used as an arbitrary date or starting date for accumulated precipitation. The NOAA (National Oceanic and Atmospheric Administration) and JAMSTEC (Japan Agency for Marine-Earth Science and Technology) definition of El Niño events and their SST anomaly values were also used to analyze their relationship with precipitation and fire activities.

![Fig. 1. Five grid cell sizes on the map of MRP](Image)

Results and Discussions

**Recent peat and forest fire trends in Indonesia**

The MODIS hotspot data provided by NASA for 2002-2011 was plotted as shown in Fig. 2. A total of 631,529 hotspots were recorded in the region covered by the study (N 6° - 11°, E 95° to 142°). About ninety percent of the hotspot cells in Fig. 2 fall fully within the borders of the grid cells covering only areas of Indonesia, the remaining is in the cells overlapping the surrounding countries as shown in Fig. 2. The limits of the cells extending outside Indonesia is an artifact of the one degree sized grid cells used in the analysis here. This paper ignores administrative boundaries to simplify the analysis and for the ease of the data treatment.

In Fig. 2, all coordinate points of MODIS hotspots are indicated with the smallest size of dots. The resulting map shows areas of dense red color regions in Indonesia (regions with high incidences of hotspots) and these can be simply identified on the map in Fig. 2. To show fire prone areas more clearly, several cells with the number of hotspots are marked at the cells as shown in Fig. 2. Eleven cells overlaid by white in Fig. 2 shows cells with fire occurrences above 0.081 hotspots/km².
There are five such cells in south Kalimantan, five in north Sumatra, and one in south Sumatra. These cells are named H-1 to H-11 (in descending order with H-1 showing the cell with the highest fire incidence: H-1, H-2, H-3, H-5, and H-8 in Kalimantan, H-4 in south Sumatra, and H-6, H-7, H-9, H-10, and H-11 in north Sumatra.

Fig. 2. Hotspot distribution and 11 highest hotspot areas in Indonesia, 2002-2011

The cell with the most fires in south Kalimantan, H-1 (also named MRP*), is located at south latitude 2.5° to 3.5° and east longitude 113.5° to 114.5° (see Fig. 1 for the exact position of this cell) had a mean 2,223 hotspots/yr and a maximum of 5,382 hotspots in 2006. To evaluate the fire incidence in this cell objectively the concept hotspot density will be introduced. The 2,223 hotspots/yr for this cell was converted to an annual mean hotspot density of 0.182 hotspots/km² (dividing the number of fires with the area of the cell in km²) and to a daily hotspot density of 0.497 NASA fire pixels/(1,000km² day) (see more detail in the NASA Earth Observations, http://earthobservatory.nasa.gov/). This 0.497 figure is not a very high hotspot density in the NASA scale but it becomes 1.8 pixels/(1,000km² day) when considering that fires only occur during about 100 fire days in July, August, and September. This high daily hotspot density shows that the fire incidence in this particular cell in south Kalimantan is among the most intense fire incidences of any area in the world.

**Precipitation-dry season**

In Fig. 3, the daily mean precipitations of two different periods are plotted with thick and thin solid lines. The thick line with a solid round mark shows the seasonal change of daily mean precipitation in the recent years of 2002 to 2011. Daily mean precipitation for the recent 10-year interval from 2002 to 2011 was 7.88 mm/day. The thin line shows the seasonal variation of daily mean precipitation for the 34-year period from 1978 to 2011. The 34-year daily mean precipitation is 7.98 mm/day. A smaller value in the daily mean precipitation for the recent 10-year interval implies dryer conditions in recent years. One more curve with a dotted line in Fig. 4-10 is a simple smoothed curve for the daily mean precipitation from the 34-year data, and was used to define the dry season.

In this paper, a daily mean precipitation of 5 mm/day was temporarily used as a threshold value to define the dry season in Palangkaraya. With this threshold value, the summer dry season (SD) period in Palangkaraya was defined as the 3-months from early July to late September, using the smoothed curve for the 34-year data, as shown in Fig. 3. Dry season in Palangkaraya is an S pattern. This period coincided with the period with the lowest under ground water level [2]. Very low daily mean precipitation (1.52 mm/day) in late September was the lowest daily mean precipitation of the last 34-year. This recent precipitation trend could also support active fires.

Fig. 3. Daily mean precipitation patterns using 10- and 34-year data from Palangkaraya, Central Kalimantan

In Fig. 4, daily mean precipitation in Pontianak from 2001 to 2010 (except 2003 due to data missing) is shown with a thick line with solid diamond symbols. A dotted thin line in Fig. 4 was a simple smoothed curve for daily mean precipitation. Daily mean precipitation in Pontianak was 7.85 mm/day. This value is almost the same amount as that in Palangkaraya, but Pontianak showed a different precipitation pattern from the pattern of Palangkaraya, as shown in Fig. 4. Pontianak had two dry periods (using the same definition as in Palangkaraya, daily mean < 5 mm/day), one was from early February to late March, and the other was from early August to mid August. This precipitation pattern or two dry season pattern is also a typical precipitation pattern in Indonesia, found in northern Sumatra [3]. In Pontianak, the winter dry season (WD) is relatively longer but wet for two periods in mid February (7 mm/day) and mid March (6 mm/day), as shown in Fig. 4. Due to this higher precipitation tendency, fires were not so active in the winter dry season. The summer dry season period in Pontianak was only 2/3 month and was shorter than three months in Palangkaraya. However, Pontianak also had a strong dry period (1/3 month with 2 mm/day) in early August. Thus, active fires in Pontianak were much more intense than in Palangkaraya.
Pontianak mainly occurred in the short summer dry season and from early to mid August.

The definition of a dry season period for each area in Sumatra follows previous analysis of Kalimantan, and the daily mean precipitation of 5 mm/day was used as a threshold value for the dry season. By using the line for daily mean precipitation in our graph in Figs. 5, 6, and 7, we can see that threshold value is apparent in Medan (N 3.66°) in the Northern Hemisphere, revealing an approximately two month winter dry season in January and February (W_D2), and a summer dry season (S_D2) in June and July. In Palembang (S 2.90°) in the Southern Hemisphere, there was a relatively long dry season, about 4-month S_D4, from June to September, and in P.Baru (N 0.47°) near the Equator, (located between Medan and Palembang, see Fig. 3-3), there was an intermediate dry season, or a one-month quasi-winter dry season with rain (daily mean precipitation in February higher than 5.5 mm/day), and a dry season of about 2-months S_D2 in June and August.

The lowest values of daily mean precipitation during the above-mentioned dry seasons were an indication of fire activities near each weather station. In Medan, the lowest values of daily mean precipitation in W_D2 and S_D2 found in Fig. 5 were about 2.1 mm/day in February and 4.3 mm/day in July respectively. In Palembang, the lowest value in Fig. 7 was 1.7 mm/day in S_D4 in August. In P. Baru, the lowest value was 3.4 mm/day only one period in each of June and August, as shown in Fig. 6. Moreover, the annual mean precipitation of P. Baru (about 3,200 mm) was considerably higher than the amounts of about 2,500 and 2,600 mm from the other two weather stations. Reasons for this were that we could estimate that the heavy precipitation in P. Baru would mainly be due to the effect of the mountain behind the area.

**Recent fire trends in Kalimantan**

**Fire prone area and peatland**

In Fig. 8, 12 cells showed a very high hotspot density (>0.129 hotspots/km² = 400 hotspots). They were named H1, H2, H3, etc. in descending order of hotspot density. The 7 highest hotspot density cells (H1, H2, H3–5, H8, and H9) were located in MRP+ area and covered most of the MRP area. Another two cells (H7 and H12) were in Sampit areas (north and east side of Sampit). H6 and H10 were in South W.K. and the lowest, H11, was in North W.K. From these distributions, we may say that most fires in Kalimantan are peatland fires because the top 10 highest hotspot density cells are located in the south coastal peatland areas.

**Average seasonal fire occurrence**

A previous study has already shown that fires in Kalimantan were common in the months of August, September, and October [1]. However, the two provinces of Central and West Kalimantan show different severe fire periods (see Fig. 9). The fire season in West Kalimantan started in early August and lasted until early September (>50 hotspots/day). There was a fire peak in mid to late August (about 136 hotspots/day). The fire season in West Kalimantan
almost coincided with the dry season in August in Pontianak (see Fig. 4). Relatively, high fire occurrence (22–45 hotspots/day) in mid September until mid October mainly occurred in the south region of West Kalimantan.

Fig. 9. Average seasonal fire occurrence tendencies in Kalimantan

Fires were most severe in Central Kalimantan. The fire season in Central Kalimantan starts in mid August and lasts until early November. A severe fire plateau (>130 hotspots/day)) formed in late August and lasted until mid October. The fire season did not coincide with the dry season from July to September in Palangkaraya (see Fig. 3); rather there was one-month difference between the dry season and the fire season. The reason for the one-month difference could be explained by the underground water level, as previously explained by our research group [2].

Fire occurrence in 2009

Firstly, this study selected 2009 because it was the third severest fire year for MRP+ and the fourth severest fire year for North W.K. (West Kalimantan), but both areas had highest daily number of hotspots, with 297 hotspots/day in MRP+ in late September and 150 hotspots/day in North W.K in early August. The severest fire occurrence among the El Niño years of 2002, 2004, 2006 and 2009 could be partially explained by the long duration of the drought conditions, which started in early July, and the lowest accumulated rainfall by late September, of 100 mm (see Fig. 10).

The fire peak for North W.K. in 2009 was short, only in early August with a daily average fire occurrence of about 150 hotspots/day (the highest peak of the recent decade). This fire peak occurred just after the short drought from early July and coincided with the dry season in North W.K. (see Figs. 4 and 10). After this peak, the number of hotspots decreased to 67 hotspots/day and the precipitation to less than 10 mm/day during early and mid August. A fire peak for interior W.K. was also found in early August, with about 110 hotspots/day, but only lasted until mid August. South W.K. showed a different trend compared to the other two areas in W.K. Namely, South W.K. had a small fire peak in mid September with about 90 hotspots/day but the fire period was more than two months, from early August to early October. This longer fire period indicates that the precipitation pattern for South W.K. could be different from that of other areas in North and Interior W.K.

Fig. 10. Seasonal fire occurrence and accumulated precipitation from June in 2009

The fire peak and period for the MRP+ area were quite different from those in the three areas in W.K. In 2009, a fire peak for MRP+ appeared in late September with about 300 hotspots/day (the highest peak of the recent decade) as in Figs. 10. Long drought conditions from around early July may make this a severe fire condition, when a very dry thick layer of peat arose from the rainless conditions. A severe fire period with more than 100 hotspots/day lasted one and 1/3 month, from early September to early October. The fire trend in Sampit area was almost the same, but the fires were not as active as those of MRP+. A fire peak for Sampit occurred in early October with only about 120 hotspots/day.

To fight against these severe fires in MRP+ and W.K. areas, we would like to highlight the small number of fires in June and July as shown in Fig. 4-26. In North W.K, fires (around 20 hotspots/day) already started in early and mid June. Fires from late July (around 30 hotspots/day) could make the highest peak for North W.K, as shown in Fig. 11c. In MRP+ area, fires indicated by around 30 hotspots/day were observed in mid July. Such pre-dry and early season fires may reflect peat and vegetation conditions as fuel for a fire. In other words, a peat and vegetation fire could only start by consuming dry peat and dry vegetation. We should thus pay more attention to these pre-dry and early dry season fires. We would like to call them "caution fires" to promote the idea of developing new measures against severe peat fires.

Typical fire distributions in El Niño years

In Fig. 11, three typical fire distributions in El Niño years are shown. Fig. 11a shows the fire distribution during the severest fire period for Central-South Kalimantan in mid October (DN = 280–289) in 2006. Fig. 11b shows the distribution of fires for West Kalimantan in August (dry season for north area of W.K.): early August (DN = 210–219) in 2009. and Fig. 11c shows the fire distribution in the pre-dry season (caution fires): late July (DN = 200–209) in 2009.
Recent fire trends in Sumatra

Fire-prone area and peatland

The 7 highest hotspot density cells (H1~4, H8, H11 and H12), located in the Dumai region or Dumai+14p (Dumai4p: H1, H3, H4, and H12), cover most of the northeast coast peatland in N. Sumatra (Riau Province). According to the peatland map (Wetlands, 2003), the Dumai region contains a peat layer that is relatively deeper (~8 mm) than other places in S. Sumatra and Kalimantan (except the MRP area). It is of note that Dumai+14p belongs to a different climate zone than most of S. Sumatra and Kalimantan (see Figs. 3, 5, 7, 12).

Fire occurrence in 2005

From Fig. 13, it is evident that the extreme fires of 2005 in N. Sumatra occurred in different regions and in different seasons. The most distinctive feature is that the 2005 extreme fires occurred during the dry seasons. The first extreme fires in Dumai 4p (a part of Dumai+14p) and P. Baru +12p occurred during a drought in the winter dry season W10 or between mid-January and mid-March. The value of more than 100 hotspots/day was considerably higher than that of 50 hotspots/day (the 10-year average value for the whole of N. Sumatra), as shown in Fig. 13. The following extreme fires occurred in late June in Dumai+14p (mostly in Dumai north). The third extreme fire peak was mostly due to fires in Dumai north and North Others (79), and occurred during early and mid-August.

The extreme fires could therefore be explained by the drought conditions (using the accumulated precipitation curves in Fig. 13) or by the flat part of the lines for both Medan (~2 mm/day) and Pekan Baru (~1 mm/day). The drought conditions in 2005 are likely to have been caused by the active winter boreal monsoon occurring under El Niño Modoki or quasi-El Niño conditions [5]. This abrupt, wide area drought affected the north of Southeast Asia, and caused a rising by about +0.5 of the average EMI (El Niño Modoki Index) values between late 2004 and early 2005, as recorded by JAMSTEC.

Fig. 11. Three typical fire distributions in Kalimantan.

Fig. 12. Map of the 12 highest hotspot cells, fire prone cells, and peatland in Sumatra

The seventh highest cell, H7, is located on the eastern side in Pekan Baru (capital of Riau Province) near the Equator and on the coast. H5 and H6 are located on the eastern side at Palembang (capital of the South Sumatran Province), and two cells in Palembang6p. H9 in the south in Pekan Baru, and H10 in southeast Jambi are two cells included in Jambi+7p (see Fig. 12).

From the distribution of these highest hotspot cells, it is evident that the most recent fires in Sumatra have occurred mainly on the coastal peatland. Many of the fires on peatland can be explained by the history of development as in the MRP area of Kalimantan [4]. The areas with dense hotspots of the MRP area were related to high human activity with deforestation, slash and burn clearing, and plantations [1].

Fig. 13. Fire occurrence and accumulated precipitation in 2005

Fires in the Dumai region, (except in Dumai4), showed another two peaks in late June and in early and mid August. These fires can be explained by the short, a devastating summer drought (S10) in Medan occurring in June and August, giving the lowest precipitation rate
over the past 12-years. Correspondingly, fires in North Others (mostly areas of non-peatland) became very active in late June and early August (see Fig. 13) under drought during S0.

Fire occurrence in 2006

From Fig. 14, we can see that the 2006 extreme fires in S. Sumatra occurred in different regions and in different seasons. Of particular note, however, is that the 2006 extreme fires in S. Sumatra also occurred during the dry season. The extreme fires in Palembang 6p (a part of Palambang+16p) and Jambi +7p occurred either during a drought in summer dry season S0 or from mid September to mid October. Their numbers (more than 200 hotspots/day) are considerably higher than that of the 100 hotspots/day of the 10-year average values for the whole of S. Sumatra (see Fig. 14). A catastrophic fire can be ascertained (with about 700 hotspots/day) by one sharp peak in early October (twice as large as in Sampit). The worst fires in the Palembang and Jambi region coincided with the fire peak in the MRP area. About 60% of these fires in early October occurred in Palembang 6p (mostly in eastern Palembang). Fire occurrences on non-peatland (or in South Others) were in early July and August, and we are thus able to refer to these fires as “warning fires” for the areas of peatland in S. Sumatra.

The extreme fires occurred in Palembang, under a devastating long-term drought involving a period of no rain lasting about 3-months. About 3-month prior to this drought, a pre-drought with very low rainfall (3.6 mm/day or the same rate as the annual rate in a dry season) was observed (see Fig. 14). These conditions are likely to be related to the El Niño event with ONI (Ocean Niño index) values in NDJ of about +1, as discussed in relation to Kalimantan [6].

Fig. 14. Fire occurrence and accumulated precipitation in 2006

Conclusions

Analysis results clearly showed trends of spatial and seasonal fire occurrence were not uniform among the peatlands in north and south regions. This condition partially could be explained by variation of precipitation patterns and severe drought enhanced by a different El Niño event in the recent decade. Therefore, the conclusions of this study can be summarized into the following five parts:

- Fire occurrence tendencies in fire-prone regions are mostly explained using the two different precipitation patterns of the region: the SP and the WSP. The southern part of Kalimantan and Sumatra, which are located in the southern hemisphere and belong to the S pattern, show severe fire activities over a relatively longer dry season over a few summer months. The northern part of Sumatra, which is located in the northern hemisphere and accords with to the WS pattern, shows separate periods of fire activities, due to two dry seasons in both winter and summer months. From a comparison of fire activities in several areas on both islands, it is evident that the most severe peatland fires occur in the southern part of Central Kalimantan, due to the relatively longer dry season (of more than 3 months under El Niño) compared with other areas.

- Two severe fire regions (7 adjacent cells) were identified in the MRP (Mega Rice Project) region in Kalimantan, and in the Dumai region in Sumatra, followed by the Sampit area in Kalimantan and the Palembang area in Sumatra (with 2 adjacent cells). Most fire-prone regions in Kalimantan and Sumatra are located on the peatland and its vicinity.

- The severest fires for the MRP area and its vicinity occurred in late September in 2009 under the driest conditions of moderate El Niño for Palangkaraya. The average number of hotspot was about 300 hotspots/day, which three times larger than the annual peak fire.

- Two extreme fires occurred both in N. and S. Sumatra in 2005 and 2006 respectively under enhanced drought or rainless conditions related to two different types of El Niño events. Both extreme fire occurrences could be classified as accidental fires. The origin of extreme fires could be from intentional fires related to practices such as land clearing and plantation development.

- One of spatial analysis showed a fire belt shape arising from severe fires that occurred mainly on the southern coastal peatlands from West to Central Kalimantan in mid October in 2006 and coincided with the drought in S0 period for Palangkaraya and Pontianak.

References