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A Case Study on the Biomass Burning in Southeast Asia and Enhancement of Tropospheric Ozone over Hong Kong

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Abstract. Substantial enhancement of ozone was frequently observed in the lower troposphere (2.5-6.0 km) over Hong Kong (22.2°N, 114.3°E). Most of these enhanced ozone layers (with peak concentration up to 138 ppbv) feature moderate and high relative humidity (50-100%) and a temperature inversion at the bottom of the layer. These phenomena predominantly occur in spring (late February to mid April) coinciding with the dry season in Southeast Asia. Back air trajectories showed that these ozone-rich air masses had passed through the Indo-Burma region of Southeast Asia, where large-scale fires were recorded at the time. A case study is presented and evidence from the fire count derived from AVHRR satellite images and carbon monoxide concentration derived from space shuttle during the MAPS experiment was used. We have illustrated with this case study that biomass-burning emissions are the source of the elevated ozone observed.

1. Introduction

Biomass burning emissions in the tropics had been reported to exert a strong influence on the abundance of trace gases in the atmosphere (*Crutzen and Andreae,* 1990). Tropical Asia is a region of extensive biomass burning (*Christopher and Kimberly,* 1996; *Christopher et al.,* 1998 and *Folkins et al.,* 1997). Christopher and Kimberly had successfully identified east-central India and the region containing Thailand, Laos, Cambodia and Vietnam as the two major areas of biomass burning in India and Southeast Asia (SE Asia). Large amounts of carbon monoxide (CO), hydrocarbons and nitrogen oxides are emitted to the atmosphere and are transported downwind. However, the effect of the emissions from large-scale fires in SE Asia is less well known when compared with fires in most other regions (*Folkins et al.,* 1997; *Christopher et al.,* 1998).

In this study, we present a case study indicating that biomass burning emissions in SE Asia are the source of ozone enhancement in the lower troposphere in springtime at Hong Kong. Evidence from ozonesonde profiles, fire-count satellite images derived from the global 1-km Advanced Very High Resolution Radiometer (AVHRR), CO levels derived from space shuttle during the Measurement of Air Pollution from Satellite (MAPS) experiment and back air trajectory analysis are used.

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2. Elevated Ozone Enhancement in the Lower Troposphere

Elevated ozone enhancement had been captured by ECC ozonesondes launched in Hong Kong throughout January 1994 to April, 1997, during which a total of 159 ozone profiles were available. Ozone enhancement with peak concentration as high as 138 ppbv was frequently captured by ozonesonde soundings during late winter and spring period (late February to mid April). The enhancement features ozone-rich layers overlying the lower troposphere at about 2.5 to 6.0 km above the ground. The layers are usually 2 - 3 km thick and are characterized by moderate to high relative humidity (50 to 100%). The high value of relative humidity distinguishes the ozone-rich air from the ones originating from the upper troposphere or stratosphere in very recent history, which are usually accompanied by dry air with low relative humidity (*Johnson and Viezee,* 1981). The ozone-rich layer also distinguishes itself from ozone in the local boundary layer by a temperature inversion at the bottom of the layer. Occasionally, the elevated ozone-rich layers may extend to 10-12 km with a moderate relative humidity of 20-40%.

A relevant case was observed in April 1994 and the corresponding tropospheric ozone profiles on April 8, 14 and 21 are presented in Figure 1. In this case, the ozone enhancement was not only observed at the typical (2.5-6.0 km) lower troposphere as reported by *Liu et al.* (1999) but also occurred throughout the whole tropospheric column and there is indication that the origins of these enhancements are similar. Peak ozone with concentration over 100 ppbv was detected in the troposphere. Enhancement in the lower troposphere (2.0-4.0 km) was caught on April 8 and April 14, which started to subside on April 21. Local peaks were found at altitudes from 2.6 to 4.0 km (Figure 1a, 1b and 1c). The peaks were 78, 101 and 55 ppbv respectively. The temperature inversions were at about 1 km. Note the substantial difference in the relative humidity below and above the ozone rich layers in the lower troposphere (Figure 1a and 1b). From figure 1b, we see that ozone enhancement also occurred at higher levels with peak concentrations at 6.8, 7.4, 9.0 and 11.2 km. The

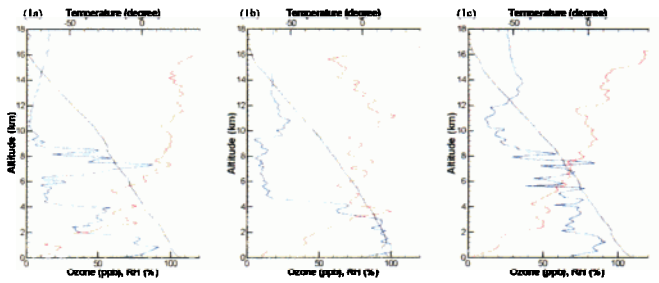

Figure 1. Ozone (red line), temperature (dark line) and relative humidity (blue line) profiles on (a) April 8, (b) 14 and (c) 21, 1994.

accompanying relative humidity however showed lower values (around 10 to 30%) than that at the lower troposphere. Such events were observed less frequently than that occurred in the lower troposphere. The value was higher than the relative humidity value usually observed in this season (< 10%).

3. Fire Count from Satellite Images and CO from MAPS

The period of ozone enhancement (late February to middle April) coincides with the dry season in the Burma and Vietnam region of SE Asia, when induced fires from human activities are frequent due to large-scale forest clearing for agricultural purposes (*Stott*, 1988). We used the global 1-km Pathfinder data from the NOAA AVHRR 11 during April 9-19, 1994, to detect and quantify the fires occurring over the India and Burma region. The study area covers the region from 10°N - 30°N and 85°E - 110°E (Figure 2a). *Christopher et al.* (1998) had described the method of fire detection. We also used CO measured from the space shuttle (Endeavor) during the

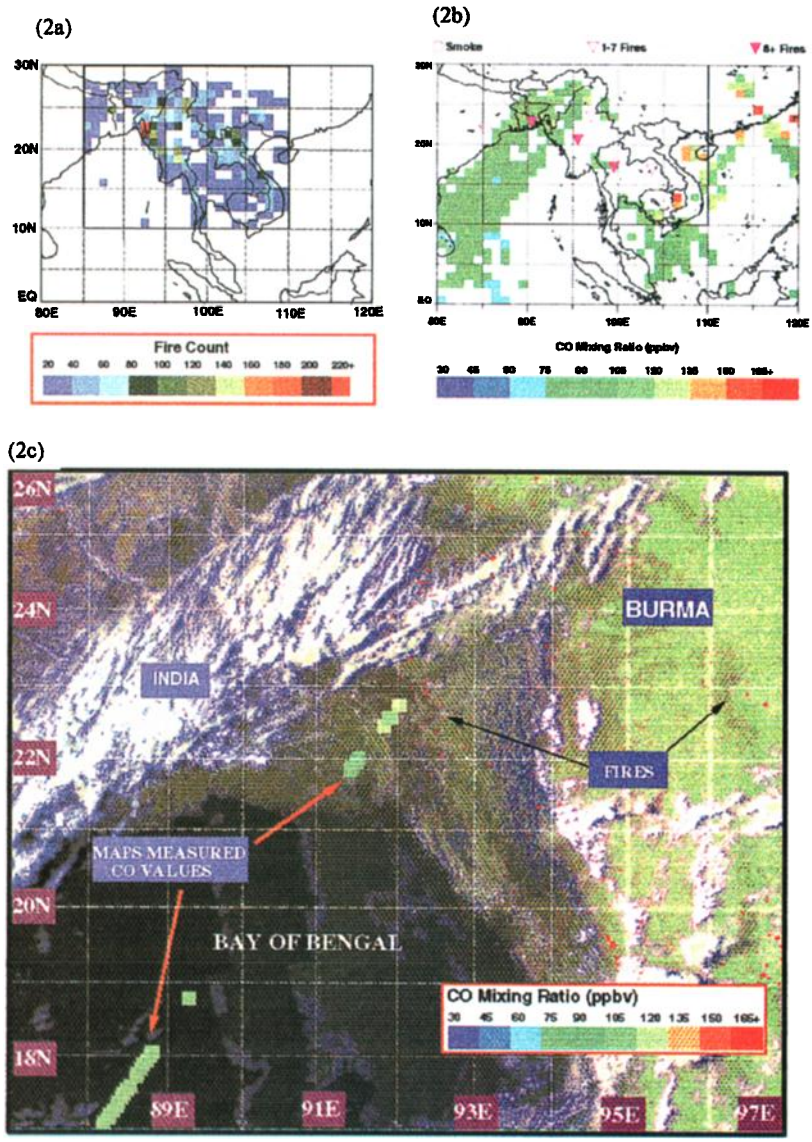

Figure 2. (a) Fire counts estimated from AVHRR (b) MAPS measured CO concentrations on 1 by 1 degree grid from April 9 to 19, 1994. The astronaut observations of fires and smoke are shown as purple triangles and circles. (c) A three-band overlay from AVHRR imagery on April 11, 1994. Fires are denoted in red. Also shown are the MAPS measured CO concentrations.

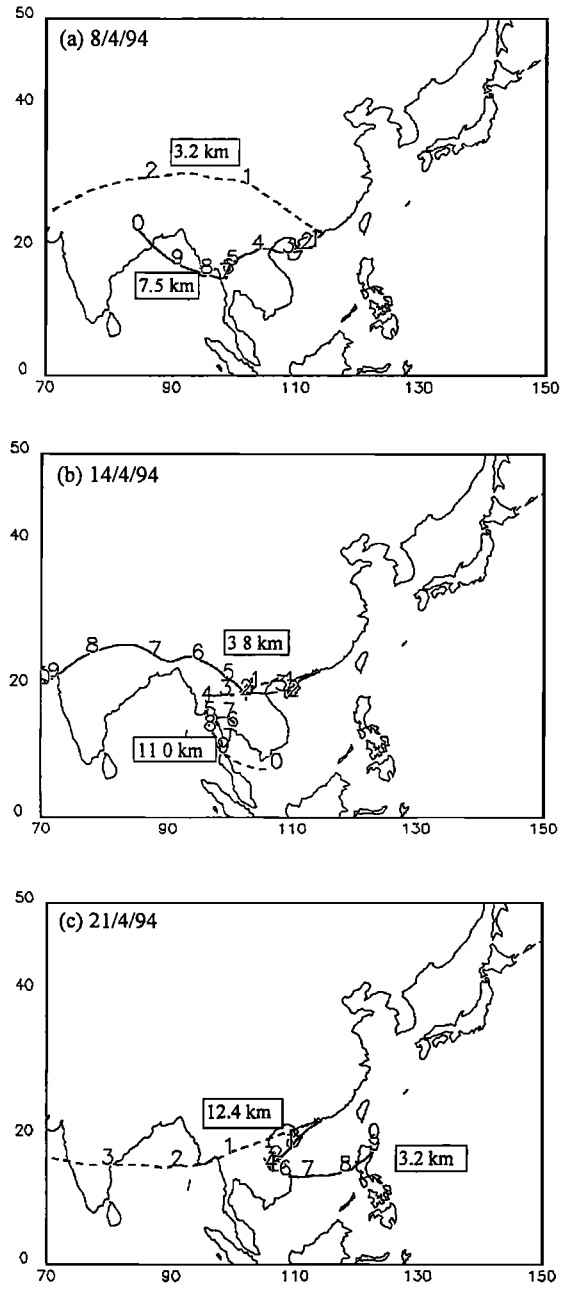

Figure 3. Back air trajectory for 00 UT at (a) 3.2 and 7.5 km on April 8, (b) 3.8 and 11.0 km on April 14 and (c) 3.2 and 12.4 km on April 21, 1994. The trajectories at 12 UT show similar patterns.

intensive experiment of the MAPS to trace the pollution plume due to the fires (Figure 2b). The CO detected from MAPS refers to the mixing ratio at middle-troposphere around 8 km and was available during the MAPS period from April 9-19, 1994. The emissions from the industrial and vehicular sources at ground level would not be expected to reach such altitude in very short time without strong buoyancy such as the one provided by forest fires.

Table 1 summarizes the total number of fires detected in the MAPS period and the relevant information of the AVHRR images used for analysis. More than 7550 fires the fire count and CO mixing ratio deduced from AVHRR and MAPS respectively (adopted from Christopher et al., 1998). Included also are the locations of fires (triangles) and smoke (circles) as observed by astronauts (Figure 2b). Active fires were found in the region of the Indo-Burma border. The maximum fire count (140) was detected between 94° and 96°E, and between 20° and 22°N. Note that the region is in the close proximity and upwind of Hong Kong. Enhanced CO (140 ppbv) was found in southeastern China and extended further to the South China Sea and Pacific Ocean (15°N, 107°E - 25°N, 120°E). These phenomena were confirmed by observations from astronauts. In particular, smoke plumes were observed in northeastern India (85°E, 22°N) and the western Pacific Ocean around 120°E and 23°N, which is close to Hong Kong. From April 9 to 13, there were a total of 2957 fires detected in SE Asia and Indo-Burma region (Table 1). Figure 2c also shows the AVHRR image over the India-Burma border from 1054 to 1063 UT for April 11, 1994, three days before the ozone peak observed at the lower troposphere on April 14. This image shows 224 fires. The smoke produced from the burning is indicated by a light yellow color. Over the active fires region, high CO values (120-135 ppbv) were detected as indicated by the yellow and orange in the figure. Such elevated level indicated that there was enhancement of CO from active fires.

4. Back Air Trajectories

We performed back air trajectory calculations for all the ozone profiles using the model described by *Harris and Kahl* (1990) and input data from European Center for Medium-Range Weather Forecasts. Figure 3 shows the trajectories for local ozone peaks at 3.2 and 7.5 km for April 8, 3.8 and 11.0 km for April 14 and 3.2 and 12.4 km for April 21. The trajectories showed that the ozone-rich air masses did traverse across the regions of active fires and enhanced CO before arriving in Hong Kong. On April 8, the air masses at 3.2 and 7.5 km came from the west and passed over India early in its journey before traversing across the Indo-Burma region and advancing to southeast China and Hong Kong (Figure 3a). Although

Table 1. Fires detected from NOAA AVHRR 11 images during April 9-19, 1994, MAPS mission.

Day	AVHRR Start time (UT)	AVHRR End Time (UT)	Latitude (N)	Longitude (E)	No. of Fires
9	9.27	9.35	8.64-29.29	89.34-121.6	1007
10	9.06	9.14	8.64-29.29	92.48-124.75	383
11	8.85	8.94	8.64-30.0	95.62-127.91	73
	10.54	10.63	5.75-30.0	70.14-103.0	224
12	8.63	8.73	5.74-30.0	98.76-131.64	14
13	10.12	10.22	8.59-29.99	76.42-109.3	1256
14	9.93	10.01	8.59-29.99	79.55-111.89	3585
15	9.72	9.81	8.62-30.0	82.69-115.04	544
16*					
17	9.31	9.39	8.62-30.0	88.96-121.35	180
18	9.1	9.18	8.62-30.0	92.10-124.51	118
19	8.89	8.98	8.6-29.29	95.25-127.67	130
	10.58	10.68	5.74-30.0	69.75-102.75	37
				Total	7551

*Image not used due to calibration problem.

we did not have fire information in this period, the high number of fires recorded on April 9 and 10 (1007 and 383 respectively) should also indicate that the fires did occur. Thus, enhanced ozone was observed in April. On April 14, the air masses at 3.8 and 11.0 km passed over the Indo-Burma region at 6 to 3 days before arriving in Hong Kong (Figure 3b), where active fires were detected at this time (Table 1). In addition, they did traverse across southeast China and South China Sea where MAPS captured enhanced CO (Figure 2c). The situation at 12.4 km on April 21 (Figure 3c) was similar.

We expect similar outflow of other trace gases such as NO_x and hydrocarbons being caught into the back air masses reaching Hong Kong like the high CO concentration along the air mass paths as indicated by the MAPS data. The CO enhancement leads us to believe that there is possible interaction of the CO-OH-CH_4 cycle that affect the partition between NO_x (NO, NO_2) and HNO_3 and other key ratios of radicals species. Because of the observed high CO, the interaction of the CO-OH-CH_4 cycle (*Sze*, 1977) will shift OH into HO_2 (i.e. elevating HO_2 relative to OH via the cycle). The reaction of HO_2 with NO followed by photolysis of NO_2 will produce atomic oxygen, which readily combines with molecular oxygen to form ozone (*Liu et al.* 1987). Also note that suppression of OH by high CO will elevate or free-up more NO_x ($NO+NO_2$), because of lesser OH for converting NO_2 into the more inert form HNO_3. One possible ozone production sequence can be written as:

$$CO + OH \rightarrow CO_2 + H$$
$$H + O_2 + M \rightarrow HO_2 + M$$
$$HO_2 + NO \rightarrow OH + NO_2$$
$$NO_2 + h\nu \rightarrow NO + O$$
$$O + O_2 + M \rightarrow O_3 + M$$
$$\text{Net:} \quad CO + 2O_2 \rightarrow CO_2 + O_3$$

Eventually, this chemical mechanism may lead to the formation of ozone within the air mass during their 3 to 6 days' transport to Hong Kong. We thus believe that the enhanced ozone observed at Hong Kong is a result of the subsequent photochemical buildup of ozone from biomass burning emissions originating from SE Asia. The trajectory of the air masses strongly affected the occurrence of ozone enhancement. In fact, the ozone profile on April 21 (Figure 1c) did not show much ozone enhancement at the lower troposphere even though fires had been detected in SE Asia at the relevant period (Table 1). On examining the trajectory at 3.2 km on this day, we found that the air mass originated from the Pacific Ocean. It traversed through South China Sea and it only passed through a small portion of the SE Asia region of active fires (Figure 3c). The air mass was thus less affected by the biomass burning emissions and there was less enhancement of ozone.

5. Conclusion

There is only limited study on ozone and biomass burning in tropical and subtropical regions of SE Asia. Our case study in April 1994 showed that there was high ozone enhancement due to biomass burning emissions from the Indo-Burma region of SE Asia and the subsequent photochemical buildup of ozone during its transport to Hong Kong. Judging from the air mass flow as indicated by the trajectory and the CO distribution displayed by the MAPS data, it is reasonable to deduce that the ozone enhancement such as observed over Hong Kong would also occur over subtropical South China and the western coast of Pacific Ocean. The high CO concentration as revealed by the MAPS data and strong correlation between CH_4 and CO in SE Asian fires point to the likelihood of the occurrence of elevated ozone production through the chemical mechanisms such as CO-OH-CH_4 cycle and photochemistry involving nitrogen oxides and hydrocarbons. Our study has shown the importance of ozone enhancement in the troposphere of subtropical South China caused by biomass burning in SE Asia.

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