Biomass Burning in the Tropics and Tropospheric Ozone

Kazuyuki KITA, Masatomo FUJIWARA, and Toshihiro OGAWA

Department of Earth and Planetary Physics,
Graduate School of Science, University of Tokyo, 113-0033 Japan

ABSTRACT

Ozone in the troposphere is one of the most significant greenhouse gases and the key component which plays the central role in atmospheric photochemistry. However, the spatial and temporal variations of global tropospheric ozone have not been fully understood because of its high variability and difficulty in global observation by satellites. In particular, its variation has not been understood well in the tropics where there are very few ground-based long-term observations. Recently, some observational campaigns focusing on the tropics were conducted, recognizing that the most significant source of tropospheric ozone there is biomass burning. We have been conducting systematic ozone observations in Indonesia for the first time in this region. The result shows that tropospheric ozone increases during the late dry season when forest fires occur. In September and October 1994, widespread forest fires took place in Sumatra and Borneo and we observed remarkable enhancements of tropospheric ozone.

Key words : biomass burning, greenhouse gas, photochemistry, tropics, tropospheric ozone

1. TROPOSPHERIC OZONE

In the Earth's atmosphere, most ozone molecules exist at altitudes between 10 and 40 km. They absorb solar ultraviolet radiation which is harmful to the surface ecosystem and heat the atmosphere to form a thermally stable region in the middle atmosphere, *i.e.*, the stratosphere. On the other hand, ozone molecules in the troposphere contribute only 10% of the total. However, they also have significant influences on the Earth's environment. Tropospheric ozone is a greenhouse gas with a strong absorption band in the infrared region. It has an ill effect directly on the living, especially on the growth of plants because of its strong oxidizing effect. Furthermore, ozone itself and the hydroxyl (OH) radical produced through ozone photolysis play a central role in tropospheric chemistry.

The spatial distribution and temporal variation of tropospheric ozone are determined by dynamic/chemical processes such as subsidence from the statosphere associated with planetary-scale atmospheric waves, photochemical production with trace gases, such as nitric oxides (NOx), carbon monoxide (CO) and hydrocarbons (HCs), and loss on the Earth's surface. However, quantitative understanding of global tropospheric ozone still remains to be completed because the details of each process are not fully understood yet. To begin with, the distribution of tropospheric ozone and its temporal variability have not been fully observed yet. Most ground-based sites for observing tropospheric ozone are located in the northern mid-latitudes so that our knowledge of the tropics and the southern mid-latitudes is insufficient. In addition, technology to measure tropospheric ozone selectively has not been established so far. Therefore, photochemistry in the troposphere, which we can reach rather easily, is still poorly understood.

There are very few regular and long-term observational data on tropospheric ozone in the tropics. Knowledge of tropical chemistry has been obtained so far mainly from some limited observational campaigns. Here we review tropospheric chemistry in the tropics by separating the area into oceanic and continental regions. Tropospheric ozone over tropical oceans is studied through ground-based observations on islands such as Hawaii (Mauna Loa) or ship/aircraft observations. There is no significant source of ozone and precursor gases in this region so that the amount is determined by transport from the mid-latitudes and continental regions and by slow photochemical loss processes with OH/HO_2 radicals and CO. In the marine boundary layer, very low ozone concentration is sometimes observed, suggesting the ozone loss process with halogen species emitted from the sea surface. Over the tropical continents, tropospheric ozone is investigated by some gound-based observations including ozonesonde and aircraft observations. Tropical forests and their soil are biotically very active so that they are thought to be significant sources of ozone precursor gases such as NOx and HCs. At the some time, the canopy of vegetation works as an ozone sink. Anthropogenic emission of ozone precursor gases is presumed to be small in the tropics even over the continental regions. However, it is possible that the anthropogenic influence will become very significant in Southeast Asia where industrial activities are rapidly developing now. In the upper troposphere, NOx can be produced by lightning and exhausted from aircraft and becomes a significant source of ozone. However, efforts to quantify the impact of each process have just started. Among the various ozone sources, biomass burning is thought to have the largest impact as a source of ozone and other greenhouse gases in the tropics. We will discuss its impact in the next section.

Table 1 Estimation of the amount of burned biomass in the tropics. Extracted from Andreae (1991).

Region	Forest	Savanna	Fuel wood	Agricultural waste	Region total	
	Tg dm/yr				Tg dm/yr	Tg C/yr
America	590	770	170	200	1730	780
Africa	390	2430	240	160	3210	1450
Asia	280	70	850	990	2190	980
Oceania	–	420	8	17	450	200
Total	1260	3690	1260	1360	7580	3410

Tg dm/yr means teragrams of dry matter per year; 1 teragram = 1 million tons = 10^{12} grams. Tg C/yr means teragrams of carbon per year.

2. BIOMASS BURNING IN THE TROPICS AND ITS INFLUENCE ON TROPOSPHERIC CHEMISTRY

In the major part of the tropics, it is well known that the seasonal variation of precipitation is obvious and that biomass burning is frequntly found at the end of the local dry season. Burned areas are found in the savanna in Africa and in northern Australia, the tropical lowland forest in Amazon and in Borneo Island, agricultural fields in Southeast Asia and so on. Table 1 shows the estimated amount of various kinds of biomass burning in each tropical area by Andreae (1991). The burnings in the African savanna and the agricultural wastes of Asia dominate total biomass burning in the tropics. Although the causes include natural fire due to lightning, the major part of biomass burning is attributable to anthropogenic activity such as combustion accompanying cutting and clearing of tropical forests and shifting cultivation.

When biomass burning takes place, a large amount of various gases is emitted into the atmosphere. They include greenhouse gases, ozone precursor gases and acid gases so that there is a potential to affect the atmospheric environment. At the same time, a large amount of aerosols are also emitted. Table 2 represents the estimation of the amount of various kinds of matters emitted by biomass burning and the percentage of each in total emissions summarized by Andreae (1991). It shows that 40% of global emissions of carbon dioxide (CO_2), which is one of the most

Table 2 Comparison of global emissions from biomass burning with emissions from all sources. Extracted from Andreae (1991).

Species	Biomass burning (Tg element/yr)	All sources (Tg element/yr)	Biomass burning (percent)	Reference for all sources
CO_2[a]	3500	8700[b]	40	Bolin et al. (1986)
CO_2[c]	1800	7000[d]	26	Bolin et al. (1986)
CO	350	1100	32	WMO (1985)
Methane	38	380	10	Cicerone and Oremland (1988)
NMHC[e]	24	100	24	Ehhalt et al. (1986)
Nitric oxide	0.8	13	6	Bolle et al. (1986)
NO_x	8.5	40	21	Logan (1983)
Ammonia	5.3	44	12	Andreae et al. (1989)
Sulfur gases	2.8	150	2	Andreae (1990)
Carbonyl sulfide	0.09	1.4	6	Khalil and Rasmussen (1984)
Methyl chloride	0.51	2.3	22	WMO (1985)
Hydrogen	19	75	25	Conrad and Seiler (1986)
Ozone	420	1100	38	Crutzen (1988)
TPM[f]	104	1530	7	Peterson and Junge (1971)
POC[g]	69	180	39	Duce (1978)
EC[h]	19	$\leq$22	$\geq$86	Turco et al. (1983)

[a]Gross from combustion.
[b]Biomass burning plus fossil fuel burning.
[c]Net from deforestation.
[d]Deforestation plus fossil fuel burning.
[e]Nonmethane hydrocarbons excluding isoprene and terpenes.
[f]Total particulate matter (Tg/yr).
[g]Particulate organic carbon including elemental carbon.
[h]Elemental (black-soot) carbon.

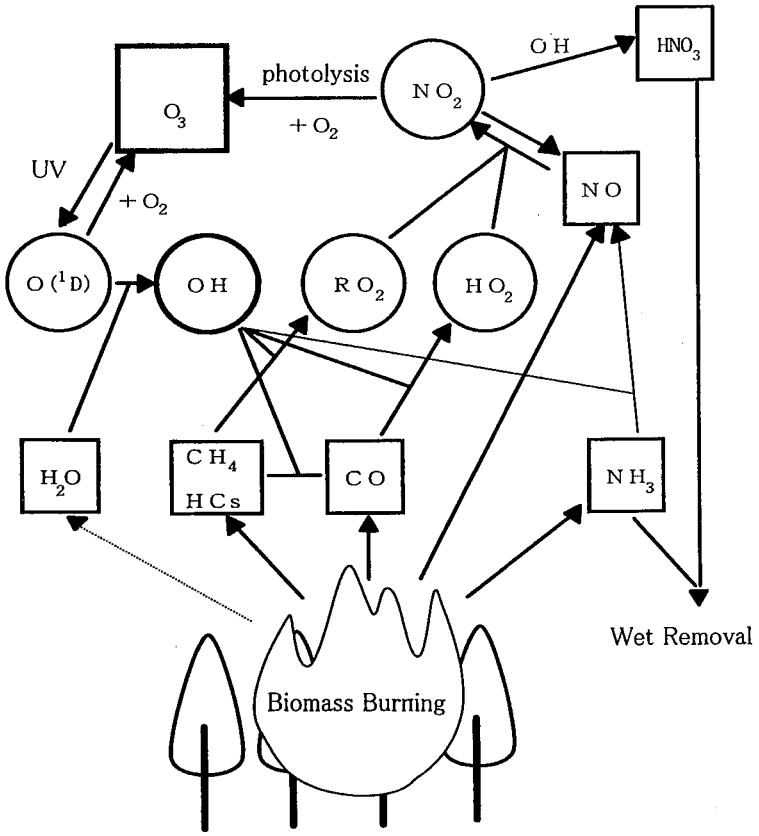

Fig. 1 Flow diagram of photochemical production of ozone from biomass burning emissions.

significant greenhouse gases, is due to biomass burning and that it is responsible for nearly the same proportion of tropospheric ozone. Furthermore, Andreae (1991) estimates the amount of emitted carbon from tropical biomass burning is 3410 Tg C/yr compared with 3940 Tg C/yr from global biomass burning, indicating significant impact of burning in the tropics.

Fig. 1 is a schematic flow diagram of ozone production processes from biomass burning emissions. The scenario is as follows : CO and HCs emitted from biomass burning react with OH radicals to yield peroxides(HO_2 and RO_2), then peroxides and NO, the latter of which also produced by biomass burning, react to yield NO_2;The photolysis of NO_2 produces atomic oxygen to form ozone with O_2 molecules. Therefore, the amount of ozone produced mainly depends on the concentration of CO, HC and NO which are increased by biomass burning. The amounts of emitted gases are supposed to be different accoding to the kind of biomass, the temporal phase in the evolution of the fire, the temperature of the fire and the ratio of incomplete combustion. Some active combustion experiments have been conducted under various conditions to study what kinds of gases are actually emitted. Furthermore, the amount of photochemically produced ozone is also thought to be dependent on atmospheric diffusion and upward transport processes. Dilution due to diffusion will reduce the effciency of the photochemical reaction greatly. The speed of upward transport to the free troposphere where solar ultraviolet radiation is much stronger will also control the effciency because the OH radical, which is the key species in air photochemistry, has a large dependence on ultraviolet flux. One important vertical transport process in the tropics is cumulus convection. During this process, water-soluble gases may be absorbed by cloud particles and the reaction chain may be modified. In the way, ozone formation from biomass burning consists of various photochemical and dynamical processes. To evaluate the amount of ozone produced by biomass burning quantitatively, we have to observe the amount of every gas emitted and investigate the details of transport processes and the photochemisty involved in them. Based on these studies, we will be able to understand the ozone production/loss system with the aid of numerical modeling.

Emitted and photochemically produced gases which have reached the free troposphere are transported widely by the relatively high-speed wind there. The tropical region is known as the one where tropospheric air enters the stratosphere so that gases in the tropical troposphere may directly affect the stratospheric chemistry. Therefore, biomass burning in the tropics can affect the global atmosphere significantly.

Although the occurrence of biomass burning has been reported in various regions(Andreate, 1993), previous observational studies on its atmospheric influence mainly targeted the Central Africa and the Amazon(Harriss *et al.*,1988 ; Fontan *et al.*, 1992 ; Andreae *et al.*, 1994b)because satellite observations have shown a very large enhancement of tropospheric ozone in these two regions in the dry season(Fishman

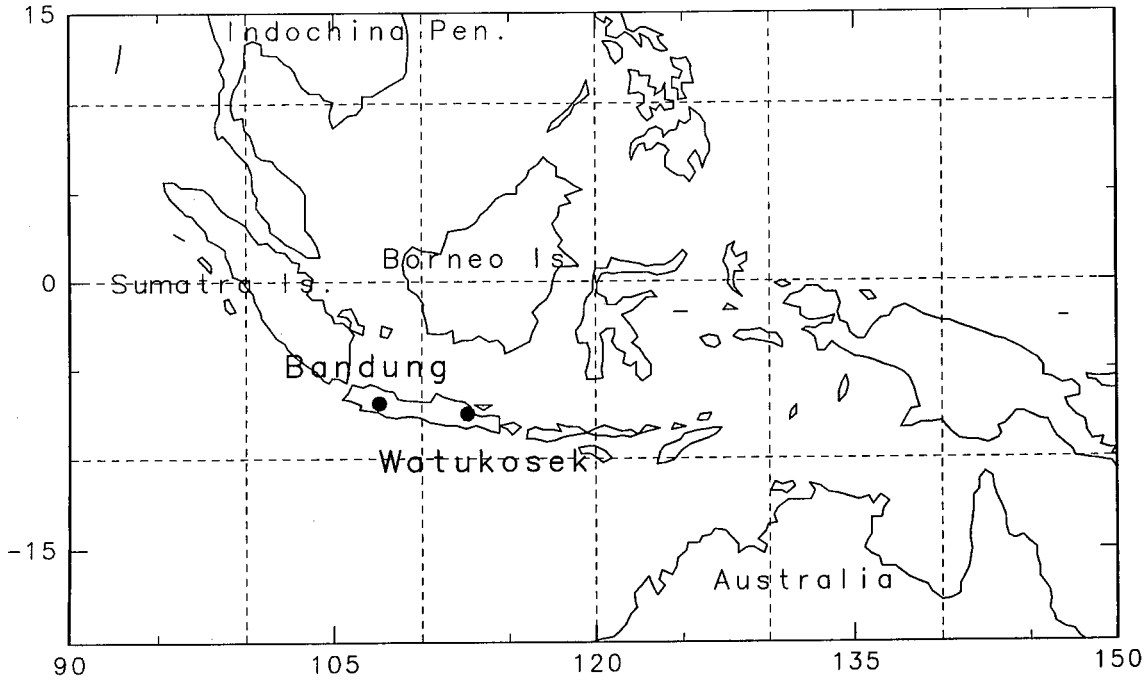

Fig. 2 Map of Southeast Asia and northern Australia. Watukosek and Bandung are shown by closed circles.

et al., 1990 ; Ziemke *et al.*, 1996). Although many cases of ozone increase in the burning plume have been observed in these studies, they were not understood quantitatively. Furthermore, systematic studies have just started in Southeast Asia.

3. OZONE PRODUCTION FROM BIOMASS BURNING IN SOUTHEAST ASIA

In the first section, we categorized the tropics as an oceanic region and a continental region. On the other hand, Southeast Asia around Indonesia, including the Indochina Peninsula and northern Australia, is called 'maritime continent' because of its mixed nature of lands and seas (Fig.2). Furthermore, these lands are divided into tropical forest regions, cultivated regions and rapidlly developing urban areas. From a meteorological point of view, this area is characterized by the most active cumulus convection in the world. Its climate is affected by phenomena with various temporal and spatial scales such as a complicated land-sea breeze system, equatorial atmospheric waves, the intraseasonal or Madden-Julian oscillation (MJO) of cumulus convection, the dry/wet seasonal change associated with the Asian monsoon, the quasi-biennial oscillation (QBO), and the El Niño-Southern Oscillation (ENSO).

3.1. Ozone Observations in Indonesia

A research group composed of members from the University of Tokyo, the Indonesian National Institute of Aeronautics and Space (LAPAN) and the National Space Development Agency of Japan (NASDA) has conducted regular ozonesonde observations since May 1993 and total ozone observations with the Brewer spectrometer since November 1993 at Watukosek (7.5°S, 112.6°E), East Java, Indonesia (Komala *et al.*, 1996 ; Fujiwara *et al.*, 1997). The

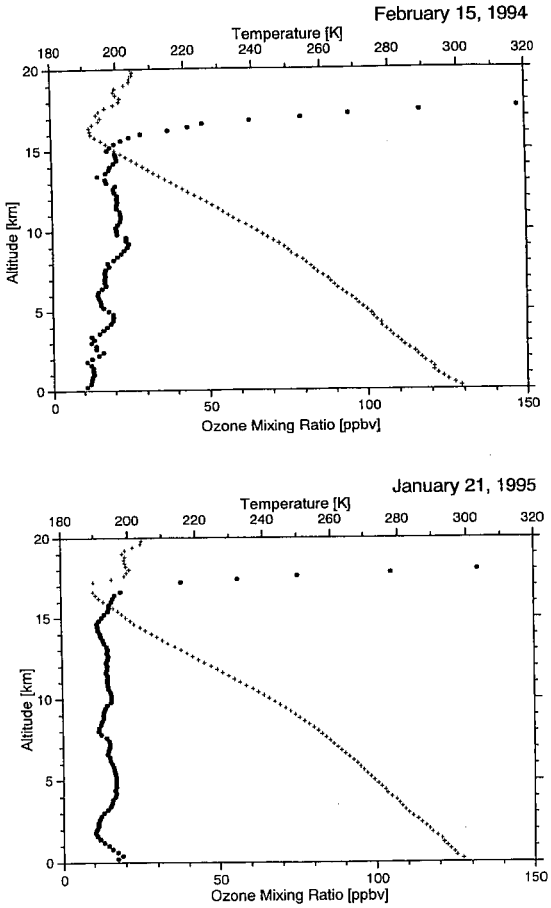

Fig. 3 Examples of vertical distribution of tropospheric ozone mixing ratio (dot) and temperature (cross) observed at Watukosek on February 15, 1994 (upper), and January 21, 1995 (lower).

University of Tokyo and LAPAN have been measuring surface ozone concentration by UV absorption

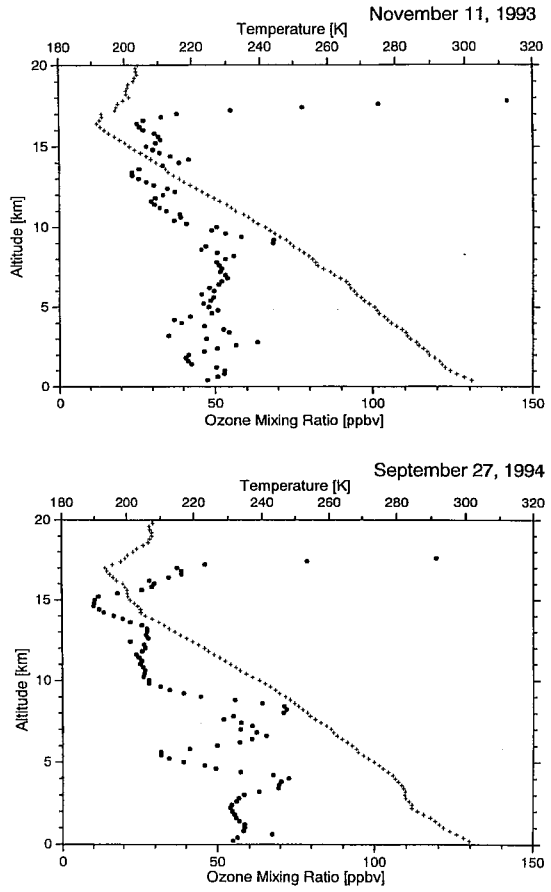

Fig. 4 Same as Fig. 3 but on November 11, 1993 (upper), and September 27, 1994 (lower).

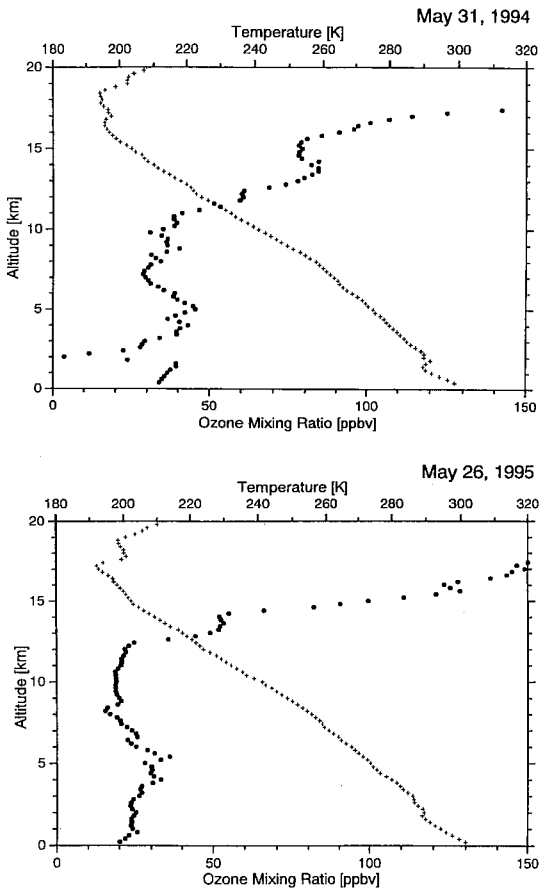

Fig. 5 Same as Fig. 3 but on May 31, 1994 (upper), and May 26, 1995 (lower).

techniques continuously at Watukosek and Bandung (6.9°S, 107.5°E), West Java, since 1986 and at Ciater (about 40 km north of Bandung, located in a rural area) since 1994. The purpose of these observations is to investigate atmospheric ozone variation in Southeast Asia where there has been no report on systematic observations.

The ozonesonde observations have revealed that the tropospheric ozone in this region has a distinct seasonal variation. The vertical distributions of tropospheric ozone are categorized into three types (Figs. 3 to 5). Fig. 3 shows the basic profiles observed mainly during the local wet season between December and March and sometimes in the early and middle dry season between April and August. They are characterized by the low ozone concentration of 20-30 ppbv throughout the troposphere implying that the photochemical production and the transport of ozone-rich air are not active. The second type of ozone profile is represented in Fig.4. It is characterized by an ozone increase of more than 50 ppbv below 10 km and is observed during the late dry season between September and November. The cause of this ozone increase is supposed to be photochemical production from ozone precursor gases emitted by active biomass burning in this period. Fig.5 shows the third type of ozone profile in which the ozone concentration increases with altitude above 10 km and exceeds 100 ppbv at the top of the troposphere. This type sometimes appears in April, May and June. We have conducted an intensive observation with ozonesondes and rawinsondes in May and June 1995 to investigate the temporal transition of this phenomenon and found that the enhanced ozone was from the stratosphere and was probably due to air mixing at the tropopause associated with the breaking of the equatorial Kelvin wave.

Next we show the result of total ozone observation with the Brewer spectrophotometer. This instrument measures solar ultraviolet intensity at five wavelengths and evaluates total ozone, which is conventionally represented by Dobson units (DU), in which 1 DU indicates a vertical atmospheric column with 1 cm^2 base area from the surface to the top of the atmosphere containing 2.687×10^{16} ozone molecules. Fig.6 shows the observed variation of total ozone between November 1993 and July 1995. It shows nearly constant values of 240-250 DU before July 1994 and a rapid increase between August and October when total ozone reaches 280 DU. After that, the amount decreases and is nearly constant again between 250 and 265 DU. The ozonesonde observation also detected an ozone increase in September and October 1994. Fig.7 shows the time series of integrated tropospheric ozone, total ozone observed with the Brewer spectrophotometer and total ozone above Watukosek obtained from the Total Ozone Mapping Spectrometer (TOMS) installed on the Russian satellite Meteor-3. The Meteor-3 TOMS measurement expired in December 1994. Note that the unit and scale of the Y-axes of the three panels is common, *i.e.*, 55

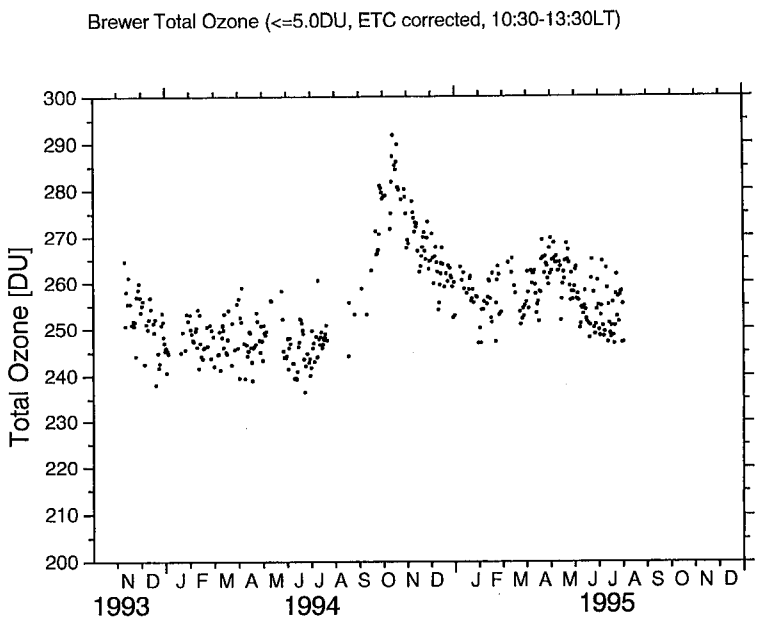

Fig. 6 Daily averaged Brewer total ozone between November 1993 and July 1995 at Watukosek.

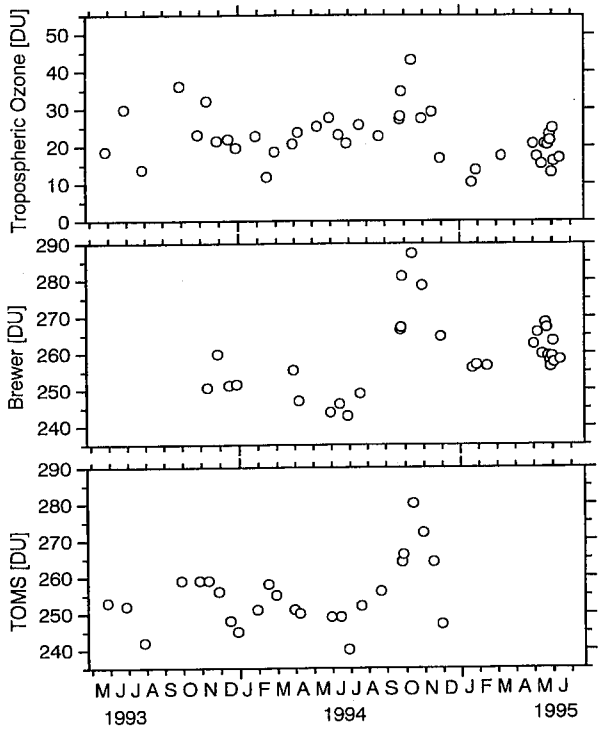

Fig. 7 Tropospheric integrated ozone (upper), total ozone observed with the Brewer spectrometer (middle) and total ozone above Watukosek obtained from the Total Ozone Mapping Spectrometer (TOMS) on the Meteor-3 (lower) when ozonesonde launchings were conducted at Watukosek.

DU. The increase of tropospheric integrated ozone between August and October 1994 was about 20 DU. On the other hand, the two total ozone observations showed on increase of about 30 DU during the same period. These facts indicate that the major part of the ozone increase can be attributed to an increase of the tropospheric ozone. Fig.8 shows the time series of total ozone above Watukosek obtained from Meteor-3 TOMS observation between August 1991 and December 1994. It shows longer-period variations as well as the ozone increase during the late dry season, September and October, almost every year. It should be noted that the ozone increase in 1994 was the most remarkable for its large amplitude and short time scale.

3.2. Widespread Forest Fires in 1994 and Ozone Production

In September and October 1994, though it was not the El Niño period according to the definition, there occurred widespread forest fires as active as those of the 1982-83 El Niño episode (Malingreau *et al.*, 1985 ; Malingreau *et al.*, 1989) on Sumatra Island and Kalimantan (the southern part of Borneo Island) because of reduced precipitation and developing agricultural activities. A large quantity of soot was emitted by the fires and affected daily life in neighboring countries seriously. A special meeting on this problem was held by the Association of Southeast Asian Nations (ASEAN) in 1995, the title of which was ' ASEAN Meeting on the Management of Transboundary Pollution'. The Singapore Meteorological Service (1995) reported the evolution of fire activities in that region by using visible/infrared images obtained by Advanced Very High Resolution Radiometer (AVHRR) onboard a satellite of the National Oceanic and Atmospheric Administration (NOAA) as well as ground-based observations. It was mentioned that the forest fires there had begun in July, spread out towards the last week of August and remained active till the end of October when the rainy season had begun.

Fig.9 shows the time variation of total ozone distribution around Indonesia between August and November observed by Meteor-3 TOMS. It is clear to see that a localized ozone enhancement centered at the southwest sea of Sumatra Island grew and decayed during this period with a maximum of more than 285

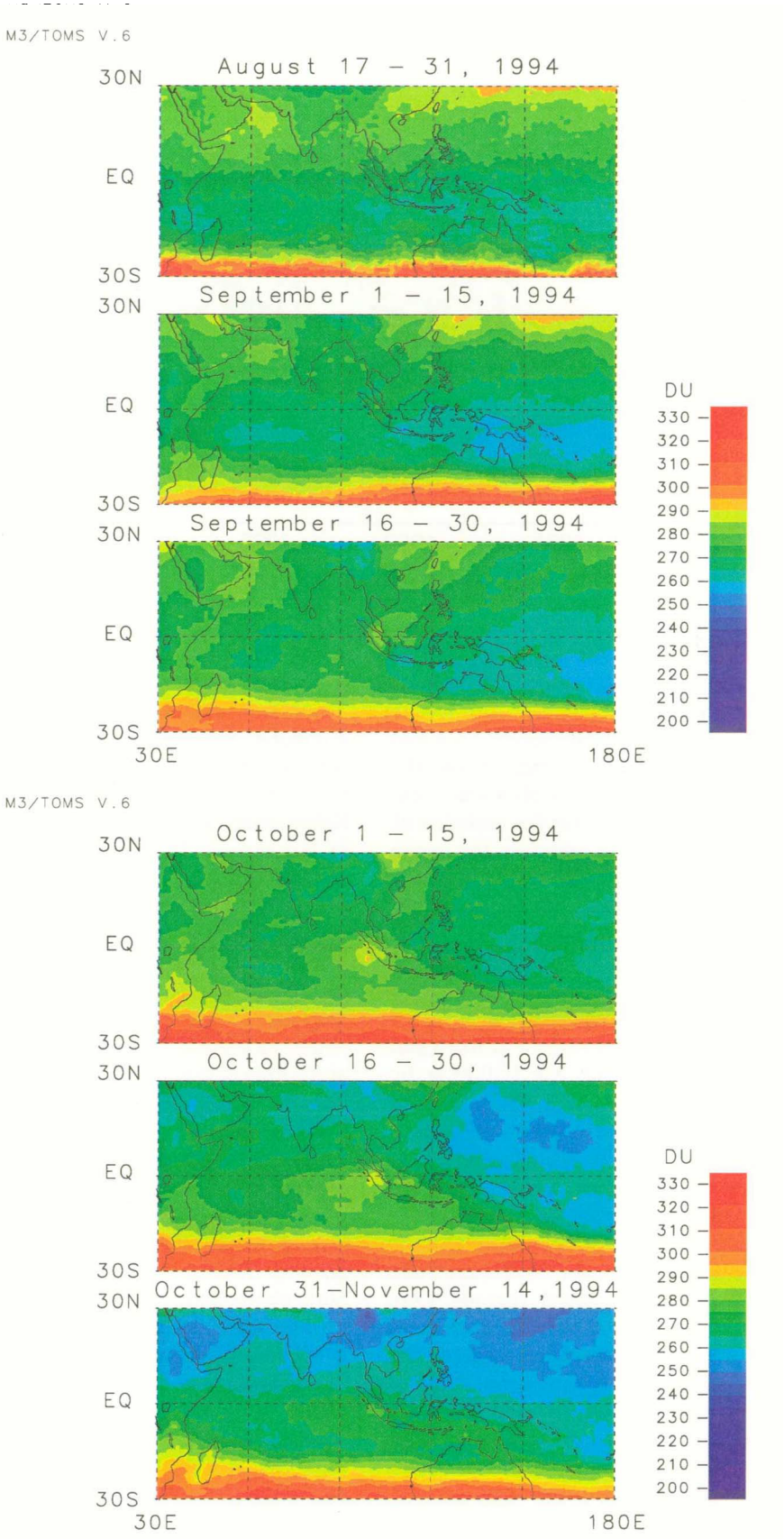

Fig. 9 15-day averaged Meteor-3 TOMS total ozone maps of the Indian Ocean, the maritime contiment and the equatorial West Pacific Ocean between the second half of August and the first half of November.

also take part. We expect that global ozone variations will be quantitatively understood by conducting comprehensive research including both observations and model calculations such as BIBLE intends to do.

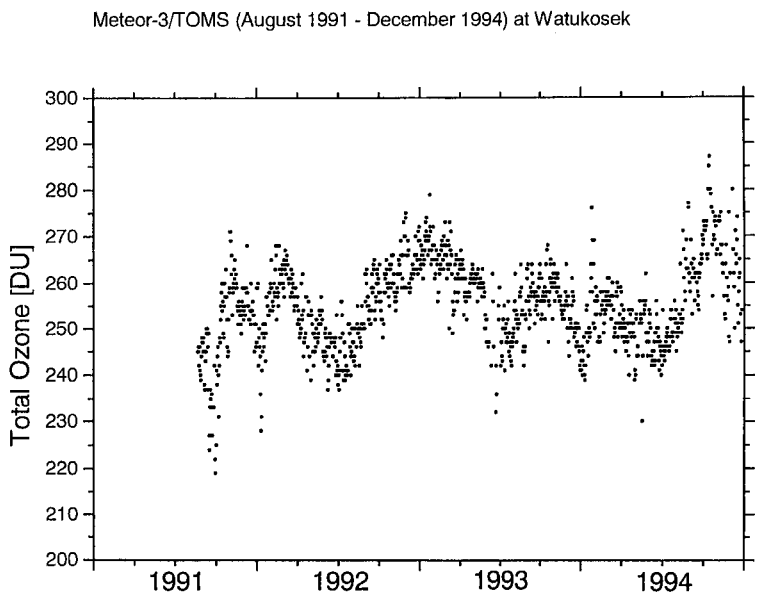

Fig. 8 Total ozone between August 1991 and December 1994 over Watukosek ob-tained by the Meteor-3 TOMS.

DU in the first half of October. After the last half of November, the total ozone in the equatorial regions became uniformly low again (not shown). The coincidence with the time evolution of the forest fires and the localized feature of enhancement suggest that the enhancement was mainly caused by the photochemical production of tropospheric ozone after the emission of precursor gases from the fires. In addition, the ozone abundant air extending from the mid-latitudes of the Southern Hemisphere to the equatorial region might also have affected the ozone variation over Watukosek.

Some other observations of atmospheric constituents also suggest that this extensive burning affected the tropospheric chemistry of that region. In April and in October 1994, Measurement of Air Pollution by Satellite (MAPS) onboard the NASA Space Shuttle observed the global distribution of CO concentrations in the middle troposphere. It measures infrared radiation from the surface and evaluates CO concentration by a gas filter correlation technique. As a result of the observation in Ocotber, a high CO concentration of more than 165 ppbv was found over Southeast Asia (Connors, 1996). Other CO-increased regions were also found around the center of South America and west of Central Africa in October, though the increases were lower than that in Southeast Asia. In the other regions including the northern mid-latitudes, CO concentrations were less than 120 ppbv. The MAPS result supports our discussion that the active fires in Southeast Asia affected the tropospheric photochemistry to produce ozone, which was observed at Watukosek.

4. CONCLUDING REMARKS

Recent studies have revealed that biomass burning in the tropics is an important source of tropospheric ozone. In Southeast Asia, where no systematic ground -based observational data have been reported, our group has started regular observations of tropospheric ozone. We found an ozone increase every year in September and October and suggested that it could be attributed to biomass burning in this area. In September and October 1994, when one of the largest forest fires on record occured on Sumatra Island and Kalimantan, a significant ozone increase was observed in Watrkosek, Indonesia. The Brewer measurement showed that the increase of total ozone reached 280 DU in the first half of October and the ozonesonde observaftion implied that the major part of the ozone increase was seen in the troposphere. TOMS data clearly showed the temporal and spatial variation of the localized ozone increase centered around Sumatra Island to suggest that the tropospheric ozone increase at Watukosek was mainly due to photochemical production from precursor gases emitted by the fires.

However, even in recent sftudies, the amount of ozone precursor gases emitted from biomass burning and the detailed processes to produce ozone have not been fully elucidated. We need to obtain a comprehensive data set of involved chemical species and to develop mesoscale 3-dimensional models in which both photochemical and dynamical processes are included. Recently, some observational campaigns have been planned or put into practice as the significance of biomass burning in the tropics has been recognized. In Japan, a group of researchers at the Univerity of Tokyo, Nagoya University, NASDA and so on is now planning a comprehensive observational campaign called the Biomass Burning and Lightning Experiment (BIBLE) in the maritime continent region in 1998. In this campaign, instruments for measuring ozone, NO, NOx, CO, CO_2, PAN, HCs, H_2O and aerosol will be installed on a jet airplane to study the ozone photochemistry associated with biomass burning and lightning. This plan also includes meteolorogical data analysis and chemical-transport modeling. This is an international campaign in which scientists from other countries such as United States and New Zealand will

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Address for correspondence :

[1] K. Kita, M. Fujiwara, and T. Ogawa, Department of Earth and Planetary Physics, Graduate School of Science, University of Tokyo, Tokyo 113, Japan. (e-mail : kita@sunepl. geoph. s. u-tokyo. ac.jp)

[1] Now at Earth Observation Research Center, National Space Development Agency of Japan.