JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. D14, PAGES 14,875–14,885, JULY 27, 2001

Effects of 1997 Indonesian forest fires on tropospheric ozone enhancement, radiative forcing, and temperature change over the Hong Kong region

C. Y. Chan, L. Y. Chan, and Y. G. Zheng

Department of Civil and Structural Engineering, Hong Kong Polytechnic University, Hong Kong

J. M. Harris and S. J. Oltmans

NOAA Climate Monitoring and Diagnostic Laboratory, Boulder, Colorado

S. Christopher

Department of Atmospheric Science, University of Alabama in Huntsville, Huntsville, Alabama

Abstract. Tropospheric ozone enhancements were measured over Hong Kong (22.2°N, 114.3°E) by electrochemical concentration cell ozonesondes during the 1997 period when many forest fires were burning in Indonesia. The enhancements have a maximum ozone concentration of up to 130 ppbv and an ozone-enhanced layer depth of 10 km. We used Total Ozone Mapping Spectrometer, advanced very high resolution radiometer satellite image, and back air trajectory to identify the source region and the transport pattern of ozone. The strong tropospheric ozone enhancements covered all of tropical Southeast Asia and subtropical south China. They were due to photochemical ozone buildup from the biomass burning emissions from the Indonesian fires. The ozone-rich air mass was transported to Hong Kong following the east Asia local Hadley circulation and an abnormal anticyclonic flow related to the El Niño phenomenon in the tropical western Pacific. A rough estimation of the radiative forcing due to the ozone enhancement was carried out for two cases in October and December in 1997 using a normalized tropospheric ozone radiative forcing parameter derived from the Unified Chemistry-Climate model [*Mickley et al.*, 1999]. The ozone enhancements induced an additional radiative forcing of 0.26 and 0.48 Wm^{-2} compared to the normal total forcing of 0.48 and 0.39 Wm^{-2} in October and December over the Hong Kong region. Estimation of the associated surface temperature change suggests that enhanced ozone from biomass burning on the scale of the 1997 Indonesian fires may have significant impact on regional surface temperature change.

1. Introduction

Extensive and widespread forest fires swept through Kalimantan and Sumatra, Indonesia, in 1997 [*Levine*, 1999; *Thomas et al.*, 1998]. The fires were initially associated with routine biomass burning for land clearing and agricultural purposes. However, they soon got out of control and spread over large regions because of severe drought conditions related to El Niño. *Levine* [1999] estimates that some 45,600 km^2 of land were burned between August and December 1997. On the basis of this figure, Levine estimates huge amounts of CO_2, CO, CH_4, NO_x, and particulates were emitted into the atmosphere. As these pollutants were transported downwind, high levels of ozone, NO_x, CO, and aerosols were induced over Kalimantan, Sumatra, and the surrounding regions in Southeast Asia (SE Asia) and Australia [*Tsutsumi et al.*, 1999]. *Matsueda and Inoue* [1999] report that there was a strong outflow of trace gases from the intense Indonesian biomass burning region and there were notable perturbations to atmospheric composition over Singapore and the South China Sea. *Fujiwara et al.* [1999] reports significant enhancements of photochemical production of tropospheric ozone because of the Indonesian forest fire over Watukosek (7.5°S, 112.6°E).

We measured substantial ozone enhancements over Hong Kong during the 1997 Indonesian fire period. Ozone is an effective greenhouse gas in the troposphere [*Fishman et al.*, 1979; *Intergovernmental Panel on Climate Change* (IPCC), 1996]. It plays an important role in the energy budget of the atmosphere. Changes in tropospheric ozone can alter the radiative forcing of the troposphere-surface system. Increases of ozone, especially in the upper troposphere, can induce a positive forcing (warming) and an increase of surface temperature [*Wang et al.*, 1993; *Mohnen et al.*, 1995]. In this study, we report and investigate two cases of abnormal ozone enhancements over Hong Kong related to the Indonesian forest fire in 1997. We present a preliminary estimation the impact of such ozone enhancements had on tropospheric radiative forcing and surface temperature changes.

Paper number 2001JD900092.
0148-0227/01/2001JD900092$09.00

2. Tropospheric Ozone Enhancement Over South China and Hong Kong

Abnormal ozone enhancements were measured in the troposphere over Hong Kong on October 16, 1997, and on December 3, 1997. From August to December 1997, when many fires were burning in Indonesia, an ozone profile was available once per month. A detailed description of the experimental procedures is given by *Chan et al.* [1998b, 2000]. Ozone was monitored by electrochemical concentration cell ozonesondes with simultaneous relative humidity (RH), temperature, and wind measurements. Figure 1a shows the ozone, RH, and temperature profiles for the enhancement cases. Figure 1b shows the respective average profiles of the relevant months from 1993 to 1998. In the October case, ozone showed a steady increase from the lower troposphere at around 4.0 km above ground to three local peaks at 8.0 (86 ppbv), 10.0 (86 ppbv), and 12.2 km (94 ppbv). Ozone had a sharp local maximum at 14.8 km (130 ppbv). In the December case, ozone showed a sharp and substantial increase from 35 ppbv at 4.0 km to 100 ppbv at 6.0 km. Ozone varied from this mixing ratio by about 10 ppbv up to 15.0 km. The ozone enhancement layer was around 10 km thick. The substantial enhancements of ozone are apparent when we compare these ozone profiles to the averaged monthly ozone profiles from 1993 to 1998. The maximum average ozone concentrations in the troposphere in these 2 months were usually lower than 60 and 65 ppbv, respectively (Figure 1b). The ozone enhancements are significant in the upper troposphere.

The ozone enhancements in our cases were accompanied by abnormally high RH values from the middle to upper troposphere when compared to the average RH profile (Figure 1). Such relatively high RH suggests that the ozone-rich air masses were not from the stratosphere. This is because the air mass from the stratosphere in recent history is usually dry with low RH [*Johnson and Viezee*, 1981]. *Chan et al.* [1998a], and *Newell et al.* [1997] report that the high water vapor air masses observed in the middle to upper troposphere over Hong Kong are originated in the tropical region. *Chan et al.* [2000] finds that the high relative humidity air masses with ozone enhancements were from the Indo-Burma region of the tropical SE Asian continent.

Table 1 summarizes the integrated tropospheric ozone column (TOC) for the two cases calculated from the surface to the first tropopause. Table 1 also shows the average TOC during October and December from 1993 to 1998. The TOC values of the enhancement cases reached 44.6 and 48.3

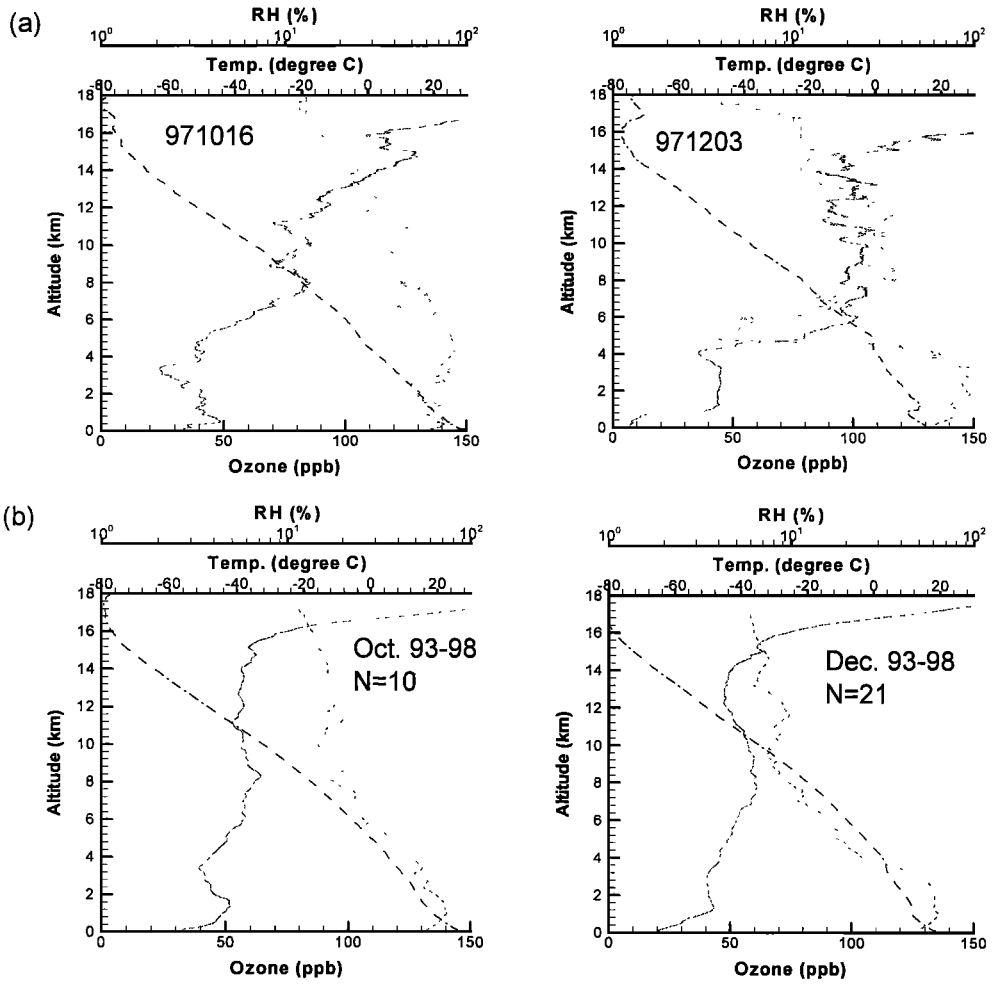

Figure 1. Ozone (solid), temperature (dot - dashed) and relative humidity (dashed) profiles on (a) October 16 and December 3, 1997, and (b) the monthly average ozone and relative humidity profiles in October and December from 1993 to 1998.

Table 1. TOC, Estimated Radiative Forcing F, and Surface Temperature T Changes due to Ozone Enhancement over the Hong Kong Region on October 16 and December 3, 1997

	TOC, DU	Additional TOC, DU	Additional F, Wm^{-2}	Temperature Change, °C
Oct. 16, 1997	44.6	8.7	0.26	0.14
Dec. 3, 1997	48.3	15.4	0.48	0.26
Oct. 1993-1998	35.9	-----	-----	-----
Dec 1993-1998	32.9	-----	-----	-----

Dobson units (DU), respectively. They were the maximum values of the respective months and exceeded the climatological values of the relevant months by 8.7 and 15.4 DU, respectively. The integrated ozone increases in the ozone enhancement layers were 7.9 and 15.2 DU, respectively. We also explored the TOC in tropical SE Asia and in the subtropical region near the vicinity of Hong Kong and south China during the ozone enhancement periods. Plate 1a shows the 9 day composite TOC mapping from October 8 to16 and November 25 to December 3, 1997. The maps were prepared by the Department of Meteorology, University of Maryland (available at http://metosrv2.umd.edu/~tropo/). Plate 1b shows the TOC maps for the corresponding periods in 1998 for comparison. The TOC is deduced by a modified-residual method using the Nimbus 7/Total Ozone Mapping Spectrometer (TOMS) level 2 data [*Hudson and Thompson*, 1998]. It has been validated by observational data [*Thompson and Hudson*, 1999]. The TOC map has a spatial resolution of 1° latitude and 2° longitude. The precision is 5 DU.

In the October case the TOC had a strong ozone enhancement in the whole of tropical SE Asia as compared with the other regions over the Pacific and Indian Oceans. The enhancement is especially apparent over the Kalimantan and Sumatra regions as well as their immediate vicinities (10° S, 75° E-10° N, 120° E). The TOC ranged from 55 to 80 DU. In the second case the enhancement was also apparent, although it is less distinct. The TOC ranged from 50 to 60 DU. The TOC in 1998 in the Pacific and Indian Oceans was usually much less than 30 DU (Plate 1b). We found that ozone enhancement in the tropical SE Asia and subtropical south China regions occurred not only in the above periods but also in the whole of October and December (not shown).

The increases of ozone concentrations and TOC in our ozone enhancement cases are higher than the ones reported by other studies for the Indonesian fires. *Fujiwara et al.* [1999] reported increases of tropospheric ozone with concentration of 50-80 ppbv on October 13, 1994, and 50-100 ppbv on October 22, 1997, over Watukosek, Indonesia. The ozone increases led to TOC enhancements of 20 and 35 DU, respectively. *Hauglustaine et al.* [1999] reported a TOC increase of 20-25 DU and an ozone-mixing ratio of 50 ppbv in the midtroposphere in November 1997 over Sumatra and Kalimantan. *Chandra et al.* [1998] detected a 10-20 DU TOC increase in the Indonesian region during the El Niño period in 1997. *Tsutsumi et al.* [1999] reported a maximum ozone concentration of 80 ppbv in the midtroposphere over Kalimantan. In our cases the maximum ozone concentration measured by ozonesonde over Hong Kong reached 130 ppbv. The maximum TOC increase derived from TOMS over SE Asia was around 50 DU. The ozone enhancements occurred mainly in autumn and winter of 1997 in the middle and upper troposphere. These ozone enhancements due to Indonesian fires are in a similar magnitude as those due to the fires in SE Asia. *Liu et al.* [1999] and *Chan et al.* [2000] report that the ozone enhancements over Hong Kong due to biomass burning in SE Asia can reach a maximum of 138 ppbv. The enhanced ozone is mainly found in the lower troposphere (2.5 – 6.0 km).

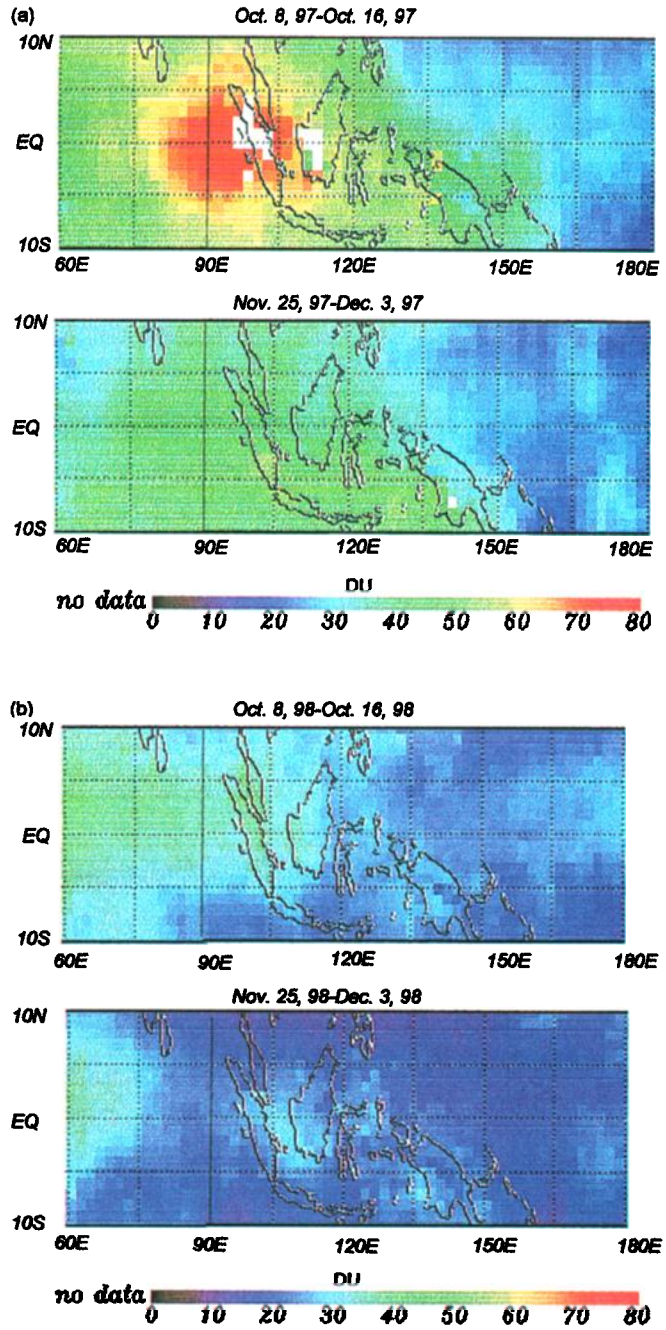

Plate 1. Tropical tropospheric ozone column from October 8 to 16 and November 25 to December 3 in (a) 1997 and (b) 1998. The enhancement is especially apparent over the Kalimantan and Sumatra regions as well as their immediate vicinities (10° S, 75°E-10° N, 120° E). The TOC ranged from 55 to 80 DU.

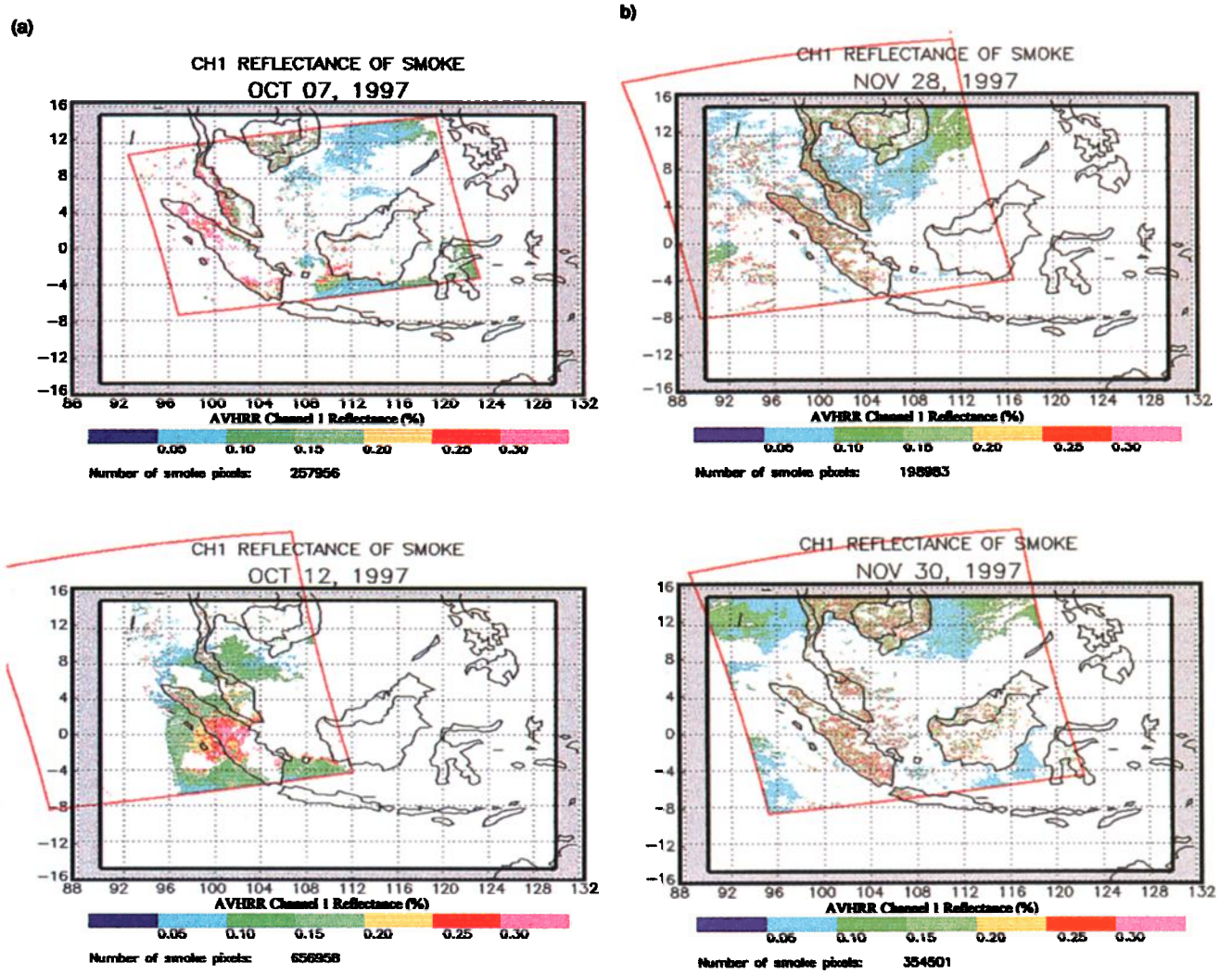

Plate 2. Smoke pixels estimated from AVHRR on (a) October 7 and 12 and (b) November 28 and 30, 1997. The borders are the coverage of the satellite images.

3. Fire and Smoke Detection

We used satellite images from the NOAA advanced very high resolution radiometer to detect and quantify the fires and smoke in the region for the periods of interest. The fire and smoke detection methods are described by *Christopher et al.* [1998]. Satellite images were available on October 7, 12, 13, and 14, November 25, 27, 28, 29 and 30, and December 1. A total of 2600 fires were detected during the periods from October 7 to 14, 1997. More than 700 fires were detected from November 25 to December 1, 1997. Active fires were found in the region of Sumatra. Some hot spots were also found in the Malaysia peninsula and Indo-China regions of the SE Asian subcontinent. Enhanced smoke was widespread over the whole of SE Asia. It extended farther to the subtropical region of south China.

The total relevant numbers of smoke pixels were 1,760,000 and 1,010,000 for the 10 days before October 16 and December 3, 1997, respectively. Plate 2a shows the smoke plots for the October 7 and 12, which were 9 and 4 days respectively, before the measurement of the ozone enhancement in October case. Plate 2b shows the smoke plots for November 28 and 30, which were 5 and 3 days before the December case. On October 7 and 12, 260,000 and 660,000 smoke pixels were detected. On November 28 and 30, 199,000 and 355,000 smoke pixels were detected. We noted that while most hot spots were found in the Sumatra region, extensive smoke pixels were also found downwind over the Malaysia peninsula, the SE Asian subcontinent, and the South China Sea. Plate 3 presents the AVHRR image captured on October 14, 1997. The locations of the fires are indicated by the red dots. A total of 1400 fires was detected in this image. The widespread smoke outflow to the subtropical region is clearly indicated by the yellowish color near the Sumatra, Kalimantan, and Malaysian regions. It is less distinguishable over the South China Sea. This was partly due to the fact that many areas were covered by cloud (Plate 3), which made the detection difficult.

Smoke formed during biomass burning is considered to be a good tracer of the associated pollutant emissions and their movements in the troposphere. *Tsutsumi et al.* [1999] report that there was an enhanced ozone concentration accompanying the middle layer of the smoke haze over Kalimantan and Australia. *Folkins et al.* [1997] reports layers of enhanced ozone concentration together with other chemical species (NO, NO_y, and CO) in the plumes from biomass burning in Indonesia, Australia, and New Guinea during September and October, 1994. *Matsueda and Inoue* [1999] also report enhancements of CO_2, CO, and CH_4 in the upper troposphere over the South China Sea in the 1997 Indonesian

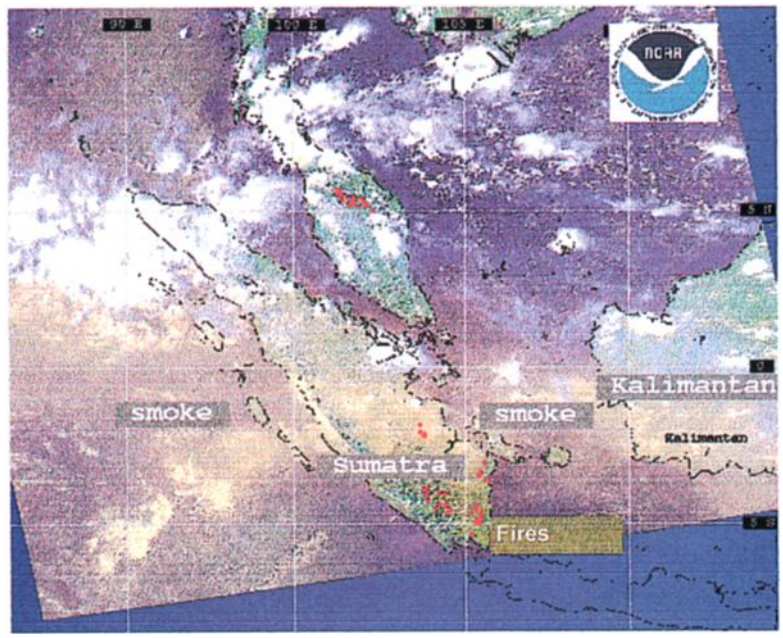

Plate 3. The AVHRR image on October 14, 1997. The locations of fires are red dots, and the smoke is a yellowish color. The cloud is white.

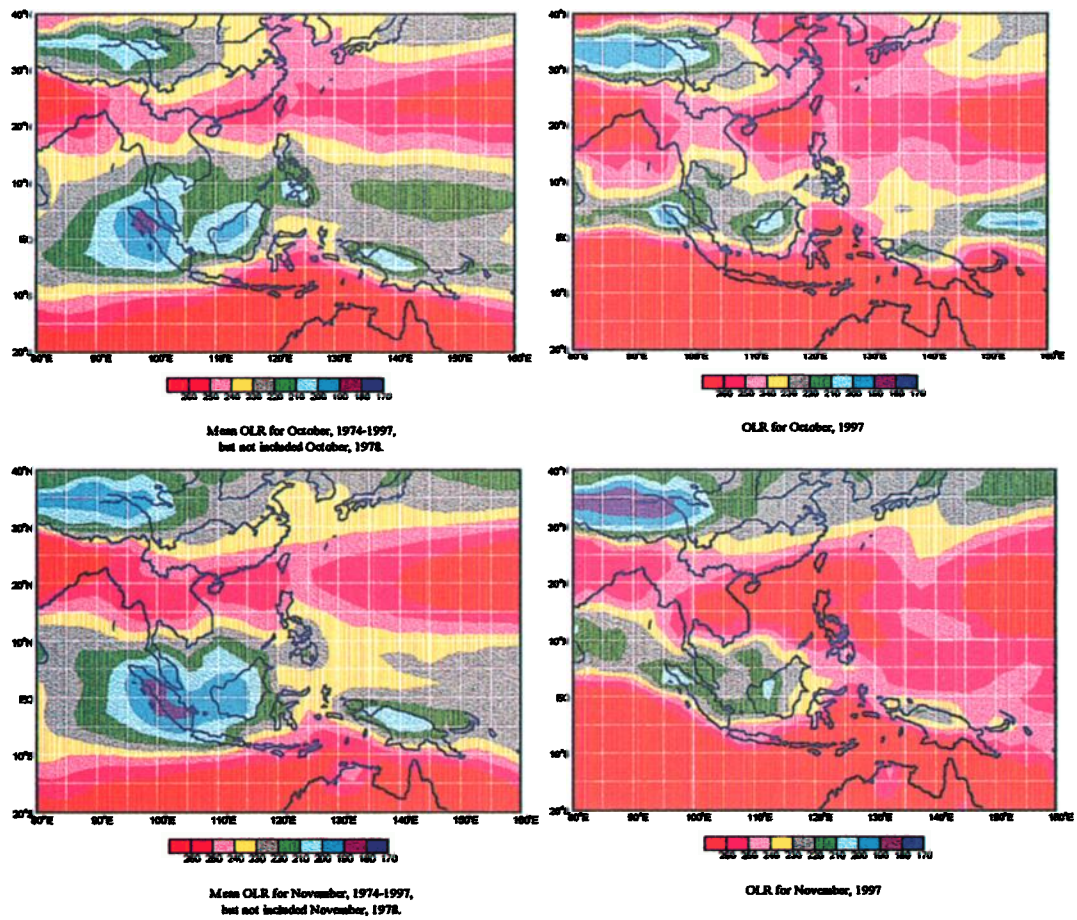

Plate 4. Monthly average OLR (Wm^{-2}) in the tropical and subtropical Western Pacific in October and November 1997 and from 1974 to 1997 (excluding 1978). High values of OLR correspond to suppressed convective activity.

fire event. The researchers find that the enhanced trace gases of the Indonesian biomass plume showed a strong linear correlation between CH_4 and CO and between CO and CO_2. *Thomas et al.* [1998] reports that there was a twofold increase in the vertical NO_2 content over large parts of the smoke cloud over SE Asia from August to October 1997. *Hauglustaine et al.* [1999] reports CO increases by up to 1000 ppbv in the free troposphere over Indonesia during the fire period in 1997.

The enhancements of these chemical ozone precursors may eventually lead to an elevated photochemical ozone production and ozone buildup in the troposphere during transport of the biomass plume. The net photochemical production of ozone in the troposphere involving its precursors (CH_4, CO, and hydrocarbons) requires only trace amount of NO_x as a catalyst. Given enough precursors in the biomass plume, the photochemical ozone production and buildup may follow the CO-OH-CH_4 cycle and photochemistry involving nitrogen oxides and hydrocarbons during the transport of the air mass. For instance, 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 less available OH for converting NO_2 into the more inert form HNO_3. One possible ozone production sequence can be written as

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

The above evidence suggests that there was enhanced photochemical production of ozone during the outflow of all trace gases to subtropical south China and Hong Kong. This is especially true in the middle and upper troposphere as the ozone lifetime is longer and the solar radiation is more available in these regions. Such photochemical ozone production occurring in biomass plumes has been reported for South American and African fires [*Crutzen et al.*, 1979; *Delany et al.* 1985; *Thompson et al.*, 1996]. It also has been reported to cause the tropospheric ozone enhancement observed over the tropical south Atlantic [*Mauzerall et al.*, 1998] and subtropical south China [*Liu et al.*, 1999, *Chan et al.*, 2000].

4. Back Air Trajectories

Figure 2 and 3 present the back air trajectories of the 2 ozone enhancement days. The trajectories used in this study were calculated by the model described by *Harris and Kahl* [1994]. In this model, air parcel is assumed to move dry adiabatically along isentropic surfaces. The model calculates 10 day back air trajectories using the input meteorological and

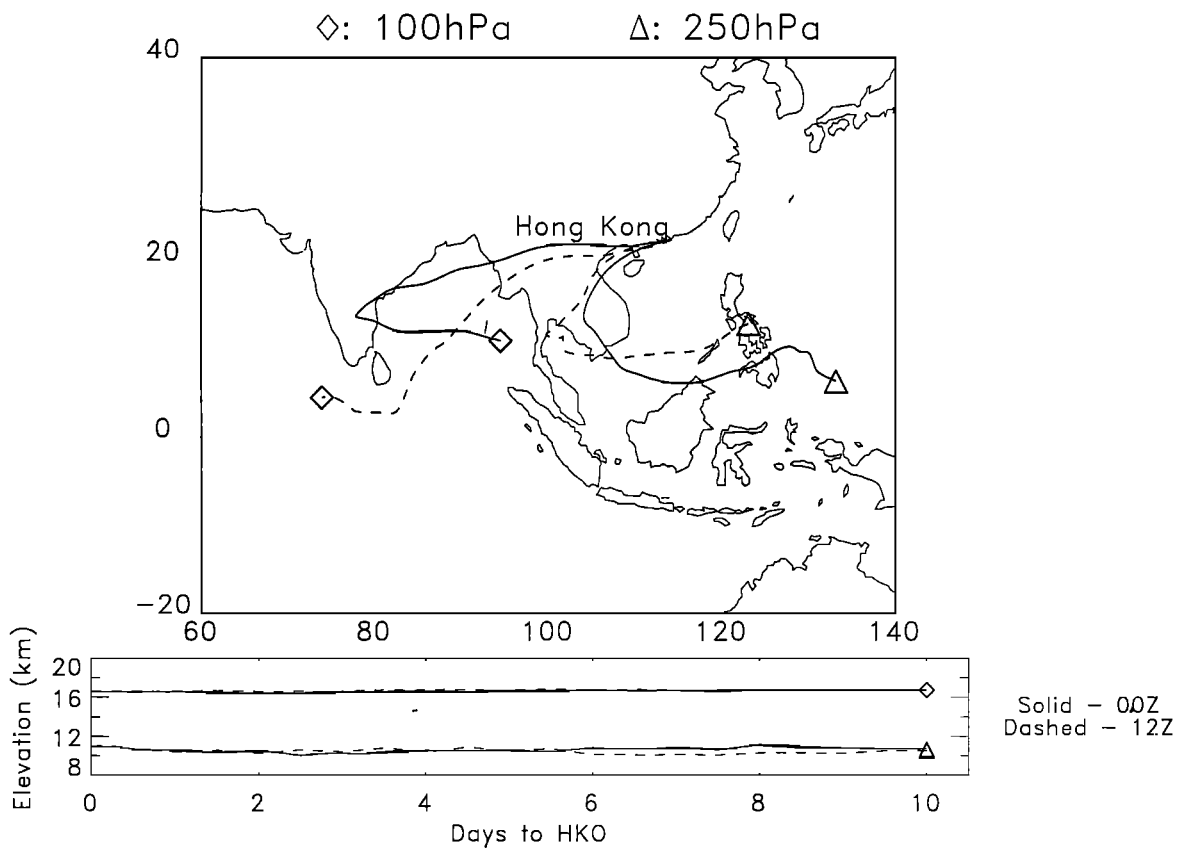

Figure 2. Back air trajectory on October 16, 1997 at 11.0 (250 hPa) and 16.6 km (100 hPa). Solid and dashed lines are for 00:00 and 12:00 UT, respectively.

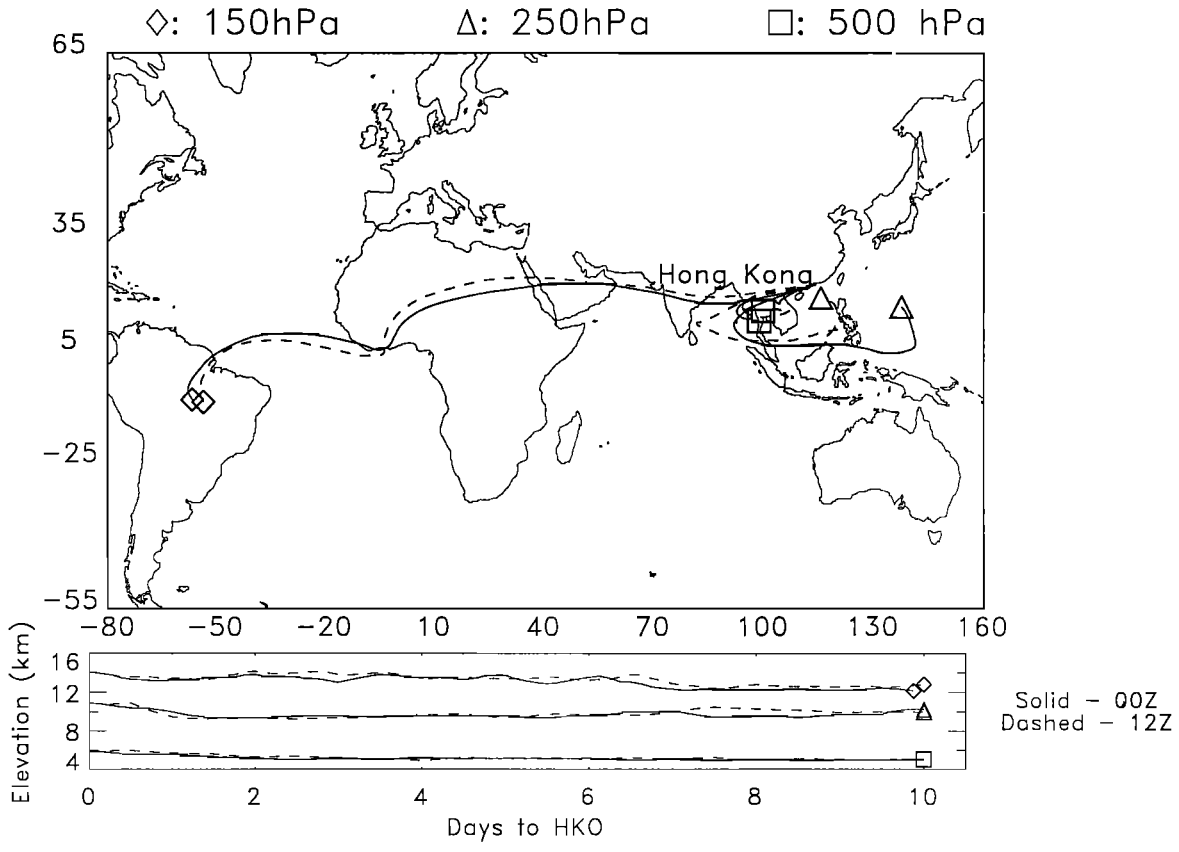

Figure 3. Back air trajectory on December 3, 1997 at 5.9 (500 hPa), 10.9 (250 hPa), and 14.1 km (150 hPa) Solid and dashed lines are for 00:00 and 12:00 UT, respectively.

topographic data from the European Center for Medium Range Weather Forecasts or National Meteorological Center of the United States. The data have a spatial resolution of 2.5° and a temporal resolution of 12 hours. Two trajectories are produced daily at 00:00 and 12:00 UT (0800 and 2000 Hong Kong time) and given together with altitude, pressure, and temperature at each point. The trajectories from the model are believed to give reasonable representations of the large-scale circulation motion. They can be used to identify the potential source region of pollutants [*Harris and Kahl*, 1994], although the specific origin of an air parcel cannot be determined exactly. Trajectory models are subject to uncertainties that arise from interpolation of sparse meteorological data, assumptions regarding vertical transport, observational errors, sub-grid-scale phenomenon, turbulence, convection, evaporation, and condensation.

The trajectories on October 16, 1997, had a similar pattern at 500 (5.9 km), 400 (7.6 km), 300 (9.7 km), 250 (11.0 km), and 200 hPa (12.4 km) levels in the ozone enhancement layer. Figure 2 shows trajectories for the 250 and 100 hPa levels. At the 250 hPa level the air masses originated in the tropical Pacific over the vicinity of the Philippines or Kalimantan Islands. The air mass then traversed through the SE Asia region for 2-4 days before advancing to the north over the Indo-China region. They finally reached south China and Hong Kong. At the 150 (14.2 km) and 100 hPa (16.6 km) levels, the trajectories tended to come from the western side over Indo-China and the Indian Ocean. These trajectories are different from the ones below 700 hPa (3.2 km) (not shown), which showed a local looping pattern around South China.

Trajectories during the ozone enhancement layer on December 3, 1997, had a similar circulation pattern from 500 (5.9 km) to 200 hPa (12.4 km) altitudes. However, they showed different degrees of looping patterns covering a wider region of SE Asia. Figure 3 shows the trajectories at 500, 250, and 150 hPa levels. The air mass circulated more around the SE Asian subcontinent and its surroundings than over the South China Sea. A similar circulation pattern of the trajectories was also observed at 400 hPa (7.6 km). At 300, 250, and 200 hPa (9.6, 10.9, and 12.5 km), the air masses had wider coverage over Kalimantan, Malaysia, and the Philippine Islands in their early journeys. They curved around over the Indian Ocean and SE Asia and reached Hong Kong. At 10 days back the air mass came from the west over the Indian region and beyond at 200 hPa at 12:00 UT. The trajectories below the ozone enhancement layer showed different circulation patterns. They showed a westerly flow at 700 hPa (3.2 km) and local looping around south China and the South China Sea (not shown) at 850 hPa (1.5 km).

Note that the trajectories showed that the ozone-rich air masses did traverse the regions of widespread smoke pixels because of the fires or in their close proximity before arriving in Hong Kong (Plate 3). These regions included the surroundings of Kalimantan and Sumatra, the Malaysia peninsula, the SE Asian subcontinent and the South China Sea. The air mass was also subject to substantial vertical motion in the 1-3 days before reaching Hong Kong in December. Thus it is reasonable to assume that the pollutants from biomass burning in the Indonesian fires were transported to Hong Kong following the air mass trajectories.

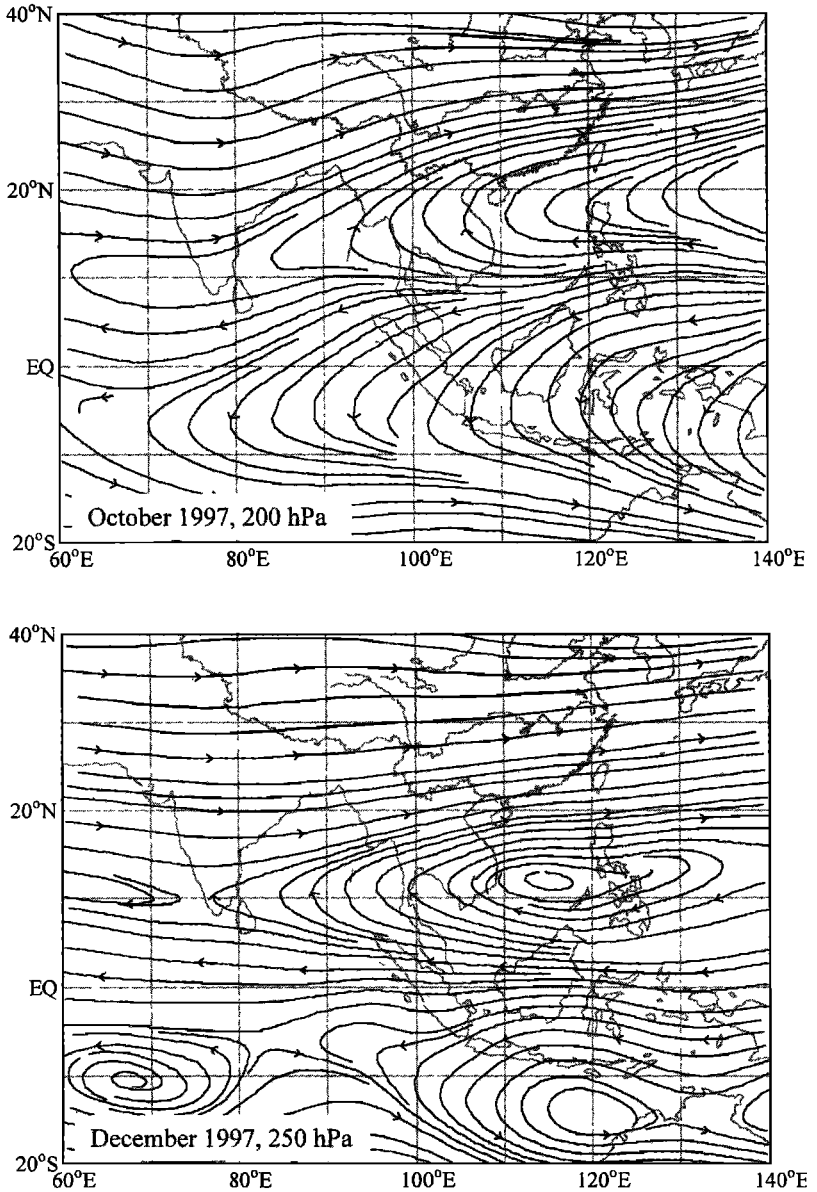

Figure 4. Monthly average streamlines at 200 hPa altitude in October and 250 hPa altitude in December 1997.

Chan et al. [1998b] attributes the similar air mass movement in the October trajectory to the east Asian local Hadley circulation. The circulation brings relatively highly humidified tropical air from the low-level convergence zone in the vicinity of the cyclonic center along the northern coast of the island of Borneo, Indonesia, through convection processes [*Chang and Lau*, 1980]. This kind of convective motion has been confirmed by the trace gas measurements on board the DC-8 aircraft during the Pacific Exploratory Mission-West mission [*Newell et al.*, 1997; *Kawakami et al.*, 1997]. *Folkins et al.* [1997] find that the deep convection in the region can inject emissions from SE Asia biomass burning to near tropical tropopause altitudes. *Jensen et al.* [1998] state that there was a collapse of the Walker circulation during the 1997 El Niño event. The result of this change in circulation is a movement of the most convective region from the western Pacific to the central Pacific and a decrease of convective activity over the tropical western Pacific. Figure 4 and Plate 4 show a comparison of the monthly mean outgoing longwave radiation (OLR) for the tropical and subtropical Pacific in October and November 1997 and 1974-1997 (excluding 1978). OLR may be viewed as a surrogate for convective activity [*Jensen et al.*, 1998]. There was an enhancement of OLR in October and November 1997, especially over the Indonesian region and its immediate vicinity. Similar OLR enhancements were also apparent over SE Asia and the South China Sea in August, September, and December 1997 (not shown). These OLR enhancements indicate that there was a decrease of the convective activity over the regions. The decrease of the convective activity in turn caused an accumulation of ozone from the biomass burning in the troposphere and an ozone outflow associated with the aged air masses to subtropical regions, such as Hong Kong.

The trajectories of the air masses strongly affected the occurrence of ozone enhancement. For example, the ozone profile on August 13 (Figure 5a) did not show many ozone enhancements in the troposphere even though fires had been detected in the Indonesian region. On examining the

trajectories on this day we found that the air masses over the troposphere over Hong Kong mainly originated from the Asian continent. Figure 5b shows the two typical trajectories at 500 (5.9 km) and 250 hPa (11.0 km). They did not traverse through the SE Asia region of active fires and smoke (Plate 2 and 3). The air mass was thus not affected by the biomass burning emissions, and there was no enhancement of ozone. The ozone profiles of October 16 and December 3 also did not show ozone enhancement at the lower troposphere and boundary layer (< 4.0 km). This is because at these levels, the air mass flow is governed by the Asian monsoon system, which results in the outflow from the Asian continent and east Asian coast [Chan et al., 1998a, 1998b].

5. Ozone Enhancement, Radiative Forcing, and Temperature Change

One of the interesting questions about the large-scale Indonesian forest fires is how the climate system responds to the associated ozone enhancement. Changes in the distribution and amount of ozone in the troposphere are expected to affect the surface-troposphere system through spatial and temporal changes in the flux of radiative energy into and out of the system [*Granier et al.*, 1999]. The impact is difficult to quantify, as it is largely dependent on complex feedback processes. It is more straightforward to calculate the radiative forcing. This quantity is defined as the response in the net radiative energy flux at the tropopause to the changes in the concentration of a radiative gas.

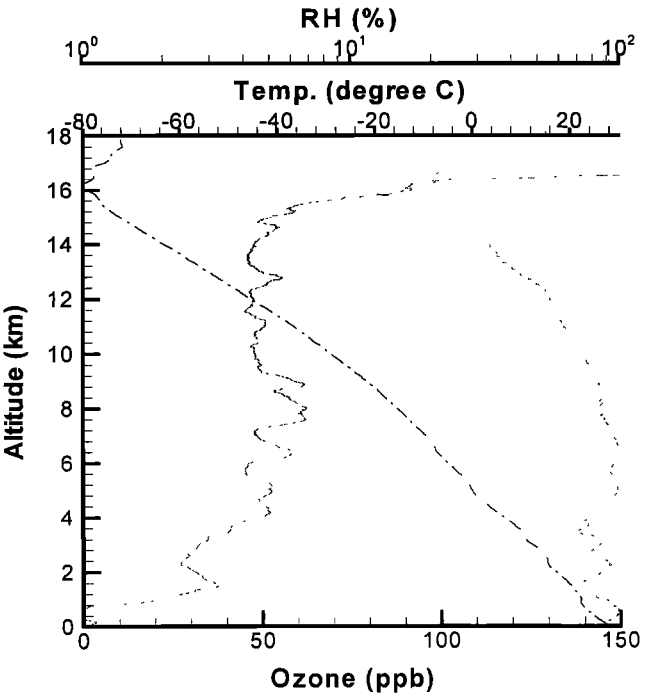

Figure 5a. Ozone (solid), temperature (dot - dashed) and relative humidity (dashed) profiles on August 13, 1997.

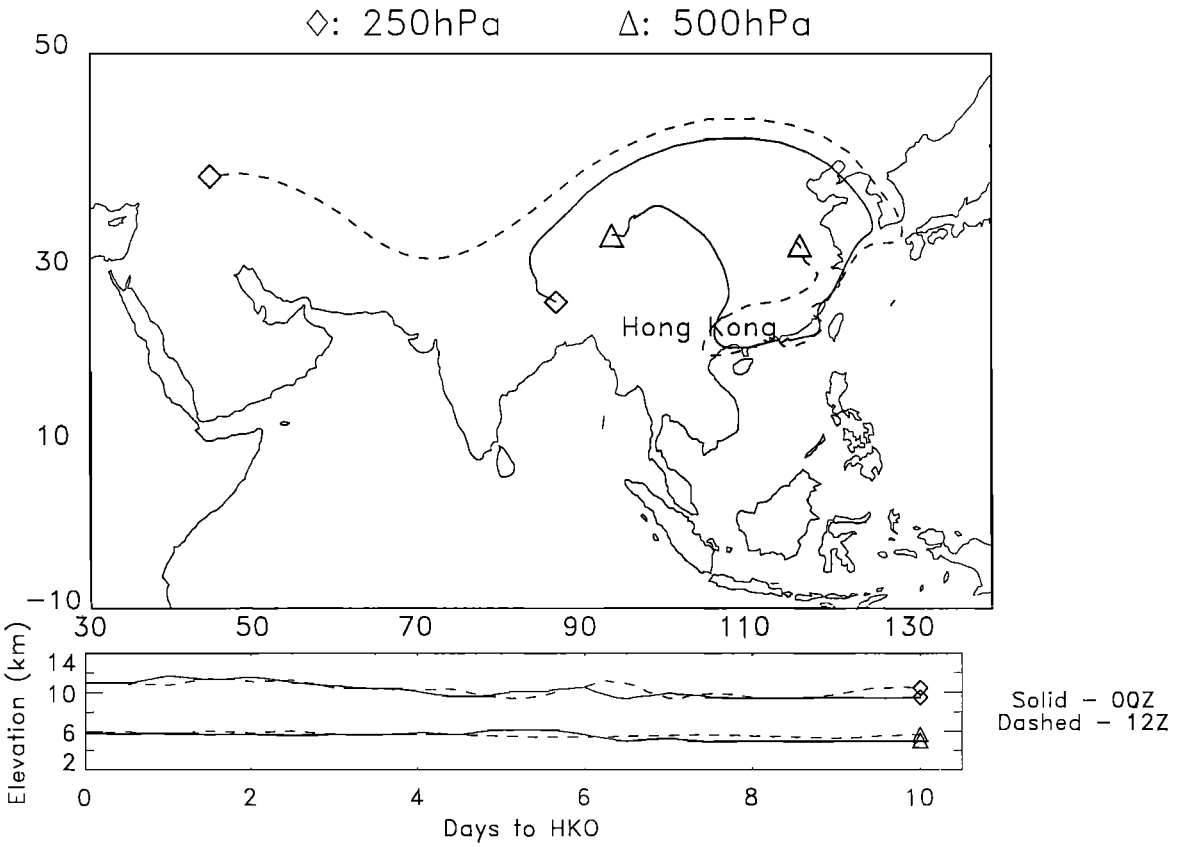

Figure 5b. Back air trajectory on August 13, 1997, at 5.9 (500 hPa) and 10.9 km (250 hPa). Solid and dashed lines are for 00:00 and 12:00 UT, respectively.

Recently, a normalized global tropospheric ozone radiative forcing formulation for shortwave and longwave radiation has been performed with a Unified Chemistry-Climate model [*Mickley et al.*, 1999]. The model incorporates a detailed simulation of tropospheric ozone-NO_x-hydrocarbon chemistry within a general circulation model. It calculates the instantaneous radiative forcing of anthropogenic ozone and a normalized radiative forcing per unit of added TOC. Using this normalized radiative forcing formulation, we performed a rough estimate of the additional forcing due to the tropospheric ozone enhancement in October and December 1997.

Assuming that the ozone enhancement occurred during all of October and December 1997, we simply multiply the additional TOC by the normalized radiative forcing coefficient for the respective months. This assumption is valid as the TOC from TOMS showed that the ozone enhancements did occur during most of October and December 1997. Figure 4a shows the average streamlines at 200 and 250 hPa for October and December 1997, respectively. The streamlines show that there were consistent high-pressure anticyclones over SE Asia and the South China Sea. The high-pressure anticyclones resulted in consistent air mass flows in the middle and upper troposphere from the Indonesian and Malaysian regions to the subtropical Indo-China and South China region. The back trajectories (not shown) of most days of October and December 1997 also suggest that the air mass flows demonstrated in Figures 2 and 3 were quite regular. We believe that such air mass flows should have enhanced the transport of the ozone formed from the biomass burning emissions to the South China and Hong Kong region in October and December 1997.

The calculation result is summarized in Table 1. The mean normalized radiative forcing in October and December from 1993 to 1998 due to tropospheric ozone was 1.09 and 1.03 Wm^{-2}, respectively [*L. J. Mickley*, private communication, 2000]. The enhanced ozone thus gives rise to an extra 0.26 and 0.48 Wm^{-2} of radiative forcing, respectively. These values are of the order of change in the mean annual forcing from 1860 to 1990 calculated by *Stevenson et al.* [1998]. *IPCC* [1996] puts the tentative forcing of tropospheric ozone between 0.2 and 0.6 Wm^{-2}. *Mickley et al.* [1999] assigns the total forcing due to the greenhouse gases, moisture, and aerosol a value of 0.48 in October and 0.39 in December over Hong Kong and the south China region. The enhancement of ozone due to the Indonesian fires thus caused an enhancement of 54 and 123% of the total forcing. Such an enhancement could imply a possible surface temperature change.

The surface temperature changes (ΔT) for a given change in radiative forcing (ΔF) can be defined by the following relationship [*Masters*, 1998; *Granier et al.*, 1999]:

$$(\Delta T) = f\,(\Delta F)$$

where f is the climate sensitivity parameter. This parameter depends on how much the outgoing radiant energy at the top of the atmosphere changes as the surface temperature changes. It also depends on the change of incoming energy that is absorbed as the surface temperature changes. *Warren and Schneider* [1979] investigate this parameter using infrared radiation obtained from satellites. The authors note that there is a linear relationship between the monthly surface temperature T and the infrared emissions Q_{rad} from the top of the atmosphere. They proposed the following relation, which works well for modest temperature change:

$$Q_{rad}\,(\mathrm{W\ m^{-2}}) = 1.83T\,(^{\circ}\mathrm{C}) + 209$$

This equation allows us to write

$$(\Delta Q_{rad})/\,\Delta T = 1.83\ (\mathrm{W\ m^{-2}})/(^{\circ}\mathrm{C})$$

Assuming there is no associated albedo change, we have

$$f = 1/1.83 = 0.55\ (^{\circ}\mathrm{C})/(\mathrm{W\ m^{-2}})$$

Although this value is roughly estimated, it is very close to the best estimate of 0.57 (range 0.34 - 1.03) given by *IPCC* [1996]. We use this deduced climate sensitivity parameter to estimate further the surface temperature change due to the increment of radiative forcing as a result of the ozone enhancement. The result of this rough estimation is summarized in Table 1. There is an increase in surface temperature of 0.14° and 0.26°C for the October and December ozone enhancement cases. For comparison, IPCC puts the best estimates of the surface temperature change associated with a doubling of the current global CO_2 concentration at 2.5°C. The actual effects of the ozone enhancement on the radiative forcing and the surface temperature depend on factors such as the associated changes in other radiative gases, water vapor content, cloud amount, albedo, incident solar radiation, and their feedback to the atmospheric-climate system [*Masters*, 1998; *IPCC*, 1996]. They also depend on the height of the added ozone and temperature contrasts between the earth's surface and the level of added ozone [*L J Mickley*, private communication, 2000]. Our rough estimation gives an initial quantification of the climate systems response to the ozone enhancement related to biomass burning on the scale of the 1997 Indonesian forest fires. However, at the moment we are not able to verify if there was an actual change of surface temperature. This is because we do not have reliable surface temperature data that are free from urban influence. This would be subject to further study. It should also be pointed out the even if we have such data, we might not have seen the temperature change as the natural variability might be much larger than the small change calculated.

6. Conclusion

In this study, we showed that the large-scale Indonesian fires caused an enhancement of tropospheric ozone on a regional scale. The TOC deduced from the TOMS satellite revealed that the enhancements covered the all of tropical SE Asia extending to subtropical south China. Such enhancements occurred throughout the middle to upper troposphere with a maximum thickness of 10 km. The extra ozone caused a substantial increase of TOC as compared to the ozone profiles observed from 1993 to 1998. Analysis of satellite images and back air trajectories indicates that there was substantial ozone buildup and outflow of ozone and pollutants in the biomass plume that eventually reached Hong Kong. The transport pattern of ozone is related to the east Asian Hadley circulation and the abnormal anticyclonic flow that was created by the collapse of the Walker circulation. Given the strong potential impact of ozone on the climate system, it is of vital importance to understand the effect of enhanced ozone on radiative forcing and surface temperature. Our rough estimate revealed that there may have been an extra of 0.21 and 0.44 W m^{-2} added to the normal forcing, which induced increases of surface temperature by 0.12° and 0.24°C, respectively.

Acknowledgments. This project is funded by the Research Grant Council of Hong Kong and a research grant of the Hong Kong Polytechnic University. The authors would like to acknowledge Hong Kong Observatory for contributing to the ozonesonde launching and the Department of Meteorology, University of Maryland, for providing tropical tropospheric ozone column maps. We greatly acknowledge the helpful discussion and comments from L. J. Mickley of Harvard University and the reviewers.

References

Chan, L. Y., C. Y. Chan, and Y. Qin, Surface ozone pattern in Hong Kong, *J Appl Meteorol., 37*, 2003-2016, 1998a.

Chan, L. Y., H. Y. Liu, K. S. Lam, T. Wang, S. J. Oltmans, and J. M Harris., Analysis of the seasonal behaviour of tropospheric ozone at Hong Kong, *Atmos. Environ., 31*, 159-168, 1998b.

Chan, L. Y., C. Y. Chan, H. Y. Liu, S. Christopher, S. J. Oltmans and J. M. Harris, A case study on the biomass burning in Southeast Asia and enhancement of tropospheric ozone over Hong Kong, *Geophys. Res. Lett., 27*, 1479-1483, 2000.

Chandra, S, J. R. Ziemke, W. Min, and W. G Read, Effects of 1997-1998 El Niño on tropospherеic ozone and water vapour, *Geophys. Res. Lett., 25*, 3867-3870, 1998.

Chang, C. P., and K. M. Lau, Northeasterly cold surges and near-equatorial disturbances over the winter MONEX area during December 1974, part II, Planetary-scale aspects, *Mon. Weather Rev. 108*, 298-312, 1980.

Christopher, S. A., J. Chou, R. M. Welch, D. V. Kliche, and V. S. Connors, Satellite investigations of fire, smoke, and carbon monoxide during April 1994 MAPS mission: Case studies over tropical Asia, *J. Geophys. Res., 103*, 19,327-19,336, 1998.

Crutzen, P. J., L. E. Heidt, J. P. Krasnec, W. H. Pollock, and W. Seiler, Biomass burning as a source of atmospheric gases CO, H_2, N_2O, NO, CH_3CL, and COS, *Nature, 282*, 253-256, 1979.

Delany, A. C., P. Haagensen, S. Walters, A. F. Wartburg, and P. J. Crutzen, Photochemically produced ozone in the emission from large-scale tropical vegetation fires, *J Geophys. Res., 90*, 2425-2429, 1985

Fishman, J., V Ramanathan, P. J Crutzen, and S C. Liu, Tropospherіc ozone and climate, *Nature, 282*, 818-820, 1979.

Folkins, A , R. Chatfield, D. Baumgardner, and D. Proffitt, Biomass burning and deep convection in southeastern Asia: Results from ASHOE/MAESA, *J Geophys Res., 102*, 13,291-13,299, 1997.

Fujiwara, M., K Kita, S. Kawakami, T. Ogawa, N. Komala, S. Saraspriya, and A. Auripto, Tropospheric ozone enhancements during the Indonesian forest fire events in 1994 and in 1997 as revealed by ground-based observations, *Geophys. Res. Lett., 26*, 2417-2420, 1999.

Granier, C., G. Brasseur, D. Erickson, and S. H. Schneider, Atmospheric chemistry and climate, in *Atmospheric Chemistry and Global Change*, edited by Goy P. Brasseur, J. J. Orlando, and G. S. Tyndall, Oxford Univ. Press, New York, 1999.

Harris, J. M., and J. D. W. Kahl, Analysis of 10-day isentropic flow patterns for Barrow, Alaska: 1985-1992, *J. Geophys. Res , 99*, 25,845-25,855, 1994.

Hauglustaine, D. A., G. P. Brasseur, and J. S. Levine, A sensitivity simulation of tropospheric ozone changes due to the 1997 Indonesian fire emissions, *Geophys. Res. Lett., 26*, 3305-3308, 1999.

Hudson, R. D., and A. M. Thompson, Tropical tropospheric ozone from total ozone mapping spectrometer by a modified residual method, *J Geophys. Res., 103*, 22,129-22,145, 1998.

Intergovernmental Panel on Climate Change (IPCC), *Climate Change 1995 The Science of Climate Change*, Cambridge Univ. Press, New York, 1996.

Jensen, M. P., J. H Mather, and T. P. Ackerman, Observations of the 1997-98 warm ENSO event at the Manus Island ARM site, *Geophys. Res Lett , 25*, 4517-4520, 1998.

Johnson, W. B., and W. Viezee, Stratospheric ozone in the lower troposphere, I, Presentation and interpretation of aircraft measurements, *Atmos. Environ., 15*, 1309-1323, 1981.

Kawakami, K., et al , Impact of lightning and convection on reactive nitrogen in the tropical free troposphere, *J. Geophys. Res., 102*, 28,367-28,384, 1997.

Levine, J. S., The 1997 fires in Kalimantan and Sumatra, Indonesia: Gaseous and particulate emissions, *Geophys. Res. Lett., 26*, 815-818, 1999.

Liu, H. Y., W. L. Chang, S. J. Oltmans, L. Y. Chan, and J. M. Harris, On springtime high ozone events in the lower troposphere from SE Asian biomass burning, *Atmos. Environ., 33*, 2403-2410, 1999.

Liu, S. C., M. Trainer, F. C. Fehsenfeld, D. D. Parrish, E. J. Williams, D. W. Fahey, G. Hubler, and P. C. Murphy, Ozone production in the rural troposphere and the implications for regional and global ozone distributions, *J. Geophys. Res., 92*, 4191-4207, 1987.

Masters, G. M., *Introduction to Environmental Engineering and Science*, Prentice-Hall, Old Tappan, N. J.,1998.

Matsueda, H., and H. Y. Inoue, Aircraft measurements of trace gases between Japan and Singapore in October of 1993, 1996, and 1997, *Geophys. Res Lett., 26*, 2413-2416, 1999.

Mauzerall, D. L., J. A. Logon, D. J. Jacob, B. E. Anderson, D. R. Blake, J. D. Bradshaw, B. Heikes, G. W. Sachse, H. Singh, and B. Talbot, Phtotochemistry in biomass burning plumes and implications for tropospheric ozone over the tropical South Atlantic, *J. Geophys. Res., 103*, 8401-8423, 1998.

Mickley, L. J., P. P. Murti, D. J. Jacob, J. A. Logan, D. Koch, and D. Rind,, Radiative forcing from tropospheric ozone calculated with a Unified Chemistry-Climate model, *J. Geophys. Res., 104*, 30,153-30,172, 1999.

Mohnen, V. A., W. Goldstein, and W. C. Wang, The potential role of tropospherіc ozone as a climate gas, *WMO Bull , 44*, 38-42, 1995.

Newell, R. E , E. V. Browell, D. D., Davis, and S. C. Shaw, Western Pacific tropospheric ozone and potential vorticity: Implications for Asian pollution, *Geophys Res Lett., 24*, 2733-2736, 1997.

Sawa, Y., H. Matsueda, Y Tsutsumi, J. B. Jensen, H. Y. Inoue, and Y. Makino, Tropospheric carbon monoxide and hydrogen measurements over Kalimantan in Indonesia and northern Australia during October, 1997, *Geophys. Res. Lett., 26*, 10, 1389-1392, 1999.

Stevenson, D. S., C. E. Johnson, W. L. Collins, R. G. Derwent, K. P. Shine, and J. M. Edwards, Evolution of tropospheric ozone radiative forcing, *Geophys Res. Lett , 25*, 3819-3822, 1998.

Sze, N. D., Anthropogenic CO emissions: Implications for the CO-OH-CH_4 cycle, *Science, 195*, 673-675, 1977.

Thomas, W., E. Hegels, S. Slijkhuis, R. Spurr, and K. Chance, Detection of biomass burning combustion products in Southeast Asia from backscatter data taken by the GOME spectrometer, *Geophys Res Lett., 25*, 1317-1320, 1998.

Thompson, A. M., and R. D. Hudson, Tropical tropospheric ozone (TTO) maps from Nimbus 7 and Earth - Probe TOMS by the modified-residual method: Evaluation with sondes, ENSO signals, and trends from Atlantic regional time series, *J. Geophys. Res., 104*, 26,961-26,975, 1999.

Thompson, A. M., K. E. Pickering, D. P. McNamara, M. R. Schoeberl, R. D. Hudson, J. H. Kim, E. V. Browell, V. W. J. H. Kirchhoff, and D. Nganga, Ozone over southern Africa during SAFARI-92/TRACE A, *J Geophys Res., 101*, 23,793-23,807, 1996

Tsutsumi, Y., Y. Sawa, Y, Makino, J. Jensen, J. Gras, and B. Ryan, Aircraft measurement of ozone, NOx, CO, and aerosal concentrations in biomass burning smoke over Indonesia and Australia in October 1997: Depleted ozone layer at lower altitude over Indonesia, *Geophys. Res. Lett., 26*, 595-598, 1999.

Wang, W. -C., Y. C. Zhuang, and R. D. Bojkov, Climate implications of observed changes in ozone vertical distributions at middle and high-latitudes of the Northern Hemisphere, *Geophys. Res. Lett., 20*, 1567-1570, 1993.

Warren, S. G., and S. H. Schneider, Seasonal simulation as a test for uncertainties in the parameterization of a Budkyo-Zellers zonal climate model. *J Atmos Sci* , 36, 1377-1391, 1979.

C. Y. Chan, L. Y. Chan and Y. G. Zheng, Environmental Engineering Unit, Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong. China. (e-mail: 95982258r@polyu.edu.hk, celychan@polyu.edu.hk)

S. J. Oltmans and J. M. Harris, NOAA, Climate Monitoring and Diagnostic Laboratory, R/E/CG1, 325 Broadway, Boulder, CO 80303.

S. Christopher, Department of Atmospheric Science, University of Alabama in Huntsville, 977 Explorer Blvd., Huntsville, AL 35899.

(Received August 6, 2000; revised December 19, 2000; accepted January 9. 2001.)