Fire – ENSO Relations in the S.E. Asia. / A Remote Sensing Perspective

Introduction

The impact of vegetation fires on the balance of the global ecosystem is generally recognized. Biomass burning emissions of CO2, trace gases such as CH4, NH3, NOx, SOx, CO, hydrocarbons, and of particulates play a significant role in global climate change. It is estimated for example that 5%-20% of the total atmospheric CO2 is produced by tropical rain forest destruction, including that by burning. Large scale vegetation fires can lead to ecosystem degradation by changing the water balance, reducing evapotranspiration and increasing soil erosion. Moreover they can be a threat to the biodiversity of flora and fauna as well as to settlements and even human life. Therefore the importance of improved monitoring and management of large-scale vegetation fires is essential (Andrea, 1991).
In Indonesia burning occurs annually but a number of unusually large fire events
have occurred in recent times. Several studies have documented the increased fire activity occurred in Indonesia during El Niño years, particularly the devastating fire activity of the extreme 1982-83 and 1997-98 ENSO periods, (Malingreau *et al.*, 1985; Wooster *et al.,* 1998; Legg and Laumonier, 1999; Wooster and Strub, 2002).Previous studies have shown a close relationship among fire activity and ENSO in various parts of the world (Simard et al., 1985; Swetnam and Betancourt, 1990; Kitzberger, 2002). The aim of this project is to investigate the relationship between fire activity and El-Nino-Southern Oscillation (ENSO) events in South East Asia during the 1982-1998 period using Borneo, Indonesia as a case-study.

Data, Methods & Results

NOAA AVHRR Global Area Coverage (GAC) satellite data were used to investigate the occurrence of active fires during the El-Nino episodes of the last 20 years. All the available GAC images that included the entire case study region of Borneo for the five study periods over ten years were downloaded from the SAA archive. AVHRR images, in both LAC and GAC format, are distributed freely online by NOAA, through the web-based Satellite Active Archive (SAA) server. Although GAC data are available since July of 1981, LAC data occur only sporadically in this archive and not for all of the years. This is mainly due to storage limitations on board the NOAA Polar Orbiting Environmental Satellites (POES) (Belward and Lambin, 1990).

GAC images were collected be in agreement with the following standards:
1. Borneo should be observed close to the sensor's nadir viewing angle to prevent use of data with a long atmospheric path and coarse spatial resolution, which may introduce a bias in the derived fire number. A cut off threshold of Borneo being between 65 and 85 pixels from the borders of the 409-pixel wide GAC image was used (Rauste *et al.*, 1997).
2. The images must be nighttime data to preclude false fire alarms by highly reflective surfaces (e.g. cloud edges) and generally to make active fire detection less sensitive to error (Lee and Tag, 1990; Cahoon, 1990; Langaas, 1993a; Langaas, 1993b).
3. Borneo must be at least 40-50% cloud free to ensure a sufficient representation of the study area.

The rationale in terms of fire detection was to use the lowest possible active fire detection threshold in order to reduce errors of omission and to minimise the along scan averaging effect of the GAC data production. Therefore, fire detection and false detection identification were performed using a multispectral approach, rather than by applying a single threshold value (Kaufman *et al.*, 1990). Thresholds were reduced progressively until contamination of resultant fire counts by the broad background environment became visually apparent.

Threshold values were defined first by examining the histograms of AVHRR channel 3, 4, 5 and channel 3 minus channel 4 (T_3-T_4) and second by calculating basics statistics of minimum, maximum, mean, variance and standard deviation values for fire affected pixels and main background features such as cloud free vegetated land, clouds, mainland waterbodies and sea.
The developed pixel-by-pixel multi-channel fixed threshold method was applied to the AVHRR data. According to this method a series of criteria must be fulfilled by a pixel in order to be classified as a fire. These criteria have the following form:

Test (1)	$T_3 > 305$?K	to detect features with high channel 3 brightness temperature i.e. likely (potential) fires
Test (2)	T_3-$T_4 > 6$?K	to avoid warm surfaces without fires
Test (3)	T_4 or $T_5 > 275$?K	to exclude clouds and sensor noise (damaged pixels)
Test (4)	p_1, $p_2 <$ 5-6 %	to prevent false detections by highly reflective surfaces

Where T_3, T_4 and T_5 represent the top of atmosphere (ToA) brightness temperatures (K) for channel 3, 4 and 5 respectively, p_1, p_2 the % ToA reflectance in channel 1 and 2 respectively while a_i is the brightness temperature threshold for test i = 1, 2, 3, 4 and 5.

However, the GAC data are produced from the original Local Area Coverage (LAC) data onboard by averaging four out of every five samples (pixels) along the scan line, skipping the fifth, and by processing data from only every third scan line, thus skipping the other two scans. This degradation of the full resolution data which is performed onboard the satellite before their transmittance to the receiving station, reduces the number of pixels from 2048 to 409 within the retained scan line and the data volume by an order of 15 for the whole image. The spatial resolution of GAC data is effectively 4.4 km x 1.1 km with a 2.2 km gap between each scan line (Belward and Lambin, 1990). Therefore, initially, a comparison of the detection capabilities of low spatial resolution NOAA-AVHRR GAC and higher, resolution LAC data has been carried out in order to investigate the potential for the long-term archive of the latter to be used in the time-series analysis of active fires in Borneo, Indonesia during El Niño conditions. Thirteen pairs of LAC, and the corresponding GAC data from the same orbit, were collected for the 1997-98 El Niño related year. Since the data volume of the original LAC images is 15 times larger than the contemporaneous GAC product, in order to create an analogous GAC fire count comparable to the LAC fire product, the GAC derived fire counts were multiplied by a factor of 15.

Results showed that the adjusted GAC fire numbers were very well related to the LAC fire counts of the coincident imagery ($r^2 = 0.99$, $n = 13$, $p < 0.0001$) (Figure 1). The mean percentage difference between the two fire count datasets was –1.6% with a standard deviation of 13.9%. Taking into account the substantial degradation of LAC data during the GAC production, these variations are minor, indicating the efficacy of GAC data for providing quantitative fire information in Borneo during El Niño periods when the fire occurrence is high.

Then the fire counts detected in each GAC image were adjusted for different cloud coverage and observation time of each GAC image. The AVHRR is a passive sensor, which cannot penetrate clouds. Clouds might obscure fire events and since each GAC image usually presents different cloud coverage, a bias in the derived fire number is likely to occur (Kaufman *et al.,* 1990). However, the spatial distribution of clouds varies significantly according to regional and local climate characteristics, the general atmospheric circulation over that region, and the topographic structure of Borneo. Consequently, some regions of Borneo are more frequently covered by clouds than others. Empirically, it was observed that the most cloud affected regions correspond to the Malaysian provinces Sarawak and Sabah, the independent sultanate of Brunei, and the Indonesian province of west Kalimantan, while the less affected regions correspond to East- (6x5?) South- (3x2?) and Central (4x4?) Kalimantan.

Therefore, active fire affected pixels were detected for each of the above seven regions/provinces separately, whose areas ranged from 1 x 1 to 6 x 5 degrees latitude-longitude. Then the average proportion of each province covered by clouds was estimated for each scene individually. Cloud detection was performed by employing a single threshold ($T_4 <$ 275K) in the AVHRR channel 4. This single criterion proved sufficient in separating the clouds, since only nighttime data were processed. Assuming that the spatial distribution of fire events is homogenous within each of the seven regions, the number of active fires detected in each GAC image was corrected for each region separately according to the proportion of that region covered by clouds. Then the total all-Borneo fire number in each individual GAC image was derived by aggregating the cloud-corrected fire counts occurring in all of the seven regions.

The difference between the two fire count series was more evident during the months with high fire activity. However, the overall fire pattern remained the same, depicting equivalent variations in fire activity in Borneo during El Niño event (Figure 2). In particular, the intra-seasonal variation was consistent, with the major fire activity to persistently concur in August-October and February-April of the successive (sequential) year. The monthly variation also remained almost constant and no shift in the peak of fire activity occurred. For example, in the 1997-98 event, the peak times (September and March) agreed in both, cloud and non-cloud normalised fire count series. Morover, the rank order of the most affected months was not altered, with respectively August/April second and October/February last.

NOAA satellites operated at different overpass local times over Borneo during the 1982-1998 study period, which is likely to introduce a bias in the derived fire dataset, due to possibly strongly diurnal fire cycle (Eva and Lambin, 1998). Therefore, a further attempt was performed to depict the diurnal cycle of fire activity of Borneo during El Niño periods.
For this reason, active fire as derived from satellite images of the Visible and Infrared Radiometer System (VIRS) onboard the Tropical Rainfall Measuring Mission (TRMM) satellite as well as AVHRR GAC estimates at different overpass times was used. The TRMM-VIRS-derived fire diurnal cycle for Borneo during the 1998 El Niño event was produced and kindly provided by Luis Giglio from Goddard Space Flight Center, NASA (Giglio *et al*., 2000). The diurnal fire cycle in Borneo during the 1998 El Niño period was found to be strong, for example negligible fire activity was observed between 01:30 and 06:30 hrs local time, with 96% of fire activity occurring within the remaining 19 hours. According to these data, the GAC derived fire counts were normalized for the overpass times of the different NOAA satellites used.

The interannual fluctuation of Borneos fire activity for the five studied El Niño events from 1982 to 1998 is shown in figure 3. Obviously, there is a distinct pattern of fire activity. The major fire activity tends to occur between August-October (ASO) of the first year (Year 0), termed as first fire sub-season, and between February-April (FMA) of the following year (Year 1), termed as 2nd fire sub-season. On the contrary, in November-January (NDJ) and March-July (MJJ) of the El Niño period, the fire activity appeared significantly weakened, revealing the domination of local/regional climate conditions driven by the monsoon circulation. As it is depicted in figure 4, during NDJ of Year 0 and MJJ of Year 1, the ENSO index, in most of the studied El Niño events, remained high enough to trigger fire occurrence. However, the Asian monsoon system is active over Borneo during these time periods, particularly during the NDJ of Year 0 when the winter (west) monsoon is substantially stronger than the summer (east) monsoon, resulting strong convection over that region. This is also supported by the fact that although El Niño is being in its mature phase during NDJ of Year 0 (MJJ of Year 1) and the ENSO index is very high, moving towards to (away from) the peak, negligible fire activity occurred. On the contrary, during the MJJ of Year 0, El Niño was still not fully developed, while in NDJ of Year 1, El Niño was already demised, which together with the strong winter monsoon influence, resulted a complete absence of major fire events.

Some interesting observations can be revealed when the fire occurrence is examined according to the total 10-years fire activity. In particular, the majority of fire activity occurred during the 1st and 2nd fire sub-seasons in August-October of Year 0 and February-April of Year 1 accounting for the 73.51% of the total El Niño related 10-years time period. The only pronounced exception was the 1993-94 fire event when the major fire activity appeared in the 3rd fire sub-season in August-October of Year 1, representing the 11.15% of the total 10-years. Some fire activity was also observed in the 3rd fire sub-season of the 1986-87 and

1991-92 El Niño events accounting however only for the 2.37% and 1.03% of the total 10-years. On the other hand, the remaining 11.95% of the total 10-years fire activity were almost evenly distributed to the remaining 72 months of the 5 El Niño events.
During the 1st fire sub-season, 18.98% of the total 10-years fire activity occurred in 1997-98 El Niño event, 8.24% of the total in 1991-92 event, 3.72% and 2.13% in 1982-83 and 1993-94 respectively, while only 0.70% in 1986-87 El Niño event. During the 2nd fire sub-season, 20.04% occurred in 1982-83, 16.03% in 1997-98, 2.56% in 1991-92, while only 0.87% and 0.23% in 1993-94 and 1986-87 El Niño events respectively. However, the most interesting fact, which is important in the later analysis, is that 80.61% of the total 10-years AVHRR-GAC observed fire activity occurred in the first 16-months from the 24-months studied in each El Niño event.

The distribution of fires in time was analyzed and compared to the strength of the El Nino-Southern Oscillation (ENSO), as measured by the sea surface temperature anomaly (SSTA) in the Niño 3 region of the Pacific Ocean. The relationship between fire and Niño 3 anomaly variation was explored in three different ways. First, by plotting the cloud and time adjusted AVHRR GAC derived fire counts together with the Niño 3 anomaly in order to observe the general signal of the association (Figure 5). Secondly, a cross-correlation analysis between the monthly fire counts and the Niño 3 anomaly was applied to identify the existence and the best range of possible lag time, in which some ENSO-fire relation occur. And finally, a regression analysis was conducted between different time composites of fire counts and the Niño 3 anomaly to accurately identify and quantitatively measure the strongest possible ENSO-fire relation.

Although the Niño 3 anomaly presented different temporal trends among the five studied El Niño events (1982-83, 1986-87, 1991-92, 94 and 1997-98), the fire activity occurred constantly during August-October and February-April of the El Niño Year 0 and Year 1 respectively. However, the overall strength of each El Niño event related closely to the corresponding fire magnitude (Figure 4).

Results from the cross correlation analysis not indicate clearly any precise and consistent lag time of ENSO-fire association (Figure 6). Various lag times were observed between the five different El Niño events when cross correlation was applied to the 24-month ENSO-fire series. Calculated lags varies between zero and seven months.

However, a more clear ENSO-fire relationship was revealed when various time composites of Niño 3 anomaly and fire counts were evaluated. The strongest ENSO-fire association was observed when the total 16-months sum of ENSO index (Niño 3 anomaly), from January of Year 0 to April of Year 1, compared against the total fire activity of the same time period (Figure 7). The stepwise linear regression for the five ENSO-fire pairs resulted in an r-square equal to 0.97 ($n = 5$, $p = 0.002$) highly significant within 99% confidence level. Consequently, the 97 per cent of the 16-months fire activity in the whole Borneo during the five studied El Niño periods could be explained by the 16-months ENSO strength as measured by the SSTA in the Niño 3 region of the Pacific Ocean. However, as was mentioned previously, these first sixteen months of each 24-months studied fire event included the majority of the entire detected fire events, representing 81% of the total 10-years fire activity in Borneo. Therefore, if this observed ENSO-fire relation remains consistent in future El -Niño events, it may be possible to predict in advance the all-Borneo fire activity based on predictions of Niño 3 anomaly. Then the accuracy of the derived fire activity would depend primarily on the forecast precision of the Niño 3 anomaly by statistical and/or dynamical-coupled models.

Conclusion

The spatially low resolution NOAA AVHRR GAC satellite data demonstrated an acceptable performance for documenting and quantitatively measuring fire activity in Borneo during El Niño events. Active fire counts on GAC imagery were derived by applying a developed multispectral fire detection method to the totally 10-years GAC dataset, which corresponds to five El Niño events from 1982 to 1998. The derived fire counts were further adjusted from different cloud coverage and observation time of each GAC image. The majority of fire activity occurred between August-October of the first calendar year (Year 0), and between February-April of the following year (Year 1) in each El Niño event. A strong ENSO-fire relationship was found when the total 16-months sum of ENSO index anomaly in the Niño 3 region of the Pacific Ocean, from January of Year 0 to April of Year 1, plotted against the total fire activity of the same time period ($r^2 = 0.97$, $n = 5$, $p = 0.002$). These 16 months counted 80.61% of the total 10-years El Niño related fire activity in Borneo.

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