A large impact of tropical biomass burning on CO and CO_2 in the upper troposphere

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Abstract A large interannual variation of biomass burning emissions from Southeast Asia is associated with the ENSO events. During 1997/98 and 1994 El Niño years, uncontrolled wildfires of tropical rainforests and peat lands in Indonesia were enlarged due to a long drought. Enhanced CO injection into the upper troposphere from the intense Indonesian fires was clearly observed in the 8-year measurements from a regular flask sampling over the western Pacific using a JAL airliner between Australia and Japan. This airliner observation also revealed that upper tropospheric CO_2 cycle largely changed during the 1997 El Niño year due partly to the biomass burning emissions. Widespread pollution from the biomass burnings in Southeast Asia was simulated using a CO tracer driven by a 3D global chemical transport model. This simulation indicates that tropical deep convections connected to rapid advection by the subtropical jet play a significant role in dispersing biomass-burning emissions from Southeast Asia on a global scale.

Keywords: biomass burning, upper troposphere, Indonesian fires, aircraft observation, carbon cycle.

1 Biomass burning emissions in Southeast Asia

Biomass burning in the tropics is estimated as a major source for the global carbon budgets of many trace gases such as carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), and other reduced gases in the troposphere[1]. Both the CO_2 and CH_4 directly influence the global warming on the earth, while changes in oxidizing capacity relating to CO variability could perturb the growth rates of many greenhouse gases. Thus, their atmospheric accumulations due to an increase of biomass burning emission will very likely cause future global climate changes. There are three unique features for biomass burning[2,3] when we make comparison between the trace gas emissions from fossil fuel combustion. First, biomass burning occurs mainly in the tropical continents such as Southeast Asia, southern Africa, South America and northern Australia. Second, biomass burning emissions in the Southern Hemisphere are concentrated during the tropical dry season of August, September and October. Third, biomass burning releases various reduced trace gases and particles due to relatively long smoldering combustion. These features imply that biomass burning has a different impact on the carbon cycle in the tropospheric environment from other anthropogenic and natural sources.

Biomass-burning carbon released from Asia is estimated at about 30% of total emission from the tropical biomass burnings around the world[2]. The most characteristic feature in Southeast Asia is a large interannual variation of trace gas emission from biomass burning that is closely connected to the El Niño/Southern Oscillation (ENSO) events. The ENSO events strongly influence precipitation and surface air temperature patterns in this tropical western Pacific, because of the eastward shift of convective clouds toward the central Pacific during El Niño years[4]. In particular, a strong El Niño event in 1997—1998 induced the largest change in tropical climate system[5,6]. As a result of this climate change, vegetation in Southeast Asia and northern Australia was exposed to severe dry condition with much less precipitation and became more susceptible to human-caused fires from the land clearing activities for plantation before the rainy season. Thus, the increase of biomass burning in Southeast Asia significantly depends on the rainfall variation associated with the ENSO events.

The burnt area in Kalimantan and Sumatra of Indonesia increased remarkably interannually with the long drought in recent El Niño years of 1994 and 1997/98[7]. A satellite observation also showed that western New Guinea was one of the major source areas for biomass burning emission enhanced by the ENSO-induced drought[8]. In the 1994 El Niño year, intense Indonesian fire produced a dense layer of smoke that reportedly covered wide regions over Singapore, Malaysia and Indonesia between August and October[9,10]. The stronger El Niño event in 1997/98 also caused the worst episode of widespread pollution from smoke haze around Southeast Asia[11].

Since a large amount of CO is produced mainly during the smoldering stage of a burn, trace gases form biomass burning generally reveal a unique chemical composition with lower CH_4/CO and higher CO/CO_2 ratios than the emission ratios of fossil fuel combustion. The emission ratios for tropical biomass burnings have been investigated by aircraft campaigns, ground-based observations, and laboratory experiments, but there are only limited field data for Southeast Asia compared with other tropical regions such as Brazil, Africa and northern Australia[12]. Lower CH_4/CO and higher CO/CO_2 ratios than the averaged emission ratios were found in air masses derived from Indonesian fires by an aircraft campaign over Singapore in October of 1997[12]. It is suggested that more CO generation for longer smoldering combustion occurred in Southeast Asia than in other tropics.

During October in 1997, another aircraft observation showed a marked difference in the trace gas composition between a thick smoke haze in Indonesia and bush fire plumes in tropical Australia[13,14]. This difference may reflect relatively low combustion efficiency of uncontrolled wildfires in Indonesia of tropical rainforest as well as peat land. Satellite surveys of burnt area indicated that peat land fires in Kalimantan and Sumatra were mainly responsible for trace gas emissions in 1997[15,16]. Aerosol properties of Indonesian fires also showed a growth of particles due to SO_2 emitted from combustion of peat bog[17,18]. All of these observations are evidence of substantial and distinctive trace gas and particle emissions from Southeast Asian fires during the 1997 El Niño year.

2 Biomass-burning CO observed in the upper troposphere

Trace gas emission from tropical biomass burning could be expected to affect not only the boundary layer but also the middle and upper troposphere, since a more general mechanism was proposed to explain the transport of smoke to high altitudes by active convections in the tropics[1]. In the middle and upper troposphere over Southeast Asia, ozone enhancement due to Indonesian fires was found during the El Niño years of 1994 and 1997/98 by long-term ozonesonde observations over Indonesia[19] and Malaysia[20]. It is pointed out that not only photochemical productions but also large-scale circulation process associated with the tropical convection pattern play an important role in the ozone enhancement in 1997[21—23]. In addition, the measurement of Air Pollution from Satellites (MAPS) observation clearly indicated that widespread biomass-burning CO from Southeast Asia was enhanced in the free troposphere over the tropical Indian Ocean in the El Niño year of 1994[24].

The ENSO-cycle variability of upper tropospheric carbon cycle over the western Pacific was well defined by the long-term observation program using a passenger aircraft of Japan Airlines (JAL) between Australia and Japan[25—27]. An 8-year record of CO from the JAL airliner observation is presented as useful indicators for measuring the spatial and temporal variations of biomass-burning carbon supplied into the upper troposphere (fig. 1(a)). In 1997, extremely rich CO around October—November widely appeared throughout the Southern Hemisphere. A maximum CO level of more than 300 ppb was observed in the southern subtropics between 15S and 25S on October 28 in 1997. This CO level was the highest value during the past 8 years over this western Pacific. A similar seasonal increase with southern spring peak in the Southern Hemisphere was found in 1994, although the increased level in this year was lower than that in 1997. In the Northern Hemisphere, an increased CO peak was also observed during the same season in both 1994 and 1997. These CO enhancements indicate a strong seasonality of CO injection from biomass burnings in the tropics during dry season. During this season, the trace gas composition in the upper troposphere showed a high enrichment of CO relative to CH_4 due to a large amount of CO production characteristic of biomass-burning emission. The other interesting variation is a clear increase of CO around March in 1998 in the Northern Hemisphere coupled with a small peak in the Southern Hemisphere south of 15S. This enhancement during early 1998 also showed an influence of biomass burning input because of an enrichment of CO relative to CH_4.

The CO spring peak in the Southern Hemisphere clearly showed an interannual variation that was closely related to the ENSO events described by the Southern Oscillation Index (SOI) (fig. 1(b)). The SOI in 1997 showed large negative anomalies, indicating the strongest El Niño event during the 1990s, when the largest CO peak appeared. Elevated CO peak in 1994 also corresponded to the El Niño year. In contrast, the SOI in 1996 and after 1999 showed positive anomalies as a weak La Niña year when the CO peak was largely reduced. The other years of both 1995 and 1998 showed a transitional situation from El Niño to La Niña events and the CO enhancement was intermediate between both events. These observational evidence indicated that such ENSO-cycle variability of CO in the upper troposphere was driven by the yearly change of biomass burning emission in Southeast Asia. It is noted that the CO in the Northern Hemisphere showed a relatively complicated interannual variation, because larger anthropogenic sources from urban/industrial emissions partly masked the ENSO-cycle variation of the biomass burning input.

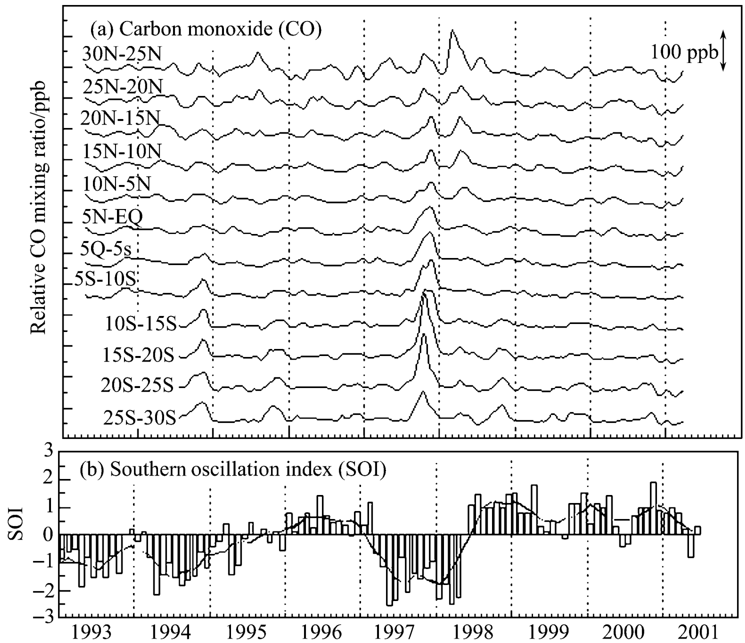

Fig. 1. (a) Time variations of relative CO mixing ratios for 12 latitudinal bands from 30N to 30S at about 10 km over the western Pacific during April 1993 to March 2001. (b) To compare with the CO data, the monthly mean of the Southern Oscillation Index (SOI) is shown with the 5-month running mean (solid curve).

3 CO_2 interannual variation observed in the upper troposphere

In the JAL airliner observation, the 8-years record of CO_2 was also obtained to clarify spatial and temporal variations in the upper troposphere (fig. 2(a)). The CO_2 in the Northern Hemisphere shows a clear seasonal cycle that is caused mainly by the propagation of the lower tropospheric variation due to the photosynthesis and soil respiration. This seasonal cycle rapidly decayed toward the equator with a delay of phase. In the Southern Hemisphere, the seasonal cycle was largely reduced, and its pattern showed a relatively complicated variation with doubly increased peaks around June—July and November—December. During the El Niño years of 1994 and 1997, the southern spring peak from November to December was enhanced in the latitudes between 5S and 20S in the Southern Hemisphere. This southern spring peak in 1997 surpassed the other peak in the southern winter, although the southern winter peak was predominant during the non-El Niño years. These results suggest that a yearly change in the pattern of the CO_2 seasonal cycle is associated with the ENSO events.

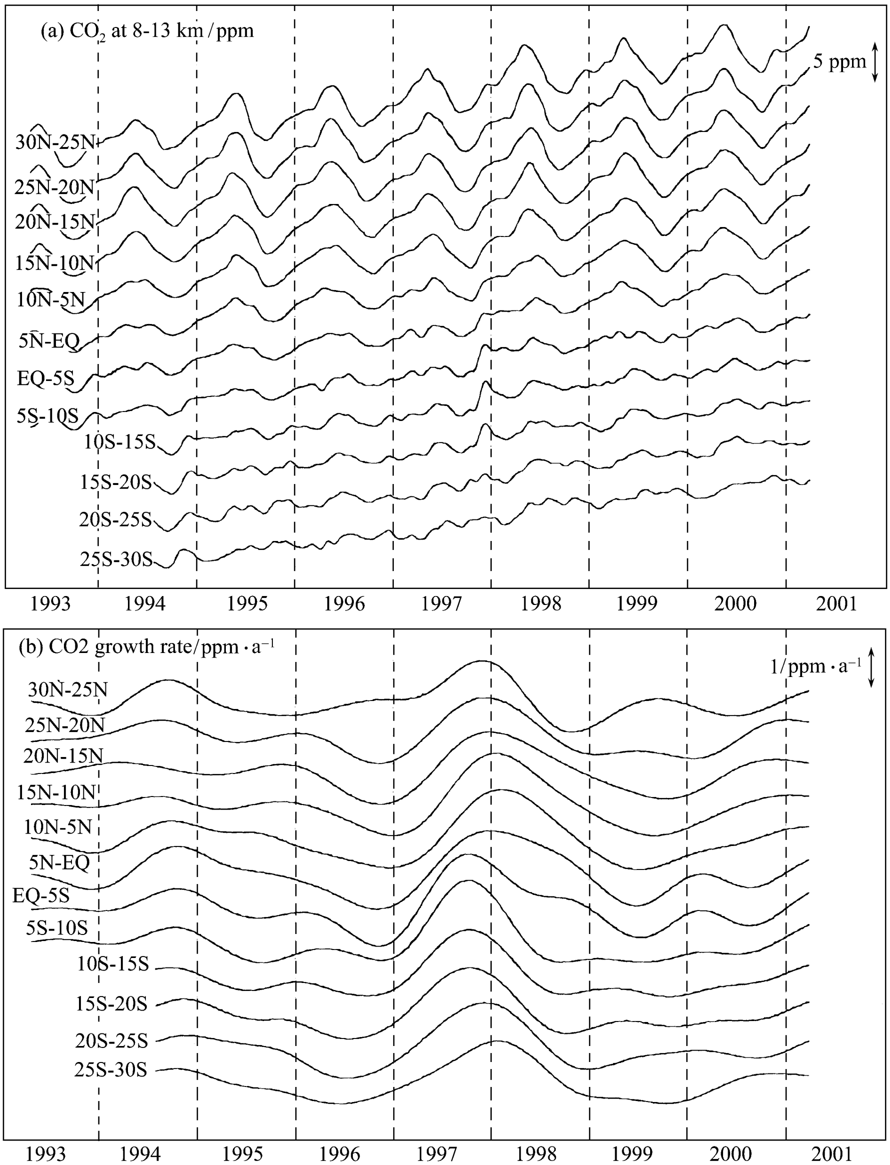

Fig. 2. Time variations of relative CO_2 mixing ratios (a) and their growth rates (b) for 12 latitudinal bands from 30N to 30S at about 10 km over the western Pacific during April 1993 to March 2001.

The most significant year-to-year change was found in an anomalous increase in the CO_2 growth rate of more than 3 ppm/a during 1997/98 that was associated with the strong 1997/98 El Niño event (fig.2(b))[28]. The growth rate in the El Niño year of 1994 also showed a larger growth rate of about 2 ppm/a. In contrast, the lowest growth rate around 1 ppm/a was found in the weak La Niña years of 1996 and 1999. Such an interannual variation pattern was similar in all latitudinal bands, although the growth rate maximum first appeared in the southern tropical regions between 5S and 20S in August—September in 1997. The lower tropospheric CO_2 also showed a similar ENSO-cycle variation of the growth rate in the western North Pacific regions[29]. However, it is of interest that the growth rate peak in the lower troposphere during the early 1998 was a couple of months later than that in the upper troposphere. The other interannual change relating to the ENSO event was found in a latitudinal distribution pattern of the annual mean CO_2. The CO_2 annual mean in the El Niño year of 1997 shows a relatively flat north-to-south gradient, while a different distribution with a clear northern tropical maximum around 10N was found in non-El Niño years.

Biomass burning enhancement is one of the possible causes for the interannual variations of upper tropospheric CO_2 associated with the ENSO event. At the same time, the ENSO events also induce other yearly changes of air-sea CO_2 fluxes especially in the equatorial Pacific, CO_2 uptake by terrestrial ecosystem, and global air circulation with upward transport[30]. In order to evaluate biomass burning effect, 3D models for atmospheric CO_2 were used in recent studies focusing on emissions from southern Africa and South America[31,32]. Without detailed model calculation, the biomass-burning influence from Southeast Asia was evaluated on the basis of the observed CO data in fig. 1(a) and their corresponding CO_2 from emission ratio of CO/CO_2 [28]. The increase of annual mean CO_2 due to the influence of biomass burning in 1997 was estimated to be about 0.3—0.4 ppm in the Southern Hemisphere and about 0.1 ppm in the Northern Hemisphere. These increases showed that the direct injection of CO_2 from biomass burning partly caused anomalies of the north-to-south gradient as well as the phase difference in the growth rate peak between the upper and lower tropospheres during the 1997/98 ENSO event. These anomalies could also be associated with circulation and transport being modified by the ENSO event. Thus, the yearly change in CO_2 distributions in the upper troposphere would appear to be largely influenced by a combination of ENSO effects such as biomass burning input and altered circulation.

4 Dispersion of biomass burning emissions simulated by a 3-D model

In order to clarify widespread products of biomass burning emission from Southeast Asia, an experimental simulation was preformed using a three-dimensional global chemical transport model (CTM) developed by National Institute of Advanced Industrial Science and Technology (AIST, former NIRE) in Japan[33]. The NIRE-CTM-96 was driven by the assimilated meteorological data in 1997 provided from European Centre for Medium-Range Weather Forecasts[34]. In this model, CO tracer was continuously released from southern part of Kalimantan in Indonesia at a constant emission rate of 500 TgC/a from January to October in 1997. The CO tracer released into the atmosphere was destroyed with an atmospheric lifetime of about 60 days during the transport, because the oxidative reaction with OH is a dominant removal process in the troposphere. It is noted that our emission scenario in the model would overestimate the upper tropospheric CO source, because intense burning over Indonesia was confined to the August–November 1997 period. Thus, this model experiment focused on qualitative evaluation of principal transport processes of Indonesian forest fire into the upper troposphere.

The model result showed that CO from Kalimantan forms a unique distribution pattern in the upper troposphere at 250 hPa on October 28, 1997 (fig. 3) when the highest CO level was observed by the JAL airliner observation. The flow of CO at 100°E on the equator west of Sumatra Island was divided into three branches, although no significant CO appeared just above the source site of southern Kalimantan. Two branches for outflow toward the Pacific Ocean was separated into the northern and southern subtropics. The southern branch passed over the northern Australia and stretched toward South America through the subtropical South Pacific along a path 20S—30S. The northern branch south of Japan extended eastward through the subtropical North Pacific along a path 20N—30N. In contrast, the third branch expanded extensively toward the African continent across the tropical Indian Ocean along the equator. This pattern with three branches of CO flow was identified as a typical distribution appearing in the upper troposphere during October in 1997. A similar distribution pattern was found at 250 hPa when we released CO tracer from Sumatra and western New Guinea in the same model.

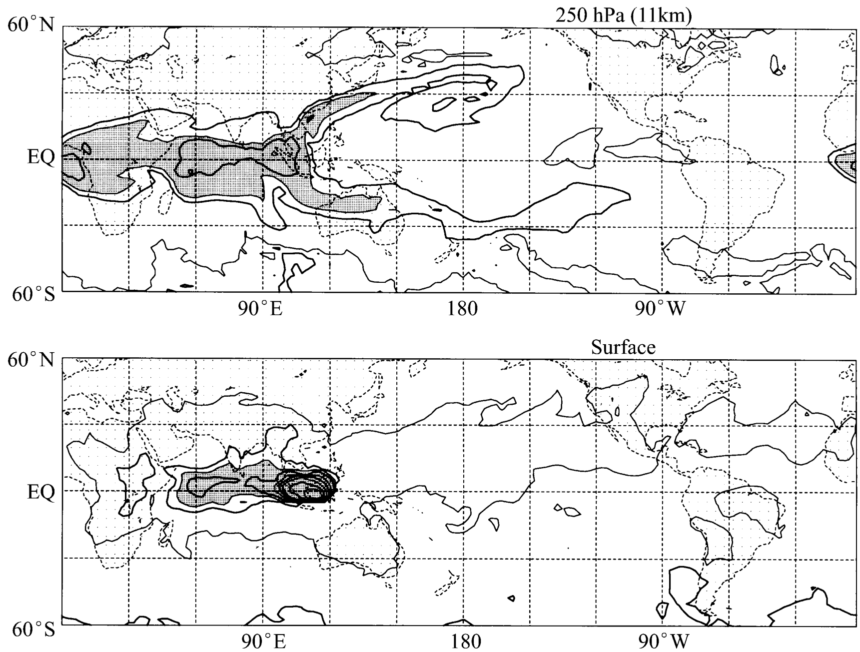

Fig. 3. Simulated CO distribution at 250 hPa (upper panel) and surface air (lower panel) on 06UTC on October 28, 1997 for emission site of southern Kalimantan of Indonesia. Counters are 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, 10000 ppb. Shaded areas indicate high CO up to 100 ppb.

The simulated CO distribution from the emissions of Southeast Asia regions was qualitatively similar to the observed CO over the western Pacific in 1997 shown in fig.1(a). The equatorial flow toward the African continent over the tropical Indian Ocean was found by the CARIBIC aircraft observation in November 1997[35]. In addition, the CO outflow through the subtropical

North Pacific from the Southeast Asia emissions in the model well coincided with an anomalous increase of CO in autumn 1997 observed at Mauna Loa in Hawaii[36]. Such a long-range transport to the northern subtropics near Hawaii was not simulated when CO tracer was released from other biomass-burning regions such as Amazon in Brazil and southern Africa at the same emission rate. Thus, the 3D model experiments strongly supported the view that biomass burning in Southeast Asia was mainly responsible for the large injection of CO into the upper troposphere over the western Pacific in 1997.

In the surface layer, CO released from Kalimantan was gradually moving toward the tropical Indian Ocean along the equator with easterly wind in the model (fig. 3). It is consistent with a similar horizontal advection of biomass burning products such as ozone and aerosols revealed by satellite data analysis[37,38]. It is of interest that the distribution area of higher CO in the surface air was much limited when we compare it with widespread CO in the upper troposphere at 250 hPa. This difference indicated that some plumes of biomass-burning CO from the Indonesian fires were rapidly transported upward due to concentrated convections around 100°E west of Sumatra in Indonesia. The CO plumes convectively lofted were separated into northward and southward outflows at the upper layer, and then were incorporated into the strong westerly wind near the subtropical jet streams to rapidly proceed toward the central Pacific. In the model, the average time required for transport of surface emissions in the Indonesian archipelago into the upper troposphere over the subtropics in the western Pacific was estimated to be about 15 days. A similar transport process was proposed on the basis of aircraft observations of plumes from extensive Indonesian fires during September and October in 1994[39]. In the Southeast Asia countries, trace gas emissions from biomass burnings as well as urban/industrial sources are expected to increase greatly in the future due to rapid growth of human activities. Thus, more observations and model assessments are necessary for a better understanding of their impacts on global carbon cycle in the upper tropospheric environment.

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