Biomass burning emission inventory from burnt area data given by the
SPOT-Vegetation system in the frame of TRACE-P and ACE-Asia
campaigns

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Abstract

One of the main uncertainties in the estimation of the climatic impact of aerosols is linked to our knowledge of gas and aerosol emissions. This is particularly crucial over Asia where a strong regional fingerprint is observed, with different emissions types, depending on the various vegetation and climate (biomass burning emissions) and on the very fast changes of the population and industrialisation (biofuel and fossil fuel emissions). The main contribution of this work is to improve the biomass burning inventory over Asia. For this purpose, a method based on a time series of satellite images for mapping burnt areas [GBA2000 project – Tansey et al., 2002; Grégoire et al., 2003], which proved to bring significant improvement in the assessment of spatial and temporal emission distribution [Liousse et al., 2003] was applied to one km resolution SPOT-VEGETATION satellite data covering the ACE-ASIA (Aerosol Characterization Experiment) and TRACE-P (Transport and Chemical Evolution over the Pacific) campaigns between March and May 2001. Regional scale maps of burnt areas have been then produced. The importance of inter-annual variability of fire activity is demonstrated. A comparison between burnt area maps over China in 2000 and 2001 shows a significant difference, which indicates the crucial need for models to use real time products. In order to obtain aerosol and gas emission inventory, burnt area maps were crossed with existing land cover maps to estimate the amount of burnt biomass. Particular attention was given to the choice of emission factors in this experiment. This biomass burning emission inventory described in this paper, called the ABBI (Asian Biomass Burning Inventory), with a spatial resolution of 1°x1° is compared with the inventory used in works dealing with TRACE-P and ACE-Asia campaigns [Streets et al., 2003]
I. Introduction

Emissions from biomass burning are known to significantly contribute to the injection of gases and aerosols in the atmosphere with local and global impacts. There is a huge uncertainty in biomass burning emission inventories, used for modelling exercises. The existing inventories [EDGAR described in Olivier and Berdowski, 2001a, GEIA (http://weather.engin.umich.edu/geia/index.html; Cooke and Wilson, 1996; Lioussse et al., 1996] are based on the relationship between the burnt biomass and the emission flux, linked by an emission factor dependent on the combustion type and consequently on the burnt vegetation type [Seiler and Crutzen, 1980]. During the last decade, the characterization of the emissions has significantly improved. A series of experiments in Africa (DECAFE 1988, 1991, see http://www.insu.cnrs-dir.fr/documentation/Insu_doc/decafe_cadre_gene.html, SAFARI 1992, 2000, see http://safari.gecp.virginia.edu/abstract/index.asp, EXPRESSO, see http://www.insu.cnrs-dir.fr/documentation/Insu_doc/expresso.html) and in the US and Brazil (SCAR C, SCAR B, see http://asd-www.larc.nasa.gov/scar/) have allowed the determination of emission factors for many chemical species, as a function of the combustion mode, with good accuracy [Andreae and Merlet, 2001; Lioussse et al., 2003]. Most of the uncertainty in emissions values now lies in the estimate of burnt biomass and in the temporal dynamics, namely seasonal and inter-annual, of this variable. Most of the inventories quoted previously were based on the determination of the mean burnt biomass value within a distribution, usually obtained from statistical data. For example, Hao et al., [1990] and Cooke and Wilson, 1996] used to consider that about 80% of the savanna is burned in Africa on an annual basis.

Recent developments centred on Africa have put forward a new method based on satellite imagery in order to better take into account spatial and temporal emission distributions with availability of long time series both past and future in space and time and a high frequency of observations [Cooke et al., 1999; Barbosa et al., 1999; Lioussse et al., 2003]. At the global
scale, a new product from the European Space Agency (ESA) based on burnt area data [Hoelzemann et al., 2003] has been released. Some of these studies have chosen to use the burnt area instead of “hotspots” (active fire occurrences) products. Indeed, as mentioned in Liousse et al., [2003], only a qualitative improvement could be possible with fire pixel products. The use of burnt area products allows us to minimize the effect of temporal sampling, i.e. the burnt areas have a spectral signature that can be observed over a longer time period and consequently this results in a quantitative improvement in the assessment of the burnt biomass.

Following this recommendation, this paper presents estimates of burnt biomass emissions for a large region of Asia based on the use of burnt area products. In the first part, the methods used to derive the burnt areas from the satellite data and to derive emissions are described. Results of this study are presented in the second part, comparisons are made firstly between ABBI (Asian Biomass Burning Inventory) estimates and existing inventories available for this region from statistical data and ACESS (Ace-Asia and Trace-P Modelling and Emission Support System) and secondly between estimates for years 2000 and 2001 using the same methodology to derive those values.

II. Method

In this first part, the procedure for deriving the gas and particle emissions from satellite data is described including a presentation of the satellite data, a description of methods used to estimate burnt areas and then to derive emissions. The study area, presented in figure 1, extends from the west of Kazakhstan (Ural Mountains) to the east of Japan and from the centre of Russia to the south of Indonesia (10°S – 60°N, 59°E – 150°E). Indeed, such a frame allows us to take into account all the fires with an impact on the ACE-Asia and TRACE-P experiment zones.
1. Data sources

SPOT-VEGETATION imagery [Eastwood et al., 1998; Fraser and Li, 2002] was used to obtain the burnt area map during the ACE-ASIA and TRACE-P campaigns from March to May 2001. The VEGETATION sensor on board the SPOT-4 platform was launched in March 1998 (http://spot-vegetation.com). The instrument observes a region of the Earth 2250 km wide with daily coverage. The satellite has an equatorial local crossing time of 10:30 in the morning local solar time. The across track resolution is approximately 1.1 km at the nadir. The data are projected and interpolated to a constant pixel resolution of approximately one km². Four spectral bands are available: B0 between 0.43 and 0.47 µm (blue), B2 between 0.61 and 0.68 µm (red), B3 between 0.78 and 0.89 µm (near infrared) and SWIR between 1.58 – 1.75 µm (short wave infrared). The SWIR band, centred on 1.65 µm, has been proved to be useful for mapping burnt areas [Eastwood et al., 1998; Eva and Lambin, 1998; Trigg and Flasse, 2000]. Daily, surface reflectance (S1) products were used for this study. Information about the land cover is also required to compute the emissions. The product chosen among the literature for this work was the University of Maryland (UMD) global land cover product [DeFries et al., 1998; Hansen et al., 2000]. This land cover map includes 11 classes of vegetation that are listed in the table 1.

2. Deriving burnt area maps from SPOT-VEGETATION S1 imagery

The processing chain was developed for the Global Burnt Area 2000 (GBA2000) project [Grégoire et al., 2003; Tansey et al., 2003]. The different modules are the pre-processing module, the processing module and the post-processing module.

a. The pre-processing module
Before we apply the algorithm developed to yield burnt areas, the satellite data need to be effectively cleaned. The quality of the results highly depends on this process. Briefly, this image pre-processing module can be separated into two parts. The first procedure removes pixels, that could be detected as burnt pixels but which are not burnt and include cloud shadows, water bodies and non-vegetated surfaces, or pixels with extreme values that could influence the operation of the algorithm. The second procedure phases the remaining data that further minimizes cloud effects and fills in any data gaps. A good intermediate composite product can be created from a small number of daily images and is used as a reference from which to map new burnt areas.

b. The processing module: burnt area algorithm

The algorithm was developed by Ershov and Novik, [2001] of the International Forestry Institute (IFI) of Russia and was applied to the ACE-Asia window. This algorithm examines spectral characteristics on sub-regions of 200 by 200 km and derived burnt areas using two different algorithms depending on whether the land cover is forested or not forested.

c. The post-processing module

In order to remove any possible large remaining errors in the burnt area results, a post-processing module is applied. It consists of the removal of a one pixel expanded water mask in order to remove problems occurring at shorelines.

d. The output products

The output products are the location (in latitude and longitude) of the pixels classified as burnt and the date of burning (http://www.gvm.jrc.it/fire/gba2000/index.htm). An important uncertainty in the estimates is determining the real area burned within each pixel, of
a regular size, detected. It is believed, although there is not a wealth of literature of this subject, that a 1 km$^2$ pixel is classified as burnt when at least 50% (50 hectares (ha) in this case) of the area covered by the pixel is effectively burnt. This introduces an uncertainty when translating the number of pixels classified as burnt into an area in hectares or square kilometres. It also introduces a spatial filter, burnt areas less than 50 hectares in size are not likely to be detected. A second uncertainty is linked to the quantity of biomass actually burnt within each pixel. The burning efficiency varies widely as a function of the vegetation type and of the meteorological conditions at the time of the fire. It is also important to note that a series of problems have been encountered during data processing, especially due to the region and the time of the study. For example, we had to cope with dense cloud cover, small and scattered fires, a wide range of vegetation cover type (desert to evergreen moist forest) and the monsoon season commencing at the end of the experimental period. Finally, in order to check the consistency of our results, high resolution satellite imagery (Landsat TM 30m resolution quick-looks) have been analysed over some areas, mainly in regions where problems were observed. We were satisfied that this procedure was sufficient because in the majority of cases, burn scars visible. This step has proven to be satisfactory, because the burnt scars observed in TM images were visible in the SPOT-VEGETATION data, despite the different spatial resolution.

3. Determination of the emission inventory

a. Multi-information map preparation

The burnt area maps, resulting from the above procedure have been crossed with other sources of data including vegetation maps, administrative maps and 1°x1° grid maps. The data sets were entered into a Geographic Information System (GIS) to provide products of different categories such as burnt areas crossed with country and vegetation type and burnt
areas crossed with country and a 1°x1° grid. These categorized products provide daily information on the vegetation type that has been burnt in each 1°x1° grid square during the time period and over the area of this study. Furthermore, the burnt area maps at a resolution of 1 km\(^2\) were crossed with the UMD land cover map, also at a resolution of 1 km\(^2\). These products were then re-sampled to a resolution of one degree. As an example, on May 4\(^{th}\) in India, burnt pixels located at 17.5°N and 76.5°E amounted to 107 km\(^2\) of wooded grassland, 6 km\(^2\) of closed shrubland, 18 km\(^2\) of open shrubland and 8 km\(^2\) of grassland (vegetation information was derived from the UMD land cover product).

b. Description of emission calculations

The method used for the emission calculation for the species x is based on the following equation given by Seiler and Crutzen, [1980]:

\[
Q(x) = M \times EF(x)
\]

(Eq. 1)

where \(Q(x)\) denotes the gas or aerosol emission flux, \(M\) the amount of burnt biomass and \(EF(x)\) the emission factor given for the species x in grams of x per kilogram of dry matter (\(gx/kgdm\)).

The emission factors given by Andreae and Merlet, [2001] are used for the gases. For particles, the emission factors for both black carbon (BC) and primary organic carbon (OC\(_p\)) are summarized in table 2 for each UMD vegetation class. These values have been specially selected for this study and for the classes of the UMD land cover map (11 vegetation classes) present in the area, including recent experiments and reviews [Liousse et al., 2003]. In some cases, \(EF\) values were not available for a vegetation class. Therefore correspondences between the UMD vegetation classes and main vegetation types with well known \(EF\) have
been assumed from vegetation properties, as shown in table 1. The main assumptions for particle EF selection were:

- Emission factors for BC, considered as inert particles may be either taken from ground and airplane measurements.
- Emission factors for OC, has to be taken from ground measurements, therefore it doesn’t include secondary formation of organics.

Values for tropical forest and savanna fires have been selected following Lioussse et al., [2003]. Values for extra-tropical forest fires have been chosen following Susott et al., [1991] and Hobbs et al., [1996]. Values for cropland burning are based on Lioussse et al., [1996].

The amount of burnt biomass $M$ is given by Seiler and Crutzen, [1980]:

$$ M = A \times B \times \alpha \times \beta $$

(Eq. 2)

where $A$ is the burnt area ($m^2$), $B$ the biomass density ($g/m^2$), $\alpha$ the fraction of aboveground biomass, and $\beta$ the burning efficiency. The value of $A$ is provided by this work.

Particular attention has been dedicated to the parameterisation of vegetation characteristics. Table 3 provides values of the burning efficiency $\beta$ for each UMD classes, based on a review conducted by Palacios et al., [2002] who summarized several studies [Akerelodu and Isichei, 1991; Bilbao and Medina, 1996; Dignon and Penner, 1996; Hoffa et al., 1996; Hurst et al., 1994; Kasischke et al., 2000; Levine, 2000]. Values of the aboveground biomass density $B'$ (= $B \times \alpha$) are given in table 3. These values that are available for the vegetation described in the OGE (Olson Global Ecosystem), 21 classes, [Olson et al., 1985] have been adapted for the UMD land cover product. Moreover, correspondence has also been found for vegetation denominations. As an example, woodland and wooded grassland in the UMD land cover product correspond to woody savanna and savanna trees in OGE. It is important to preserve
the details within the eleven UMD classes that permit us to consider important variations in biomass density values. Indeed, as shown in table 3, the range of these values is from 1250 \text{g/m}^2 for grassland to 36,700 \text{g/m}^2 for evergreen needleleaf forest.

c. **Temporal distribution**

The main goal of this work is to provide burnt area data with a high temporal resolution. However, we have to consider certain characteristics of the satellite data that we utilized. Although the SPOT-VGT system provides spectral measurements every day, it is only every five days that these measurements are provided under exactly the same viewing conditions. The consequence of this is that the radiometric values for a given location on the ground change from day one to day five and then return to the original value on day six (provided nothing has changed on the land surface). Ultimately, better confidence is obtained by computing a moving average over five days.

d. **Adaptation of the gaseous inventory to the need of model input**

Emission inventories have been derived for 58 gaseous species from Andreae and Merlet, 2001] emission factors. The model input, that we are going to use, needs species included in RACM list of 67 species [Stockwell et al., 1997] or its reduced version ReLACS of 37 species [Crassier et al., 2000]. For this purpose, an aggregation of 58 gaseous species into RACM species has been done following Middleton et al., [1990], Stockwell et al., [1997] and Stockwell et al., [1990]. An aggregation into ReLACS species was performed following Crassier et al., [2000]. Table 4 summarizes the gaseous species that have been taken into account and their distribution for the different RACM and ReLACS classes.
III. Results

Figure 2 presents the geographic distribution of Black Carbon (BC) emissions obtained with the method previously described, from March 1st to May 10th, 2001. More details dealing with spatial and temporal variation are presented in the third subsection below.

1. Comparison of our inventory (ABBI) with ACESS inventory

A number of modifications were made to ABBI in order to study any similarity and difference with ACESS inventory, which is used by ACE-Asia and TRACE-P scientists. BC emission factors from Andreae and Merlet, [2001] were chosen for conducting the comparison, such as in ACESS inventory. The ACESS window is smaller than the ABBI window: therefore a common window has been selected for the comparison: 10°S – 53°N, 60°E – 150°W.

ACESS inventory, with region-annual emissions obtained from National survey and researches may be considered as representative for a generic year in the interval of the 1990-2000. In order to grid daily emissions, ACESS has used remote sensing data (hotspots, instead of burnt area maps): The World Fire Web’s 0.5° fire count data of 2001 (NOAA-AVHRR), and the TOMS-AI data as an additional information source [Streets et al., 2003; Woo et al., 2003]. In this gridding phase, satellite fire counts have been seen to vary significantly for the FSU countries and the Kazakhstan: contribution of these countries have been consequently excluded from ACESS inventory.

Figures 2 show the results of the comparison of BC emissions. The total amount of BC is roughly of the same order in the two inventories, that is 1.83E+05 tonnes and 2.50E+05 tonnes respectively in ACESS and ABBI. Let us note that FSU and Kazakhstan countries represents 55% (1.39E+05 tonnes of BC) of the total amount of ABBI.
However, the spatial distribution is different; at the beginning of TRACE-P in the ACESS inventory, the emissions are predominant in Thailand, whereas the main emission areas are located in central China in ABBI. In the middle and at the end of the campaign, ABBI shows strong emissions in the northern part of the window, contribution which are not included in ACESS inventory. Also, ABBI doesn’t observe the large burning activity in India, underlined by ACESS. Huge differences are also observed in terms of temporal distributions. Figure 3 shows that ACESS inventory, when compared to ABBI, are higher at the beginning of the campaign. At the end of the campaign, due to the important contribution of the FSU and Kazakhstan countries, ABBI is greater than ACESS.

As mentioned in the introduction, the use of burnt areas seems to be more appropriate to quantitatively derive biomass burnt emissions, especially because it gives more structural information (i.e. geographical area of burnt scar).

The fire events detected by the polar orbiting satellite systems such as NOAA-AVHRR correspond to only a small fraction of the fire events, which are active during the day. Actually, there is a large sampling bias in all these products. The bias is much higher when using fire counts than when using burnt areas, as burnt areas integrate the fire activity over a rather long period of time (~ two weeks) while fire count is an instantaneous measurement. Moreover duration of fire events can be very short, less than one hour in the tropical belt, which means that it is extremely difficult to translate a fire count into a quantitative assessment of area burnt.

The hot spot type approach could be more appropriated in the estimation of the fast response of global biomass burning emissions, that would be beneficial for forecasting for example. However, recent regional development allowed fast response of biomass burning emissions from burnt area products derived from MODIS data [Eva et al., 2003]. The heat flux, available in the hotspot approach, could have more direct correlation with emissions
than burnt area. Moreover, the hotspot approach is probably more efficient for assessing the
fire activity in the dense tropical forest, where fires are often hidden by the tree canopy and
detectable only via the heat flux: the differences between ACESS and ABBI in South East
Asia could be explained by such a problem. But that is not right for intensive fires which tend
to saturate the heat flux sensors.

Uncertainty also exists in the use of burnt area products, especially knowing the pixel
fraction that is really burnt. Indeed, a 1 km² pixel is classified as burnt when at least 40% to
50% of the area covered by the pixel is effectively burnt. Let us note however that this type of
uncertainty does exist when using the hotspot approach: in humid savanna, for instance, a fire
front of 50 m gives the spectral signature of an active fire for 1 km² pixel.

Consequently, it is difficult to find explanations for the differences observed between
ACESS and ABBI. Indeed, in the hotspot methods, emissions could be either overestimated,
due to the number of pixel really active, or underestimated, due to the heat flux saturation,
and to the temporal sampling (satellite passage).

Finally, this comparison between inventories clearly shows that it is difficult to find a
systematic correlation between the number of fire events and the burnt areas as it is highly
variable depending on the type and condition of the vegetation and time of the year. Better
compromise between all these methods is a multi-system approach which would allow the
modellers to take benefit of all the global fire products made available by the remote sensing
community:

- the hotspot products in the dense tropical forest, as derived from the NOAA-
  AVHRR and TRMM-VIRS systems (both day time), and from the ERS-ATSR
  system (night time)
- the burnt area products in all the other types of vegetation cover, as derived from the SPOT-VGT (GBA2000), ERS-ATSR (GLOBCAR) and TERRA/AQUA MODIS systems.

2. Comparison with burnt areas given by national statistics

We compared burnt area data obtained with our method and national statistical data given by the relevant countries (this data was mainly taken from the International Forest Fire News (IFFN) web site at http://www.fire.uni-freiburg.de/iffn/country/country.htm). Due to the lack of data for 2000 and 2001, available average data given for the 1990s or data for 1999 were taken into account. Also, yearly statistical data were compared to our few months of data, corresponding to the period of maximum fire activity during the year.

Generally, it is noted that our estimates are much higher than the national statistical data, except for India. In China, the average annual burnt area during the 1990s according to IFFN was 1220 km². This value is considerably lower than the 41,000 km² and 47,000 km² for the years 2000 and 2001 respectively in ABBI. In South Korea, burning activity tends to occur in spring and in late autumn and early winter. Between 1995-1999, the contribution of spring fires is of 63% compared to 7% in autumn and 30% in winter (from IFFN). Even if ABBI only considers spring fires, our burnt area estimates are still very high; 912 km² and 1187 km² of burnt forest respectively for 2000 and 2001 compared to an average during the 1990s of 14 km² according the IFFN. For Kazakhstan, national statistics of forest fires indicate 129 km² of burnt forest for the year 2000 compared to 71 km² and 34 km² respectively for 2000 and 2001 in the ABBI. However, in ABBI, total burnt areas including forest, grassland and cropland are estimated at 35,000 km² and 50,000 km² respectively for 2000 and 2001. IFFN data suggest that such an amount could be burnt in this country as burnt forest and steppe for the year 2000 represent a total area of 10,000 km². In India, the forest
fire season occurs from February to mid-June. According the Forest Survey of India, in a study presented in 1995, 14,500 km$^2$ of forests are affected by fires annually, whereas an assessment of the Forest Protection Division of the Ministry of Environment and Forest gives a figure of 37,000 km$^2$. In our inventory, forest fire contributes to only 1.5% of the total burnt areas with 154 km$^2$ and 316 km$^2$ of burnt forest respectively for 2000 and 2001 (the total burnt area in India was 11,000 km$^2$ and 19,000 km$^2$ for 2000 and 2001 respectively).

Such differences may have different origins. Firstly, it could be due to the definition of the vegetation cover, for example, what is really considered in the group “forest”? The definition of “forest” is quite variable depending on the countries. Also, the location of the different cover types is often different from one land cover map to another. Secondly, it is difficult to use ground observations to monitor regional fires and burnt areas. Moreover, the methods used to make these fire inventories are quite variable from one country to another one, which makes comparisons between regional or sub-continental inventories questionable. Thirdly, the satellite data acquisition has been seen to be a great improvement in the biomass burning emission estimates. But, in some regions such as India or Indonesia, the process has encountered some problems because of the dense cloud cover resulting in burn scars being missed. Furthermore, burn scars occurring in agricultural areas could be very small and are not detected by a one km resolution satellite.

3. Intercomparison of our inventory for 2000 and 2001

In this section, we will first focus on the type and distribution of the burnt biomass during the ACE-Asia and TRACE-P campaigns in 2001, then on CO and BC emissions. A comparison with the year 2000 is also presented, which has been processed using the same method as 2001.
a. Description of the burnt biomass

Figure 4 shows the temporal distribution of burnt areas in March, April and the first half of May 2001. Vegetation fires are low at the beginning before growing in number until the end of the campaign. The maximum is in April and early May, which seems to signify the end of fire activity in this region, probably caused by the onset of the monsoon rains that occur in late May. This is especially true in the southern part of the study area. The results for 2000 have been added in figure 4. We see that the total estimate of burnt area in 2000 is slightly lower than in 2001 (except in May) with 189,238 km² compared to 213,626 km². Overall, the temporal distribution of burning activity is similar. Figure 5 shows that the main vegetation types burnt during the observation period (at 15 day intervals) is cropland, which represents 27% of the total burnt area. Grassland, woodland and wooded grassland also burn in considerable amounts when compared to the forest and shrubland families. A similar repartition (not presented here) is observed in the year 2000, except for the 1 to 15 May period as in this year, grassland and cropland were less affected by biomass burning than in 2000, the relative importance of these fires being halved. For the same period, but contrary to the previous example, burning activity in deciduous broadleaf forest is doubled for the year 2000. For evergreen broadleaf forest, estimates for the year 2000 were recorded at 140 km², but almost zero (only 2 km² burnt) for the 2001.

If we scrutinize now the latitudinal distribution of burnt areas per vegetation types, we may see that the spatial distribution of fires is highly dependent on the time period. Figure 6 shows the distribution of burnt areas for five periods of 15 days along 14 latitudinal strips, five degrees wide in 2001. In March, the vegetation fires are located between 15°N and 45°N as at latitudes greater than 45°N there is still a snow cover. However, a few days after the snow has melted, from the beginning of April onwards, the northern region is affected by fires. Such latitudinal distribution is also observed in the year 2000.
If we now focus on the burnt biomass results, we see that the amount of burnt biomass is quite similar for the years 2000 and 2001, approximately 561 and 607 Tg of dry matter respectively. Furthermore, the temporal distribution of burnt biomass data is in general agreement with the distribution of burnt areas. Differences occur when we focus on biomass burning per vegetation type. A few of these differences are noted here, for example, for the second half of March, the amount of burnt biomass is lower in 2001 (52.61 Tg of dry matter) than in 2000 (55.07 Tg of dry matter), whereas the burnt areas is seen to be higher in 2001 than in 2000. The same pattern is observed for the second half of April and in early May, again the difference between 2000 and 2001 is lower in terms of burnt biomass than in terms of burnt areas. It appears that burning of forests, characterized by high biomass density coefficients, causes these differences. This confirms the sensitivity of vegetation parameterisation (choice of biomass density and burning efficiency) in the calculation of the emissions and also the importance to use an accurate land cover map.

b. Distribution of biomass burning emissions

As for burnt areas and burnt biomass, differences between emissions in 2000 and 2001 are not very significant in terms of total amount of gases or particles, however an important difference may be also underlined concerning the spatial and temporal distributions. Figure 7 shows the distribution and amount of CO emissions for the year 2001 during the months of March, April, and May. Values for the year 2000 have been added for comparison. For the whole studied period, the CO emissions are of the same order for the both years: 4.99E+7 and 5.39E+7 tonnes of CO are emitted in 2000 and 2001 respectively.

- Temporal distributions
Temporal distribution of emissions (on the basis of 15 day comparisons) is in agreement with the burnt area and the burnt biomass temporal distributions. However, due to differences between the burnt vegetation types, more CO emissions are detected in 2000 than in 2001 for the second period of March: $5.40 \times 10^6$ tonnes (2000) compared to $4.64 \times 10^6$ tonnes (2001) and for the first period of April: $6.52 \times 10^6$ tonnes (2000) compared to $5.61 \times 10^6$ tonnes (2001). Let us now focus on the daily temporal distributions of CO emissions. Results are shown in figures 8a, 8b, 8c, respectively for March, April and for May. Values for both years, 2000 and 2001 are presented. Very high variations of the daily emissions are observed between 2000 and 2001. For example, on March 11th and May 14th, the CO emissions are 3 times higher in 2000 than in 2001, whereas on April 7th and May 3rd 2001, emissions are twice higher than in 2000. This shows the need for considering daily emissions in regional modelling exercises that are usually based on a few day simulations.

- Spatial distribution

At the beginning of ACE-Asia and TRACE-P period (March 2001), emissions are located in India, South-East Asia, South and East of China. As previously seen with the burnt area distributions, from the end of March and during April, the emissions grow in the northern part of the window in Kazakhstan, southern Russia, Mongolia, and northern China, though being still present in the South-East Asia. This evolution is the same for the both years. Nevertheless, some important shifts in space and time may be noticed with important differences in the intensity of the emissions. Figure 9 shows the temporal distribution of BC emissions over China, India, and Kazakhstan in 2000 and 2001. During the first period of March over India and China, BC emissions in 2000 are less than half the value of 2001, whereas, during the second period of March, an opposite tendency is noticed in China. At the end of the studied period, a difference, amounting to a factor of 100, of the BC emissions
appears between the two years over Kazakhstan (2.38E+3 tonnes of BC in 2000 compared to 2.12E+4 tonnes in 2001). Focus over Thailand shows that there were no emissions during the first period in 2001, whereas 903 tonnes of BC was emitted in 2000. This amount is important knowing that during the other months, emissions never exceeded 100 tonnes of BC.

c. Discussion

The main differences encountered when comparing the evolution of burnt areas, burnt biomass and BC and CO emissions, between 2000 and 2001 are found in their temporal and spatial distributions which can be explained by variations in the type of vegetation burnt. Figure 10 shows the quantity of burnt areas per vegetation types versus the total vegetated area for 2000 and 2001. It can be seen that the land cover classified as grasslands, comprising grassland, open and closed shrubland, woodland, wooded grassland, are always higher in 2001 than in 2000, except for the woodland class. For the forest classes, burning in both the evergreen forest and the deciduous needleleaf forest is more significant in 2000 than in 2001. If we now focus on the repartition in terms of percentage of the burnt areas per country and per vegetation type, large differences appear between both years. For forest classes, in Russia, 45% burnt in 2000 compared to 38% in 2001, in China 38% burnt (2000) compared to 44% (2001). For grassland classes, the highest difference occurs in Mongolia, 10% in 2000 and 2% in 2001 and Kazakhstan, 16% in 2000 and 23% in 2001. In India, 10% burnt in 2000 and 15% burnt in 2001. It is interesting to note that in this context, BC emissions in China are always lower in 2000 compared to 2001, whatever the vegetation type. The figures show that 43 Gg of BC were emitted in 2000 compared to 52 Gg in 2001 from grassland burning, 32 and 35 Gg of BC from forest burning and 18 and 23 Gg of BC from cropland burning in 2000 and 2001 respectively. Similar patterns are observed in South Korea, the total amount of BC
emitted during ACE-Asia is 39 Gg and 51 Gg and in North Korea, 63 Gg and 103 Gg in 2000 and 2001 respectively.

This systematic difference between 2000 and 2001 for this area and this period could be linked to the La Nina global climatic event. The years 2000 and 2001 were considered to be La Nina years. The magnitude of the event was stronger in 2000. One of the cool spot, resulting in a wetter climate and consequently less biomass burning underlined by ENSO specialists (http://www.cpc.ncep.noaa.gov) was thought to be situated in the north-eastern China, North Korea and South Korea. In our inventory, emissions for these countries are always lower in 2000 than in 2001. Such a result supports previous assumptions already seen for Africa [Barbosa et al., 1999], by suggesting a link between ENSO variability and biomass burning emissions.

IV. Conclusion

This work, devoted to the construction of a biomass burning emission inventory (called ABBI) from satellite burnt area data over Asia, allows us to quantitatively improve the existing knowledge on global biomass burning emission inventories. Our results show that Asian biomass burning contributes significantly to the injection of gases and aerosols into the atmosphere. Indeed, values of the BC emissions from Asian fossil fuel consumption and biomass burning during the studied period, are found to be of the same order: 5.57E+5 tonnes of fossil fuel BC [Lioussse et al., 1996] compared to approximately 3.90E+5 tonnes of biomass burning BC. Some uncertainties still remain, mainly concerning knowledge of the true fraction of a one km² pixel actually burnt. Investigations are ongoing to better improve this knowledge using a multi satellite approach [Pers. Com. Jean-Marie Gregoire, EU Joint Research Centre]. Also, choosing vegetation parameters and emission factors is very
important. In fact, total BC emissions over Asia from March 1 to May 15, 2001 are quite different depending on the choice of emission factor. From our value of EF(BC), 3.90E+5 tonnes of BC are estimates, compared to 4.77E+5 tonnes of BC with the EF(BC) estimate of Liousse et al., [2003] and to 3.49E+5 tonnes of BC with the EF(BC) from Andreae and Merlet, [2001].

A comparison of Asian biomass burning emissions for the same period and area, derived from two different methods, one based on the fire pixel distribution (ACCESS) and our inventory based on the burnt area mapping (ABBI), shows regional estimates of the same order (1.11E+5 tonnes of BC for ABBI (values excluding FSU and Kazakhstan contribution) and 1.83E+5 tonnes of BC for ACCESS). However, high spatial and temporal differences are observed. The correlation between the two products depends strongly on the type and condition of the vegetation and time of year. A better compromise would be a multi-system approach including both hotspot and burnt area products, which will be the only way to know when it burns, where it burns and what burns. Results of this study have also been compared with national statistics and show large differences between both estimates. Generally, our values are much higher than IFFN values except for India where more studies are needed on the distribution of agricultural fires, which may be underestimated by acquisitions made at one km resolution. Furthermore, it is likely that cropland fires, that are usually very small, could have been missed. The comparisons made between 2000 and 2001 have pointed out important inter-annual variability’s, especially the spatial and temporal distribution of burnt areas, burnt biomass and emissions. This variation is slightly different for the three parameters, which are highly dependent on the burnt vegetation type and competitive effects between the variation of the biomass density and the emission factors. Also, it is interesting to note that monthly values are of the same order between both years, but the daily temporal distribution is completely different.
Due to the importance of vegetation type, a future study will cross the burnt area products with the Global Land Cover 2000 (GLC2000) product (http://www.gvm.jrc.it/glc2000), considered to be an improvement from existing land cover products such as IGBP-DIS, UMD and MODIS. A comparison of emission inventories could be made for each of these land cover products. The key method used in this paper to derive emissions, is highly linked to the availability of burnt area products. An encouraging development for our research community is the preparation of the GLOBCARBON (Global Land Products for Carbon Model Assimilation) project from the European Space Agency (ESA) based on methods developed by the GBA2000 project and covering the period 1998 to 2003. Future work will also involve and test the ABBI emission inventory within a regional model (MesoNH-C) to study the sensitivity of the results to the chosen biomass burning inventory. The main aim will be to study the relative importance of biomass burning and fossil fuel emissions on Asian carbonaceous particle concentration and focusing on secondary organic aerosol formation during the ACE-ASIA campaign.
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| Vegetation Class                      | Corresponding EF              |
|--------------------------------------|------------------------------|
| evergreen needleleaf forest          | extra-tropical forest        |
| evergreen broadleaf forest           | tropical forest              |
| deciduous needleleaf forest          | extra-tropical forest        |
| deciduous broadleaf forest           | extra-tropical forest        |
| mixed forest                         | extra-tropical forest        |
| woodland                             | mean (extra-tropical + grassland) |
| wooded grassland                     | grassland                    |
| closed shrubland                     | mean (extra-tropical + grassland) |
| open shrubland                       | grassland                    |
| grassland                            | grassland                    |
| cropland                             | cropland                     |

Table 1: Emission factors for the different vegetation classes of the UMD product.

| Vegetation Class          | EF(BC) | EF(OC) |
|---------------------------|--------|--------|
| evergreen needleleaf forest| 0.6    | 6      |
| evergreen broadleaf forest | 0.7    | 6.4    |
| deciduous needleleaf forest| 0.6    | 6      |
| deciduous broadleaf forest | 0.6    | 6      |
| mixed forest              | 0.6    | 6      |
| woodland                  | 0.61   | 5      |
| wooded grassland          | 0.62   | 4      |
| closed shrubland          | 0.61   | 5      |
| open shrubland            | 0.62   | 4      |
| grassland                 | 0.62   | 4      |
| cropland                  | 0.725  | 2.1    |

Table 2: Primary carbonaceous aerosol emissions factors for the eleven vegetation classes of the UMD landcover.

| Vegetation Class          | Biomass Density (g/m²) | Burning efficiency |
|---------------------------|------------------------|--------------------|
| evergreen needleleaf forest| 36700                  | 0.25               |
| evergreen broadleaf forest | 23350                  | 0.25               |
| deciduous needleleaf forest| 18900                  | 0.25               |
| deciduous broadleaf forest | 20000                  | 0.25               |
| mixed forest              | 22250                  | 0.25               |
| woodland                  | 10000                  | 0.35               |
| wooded grassland          | 3300                   | 0.4                |
| closed shrubland          | 7200                   | 0.5                |
| open shrubland            | 1600                   | 0.85               |
| grassland                 | 1250                   | 0.95               |
| cropland                  | 5100                   | 0.6                |

Table 3: Biomass densities and burning efficiencies for the eleven vegetation classes of the UMD landcover.
| ReLACS species | aggregation factors | RACM species | aggregation factors | Andrea et al., species |
|----------------|---------------------|--------------|---------------------|-----------------------|
| NO             | 1                   | NO           | 1                   | NO                    |
| NO2            | 1                   | NO2          | 1                   | NO2                   |
| SO2            | 1                   | SO2          | 1                   | SO2                   |
| CO             | 1                   | CO           | 1                   | CO                    |
| CO2            | 1                   | CO2          | 1                   | CO2                   |
| CH4            | 1                   | CH4          | 1                   | CH4                   |
| N2             | 1                   | N2           | 1                   | N2                    |
| H2             | 1                   | H2           | 1                   | H2                    |
| ETH            | 1                   | ETH          | 1                   | ethane                |
| NO             | 0.57                | propane      |                     |                       |
| NO2            | 1.11                | n butane     |                     |                       |
| NO2            | 1.11                | i butane     |                     |                       |
| SO2            | 0.41                | acetylene    |                     |                       |
| CO2            | 0.49                | methanol     |                     |                       |
| CH4            | 0.49                | methyl acetate|                    |                       |
| N2             | 1.37                | ethanol      |                     |                       |
| ETH            | 0.77                | HC3          |                     |                       |
| NO             | 0.97                | n pentane    |                     |                       |
| NO2            | 0.97                | n hexane     |                     |                       |
| NO2            | 0.97                | iso hexane   |                     |                       |
| CO2            | 1.07                | 1 propanol   |                     |                       |
| CH4            | 1.07                | butanol      |                     |                       |
| N2             | 1.58                | HC8          | 0.94                | heptane               |
| ETH            | 0.96                | ETE          | 1                   | ethene                |
| NO             | 1.04                | OL T         | 1                   | propene               |
| NO2            | 1                   | 1 butene     |                     |                       |
| NO2            | 1                   | 1 pentene    |                     |                       |
| NO2            | 1                   | 4 methyl 1 pentene|                |                       |
| CO2            | 1                   | 1 hexene     |                     |                       |
| CH4            | 0.5                 | octene       |                     |                       |
| N2             | 1                   | i butene     |                     |                       |
| ETH            | 1.07                | styrene      |                     |                       |
| NO             | 1.04                | OLI          | 1                   | trans 2 butene        |
| NO2            | 1                   | 1 cis 2 butene|                    |                       |
| NO2            | 1                   | cyclopentene |                     |                       |
| CO2            | 0.5                 | i butene     |                     |                       |
| CH4            | 1.04                | DIEN         | 1                   | butadiene             |
| NO             | 1.04                | ISO          | 1                   | isoprene              |
| NO2            | 0.87                | TOL          | 0.29                | benzene               |
| NO2            | 1                   | toluene      |                     |                       |
| NO2            | 1                   | ethylbenzene |                     |                       |
| NO2            | 1                   | styrene      |                     |                       |
| CH4            | 1.04                | XYL          | 1                   | xylene                |
| CH4            | 1.04                | CSL          | 1                   | phenol                |
| HCHO           | 1                   | HCHO         | 1                   | formaldehyde          |
| ALD            | 1                   | ALD          | 1                   | propenal              |
| ALD            | 1                   | 1 acetaldehyde|                    |                       |
| ALD            | 1                   | 1 propanal   |                     |                       |
| ALD            | 1                   | 1 butanal    |                     |                       |
| ALD            | 1                   | 1 hexanal    |                     |                       |
| ALD            | 1                   | 1 furfural   |                     |                       |
| ALD            | 1                   | 1 heptanal   |                     |                       |
| ALD            | 1                   | benzaldehyde |                     |                       |
| KET            | 1                   | KET          | 0.33                | acetone               |
| KET            | 1.61                | 2 butanone   |                     |                       |
| KET            | 1.61                | heptanone    |                     |                       |
| KET            | 1.61                | 2-3 butandione|                    |                       |
| KET            | 1.61                | pentanone    |                     |                       |
| KET            | 1.61                | octanone     |                     |                       |
| ORA1           | 1                   | ORA1         | 1                   | formic acid           |
| ORA2           | 1                   | ORA2         | 1                   | acetic acid           |

Table 4: Lumping of the gas species into RACM and ReLACS species and their corresponding aggregation factors.
Figure caption:

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