

Spatio-temporal variation of biomass burning sources over South and Southeast Asia

L. K. Sahu · Varun Sheel

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Abstract In this study, we have investigated the seasonality and long-term trends of major biomass burning (BB) sources over South and Southeast Asia (S-SE Asia). The activities of BB and related emissions show bi-modal seasonality in S-SE Asia. From January to May period, the BB dominates in the northern hemisphere parts of S-SE Asia. From July to September, the activities shift to the southern hemisphere where the emissions from Indonesian and Malaysian islands make largest contributions. Overall, the activities of BB are lowest during October–December period in S-SE Asia. The seasonality of BB intensity and rain are just opposite in the phase over India. The climatological (1997–2008) emissions of carbon monoxide (CO), oxides of nitrogen (NO_x) and non-methane hydrocarbons (NMHCs) show strong spatio-temporal variation. The trends show large inter-annual variations with highest and lowest values during years 1997 and 2000, respectively. In the southern hemisphere parts of S-SE Asia mainly in Indonesia, the intensity of biomass fires has been modulated by the large scale climatic phenomena like El Niño and Southern Oscillation (ENSO). The annual emissions of trace gases in southern hemisphere region during the El Niño years exceed to those for the normal years. The estimates for northern hemisphere region during the La Niña years were significantly higher than those for the normal years. The Model for Ozone And Related Chemical Tracers (MOZART) simulations of columnar CO and NO_x tend to capture the prominent features of BB emissions in S-SE Asia. The impacts of extensive fires in Indonesia during El Niño year of 2006 compared to a normal year of 2005 were clearly seen in the MOZART-4 simulations of both CO and NO_x.

Keywords Asia · Biomass burning · Emission · ENSO · India · MOZART-4 · Trace gases

1 Introduction

To explain the observed variations of various key atmospheric constituents we rely on several global scale models. The two most important resources namely the emission inventory and

L. K. Sahu (✉) · V. Sheel
Physical Research Laboratory (PRL), Navrangpura, Ahmedabad, India 380009
e-mail: lokesh@prl.res.in

L. K. Sahu
e-mail: l_okesh@yahoo.com

back trajectory model have been widely used to characterize the origin and transport of air masses, respectively. On the other hand, typically, such resources are subject to large uncertainty and coarse spatio-temporal resolutions. The anthropogenic sources which include use of fossil fuel and bio-fuel are controlled combustion processes for which emission methodologies are fairly well parameterized (Ito and Penner 2005; Streets et al. 2003a). However, activities of BB are uncontrolled and require much information to estimate the emission data (Streets et al. 2003b). Nonetheless, it is imperative to develop reliable inventories of key species which play important roles in the atmospheric chemistry and climate. The typical fractions of different biomasses burned in Asian countries are reported in Streets et al. (2003b). In the South and Southeast Asia (S-SE Asia) region, forest fires account for the highest followed by the burnings of crop residue and grassland among the BB category.

The cause, location and timing of BB emission are different from those related to the use of fossil and bio fuels. The emission estimates from the BB sources cannot be allocated over time and space in the same way as those from the use of fossil and bio fuels (Streets et al. 2003b). Generally, the burning of agricultural wastes is linked with harvesting practices and crop types. On the other hand, forest and other wild fires can be linked with both natural and anthropogenic factors such as thunderstorm, rainfall, land clearing, etc. However, the in-situ observations of these factors controlling the activities of BB are not practical in many parts of world. Alternatively, the space borne remote sensing observations have been widely used to detect and analyze the parameters related to the global BB (Duncan et al. 2003; Heald et al. 2003).

The related BB emissions are important source of the precursors of ozone (O_3) and various other pollutants (Crutzen et al. 1979; Andreae et al. 1994; Lelieveld et al. 2001). In the tropical regions of Asia, the activities of BB are widespread which show large spatio-temporal variation (Christopher et al. 1996; Folkins et al. 1997). As documented in many research studies, the BB emissions from S-SE Asia contribute substantially to the budgets of various aerosols and gaseous species in Asia (Streets et al. 2003b; Bond et al. 2004). The transport of these pollutants from S-SE Asia over the remote Indian Ocean was a major objective of the Indian Ocean Experiment (INDOEX) campaign in the late 1990s (Lelieveld et al. 2001). In S-SE Asia region, the in-situ measurements of mixing ratios of CO and NO_x have been reported at several sites but other important species like volatile organic compounds (VOCs) data are rarely reported (Sahu and Lal 2006a, b).

The environmental and climatic impacts of BB in S-SE Asia region have been well recognized in several studied. In several observational studies, the large-scale enhancements in the mixing ratio of tropospheric O_3 over S-SE Asia were attributed to the emissions from BB (Chan et al. 2003; Thompson et al. 2001). In spite of the large emissions of various aerosols and trace gases from S-SE Asia, studies of the spatio-temporal variations in the emissions of these species are limited compared to other regions of the world, for example South America and Africa, where BB is an important source of aerosols and trace gases (Folkins et al. 1997; Christopher et al. 1998; Sahu et al. 2012). Previous studies (van der Werf et al. 2006, 2010; Chang and Song 2010) have reported the trends in BB related parameters however, details of seasonal and regional variations are not elaborated. In this study, we have analyzed the spatio-temporal variation of BB and related emission products from S-SE Asia. We have used climatological fire count data, wind field, and inventory data of trace gases from 1997 to 2008. The fire counts detected by the Along Track Scanning Radiometer (ATSR) and wind field data taken from the National Centers for Environmental Prediction (NCEP) reanalysis have been used in the present study. The seasonality in BB activities and relations with the rainfall and El Nino are also discussed. We have also discussed the spatio-temporal emissions of some major precursor gases such as CO, oxides of nitrogen (NO_x = NO + NO₂), non-methane hydrocarbons (NMHCs) over S-SE Asia based on the Global Fire Emissions

Database version 3 (GFED3) (van der Werf et al. 2006, 2010). We have also presented the MOZART-4 simulations of CO and NO_x column number densities for the years 2005 and 2006. A map of study domain representing the different continental and oceanic region in S-SE Asia are shown in Fig. 1.

The global biomass mass is usually classified in three major categories: (1) savanna grassland, (2) forest (tropical, temperate, and boreal), and (3) agricultural land after the harvest (crop residue). The continental break-up of the global biomass loadings are presented in Streets et al. (2003b). Very clearly, Asia leads with ~43 % followed by Africa (~22 %) and Latin America (~12 %). The amount of biomass consumed in a fire can be calculated using following linear equation.

$$M = A \times B \times E \quad (1)$$

Where

- M* Mass of dry matter burned (tons)
- A* Area burned (km²)
- B* Biomass loading (tons km⁻²)
- E* Fractional burn efficiency (dimensionless)

Reasonably accurate estimation of ‘*M*’ depends on the level or quality of information available about the parameters in the right hand side of Eq. (1). After all, the estimation of ‘*M*’ does not give direct information of a particularly constituent emitted from the biomass fire, but can be used as an important parameter to estimate the emission of given species ‘*x*’. To estimate the emission of ‘*x*’, another equation known as BB equation has been used (Levine 2000). Reid et al. (2005) have reported typical ranges of various parameters for different global BB sources.



Fig. 1 Map of the study domain (S-SE Asia) (taken from wikimapia <http://wikimapia.org>)

For a specific fire at a given location and time the amount of emission can be readily calculated using the above described method. However, to calculate the amount of emissions on regional and global scales of BB, getting the reliable information of various controlling parameters is complicated. Nonetheless, there has been significant progress in the global and regional inventory developments from BB sources which are invaluable to the scientific community (Streets et al. 2003a, b; Bond et al. 2004; Olivier et al. 2003, 2005; and references therein). The examples of inventories from the bottom-up approach are POET (Precursors of Ozone and their Effect on the Troposphere) and REAS (Regional Emission inventory in Asia), GFED, etc. The POET inventory (<http://www.aero.jussieu.fr/projet/ACCENT/POET.php>) is based on the European projects GEIA (Global Emission Inventory Activity) and EDGAR (Emissions Database for Global Atmospheric Research). In the present study, we have used GFED3 dataset using the Carnegie-Ames-Stanford-Approach (CASA) biogeochemical model and improved satellite-derived estimates of area burned, fire activity, and plant productivity to calculate fire emissions for the years 1997–2008 with a monthly time step (van der Werf et al. 2010).

In this study, we have used the ATSR fire count data which represent the location and activities of BB. The ATSR were detected in four bands centered at 1.6, 3.7, 11.0, 12.0 μm . It is to be noted, that the ATSR fire data only use nighttime observations with 1 km of resolution. Further details of the detection methodologies of ATSR hot spot data can be found elsewhere (Buongiorno et al. 1997; Arino et al. 2001). The main drawback with the ATSR algorithm is the dependence of the 3.7 μm nighttime brightness temperature (BT) values from the warm surface, i.e. from the non-burning activities. The nighttime overpass is another drawback with ATSR with the fact that biomass fire activity peaks in the afternoon due to both human activity and meteorological conditions. The ATSR active fire counts detected over the forest can repeat the calculation as forest fire could last several days. Cloud coverage could also a source of significant uncertainty as it prevents the detection of surface fires. Wiedinmyer et al. (2006) have provided a modeling based methodology to reduce the uncertainties of fire emissions using the Moderate Resolution Imaging Spectroradiometer (MODIS) data. The study should be treated as more qualitative than quantitative due to large uncertainties in ATSR and GFED data. Despite several shortcomings, the ATSR data provide best current information on the seasonal and spatial variations of biomass burning activity in many parts of the world. In the present study, the interpretation of BB variability using the ATSR data is intended to be qualitative. The burned area biases between MODIS versus ATSR and MODIS versus VIRS (Visible and Infrared Scanner) were factor of about 1.4 in S-SE Asia region. The GFED3 data set closely resembled the MCD45A1 data, both in terms of the spatial distribution of burned area, as well as the annual area burned in most regions of the world (Giglio et al. 2010).

2 Variations in meteorology and biomass burning

2.1 Meteorology in S-SE Asia

The climate of S-SE Asia region is mainly tropical and this results in hot and humid weather conditions during most of the year. The seasonal variation in meteorological parameters is related to the seasonal shift in the large scale transport pattern defined by the movement of the inter-tropical convergence zone (ITCZ) (Asnani 1993; Sahu et al. 2009). The ITCZ is an area of low pressure where the northern and southern hemispheric trade winds converge. In addition, several local factors can also affect the prevailing weather conditions in a particular region or country. The seasonal mean wind streamlines plots at 925 mb based on the NCEP

reanalysis data over S-SE Asia for the years 1997–2008 are shown in Fig. 2. Generally, from the month of May to September the ITCZ moves northward which and cleaner marine mass from the Indian Ocean dominates over the continental regions of S-SE Asia. This circulation is also known as the southwest (SW) monsoon or summer monsoon flow. In the transition period, between the months of September and October, the mixed air masses from marine and continental origins impact many parts of S-SE Asia. From November to March period, the S-SE Asia region is influenced by the flow of continental air masses due to the northeast (NE) and northwest (NW) winds, this period is also known as winter monsoon. On the regional scale, considering the magnitude and timing of wind circulation, there can be considerable inter annual variation in prevailing climatic conditions over S-SE Asia. The above description of seasonality in wind is mainly for the northern hemispheric parts of S-SE Asia. However, the climatic condition and phase of seasonality in winds over Indonesian and Malaysian islands are somewhat different than the rest of S-SE Asia. In the southern hemispheric region, the wind circulations are moderate and influenced by the flows from the SE direction during June–September and from the NW direction during December–March months. The air temperature shows rather weak seasonal variation in Indonesia. Due to entirely tropical and surrounding oceanic environments, the relative humidity (RH) remains high and varies between 70 % and

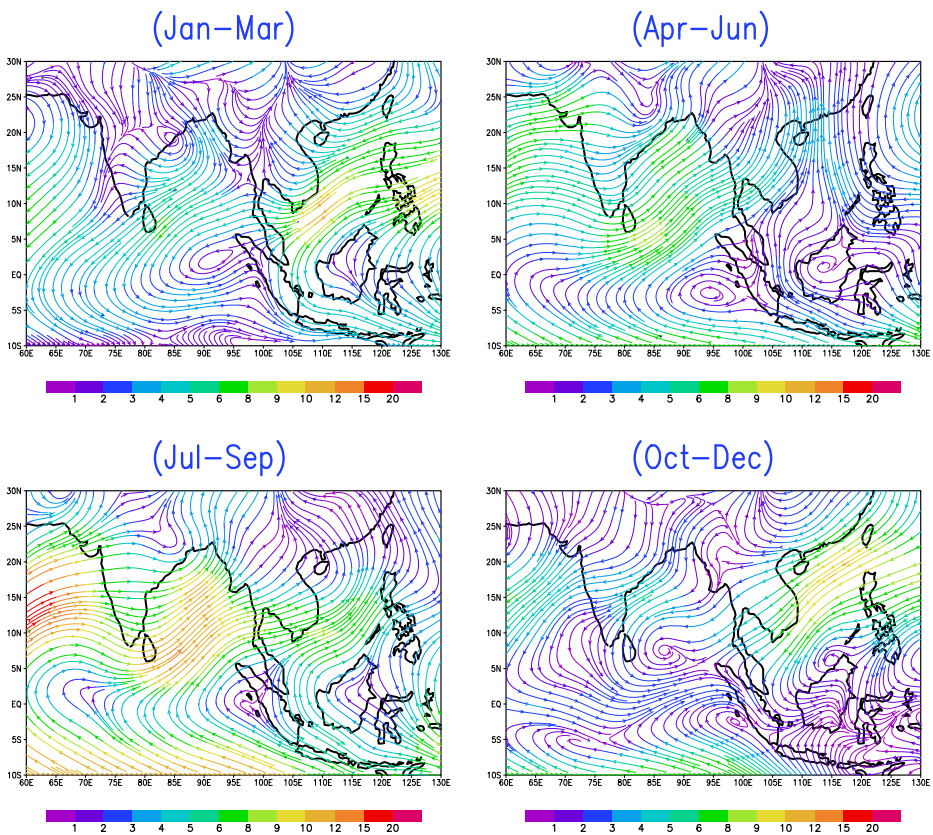


Fig. 2 The climatological mean wind streamlines at 925 mb level (data taken from NCEP) during the four different periods of years 1997–2008 over S-SE Asia region. Color bar represents the magnitude of wind speed (m s^{-1})

90 % during the year. In addition to the seasonal reversal in winds as defined by the ITCZ, the large scale phenomena like El Niño have been known to greatly impact many parts of S-SE Asia region. The El Niño phenomenon causes abnormal warming of surface ocean waters in the eastern tropical Pacific Ocean and shifts the global weather patterns. Several countries in S-SE Asia are greatly affected by its impacts, but mostly notably is Indonesia. During the years 1997–98, the strong El Niño conditions impacted the normal life (Jayachandran 2005). Severe droughts over Indonesia were attributed mainly to the El Niño conditions. Other calamities like poor crop yields, forest fires, navigational hazards, smoke haze, etc. were related to the El Niño events.

In Indonesia, the total monthly rainfall ranges from 180 mm to 280 mm. Typically, the largest totals are observed during the October–January period. Across the SE Asia region, the monthly rainfall can reach 200 mm with an annual total of around 1,000 mm. In India, the large areas of western and central India receive more than 90 % of total annual rainfall during the summer monsoon period. The annual rainfall in India ranges between 200 mm and 300 mm with the highest rainfall recorded during July–August period.

2.2 Variation in biomass burning

The biomass loading in Asia is highest among the continental regions of the world (Streets et al. 2003b). In the S-SE Asia region, the average densities of forest, shrubland, grassland, and cropland were estimated to be about 23.5, 2.8, 0.6 and 0.15 kg m⁻² of dry matter, respectively (Chang and Song 2010). The peatland area in SE Asia accounts for about 69 % of all tropical peatlands (Rieley and Page 2005). On the other hand, the amount of biomass consumed varies greatly depending on vegetation type, biomass loading, burning efficiency, etc. These parameters show strong spatio-temporal variation causing large regional and seasonal variations in the emissions of trace gases and aerosols from BB sources. The forest fires in S-SE Asia are believed to be caused mainly by human activities. Burning of crop wastes, mostly rice straw/husk, is also important type of BB. The annual mean burned areas in S-SE Asia during 1997–2008 were estimated to be in the range of 4.9×10^4 – 13.3×10^4 km² with a mean of 8.9×10^4 km² (Chang and Song 2010; Giglio et al. 2010).

van der Werf et al. (2006, 2010) have reported the long-term trends of major BB related species for the different regions of the globe. The emission data from global BB sources show clear intra- and inter-annual variations. Although the satellite derived fire counts do not directly represent the actual burned area, they can primarily be used to identify the spatio-temporal variations of major BB activities. The fire count data detected by the ATSR instruments has been used in the present study. Typically, the major biomass sources are broadly categorized as deforestation, fuel-wood, forest and agricultural residues. The seasonal maps of fire count detected over S-SE Asia region during year 1997–2008 are shown in Fig. 3. As can be inferred from this figure, the BB in S-SE Asia shows strong regional, seasonal and inter-annual variations. From January to March, the BB related emissions are attributed mainly to the activities in Thailand and Myanmar. From March to May, the activities in India take the lead among the S-SE Asian countries. Overall, the fire count data in continental SE Asia are highest during March of every year (Pochanart et al. 2003). Later from April to June, BBs were mostly detected over northern India, Pakistan, Myanmar, Laos and northern Thailand. The wind over the fire impacted region is mostly from NE and NW directions during these periods. Therefore, the emitted species from these fires are transported southward and can significantly pollute the northern region of the Indian Ocean (Lelieveld et al. 2001; Sahu et al. 2006). Due to prevailing summer monsoon circulation during July–September, the spatial pattern of BB shows strong seasonal shift from northern to southern hemisphere. In this season, the fires in the forested and peatland areas of Indonesia make greatest contribution among the BB activities in S-SE Asia.

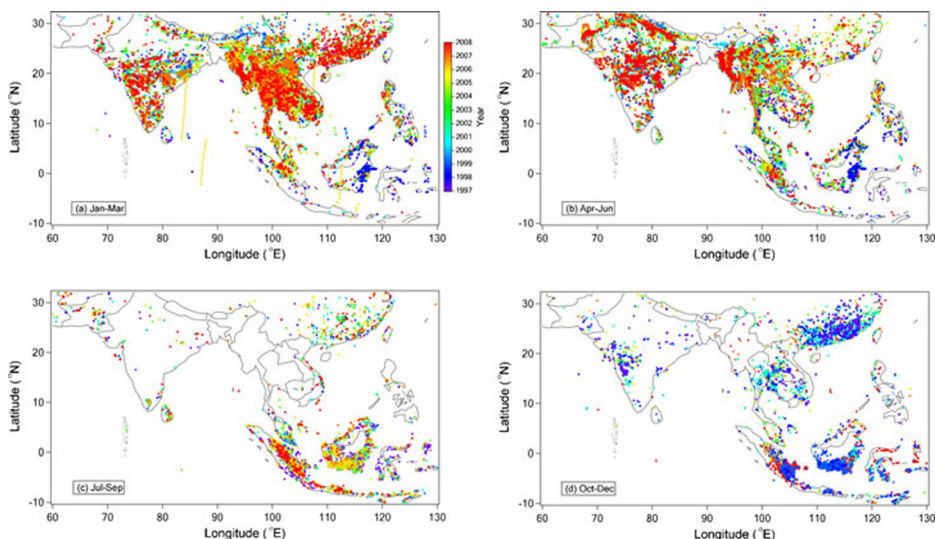


Fig. 3 Fire count maps (data taken from ATSR) for four different periods of years 1997–2008 over S-SE Asia region

Except for Malaysia and Indonesia, all other countries show major activities of BB during February to May when relatively dry weather prevails. On an average, the activities of BB were lowest during October to December period in S-SE Asia. The highest BB in Thailand was during the months of February and March. In India, the major BB occurs from February to May but the month of April experiences the highest activities. In Pakistan the major events are during the Month of May due to the extensive burning of crop residues. From mid of June to October, the major BB shifts to southeast part of S-SE Asia caused by the fires in Indonesian and Malaysian islands. Annually, the BB in India and Indonesia accounted for the most of the activities in S-SE Asia with the total fire counts values ranging between 1308–3796 and 918–29451, respectively during years 1997–2008.

There are several meteorological and climatic factors resulting in spatio-temporal variation of BB, however, some key parameters can be directly used to study the relations with BB. For example, we have used the trends of rainfall and fire count data over India during year 1997–2008 (Fig. 4a). Very clearly, the rainfall and fire count data show strong but just opposite phase seasonality. From February to March, the activities of BB were intense but rainfall was almost negligible. In contrast, during the rainy season (July to September) the activities of BB are negligible. The months of June and July represent the transition phase when both rainfall and biomass can co-exist to some extent. Owing to the vast geographical area of India, the events may not be co-located but require further analysis to assert this statement. On the other hand, we do not see any direct relation between the magnitudes of rainfall and BB. Details of the seasonal patterns of BB and atmospheric transport over Thailand have been presented in Sahu et al. (2011a).

The large scale phenomena like El Niño and La Niña have been known to greatly impact the S-SE Asia region. The coupled phenomena of ‘El Niño–Southern Oscillation’ (ENSO) result from the cyclic warming and cooling of central and eastern Pacific Ocean. In other words, the ENSO causes abnormal warming of surface ocean waters in the eastern tropical Pacific Ocean and shifts global weather patterns. The ENSO is parameterized as the multivariate ENSO Index (MEI). The MEI is computed based on 6 different variables viz., sea level pressure, wind components, sea surface temperatures (SST), air temperatures, and total cloudiness fraction of the sky. The extreme weather events like flood, drought typhoon, etc. in many

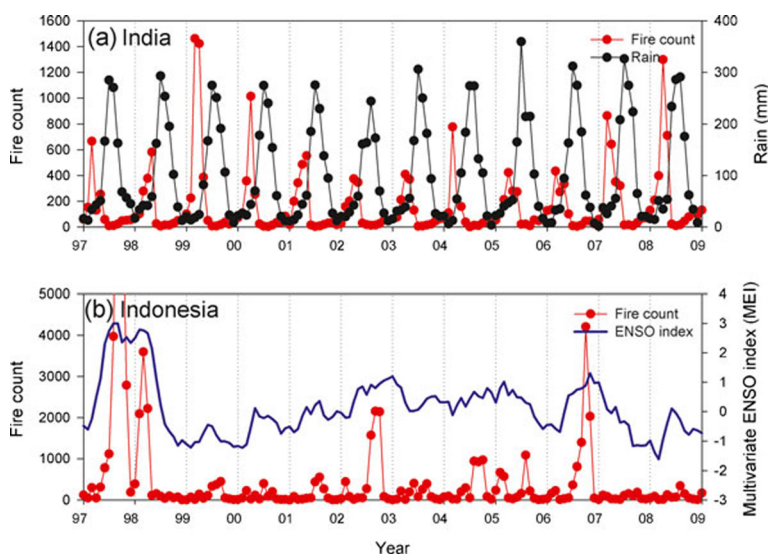


Fig. 4 a The long-term trends of monthly fire count and total rainfall data over India during the period of 1997–2008, b long-term trends of monthly fire count detected over Indonesia and the multivariate ENSO index (MEI) during the period of years 1997–2008

regions of the world were related to ENSO. The time series plots of monthly fire count over Indonesia and MEI data for 1997–2008 are shown in Fig. 4b. In this study we have taken the MEI data from NOAA (<http://www.esrl.noaa.gov/psd/data/correlation/mei.data>). The major BB events during 1997, 1998, 2002, 2006 and 2009 in the Indonesian islands coincided with the higher values of MEI suggesting the role of ENSO in extensive forest fires. The most prominent correlation between the fire count and MEI data can be noticed for the period of 1997–1998. As shown in Fig. 4b, the forest fires during 1997–1998 were the most extreme, the ATSR fire count exceeded 20000 during September and October 1997. The forest fires were wide spread across many Indonesian islands (Mori 2000). During the years 1997–1998, the ENSO condition impacted the normal life. Severe droughts over Indonesia have been attributed mainly to El Niño conditions. Other calamities like poorer crop yields, forest fires, navigational hazards, smoke haze, etc. were related to ENSO. Developing nations particularly those bordering the Pacific Ocean are the most impacted due to the ENSO events, but most notable in Indonesia.

The amount of carbon ($400 \text{ Tg C month}^{-1}$) emitted in 1997 from the fire in Indonesian fire was estimated to be higher by 4–6 times than a normal year (van der Werf et al. 2006). Levine (2000) have reported the total emissions of about 191 Tg C, 32.8 Tg C and 0.97 Tg N of CO_2 , CO and NO_x , respectively due to 1997 fires in Sumatra and Kalimantan islands. The Measurements of Ozone by Airbus In service airCRAFT (MOZAIC) data show enhancement in the tropospheric O_3 over the peninsular region of India caused by extensive forest fires in Indonesia during September–October 1997 (Sahu et al. 2011b).

3 Emissions of gaseous species from biomass burning

The global BB emission is a significant source of various primary aerosols and trace gases in the atmosphere. Many primary species emitted from BB sources are the precursors of O_3 and secondary organic aerosol (SOA). Halogenated hydrocarbons, especially CH_3Cl and CH_3Br ,

emitted from major BB sources can reach the stratosphere and take part in the O_3 depletion cycles. The elevated concentrations of gaseous and particulate species in BB plumes deteriorate the air quality and can adversely impact human health and crop yields. The mixing ratio of CH_3CN has been widely used as a tracer to identify the BB plume if anthropogenic sources co-exist (de Gouw et al. 2003).

In the S-SE Asia region, the BB sources emit large amounts of trace gases to the atmosphere (Elvidge and Baugh 1996). The global chemical transport models require emission estimates of trace gases and aerosols from the biomass fires. As reported in several studies, the global emissions of various species from BB sources vary substantially from year to year (van der Werf et al. 2006 and references therein). The emission estimates on the regional and global scales are more uncertain because considering each individual species in each grid point of a global/regional map requires detailed information of BB. Specifically, the uncertainties in the estimates of emissions are highest in deforested and peat fires regions (van der Werf et al. 2006).

In this study, we have used the monthly averaged BB emissions for the years 1997–2008 taken from the GFED3 (van der Werf et al. 2006, 2010). The average emission fluxes of CO and NO_x (in the unit of molecules $cm^{-2} s^{-1}$) from BB sources over S-SE Asia for four different periods of years 1997–2008 are shown in Figs. 5 and 6, respectively. During January–March, the emissions from central region of India and northern hemispheric parts of SE Asia (Myanmar and Thailand) made major contribution. In this period, the highest emission rates of CO and NO_x were of the order of 10^{13} molecules $cm^{-2} s^{-1}$ and 10^{11} molecules $cm^{-2} s^{-1}$, respectively. During April–June period, the emission regions shifted northward over S-SE Asia. In addition to contributions from central India, Myanmar, northern Thailand Laos, etc. the emissions in Indo Gangetic Plain (IGP), Pakistan and Nepal were also prominent. During July–September the emission activities shift to the southern hemispheric parts of S-SE Asia. The

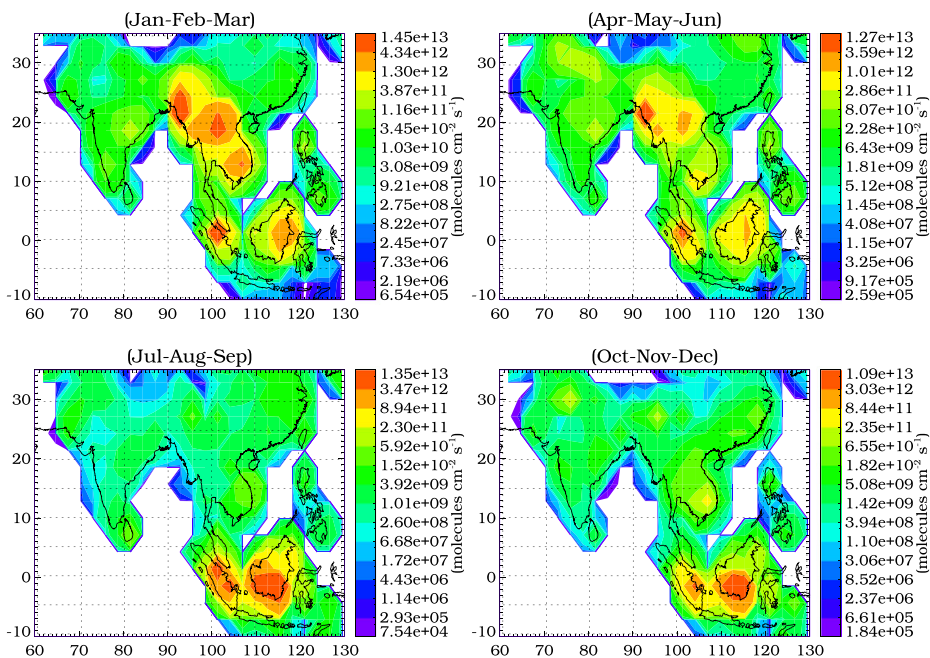


Fig. 5 The climatological mean emission fluxes of CO (in the unit of molecules $cm^{-2} s^{-1}$) from BB sources during four different periods of years 1997–2008 over S-SE Asia

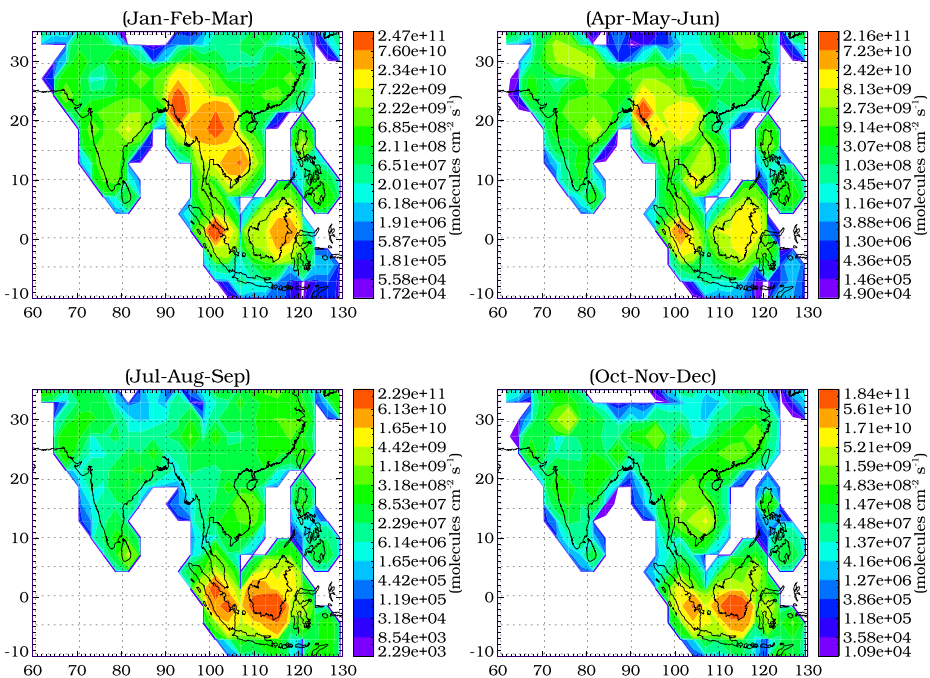


Fig. 6 The climatological mean emission fluxes of NO_x (in the unit of molecules cm⁻² s⁻¹) from BB sources during four different periods of years 1997–2008 over S-SE Asia

forest fires in the Indonesian and Malaysian islands account for major emissions of CO and NO_x from S-SE Asia. In Indonesia, the fires in Kalimantan and Sumatra islands contributed the largest emissions of CO and NO_x. The BB emissions of CO and NO_x were estimated to be lowest during October–December period. Overall, though emission rates of CO are significantly higher compared to NO_x but their spatio-temporal distributions show similar pattern.

The country wise annual emissions of CO and NO_x from the year 1997 to 2008 are shown in Fig. 7. Emissions of both the species from major BB sources in Indonesia make highest contribution among the countries in S-SE Asia region. The BB activities in India, Myanmar, Thailand and Laos also make significant contribution to the annual budgets of CO and NO_x in S-SE Asia. Importantly, the estimates for the different countries show large inter-annual variation. Similar features were noticed in the annual data of NMHCs (not shown in the plot). The contribution in annual emissions of CO, NO_x and NMHCs from the northern hemisphere (NH-SSEA) and southern hemisphere (SH-SSEA) regions of S-SE Asia are shown in Fig. 8. The emissions of trace gases in both hemisphere of S-SE Asia are almost comparable for the normal years. The annual emission estimates for SH-SSEA region during the El Niño years 1997, 2002 and 2006 exceed considerably to those for the normal years. On the other hand, the annual emission estimates for NH-SSEA region during the La Niña years 1999, 2004 and 2007 exceed considerably to those for the normal years.

The total emission estimates for entire S-SE Asia region show good correspondence with the ATSR fire count data. During years 1997–2008, the GFED 3 annual means of CO and NO_x in S-SE Asia region varied in the ranges of 150–350 Tg CO yr⁻¹ and 367–4955 Gg NO_x yr⁻¹, respectively. The annual emission of NMHCs was in the range of 1.0–14.9 Tg NMHCs yr⁻¹ during years 1997–2008. The highest and lowest emissions of all the trace gases were estimated for the years 1997 and 2000, respectively. Streets et al. (2003b) have reported the emission

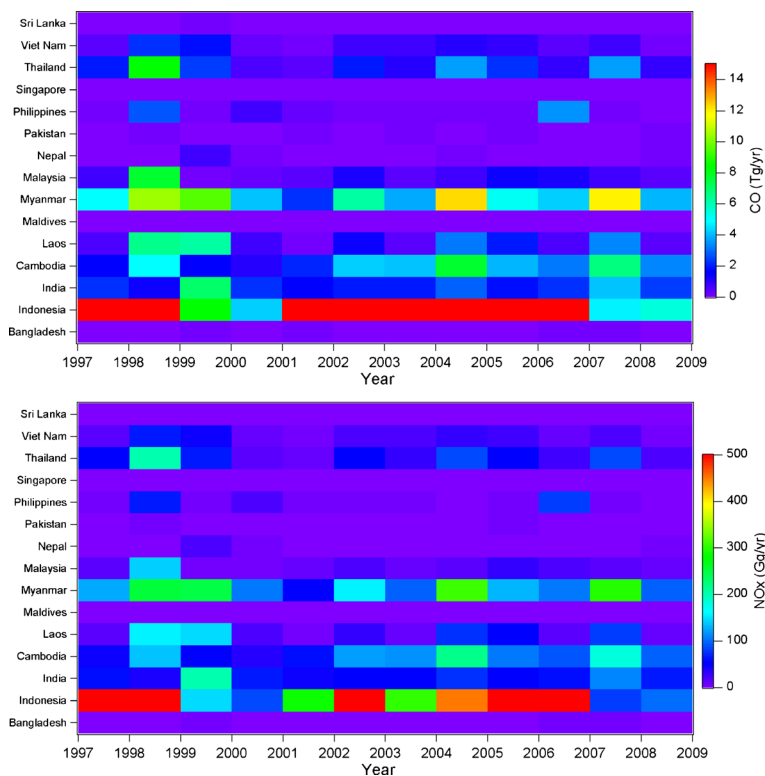


Fig. 7 The annual emission estimates of CO and NO_x from major biomass burning sources in different countries of S-SE Asia during years 1997–2008

inventories of various trace gases and aerosols emitted from biomass burning sources in Asia. In this study, for a period of years 1999–2000, the annual emissions of CO and NO_x were estimated to be about 48 Tg CO yr⁻¹ and 1764 Gg NO_x yr⁻¹ from biomass burning sources in S-SE Asia region.

The emission and fire data show bi-modal seasonality embedded in the large inter annual variations. The primary mode from February to May and secondary mode from July to September can be clearly seen. The primary mode is due to the BB in the northern hemispheric parts of S-SE Asia. On the other hand secondary mode is attributed to the forest fires in the southern hemisphere parts of S-SE Asia. The fire counts in S-SE Asia during October–December account for less than 2 % of total global fire count during this period of a year. The highest emissions in all the species fall in the months of March and April. The prediction of estimates from BB requires detailed understanding of parameters controlling the BB emission. This is a key to evaluate the future changes in climate and environment as the simulations from chemical and climate models are very sensitive to emission estimates.

4 MOZART simulations of CO and NO_x

The MOZART is a three dimensional (3-D) global chemical transport model of atmospheric composition to study the chemical and transport processes in the troposphere. In the present

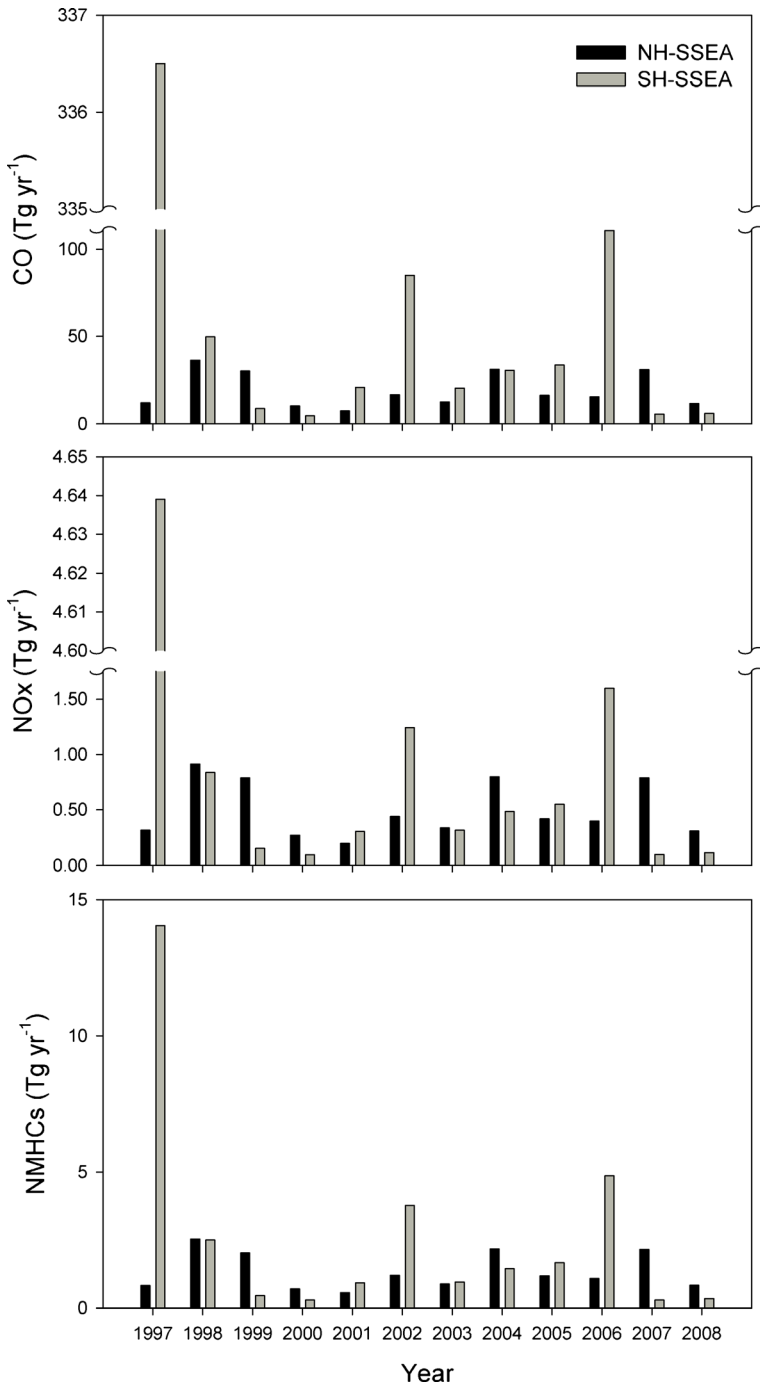


Fig. 8 The annual emission estimates of CO, NO_x and NMHCs from major biomass burning sources in northern hemisphere (NH-SSEA) and southern hemisphere (SH-SSEA) regions of S-SE Asia during years 1997–2008

study, we have used the Global Forecast System (GFS) meteorological fields from the National Centers for Environmental Prediction (NCEP). The inventories for major anthropogenic sources are taken from the POET (Granier et al. 2004). The POET data gridded at $1^\circ \times 1^\circ$ includes the emissions from anthropogenic activities, BB (fire), and natural sources. The representation of emissions for fire and natural sources is monthly data, while anthropogenic emissions are on annual basis. Anthropogenic emission data have been updated over Asia using the REAS data developed (Ohara et al. 2007). The monthly average BB emissions are taken from the GFED3. MOZART-4 simulates at a resolution of $2.8^\circ \times 2.8^\circ$ with 28 sigma pressure levels from the surface to ~ 2 mb pressure level. We run the MOZART-4 model on the 3 Terraflop HPC Linux cluster with 20 nodes in our institute (Physical Research Laboratory).

We have simulated the column densities of CO and NO_x over S-SE Asia for the years 2005 and 2006. It is important to mention that the year 2005 was a normal year but year 2006 was an El Niño year. Analyzed for the four different periods, the total column number densities (molecules cm^{-2}) of CO and NO_x for the year 2005 are shown in Figs. 9 and 10, respectively. While seasonal column loadings of CO and NO_x for year 2006 are presented in Figs. 11 and 12, respectively. Overall, the column densities of CO and NO_x over S-SE Asia show highest loading during January–March period for both the years. During January–March and Apr–

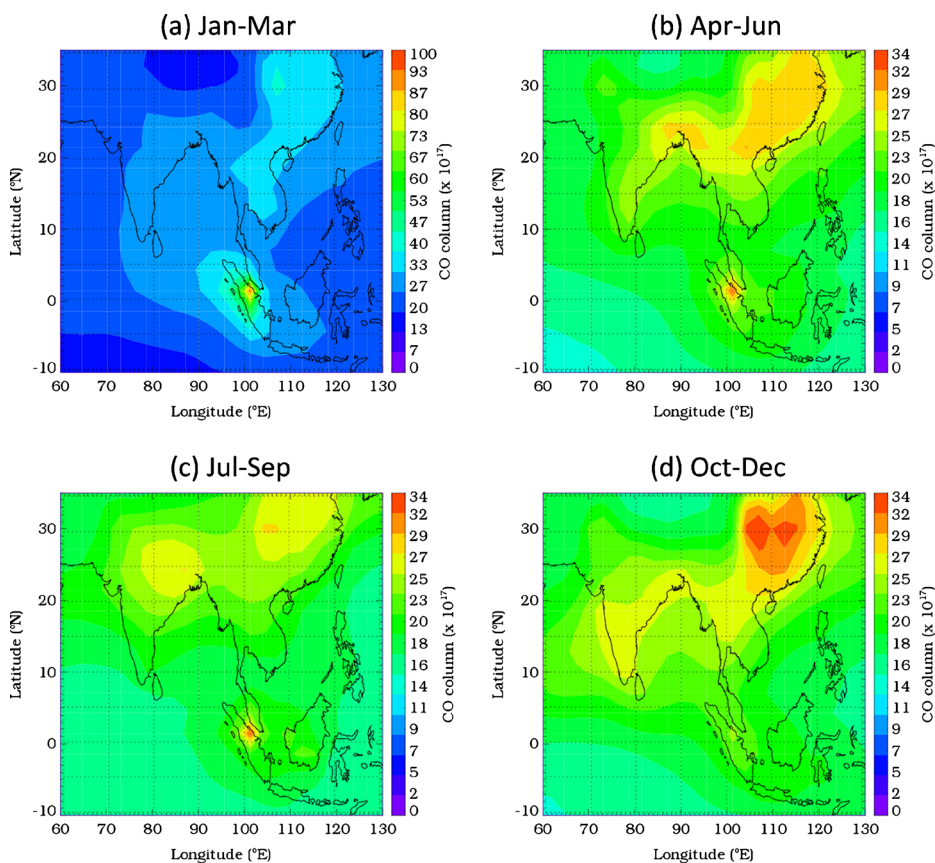


Fig. 9 The seasonal column density (molecules cm^{-2}) of CO over S-SE Asia during year 2005

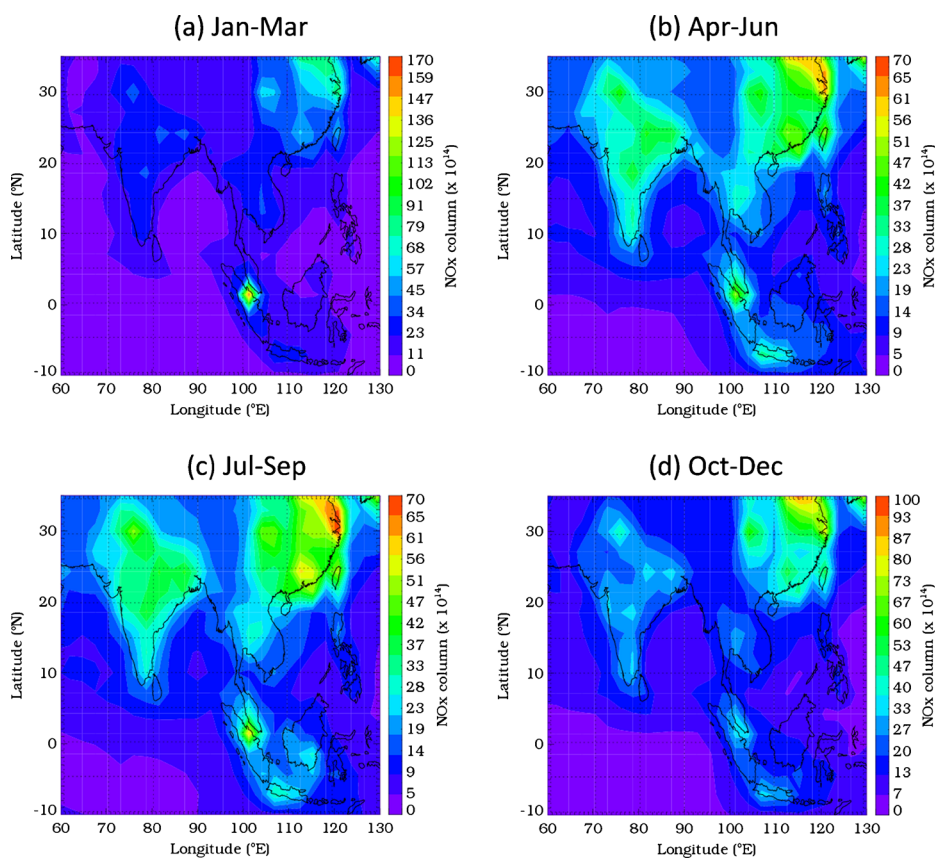


Fig. 10 The seasonal column density (molecules cm^{-2}) of NO_x over S-SE Asia during year 2005

June periods, the column densities over the northern hemisphere parts of SE Asia were higher than rest of S-SE Asia. The enhanced column number densities of both CO and NO_x over the Indonesia and Malaysia were simulated during July–December periods. In this period, the enhancements in CO and NO_x in the southern hemisphere parts of S-SE Asia during year 2006 were significantly higher than those during the same period of year 2005. For example, during July–December period, the MOZART-4 simulations of CO in several grids over Indonesia indicate values exceeding the levels of 35×10^{17} molecules cm^{-2} and 60×10^{17} molecules cm^{-2} for the years 2005 and 2006, respectively. Similarly, the model simulations of NO_x exceeded the levels of 60×10^{14} molecules cm^{-2} and 90×10^{14} molecules cm^{-2} for years 2005 and 2006, respectively. These enhancements in CO and NO_x loadings during 2006 can be attributed mainly to the El Niño-driven extensive forest fires in Indonesia and Malaysia. The GFED emissions of CO from Indonesia were only 5.8 Tg in September to December 2005 compared with 67.3 Tg for the same period in 2006 (Nassar et al. 2009). On the other hand, except near the large BB emission sources, the features of column loading of CO and NO_x do not visibly match with the BB maps of these species. There can be several reasons for this apparent mismatch as the simulations trace gases also include the contributions of other processes like anthropogenic emissions and global transport. However, combined analysis of wind streamline and emission map suggests significant loadings of both CO and NO_x in the downwind regions

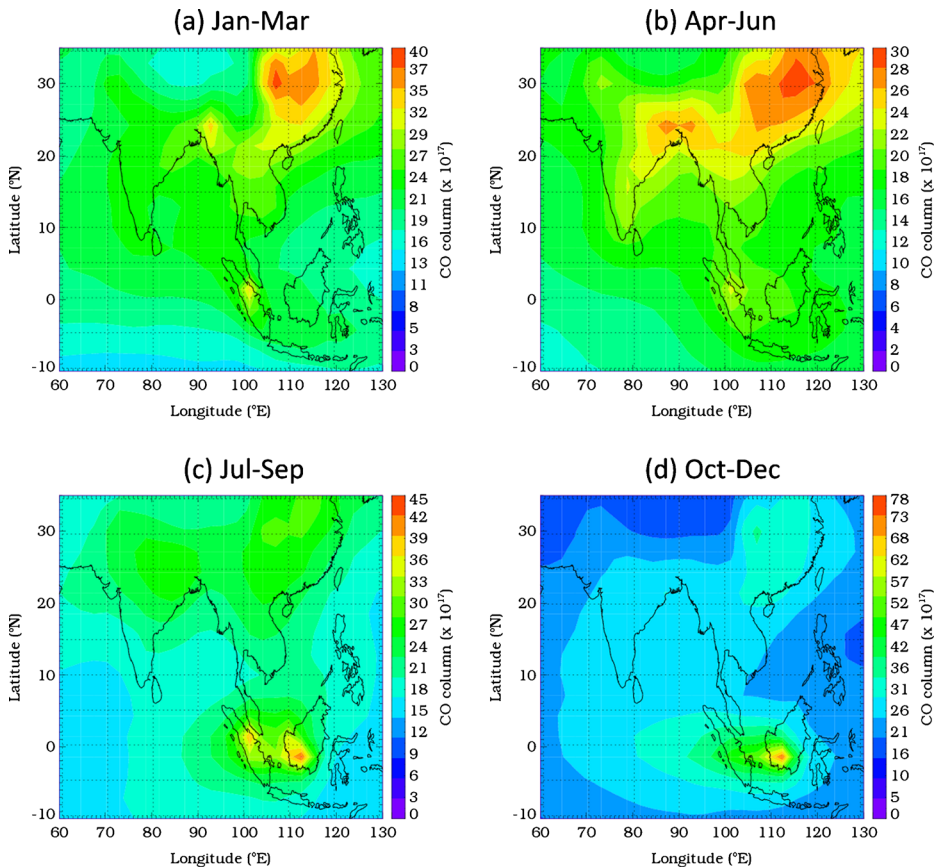


Fig. 11 The seasonal column density (molecules cm^{-2}) of CO over S-SE Asia during year 2006

of BB sources. But for certain prominent features of CO and NO_x densities can be directly mapped to the spatio-temporal variations in the BB emissions in S-SE Asia. Recently several studies have reported the detailed simulation studies of CO, NO_x and other trace gases using the different models over S-SE Asia (e.g., Nassar et al. 2009; Zhang et al. 2011) and further discussion in this paper will be beyond our objective. Since models mostly rely on several parameters which carry large uncertainties, the field observations of trace gases with good spatial and temporal resolutions over this region will greatly improve both emission estimates and atmospheric simulation.

5 Conclusions

The S-SE Asia region is geographically vast and tropical climate prevails during most of the year. The pattern of long-range transport varies with the season over different parts of S-SE Asia controlled mainly by the movement of the ITCZ. We have presented the long-term spatio-temporal variation in BB sources using ATSR fire count data for years 1997–2008 over this region. The distinct seasonality in the BB activities can be related to the seasonal variations in agricultural practices and prevailing meteorology in different countries in S-SE Asia. In India,

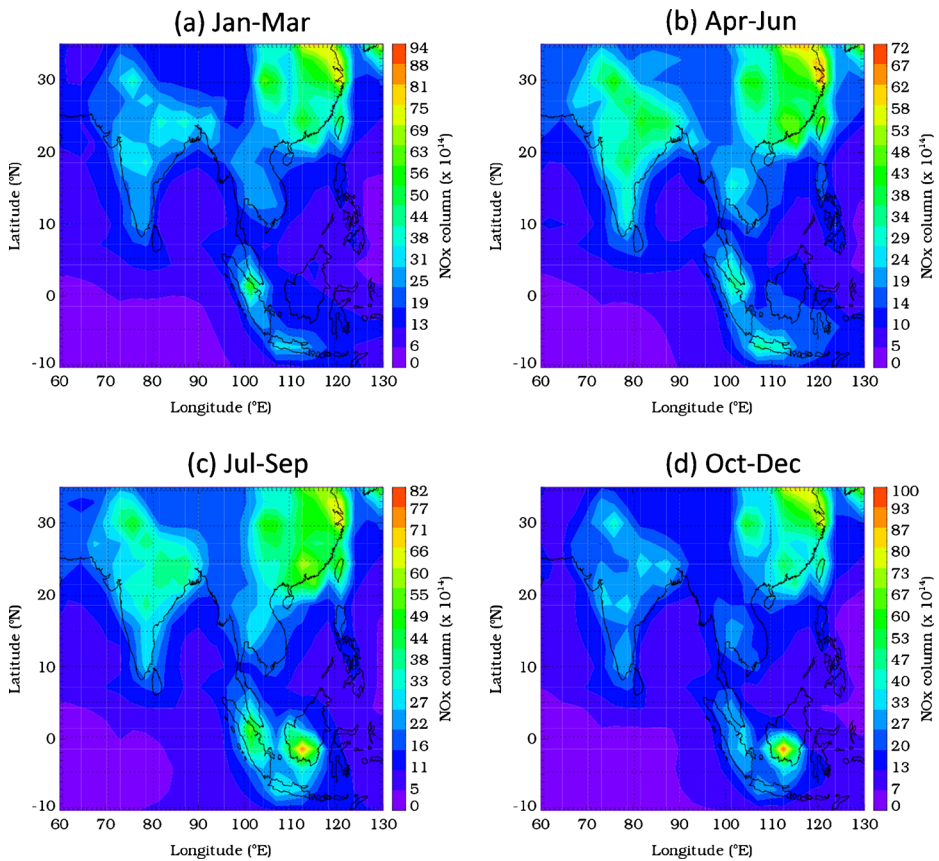


Fig. 12 The seasonal column density (molecules cm^{-2}) of NO_x over S-SE Asia during year 2006

the BB and rainfall show strong seasonality but they were just opposite in phase. The annual magnitude and inter annual variations in the forest fires over Indonesian and Malaysian island were influenced by the large scale phenomena like ENSO. The BB activities were lowest during the summer monsoon and highest during the winter monsoon in the northern hemisphere parts. The major activities shift to the southern hemisphere parts of the S-SE Asia during July–September. To study the inter-annual variability in the emissions of CO, NO_x and NMHCs from BB we have used the GFED3 inventory data for the years 1997–2008. Consistent with the seasonality in ATSR data the emission estimates of gaseous species show bi-modal seasonality. During the primary mode, from February to May, the highest emission rates of CO and NO_x were of the order of 10^{13} molecules $\text{cm}^{-2} \text{s}^{-1}$ and molecules $10^{11} \text{cm}^{-2} \text{s}^{-1}$, respectively. The annual emission estimates of all the trace gases show large inter-annual variations during 1997–2008; however, the highest and lowest emissions were estimated for the years 1997 and 2000, respectively. The annual emission estimates of trace gases in southern hemisphere region during the El Niño years exceed to those for the normal years. While the emission estimates for northern hemisphere region during the La Niña years exceed considerably to those for the normal years. The MOZART-4 simulations of CO and NO_x capture the extensive BB episodes in S-SE Asia. The atmospheric column densities of CO and NO_x during Jul–Sep and Oct–Dec of year 2006 over Indonesia show significant

enhancements compared those during the same period of year 2005. Our results clearly suggest the impact of large scale impacts of El Niño in the emissions of CO and NO_x from BB sources.

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