Meteorological and Chemical Characteristics of the Photochemical Ozone Episodes Observed at Cape D'Aguilar in Hong Kong

TAO WANG, K. S. LAM, AND AGATHA S. Y. LEE

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

S. W. PANG AND W. S. TSUI

Environmental Protection Department of the Hong Kong Special Administrative Region, Hong Kong, China

(Manuscript received 5 November 1996, in final form 28 April 1997)

ABSTRACT

As in many metropolitan areas around the world, air pollution in Hong Kong is an increasing concern. In this paper the authors present the observations of ozone (O_3) pollution episodes made at a nonurban coastal location in Hong Kong. Four O_3 episodes were observed in 1994, during which hourly averaged O_3 concentrations exceeded 100 ppbv and in one case reached 162 ppbv. Recirculation of urban air caused by the reversal of surface winds was found to be an important mechanism for transporting the ''aged'' urban plumes to the monitoring site. Concurrent measurements of CO, SO_2, NO, and O_3 provided an insight to the chemical characteristics of the air masses, and the chemical data appeared to suggest that the high levels of O_3 during the episodes were produced in the urban plumes that were mainly characteristic of vehicle emissions. The relationship between O_3 and CO in two of the episodes may be represented by a linear approximation, and a nonlinear relationship between O_3 and CO was found in another. Ozone levels observed at the nonurban site were higher than those at two urban locations.

1. Introduction

Since the discovery of urban photochemical smog in the 1940s, a huge volume of research has been conducted on this phenomenon. Yet, despite the implementation of costly control measures in some countries, it is still a serious environmental problem in many cities (NRC 1991), including those of Asia (e.g., Liu et al. 1990; Xu and Zhu 1994).

In Hong Kong, ambient O_3 levels have been monitored since the early 1980s by the Environmental Protection Department (EPD) of Hong Kong through a network of ambient air-quality monitoring stations. These monitoring stations are located mainly in densely populated urban areas. According to the data obtained from this network, O_3 was not found to be a cause of concern in urban areas with regard to meeting the air-quality objectives of Hong Kong (Tsui et al. 1996). Prior to 1993, however, no long-term O_3 data was available for locations outside urban centers. Therefore, a regional air monitoring station was established at Cape D'Aguilar by The Hong Kong Polytechnic University. The primary objectives of this station are to monitor the trends in regional air quality and to address the issue of long-range transport of air pollutants. The initial results on the seasonal variations of O_3 and CO and on the levels of O_3, CO, NO, NO_y, and SO_2 in early spring of 1994 were summarized by Lam et al. (1995, manuscript submitted to *J. Geophys. Res.*) and Wang et al. (1997), respectively. In this study, we present the data on four O_3 pollution episodes observed in 1994, focusing on the unique local transport pattern of air pollutants and the relationships among the air pollutants during the episodes. Additionally, O_3 levels at Cape D'Aguilar will be compared with those at two of the urban EPD stations.

2. General characteristics of the environment in Hong Kong

Hong Kong is located by the south China coast (22°N, 114°E) and is bounded to the north by the huge landmass of the Chinese mainland, to the south and east by the South China Sea, and to the west by the Pearl Estuary.

The territory of Hong Kong consists of Hong Kong Island, Kowloon Peninsula, the New Territories, Lantau Island, and a number of small islands (see Fig. 1). It stretches 55 km from east to west and 35 km from north to south. The territory has a complex terrain; Tai Mo Shan

Corresponding author address: Dr. Tao Wang, Environmental Engineering Unit, Dept. of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China.
E-mail: cetwang@polyu.edu.hk

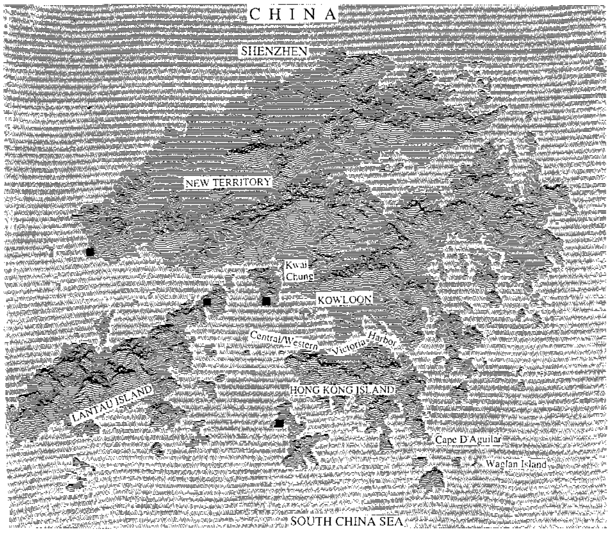

FIG. 1. Topographic map of Hong Kong showing the locations of the monitoring sites and the power stations (solid squares).

is the tallest peak (957 m above sea level), and its hilly regions make up about 70% of the total land area.

The population of Hong Kong currently stands at 6.2 million and is concentrated along the territory's irregular coastline, reclaimed land, the northern part of Hong Kong Island, Kowloon Peninsula, and the new towns of the New Territories. Hong Kong roads have one of the highest vehicle densities in the world. By the end of 1996, there were about 480 000 vehicles on 1700 km of roads. About one-third of the fleet are diesel vehicles, which account for about 60% of the overall mileage. Major port facilities are located in the western Kowloon, and power plants are also located in the western side (see Fig. 1). In 1994, the territory emitted about 140 000 tons of SO_2, 150 000 tons of NO_x, and 100 000 tons of CO. Among various sources, power plants are the biggest emitters of SO_2 and NO_x, accounting for about 77% and 60% of the total emissions, respectively. Vehicle emissions account for a significant fraction of the CO emission (about 80%). In urban areas, high levels of suspended particulate matter and NO_2 are mainly related to vehicle emissions (EPD 1996a).

The climate of Hong Kong is governed by the Asian monsoons (e.g., Chiu and So 1986). Winter, which is from November to February, is cold and dry. Spring, which is short, lasting from March to April, is misty. Summer, which is long, lasting from May to mid-September, is hot and humid. Autumn, which extends from mid-September to early November, is sunny and dry.

Prevailing synoptic winds arriving in Hong Kong are from the north and northeast in winter, east in spring and autumn, and south and southwest during the summer months. Tropical cyclones originated in the western Pacific can alter day-to-day weather, including surface synoptic winds. Small-scale winds at different locations in Hong Kong can differ significantly due to differential heating, complicated terrain, and their combined effects (Yeung et al. 1991). Sea breeze from the Pearl Estuary and South China Sea is often observed under light synoptic winds, and it is well known that prevailing northerly winds become northwesterlies in the Victoria Harbor due to deflection by hills and channeling effects of the harbor (Yeung et al. 1991).

Beside Hong Kong, several other major cities in the region are worth mentioning. Shenzhen, the nearest Chinese city (population: ~4 million), is roughly 30 km from Victoria Harbor. Zhuhai and the Portuguese colony of Macau are located about 70 km west of Hong Kong, on the opposite side of the Pearl Estuary, while Guangzhou is located 120 km northwest of Hong Kong. Approximately 500 km east of Hong Kong is the island of Taiwan.

3. Monitoring locations

a. The Hong Kong Polytechnic University air monitoring station

The Hong Kong Polytechnic University air monitoring station is located at Cape D'Aguilar, which is located at the southeastern tip of Hong Kong Island (Fig. 1). It is a relatively remote coastal site in Hong Kong, and metropolitan Hong Kong (Victoria Harbor) is situated about 10 km north and northwest of the station. The monitoring station is on a cliff, 60 m above sea level, and has a 240° sea view stretching from northeast to west. Between Cape D'Aguilar and the Victoria Harbor, there are ridges and hills with the peak heights ranging from 300 to 550 m. The D'Aguilar Peak (height: 325 m) is about 1.5 km northwest of the station. Major sources of emissions, including those from vehicles,

TABLE 1. Summary of the characteristics of meteorological parameters during the ozone episodes observed.

Episode date	Max hourly O_3 concentration (ppbv)	Mean wind speed (m s^{-1})	Max air temperature (°C)	Mean RH (%)	Daily global solar radiation (MJ M^{-2})	Total bright sunshine (h)	Mean pressure (hPa)
8 May	105 (33)*	3.2 (5.9)	30.2 (30.2)	68 (73)	19.51 (16.57)	10.0 (6)	1012.2 (1008.6)
10 Jul	162 (21)	5.0 (6.7)	34 (30.4)	74 (86)	21.29 (13.28)	11.8 (4.4)	997.8 (1003.1)
11 Sep	116 (52)	5.2 (6.5)	30.8 (29.2)	85 (83)	9.38 (12.10)	3.1 (4.16)	1006.1 (1009.7)
9–11 Oct	108, 87, 96 (60)	5.1 (7.2)	30.7 (27.5)	65 (67)	17.5 (16.75)	9.3 (8.6)	1008.9 (1015.5)

* Denotes the respective monthly mean values. The maximum O_3 levels were observed in early afternoon. Monthly median afternoon values are included for comparison.

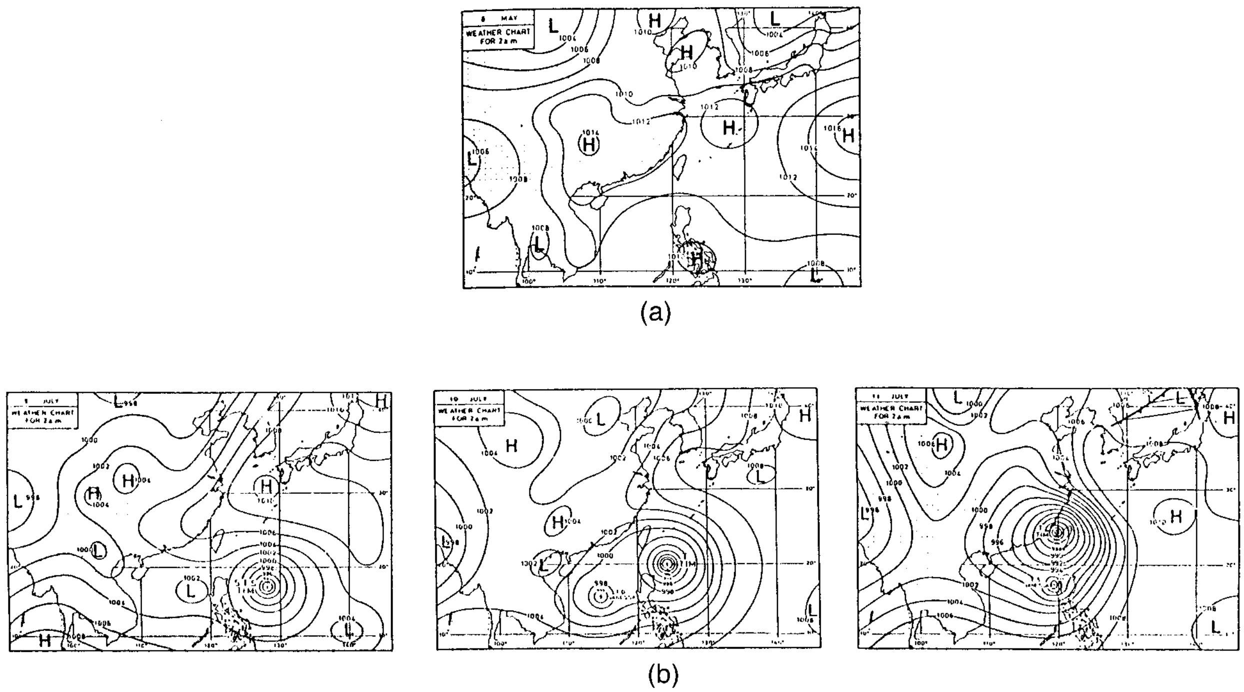

FIG. 2. Synoptic weather maps for episode days: (a) a weak high pressure system over the southern part of China on 8 May and (b) the movement of Typhoon Tim from the western Pacific Ocean on 9–11 July (maps were provided by the Hong Kong Observatory).

power plants, and industrial complexes, are mainly located in the north and west quadrant. The nearest coal-fired power plant is about 15 km west of the station. Transpacific ocean liners pass approximately 6 km south of the station. The nearby city of Stanley (well known for its luxury apartments and as a tourist spot) is about 4 km west. The town of Shek O is about 3 km north of the station, and a small village of about 10 families and a small residential facility are located about 1 km west of the station. Near the station, a residential facility of the Marine Science Laboratory of the University of Hong Kong is located about 100 m south and southeast. The only emissions are from limited domestic cooking using liquid petroleum gas. A telecommunication transfer station is about 50 m south, and it has little emission except from a diesel emergency power generator that is normally tested every alternate Friday. For a majority of the time, the Cape D'Aguilar is upwind of urban Hong Kong. During the high O_3 episodes, however, surface winds changed dramatically from the prevailing directions, and the Cape D'Aguilar came under the direct impact of urban plumes as well as the emissions from the above local sources.

b. EPD stations

To examine the extent of the O_3 episodes, O_3 data recorded from two urban locations were compared with those from Cape D'Aguilar. In 1994, EPD operated eight air monitoring stations, two of which had O_3 measurements (EPD 1996a). These two monitoring stations are located primarily in the areas with large emissions of O_3 precursors (Fig. 1). The central/western (c/w) station is located on top of an 18-m-tall building in an urban residential area in the western region of Hong Kong Island. The other station, Kwai Chung (KC), is situated in a mixed industrial and residential area in the western part of the New Territories. It is also a rooftop station (25 m above ground).

4. Overview of the ozone and carbon monoxide data obtained at Cape D'Aguilar

To place the high ozone episodes into perspective, a brief overview is given on the O_3 and carbon monoxide (CO) data obtained for 1994–95. The dataset was discussed in detail by Lam et al. (1995, manuscript submitted to *J. Geophys. Res.*). The O_3 and CO concentrations exhibited strong seasonal variations. Their levels reached the year-round low in summer with typical values of about 20 ppbv for O_3 and about 90 ppbv for CO. Carbon monoxide (and other primary pollutants as well) reached its highest levels in the winter months with typical values from 400 to 500 ppbv, while spring and autumn were the transition periods with moderately high levels of CO (200–300 ppbv). Ozone levels tended to be highest in autumn with typical values of 50–60 ppbv. The seasonal trend for CO (and for other primary pollutants as well) is mainly determined by the Asian monsoons. In the summer, winds are generally from above the ocean (from the south and southwest), bringing in clean oceanic air to Hong Kong for most of the time.

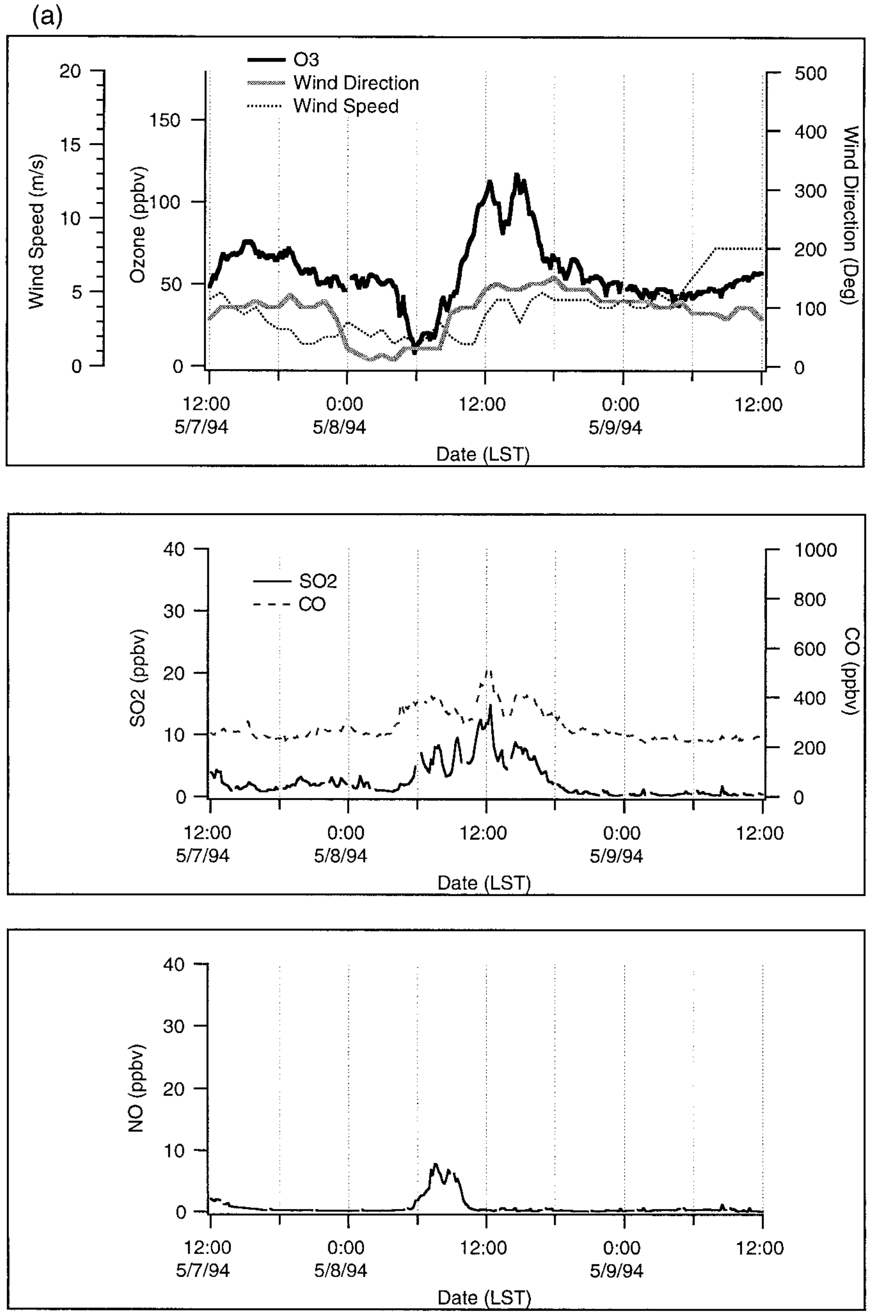

FIG. 3. Time series of the concentrations of O_3, CO, SO_2, NO, wind speed, and direction on (a) 8 May, (b) 10 July, (c) 11 September, and (d) 9–11 October.

In contrast, outflow of polluted continental air from the north is attributed to relatively high CO concentrations observed in winter at Cape D'Aguilar. In addition to the availability of the precursor species, O_3 levels also depend on the degree of photochemical processing in the atmosphere. Relatively high O_3 in autumn can be attributed to the sunny and dry weather and prevailing easterly winds. These conditions facilitate the photochemical production of ozone.

5. Meteorological conditions during the high ozone episodes

a. Local meteorological conditions

Four high O_3 episodes were observed at Cape D'Aguilar in 1994 during which maximum hourly averaged O_3 concentrations exceeded 100 ppbv. These episodes occurred on 8 May, 10 July, 11 September, and 9–11 October. The October episode was a 3-day event.

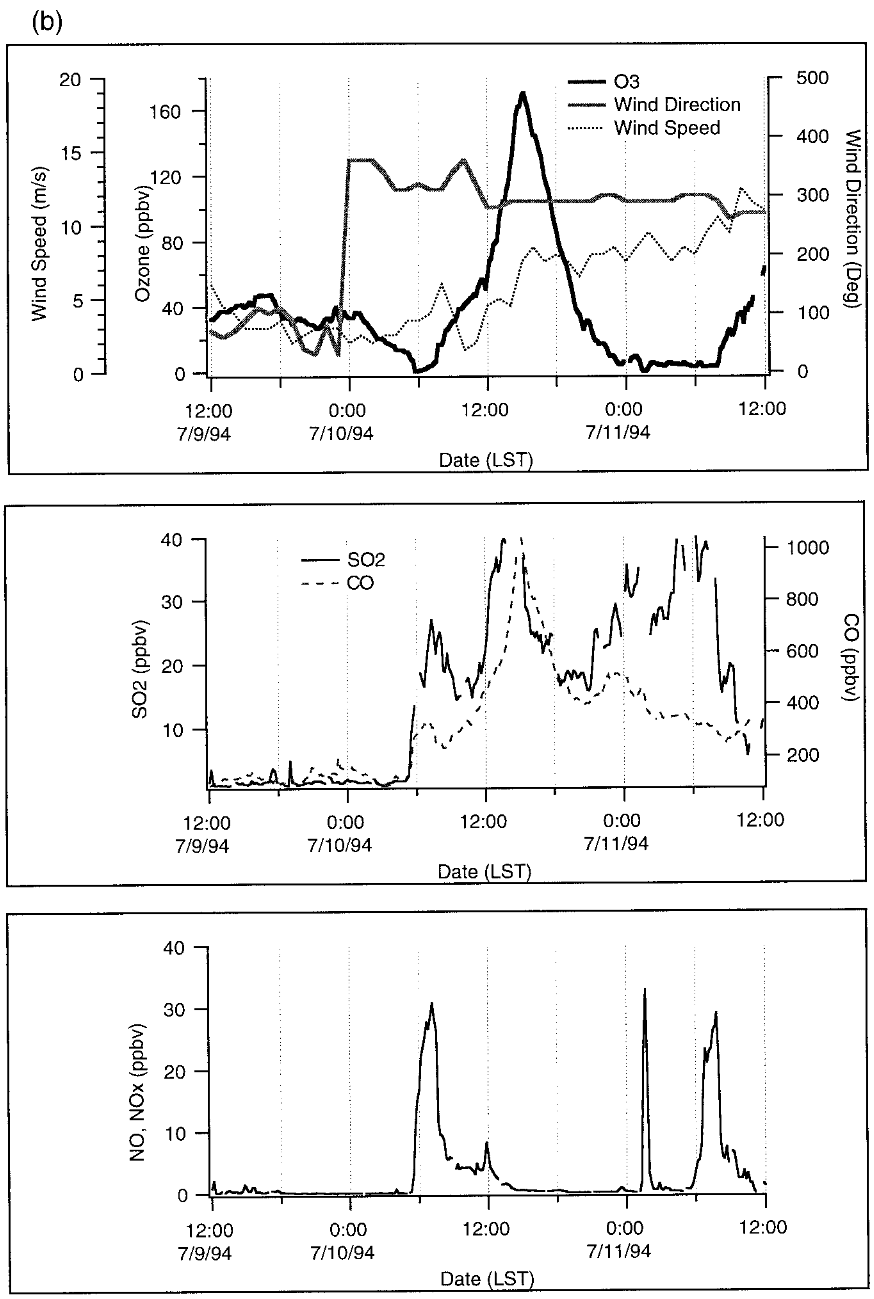

Fig. 3. (*Continued*)

As found in numerous studies, certain meteorological conditions are required for the formation and accumulation of high concentrations of O_3. These conditions often include a well-defined boundary layer, subsidence inversion, light winds, high temperatures, and high solar radiation [Colbeck and Mackenzie (1994), and references therein]. Such conditions promote photochemical O_3 pollution by increasing solar insolation, reducing ventilation of the source region, increasing temperature-dependent emissions, and increasing most of the photochemical rate coefficients (Colbeck and Mackenzie 1994).

In this study, we compared some surface meteorological parameters during the episode days with those typical for the respective months. These results are summarized in Table 1, which also includes the peak O_3 concentrations. [The meteorological data were obtained from the Hong Kong Observatory (HKO), and the data used here (except wind direction and speed) were recorded at the HKO King's Park Station in Kowloon.]

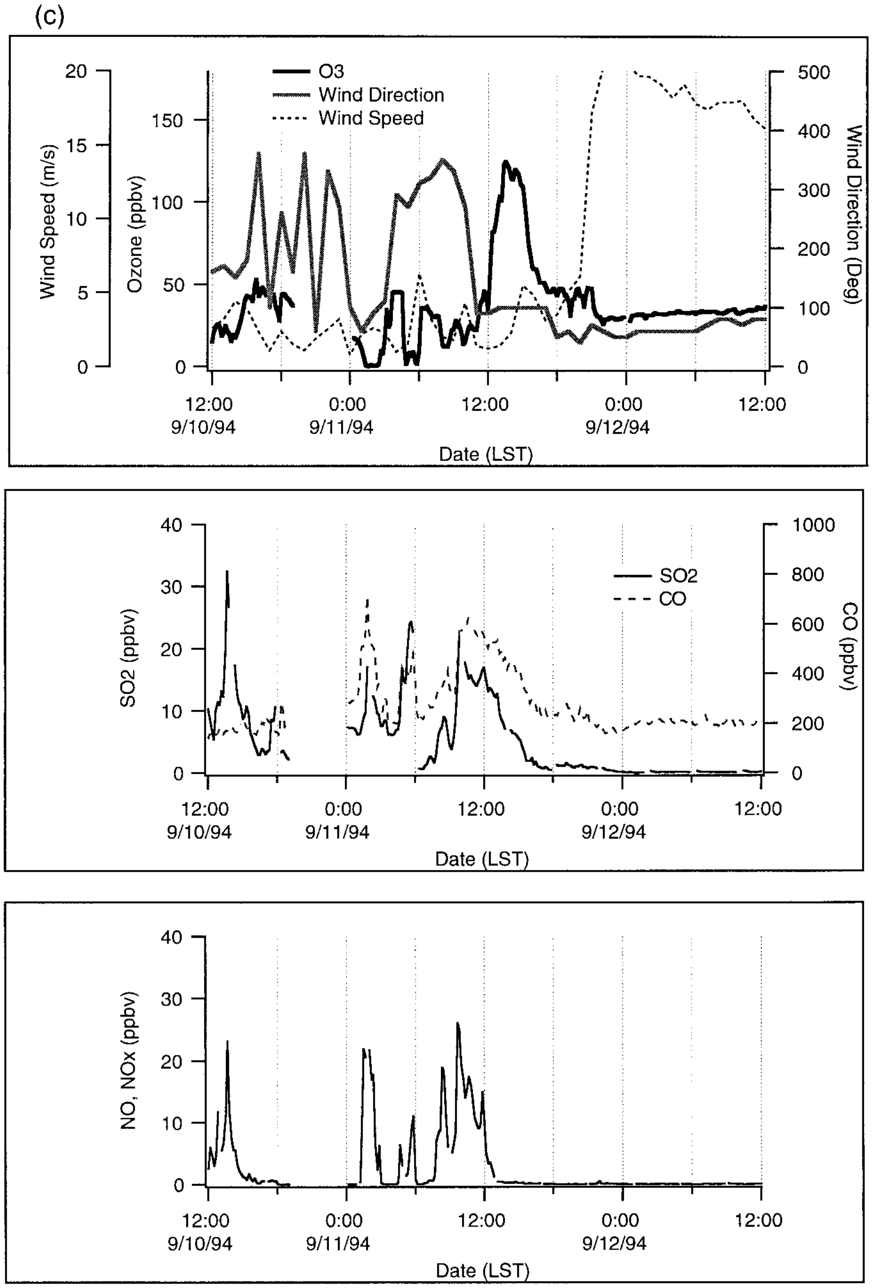

FIG. 3. (*Continued*)

During the episode days 1) peak ozone concentrations are much higher than the normal values, 2) wind speeds are always lower, and 3) solar radiation is high with the exception of the September episode. However, temperatures during the episode days are comparable to or only slightly higher than the monthly means. It is believed that the occurrences of elevated ozone at Cape D'Aguilar were mainly due to the unique local recirculation (see below). In addition, calm conditions, plentiful sunshine, and warm weather also facilitated the ozone production.

b. Synoptic weather

In many previous studies, meteorological conditions favorable to O_3 production (e.g., light winds, high temperature, intense solar radiation, and inversion) are often found to be associated with stagnating or slow-moving anticyclones (high pressure systems) [Colbeck and Mackenzie (1994), and references therein]. In this study, light regional winds on 8 May correlated to the presence of a weak high pressure system over the southern part of China (Fig. 2a). For the July, September, and October

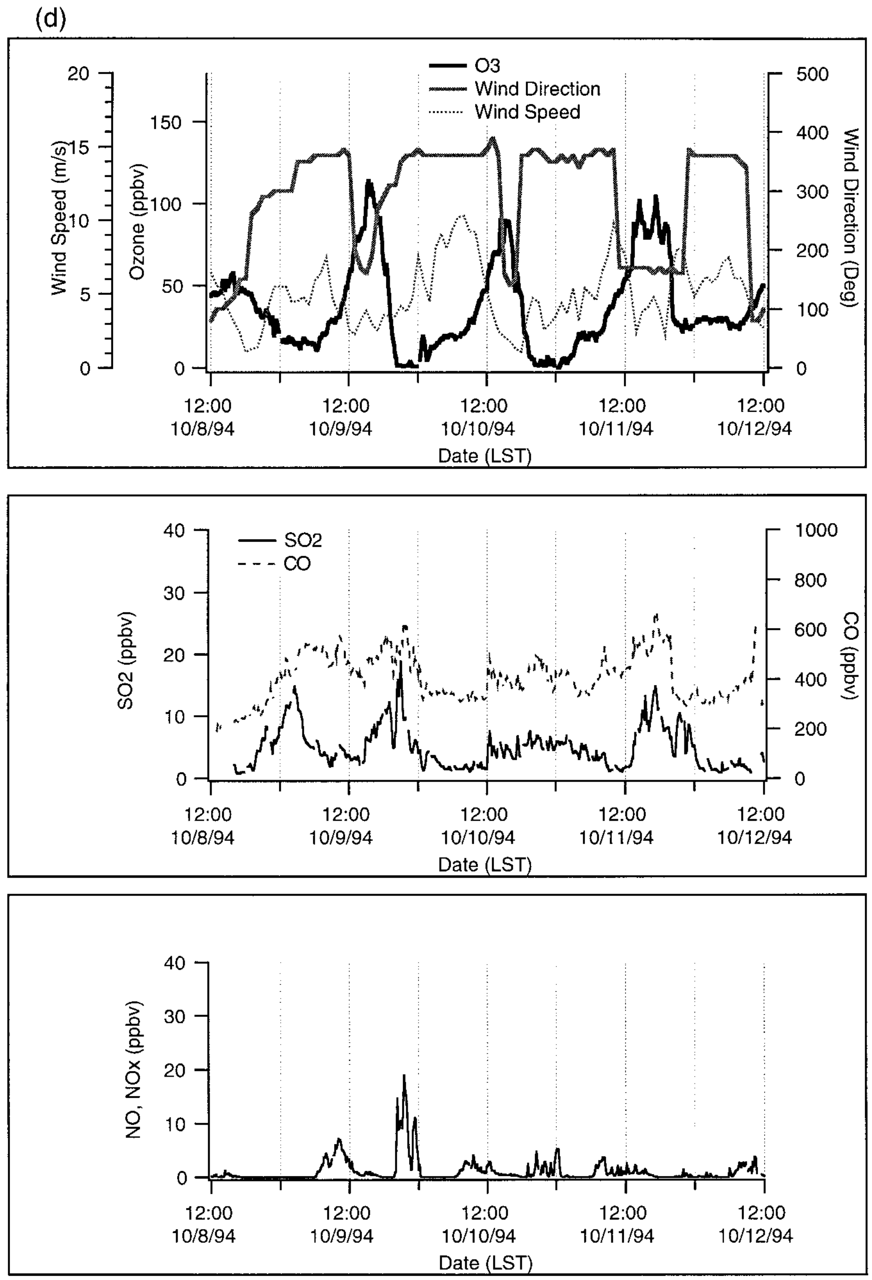

Fig. 3. (*Continued*)

events, the synoptic weather patterns were strongly influenced by the tropical cyclones located east and southeast of Hong Kong. Figure 2b shows the synoptic weather patterns for the July episode and indicates the northwesterly movement of Typhoon Tim from the western Pacific Ocean.

c. *Local circulation*

Recirculation of urban pollutants caused by the reversal of wind directions can contribute to high O_3 episodes. In particular, land and sea breezes have been found to be responsible for the occurrence of O_3 episodes in the urban areas located near the coast (e.g., Liu et al. 1994). The indications of circulating urban plumes to Cape D'Aguilar can be seen most clearly in three of the cases. Figure 3 shows the time series for O_3, wind direction, and speed in conjunction with the time series for the air pollutants CO, SO_2, and NO.

Wind speed and direction used in this study were recorded at Waglan Island, which is located about 6 km east and southeast of the present station. Waglan Island is more exposed geographically than the urban regions of Hong Kong and is not directly affected by urbanization (e.g., high-rise buildings). Therefore, the wind recorded at Waglan Island is more representative of the general wind flow over Hong Kong. The Waglan wind data, which were recorded at a 56-m level above the sea surface, were compared with those obtained at the present station (75 m) for the later periods. They agreed well except for the periods of weak (<2 m s^{-1}) northeasterly winds. When Waglan Island recorded weak northeasterly winds, Cape D'Aguilar tended to detect northerly directions with lower speeds. This difference is likely to be caused by the effects of terrain. Under the conditions of northerly winds, Cape D'Aguilar and Waglan become downwind of the hilly topography of Hong Kong.

In Fig. 3, wind data from the HKO contain hourly values, whereas ozone and other trace gases measured at the present station are 10-min averages. We include 12-h data before and after an episode day for the purpose of comparison. The four episodes are described below.

1) 8 May and 11 September: During these two episode days, prior to the peak O_3 in the afternoons, surface winds at Waglan became weak and indicated a general direction of northwest to northeast. The O_3 concentrations increased dramatically as the winds turned easterly or southeasterly, and this increase was even more rapid in the 11 September episode. In both cases, maximum O_3 concentrations were observed during periods with winds coming from over the ocean. It is believed that in these two cases, large-scale weak northerly winds were deflected in the morning hours at Victoria Harbor to a northwesterly or westerly direction. This facilitated the transport of the pollutants emitted from both sides of the harbor and possibly from areas farther north of Kowloon to the locations above the ocean east and southeast of Hong Kong Island, where O_3 was produced photochemically and accumulated due to the lack of mixing and reduced deposition over water. When winds changed later to easterly and southeasterly, the ozone-rich plumes were then transported to the measurement site at Cape D'Aguilar. After the O_3 peaked, winds became stronger. For the 11 September episode, wind speeds increased to over 20 m s^{-1} in the evening as the Tropical Cyclone Luke approached the region.
2) 10 July: At about midnight on 10 July, wind directions changed counterclockwise from easterly to northeasterly, northerly to northwesterly, and then to westerly at noon and maintained at westerly throughout the day. Wind speeds were, in general, low in the morning, and started to increase at noon. The O_3 levels peaked at about 1500 LST. On this day, two EPD urban stations also detected high levels of O_3 (shown below), suggesting that this O_3 episode was a territory-wide event. Judging from the persistent northerly and northwesterly winds at Waglan Island, it appears that long-range transport of O_3 and/or O_3 precursors may have played a role in this territory-wide event. However, having noticed that the prevailing winds before 10 July were of an easterly direction, we cannot rule out the possibility, without the information on air trajectories and O_3 precursors data at upwind locations, that the pollutants emitted in Hong Kong during days prior to the episode were brought back to the territory and contributed to the observed event. This point warrants further study.
3) 9–11 October: In this 3-day episode, winds at Waglan Island showed a clear pattern of reversing wind directions. Each day, northerly winds dominated from evening to about noon of the next day, and they reversed to southerly and southeasterly and remained there for 3–5 h in the afternoon. The O_3 peaks were observed during the periods of wind flows from the ocean (southerly and southeasterly flow). This surface flow pattern resembles those of a land- and sea-breeze phenomenon. However, radiosondes launched at approximately 0800 LST at the HKO King's Park Station, Kowloon, showed that surface winds (0–3 km) came from the northeast and north, and no returning upper winds were found. Moreover, it was noted that wind speeds at night were higher than those during the day. This evidence suggests that the reversal in the surface winds during this episode may not have been exclusively caused by the differential heating of land and water. Additionally there are indications, according to the data from HKO's territory-wide aeronometer network, that the reversal of winds occurred only on small spatial scales and was not a territory-wide feature. The attributing mechanism for the observed wind reversal deserves further investigation but is beyond the scope of this study. In this episode, we also noted that the Kwai Chung Station did not record high O_3 concentrations (shown below).

6. Measurements of other air pollutants

Concurrent measurements of other pollutants provide an opportunity to examine the relationships of O_3 with its precursors and with tracers of anthropogenic pollution. Recognizing the difficulties involved in the study of local wind flow, these chemical measurements provide insights as to the chemical characteristics of the air masses arriving at the site, which, in turn, yield useful information on the origin of an air mass. At the station, CO, SO_2, and NO were continuously measured in conjunction with O_3. The analytical methods used for detecting these trace gases were described in Lam et al. (1995, manuscript submitted to *J. Geophys. Res.*) and Wang et al. (1997). The time series for these measurements are shown in Fig. 3 and are separately detailed below.

1) 8 May: The station reported enhanced levels of CO, SO_2, and NO at about 0500 LST. The elevated SO_2 and CO lasted for about 12 h until 1800 LST when they decreased to the levels near their respective typical levels for May. The observed early morning peak coincided with the period of morning traffic. Two additional peaks of SO_2 and CO were observed at noon and in the afternoon, during the periods of easterly and southeasterly winds (ozone concentrations showed corresponding enhancements). These two peaks of SO_2 and CO were not related to the local traffic patterns but may have to do with transport of the plumes emitted in the early morning on that day. We also noted that NO levels were low in the afternoon, which is presumably due to photochemical conversions of NO. As discussed before, it is believed that the urban plumes were transported to the areas over the ocean east and southeast of the station in the morning and were brought to the station after winds changed to easterly and southeasterly. The SO_2 and CO levels correlated. The correlation coefficient is (r) is 0.88, and the slope ($\Delta CO/\Delta SO_2$) is 20 (ppbv/ppbv). This slope compares very well with the value calculated from the emission inventory in Hong Kong for mobile sources ($CO/SO_2 = 23$, including both diesel- and petrol-powered vehicles). For other emission sources, this ratio is 0.10 for power plants, 0.55 for industrial fuel combustion, and 4.8 for ships.
2) 10 July: Like the previous episode, the levels of NO, SO_2, and CO started to increase at about 0600 LST. However, the plumes in this episode contained much more concentrated pollutants and lasted for a much longer period (about 32 h). The center of this large-scale plume (indicated by the highest levels of O_3, CO, and SO_2) arrived at the station at about 1500 LST 10 July. The chemical signatures in the air masses observed in this episode are not easy to interpret. Air masses carrying the signatures of both vehicle and power plant emissions were seen. For the period from 0600 to about 1800 LST 10 July, CO and SO_2 levels generally correlated. The presence of positive correlation between SO_2 and CO and the magnitude of the slope ($\sim$21) seem to suggest that air masses sampled during that period mainly contained the signatures of vehicle emissions. For the period after 0000 LST 10 July, while CO levels continued the decreasing trend, SO_2 increased. During this period winds were from the west and the speeds were high ($\sim$7 m s^{-1}). Here contribution from sources emitting large amounts of SO_2 (but not CO) was indicated. There were two NO peaks on 11 July a narrow peak at about 0200 LST and a longer one at about 0600 LST. The SO_2 levels exceeded the range of the analyzer (40 ppbv) during the two periods, but CO did not show strong enhancements. It is likely that the enhancements in the SO_2 levels after 0000 UTC on 11 July may have been a result of emissions from power plants in the western side of the territory.
3) 11 September: During morning hours, the station sampled several highly concentrated plumes, each lasting 1–3, h during which CO, SO_2, and NO all showed significant enhancements in their levels (note that O_3 dropped). Unlike the 8 May and 10 July cases, the morning pollutant trends did not follow the traffic patterns (e.g., the 0600 LST peak was not obvious). The highly variable levels suggest that air masses had not experienced strong mixing since the pollutants were emitted. As in the 8 May episode, CO and SO_2 corrected well ($r = 0.86$), and the observed slope ($\Delta CO/\Delta SO_2$) is 19, which again compares well with the value from vehicle emissions in Hong Kong.

   An interesting feature is that around noontime NO, SO_2, and, to a lesser degree, CO showed a rapid drop, whereas O_3 levels sharply increased. Maximum O_3 in the afternoon with reduced levels of NO during the periods of easterly winds suggest the afternoon air mass is photochemically ''aged'' compared to that before noon.
4) 9–11 October: As discussed in the previous section, surface winds showed clear patterns of diurnal variations. At night, winds were from the north and the speeds were generally higher, as compared to the weak southerly winds in the afternoons. The trends for CO, SO_2, and NO were closely related to the changes in surface winds (both directions and speeds). In the first two days (9–10 October), their concentrations increased as winds changed from southerly to northerly, which facilitated the transport of fresh pollutants to the station (note that ozone levels dropped due to titration). As the wind speeds increased, the levels of these gases reduced due to the effect of dilution (e.g., 0600–1200 LST 10 October). On the third day, enhanced levels of pollutants were seen with weak southerly winds.

   As discussed before, the causes of the changing wind directions are not clear. During this 3-day event, the CO and SO_2 showed a weaker correlation ($r = 0.59$), as compared to the 8 May and 11 September episodes, although the slopes were similar. The weaker correlation may be attributed to the mixing of air masses with different initial characteristics. It is also noted that the O_3–CO correlation in this episode was not as good as that observed in the other three episodes (see section 7).

In summary, concurrent observations of CO, SO_2, and NO with O_3 allowed closer examinations of the possible sources of the plumes and the transport patterns. For 8 May and 11 September episodes, the correlated levels of SO_2 and CO indicate that the pollutants in measured plumes may have been contributed by the same source category but their highly variable levels, which is particularly the case for the 11 September ep-

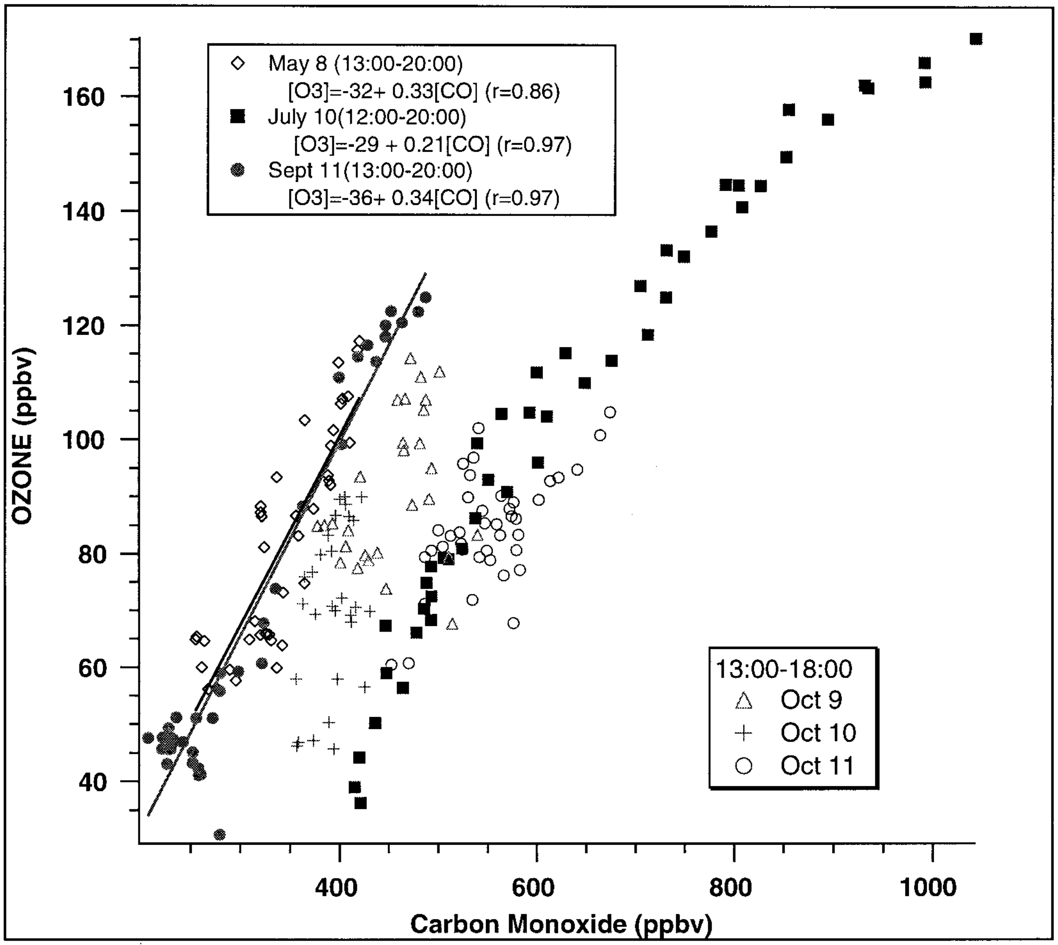

FIG. 4. Ozone vs carbon monoxide. Each point is a 10-min average. Only afternoon and early evening data are included.

isode, suggest that the plumes were isolated and had not undergone intense mixing. It is possible that the station may have encountered the plumes emitted from nearby sources or only a small portion of the general urban plume, therefore the observed peak ozone concentrations may not necessarily represent the highest O_3 levels in the Hong Kong airshed during the episode days. For the 10 July episode, the station encountered a large-scale plume. The first half of the plume, which contained high levels of O_3, seemed to be a plume of mainly urban vehicle emissions, whereas in the second half, power plant emissions were indicated. For the 9–11 October event, trace gases exhibited strong relationships with winds, and mixing of different air masses was indicated.

A better understanding of the distribution of emission sources and their characteristics would help give a more satisfactory explanation of the observations made in the study. Nevertheless, the data and the initial interpretations provide useful information for future modeling study of atmospheric transport and chemistry for Hong Kong.

7. Relationship between ozone and carbon monoxide

To examine the O_3 chemistry and transport, the correlation between O_3 and CO is examined and shown in Fig. 4. Carbon monoxide has been used as an effective tracer of anthropogenic pollution. The measured relationship between CO and O_3, when coupled with the inventoried CO and NO_x, can give an estimate of the lower limit of O_3 production efficiency (number of ozone molecules produced for each NO_x oxidized) and total ozone molecules produced from anthropogenic emissions (Parrish et al. 1993; Chin et al. 1994). In our study, only data in the afternoon and early evening were used in the correlation study. This was done to include only the period of active photochemistry and to exclude the titration effect of fresh pollutants. Here, the data points represent 10-min averages and are shown using different symbols for individual events. Several features are worth mentioning.

First, the O_3–CO relationships on 8 May and 11 September are very similar. The two species are linearly

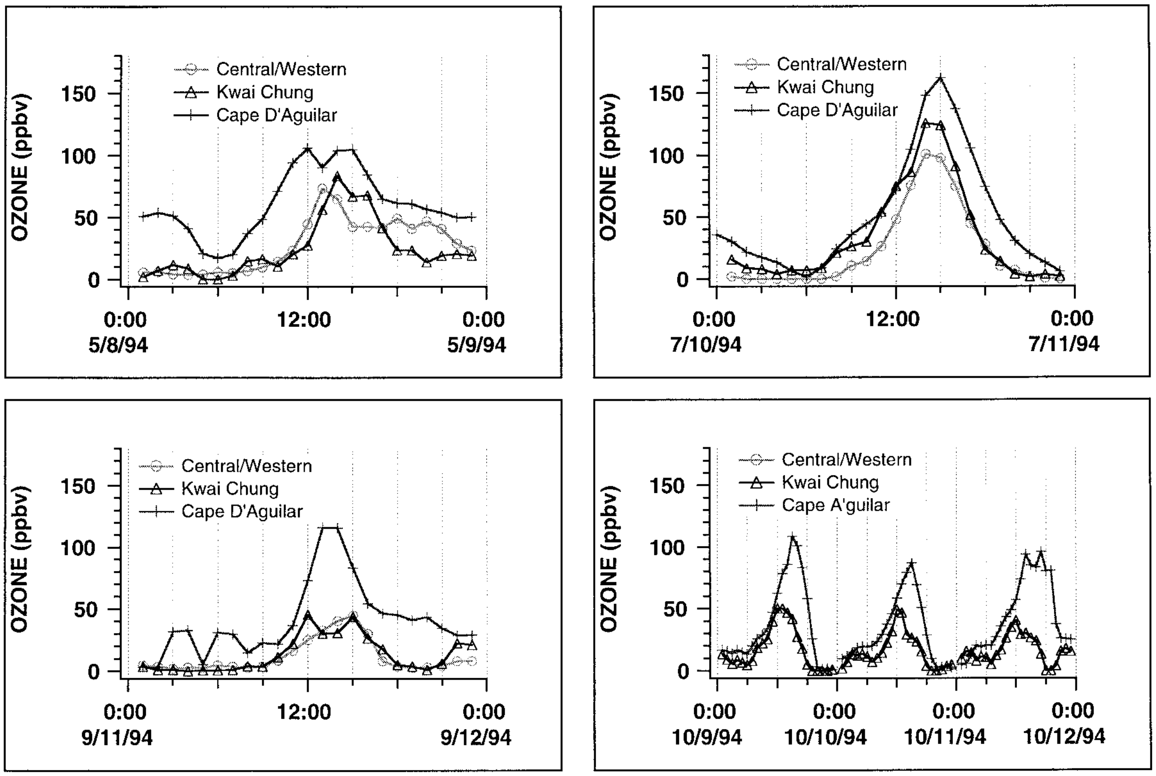

FIG. 5. Comparison of hourly O_3 levels at Cape D'Aguilar vs two urban stations.

correlated [correlation coefficients (r): 0.86 and 0.97 for 8 May and 11 September, respectively]. The slopes ($\Delta O_3/\Delta CO$) and intercepts are similar in these two episodes. These slopes (0.33–0.34) are comparable to those obtained in September 1991 from three locations off the coast of eastern Canada (slopes ranging from 0.22 to 0.29) (Parrish et al. 1993). Here, some differences about the two studies should be noted. The previous study was conducted at the islands in the North Atlantic, about 500 km downwind of northeastern urban corridor of the United States, whereas this study was carried out at a location much closer to the urban areas ($\sim$10 km). The traveling times required for urban plumes to reach the measurements sites are very different in the two studies. Such transport times affect the degrees of photochemistry and physical mixing as the plumes travel to downwind locations. Also, the emission characteristics (i.e., the ratios of CO to NO_x and to VOC) in Hong Kong and in South China may be different from those in North America. Despite the above differences, each of which can affect the relationship between O_3 and CO, the observed similar O_3–CO relation is an interesting phenomenon.

Second, the 10 July data show a nonlinear relationship between CO and O_3. At low concentrations (CO = 400–600 ppbv, in a relative sense), the slope is similar to those for 8 May and 10 July, and the slope reduces as CO levels increase. Closer examination of the data show that the points in the lower CO range include those from both early afternoon and early evening, and similarly, the points in higher CO range comprise those from both before and after the ozone peak. This suggests that the photochemical age may not be the cause of the observed larger slope at lower CO levels or the smaller slope at higher CO levels. Instead, the larger slope may be related to possible higher ozone production efficiency at lower CO levels or due to different initial emission ratios (i.e., different emission ratios of CO to NO_x and VOC) for air sampled around the ozone peak and for that sampled during other times.

Finally, unlike the previous three cases, the October episode does not show an obvious correlation between O_3 and CO, which may be attributed to the mixing of air masses with different loading of O_3 and CO.

8. Comparison of the O_3 episodes observed at Cape D'Aguilar and at two urban stations

Figure 5 shows the diurnal variations of hourly O_3 at the station compared with those at the two urban locations: c/w of Hong Kong Island and KC in the New Territories. In each episode, O_3 peak concentrations at the station (nonurban site) are higher than those at urban stations. In the September and October episodes, O_3 levels at the station were much higher. Relatively high O_3 levels in urban locations on 8 May and 10 July appeared to be related to local calm weather and the reversal of winds (urban wind data not shown). The wind reversal was not observed at the two urban locations on 11 September and 9–11 October, which may explain the relatively low O_3 concentrations observed during these events.

9. Summary and conclusions

In 1994, four O_3 pollution episodes ($O_3 > 100$ ppbv) were observed at a regional background air monitoring station located at Cape D'Aguilar, which is normally upwind of urban areas of Hong Kong. In one episode, the hourly O_3 level reached 162 ppbv. The O_3 concentrations at this station were higher than those observed at two urban locations.

1) The concentrations of O_3 and other pollutants measured at Cape D'Aguilar were sensitive to local wind directions. Recirculation of urban plumes is an important mechanism for transporting the ''O_3-rich'' air masses to the measurement site. Synoptic weather patterns were influenced by the tropical cyclones in the western Pacific and, in one case, by a weak high pressure system over southern China.
2) Simultaneous measurements of chemical and wind data provided valuable insight in studying source origin and the transport patterns. Chemical data (CO, SO_2, and NO) showed that plumes encountered could be quite inhomogenous in pollutant loading, suggesting the nearness of the source locations and/or limited mixing during transport. The chemical data appeared to suggest that the high levels of O_3 during the episodes were produced in the urban plumes that were mainly characteristic of vehicle emissions. Here O_3 and CO showed a linear relation in two cases, with slopes ($\Delta O_3/\Delta CO$) similar to those obtained in a study in the North Atlantic. The nonlinear relationship between O_3 and CO was observed in another episode.

A more comprehensive assessment of the photochemical smog problem in the territory requires information on the spatial distributions of O_3 and its precursors outside urban areas and a better understanding of the wind flow over Hong Kong. There is a need to expand the current O_3 monitoring network, especially to include the downwind locations, under the prevailing wind flows, where photochemical O_3 pollution is expected to be more serious. Indeed, according to an aircraft survey organized by the EPD (EPD 1996b) in October and November 1994, high concentrations of O_3 and other pollutants were found over the western and southwestern parts of the territory. Finally, the potential for cross-border transport of O_3 and its precursors from the Pearl River Delta region should be addressed in the future.

Acknowledgments. The team wishes to thank Prof. M. Anson, the coordinator of the Polytechnic University Air Monitoring Project, and various personnel taking part in the NASA Global Tropospheric Experiment Project for the technical advice and support in establishing the Polytechnic University Air Monitoring Station. The authors express their gratitude to the Data Processing Division of the Hong Kong Observatory for providing the meteorological data. Special thanks are due to Dr. W. L. Chang, Mr. K. P. Wong, and Dr. K. K. Yeung at the Hong Kong Observatory. The team also wishes to thank the Department of Civil and Structural Engineering and the Industrial Center within The Hong Kong Polytechnic University for providing mechanical and electrical support, and Hong Kong Telecom for its assistance in station setup, maintenance, and staff transport. Comments and suggestions from two anonymous reviewers were very helpful in revising the manuscript. This study was funded by The Hong Kong Polytechnic University.

REFERENCES

Chin, M., D. J. Jacob, J. W. Munger, D. D. Parrish, and B. G. Doddridge, 1994: Relationship of ozone and carbon monoxide over North America. *J. Geophys Res.,* **99,** 14 565–14 573.

Chiu, T. N., and C. L. So, 1986: *A Geography of Hong Kong.* 2d ed. Oxford University Press, 403 pp.

Colbeck, I., and A. R. Mackenzie, 1994: *Air Pollution by Photochemical Oxidants. Air Quality Monogr.,* Vol. 1, Elsevier Science, 376 pp.

EPD, 1996a: Air quality in Hong Kong—Results from the EPD air quality monitoring network in 1994. Rep. EPD/TR2/1996, 19 pp.

——, 1996b: Airborne instrumented research-characterization of air pollution. Tech. Paper EPD/TP 4/96, 27 pp. [Available from Environmental Protection Department, 40/F, Revenue Tower, 5 Gloucester Rd., Wan Chai, Hong Kong, China.]

Liu, C. M., S. C. Liu, and S. H. Shen, 1990: A study of Taipei ozone problem. *Atmos. Environ.,* **24A,** 1461–1472.

——, C. Y. Huang, S. L. Shieh, and C. C. Wu, 1994: Important meteorological parameters for ozone episodes experienced in the Taipei Basin. *Atmos. Environ.,* **28,** 159–173.

NRC, 1991: *Rethinking the Ozone Problem in Urban and Regional Air Pollution.* National Academy Press, 500 pp.

Parrish, D. D., J. S. Holloway, M. Trainer, P. C. Murphy, G. Forbes, and F. C. Fehsenfeld, 1993: Export of North American ozone to the north Atlantic Ocean. *Science,* **259,** 1436–1439.

Tsui, W. S., S. W. Pang, and C. P. Chin, 1996: Causes of ozone episodes in Hong Kong. Preprints, *89th Annual Conference of Air and Waste Management Association,* Nashville, TN, Air & Waste Management Association.

Wang, T., K. S. Lam, L. Y. Chan, M. A. Carroll, and S. Y. Lee, 1997: Trace gas measurements in coastal Hong Kong during the PEM–WEST (B). *J. Geophys Res.,* **102,** 28 575–28 588.

Xu, J. L., and Y. X. Zhu, 1994: Some characteristics of ozone concentrations and their relations with meteorological factors in Shanghai. *Atmos. Environ.,* **28,** 3387–3392.

Yeung, K. K., W. L. Chang, B. Wan, F. Kimura, and T. Yosakawa, 1991: Simulation of boundary layer flow over Hong Kong. *Atmos. Environ.,* **25A,** 2161–2172.