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Tropospheric ozone enhancements during the Indonesian forest fire events in 1994 and in 1997 as revealed by ground-based observations

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Abstract. Pronounced enhancements of total and tropospheric ozone were observed with the Brewer spectrophotometer and ozonesondes at Watukosek (7.5°S, 112.6°E), Indonesia in 1994 and in 1997 when extensive forest fires were reported in Indonesia. The integrated tropospheric ozone increased from 20 DU to 40 DU in October 1994 and to 55 DU in October 1997. On October 13, 1994, most ozone mixing ratios were more than 50 ppbv throughout the troposphere and exceeded 80 ppbv at some altitudes. On October 22, 1997, the concentrations were more than 50 ppbv throughout the troposphere and exceeded 100 ppbv at several altitudes. The coincidences of the ozone enhancements with the forest fires suggest the photochemical production of tropospheric ozone due to its precursors emitted from the fires for both cases. The years of 1994 and 1997 correspond to El Niño events when convective activity becomes low in Indonesia. Thus, in this region, it is likely that pronounced enhancements of tropospheric ozone associated with extensive forest fires due to sparse precipitation may take place with a period of a few years coinciding with El Niño events. This is in a marked contrast to the situation in South America and Africa where large-scale biomass burnings occur every year.

1. Introduction

An aircraft measurement program in Brazil in 1979-1980 was one of the earliest in situ observations that confirmed that the elevated ozone concentrations were a result of photochemical production due to the ozone precursor gases (nitric oxide (NO), carbon monoxide (CO), and hydrocarbons) emitted from biomass burning [*Crutzen et al.*, 1985]. Since then, the significant contribution of forest and savanna fires to the tropical tropospheric ozone has been widely recognized. By using satellite data, *Fishman et al.* [1990] estimated the tropical distribution of integrated tropospheric ozone and found that the maximum concentration occurred in September-November over the tropical Atlantic. Meteorological analyses [e.g., *Krishnamurti et al.*, 1993] and intensive field campaigns [e.g., *Fishman et al.*, 1996; *Lindesay et al.*, 1996] were made to investigate the cause of this seasonal-regional maximum, and the primary role of burnings in tropical South America and in central Africa was confirmed. Several other aircraft observations of enhancements of ozone and its precursors have been reported in association with the tropical burnings in South America and in Africa [e.g., *Browell et al.*, 1988; *Marenco et al.*, 1990; *Andreae et al.*, 1992; *Andreae et al.*, 1994]. These observations confirmed that a large amount of ozone precursors and aerosols was emitted from the fires and that tropospheric ozone was produced photochemically near the burning plumes. Observed ozone increases due to the burning emissions were mostly in the range of 40-100 ppbv and sometimes up to 160 ppbv. The enhancements of ozone correlated with those of aerosols and other trace gases in almost all the cases.

Biomass burning is most intense in the tropics during the August-October period in the southern-hemispheric part of South America, Africa, and Asia including northern Australia, but is always observed somewhere within 60°N and 40°S latitudes throughout the year [*Andreae*, 1993]. However, tropical observations of atmospheric composition influenced by the fires are limited to South America and Africa; the situation around Indonesia is scarcely known though the area also has a rich biomass of tropical rain forests and cultivated fields. We have been conducting total ozone observation with the Brewer spectrophotometer since November 1993 and regular ozonesonde sounding since May 1993 at Watukosek (7.5°S, 112.6°E), East Java, Indonesia (Figure 1) [*Komala et al.*, 1996; *Fujiwara et al.*, 1998a; *Fujiwara et al.*, 1998b]. In this paper, we focus on pronounced enhancements of total and tropospheric ozone observed in 1994 and in 1997 when extensive forest fires were reported in Indonesia.

2. Observations

An MKIV-type Brewer spectrophotometer has been used to measure total ozone at Watukosek since November 1993. Observations were conducted every hour in the daytime. The daily representative values were determined as follows: The raw data obtained at small solar zenith angles between 1030 and 1330 LST with the standard deviation of less than 5 Dobson units (DU) were corrected according to the daily standard lamp test and averaged.

Vertical distributions of atmospheric ozone, temperature, pressure, and horizontal wind were measured by electrochemical carbon-iodine ozonesondes of Meisei RSII-KC79D with TX3000-type TOTEX balloons and a tracking system. There was a total of

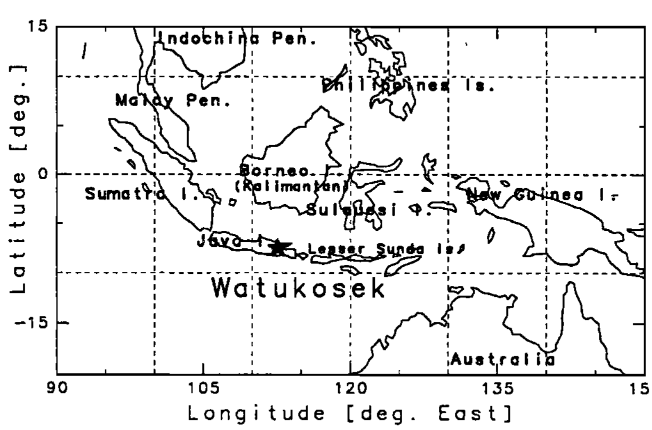

Figure 1. Location of Watukosek (7.5°S, 112.6°E), East Java, Indonesia.

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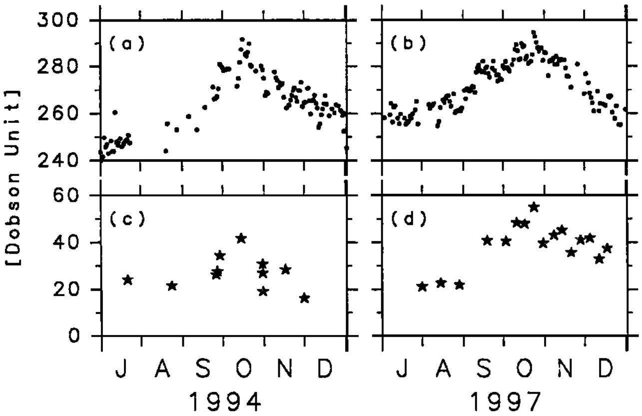

Figure 2. Temporal variations of: (a) total ozone measured by the Brewer spectrophotometer from July to December 1994; (b) same as (a) but for 1997; (c) same as (a) but for the integrated amount of ozone between 0 and 15 km altitudes by ozonesondes; and (d) same as (c) but for 1997.

15 soundings between July and November 1994 and 18 soundings between July and December 1997. In this paper, we use 11 results for 1994 and 16 for 1997 in which ozone concentrations were successfully measured at least up to 16.6 km altitude which is the average tropopause altitude defined by the temperature minimum (~195 K). We did not apply the total ozone correction to the data.

3. Results and Discussion

Figure 2 shows the temporal variations of total and tropospheric ozone during the July-December period of 1994 and of 1997. In both years, the total ozone concentration increased from 250-260 DU in July to 290 DU in October (~12% increase), which was the highest value at Watukosek between 1993 and 1997, and recovered by December. The tropospheric ozone defined as an integration of the ozonesonde data between the surface and 15 km also showed enhancements during the same periods, with a maximum of 40 DU in 1994 and 55 DU in 1997, which were also the highest values. If the bottom level of the tropospheric ozone is taken as 20 DU obtained in August, which also corresponds to the average value for the non-burning season at this site [*Komala et al.*, 1996], 40 DU and 55 DU correspond to 100% and 175% increases of the tropospheric ozone, respectively. These increases of the tropospheric ozone correspond to 60% and 100% of the total ozone increases in 1994 and in 1997, suggesting that most of the total ozone enhancements during these periods originated in the troposphere.

3.1. 1994 Enhancement

The period between June 1994 and March 1995 coincided with an El Niño event [*Trenberth,* 1997]; thus the convective activity in Indonesia was low. Between August and October 1994, widespread forest fires occurred in Sumatra Island and the southern part of Borneo Island (Kalimantan) due to sparse precipitation and developing agricultural activity. *Singapore Meteorological Service* [1995] reported the temporal variation of the fires as follows: They began in July, spread in the last week of August, and lasted till the beginning of November when it began to rain. By using the satellite total ozone data from the Meteor-3/Total Ozone Mapping Spectrometer (TOMS), we investigated the monthly mean total ozone distribution around Indonesia during this period. We found that a regional-scale enhancement with a maximum of 280 DU was centered over the eastern Indian Ocean adjacent to Sumatra Island in October and that Watukosek was located at the easternmost side of the ozone-enhanced region [*Fujiwara et al.,* 1998a]. From the observations at Watukosek, the major part of the TOMS enhancement can be attributed to the tropospheric ozone enhancement.

To investigate the temporal variation of vertical distribution of tropospheric ozone and wind in 1994 in detail, the five ozonesonde sounding results are shown in Figure 3. On July 20, the ozone mixing ratios below 12 km were mostly less than 40 ppbv, whereas that above 12 km increased rapidly with altitude (Figure 3(a)). The large positive vertical gradient of ozone in the uppermost troposphere may suggest a transport from the stratosphere (see also Figures 4(a) and 4(d)) [cf. *Fujiwara et al.,* 1998b]. On August 22, while the concentrations between 7 and 12 km increased to more than 50 ppbv, those below 6 km were 10-30 ppbv (Figure 3(b)); the integrated tropospheric ozone, which has larger weight for the mixing ratios in the lower atmosphere, was still as low as 20 DU. On September 27, the concentrations below 9 km mostly exceeded 50 ppbv, enhancing the tropospheric ozone up to 35 DU (Figure 3(c)). The wind below 10 km where the mixing ratios increased blew from the east or southeast at less than 10 m s^{-1}, while the wind above 10 km where the concentration was less than 30 ppbv blew from the northeast at more than 30 m s^{-1}. The largest ozone enhancement was observed on October 13 (Figure 3(d)); the concentrations were mostly much more than 50 ppbv throughout the troposphere and exceeded 80 ppbv at some altitudes, resulting in a maximum tropospheric ozone of 40 DU. At that time, the wind blew from the southeast at less than 10 m s^{-1} throughout the troposphere. On November 29, the concentration had returned to 20-30 ppbv throughout the troposphere (Figure 3(e)); this profile corresponds to the basic type at Watukosek [*Komala et al.,* 1996].

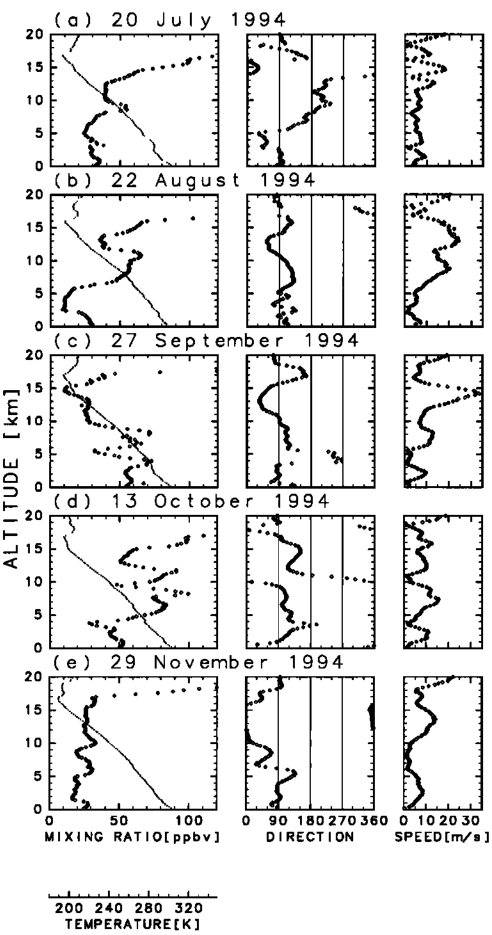

Figure 3. Vertical distributions of ozone (diamonds), temperature (dots), wind direction, and wind speed on (a) July 20, (b) August 22, (c) September 27, (d) October 13, and (e) November 29, 1994. Direction of 0° corresponds to the wind from the north, and 90° from the east.

The coincidence of the 1994 enhancement with the extensive forest fires and the horizontal extent of the ozone-enhanced region revealed by TOMS suggest that the enhanced ozone observed over Watukosek was produced in the troposphere by photochemical reactions of its precursors emitted from the fires. The wind direction data implied that the ozone-enriched air masses did not come directly from the burning areas; the wind blew from the southeast at less than 10 m s^{-1} when the enhancement was observed. *Hashiguchi et al.* [1995] found lower tropospheric east-west wind fluctuations over Indonesia associated with hierarchical convective activities with periods of 1-2 days and about 10 days by analyzing the boundary layer radar data in Indonesia and the global meteorological analysis data from the Japan Meteorological Agency (GANAL). They also showed from GANAL data that horizontal eddies with a diameter of about 1000 km, not a jet-like laminar flow, were dominant over Indonesia. Considering that Watukosek was located at the easternmost side of the TOMS ozone-enhanced region and that the average horizontal wind is weak with large fluctuations in the tropics, the ozone-enriched air masses observed at Watukosek may be transported from the burning areas with the synoptic-scale eddy-like air motions. We also made air mass trajectory calculations by using the global analysis data from the European Centre for Medium-Range Weather Forecast (ECMWF). Linear interpolation was used to temporally interpolate the data, whose original time resolution was 12 hours, to 1-hour time step. Vertical movements of air parcels were computed with the vertical velocity data. Five-day backward trajectories from Watukosek in October 1994 showed that the site was mainly influenced by the air masses over Java I., Kalimantan (one of the major burning areas), Lesser Sunda Is., and Sulauesi I., being consistent with the above interpretation. In the middle and upper troposphere, the site was sometimes influenced by southern midlatitudes over the Indian Ocean and Australia.

Other observations which indicated the influence of the 1994 burning on the atmospheric chemistry around Indonesia have been also reported. *Connors* [1995] measured very high concentrations of CO (more than 165 ppbv) over Indonesia with the Space Shuttle remote sensing; *Folkins et al.* [1997] observed atmospheric layers highly enhanced in NO, NO_y, CO and ozone near Fiji with the NASA ER-2 aircraft; *Tsuruta et al.* [1997] reported ozone enhancement from 30 to 60 ppbv throughout the troposphere over Malaysia observed with ozonesondes; and *Matsueda et al.* [1998] measured very high concentrations of CO (130 ppbv) over New Guinea Island by air samplings onboard a commercial airliner.

3.2. 1997 Enhancement

A very strong El Niño event occurred again in 1997, and extensive forest fires again occurred in mostly the same regions as in 1994 [e.g. *Wooster et al.*, 1998; *Fang and Huang*, 1998]. As seen in Figure 2, the increase of tropospheric ozone explained 100% of the total ozone increase at Watukosek. Moreover, the analysis of preliminary Earth-Probe/TOMS data also showed a total ozone enhancement with similar horizontal extent and temporal variation to the 1994 case: In October, the ozone-enhanced region with 280~290 DU spread between 75°E and 110°E in longitude and between 8°N and 10°S in latitude, and Watukosek was located at the eastern edge of the enhancement. (See also the TOMS data analysis by *Chandra et al.* [1998].) The 280 DU concentration was about 20 DU larger than the concentration in the region in August and that over the central Pacific in October. These results suggest that the enhancements of total and tropospheric ozone observed at Watukosek in 1997 were also caused by the forest fires in Indonesia.

Five of the 1997 sounding results are shown in Figure 4. On August 13, the ozone mixing ratios in the troposphere were still 15-30 ppbv except for the altitude regions below 1 km and above 15 km (Figure 4(a)). On September 17, the concentrations increased to above 40 ppbv throughout the troposphere, and a maximum of 90 ppbv was found at 6-7 km (Figure 4(b)). The largest ozone enhancement was observed on October 22 (Figure 4(c)); the concentrations exceeded 50 ppbv throughout the troposphere and exceeded 100 ppbv at several altitudes, resulting in a maximum tropospheric ozone of 55 DU. *Chandra et al.* [1998] discussed that the effect of the fires had been probably confined to the lowermost troposphere because the upward air motions over Indonesia were suppressed due to the strong El Niño event. However, our observation showed that the ozone-enriched air masses influenced by the fires well reached to the upper troposphere. In October and November, the wind below 10 km blew mostly from the east at less than 15 m s^{-1}, similar to the 1994 case. In contrast, the wind direction above 10 km exhibited east-west alternations during the same period. When the wind blew from the west, the concentrations increased significantly to more than 80 ppbv as shown in Figure 4(d). These results suggest the following scenario. The forest fire emissions had been basically transported westward from Sumatra and Borneo Islands (but Java Island was also under the influence); ozone was photochemically produced during the transport, resulting in the TOMS total ozone maximum over the eastern Indian Ocean adjacent to Sumatra Island; some of the ozone-enriched air masses which had been lifted to the upper troposphere were then sometimes transported eastward over Watukosek to increase the upper tropospheric concentration significantly. The backward trajectory analysis with the ECMWF data in October-November showed basically similar characteristics to the 1994 case; most of the trajectories in the lower and middle troposphere were stagnant near Java Island including Kalimantan. In the upper troposphere, some air masses came from the east and some came from the west, corresponding to the east-west wind oscillations observed by ozonesondes. It is also noteworthy that a positive vertical gradient of ozone is seen in the upper troposphere in Figure 4(d). This may indicate that a transport from the stratosphere had occurred at the same time. On December 16, the concentration was recovering but still very high (Figure 4(e)).

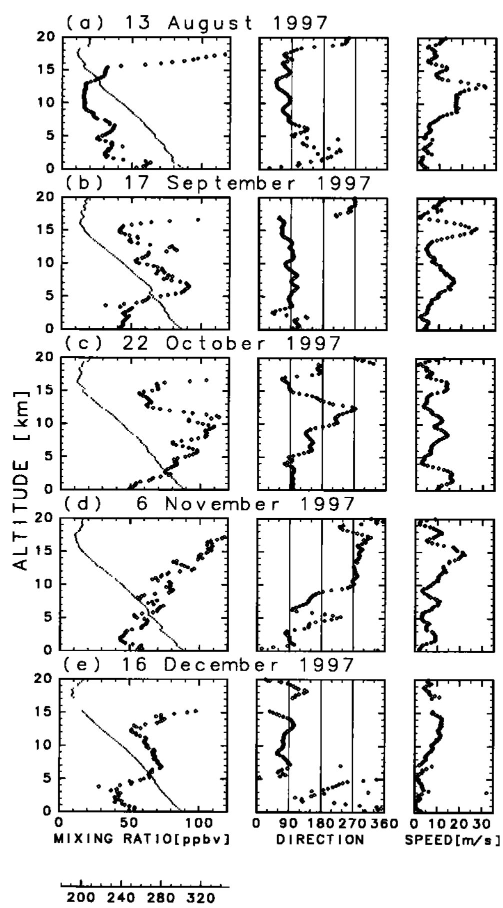

Figure 4. Same as Figure 3 but for (a) August 13, (b) September 17, (c) October 22, (d) November 6, and (e) December 16, 1997.

Reports of other in-situ observations are being prepared at present. In October 1997, aircraft measurements were conducted over Kalimantan, and extremely high CO concentrations (7-9 ppmv at 1.3 km altitude and 0.5-1 ppmv at 4.4 km) were obtained [*Sawa et al.*, 1998]. During the same campaign, *Tsutsumi et al.* [1998] reported ozone enhancements just above the planetary boundary layer where solar ultraviolet radiation could reach, suggesting photochemical production of ozone, though they also observed rather low ozone concentrations in the heavily hazy boundary layer.

4. Summary

In 1994 and in 1997 when extensive forest fires were reported in Indonesia, pronounced enhancements of total and tropospheric ozone were observed at Watukosek, Indonesia. The integrated tropospheric ozone increased from the bottom level of 20 DU up to 40 DU in 1994 and up to 55 DU in 1997. In both cases, most of the total ozone enhancements observed in the same periods originated in the troposphere. On October 13, 1994, the ozone mixing ratios were mostly above 50 ppbv throughout the troposphere and exceeded 80 ppbv at some altitudes. On October 22, 1997, the concentrations were above 50 ppbv throughout the troposphere and exceeded 100 ppbv at several altitudes. The coincidences of the enhancements with the forest fires suggest that they were both caused by the photochemical production in the troposphere through the ozone precursor gases emitted from the fires.

The years 1994 and 1997 correspond to years of El Niño events when convective activity becomes low in Indonesia. Under such a condition, the precipitation becomes considerably sparse compared to the normal year, and forest fires may occur and widely spread. Thus, it is likely that, in the Indonesian region, pronounced enhancements of tropospheric ozone associated with extensive forest fires may take place with a period of a few years coinciding with El Niño events. This is in a marked contrast to the situation in South America and Africa where large-scale biomass burnings occur every year.

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