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Fire, drought and El Niño relationships on Borneo during the pre-MODIS era (1980–2000)

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Abstract

Borneo (Indonesia) is Earth's third largest island, and the location of both extensive areas of rainforest and tropical peatlands. It is the site of both regular (seasonal) biomass burning associated with forest clearance and agricultural production preparations, and occasional, but much more severe, large fire episodes releasing enormous volumes of carbon from burning vegetation and peat. The latter's extreme magnitude is believed to be associated with the severity of El Niño related droughts. Over the last decade, data from the EOS MODIS satellite instruments have been used to study fire on Borneo, but earlier large fire events remain less well documented. Here we focus on the study of Borneo's large fire episodes in the "pre-MODIS" era, and specifically a 20 year period covering both the two strongest El Niño-Southern Oscillation (ENSO) events on record (1997–1998 and 1982–1983) and an unprecedented series of more frequent, but weaker, El Niño's. For the five El Niño episodes occurring between 1980 and 2000, we develop quantitative measures of Borneo's fire activity based on active fire counts derived from NOAA AVHRR Global Area Coverage (CAC) satellite data. We use these metrics to investigate relationships between the strength and timing of the El Niño-Southern Oscillation (ENSO) event, the associated drought, and the fire activity magnitude. Significant fires are identified across parts of South, Central, East and West Kalimantan, always occurring within two or three fire sub-seasons separated by monsoons. We find that the length, overall strength, and growth rate of individual El Niño episodes effects the extent and harshness of the drought, and the magnitude of fire activity. We confirm significant correlations between monthly ENSO index and rainfall deficit measures, and between rainfall deficit and fire. The two strongest El Niño episodes are accompanied by the most abundant fires, showing two and three times the active fire count seen in the next largest fire year. The most significant statistical association found between ENSO strength and fire activity is that between the 16-month sum of the Niño-3 anomaly and the simultaneously recorded number of active fire counts (r^2=0.98, based on the five El Niño episodes between 1980 and 2000). We independently test our relationship using data from the 2002–2003 El Niño event, and find that it continues to be robust. Our results confirm that the ENSO phenomenon, via its effects on precipitation, is the primary large-scale, short-term climatic factor controlling fire activity in Borneo.

1 Introduction

Fire is a major driver of land cover change in many tropical forest areas, including Southeast Asia (Cochrane, 2003). In this region, in addition to the carbon stored in forest biomass, the approximately 250 000 km^2 of peatlands represent an immense reservoir of fossil carbon (Jaenicke et al., 2008; Couwenber et al., 2010). The Indonesian island of Borneo possesses more than 40% of SE Asia's peatland, and via a combination of drought, peatland draining, land clearance and forest degradation, the normally moist peatland and forest vegetation can dry out and maybe ignited and burn for many months (Page et al., 2002; Goldammer, 2007). Fire activity in the SE Asian region, including Borneo, shows considerable inter-annual variability, with peaks generally coinciding with El Niño-Southern Oscillation (ENSO) events (van der Werf et al., 2006). ENSO-related rainfall droughts, coupled with changing land-use patterns and variations in the extent of anthropic practices, are believed to be the main controls of this variability (e.g., Fuller and Murphy, 2006; Goldammer, 2007; Langner and Siegert, 2009; Miettienen et al., 2010).

The largest fire events on Borneo in the late 20th century coincided with the 1997–1998 and 1982–1983 ENSO events, which are the strongest on record and likely affected the composition of the atmosphere at globally detectable scales (Page et al., 2002; Jones and Cox, 2005; Ramonet et al., 2005). Driven by the potential significance of these events, over the last 25 years a series of remote sensing studies have attempted to document the spatial and temporal patterns of Indonesian fire episodes, particularly those occurring in El Niño years (e.g., Malingreau et al., 1985; Wooster et al., 1998; Legg and Laumonier, 1999; Wooster and Strub, 2002; Fuller and Murphy, 2006). Studies conducted in North and South America have shown how that region's fire activity shows a strong relationship to climatological characteristics related to ENSO events (e.g., Swetnam and Betancourt, 1990, 1998; Kitzberger, 2002). Such relationships provide information on the strength of the coupling between large fire episodes and ENSO characteristics, and may potentially be useful for predicting levels of fire activity many months in advance based on seasonal forecasting methods (e.g., Roads et al., 2001, 2005; Li et al., 2008; Barnston et al., 2010). If such relationships were available for Borneo, then the magnitude of the terrestrial and atmospheric impacts of the forthcoming fire season may be better able to be anticipated, including the potential for fire spread into Borneo's forest reserves and the degree of polluting haze that can leave large areas of SE Asia with serious air quality problems (Aiken, 2004; Goldammer, 2007). (Temporary) controls on the major land clearance activities that are believed to be the foremost fire ignition source may also then be able to be considered (Langner et al., 2007).

In this context, the purpose of the current work is to: (i) develop a quantitative record of fire activity on Borneo covering ENSO episodes going back to the start of the 1980s, well before those of current fire databases (e.g., Stolle et al., 2004; Langner and Siegert, 2009; van der Werf et al., 2006, 2008). In particular, the 20 year period between 1980 and 2000 is unique in the ENSO record, capturing an unprecedented series of rapid El Niño events and encompassing the two strongest ENSO events on record (Trenberth and Hoar, 2006); and (ii) to use this record to help elucidate the nature and strength of the empirical linkage between ENSO, drought and fire. Since this period is prior to the MODIS era, we use active fire (AF) measures derived from the long-running NOAA AVHRR sensor as our fire activity metric.

2 Study area

2.1 Geography

Borneo (Fig. 1) is located on the equator, and is Earth's third largest island covering ca. 746 000 km^2. Together with Sumatra and Malaysia, Borneo possesses the world's highest concentrations of Dipterocarp forest ecosystems; these forests are drought-susceptible and vulnerable to fire, particularly following disturbance (Guhardja et al., 2000; Siegert et al., 2001; Cochrane, 2003; Goldammer, 2007). Since the 1960s, large-scale exploitation has transformed much of the formerly forested lowlands of Borneo, including extensive peatlands, into agricultural plots, plantations, or degraded them via logging (Guhardja et al., 2000; Curran et al., 2004). The outcome is a highly fragmented landscape, in which there occur many anthropogenically driven ignition events. If these ignitions coincide with a period of low fuel moisture, caused for example by an ENSO-related drought, then this can allow fires to spread from heavily exploited areas into the less disturbed forests and peatlands (Guhardja et al., 2000; Langner et al., 2007).

2.2 Climate

Borneo has an equatorial tropical climate, experiencing only small annual temperature and humidity variations. Rainfall is more variable, and is characterized by a bi-modal monsoonal pattern, related to the north-south movement of the Intertropical Convergence Zone (ITCZ). A longer "wet" northeast monsoon is typical between November and March/April, and a shorter "dry" southwest monsoon between May/June and September/October (Langner et al., 2007). Winds are often light, particularly in the monsoon transition periods (March–April and October–November) and precipitation is generally highest in the northwest and over the central mountainous regions, lower in the northeast and southeast, and lowest in the south and east coastal lowlands (Tapper, 2000; Kirono et al., 1999; Guhardja et al., 2000; Kirono, 2004). On inter-annual time scales, ENSO is believed to be the major factor influencing Borneo's climate, most particularly rainfall, which can show strong deficits during major ENSO events (Tapper, 2000; Haylock and McBride, 2001; Aldrian et al., 2007). Gutman et al. (2000) previously used NOAA AVHRR data to illustrate the major impact of the 1997–1998 ENSO on Borneo's surface-atmosphere conditions.

2.3 Fire

The paleoenvironmental record provides evidence for recurrent periods of fire activity on Borneo over the Pleistocene and the Holocene, presumably as climatic oscillations (e.g., glacial-interglacial cycles and the ENSO) resulted in conditions favorable for fire (Goldammer, 2007). However, over the late 20th century fire has become an annual occurrence, being seasonal in nature and apparently closely coupled to spatio-temporal shifts in rainfall and changes in land cover (Goldammer, 2007; Langner and Siegert, 2009). Studies of East Kalimantan (1978–1995) suggest that only ENSO-related rainfall deficits can account for the high fire danger indices seen in 1982–1983, 1987, 1991–1992 and 1994 (Deeming, 1995; Fuller and Murphy, 2006). Satellite data confirm that it is these years of El Niño-related drought that are associated with the most extreme fire activity (e.g., Malingreau et al., 1985; Wooster and Strub, 2002; Fuller, 2003; van der Werf et al., 2006, 2008; Langner and Seighter, 2009), with monthly rainfall totals below ~100 mm appearing to be a critical threshold (Goldammer, 2007). There is anecdotal evidence extending back to the 1880s of significant forest mortality during such droughts, although interestingly these reports do not mention fire (Goldammer, 2007). During more recent El Niños, large fire events have become commonplace, though drought, per se, can apparently cause as significant an amount of tree mortality and biomass reduction in the affected rainforests as do the associated fires (van Nieuwstadt and Sheil, 2005). It is clear that there are strong links between ENSO, drought and fire on Borneo, although the empirical nature and strength of these relationships has yet to be fully determined, at least for the unique series of ENSO episodes we consider here, which mostly pre-date the times of existing analyses (e.g., Fuller and Murphy, 2006; Langner and Seighter, 2009).

3 Datasets

3.1 Satellite active fire detections

Infrared (IR) observations from Earth orbiting satellites provide spectral radiance and brightness temperature (BT) measures that at some wavelengths are highly sensitive to the radiant energy emissions from even highly sub-pixel fires, particularly so at middle infrared (3–5 µm) wavelengths (Robinson, 1991). To be most useful these MIR measurements must be accompanied by longwave IR (8–12 µm) observations useful for helping avoid "false alarms" and for cloud masking. By day, VIS/NIR measurements (0.4–1.1 µm) are also useful for this purpose (Zhukov et al., 2006). The MODIS sensor flying on the EOS Terra and Aqua satellites (launched in 2000 and 2002, respectively) currently provides probably the most commonly used active fire observations, and these Active Fire and Thermal Anomaly products (MOD14 and MYD14; Giglio et al., 2003a) have provided a regular, well-characterised global record of active fires since 2000. A series of spatio-temporal studies aimed at elucidating patterns of fire activity and their interannual variability have been based on these MODIS products (e.g., Chuvieco et al., 2008), including studies focusing explicitly on Borneo and which combine the record with those from other remote sensing systems (e.g., Fuller, 2003; Simmonds et al., 2004; Langner and Siegert, 2009).

Prior to the MODIS-era the Advanced Very High Resolution Radiometer (AVHRR), carried onboard NOAA's Polar Orbiting Environmental Satellite (POES) series, provided data for the majority of active fire studies (Robinson et al., 1991), and also provides the data source for the current study. A single AVHRR swath is ca. 2400 km wide, and the raw "Local Area Coverage" (LAC) format data AVHRR data has a 1.1 km spatial resolution at nadir, very similar to that of MODIS. Figure 2 illustrates three typical AVHRR LAC scenes of southern Borneo collected during the fire season of three climatologically quite different years; (a) the 1997 El Niño, (b) the 2001 "normal" year, and (c) the 1999 La Niña. Pixels containing actively burning fires appear black in this rendition, and the greatly increased fire activity observed during the El Niño year (a) when compared to the "normal" year (b), and the further reduced number of fires seen during La Niña conditions (c), is typical of other AVHRR data we examined. Our analyses of these and other LAC scenes confirms previous conclusions that AVHRR data are capable of detecting gross variations in fire activity in this tropical environment (e.g., Fuller and Fulk, 2000; Siegert and Hoffmann, 2000; Langner and Siegert, 2009).

While LAC data are the optimum data source for AVHRR-based active fire studies, unfortunately this full spatial resolution data format was not routinely archived by NOAA at a global scale due to onboard data storage limitations of the POES system. For many areas outside of the continental USA, LAC data coverage is, in fact, rather infrequent, and NOAA's central repository for AVHRR data (the online CLASS database; http://www.class.noaa.gov) indicates that Indonesia is sparsely covered. Instead, daily coverage of AVHRR data is available globally via the reduced spatial resolution Global Area Coverage (GAC) AVHRR data product. The pixel averaging and pixel/line skipping procedures used to derive the spatially sub-sampled GAC data from the original AVHRR LAC observations are conducted onboard the POES satellite according to the procedures detailed in Robel et al. (2009), as described for example in Wooster and Strub (2002). The resultant GAC data record is sufficiently low volume (1/16th of the original LAC data) that it can be continuously recorded until the POES satellite is within site of a US data-down link station, and thus a global GAC data record exists back to the early years of POES operations.

In terms of detailed characteristics, each AVHRR GAC pixel can be considered as representing the spectral radiance signal from a 4.4×1.1 km area (at nadir), with a 3.3 km gap between each scan line of data. Despite these unusual spatial characteristics, AVHRR GAC data processed through standard fire detection algorithms have long been used to document variations in fire activity (e.g., Koffi et al., 1996). In the pre-MODIS era, the only alternative global active fire datasets are the ERS-2 ATSR and TRMM VIRS active fire products (Giglio et al., 2003b; Schultz, 2002; Mota et al., 2006). Both the ATSR and VIRS sensors possess a similar set of spectral bands to AVHR but have significantly narrower swaths (ATSR: 512 km; VIRS: 720 km), meaning that a single scene is insufficient to cover the whole of Borneo and thus limiting temporal coverage. Furthermore, ATSR and VIRS data only extend back to the 1996 and 1998 fire seasons respectively, only a few years before the start of the MODIS record. In contrast, AVHRR GAC data are available over Borneo back to the 1982–1983 extreme El Niño year, so we focus our study on exploitation of this record. These alternative active fire datasets can be used to evaluate the robustness of the GAC-derived fire data record during overlapping time-periods, and because TRMM provides observations with a varying local overpass time it allows important information on the fire diurnal cycle to be derived (Giglio, 2007).

Using AVHRR data, Malingreau et al. (1985) and Wooster et al. (1998) illustrated the extreme magnitude of Borneo's 1983 and 1997 fire activity, and Wooster and Strub (2002) demonstrated that fire activity variations could be quantified using AVHRR GAC data over the period of the extended 1997 ENSO-related drought. Figure 3 shows an example of matching AVHRR LAC and GAC data collected during the 1997 El Niño, indicating that the signature of active fires is evident in the GAC data record. Here we focus on using GAC data to construct a robust and reliable multi-year active fire dataset for Borneo covering five ENSO events, in order to allow quantitative comparisons of fire activity with the climatic conditions (e.g. rainfall deficits) believed to be strong regional drivers of fire. We obtained GAC imagery from the NOAA CLASS database, and apply an active fire detection algorithm previously demonstrated to be capable of quantifying fire activity on Borneo (Wooster and Strub, 2002; Zoumas et al., 2004).

3.2 ENSO Indices

El Niño events vary in their evolution, intensity, duration and climatic teleconnection patterns (Kitzberger, 2002). The regional effects of each ENSO event also vary, depending on how its specific characteristics interact with the normal atmospheric circulation patterns (Simard et al., 1985; Langner and Siegert, 2009). The monthly strength of an ENSO event is typically quantified using an ENSO index. These so-called NINO-X indices are based on Pacific Ocean sea surface temperature anomaly (SSTA) measures, with “X” denoting the particular area of the ocean used (e.g. NINO-3 being the eastern tropical Pacific; Stenseth et al., 2002; Sarachik and Cane, 2010). By all common measures, the 1982–1983 and 1997–1998 El Niño events are considered by far the strongest on record (Wolter and Timlin, 1998). Forecasting of ENSO indices based on modelled equatorial SST anomalies is gaining increased attention, with predictions of up to two years lead time being made using physically-based modelling approaches (Barnston et al., 1998; Chen et al., 2004). For the 1997–1998 El Niño, Barnston et al. (1998) evaluated the predictive performance of 15 dynamical and statistical models, and found a moderate prediction capability at one to three seasons lead-time (correlations between observations and predictions of 0.6–0.8 for the best performing approaches).

In the current study, monthly ENSO indices for 1980–2000 were obtained from the NOAA Climate Prediction Centre (USA). Five El Niño events occurred over this period: 1982–1983, 1986–1987, 1991–1992, 1993–1994 and 1997–1998 (Sarachik and Cane, 2010). Other studies have confirmed these as the years where fire activity levels were elevated across large parts of Indonesia (e.g., Malingreau et al., 1985; Wooster and Strub, 2002; Dennis, 1999; van der Werf et al., 1996; Langner and Siegert, 2009), again highlighting the likely link between ENSO and fire. For our purpose, the temporal evolution of each individual ENSO event was considered across a two year period, separated into two twelve month episodes (ENSO Year 1 and ENSO Year 2).

3.3 Rainfall

The large scale temporal pattern of Indonesian rainfall is almost exclusively controlled by the monsoon, resulting in discrete wet and dry seasons (Kirono et al., 1999). On Borneo, El Niño episodes tend to significantly reduce the amount of monsoonal rainfall, although this never fails completely (Kirono et al., 1999; Guhardja et al., 2000). We obtained monthly rainfall data from twelve climate stations, selected on the basis of data availability and reliability (Kirono, 2004; Fig. 1). Although the number of locations is limited, these stations are approximately evenly spaced across Borneo and they broadly reflect the overall climate conditions and influence of El Niño on the Island (Kirono et al., 2000; Haylock and McBride, 2001).

4 Methodolgy

4.1 Derivation of active fire metrics

4.1.1 Observation time

Fire activity generally shows a strong diurnal cycle, with fires in most environments being more prevalent during the afternoon than during the early morning or night (Giglio, 2007). For many investigations, metrics based on daytime active fire detections are therefore preferred since fire numbers are maximised, although these datasets can be subject to a greater false alarm frequency due to the presence of sunglints from unmasked water bodies or clouds (Robinson, 1991). Fire detection algorithms attempt to minimise daytime false alarms by using multi-spectral methods to separate sunglints and homogenously hot surfaces from active fires (Zhukov et al., 2006). However, Wooster and Strub (2002) found that this discrimination was much more difficult to accomplish when using GAC rather than LAC data, due to the significant spatial averaging involved in the former's production. A number of previous AVHRR-based active fire studies have therefore relied on nighttime active fire data records (e.g., Langaas, 1993; Legg and Laumonier, 1999), and indeed the widely used ATSR World Fire Atlas (Schultz et al., 2002; Mota et al., 2006) that is exploited in the global fire emissions database of van der Werf et al. (2006) and updates is also a nighttime-only dataset. Difficulties with identifying daytime false alarms in GAC data, coupled with the fact that sunset on Borneo occurs at the relatively early time of 18:00 h ± 30 min LT, when fire activity might still be quite strong, suggested that GAC data taken during the early nighttime period may be quite suitable for our study. To confirm this, we compared AF detections derived from eleven matched daytime (14:30–15:30 h LT) and nighttime (18:30–19:30 h LT) GAC image pairs, based on data from the 1991–1992 and 1997–1998 El Niño events. With this small test dataset, unlike for our subsequent multi-year study which used many hundreds of images, we could manually screen the daytime datasets for sunglint-induced false alarms. Figure 4 illustrates a strong, linear relationship between the matched daytime and nighttime active fire counts, suggesting that AF metrics based on early nighttime GAC observations do provide a temporal pattern similar to that which would be derived using carefully screened daytime observations. Perhaps surprisingly, in most cases we found that the AF counts derived from the early night-time scenes are actually higher than those in the daytime scenes, the reason for which is discussed in the following section.

4.1.2 Normalisation for orbital drift

Although we focus on nighttime data here, a further consideration with regard to any multi-year active fire dataset is the potential for orbital variations to impact the active fire metrics through its interaction with the strong fire diurnal cycle (Giglio, 2007). In particular, it is well known that the local overpass time of the POES satellites drifts by around one or two hours over the nominal three or four year lifetime of each satellite mission (Price, 1991). The interplay between this drift and the fire diurnal cycle may induce bias into any AVHRR-derived multi-year AF record. To investigate this, information on Borneo's diurnal fire cycle was extracted from the TRMM VIRS AF record used by Giglio (2007) for both El Niño and non-El Niño periods (Fig. 5). During non-El Niño periods, fires in Borneo were confirmed as showing a strong diurnal cycle, with fire activity concentrated in the early afternoon over a relatively short duration. This pattern likely reflects the relatively low flammability of the forest and agricultural fuels seen under the region's normal climatic conditions. However, during El Niño years the fire diurnal cycle appears damped, with fires being more evenly distributed across the day, possibly as a result of the increasingly dry and flammable fuel conditions resulting from drought. Under these conditions, AF counts peak early in the evening; which explains why counts of AF numbers were often higher at night than by day (i.e. as seen in Fig. 4). We used the fire diurnal cycle information derived from TRMM VIRS to normalise the GAC-derived AF counts for the effect of variations in the NOAA POES local overpass time.

4.1.3 Selection of observation years

Figure 2a illustrates the severe nature of fire activity on Borneo during the 1997 El Niño, and Fig. 3 confirms that under these conditions AVHRR GAC data allows active fire pixels to be clearly discriminated, despite the spatial subsampling and pixel averaging involved in the datasets generation. To investigate whether this ability to discriminate fires is also present under other climatological conditions, a series of matching LAC and GAC images were obtained for both El Niño and non El Niño years, and the AVHRR active fire detection algorithm developed for Borneo by Wooster and Strub (2002) was applied to both. There is a strong linear relationship between active fire counts derived from the LAC and GAC versions of the same AVHRR data during El Niño periods (r^2=0.99, n=13: Fig. 6a). The agreement is weaker during "normal" and La Niña years (r^2=0.78, n=19), although active fire pixel numbers are typically an order of magnitude or more lower at these times than during El Niños (cf. Fig. 2). The weaker relationship between the LAC and GAC active fire counts during non-El Niño periods is a direct result of the AF pixels radiating more weakly and being more spatially isolated under these climatic conditions (Fig. 2b and c). Under such non-optimal burning conditions, the subsampling and line skipping procedures used to derive the GAC data cause many of the active fires present in the LAC scene to fail to result in a matching GAC AF pixel detection. Thus, we limit our analysis to the five ENSO episodes occurring between 1980 and 2000, which in any case represent the times of maximum fire activity on Borneo over the study period (Langner and Siegert, 2009).

AVHRR GAC data covering 1980–2000 comes from multiple POES systems, from NOAA-7 (earliest El Niño) to NOAA 12 (latest El Niño), and for each ENSO episode many scenes were processed each month using the GAC-optimised fire detection algorithm of Wooster and Strub (2002). A multi-year AF record based on an average of 120 ± 15 (mean ± 1 SD) scenes per year was derived, with the GAC images selected for processing based on (i) Borneo lying towards the centre of the AVHRR swath (for the highest spatial resolution and minimum geometric distortion), and (ii) minimal cloud obscuration of the island, particularly in the coastal regions which are the locus of fire activity (Fuller and Fulk, 2009; Langner and Siegert, 2009).

4.1.4 Normalisation for cloud cover

Although active fires can be readily detected through smoke, the obscuring effects of meteorological cloud cover generally require that fire pixel counts be normalised for inter-scene variations in cloudiness if they are to be used to quantify changes over time (e.g., Heald et al., 2003). Given Borneo's tropical climate and thus relatively high surface temperature, cloud detection by night is relatively easy to perform using brightness temperature thresholding, for example of the AVHRR 11 µm channel data (Kaufman et al., 1990). In fact, in terms of cloud obscuration, the climatological shifts experienced during El Niño fortunately make cloud cover far less of a problem for our study than would be the case in non-El Niño years, when some areas of Borneo can be almost continuously cloud-obscured (Langner et al., 2007). The method used for cloud normalisation is based on the common assumption that fire occurrence across a region is spatially uncorrelated with cloud-cover (e.g., Kaufman et al., 1990; Giglio et al., 2003b; Heald et al., 2003). In fact, it was observed that the majority of Borneo's fire activity occurred in the more coastal areas, as opposed to the more cloud-affected and mountainous interior (Fig. 1). Additionally, an initial analysis showed that fires did not always occur in a temporally synchronous manner across the various regions of Borneo, typically peaking, for example, between August and October in Southern and Central Kalimantan, but between February and April in East Kalimantan. Because of this, cloud-normalisation was not conducted on an island-wide basis, but rather AF detections made in each of Borneo's seven regions were normalised by the cloud cover percentage in that particular region. The total AF pixel count, normalised for both cloud cover and satellite overpass time, was then derived by aggregating these adjusted fire counts across the entire island.

4.1.5 Comparison to ATSR world fire atlas fire product

Using the GAC processing chain described above, we constructed a multi-year active fire record for Borneo, normalised for temporal variations in both satellite overpass time and cloud cover. The dataset covered the 1982–1983, 1986–1987, 1991–1992 and 1993–1994 and 1997–1998 El Niño events, the majority of which had not previously been examined in terms of AF spatio-temporal metrics. To evaluate our AF data record, GAC-derived active fire counts for Borneo for the 1997 El Niño were compared to those from the ATSR World Fire Atlas, as employed in the widely used global fire emissions database (van der Werf et al., 2006). Both the GAC and ATSR active fire data records indicate that the vast majority of fires burning during 1997 occurred in central and east Kalimantan, and a strong agreement was found between the temporal pattern depicted by the different datasets (Fig. 6b).

4.2 Comparison of trends in ENSO, rainfall and fire

4.2.1 Derivation of rainfall information

For comparison to the monthly active fire count data, we derived a monthly rainfall measure for Borneo by averaging the individual monthly rainfall totals for the twelve meteorological stations shown in Fig. 1. This measure was used to calculate: (i) the monthly "all-Borneo" rainfall deficit as compared to the long-term (1950–1998) mean, and (ii) the "all-Borneo rainfall index" (RI_i) of Haylock and McBride (2001); essentially representing monthly rank percentile (0–100%):

$$\mathrm{RI}_i = 100 - (100 \cdot R_i / N_r - 1) \tag{1}$$

where R_i is the rank order of precipitation for month i and N_r is the total number of months studied (here equal to 24 for each separate ENSO event).

4.2.2 ENSO-rainfall-fire intercomparison methods

At a monthly time-step, temporal trends in Borneo's active fire counts were compared to the metrics derived from the all-Borneo rainfall measure and to the suite of SST-based NINO-X indices collected from the NOAA climate prediction centre. To evaluate the temporal relationship between ENSO index, drought and fire occurrence, we used across-correlation (similar to Fuller and Murphy 2006); we limited consideration to negative lags as we were solely interested in ENSO effects and rainfall deficits leading to (i.e. preceding) fire activity variations. We explored temporal associations between NINO-X indices and (i) rainfall and rainfall deficit, and (ii) fire activity. Cross-correlation analyses were conducted on "pre-whitened" time series to minimise the risk of spurious correlations (following Chatfield, 2004).

5 Results

5.1 The 1982–1983 ENSO event

Here we concentrate on the 1982–1983 El Niño as an example of the analyses conducted for each ENSO episode studied herein. Figure 7 shows time series plots of (a) monthly rainfall and the long-term mean rainfall, (b) (cumulative) rainfall deficit, and (c) active fire counts and ENSO index. For the 24 months surrounding this extreme El Niño episode, a broad agreement between temporal trends in fire occurrence and drought is apparent, albeit somewhat interrupted by the November 1982–January 1983 "wet" monsoon. Significant fire activity commenced in July 1982 (Fig. 7c), coincident with the first month of a positive rainfall deficit (Fig. 7b) and with a monthly mean rainfall measure close to the 100 mm "critical threshold" identified by Goldammer (2007). This is around half of the long-term mean rainfall for the month (Fig. 7a), and likely resulted in commencement of extensive leaf-shedding, surface fuel flammability increases and peatland desiccation (Brady, 1997; Goldammer, 2007), all of which contribute to the subsequent growth of excessive fires. Indeed, fire activity peaked two months later in September 1982, a month later than the August peak in monthly rainfall deficit. Rainfall deficit remained positive until the end of ENSO Year 1, by which time fire activity had declined to low levels during the monsoon rains of November and December 1982.

Around the start of ENSO Year 2 (1983), the majority of NINO-X indices show El Niño conditions reaching peak strength (Fig. 7c). This is the time of the northeast "wet" monsoon, and in January 1983 monthly rainfall totals were actually close to the long-term mean (Fig. 7a). However, a positive rainfall deficit returned in February, followed by the highest rainfall deficits of ENSO Year 2 in March and April (Fig. 7b), coinciding with the months of peak fire activity (Fig. 7c). Rainfall returned to levels slightly higher than the long-term mean in May 2003 (Fig. 7a), with a consequent weakening of the cumulative rainfall deficit and a severe reduction in fire activity (Fig. 7c). Almost all the ENSO indices show a significant decline in ENSO strength by this time (Fig. 7c), though unlike the other ENSO events studied here, the 1982–1983 event was not immediately followed by a La Niña episode. Overall, fires were much more numerous in ENSO Year 2, with the total active fire pixel count being five times higher in 1983 than in 1982 (Fig. 7c).

The AF density map for the 1982–1983 El Niño episode (Fig. 8; top left panel) indicates the majority of fire to have been concentrated in East Kalimantan, with far less activity in West, Central and South Kalimantan. These satellite-derived AF data confirm previous suggestions that fires were absent from Sarawak even during this extreme El Niño event, reportedly due to a lack of drought in this part of Borneo (Goldammer, 2007). However, we do detect fires in Sabah, where precipitation levels apparently fell by an average of 60% over the 1982–1983 period (Woods, 1989). In general, we see that the 1982–1983 fire activity is confined to a zone extending inland a maximum of ~200 km. Goldammer and Seibert (1990), Walsh (1995) and Goldammer (2007) report this to be the approximate spatial limit within which monthly precipitation fell below the previously identified 100 mm "critical threshold", with higher rainfall generally seen within the elevated areas further inland (Fig. 1).

5.2 Multi-ENSO patterns of fire activity

Figure 9a shows cloud and overpass adjusted active fire counts for each of the five ENSO episodes spanning the 1980–2000 period. Three "fire sub-seasons" are clearly identified; the first during August–October of ENSO Year 1, the second during February–April of ENSO Year 2, and the third during August–October of ENSO Year 2. However, only some El Niño events show fire activity during the third fire sub-season, it being absent, for example, during the major 1982–1983 ENSO. Importantly, the overall temporal pattern of fire activity shown in Fig. 9a remains the same if the fire counts remain unadjusted for cloud-cover variations, with the same rank order of fire-affected months in each ENSO year. This indicates that our results are not dependent upon assumptions made during the cloud-normalisation procedure. The data in Fig. 9b confirm the enormity of the 1982–1983 and 1997–1998 El Niño episodes, and Fig. 9a indicates that fire activity in these years was similarly of an overwhelming magnitude, with total AF counts respectively more than two and three times greater than those seen in the next highest event (1991–1992).

Typically, the vast majority (>80%) of total active fire counts seen in the AVHRR-GAC record occur within the first 16-months of an ENSO event. Specifically, for the five El Niño events studied here, 34% of the total AF counts are associated with the first fire sub-season, 41% with the second, and 18% with the third, the latter being dominant in only the 1991–1992 and 1993–1994 El Niño's (Fig. 8a). The remaining 7% of detected active fires occur outside of these three fire sub-seasons. By contrast, analysis of the TRMM VIRS and ERS-2 ATSR AF records indicate that in non-El Niño years the first fire sub-season accounts for the vast majority of fires (e.g. ca. 80% in the 1999–2000 period). The fact that the El Niño cycle often matures relatively close to the timing of the second fire sub-season (e.g., Fig. 9b) is the likely explanation for this difference, further supporting a strong link between ENSO development and fire.

Figure 8 illustrates the spatial pattern of fire activity for each of the additional four El Niño's studied, alongside that of the 1982–1983 event discussed in Sect. 5.1. These

“AF density” maps confirm the relative lack of fires during the 1986–1987 El Niño episode, and the overwhelming amount of fire activity that occurred in the strongest (1997–1998) El Niño during both the first and second fire sub-seasons (c.f. Fig. 9a).

Later El Niño’s show a spatial pattern of fire rather different to that seen in 1982–1983, although with fire activity still mostly confined within a ~200 km boundary of the coast. In these later El Niño’s years, fire is much more prevalent in Central and South Kalimantan, possibly due to increasing amounts of forest degradation and fragmentation in these areas (see also Langner and Siegert, 2009). In particular, from the 1991–1992 El Niño onwards, significant fire activity is also seen in inland parts of West Kalimantan. However, not until the 1997–1998 El Niño is fire really heavily concentrated in East Kalimantan once more, and this again occurs during the second fire sub-season as it did during the 1982–1983 ENSO event. Using optical remote sensing data of Borneo from 2002, Langner et al. (2007) identified areas of fire-prone “cultivation-forest mosaic” and “bare ground/grasslands/agriculture” to be primarily located along the coasts of East, South and Central Kalimantan, and in both the coastal and inland regions of West Kalimantan. The forest/non-forest maps derived in the earlier Fuller et al. (2004) study confirm this spatial distribution. Yamagata et al. (2010) recently used similar optical remote sensing data to produce a time series map of the forest cover changes seen on Borneo in the 26 years since 1982, confirming the development of these non-forest areas in the coastal regions of East, South and Central Kalimantan, and further inland in West Kalimantan. The maps shown in Fig. 8 indicate these areas as those which developed by far the severest fire activity over the same period, helping confirm the strong fire-deforestation link highlighted in so many past works (e.g., Cochrane, 2003; Fuller, 2006; Goldammer, 2007).

5.3 Relationship between ENSO, rainfall and fire

Our correlation analysis determined monthly rainfall to be more correlated to ENSO strength during the 1982–1983 and 1997–1998 events (absolute r of 0.3 to 0.36 and 0.6 to 0.68, respectively; Table 1), than during the intervening ENSO events

(1986–1987, 1991–1992 and 1993–1994). Correlations between ENSO and rainfall deficit were found to be stronger than those between ENSO and rainfall, especially for the 1982–1983 event (1982–1983: absolute r of 0.5 to 0.6; 1997–1998: absolute r of 0.6 to 0.7; Table 1).

Cross-correlation analysis between the active fire and rainfall data revealed a robust relationship between the rainfall deficit metrics, especially the RI_i measure of Haylock and McBride (2001; Eq. 1), and the AF count. The correlation peaks at zero lag (i.e., simultaneously) or, at lower significance, at one-months lag for all five El Niño's (r values between −0.5 and −0.6). This simultaneous rainfall-fire association was stronger for the post-1990 El Niño events than for earlier ENSO's; indeed, the relationship between rainfall and fire activity was weakest in 1982–1983. Again, this possibly reflects the increased forest degradation that reportedly occurred during the 1990's (FWI/GFW, 2002) and the fact that degraded forest and agricultural areas are likely to respond more rapidly to drought than are closed canopy forests, which can maintain fuel moisture levels for some weeks even during drought (Guhardja et al., 2000; Cochrane, 2003).

A similar cross-correlation analysis was applied to the monthly ENSO indices and AF data, but showed no clear relationship. The relationship between peak ENSO index and peak fire occurrence timing varied between El Niño episodes (Fig. 8b), and weak lags, varying between zero and nine months, were seen during the different El Niño events, and for different ENSO indices, reflecting the teleconnection lag between ENSO and Indonesian climate variables and the time over which forest fuels become increasingly flammable during drought. The differing lag times are likely to be related to variations in the timing of the ENSO-related sea surface temperature anomaly development in the various regions of the Pacific Ocean used to calculate the ENSO indices, and the action of the monsoon rains, which outweigh the precipitation-reducing influence of El Niño during the specific monsoon periods. We therefore complemented our monthly-analysis with a comparison of the total ENSO-integrated AF count and ENSO strength, with the latter measured via the cumulative NINO-X anomaly. The strongest statistical relationship was found using the NINO-3 index, and when considering the sixteen months covering the first and second fire sub-seasons (i.e. January ENSO Year 1 to April ENSO Year 2). These data are shown as the grey-circles in Fig. 10, but, of course, omit the fires occurring in the third fire sub-season (August–October of ENSO Year 2). Excluding the 1993–1994 ENSO, which showed the highest proportion of third fire sub-season activity (Fig. 8a), the same strength of relationship (i.e. r^2=0.97) is seen when extending the cumulative fire count record included in Fig. 10 to the entire 24 months of each ENSO episode. The 1993–1994 El Niño is unusual in that it immediately followed the 1991–1992 El Niño (Trenberth and Hoar, 2006), and was characterised by a NINO-3 ENSO index that peaked early in ENSO Year 1, weakened significantly over the following 12 months, and then peaked again in the third fire sub-season (Fig. 9b). The unusual nature of this El Niño event probably explains the occurrence of so much fire activity in the 1993–1994 third fire sub-season (as seen in Fig. 9a).

6 Discussion and conclusions

Analysis of active fire signals present in AVHRR GAC data of Borneo for the five El Niño events that occurred during the 20 years prior to the MODIS era (1982–1998) has revealed three clearly identifiable fire sub-seasons and a robust, zero-lag correlation between ENSO-driven rainfall deficit and active fire counts. The vast majority of fire activity occurs during August–October of ENSO Year 1 (first fire sub-season) and February–April of ENSO Year 2 (second fire sub-season). In the intermediate period (November–January) monsoon rains temporarily weaken El Niño's influence by breaking the associated drought, resulting in an almost complete absence of fire. During some El Niño's (most particularly that of 1993–1994), major fires also occurred during the August–October period of ENSO Year 2 (third fire sub-season). The magnitude of fire activity appears to be related as much to the length of El Niño conditions (i.e. how prolonged the ENSO event is) as to its peak intensity (e.g., the maximum of the ENSO index). For example, the unprecedented duration of the 1991–1994 El Niño (here separated into 1991–1992 and 1993–1994) resulted in severe fires, despite the ENSO index maxima being relatively modest. Among the various ENSO indices tested, the time-integrated (i.e. cumulative strength) NINO-3 anomaly showed the strongest relationship with the total number of active fires detected over each 24 month ENSO episode, explaining more than 80% of the variation over the five El Niño events examined. In a similar vein, Fuller and Murphy (2006) found that annual sums of the SOI were strongly associated with annual fire activity in Borneo under conditions when the annual SOI was negative. Excluding the third fire sub-season, the cumulative Niño 3 anomaly shows an even stronger association with the cumulative fire count over the first 16 months (January–April) of an El Niño period (r^2=0.97, n=5). Unlike Fuller and Murphy (2006), who found a weakly significant three month lag between the SOI and fire activity during the 1996–2001 period, we found no evidence for a temporal lag between the NINO indices we tested and fire activity during the five ENSO events occurring between 1982 and 1998.

Relationships between rainfall, El Niño and fire activity provide a potential framework for establishing an empirical ENSO-based fire-forecasting scheme for Borneo that could perhaps be employed to attempt to mitigate fire-related impacts of future El Niño's (see also Fuller and Murphy, 2006). Seasonal forecasts of the ENSO index (e.g., Chen et al., 2004) could be used with the cumulative ENSO-fire relationships established herein to evaluate the potential magnitude of forthcoming fire activity, and associated impacts such as regional haze (Tapper, 2000; Aiken, 2004). However, these relationships are underpinned by only five El Niño events, and assume that the ENSO-fire relationship is stationary. This may not be the case for dynamically unstable processes such as fire regimes, and future changes in land-cover, vegetation composition and structure, etc. may alter ENSO-fire relations (e.g. via the types of positive feedback loops described by Cochrane et al., 2003). Much higher sample numbers (50 years or more) have typically been used to develop robust ENSO-fire relationships in the Americas (e.g., Simard et al., 1985; Swetnam and Betancourt, 1990; Kitzberger, 2002). Early in the MODIS era, the first post-1997/98 El Niño episode occurred (2002–2003), and we used AVHRR GAC data of this event to provide a brief check on the robustness of our empirical ENSO-fire relationship. Figure 10 indicates that despite the unprecedented extent and environmental damage caused by the 1997–1998 Borneo fires, the 2002–2003 fire activity continues to conform to the existing ENSO-fire relationship. We conclude that, at present, the overall (i.e. time-integrated) strength of the ENSO episode continues to be the most significant control on the degree of fire activity experienced on Borneo during El Niño episodes.

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Table 1. Correlation between monthly El Niño strength (as measured by the NINO 3, NINO 3.4 and SOI indices) and rainfall and rainfall deficit during the five events; the two most significant events over the period considered here are at the top (1982–1983 and 1997–1998).

	1982–1983			1997–1998		
	NINO 3	NINO 3.4	SOI	NINO 3	NINO 3.4	SOI
Rainfall	−0.299	−0.355	0.326	−0.607	−0.634	0.678
RF Deficit	0.468	0.604	−0.562	0.611	0.701	−0.744

	1986–1987			1993–1994			1991–1992		
	NINO 3	NINO 3.4	SOI	NINO 3	NINO 3.4	SOI	NINO 3	NINO 3.4	SOI
Rainfall	−0.097	−0.086	0.278	0.162	0.058	0.453	−0.047	0.078	−0.211
RF Deficit	0.095	0.154	−0.345	0.019	0.137	−0.087	0.180	0.143	0.088

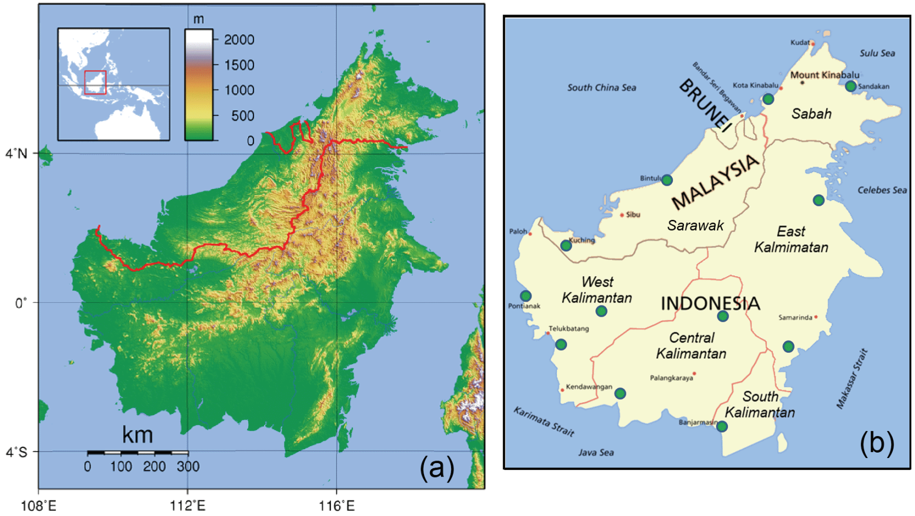

Fig. 1. The island of Borneo, which contains territory of three countries; Malaysia (Sarawak and Sabah), Indonesia (Kalimantan) and Brunei, outlined on **(a)**. Kalimantan is further subdivided into western, central, eastern and southern regions, as detailed in **(b)**. The island is mountainous, with a dorsal range rising to a maximum elevation of 4101 m at Mount Kinabalu in the far northwest. The location of the twelve meteorological stations used in this study are circled in **(b)**. Towards the lowest lying coastal regions landcover is largely dominated by agricultural mosaics and peat swamp forest, with larger areas of evergreen lowland forest, degraded and/or regrowing forest becoming more prevalent towards the higher elevations shown in **(a)** (Langner et al., 2007).

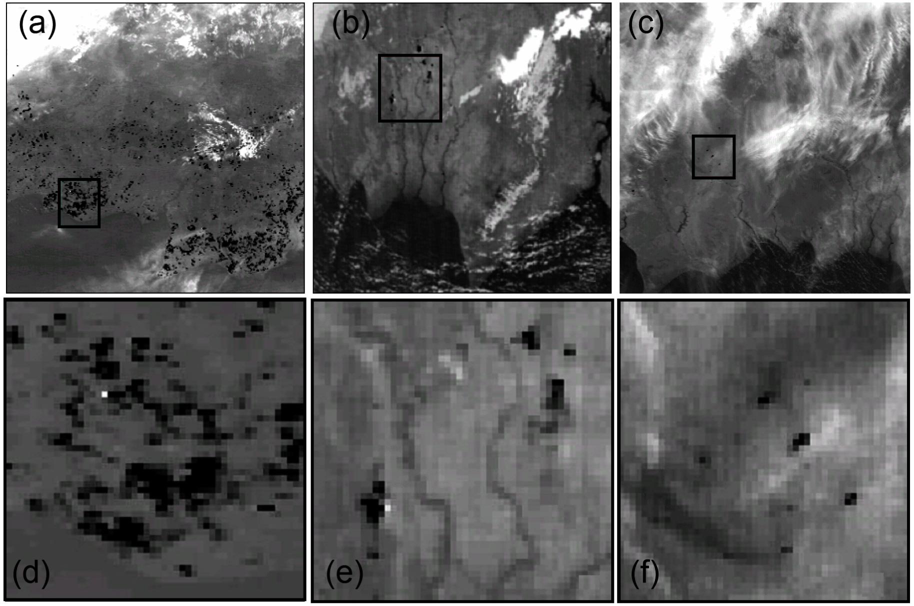

Fig. 2. Raw uncalibrated data night-time AVHRR Local Area Coverage (LAC: 1.1 km spatial resolution at nadir) imagery of the coast of Central Kalimantan, collected in AVHRR Channel 3 (3.7 µm), with boxed areas shown magnified beneath. Data were collected during **(a)** El Niño (21 October 1997), **(b)** “normal” (6 September 2001) and **(c)** La Niña (29 July 1999) climatological episodes. Each top-row image covers an area of around 300 km × 300 km, and the Java Sea can be seen towards the bottom of each. The AVHRR 3.7 µm channel is highly sensitive to active fires, with increased pixel radiances resulting even from highly sub-pixel events (Robinson, 1991). Such fire affected pixels show elevated 3.7 µm channel spectral radiances, which appear black in this rendition. Meteorological clouds have low 3.7 µm channel spectral radiances and appear white in this rendition. Active fire pixels can be seen in each scene, but their number decreases substantially from El Niño to non El Niño conditions.

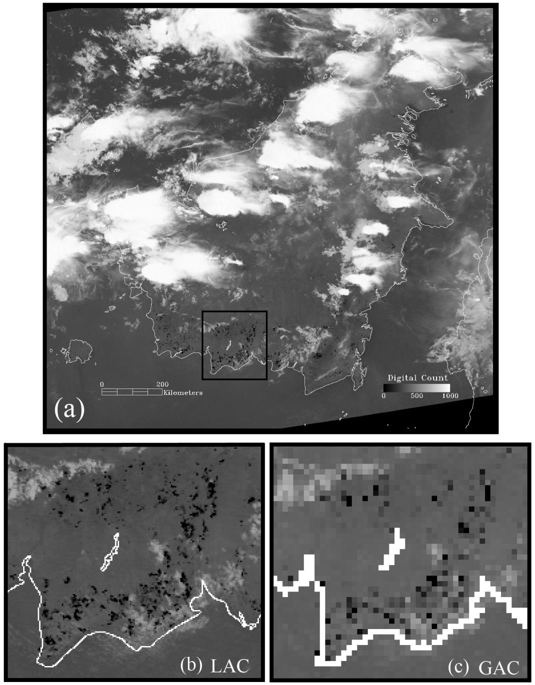

Fig. 3. Matching nighttime AVHRR 3.7 µm channel LAC and GAC data of Borneo taken on 12 October 1997 during the height of the El Niño episode when many fires were burning, particularly along the coast of Central Kalimantan (Wooster and Strub, 2002). Data are shown in an uncalibrated form to aid interpretation, resulting in high radiance (i.e. low AVHRR digital count) fire pixels appearing black in this rendition. A raster coastline is superimposed on the imagery to outline the island of Borneo. **(a)** shows the full AVHRR LAC scene of Borneo, with the most heavily fire-affected area outlined in black. This area is shown magnified in the LAC and matching GAC data subsets shown as **(b)** and **(c)**, respectively. Despite the GAC sampling and pixel averaging process, the low digital count fire pixels are seen in both LAC and GAC data formats.

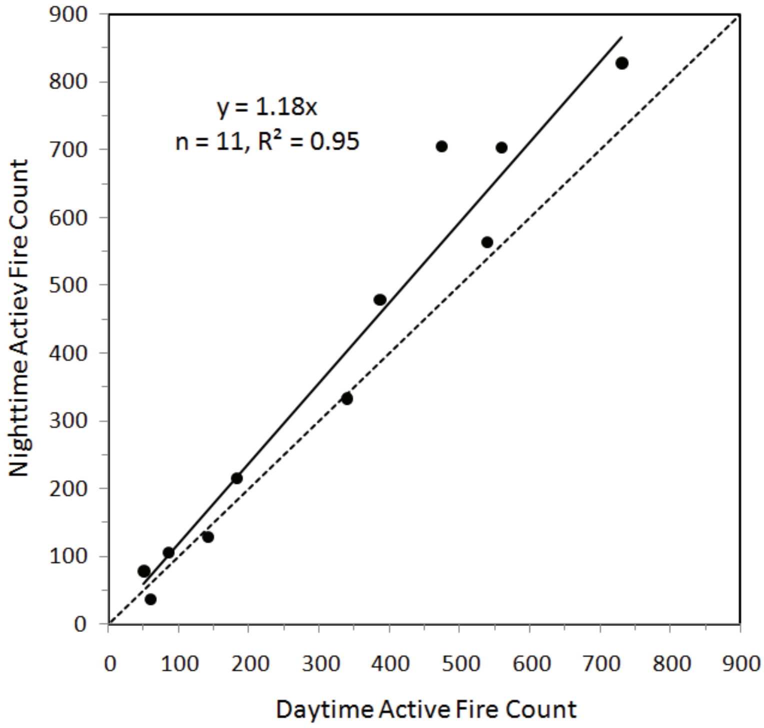

Fig. 4. Comparison of nighttime and daytime active fire counts derived from the type of AVHRR GAC data of Borneo shown in Fig. 3c. Each point represents the number of active fire pixels detected on the same day from AVHRR GAC scenes collected at two different times of day. Daytime scenes were collected between 14:30 and 15:30 h, and nighttime scenes between 18:30 and 19:30 h LT. Scenes were taken during the 1991–1992 and 1997–1998 El Niño episodes, and a significant positive correlation can be seen between the number of active fire pixel counts measured at the two different overpass times. Perhaps somewhat surprisingly, the best-fit linear relationship (black line) indicates that nighttime active fire counts are typically higher than the matching daytime active fire count numbers. The 1:1 line is also shown.

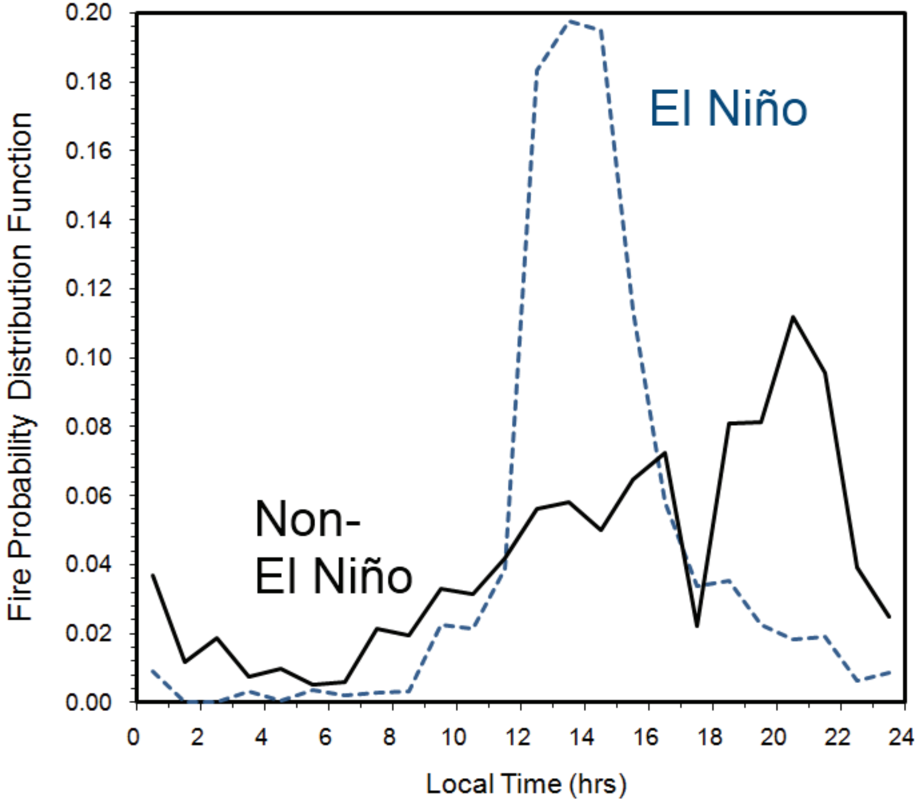

Fig. 5. Fire diurnal cycle in Borneo during El Niño and non-El Niño periods, as derived from TRMM VIRS active fire data (Giglio, 2007). During non-El Niño periods, the majority of fire activity is centred on a relatively short period between noon and 16:00 h LT, whilst during El Niño periods the fire diurnal cycle appears significantly damped, with the peak is shifted towards early night-time (∼ 21:00 h).

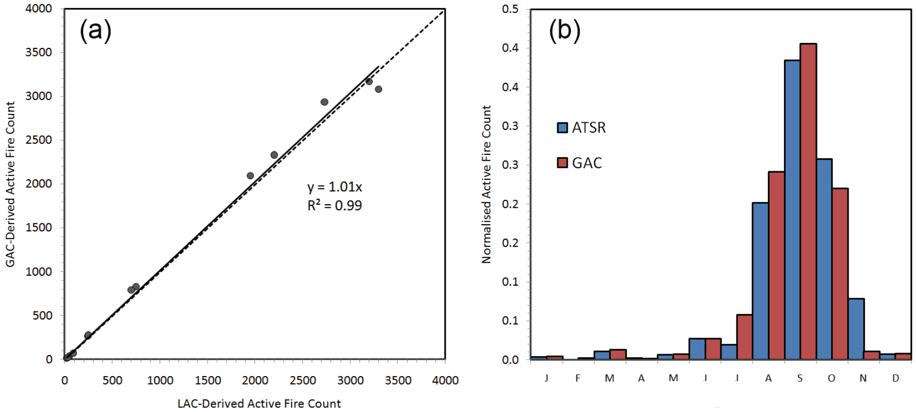

Fig. 6. Comparison of active fire count numbers for Borneo derived via different approaches for the 1997 El Niño period. **(a)** Comparison between active fire pixel counts derived from GAC and LAC versions of the same AVHRR scene (such as are shown in Fig. 3b and c). The 1:1 line is also shown. **(b)** Temporal comparison between the normalised monthly AVHRR GAC-derived active fire pixel counts and the fire pixel counts contained in the ATSR World Fire Atlas for the 1997 El Niño period. Note: To aid the LAC to GAC comparison in **(a)**, the GAC-derived active fire counts were adjusted for the x15 sub-sampling factor involved in their production.

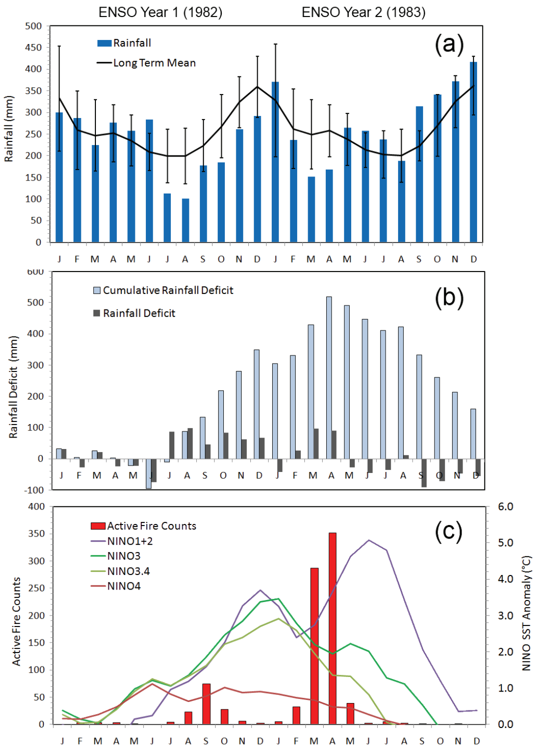

Fig. 7. Rainfall, ENSO and active fire count data for the major 1982–1983 El Niño event. **(a)** Mean monthly rainfall calculated for the stations shown in Fig. 1, along with the long term monthly mean and its standard deviation calculated for the 1950–1998 period, **(b)** Rainfall deficit and cumulative rainfall deficit, calculated from the rainfall data shown in **(a)**, and **(c)** monthly active fire counts derived from 105 AVHRR GAC images, together with the matching set of NINO SST anomaly measures taken from the NOAA Climate Prediction Centre (USA). Peaks in fire activity seen in August–October 1982 and February–May 1983 broadly match the periods of greatest rainfall deficit.

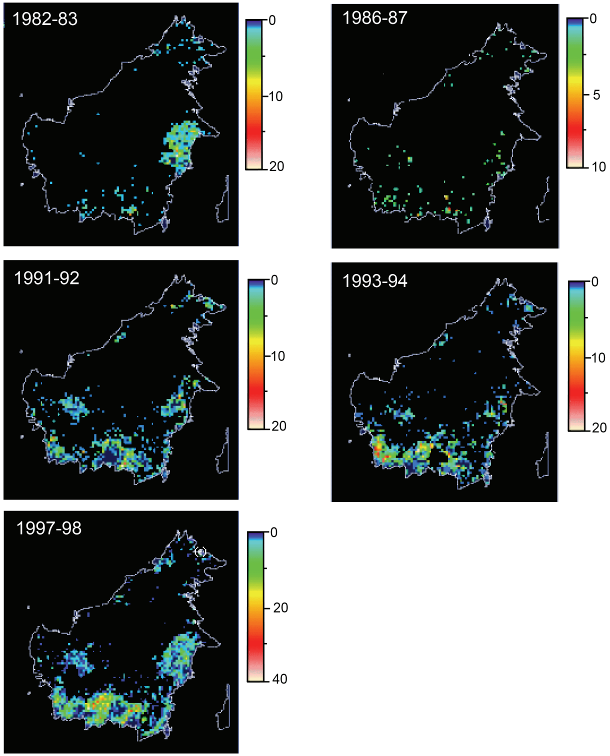

Fig. 8. Maps depicting the spatial pattern and density of active fire pixel counts detected using AVHRR GAC data during the five El Niño episodes occurring between 1980 and 2000. Grid cells are 12 km × 12 km and colours indicate the number of active fire pixels detected in each grid cell within the 24 months surrounding each ENSO period, including all three fire-subseasons shown in Fig. 9. Note the different colour-scales used for the 1986–1987 and 1997–1998 ENSO episodes, required to accommodate the relatively low and high active fire counts seen respectively in these two El Niño episodes.

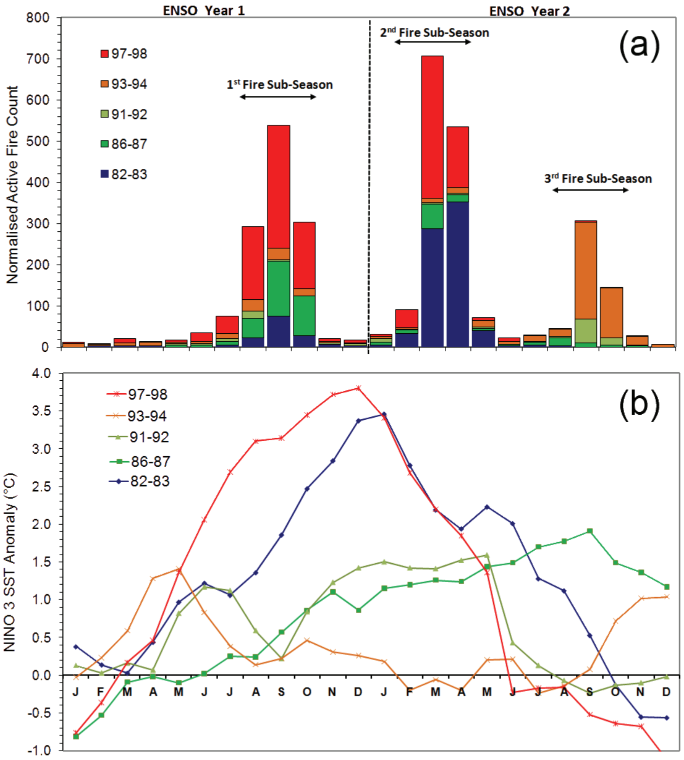

Fig. 9. Active fire and ENSO index data for the five El Niño episodes occurring between 1980 and 2000. **(a)** Monthly active fire counts derived from AVHRR GAC data, indicating the presence of three fire sub-seasons over the 24 month period. **(b)** ENSO strength as measured by the NINO 3 seas surface temperature (SST) anomaly. The 1982–1983 and 1997–1998 El Niño's are confirmed as the strongest ENSO events in terms of SST anomaly maximum, integrated SST anomaly magnitude, and the rapidly of the SST anomaly increase. This matches with the particularly high active fire counts recorded for these two El Niño's episodes in **(a)**.

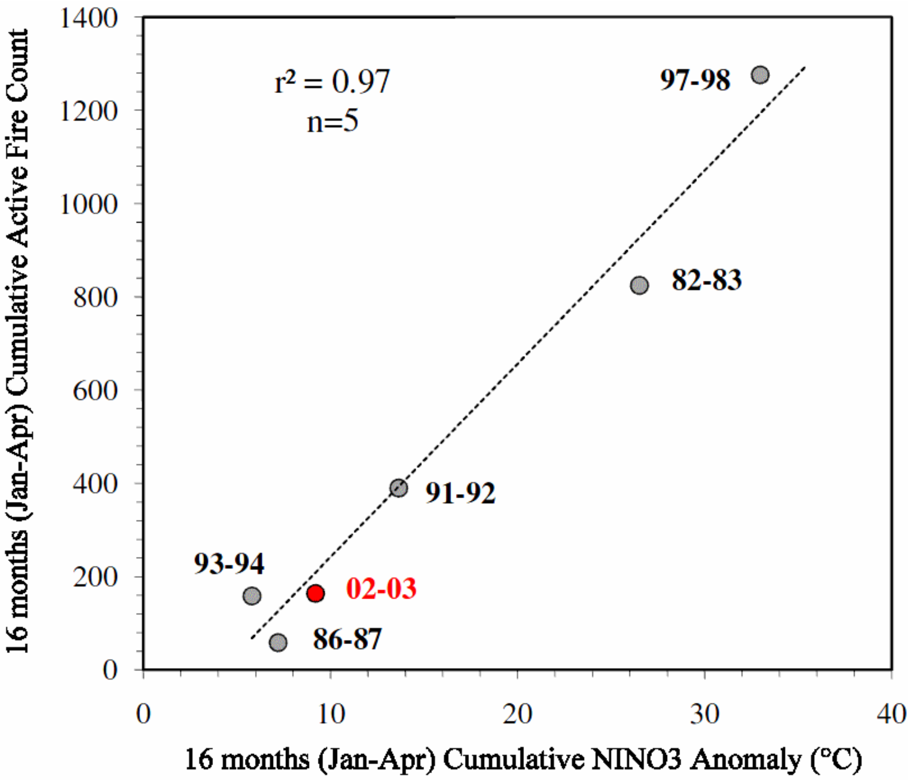

Fig. 10. Relationship between cumulative fire activity and cumulative ENSO strength and cumulative fire activity during five ENSO fire seasons (grey circles and dotted line), along with that for the 2002–2003 event for comparison.