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Total ozone increase associated with forest fires over the Indonesian region and its relation to the El Niño-Southern oscillation

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Abstract

Significant increases of total ozone were observed both by the total ozone mapping spectrometer (TOMS) and by the Brewer spectrophotometer in Indonesia in September and October of 1994 and 1997, during the El Niño periods, when extensive forest fires were reported in Sumatra Island, Kalimantan (the southern part of Borneo Island) and south New Guinea. The two observations were consistent with each other, and the total ozone increases were attributed to the tropospheric ozone increases because their amplitudes agreed with those of integrated tropospheric ozone increases derived from ozonesonde observations. The TOMS data indicated that the horizontal distributions and temporal variations of the ozone increases were similar in both years; the ozone increases were found mainly over Sumatra Island and the Malay Peninsula in September, and spread out from Kalimantan to the central Indian Ocean in October. This ozone distribution was partly different from the reported fire areas. This difference suggested the importance of the horizontal advection due to the easterly wind in the lower troposphere and of the vertical transport due to the upward wind at the west of Sumatra Island, in the ozone maximum area. Distinctive total ozone increases similar to those in 1994 and 1997 repeatedly appeared over the Indonesian region in the TOMS data between 1979 and 1998. The average ozone increase in this region was estimated by subtracting the background structure of total ozone in the tropics, and this analysis showed that large ozone increases mostly occurred in the dry season during the El Niño periods when the precipitation decreased significantly and extensive forest fires occurred frequently in Indonesia.

Keywords: Tropospheric ozone; Biomass burning; Tropics; TOMS; El Niño

1. Introduction

Biomass burning in the tropics is considered to significantly affect the regional and global distributions of tropospheric ozone because it emits a large amount of ozone precursor gases, such as nitrogen oxides, carbon monoxide and hydrocarbons (e.g. Crutzen and Andreae, 1990). Various in situ observations have revealed that the concentrations of ozone precursor gases and ozone increased in the air masses affected by the burning, and have suggested that the tropospheric ozone was produced photochemically in them (e.g. Crutzen et al., 1985; Browell et al., 1988; Andreae et al., 1992,1994; Anderson et al., 1993; Thompson et al., 1996; Folkins et al., 1997). However, it is not so easy to obtain information on the spatial extent of the ozone increases from the in situ observation data. The regional distribution of the ozone increase in the tropics and its relation to the tropical biomass burning activity have been investigated by using

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the TOMS and other satellite data although satellite observations have not been able to measure tropospheric ozone directly. In earlier studies, the climatology of the tropospheric ozone distribution in the tropics was shown, and the ozone maximum in the south tropical Atlantic region was noted (Fishman et al., 1990, 1991,1992; Ziemke et al., 1996; Fishman and Bracket, 1997). A number of studies discussed this ozone maximum with reference to biomass burning in the African savanna and/or Amazonian forest (Fishman et al., 1991,1992,1996; Kim et al., 1996; Ziemke et al., 1996; Kim and Newchurch, 1998). Several methods have been proposed to improve the evaluation of the tropospheric ozone from the TOMS data (Kim et al., 1996; Ziemke et al., 1998; Hudson and Thompson, 1998; Thompson and Hudson, 1999), and have been applied for discussing the long-term trend of the tropospheric ozone (Kim and Newchurch, 1996; Jiang and Yung, 1996; Chandra et al., 1999; Thompson and Hudson, 1999) as well as seasonal and interannual variations of the tropospheric ozone in various regions (Kim and Newchurch, 1996,1998; Ziemke et al., 1998; Chandra et al., 1998; Thompson and Hudson, 1999; Ziemke and Chandra, 1999). These studies indicated that the variation of tropical tropospheric ozone related to El Niño-Southern oscillation (ENSO) activity varied largely with longitudes.

In the Indonesian region, large-scale biomass burning occurred repeatedly. From 1982 to 1983, extensive forest fires in Indonesia were reported (Malingreau et al., 1985; Goldammer and Seibert, 1990). By using the TOMS data, Fishman et al. (1990) and Fishman (1999) suggested that tropospheric ozone increased over Borneo Island in March–April 1983. Kim and Newchurch (1998) also showed that tropospheric ozone deduced from the TOMS data increased in the west of New Guinea in September–October 1982. In the 1990s, ground-based observations were initiated in Indonesia and detected increases of tropospheric ozone over the Indonesian region. Komala et al. (1996) reported that tropospheric ozone observed at Watukosek (7.6°S, 112.6°E), Indonesia, increased in September–October 1993.

In 1994 and 1997, extensive forest fires occurred in Indonesia again. Analyses of satellite infrared image data and the TOMS aerosol index (e.g. Hsu et al., 1996) indicated that the fires occurred in south Sumatra Island, Kalimantan and south New Guinea (e.g. Singapore Meteorological Service, 1995; Nichol, 1997; Wooster et al., 1998; Nakajima et al., 1999). Fujiwara et al. (1998, 1999,2000) showed that significant ozone increases were found both in the ozonesonde data and in the Brewer spectrophotometer data obtained at Watukosek during September and October in 1994 and 1997. They showed that the observed increases of total ozone were caused by the ozone increase mainly in the lower and middle troposphere, suggesting that these increases were attributed to the forest fires. Based on the TOMS data, Chandra et al. (1998) and Thompson and Hudson (1999) showed that the integrated tropospheric ozone in the Indonesian region increased during the 1997 extensive forest fire event. Ziemke and Chandra (1999) showed that the tropospheric ozone increased over the western Pacific region including Indonesia during El Niño periods.

Several observations showed that ozone precursor gases increased during the forest fire events in Indonesia, suggesting the active photochemical production of tropospheric ozone. Connors et al. (1999) showed that the Measurement of Air Pollution from Satellites (MAPS) detected the increase of carbon monoxide in the middle troposphere of the tropics including Indonesia in October 1994. Airborne measurements by Tsutsumi et al. (1999) and Sawa et al. (1999) indicated that the concentrations of carbon monoxide and nitrogen oxides as well as aerosol density largely increased over Kalimantan during the October 1997 forest fire event, and that ozone mixing ratios exceeding 50 ppbv were measured above an altitude of 6000 ft (1.8 km). Matsueda et al. (1999) reported that carbon monoxide and methane in the upper troposphere increased in the tropics and subtropics over New Guinea and Australia in October 1997, and suggested the transport of these gases emitted from the Indonesian forest fires to the upper troposphere. Burrows et al. (1999) showed that the excess tropospheric column density of nitrogen dioxide and ozone measured by the Global Ozone Monitoring Experiment (GOME) was significantly large over Indonesia in September 1997.

The purpose of this paper is to characterize the distribution of ozone increases, which were found by the ground-based observation in 1994 and 1997, over the Indonesian region and to indicate that the ozone increases similar to those in these years repeatedly appeared over the Indonesian region in association with the ENSO activity. For this purpose, we show that the TOMS observation could quantitatively detect the ozone increases over Indonesia by comparing with the ground-based observation data. To understand the derived distribution of the ozone increases, we discuss the transport of air masses affected by the forest fires.

2. Observation data

In this paper, we used the TOMS data in the form of daily maps with a resolution of 1° latitude by 1.25° longitude. These gridded data were used without any selection or correction. We obtained the TOMS data from the CD-ROMs (TOMS Version 7 O_3 Gridded Data CD-ROM for the 1979–1992 period and The Meteor-3/TOMS Version 7 O_3 and Reflectivity Data CD-ROM for the 1993–1994 period) which were provided by NASA Goddard Space Flight Center (GSFC). We also adopted the preliminary Earth-Probe (EP)

TOMS data available in the archived datasets released by NASA/GSFC for the 1996–1998 period. Since the three satellite observations may have systematic differences, we separately analyzed the data from the different satellites.

We compared the TOMS total ozone data over Indonesia with the total ozone observed using an MKIV-type Brewer spectrophotometer, and with the integrated tropospheric ozone obtained from the Meisei RSII-KC79D-type ozonesonde observation. The Brewer and ozonesonde observations have been conducted regularly at Watukosek (7.6°S, 112.6°E), East Java, Indonesia since 1993. The maintenance of the instruments is performed every year. Details of these observations have been reported (Fujiwara et al., 1999,2000). In 1993, before being sent to Indonesia, the Brewer instrument was operated side by side with a Dobson spectrophotometer at Tsukuba/Tateno (36°S, 140°E), Japan, to confirm that the Brewer measurement was identical to the Dobson one within $\pm 5\%$ with a time difference of < 30 min. In 1996, the Brewer instrument was overhauled and calibrated by the manufacturer (SCI-TEC Instrument Inc.) in Canada. The data used here were selected based on the criteria shown by Fujiwara et al. (2000).

3. Results and discussion

3.1. Total ozone increases over the Indonesian region in 1994 and 1997

Figs. 1(a)–(c) compare the total ozone data obtained from TOMS observations aboard the Meteor-3 (1993–1994) and EP (1996–1998) satellites with that observed using the Brewer spectrophotometer at Watukosek. In Fig. 1(a), we averaged the TOMS data at four grid points, (7.5°S, 111.875°E), (7.5°S, 113.125°E), (8.5°S, 111.875°E) and (8.5°S, 113.125°E), surrounding Watukosek. In Fig. 1(c), the TOMS/Brewer ratio indicates that the short-term random difference between the two observations was mostly less than $\pm 5\%$, and that systematic differences were insignificant although the TOMS data were averagely 2–3% smaller than the Brewer data during the September–October 1994 and the September–December 1997 periods. It should be noted that clouds or dense aerosols emitted from forest fires might interfere with the detection of tropospheric component in the TOMS observation (e.g. Thompson et al., 1993; Bhartia et al., 1993). The agreement between the TOMS data and the Brewer data implies that the TOMS data were reliable, and that the interference was not significant over Watukosek in 1993–1998 period.

Figs. 1(a) and (b) also indicate that the total ozone observed by TOMS and the Brewer spectrophotometer had a significant peak between September and November in 1994 and 1997. In both years, the total ozone

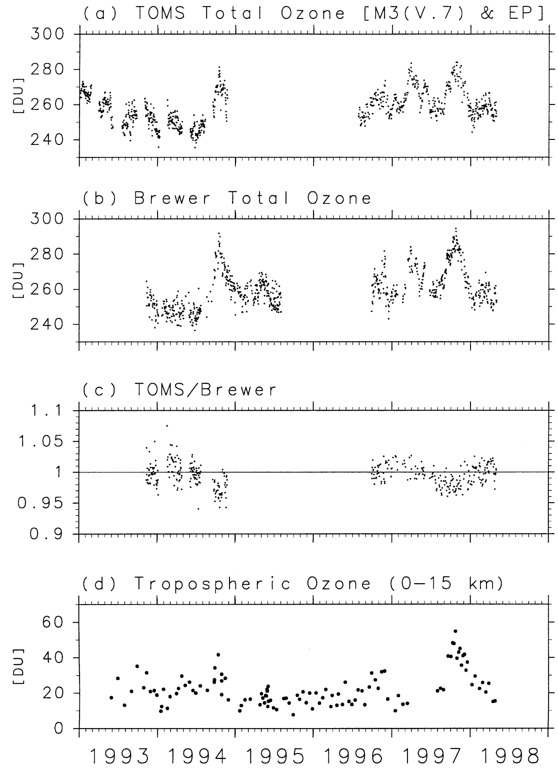

Fig. 1. Time series between January 1993 and April 1998 of (a) the total ozone over Watukosek obtained from Meteor-3 and Earth Probe TOMS observations, (b) the total ozone observed by the Brewer spectrometer at Watukosek, (c) the ratio of the TOMS total ozone to the Brewer total ozone, and (c) the integrated tropospheric ozone obtained from ozonesonde data at Watukosek (see the text). (b) and (d) are taken from Fig. 6 of Fujiwara et al. (2000).

values increased during August and September, reached the highest values of 280–290 Dobson units (DU) (1 DU $= 2.687 \times 10^{16}$ molecules of ozone cm^{-2}) in October, and decreased during November and December. Compared with the total ozone values of 250–260 DU in August and in December of both years, the increases of the total ozone in October were about 30 DU. Fig. 1(d) shows the time variation of tropospheric ozone obtained from the ozonesonde data by integrating between the surface and an altitude of 15 km, and indicates that the integrated tropospheric ozone showed a peak in these periods. The 15 km level was chosen to avoid the influence of the tropopause height fluctuation, and column ozone amount between 15 km and the tropopause (16–18 km) is negligibly small (< 0.4 DU) at Watukosek. Fujiwara et al. (1999,2000) noted that the increases of the integrated tropospheric ozone (about 20 DU in 1994 and about 35 DU in 1997) were comparable with those of the total ozone, implying that most of these total ozone variations originated in the troposphere. The ozone increase was observed in the lower and middle troposphere below an altitude of 12 km in these periods and was sometimes observed through the troposphere (Fujiwara et al., 1999). They suggested that the ozone increase could be attributed to the photochemical production of ozone through increased ozone precursor gases emitted from extensive forest fires in Sumatra Island and Kalimantan.

Figs. 2 and 3 present the horizontal distributions of the TOMS total ozone over the Indonesian region in August–November 1994 and 1997, respectively. In each panel, the data of each grid point are averaged for a month, except for periods of missing data. The variations during the August–November periods in both years were similar. In August (Figs. 2(a) and 3(a)), the total ozone distributions showed no evident increase over the Indonesian region. Such a distribution is typical in this region. As shown in the climatological study by Fishman et al. (1990), integrated tropospheric ozone in this region generally has the lowest value in the tropics, and shows little seasonal variation. In September (Figs. 2(b) and 3(b)), however, the total ozone over the Indonesian region increased, and the regional ozone maximum, which exceeded 270 DU in 1994 and 280 DU in 1997, appeared over Sumatra Island, the south Malay Peninsula and the sea between the Malay Peninsula and Borneo Island in both years. In October (Figs. 2(c) and 3(c)), the ozone-increased area shifted southwestward and expanded to the central Indian Ocean in both years. The total ozone maximums exceeding 280 DU in 1994 and 285 DU in 1997 were found around central Sumatra Island and the adjacent Indian Ocean. The total ozone over central Sumatra Island was about 20 DU larger than that in August and larger than that over the central Pacific in October in both years. Defining the ozone-increased area by the total ozone amount exceeding 270 DU for the 1994 case and 280 DU for the 1997 case, it extended from about 70°E to 130°E in longitude and from about 8°N to 10°S in latitude. In November, the total ozone amounts over this area decreased by about 15 DU compared to those in October in both years, and the regional ozone maximum became unclear (Figs. 2(d) and 3(d)). This result shows that the ozone increase observed at Watukosek had a large regional extent, more than about 60° in longitude and about 20° in latitude, and that the ozone increase larger than at Watukosek appeared

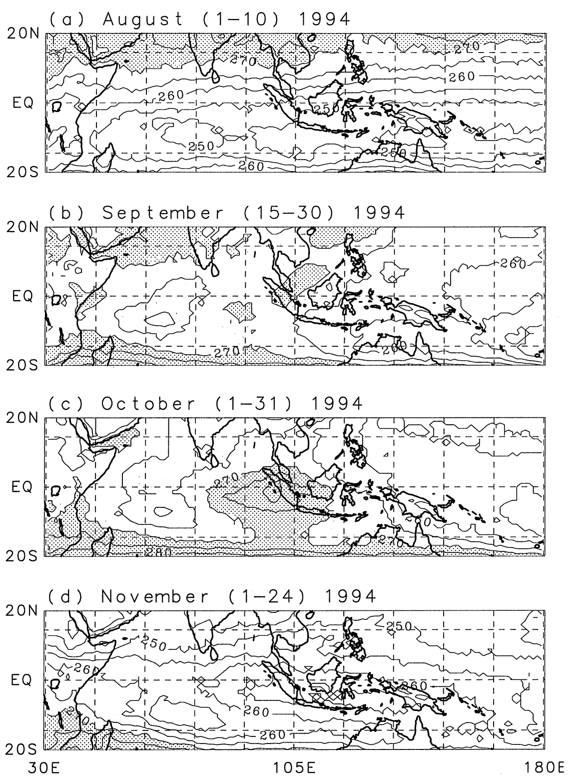

Fig. 2. Monthly averaged total ozone distributions over a region including Indonesia in (a) August; (b) September; (c) October; and (d) November 1994 determined from the TOMS observations. The unit is DU with a contour interval of 5 DU. The regions of more than 270 DU are shaded.

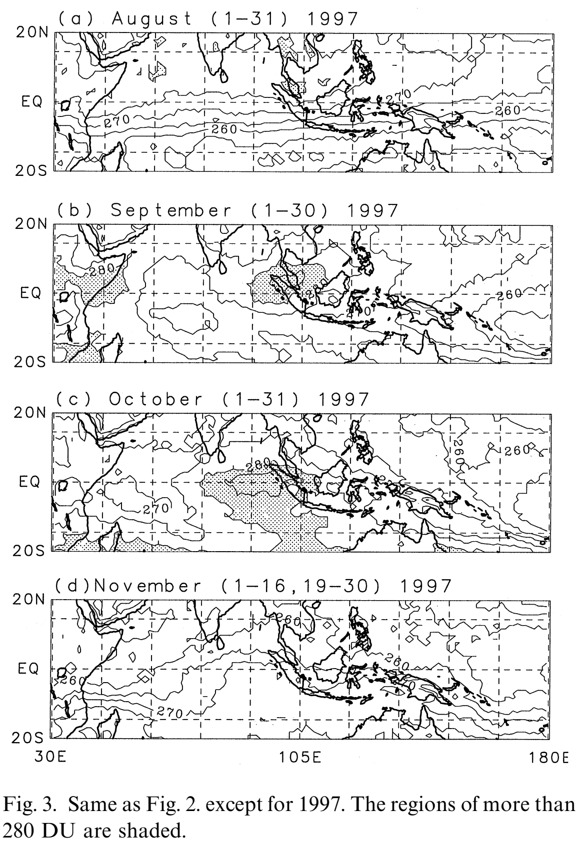

Fig. 3. Same as Fig. 2. except for 1997. The regions of more than 280 DU are shaded.

over the Sumatra Island and Kalimantan, where the forest fires occurred.

It is interesting to note that the distribution of the ozone increase overlapped with, but showed a significant shift from, the reported active burning areas: south Sumatra Island, south and east Kalimantan and south New Guinea. The period and the distribution of the ozone increases were also partly different from those of aerosol enhancements. Since aerosol is directly emitted from the burning, the aerosol distribution can be considered as an indicator of the burning. The particulate matter data obtained from the ground-based measurement (Nichol, 1997; Nurhayati et al., 1998) and the TOMS aerosol index (appeared on the web site by NASA/GSFC, URL = http://toms.gsfc.nasa.gov/) showed that the aerosol increase began in August and became larger in September of both years. Maximums of the TOMS aerosol indices exceeding 1 were found over the three reported burning areas in September–November 1997 (Nakajima et al., 1999). In contrast, the regional maximum of the total ozone appeared only over Sumatra Island and the adjacent Indian Ocean in September and October.

Considering that the ozone increase was attributed to the forest fires, we suggest that this regional shift of the ozone distribution implies the significance of the horizontal and upward transport of the burning-affected air masses for the ozone increase. Figs. 4(a) and 5(a) show the monthly-averaged streamlines at the 700 hPa pressure level, near the top of the boundary layer in Indonesia (cf. Hashiguchi et al., 1996), in October 1994 and 1997, respectively. The streamlines were calculated by using the European Center for Medium–Range Weather Forecast (ECMWF) $2.5^{\circ} \times 2.5^{\circ}$ grid point data. Easterly winds prevail in the lower troposphere (below about 6 km) over the Indonesian region in the dry season, and they probably transported the ozone precursor gases from the burning areas toward the ozone-increased area. Ozone might be produced photochemically during this transport. Upward transport is probably essential for the ozone photochemical production in the burning-affected air masses because the ozone production is more active in the free troposphere due to more intense ultraviolet (UV) radiation and less water vapor. The UV radiation is presumably insufficient in the burning-affected boundary layer, where it is absorbed and/or scattered by the dense aerosol, and abundant water vapor induces the ozone loss in the lower troposphere. Tsutsumi et al. (1999) showed that the photochemical ozone production in burning-affected air masses over Kalimantan was not active in the boundary layer. Figs. 4(b) and 5(b) show the distribution of the monthly averaged vertical pressure velocity calculated from the ECMWF data at 700 hPa in October 1994 and 1997, respectively. Although the convective activity was suppressed over the Indonesian region during the El Niño periods, the upward

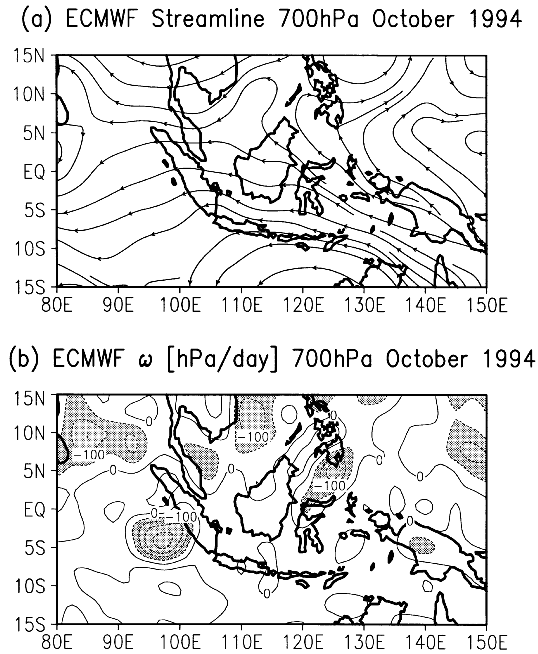

Fig. 4. (a) Monthly averaged streamlines over the Indonesian region at 700 hPa in October 1994; (b) Monthly averaged vertical pressure velocity (hPa day^{-1}) with a contour interval of 50 hPa day^{-1} over the same region in October 1994. In Fig. 4(b), negative values show the upward wind, and the regions of less than -50 hPa day^{-1} are shaded.

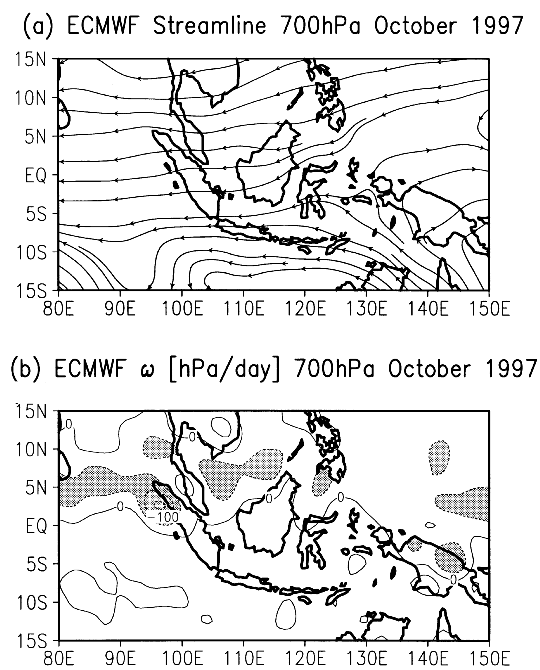

Fig. 5. Same as Fig. 4 except for 1997.

wind exceeding -100 hPa day^{-1} was found over the west of Sumatra Island in the ozone maximum area in September and October of both years. This upward wind area was found at pressure levels between 200 and 1000 hPa, suggesting the upward transport of increased ozone precursor gases in the boundary layer to the free troposphere and the subsequent ozone production. In contrast, although there were other upward wind areas over Kalimantan and New Guinea in the lowermost troposphere, they did not appear above the 700 hPa level. The upward transport of the ozone precursor gases to the middle and upper troposphere was suggested by Matsueda and Inoue (1999), who showed that the carbon monoxide concentration in the middle and upper troposphere over Singapore significantly increased in October 1997.

There may be other significant factors for the ozone increases. Chandra et al. (1998) and Ziemke and Chandra (1999) suggested that the downward motion over Indonesia might cause the increase of tropospheric ozone due to the downward transport of the ozone producing air masses in the middle and upper troposphere. Although they did not preclude the biomass burning effect, they suggested that the burning-affected air masses probably confined to the lowermost troposphere by the downward transport. However, the upward wind in the ozone maximum area implied that the burning-affected air was not confined to the boundary layer there, and suggested that the ozone could be produced in the burning-affected air masses transported upwardly. Chandra et al. (1998) and Ziemke and Chandra (1999) also suggested that the suppressed convection probably decreased the upward transport of ozone-poor and humid air masses over the ocean. These upward and downward transport effects should be examined quantitatively. Comprehensive observations of ozone and its precursor gases over the Indonesian region and three-dimensional chemical-transport model studies are necessary to understand the ozone increases.

There is a possibility that the cloud or aerosol interference with the TOMS measurement affect the ozone distributions shown in Figs. 2 and 3. The convective cloud differential method (Ziemke et al., 1998) and the modified-residual method (Hudson and Thompson, 1998; Thompson and Hudson, 1999) were proposed to estimate the tropospheric ozone amount from the TOMS data without the cloud interference. The tropospheric ozone distribution in October 1997 derived using both methods (Chandra et al., 1998; Thompson and Hudson, 1999; Ziemke and Chandra, 1999) showed the tropospheric ozone maximum over Indonesia similar with the total ozone maximum shown in Fig. 3(c). In addition, the difference of the distributions between the ozone increase and the TOMS aerosol index enhancement suggested that the aerosol interference was not serious in this case.

3.2. *Year-to-year variation of Indonesian total ozone increase and its relation to the ENSO*

The TOMS data between 1979 and 1998 show that total ozone increases, which had a regional distribution similar to those in 1994 and 1997, repeatedly appeared over the Indonesian region. Fig. 6 presents the total ozone distribution over the Indonesian region in October of 1982, 1987 and 1991. Similarly to the 1994 and 1997 cases, the regional ozone maximum appeared over Sumatra Island, the Malay Peninsula, Kalimantan and the Indian Ocean adjacent to Sumatra Island in 1982 and 1987. In October 1991 case (Fig. 6(c)), the total ozone over Sumatra Island and Kalimantan was larger than that over the Pacific and Indian Oceans in the equatorial latitudes although there was no closed contour lines like the other cases. In these cases, the zonal extent of the ozone-increased areas was limited over the Indonesian region. Such a limited zonal-scale, geographically fixed structure of total ozone in the tropics presumably originates in the troposphere, as shown in the 1994 and 1997 cases. The tropospheric ozone maps derived from the TOMS data by applying the modified-residual method (Thompson and Hudson, 1999) also show the ozone maximum over this region during the same periods (appeared on the website, URL = http://metosrv2.umd.edu/~tropo).

Fig. 7 illustrates the longitudinal distributions of the TOMS total ozone over the equator averaged over

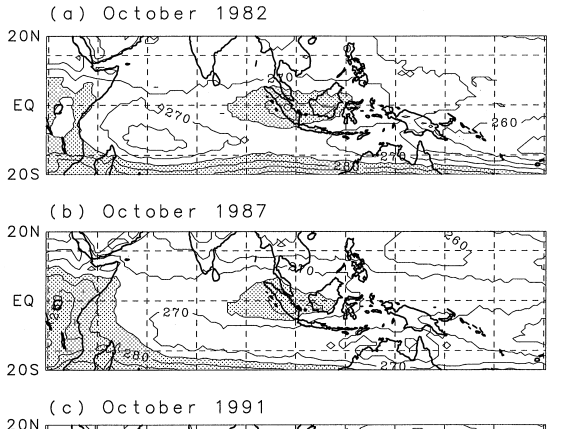

Fig. 6. Monthly averaged total ozone distributions over the region same as Figs. 2 and 3 in (a) October 1982; (b) October 1987; and (c) October 1991 determined from the TOMS observations. The regions of more than 275 DU are shaded.

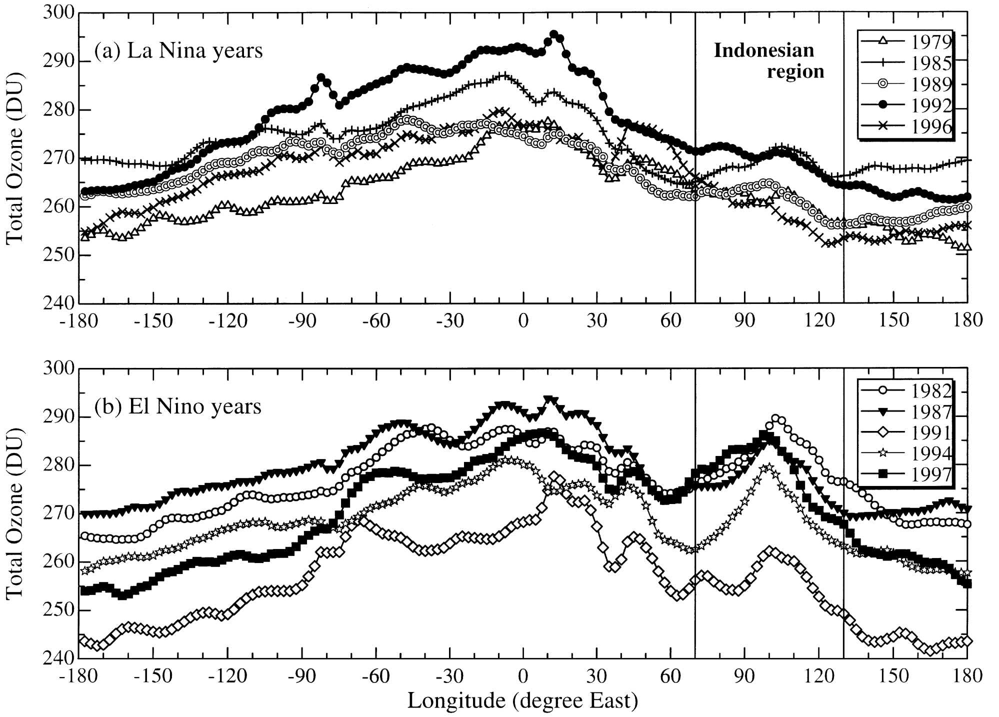

Fig. 7. Longitudinal distributions of total ozone over 0.5°N–0.5°S latitude averaged for October 1–10 of some representative years: (a) in La Niña years of 1979, 1985, 1989, 1992, and 1996; and (b) in El Niño years of 1982, 1987, 1991, 1994 and 1997. The data at the latitudes of 0.5°N and 0.5°S were averaged, and were conducted a running mean of 5° (4 data) in longitude.

October 1–10 in some representative years. On a global scale, the longitudinal distribution over the equatorial region exhibits a zonal structure of wave number one throughout the year, which originates in the troposphere (Fishman et al., 1990; Ziemke et al., 1996); the stationary ozone maximum is located around 0°E, and total ozone generally decreases toward the date line. The longitudinal distributions in 1979, 1985, 1989, 1992, and 1996 showed this structure (Fig. 7(a)). However, corresponding to the ozone increases shown in Figs. 2, 3 and 6, total ozone exhibited a distinctive peak structure over the Indonesian region, between 70°E and 130°E, in 1982, 1987, 1991, 1994, and 1997 (Fig. 7(b)). These longitudinal structures were quite similar to each other except for the absolute value which has longitudinally uniform fluctuations associated with the quasi-biennial oscillation (QBO) in the stratosphere (e.g. Shiotani, 1992). The latitudinal extent of this structure was between 6°N and 8°S in most cases. It should be noted that this structure appeared only over the Indonesian region, and that October in 1982, 1987, 1991, 1994, and 1997 corresponded to the El Niño periods.

Fig. 7 suggests a relation between the ozone peak structure over the Indonesian region and the ENSO activity. To indicate the year-to-year variation, we estimated the average ozone increase over this region by separating the ozone peak from the global background component, including the stratospheric ozone and the wave number one structure in the troposphere. Assuming that the longitudinal range of this structure is limited between 70°S and 130°E, we infer the global component in this range by fitting a sinusoidal curve expressed by A cos (east longitude) $+ B$, where A and B denote the amplitude and the offset of the curve, respectively. At each latitude between 6°N and 8°S, the values of A and B are chosen to fit the curve to the TOMS data averaged in the two longitudinal regions of 60°E to 70°E and 130°E to 140°E. The average ozone increase is derived by subtracting this global component from the raw data at each grid point and by averaging the residuals for all grid points within the region of 6°N to 8°S and 70°E to 130°E for each day. The derived values are not sensitive to the expression of the global component; if we adopt a straight line instead of the sinusoidal curve, the difference of derived values is insignificant, averagely less than 0.2 DU.

Fig. 8 shows the 30-day running mean of the average ozone increase between January 1979 and April 1998 and 5-month running mean of the Southern Oscillation Index (SOI) which indicates the El Niño periods by large

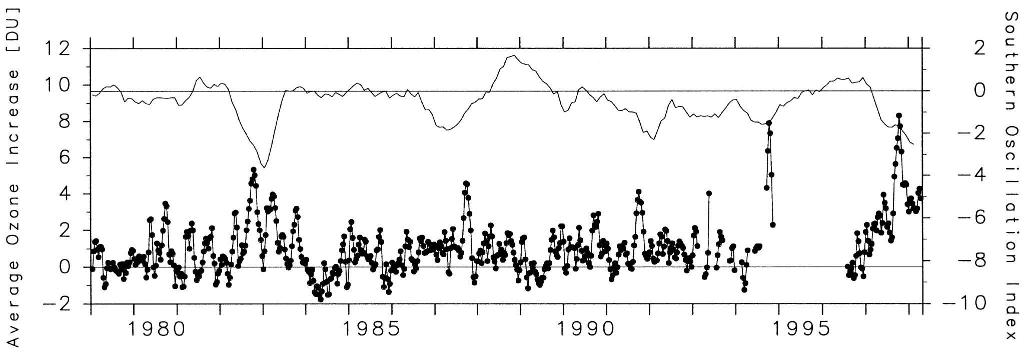

Fig. 8. Time series of 30-day running mean of the average ozone increase over Indonesia (shown by dots connected with lines) together with five-month running mean of SOI (shown by a curve) between 1979 and 1998. The average ozone increase is indicated with a time interval of 10 days. Zero levels of the average ozone increase and SOI are also indicated by horizontal lines.

negative values. The SOI data were derived from US Department of Commerce (1998). In this figure, the average ozone increase was less than 2 DU in general and sometimes exhibited a spike-like increase exceeding 3 DU. Major spikes appeared during the September–November periods of 1980, 1982, 1983, 1987, 1991, 1994, and 1997. Some spikes were also found during the March–June periods of 1980, 1982, 1983, and 1997. It should be noted that the September–October period corresponds to the late dry season in the major part of Indonesia including south Sumatra Island and south Kalimantan, and that the March–May period is also the dry season in north Sumatra Island and north and east Kalimantan. Fig. 8 indicates that most of the large spikes occurred in the dry season during El Niño periods as in 1982–1983, 1987, 1991, 1993, 1994, and 1997. The precipitation is small in the dry season and decreases considerably during El Niño periods in the Indonesian region (e.g. Goldammer and Seibert, 1990; Nichol, 1997), and the frequency of active forest fires is considered to increase in these periods. In the El Niño periods of 1982–1983, 1987, 1994, and 1997, active forest fires in Indonesia were reported (e.g. Goldammer and Seibert, 1990; Singapore Meteorological Service, 1995; Nichol, 1997; Wooster et al., 1998). The ground-based observations in Malaysia showed significant increases of the particle matters at several observation sites in 1982–1983, 1987, 1991, 1994 and 1997, implying that active forest fires occurred in these years (Lim et al., 1998). Therefore, the large ozone increases over the Indonesian region mostly occurred during the active forest fire events in this region. Ziemke and Chandra (1999) showed that the tropospheric ozone over the western Pacific region including Indonesian region significantly increased during the El Niño periods of 1982–1983, 1987, and 1997. However, the ozone increases in 1991 and 1994 did not appear in their result (see Figs. 10–12 in Ziemke and Chandra (1999)). We suggest that the three-month running mean or the de-seasonalizing procedure may mask the ozone increase in the 1991 case, and that their simplified method may incorrectly estimate the tropospheric ozone in the 1994 case.

Fig. 8 shows that extensive forest fires in 1994 and 1997 have remarkable impacts on the tropospheric ozone distribution in the Indonesian region. The average ozone increase in October of both years was about 8 DU. It corresponds to a roughly 40% increase of the integrated tropospheric ozone averaged over the region of 6°N to 8°S and 70°E to 130°E, considering that the integrated tropospheric ozone was about 20 DU in this region when the tropospheric ozone did not increase (Fishman et al., 1990; Fujiwara et al., 1999). The ozone increases of these periods might be larger than those in other years. However, uncertainties due to systematic differences of the three satellite observations and due to variability of the regional extent of the ozone-increased area make it difficult to accurately compare the derived ozone increase values in different years.

4. Summary

We compared the TOMS total ozone data with the ground-based observation data at Watukosek, Indonesia, and showed that the TOMS observation could quantitatively detect large increases of the total ozone associated with the extensive forest fires in Indonesia during September–October in 1994 and 1997. The TOMS data indicated that these ozone increases widely spread over the Indonesian region for more than 60° in longitude and about 20° in latitude, and that their horizontal distributions and their temporal variations were similar in the two cases. The ozone maximum area appeared over Sumatra Island and the adjacent Indian Ocean in both years, and this distribution was overlapped with, but shifted from, the distribution of the reported active burning areas. We suggested that this shift was partly due to the horizontal transport by easterly winds prevailing in the lower troposphere over Indonesia in the dry season, and that it was also due to the upward wind near central Sumatra Island. The upward wind probably played an important role in the ozone increase because it could transport the ozone precursor gases emitted from the fires to the free troposphere where the photochemical ozone production is more active than in the boundary layer.

The 20-year TOMS data showed that ozone increases similar to the 1994 and 1997 cases repeatedly appeared over the Indonesian region. By subtracting the background longitudinal structure of total ozone, we derived the average ozone increase over this region. This analysis revealed a variation with several spike-like increases; the spikes larger than 3 DU mostly occurred in the dry seasons in Indonesia during the El Niño periods of 1982–1983, 1987, 1991, 1994, and 1997. This result suggested that the total ozone over the Indonesian region repeatedly increased in association with the active forest fires during the El Niño periods. The average ozone increases in 1994 and 1997 were remarkable and corresponded to an about 40% increase of the integrated tropospheric ozone over the Indonesian region.

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