Dear Dr. Zemp

We appreciate the comments on our draft. Please find a detailed response below with the reviewer's comments in italics.

Specific comments

The authors did still not address my concern properly. Worse, by trying to justify their choices and explain their methodology, they create confusion and mistakes: "We used a 4-month time period because this yielded the highest correlation (R2 = 0.69)." (L. 177). However, from table 1 I see that R2 decreases with the length of the time window, so that in fact the 4-month doesn't lead the highest R2. The reason for this decrease is not properly discussed. They continue "However, the results are relatively insensitive to this time period, lowering or lengthening the time period gave comparable results (Table 1)". In my opinion, it makes no sense to justify this statement by showing R2 for different time windows. They should rather use this table to explain and discuss their approach from a statistical point of view, as mentioned above. Instead, the authors should have performed a sensitivity analysis to see how this actually affect the results (ex Fig.2).

The reviewer correctly notes that our choice for the 4-month time window was not described well. We have redone all analyses using different time windows but in the end settled again on a 4-month window and show the sensitivity to using different time windows. First of all, the R^2 values are very similar (Figure R1) for the time frames between 2 and 8 months. While in principle it might make most sense to chose 2 months (which had the highest R^2) we prefer to keep 4 months because, once applied to GPCP, the fit between adjusted GPCP and TRMM is best for 3 and 4 months for grid cell with fires (Figure R1, 3 months yields a slope of 1.01 and an R^2 of 0.97, and 4 months has a slope of 0.99 and an R2 of 0.97). This is now more clearly justified in the manuscript with this paragraph:

"We investigated time frames from 2 to 8 months. Our choice for 4 months was to some degree arbitrary because the differences are very small when looking at the fit between converted GPCP and TRMM. However, converted GPCP based on a 4 month time frame to calculate the correction factor yielded close resemblance for the overlapping period with TRMM in grid cells where a fire occurred during our study period (slope: 0.99, R2: 0.97). Results are relatively insensitive to the choice of the time periods as will be shown in the result section. "

In the manuscript we also added a paragraph in our results to demonstrate the sensitivity of the different time frames to calculate the correction factor. In 1997 the mean rainfall for Indonesia varied between 51.7 and 52.9 mm during the dry season (Fig. 10) depending on the time frame chosen. This indicates that our new rainfall dataset is not very sensitive to the choice of time frame. Furthermore, we have tested the different time frames on the experiment from Figure 9. We show that with a 120 days buildup in 1997, rainfall accumulation before a fire would have varied between 239 and 248 mm (Fig. 11). This shows that the choice of time frame does not influence the key findings from this study. The strong non-linear response of fire to rainfall would not change, as 1997 is the only year affected by the choice of correction factor, the remaining years being based on TRMM data.

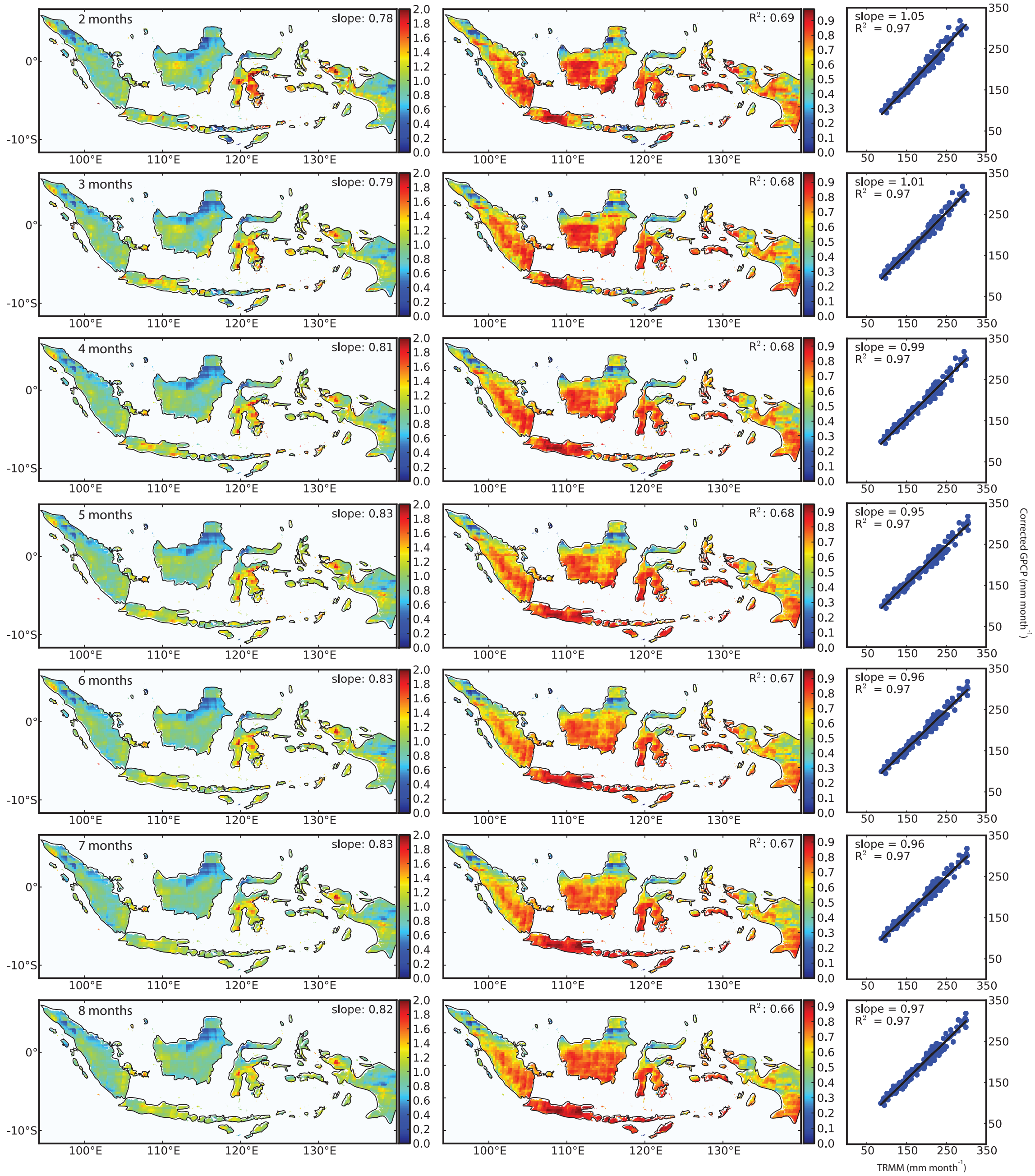

Figure R1: Spatial distribution of slope (left panels) and coefficient of determination (R^2, panels in the middle) from a linear regression between GPCP and TRMM rainfall based on the total rainfall for the 2 to 8 driest months between 1998 and 2014. The scatter plots in the right panels show the corrected monthly GPCP and TRMM rainfall rates for the same time period in grid cells where a fire occurred between 1997 and 2015.

In addition, as mentioned in my first review report, the statistical analysis that the authors perform for the merging of the fire dataset is also weak (for example, they claim to have tested several regressions but no results appear in the manuscript).

We made a new figure (Figure R2) showing the results of the 3 different methods tried (ratio, linear regression, exponential regression). We decided not to include it in the manuscript to avoid confusion for the reader. With this Figure we demonstrate that the ratio was the most appropriate method to combine our fire datasets. Furthermore, to make a monthly regression method, we needed several points (monthly fires) in each grid cell. Unfortunately some grid cells have only one fire in a particular month during our study period, resulting in omitting to correct these fires. For example, if between 2001 and 2011 a 1 quarter-degree cell had only one year with fires in November, this particular fires will not be corrected as the regression could no be calculated, resulting in an underestimation of regions with lower active fire detections.

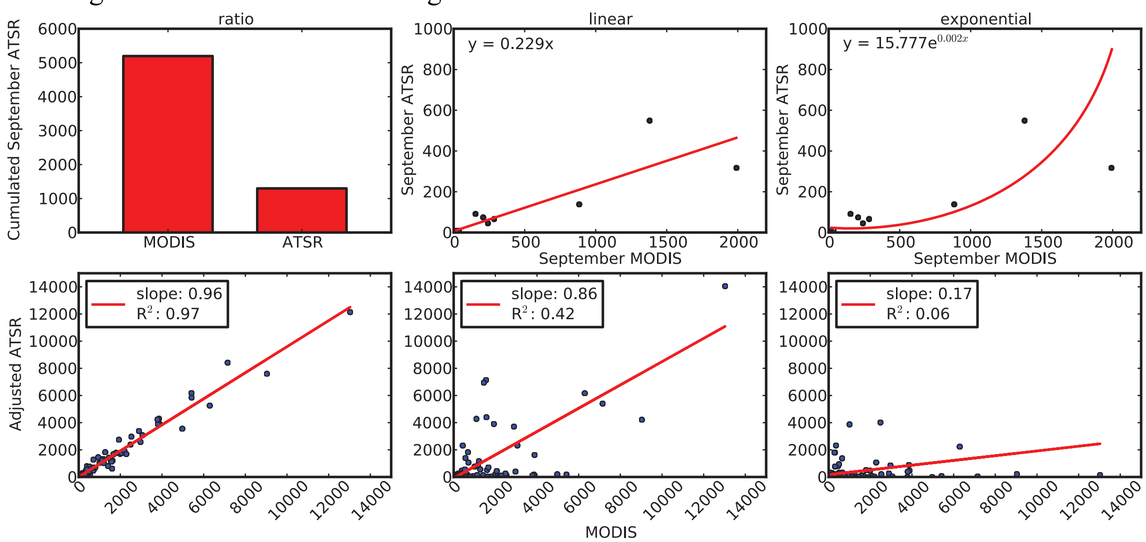

Figure R2: Examples of three approaches for adjusting the 1997-2000 ATSR data. All values are in number of fires. The first column shows the ratio method used in the paper, the second a linear fit, and the third one and exponential fit. The top row shows the number of September fires in a 1° grid cell (2.5°S, 114.7°E, east of Palangkaray, southern Kalimantan) between 2001 and 2011. The ratio method uses the total number of MODIS and ATSR in a particular month (here: September) for those 11 years to calculate the conversion factor (ratio). For the linear and exponential regression method the number of yearly fires in a particular month is used to calculate the regression that would then be used as a conversion factor. Not all grid cells have fires in each month, resulting in poorer linear or exponential fit. All approaches vary spatially as shown in Figure 3 with the ratio method. The bottom row shows how the adjusted number of ATSR active fire detections compares to the MODIS data when the different conversion approaches are used for the whole domain.

Precipitation-fire linkages in Indonesia (1997-2015)

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Abstract

Over the past decades, fires have burned annually in Indonesia, yet the strength of the fire season is for a large part modulated by the El Niño Southern Oscillation (ENSO). The two most recent very strong El Niño years were 2015 and 1997. Both years involved high incidences of fire in Indonesia. At present, there is no consistent satellite data stream spanning the full 19-year record, thereby complicating a comparison between these two fire seasons. We have investigated how various fire and precipitation datasets can be merged to better compare the fire dynamics in 1997 and 2015 as well as in intermediary years. We combined night-time active fire detections from the Along Track Scanning Radiometer (ATSR) World Fire Atlas (WFA) available from 1997 until 2012 and the night-time subset of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor from 2001 until now. For the overlapping period, MODIS detected about 4 times more fires than ATSR, but this ratio varied spatially. Although the reasons behind this spatial variability remain unclear, the coefficient of determination for the overlapping period was high (R^2=0.97 based on monthly data) and allowed for a consistent time series. We then constructed a rainfall time series based on the Global Precipitation Climatology Project (GPCP, 1997-2015) and the Tropical Rainfall Measurement Mission Project (TRMM, 1998-2015). Relations between antecedent rainfall and fire activity were not uniform in Indonesia. In southern Sumatra and Kalimantan, we found that 120 days of rainfall accumulation had the highest coefficient of determination with annual fire intensity. In northern Sumatra, this period was only 30 days. Thresholds of 200 mm and 305 mm average rainfall accumulation before each active fire were identified to generate a high fire year in southern Sumatra and southern Kalimantan, respectively. The number of active fires detected in 1997 was 2.2 times higher than in 2015. Assuming the ratio between night-time and total active fires did not change, the 1997 season was thus about twice as severe as the one in 2015. Although large, the difference is smaller than found in fire emission estimates from the Global Fire Emissions Database (GFED). Besides different rainfall amounts and patterns, the two-fold difference between 1997 and 2015 may be attributed to a weaker El Niño and neutral IOD conditions in the later year. The fraction of fires burning in peatlands was higher in 2015 compared to 1997 (61% and 45%, respectively). Finally, we found that the non-linearity between rainfall and fire in Indonesia stems from longer periods without rain in extremely dry years.

Keywords: night-fires, Rainfall, Indonesia, Peatland, El Niño

1 Introduction

High forest clearing rates, drainage of carbon-rich peatlands, and lack of compliance with existing laws have made Indonesia the country with the highest density of fire emissions world wide. These fires impact air quality (Johnston et al., 2012; Marlier et al., 2013) and establish Indonesia as one of the world's largest greenhouse gas emitters when combining fossil fuel, deforestation, fire, and peat oxidation emissions (Andres et al., 2011; Hansen et al., 2013; van der Werf et al., 2008a; Hooijer et al., 2010). In Sumatra, large fires have occurred since at least the 1960s, while in Kalimantan (the Indonesian part of Borneo), large fires began to occur two decades later, most likely due to changes in land use and population density (Field et al., 2009). After 1996, Kalimantan's fire condition deteriorated when the Indonesian government initiated the mega rice project. The objective was to convert one million hectares of tropical swamp forest to rice paddy fields and promote transmigration. This resulted in large scale deforestation and peatland drainage mostly in the province of Central Kalimantan (Putra et al., 2008).

Fires are generally not a natural occurrence in tropical rain forests due to their high humidity. This is especially true for most of Indonesia, which is located on the equator and therefore most of the country has high rainfall rates year-round and thus low natural fire incidences. Nevertheless, human-induced fires are frequently used as an inexpensive method for clearing forest and maintaining an open landscape. In 1997-98, the last very strong El Niño event recorded before 2015, 117,000 km^2 was burnt according to Tacconi (2003) and 100,000 km^2 according to Global Fire Emissions Database (GFED4s) (Randerson et al., 2012; Giglio et al., 2013). Biomass burning fuel consumption reached up to 20 kg C m^{-2} burned (Page et al., 2002).

The high fuel consumption stems from the extended peat deposits in Indonesia. Peat is a layer of partially decomposed plant material with a high proportion of organic matter. Tropical peatlands represent one of the major near-surface terrestrial organic carbon reserves. Peat thickness in Indonesia can extend to 20 m (Page et al., 2002). Page et al. (2007) estimated the area of peatland in Indonesia to be between 168,250 and 270,000 km^2, storing between 10 to 32 Pg (Petagram or 10^{15} gram) of carbon, although other studies have produced higher values (Jaenicke et al., 2008). Peatlands on Sumatra represent 15% of the island surface area (Wahyunto et al., 2003), while for Kalimantan it is 11% (Wahyunto et al., 2004). Peatlands support the growth of peat swamp forests, which rarely burn under natural conditions. Drainage and deforestation causes peatlands to become drier and more susceptible to fires (Page et al., 2002). The depth of burning into the peat layer varies. Ballhorn et al. (2009) reported that in 2006 the average depth of burning was 33±18 cm for a study region in Central Kalimantan, and field reports found burning depth up to 1.5m in certain locations (Boehm et al., 2001). Peat fires release a large amount of carbon. During the 1997 event, within a 2.5 million hectare area in central Kalimantan, 0.19-0.23 Pg of carbon was released from peat combustion and 0.05 Pg from overlying vegetation according to Page et al. (2002). These peat fires that burn predominantly in the smouldering phase are the main reason for deteriorated air quality during the fire season (Aouizerats et al., 2015). A study conducted between 2002 and 2010 in

Palangkaraya, located in central Kalimantan, showed that the longest hazardous air pollution episode occurred in 2002 and lasted for about 80 days (Hayasaka et al., 2014). By 2010, 23,000 km^2 of peatswamp forests were clear-felled, becoming degraded lands (Koh et al., 2011).

Indonesia has high inter-annual fire variability, closely related to the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Saji et al., 1999; Diaz and Markgraf, 2000; Field and Shen, 2008). ENSO represents a mode of inter-annual variability in the Earth system related to the strength of the Walker circulation governing sea surface temperatures in the tropical Pacific ocean (Rasmusson and Wallace, 1983). An El Niño event corresponds to the warm phase of ENSO, La Niña to the cool phase (Trenberth, 1997). El Niño, coupled with reversed Walker circulation, leads to drought over most of Indonesia, while La Niña events bring increased rainfall. El Niño and La Niña can be classified in various ways, one approach relies on the magnitude of the sea surface temperature anomalies over the equatorial pacific region: Weak (with a 0.5° to 0.9° sea surface temperature anomaly), moderate (1.0° to 1.4°), strong (1.5° to 1.9°) and very strong (≥ 2.0°) (Zopf et al., 1978). Extreme El Niño events occurred last in 1997 and 2015 with different level of intensity. In 1997 large anomalies were already occurring in July (2.8°C), reaching highs at 3°C in August and September, while in 2015, the highest anomaly was 2.5°C in September. IOD is another air-sea coupled climate mode active in the tropical Indian Ocean influencing rainfall in the region. The Indian Ocean Dipole Mode Index (IODMI) was established to quantify IOD. It was defined using the difference in sea surface temperature between the tropical western Indian ocean and the tropical south-eastern Indian Ocean (Saji et al., 1999).

Rainfall sensitivity to ENSO and IOD varies throughout Indonesia, and to study these sensitivities, Indonesia is often separated into three climatic regions (Aldrian and Dwi Susanto, 2003). ENSO is an important driver for droughts on Kalimantan (Harrison, 2001). There, 58% of the variability in mean July-November precipitation between 1948 and 2006 could be explained using a linear model based on Niño 3.4 region (5°N–5°S, 120°W–170°W) (Field et al., 2009). Rainfall in Sumatra, on the other hand, was explained for 61% by IOD (Field et al., 2009). According to Aldrian and Dwi Susanto (2003), Sumatra itself is again divided into two climatic regions. Both of them have varying sensitivity to the two climate modes (Iskandar et al., 2013).

Using NOAA AVHRR Global Area Coverage (GAC) Earth Observation satellite data, Wooster et al. (2012) found two to three times more active fires in Kalimantan during the 1997-98 very strong El Niño event than in the next largest fire years (e.g., 2002) due to extreme drought at the time. However, fires do not solely occur during strong ENSO events. In 2006 for example, with only a weak El Niño, MODIS active fire data (Giglio, 2010) detected about 149,000 fires over the whole of Indonesia, against 151,000 in the 2015 very strong El Niño year. Most of Indonesian fires burn on Kalimantan and Sumatra. In 2006, both regions generated 84% of all fires in Indonesia (47% and 37%, respectively, Yulianti et al. (2012)). Although Kalimantan has higher emissions, Sumatra contributes more to smoke concentrations in populated areas in Southeast Asia outside of Indonesia due to its location west of the Malaysian peninsula

(Marlier et al., 2015) making Singapore and Malaysia most vulnerable to fire emissions from Sumatra (Hyer and Chew, 2010; Salinas et al., 2013; Aouizerats et al., 2015). Under future climate change scenarios and without changing fire management practice, Indonesia could become even more vulnerable to fire (Herawati and Santoso, 2011).

Previous studies have investigated the relationship between precipitation and fires. Field and Shen (2008), using cross-calibrated ATSR, TRMM, and MODIS active fire detections and the Global Precipitation Climatology Project (GPCP) data set for rainfall for the 1997-2006 period, showed that there was a risk of severe burning when, for a period of 4 months, precipitation falls below a threshold of 350 mm in southern Sumatra and 650 mm in southern Kalimantan. Van der Werf et al. (2008a) found a strong nonlinear relation between fire and rainfall, where active fire detections increased exponentially below 100 mm $month^{-1}$ of rainfall during the dry season. Using visibility records from Sumatra and Kalimantan's World Meteorological Organization (WMO) meteorological stations, Field et al. (2009) calculated monthly mean light extinction coefficients between 1960 and 2006. The optimal timeframe to explain variances in extinction coefficients on Sumatra was after 5 months of rainfall accumulation. With a piecewise linear regression, this could explain 67% of the observed patterns with a threshold of 609 mm, between 1960 and 1983, and 85% with a threshold of 631 mm between 1984 and 2006 on Sumatra. On Kalimantan, 4 months' rainfall accumulation explained 78% of the extinction coefficient variances with a threshold of 672 mm between 1984 and 2006.

For the last two decades, the large fire season of 1997-98 has frequently been used as a reference point. Since then, fire years have been relatively low, except for moderate or weak El Niño events (2002, 2006, 2009, 2012). The amount of fires in 2013 was below our study period average, but northern Sumatra experienced a large amount of fires over a very short period of time (Gaveau et al., 2014). In 2014, fire activity was for the first time above average despite that year being ENSO neutral followed by the very strong El Niño event of 2015 with disruption of regular life in large parts of Indonesia due to dense smoke from the large number of fires. The aim of this study is to better understand the fire-precipitation dynamics in general and focus on the dynamics of 2015, 2014, 2013, and 1997 in particular, based on a merged but consistent fire and rainfall dataset.

2 Datasets and Methods:

Our study region includes all of Indonesia, but we focused primarily on the islands of Sumatra and Kalimantan, as they generate most of the fire activity within the country (Fig. 1). Sumatra is situated between 6°N-6°S and 95°E-107°E. Between 1990 and 2010, 75.400 km^2 of primary forest was cleared (Margono, 2013), but primary forests remain on the mountainous coastal range of the island facing the Indian Ocean. The other side of the island with the provinces of Riau, Jambi, and South Sumatra is largely covered with rainfed agriculture for subsistence and commercial forestry with agricultural activities (114.928 km^2 and 44.307 km^2 respectively, (LADA, 2008)). With approximately 77.000 km^2, peatlands are abundant in this region (Wahyunto et al., 2003), especially in the low-lying areas towards the Northeast. Kalimantan is the Indonesian part of Borneo. It is located between 5°N-4°S and 108°E-118°E. Intact forest remains in the northern part of Kalimantan, but most of southern Kalimantan consists of forestry with agricultural activities or rainfed agriculture for subsistence and commercial (115.351 km^2 and 92.858 km^2 respectively, (LADA, 2008)). An approximately 10.000 km^2 of deforestation scar remains in the south, due to the mega rice project (Boehm and Siegert, 2001; Aldhous, 2004). This widespread area contains some of the deepest peat in Indonesia but has been extensively drained.

To better understand the rainfall patterns preceding and coinciding with the fire season, we based our analysis on a somewhat modified division of the three climatic regions identified by Aldrian and Dwi Susanto (2003) to better account for differences in fire patterns: Their first region is the southern part of Indonesia, from southern Sumatra to Timor island, southern Kalimantan, Sulawesi and part of Irian Jaya. Their second is northwest Sumatra and northwest Kalimantan, and finally the last one includes Maluku and northern Sulawesi. We separated their first region into southern Sumatra (SoSu) and southern Kalimantan (SoKa). Our third region is Sumatra north of the equator (NoSu). Finally, their last region and the area not included in our analysis was classified as "Other" due to less fire activity (Fig. 1).

One key issue when aiming to compare 1997 with 2015 is that there is no fire dataset covering the full period of time based on one satellite stream. There is one for precipitation, but its resolution is relatively coarse (1° spatial resolution). To obtain rainfall data across Indonesia for the 1997-2015 period we combined two datasets: for 1997, the One-Degree Daily (1DD) product from the Global Precipitation Climatology Project (GPCP, (Huffman et al., 2001)) and from 1998 until 2015, the Tropical Rainfall Measurement Mission (TRMM) 3B42 data version 7 (Simpson et al., 1996; Huffman et al., 2007). We merged these two datasets (explained below) to have the higher spatial resolution from TRMM for most of the time period and still cover the full time period. TRMM data is produced at a 0.25° spatial resolution and is based on a combination of TRMM precipitation radar (PR) and TRMM microwave imager (TMI) and rain gauge measurements (Kummerow et al., 1998; Islam and Uyeda, 2007). It lost radar data after mid-2015. TRMM 3B42 has a 3-hourly temporal resolution available since 1998. For the purpose of this study, TRMM 3B42 data was cumulated to daily temporal resolution.

Daily GPCP uses the Threshold Matched Precipitation Index (TMPI) and geostationary infrared satellite data to determine the daily rainfall rate at 1° spatial resolution from the monthly data produced from gauge stations, satellites and sounding observations (Pendergrass, 2015). To aggregate 1997 GPCP data with the remaining TRMM data, we calculated a correction factor for each 1° grid cell derived from a linear regression between GPCP and TRMM data based on the 4 driest months of each year between 1998 and 2014 (Fig. 2). We investigated time frames from 2 to 8 months. Our choice for 4 months was to some degree arbitrary because the differences are very small when looking at the fit between converted GPCP and TRMM. However, converted GPCP based on a 4 month time frame to calculate the correction factor yielded close resemblance for the overlapping period with TRMM in grid cells where a fire occurred during our study period (slope: 0.99, R^2: 0.97). Results are relatively insensitive to the choice of the time periods as will be shown in the result section. We then used the slope to make the 1997 GPCP rainfall data consistent with the TRMM data. We found a slope relatively homogenous over the country (average slope over Indonesia: 0.81). The coefficient of determination showed large spatial variability. South of the equator, it was high; with most areas having R^2 values exceeding 0.8. North of the equator and in mountainous regions, R^2 was lower, for a large part related to lower interannual variability here, but it still exceeded 0.5 in most areas (93% of the grid cells in our study region had an R^2 higher than 0.5).

To cover our study period we also had to merge two fire datasets. We used the Along Track Scanning Radiometer (ATSR) World Fire Atlas (WFA) algorithm 2 (Arino et al., 2012) available from 1995 until 2012, and the Thermal Anomalies/Fires product MOD14A1 (Terra) from the Moderate Resolution Imaging Spectroradiometer (MODIS) available from 2001 until 2015 (Justice et al., 2002). The ATSR fire algorithm (in the remainder referred to as ATSR) detects active fire data at 10:30 PM local time, avoiding flagging hot surfaces or solar reflection as fire. Using the 3.7-micrometer band, it observes hot spots warmer than 308 Kelvin. Because of night-time detection, it underestimates the total number of fires due to the strong diurnal cycle of fires with in general a peak in the afternoon (Giglio, 2007).

Terra MODIS acquires data twice daily (10:30 AM and PM) at 1km spatial resolution using three different tests to identify fire activity. The first is an absolute threshold test (Kaufman et al., 1998), where grid cells with temperatures higher than 360K during daytime or 320K at night are potentially fires. The second is a background characterisation; the neighbouring pixels of the potential fire pixel are used to estimate a background value. Using different statistical techniques it inspects neighbouring pixels to identify fire activity comparing the potential fire pixel with the background value to flag the pixel as burned or to eliminate false alarms. Finally, if previous tests are successful, it looks for characteristics in the active fire signature with the 4µm brightness temperature (T4) to find variations from non-fire backgrounds applying various thresholds (Giglio et al., 2003). These methods are highly effective at identifying smaller fires, yielding near-time information (Roy et al., 2008).

For consistency in data acquisition time, we limited our use of MODIS data to night-time (10:30PM) to have late evening fires at nominal and high confidence. While MODIS revisits the same site every day, ATSR overpasses the same grid cell only once every 3 days (Mota et al., 2006). To combine ATSR and MODIS we used a correction factor based on the fire detection ratio between monthly ATSR and MODIS observations for the period of 2001 and 2011 averaged over 1° grid cells. If we had based the correction factor on linear or exponential relationships between ATSR and MODIS for every 1° grid cells the coefficient of determination between the converted ATSR and MODIS based on monthly total fire detections for the overlapping period was 0.42 and 0.06, versus 0.97 for the ratio method, based on data from Fig 3.

We then multiplied the ATSR data with the correction factor for the period 1997 – 2000 for all grid cells within the 1° grid cells. This correction factor showed substantial spatial variability. In most high fire regions, ATSR was around 4 times lower than MODIS, although in some grid cells the difference was a factor 12 (Fig. 3). The grid cells with high correction factors were often those that burned relatively little, in general less than 500 fires during the full time period. This represents 18% of grid cells burning during our study period. After applying the correction factor to the whole ATSR dataset, our fire correction factor compensated for the lower sampling rates from ATSR over MODIS between 2001 and 2011 across all of Indonesia. The resulting R^2 between monthly MODIS active fire detections and those based on ATSR with the correction factor applied was 0.97 for the full time period. We have not used the burned area or emissions dataset from the Global Fire Emissions Database (GFED) because it relies on the ratio between all MODIS data and ATSR, not just the night time subset. In the remainder of this paper, we will refer simply to the number of active fire detections instead of the number of nighttime fires from the merged product.

Previous work has shown that 4 months of rainfall accumulation has the best coefficient of determination to identify the potential risk of high fire activity in southern Sumatra and Kalimantan (Field and Shen, 2008). However, this period may be different in other regions including northern Sumatra because of different rainfall patterns (Aldrian and Dwi Susanto, 2003). We therefore investigated different lengths of rainfall accumulation to identify the most appropriate time window for different regions. Using the daily rainfall data, we calculated the accumulated precipitation of rain prior to each fire on time frames of 0, 7, 15, 30, 60, 90 and 120 days. We calculated for each fire detection and grid cell the accumulated rainfall for the different time frames ending on the day of active fire detection.

In our analyses we used two additional datasets. To better understand the diurnal fire dynamics, we calculated the fraction of daytime fires burning overnight between 2003 and 2015. Daytime fires were acquired from the Thermal Anomalies/Fires product MYD14A1 (Aqua) from MODIS. It uses the same detection algorithm as MOD14A1 (Terra) mentioned above but with an acquisition time at 2.30 PM and AM. To estimate the number of daytime active fire detections, we only kept the 2.30 PM fires. To observe the proportion of daytime fire burning through the night we compared the annual day and night fire. Due to data availability, this could only be done for the 2003 onwards period. We used the Wetlands International (WI) PeatAtlas of Sumatra, Kalimantan and Papua (Wahyunto et al., 2003, 2004) to better understand peat fire dynamics. Finally we used ENSO and IOD data to observe how our different regions were influenced by fluctuations in sea temperature (NOAA, 2016; OOPC, 2016). While land cover and land cover change influences fire patterns, we have not included this in our analysis due to a lack of consistent data.

3 Results

Indonesia's position on the equator, surrounded by two ocean basins, caused substantial regional variability in the fire season. In southern Sumatra and Kalimantan, the dry season lasted from June until heavier rainfall started again sometime in October for a total of 4-5 months (Fig. 4). During our study period, the months with the highest incidence of active fires were September and October. Average rainfall during the dry season was 140 mm per month in southern Sumatra, compared to 170 mm in southern Kalimantan, but with substantial regional variation. Northern Sumatra, on the other hand, had two fire seasons, a first one in February – March (early dry season) followed by a second in June lasting up to 3 months, depending on the year (late dry season).

The dataset covering the 1997- 2015 period enabled us to observe several large fire years, including two during very strong El Niño events (1997 and 2015). In 1997, approximately 119,000 active nighttime fire detections were made according to our merged dataset, compared to less than half that number in 2015. The number for 1997 was to some degree a virtual number based on the observed ATSR fires and the correction factor to bring the ATSR fires in line with those observed by MODIS at night. These two extreme drought years mainly affected southern Sumatra and southern Kalimantan, with approximately 50,000 active fires in 1997 and 20,000 active fires in 2015 in both regions (Fig. 5). Other relatively high fire years in these two regions occurred during weak or moderate El Niño events in 2002, 2006, 2009 and 2014.

Northern Sumatra's inter-annual variability was very different from that of the other regions. Years of strong active fire activity did not always line up with El Niño events as shown earlier by Gaveau et al. (2014). Fires there were also less frequent than in southern Sumatra and Kalimantan. Nevertheless, in 2005 and 2014 more than 10,000 active fires were detected in northern Sumatra. Northern Sumatra had a large proportion of active fire detections in peatlands (Table 1). During our study period, on average 75% of the total active fires occurring in northern Sumatra were on peatland, with higher values of 87% and 88% in 2005 and 2014, respectively. In Indonesia south of the equator, the proportion of peat active fires was lower, averaging 61% in southern Sumatra and 50% in southern Kalimantan. Between 1997 and 2015, our dataset indicated 192,000 active fires in the 127,425 km^2 of peatland in Sumatra and Kalimantan.

The number of active fires burning through the night across Indonesia (expressed as the ratio between nighttime and daytime active fires) varied from 11% in 2003 up to 36% in 2015, on average 20%. Northern Sumatra, although having fewer active fires than the southern regions, had between 14% (low fire year) up to 52% (high fire year) of daytime fires burning overnight, and on average 33%. Southern Sumatra and southern Kalimantan had a lower proportion of fires burning through the night with years as low as 4%, but on average 23% and 22% respectively. In both of these regions, 2015 had the highest proportion of fires burning through the night with 53% and 43% respectively (Table 2).

Using daily rainfall and active fires, we observed that in southern Sumatra and southern Kalimantan, the fire season and dry season (defined here as the period with the 120 days with lowest rainfall accumulation, based on daily data) followed relatively similar patterns on both islands but still had important differences. In 1997, the dry season started in early July on both islands, but while days with more than 500 active fires began in mid-August in southern Kalimantan, the fire season in southern Sumatra began almost one month later, potentially because rainfall still occurred in Sumatra (Fig. 6). On both islands most active fires burned during the driest 120 days. 2006 had a weak El Niño, with more days with rainfall during the dry season than in 1997 and 2015, resulting in lower fire activity. In southern Sumatra, strong rainfall in late October

2006 ended the fire season earlier in that year than in 1997. In southern Kalimantan, the late October rain did not exceed 8 mm/day, which enabled further burning before the return of the monsoon with higher rainfall. In 2015, the dry season as defined here began earlier than in 1997 while active fires started mildly in mid-August, rising in September for about two months, as had occurred in 1997. During the dry season, however, there were more days with rainfall and the number of fires detected was lower than in 1997. Furthermore, in 2015 active fires stopped already late October, while in 1997 they burned for another week in November.

The amount of rainfall during the dry season did not influence the number of active fires equally in the different regions. In other words, there was large spatial variability in the vulnerability to fire. In 1997, all of Indonesia was dry, but most active fires occurred south of the equator, northern Sumatra being only mildly affected by fires. Obviously, all high fire years in southern Sumatra and southern Kalimantan had a relatively low amount of rainfall during the entire dry season, but rainfall amount differed between the high fire years. While in 1997 no grid cell in these two regions exceeded 50 mm of rainfall during the driest 120 days period, 2015 almost reached 150 mm in both regions (147 mm in southern Sumatra and 149 in southern Kalimantan). Northern Sumatra had a rainfall accumulation of 194 mm during the dry season in 2005, while 2014 was drier with only 147 mm (Fig. 7).

Observations of the accumulation of rain before active fires showed that in all regions studied, extreme fire years had less than 1 mm of rain on the day of fire detection (Fig. 8). Yet, this also applies to some very mild fire years and is therefore not a good predictor for high fire years. In line with previous studies, we have therefore examined up to 120 days of rainfall preceding active fire observations in order to observe the influence of rainfall on fires. The novelty in our approach is that we used daily data for this instead of monthly. In southern Sumatra and southern Kalimantan this did not lead to new results; cumulative rainfall for 120 days prior to active fires were the most effective to identify fire vulnerability to rainfall. On the other hand, in northern Sumatra, a 30-day timeframe was more appropriate (Table 3). This shows that northern Sumatra is more responsive to relatively short-term drought periods, or that droughts last shorter.

This method allowed us to observe rainfall thresholds to generate high fire years. In northern Sumatra, we found that years with less than 120 mm of cumulated rainfall within 30 days prior to active fires could generate a high fire year. Analysing high fire years in 2005 and 2014, we found substantial differences. In 2005, 93 mm of cumulated rainfall prior to active fire detections was measured against only 33 mm in 2014. This shows that the vulnerability of fires to rainfall is harder to evaluate in this region. For example, in 1997, with 12 mm less cumulated rainfall within 30 days prior to active fires than in 2005, northern Sumatra had 42% less burning, highlighting the role of other factors. In Sumatra, south of the equator, both very strong El Niño events of 1997 and 2015 (Fig. 9) were high fire years with less than 200 mm of cumulated rainfall within 120 days prior to active fires. For these two years in Kalimantan, the threshold was higher at around 300 mm. In both southern regions we observed that 1997 burned much more than

2015, with in absolute terms a relatively small difference in rainfall accumulation prior to active fires (118,685 and 53,659 active fires respectively).

To compensate the absence of TRMM dataset in 1997 we used a ratio to convert GPCP to TRMM. We investigated time frames from 2 to 8 months to find the best correlation between both datasets. We found that our results are relatively insensitive to the choice of time window. For the 1997 dry season, the mean rainfall for Indonesia varies between 51.7 and 52.9 mm depending on the time frame chosen (Fig. 10) and cumulative rainfall 4 months prior to a fire varied between 239 and 248 mm (Fig. 11), not changing the strong non-linear response of fire to rainfall.

4 Discussion

The use of a correction factor to merge two rainfall and fire datasets enabled us to obtain a relatively consistent 19-year time series covering two very strong El Niño episodes. Interannual variability in fire activity in Indonesia was not solely linked to ENSO and varied between regions. The regions that were most closely linked to droughts associated with El Niño events, such as in 1997 and 2015, were those south of the equator in Sumatra and Kalimantan. We found that 2015 had only about half the number of active fires observed in 1997 (Fig. 5). This large difference came mostly from lower rainfall in 1997 between mid-July and mid-September. The dry season in the areas south of the equator lasted for approximately 4 months in those two years but 2015 saw more relatively minor rain events of a few mm day^{-1} during the dry season (Fig. 6). These minor events could be one of the causes of the strong non-linearity found in previous studies (van der Werf et al., 2008b); they add relatively little rainfall but are apparently capable of pausing the fire season for some time.

We have shown that in southern Sumatra and southern Kalimantan rainfall accumulation over 120 days had the best coefficient of determination to estimate the number of fires observed. The amount of rainfall during the transition between the wet and dry season was essential to estimate the beginning of the fire season. The El Niño during this transition period was stronger in 1997 than in 2015 and may be part of the explanation for 2015 having only half the number of active fires detected in 1997 (Fig. 9). Although both years were very strong El Niño years, their temporal dynamics were different. In 2015, the highest sea surface temperature anomaly in the Pacific occurred in September (2.5°C). In 1997, however, anomalies were already at 2.8°C in July, rising to above 3°C in August and September. A second difference was that the Indian Ocean temperature anomalies in 1997 were twice as high as in 2015. Here we can only show that the ENSO and IOD dynamics were different between the two years and hypothesize this to be the root cause for the difference in rainfall. Another factor in explaining the large difference in number of active fires detected may be that the 1997 event occurred just after the mega rice project, which increased the flammable area substantially. However, according to Field et al. (2015) Kalimantan as a whole has become even more vulnerable to fire over the years.

While in the southern hemisphere IOD and ENSO dynamics and their impact on 120-day rainfall amounts could explain the variability in active fires detected between the various years, in northern Sumatra, the number of active fires annually detected was more closely correlated with shorter periods of rainfall. The dry season in general lasts shorter there, but northern Sumatra has two of them in some years (Yulianti et al., 2013) making comparisons between various years difficult. 2005 and 2014 saw active fires during both dry seasons but the early dry season had most fires (Fig. 5). In 2013, burning only occurred in the late dry season with the months of May and June being drier than usual. This short period contained most of the yearly fire activity and generated more atmospheric pollution over Singapore than the 1997 fires because the winds carried smoke from this region directly to Singapore (Gaveau et al., 2014).

We observed that in northern Sumatra more active fires burned overnight than in southern Sumatra and Kalimantan. Linked to this, the southern regions also had a relatively low fraction of active fires burning overnight, except in 2015, coinciding with a very strong El Niño event. Unfortunately, due to data availability we do not know whether the same holds for the 1997 El Niño (Table 2).

Having focused exclusively on active fires detected at night, this study is not readily comparable with Field and Shen (2008) rainfall accumulation threshold of 350 mm in southern Sumatra and 650 mm in southern Kalimantan. In southern Sumatra, the threshold of 350 mm within 4 months prior to active fire detected by Field and Shen's (2008) was valid for high fire years. While our estimate of 200 mm seems much lower, there were no years with rainfall accumulation in between 200 mm and 350 mm rainfall accumulation within 4 months prior to active fire (Fig. 8).

This study relied exclusively on nighttime data in order to remain consistent with the datasets used to cover the entire study period. One uncertainty for this methodology is an eventual change in diurnal cycle within similar climatic and ENSO conditions. We found that 36% of active day fires burned overnight in 2015, compared to only 21% in 2006, yet 2006 had a much weaker El Niño. Unfortunately, no consistent daytime fire data was available to evaluate the diurnal cycle extending back to 1997.

Our approach carries a number of uncertainties. First, the focus on night time fires enabled a consistent time series but, as mentioned above, potential changes in the number of fires observed during the day without impacting the number of night time fires (i.e. a change in the number of fires that burn through the night) would remain undetected. Whether this is the reason behind the different ratio between 1997 and 2015 found here (just over 2) and in the GFED carbon emission estimate (almost 3) cannot be resolved. Second, active fire datasets have a large omissions rate. Tansey et al. (2008) compared MODIS data (MOD14A1) hotspots with disaster monitoring constellation (DMC) and Landsat TM data. They found an omission error of 60% during the 2002, 2004 and 2005 dry seasons. The advantage of using active fires is the high temporal resolution, which enabled us to better study fire-precipitation rates. Finally, our approach of stitching together different datasets revealed the substantial spatial variability in ratios mostly between ATSR and MODIS active fires for which we do not have a plausible explanation but potentially impacted the time series. In addition, the lower sampling rate of ATSR means that the daily time step for 1997 is actually a constructed one, the actual data has a 3 days revisit time.

5 Conclusions:

We have constructed a rainfall and active fire dataset by combining two datasets for each to cover the 1997 – 2015 period thus capturing two strong El Niño events. The dataset provides daily temporal resolution and focused on night time fires to provide consistency over the full time period. We analysed the fire patterns in Indonesia by identifying 4 regions with different spatio-temporal variability in fire activity. The main findings can be summarized as follow:

- While most fires in southern Sumatra and Kalimantan occurred between August and October, northern Sumatra had two fire seasons: a short one in February followed by a longer one between June and August. In high fire years northern Sumatra most active fires occurred in the early dry season, except in 2013 when almost all active fires occurred during the later dry season.
- The 2015 El Niño event involved approximately 52,000 active fires, compared to approximately 119,000 in 1997. This difference came mostly from southern Sumatra and Kalimantan. While both 1997 and 2015 were very strong El Niño years, the Indian Ocean Dipole (IOD) was more favourable for droughts and the El Niño event in 1997 occurred somewhat earlier, thus aligning closer to the start of the fire season. While 1997 was anomalous in the sense that the mega rice project was just initiated in 1996 in Kalimantan and greatly extended the flammable area which may have been another factor explaining the difference, our study did not explicitly take land cover changes into account.
- While amounts of rainfall in 1997 and 2015 were relatively similar 120 days prior active fires (respectively 281 mm and 303 mm in southern Sumatra and 248 mm and 269 mm in southern Kalimantan), there were more days with rainfall in 2015 than in 1997. This may be one of the key reasons behind the strong non-linear response of fires to rainfall; while those days with little rainfall do not add much to the total dry season rainfall, they are capable of halting fires.
- Northern Sumatra, with approximately 42,000 km^2 of peatland, had the highest proportion of active fires observed in peatland (75%), compared to 61% in southern Sumatra. Although southern Kalimantan has the largest peatland area, with more than 50,000 km^2, the incidence of active peat fires in that region was 50% of all active fires, which is also the average percentage when considering all of Indonesia.
- In agreement with other studies, we found that 120 days of rainfall accumulation prior to an active fire was the best correlated timeframe to a severe fire year in southern Sumatra and Kalimantan. In northern Sumatra this period was lower, 30 days. Part of the reason is that the dry season there is shorter. However, the response time is faster than in other parts of Indonesia as well.

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Tables

Table 1: Number of active fire detections for the different regions including the number of fires detected in peatlands , with percentage of peatland. For each region the total surface of peatland is shown on top of each column.

Year	North Sumatra (41,792 km^2)			South Sumatra (35,546 km^2)			South Kalimantan (50,087 km^2)			Others (100,441 km^2)			Total (227,866 km^2)		
	Peat fire	Non-peat fire	%	Peat fire	Non-peat fire	%	Peat fire	Non-peat fire	%	Peat fire	Non-peat fire	%	Peat fire	Non-peat fire	%
1997	4,031	2,881	58	24,645	21,842	53	22,624	30,349	43	2,228	10,085	18	53,528	65,157	45
1998	1,714	1,322	56	138	378	27	599	3,126	16	873	19,952	4	3,324	24,778	12
1999	1,691	990	63	918	841	52	494	654	43	103	1,111	8	3,206	3,596	47
2000	1,624	2,496	39	215	564	28	146	332	31	83	904	8	2,068	4,296	32
2001	1,287	553	70	257	243	51	1,600	766	68	54	1,187	4	3,198	2,749	54
2002	3,720	1,063	78	1,220	697	64	7,336	5,836	56	134	3,579	4	12,410	11,175	53
2003	1,582	685	70	1,054	557	65	1,125	1,249	47	17	996	2	3,778	3,487	52
2004	2,138	915	70	2,100	786	73	2,543	3,497	42	200	2,389	8	6,981	7,587	48
2005	9,627	1,497	87	559	187	75	1,032	770	57	226	1,402	14	11,444	3,856	75
2006	2,649	741	78	5,518	2,872	66	8,309	8,521	49	394	2,418	14	16,870	14,552	54
2007	968	146	87	219	519	30	90	409	18	91	1,175	7	1,368	2,249	38
2008	777	263	75	551	980	36	42	195	18	57	996	5	1,427	2,434	37
2009	2,686	985	73	1,831	1,436	56	4,928	4,232	54	476	2,529	16	9,921	9,182	52
2010	655	176	79	69	94	42	7	93	7	29	789	4	760	1,152	40
2011	1,339	373	78	2,191	1,284	63	1,116	914	55	280	865	24	4,926	3,436	59
2012	1,898	540	78	2,195	1,867	54	1,320	701	65	147	1,355	10	5,560	4,463	55
2013	5,320	1,133	82	263	791	25	357	196	65	106	957	10	6,046	3,077	66
2014	10,807	1,453	88	4,147	1,185	78	3,549	2,262	61	783	3,651	18	19,286	8,551	69
2015	1,551	608	72	17,312	5,577	76	13,227	7,757	63	579	7,048	8	32,669	20,990	61
total	56,064	18,820	75	65,402	42,700	61	70,444	71,859	50	6,860	63,388	10	395,537	196,962	67

Table 2: MODIS Terra (10:30pm) and MODIS Aqua (2:30pm) active fire detections.

Year	North Sumatra			South Sumatra			South Kalimantan			Others			Total		
	day fire	night fire	%	day fire	night fire	%	day fire	night fire	%	day fire	night fire	%	day fire	night fire	%
2003	9,442	2,267	24	14,430	1,611	11	19,895	2,374	12	23,406	1,013	4	67,173	7,265	11
2004	13,395	3,053	23	21,053	2,886	14	36,234	6,040	17	41,009	2,589	6	111,691	14,568	13
2005	28,654	11,124	39	8,656	746	9	13,649	1,802	13	19,983	1,628	8	70,942	15,300	22
2006	13,045	3,390	26	42,031	8,390	20	55,614	16,830	30	38,696	2,812	7	149,386	31,422	21
2007	5,771	1,114	19	13,468	738	5	9,133	499	5	16,339	1,266	8	44,711	3,617	8
2008	7,039	1,040	15	13,391	1,531	11	6,284	237	4	14,933	1,053	7	41,647	3,861	9
2009	12,100	3,671	30	19,830	3,267	16	36,817	9,160	25	29,502	3,005	10	98,249	19,103	19
2010	5,846	831	14	3,942	163	4	2,118	100	5	8,465	818	10	20,371	1,912	9
2011	8,425	1,712	20	17,498	3,475	20	17,249	2,030	12	17,992	1,145	6	61,164	8,362	14
2012	8,661	2,438	28	21,300	4,062	19	17,691	2,021	11	21,175	1,502	7	68,827	10,023	15
2013	14,761	6,453	44	9,617	1,054	11	12,721	553	4	16,440	1,063	6	53,539	9,123	17
2014	23,736	12,260	52	18,521	5,332	29	29,484	5,811	20	35,473	4,434	12	107,214	27,837	26
2015	6,155	2,159	35	43,211	22,889	53	49,237	20,984	43	52,429	7,627	15	151,032	53,659	36
total	157,030	51,512	33	246,948	56,144	23	306,126	68,441	22	335,842	29,955	9	1,045,946	206,052	20

Table 3: standard error of the regression for each region according to the number of days of rainfall accumulation. NoSu is northern Sumatra, SoSu southern Sumatra, and SoKa is southern Kalimantan.

	0	7	15	30	60	90	120
NoSu	2,418	1,940	1,961	1,897	1,981	2,468	2,874
SoSu	6,638	8,254	8,579	7,299	5,933	5,053	4,550
SoKa	10,022	11,183	10,069	7,843	7,940	6,866	4,894

Figures

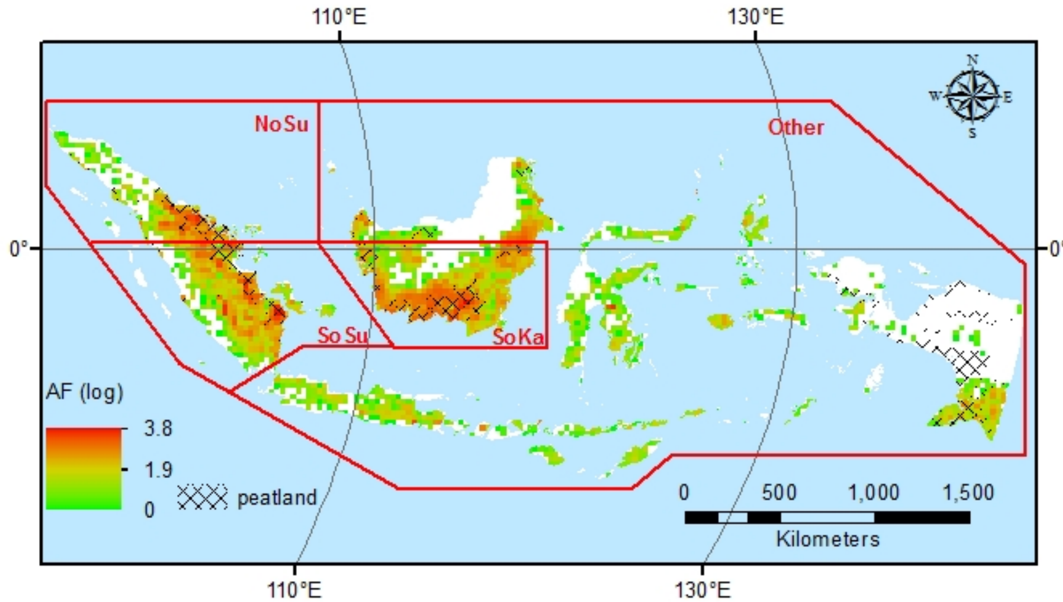


Figure 1: Region definition, number of active fires detected between 1997 and 2015 (log scale, rescaled to quarter degree) and peatland extent for Indonesia. NoSu is northern Sumatra, SoSu southern Sumatra, and SoKa is southern Kalimantan. The white areas are where no active fires were detected.

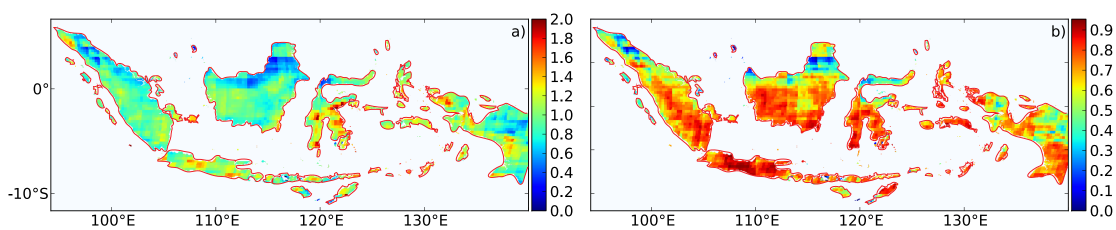


Figure 2: a) Slope and b) R^2 of a linear regression between GPCP and TRMM rainfall based on the cumulated rainfall for the 4 driest months between 1998 and 2014.

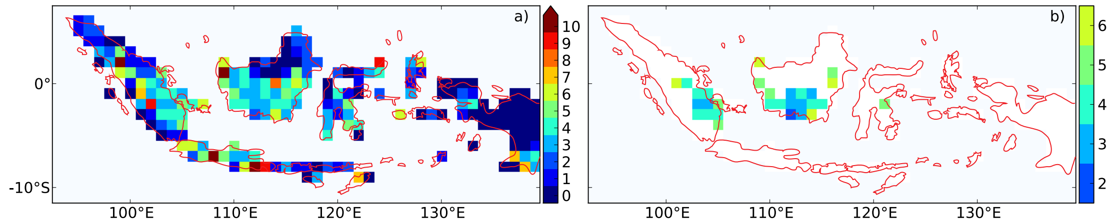


Figure 3: Ratio between MODIS and ATSR (both 10:30pm overpass) active fire detections over the 2001-2011 overlapping period for a) all grid cells with active fire detections and b) only for those grid cells with more than 500 MODIS active fires detected between 2001 and 2011.

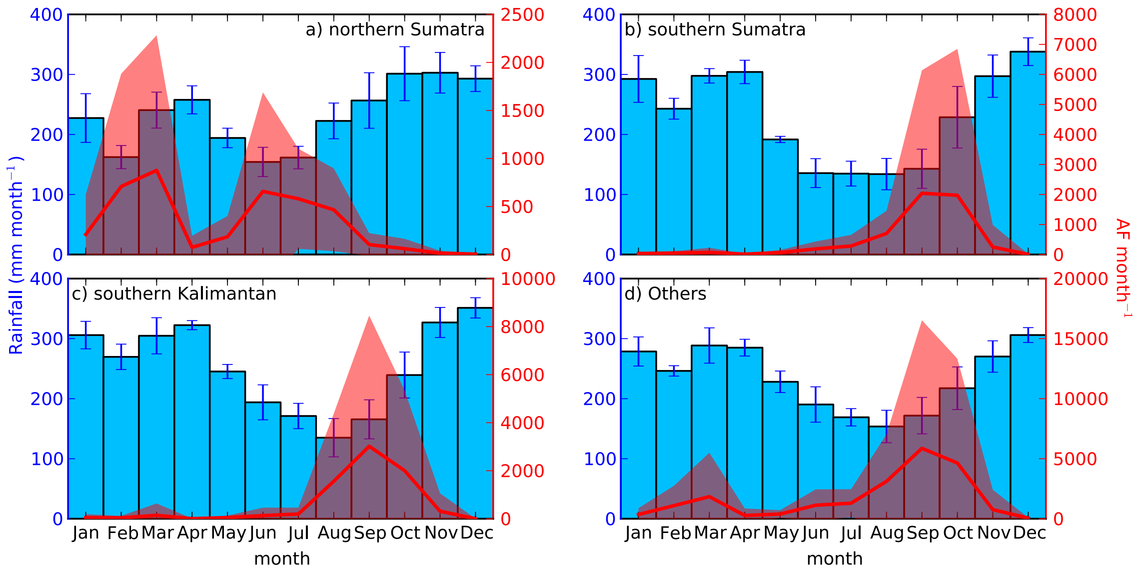


Figure 4: Monthly rainfall with standard deviation (blue) and active fire detections with standard deviation (red), averaged over 1997 -2015.

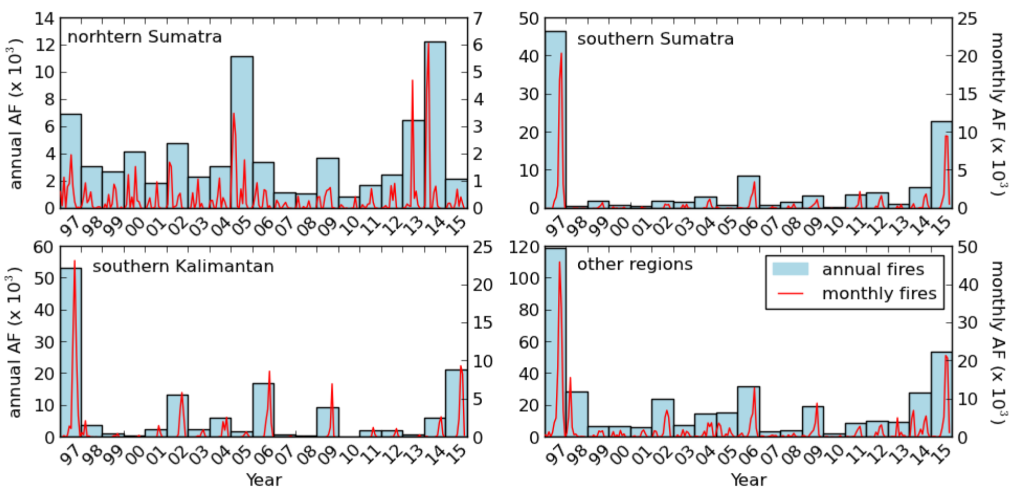


Figure 5: Number of annual and monthly active fire (AF) detections.

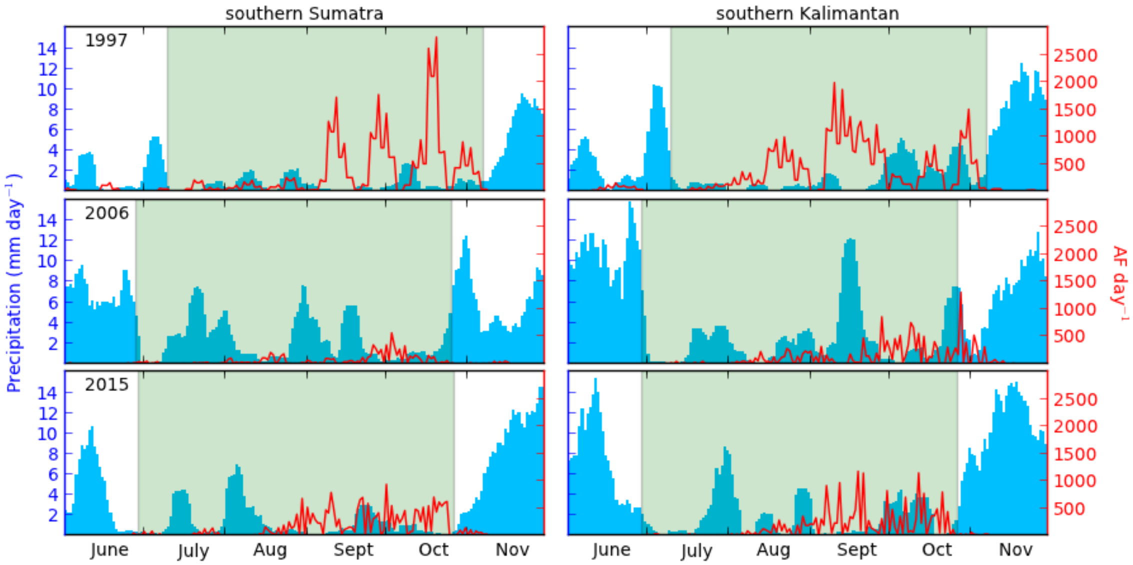


Figure 6: Daily active fire (AF) detections (red) and rainfall (blue) in southern Sumatra and southern Kalimantan during dry seasons of 1997, 2006 and 2015. The green shaded period indicates the dry season defined here as the 120 day period with lowest rainfall.

Figure 7: Rainfall and active fire detections (log scale) aggregated to 1° spatial resolution during the dry season.

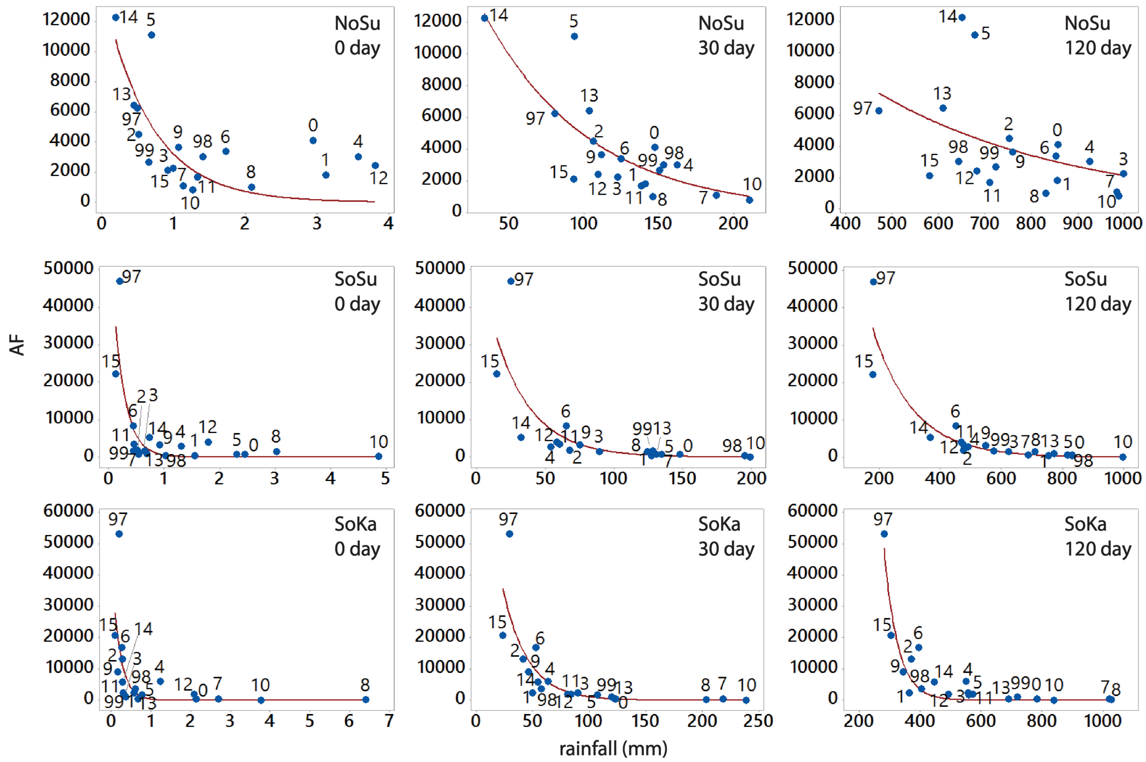


Figure 8: mean rainfall accumulation before fire (with exponential trend line) for each climatic region with a 0, 30 and 120 days buildup. The numbers in the graph denote the year (97 is 1997, 0 is 2000, through 15 is 2015).

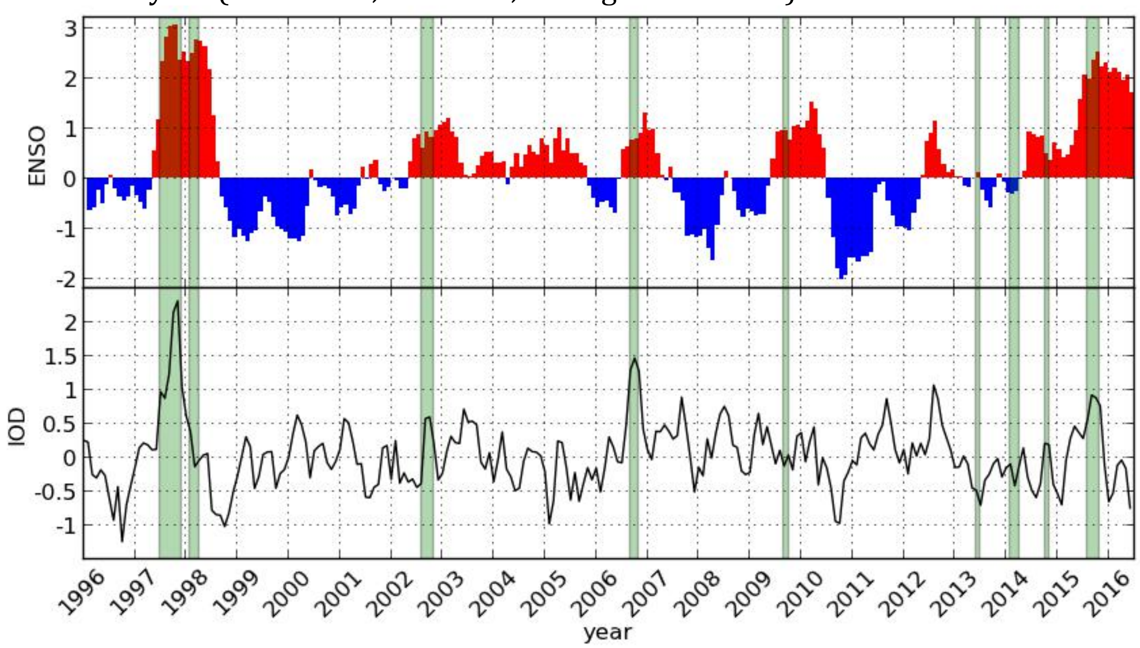
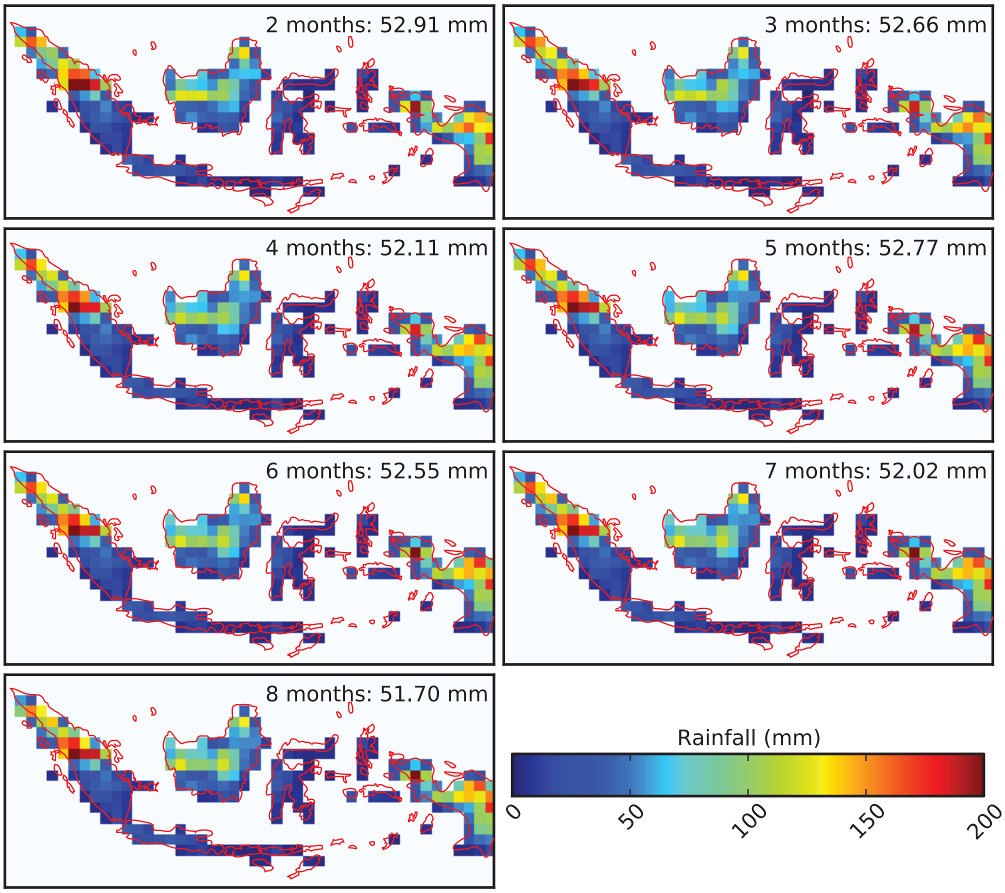
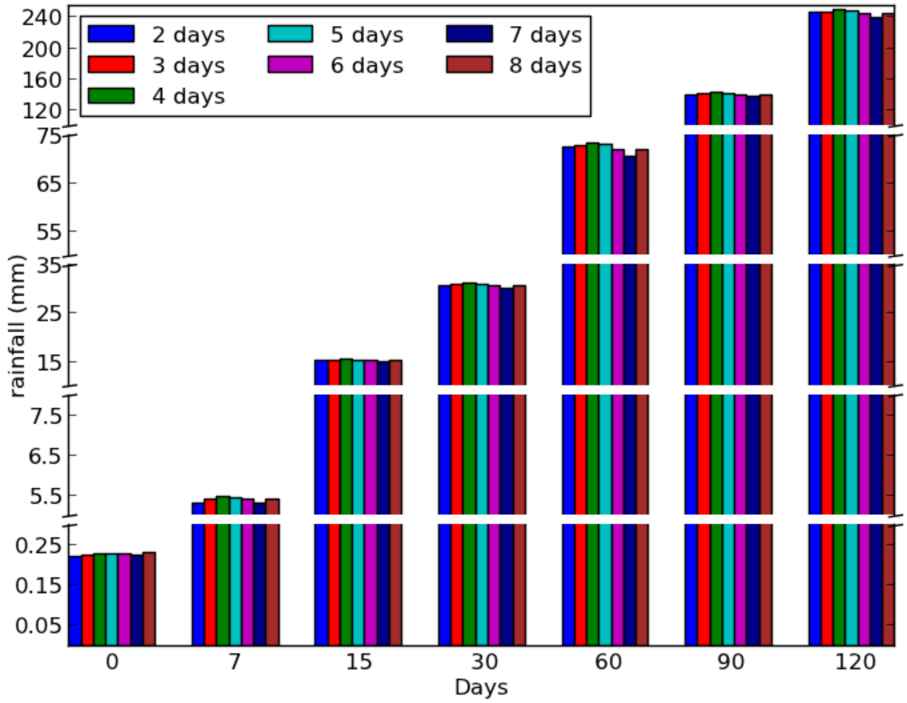


Figure 9: ENSO and IOD with periods of strongest fire activity in green (more than 5.000 AF month^{-1}). (NOAA, 2016; OOPC, 2016)



765 Figure 10: 1997 mean corrected GPCP rainfall rates during dry season based on using different time frames to convert GPCP to TRMM. The numbers indicate the 1997 mean rainfall for Indonesia during the dry season.



770 Figure 11: mean rainfall accumulation before fire in 1997 (based on Figure 9) in Indonesia with a 0, 7, 15, 30, 60, 90 and 120 days buildup, showing results for all the time frames tested to select our correction factor.