Relationship between Air Pollution in Hong Kong and in the Pearl River Delta Region of South China in 2003 and 2004: An Analysis

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ABSTRACT

Air pollution in the Pearl River Delta (PRD) region of south China, which is one of the four regions in China most heavily affected by haze, is found to correlate with that of Hong Kong, indicating the regional nature of the Hong Kong problem. Of the 10 territory-wide episode days occurring in Hong Kong in 2003 and 2004, 3 of them coincide with the most polluted days of the month in the PRD. On two other episode days, the most polluted days in the PRD occurred within 2 days of the Hong Kong episodes. The air pollution trends of the PRD cities and Hong Kong are found to resemble each other more under certain meteorological conditions than others, notably when a tropical storm is positioned at the Luzon Strait between Taiwan and Luzon in the Philippines, and the entire PRD, including Hong Kong, is equally affected by it, resulting in photochemical events. During this time, Hong Kong is downwind of nearly all pollution sources in the region. At other positions of the storm, the eastern part of the PRD is often affected more significantly. In winter episodic conditions, which occur when weak anticyclones prevail over south China, local meteorological factors, namely, inversions and sea-breeze convergences, are believed to contribute to the temporal difference of the pollution peaks in Hong Kong and the rest of the PRD.

1. Introduction: Air pollution in the Pearl River Delta region of South China

Because Hong Kong is situated at the mouth of the Pearl River estuary and downwind of Guangdong Province (Fig. 1) in the cool season and the tropical cyclone season, its air pollution, which reached record levels in 2003 and 2004, is believed to be part of the regional problem.

The Pearl River Delta (PRD) region of the Guangdong Province in south China is one of the four main regions in China heavily afflicted by haze. The other seriously affected regions are (i) the North China Plain (or the Yellow River–Huaihe–Haihe Plain), (ii) the Yangtze Valley, and (iii) the Sichuan basin. These regions appear to coincide with elevated levels of aerosol optical thickness (AOT) as shown in Fig. 2, which depicts monthly averages of AOT over China for the months of January and September 2004, as received from the standard National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) retrieval. The AOT is proportionally related to the particulate part of anthropogenic air pollution, because the satellite data are screened for clouds and high water vapor during the retrieval (King et al. 1992). Because the monthly averages are accumulated from daily satellite passes, Fig. 2 demonstrates the persistent presence of elevated particulate pollution over relatively concentrated regions. Daily MODIS passes shown in section 3c give further visual evidence of smog restricted to certain regions, namely, lower elevations. These pictures are markedly distinctive from naturally born aerosols like the ones from dust storms or fires. While dust storm aerosols are windblown over thousands of miles and thus reveal horizontal isotropy, fires are seen as point sources with a smoke wake driven by the surface airflow.

The rapid development and industrialization in the PRD are believed to have led to the regional air pol-

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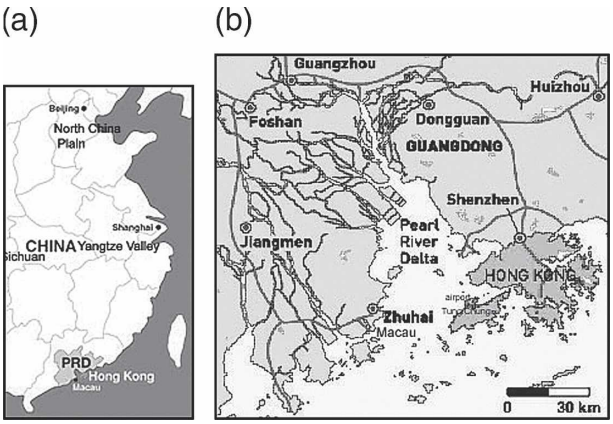

FIG. 1. Maps of (a) east and south China (taken from http://www.tdctrade.com/prd/) and (b) the Pearl River Delta region (taken from http://www.scmp.com).

lution problem, which has existed for well over a decade and does not show any sign of easing off soon. Growth in the municipalities began in the 1980s when Hong Kong manufacturers moved their operations into the region in large numbers. After years of development, the estimated 53 000 Hong Kong enterprises employ some 10 million people (Hong Kong Government 2004a) (over 50 times the size of Hong Kong's own manufacturing workforce). Now established as China's largest light industry production base, Guangdong Province is known to attract a significant fraction of China's foreign direct investment. The gross domestic product (GDP) growth of Guangdong in 2003 was 13.6% as compared with an average GDP growth of 13.3% since 1981 (Guangdong Environmental Protection Bureau News 2004).

Regarding haze in the PRD, a very serious problem has been reported in the municipalities of Foshan (Fig. 1) (Guangdong Environmental Protection Bureau News 2004) and Guangzhou, the provincial capital of Guangdong (Green GuangZhou net 2004; Guangdong Environmental Protection Bureau News 2003a,b,c). The visibility in Guangzhou on the episode days in January 2003 was reported to reach as low as 300 m (Guangdong Jindun net 2003). The situation has worsened, with the number of hazy days (January–June) in Guangzhou increasing from 53 days in 2002 to 66 in 2003 (Guangdong Environmental Protection Bureau News 2003b). The severe haze problem in Guangzhou has been suggested to be related to (i) calm wind conditions, (ii) inversions over the PRD, and (iii) industrial emissions (Guangdong Environmental Protection Bureau News 2003b). A report on pollution in the PRD region (South China News 2003) attributed it to metallurgical and paper industries and vehicle exhaust, as well as biomass burning in the region.

This paper examines air pollution episodes in Hong Kong in 2003 and 2004, putting them in the context of the state of pollution in the region in the same

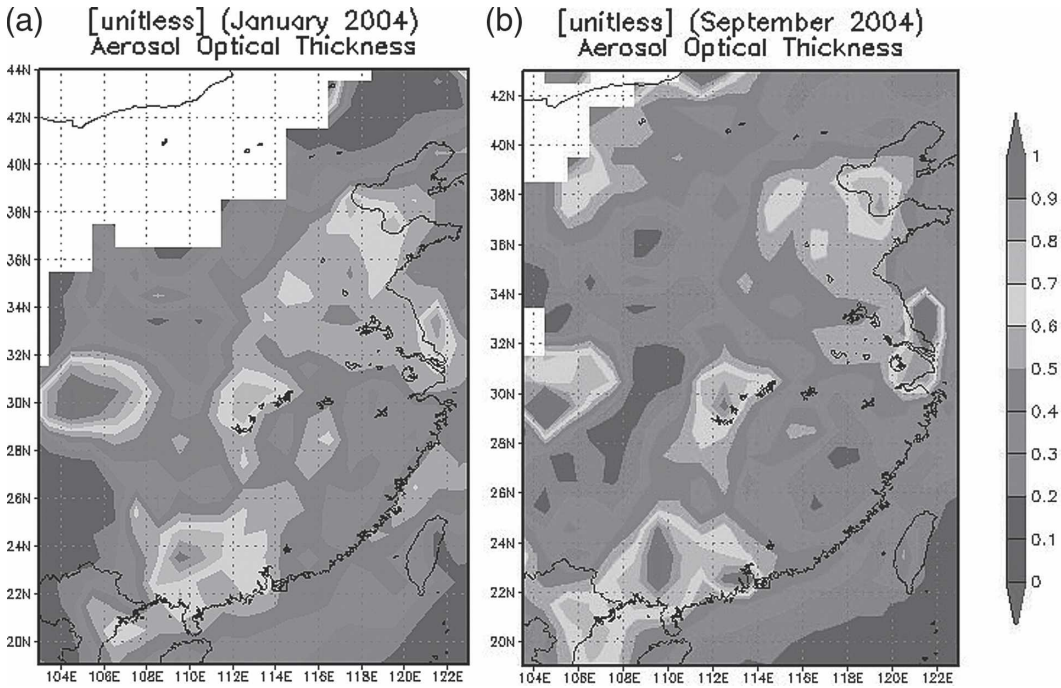

FIG. 2. Aerosol optical thickness of China in (a) January and (b) September 2004 (generated by the MODIS Online Visualization and Analysis System).

period. Common synoptic factors and local meteorological factors contributing to the pollution are explained.

2. Pollution episodes in Hong Kong in 2003 and 2004

Territory-wide pollution episodes that occurred in Hong Kong in 2003 and 2004 are summarized in Table 1, with data presented on the maximum hourly concentrations of nitrogen dioxide (NO_2), 10-μm particulate matter (PM_{10}), ozone (O_3), and minimum hourly visibilities. The air quality and meteorological data have been obtained from the Environmental Protection Department and the Hong Kong Observatory of the Hong Kong Government, respectively. The Hong Kong air quality objectives (i.e., ambient air standards; listed in the notes of Tables 1 and 3) can conveniently be used for comparison.

Photochemical episodes occurring on 6 and 7 September 2004, and from early to around mid-October 2004 at Tung Chung (near the Hong Kong International Airport) located on the eastern part of the Pearl River estuary, have not been included because, on these days, the rest of Hong Kong was not so badly affected and did not record violations of the air quality objectives. Locations of the monitoring stations listed in Table 1 are found in Lee et al. (2002) and Lee and Hills (2003).

No dust storm–related episode occurred in the spring of these two years. The pollution events that occurred in other seasons are described below.

a. Autumn

The worst pollution of 2003 and 2004, contrary to previous years, occurred in this season. Though this seemingly new trend of pollution has yet to be established with more data and more information about possibly new seasonal sources, there is no doubt that the pollution in the region has deteriorated to an extent that warrants immediate concern. The autumn episodes on 14 and 15 September 2004 represent the most serious so far experienced, recording on 14 September an all time high air pollution index (API) of 201 at Tung Chung, signifying "severe" air pollution. In the thick smog shrouding Hong Kong on that day, the O_3 concentration reached a record high of 403 μg m^{-3} (Table 1, Fig. 3a). In other parts of the territory NO_2 and PM_{10} levels are elevated.

Back in 2003, the November ozone episode in Hong Kong was the most serious episode for the year, and the first major autumn episode recorded since air quality monitoring by the Environmental Protection Department commenced in the early 1980s. The hourly reported API on the episode day exceeded 100 in nearly all ambient stations with a high of 126, representing violations of the short-term and/or long-term air quality objectives of Hong Kong. In the haze of the day, the visibility inside the harbor fell to 1800 m while that at the Hong Kong International Airport dropped to 1000 m, setting a new record of low visibility in Hong Kong (Hong Kong Observatory 2003a). As shown in Table 1, PM_{10} and NO_2 as well as O_3 concentrations were elevated.

b. Summer

The summer of 2003 was relatively uneventful in comparison with other years. The episode on 18 June 2003 was the only summer episode in 2003, and was early by comparison with episodes of previous years, which all fell within the months of July and August (Lee et al. 2002). A fairly elevated O_3 concentration of 282 μg m^{-3} was recorded.

TABLE 1. Maximum hourly pollutant concentrations (ambient) on territory-wide episode days 2003–04. "Teom" is the tapered element oscillating microbalance sampler. "Visibility" indicates the minimum hourly value measured at the Hong Kong Observatory Headquarters. The hour (LT) and station of maximum concentration appear in parentheses.

Date	NO_2	PM_{10} (Teom) (μg m^{-3})	O_3	Visibility (m)
Autumn				
2 Nov 2003	337* (2300, Kwun Tong)	381 (1700, Tsuen Wan)	246* (1400, Tung Chung)	1800
14 Sep 2004	298 (1500, Kwai Chung)	234 (1500, Tsuen Wan)	403* (1500, Tung, Chung)	6000
Winter				
19 Jan 2003	356* (1600, Tsuen Wan)	294 (1600, Tsuen Wan)	182 (1700, Tung Chung)	4200
31 Dec 2003	331* (1900, Kwai Chung)	320 (1400, Tsuen Wan)	218 (1600, Tung Chung)	2000
2 Jan 2004	293 (1500, Kwai Chung)	452 (1400, Tsuen Wan)	176 (1700, Tap Mun)	2200
14 Feb 2004	289 (1400, Tung Chung)	321 (1400, Tung Chung)	193 (1700, Tap Mun)	4000
Summer				
18 Jun 2003	264 (1800, Kwun Tong)	206 (1600, Tai Po)	282* (1400, Tap Mun)	5000
29 Jun 2004	245 (1900, Tsuen Wan)	211 (1900, Yuen Long)	281* (1800, Tung Chung)	9000
18 Aug 2004	284 (1900, Kwai Chung)	256 (1900, Yuen Long)	330* (1700, Tung Chung)	3000
25 Aug 2004	188 (1400, Kwun Tong)	158 (1400, Central western)	277* (1400, Sham Shui Po)	3500

* Exceedance of Hong Kong 1-h Air Quality Objectives: 300 μg m^{-3} for NO_2, 240 μg m^{-3} for O_3.

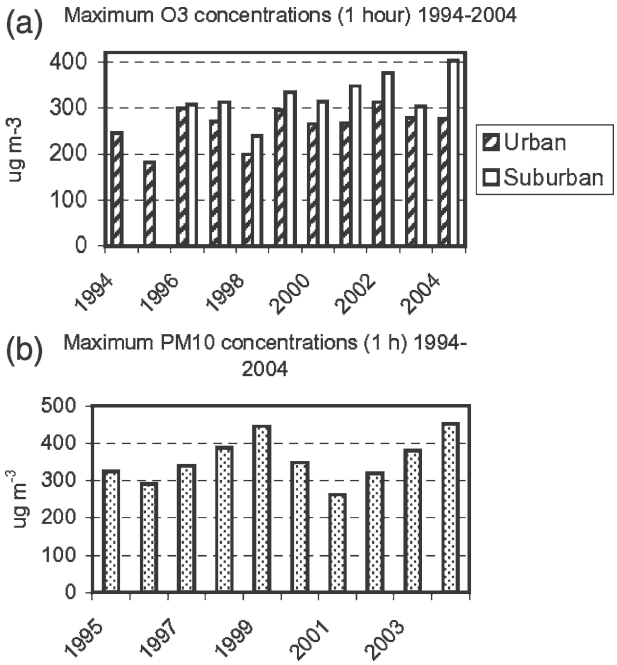

FIG. 3. (a). Maximum O_3 (1 h) concentrations of 1994–2004. (b) Maximum PM_{10} (1 h) concentrations of 1995–2004.

The summer of 2004 saw O_3 episodes occurring on 29 June and 18 and 25 August, with the highest O_3 concentration of 330 μg m^{-3} recorded on 18 August 2004 at Tung Chung (Table 1). The levels of NO_2 and PM_{10} were also elevated on most summer episode days.

c. *Winter*

Among the winter episodes of 19 January and 31 December 2003 and 2 January and 14 February 2004, the 2 January 2004 episode was the most serious, measuring a maximum hourly PM_{10} concentration of 452 μg m^{-3}, which is the highest ever recorded in Hong Kong (Fig. 3b). Apart from particulate pollution, NO_2 was also a major problem on these days as shown in Table 1. Though photochemical contributions were smaller than in the summer and autumn episode days, moderate O_3 concentrations were still reached with the maximum ranging from 176 to 218 μg m^{-3} (Table 1). Heavy haze prevailed on all days. The visibilities measured at the Hong Kong Observatory Headquarters ranged from 2000 to 4200 m (Table 1).

3. Air pollution in the Pearl River Delta in 2003 and 2004

a. *Influence on Hong Kong*

Pollution transport into Hong Kong from the nearby Guangdong Province during tropical storms and in the northeast monsoon seasons, and especially the former, has been demonstrated by airmass back trajectories and airflow in streamline analysis charts in earlier papers (Lee et al. 2002; Lee and Hills 2003). Sources of pollutants from Guangdong are believed to be industrial and vehicular sources, as well as power stations, which burn coal and petroleum of sulfur content mostly exceeding 0.8% (Environmental Protection Department 2005). This contribution is additional to the impact of local vehicular sources and power plants. The latter, in particular, have steadily increased production after a significant drop in 1994 (Census and Statistics Department 2004).

b. *Pollution indicator*

Air pollution data of Macau are obtained from the Climate and Atmospheric Environment Center of the Macao Meteorological and Geophysical Bureau, but data are not yet available for the Guangdong Province cities. As an alternative, the API values for these cities reported on the Guangdong Environment Bureau Web site (online at http://www.gdepb.gov.cn) are used in this paper to grossly illustrate the degree of severity of the pollution on episode days in these places as compared with the Hong Kong situation.

As in the United Staes (Environmental Protection Agency 1999), Canada, and Australia, the API/air quality index (AQI) for Hong Kong, Macau, and the Guangdong Province cities are each chosen from the highest of the subindices computed for the PM_{10}, SO_2, NO_2, CO, and O_3 pollutants in an area and correlate directly with the severity of the pollution. The pollutant giving rise to API/AQI for the area is the "critical pollutant." However, while NO_2 is not required to be reported by the Environmental Protection Agency (EPA), $PM_{2.5}$ is not yet included by Hong Kong and the region, and O_3 has yet to be reported in mainland China. Therefore, in summer and autumn episodes, PM_{10} or SO_2 are reported instead of O_3, as shown in Table 2.

While the API values are capable of indicating the general trend of the pollution in the region, it must be noted that the air quality criteria as well as the pollutant concentration breakpoints for the pollutant subindices differ slightly between Hong Kong, Macau, and mainland China (Table 3). In fact the standards for the latter two are more stringent than those of Hong Kong, notably when defining the 100 index points for SO_2 and PM_{10} whereas the breakpoint concentrations for the API/AQI from 200 to 500 for the regions are almost the same as the corresponding EPA values (Environmental Protection Agency 1999). However, Hong Kong reports the API hourly, versus the daily reports of Macau

TABLE 2. Maximum API in Guangdong Province cities 2003–04.

Hong Kong			Maximum API in Guangdong Province cities					
Episode day	Max API	Critical pollutant	Max API in Guangdong on the Hong Kong episode day (city)	Critical pollutant	Max API of the month (city)	Date of max API	Critical pollutant[a]	Synoptic condition on Hong Kong episode day
Autumn								
2 Nov 2003	126	NO_2	303[b] (Guangzhou)	PM_{10}	303[b] (Guangzhou)	2 Nov 2003	PM_{10}	A broad ridge of high pressure over southeast China with severe Topical Storm Melor at the Luzon Strait
14 Sep 2004	201	O_3	99[c] (Meizhou)	PM_{10}	118 (Shenzhen)	16 Sep 2004	PM_{10}	Weak continental airstream with a trough of low pressure covering part of the Pearl River Delta
Winter								
19 Jan 2003	114	NO_2	190[c] (Guangzhou)	PM_{10}	228 (Guangzhou)	18 Jan 2003	PM_{10}	Northeast monsoon weakens
31 Dec 2003	145	NO_2	142 (Shenzhen)	NO_2	192 (Guangzhou)	25 Dec 2003	NO_2	Northeast monsoon moderates
2 Jan 2004	123	PM_{10}	119 (Foshan)	PM_{10}	149 (Guangzhou)	6 Jan 2003	NO_2	Northeast monsoon further moderates
14 Feb 2004	150	NO_2	148[b] (Shenzhen)	NO_2	148[b] (Shenzhen)	14 Feb 2004	NO_2	Weak pressure over continent
Summer								
18 Jun 2003	126	O_3	97 (Donguan)	NO_2	100 (Foshan)	13 Jun 2003	PM_{10}	Typhoon Soudelor crosses East China Sea
29 Jun 2004	126	O_3	93 (Guangzhou)	SO_2	114 (Guangzhou)	11 Jun 2004	PM_{10}	Typhoon Mindulle northeast of Luzon
18 Aug 2004	156	O_3	100[b] (Shenzhen)	PM_{10}	107 (Guangzhou)	8 Aug 2004	SO_2	Typhoon Megi in East China Sea affects eastern part of PRD
25 Aug 2004	123	O_3	75 (Maoming)	PM_{10}	107 (Guangzhou)	8 Aug 2004	SO_2	Typhoon Aere in northwest Taiwan

[a] Ozone is not reported.
[b] Maximum in Guangdong occurring on the same day as Hong Kong.
[c] Maximum in Guangdong occurring within 2 days of the Hong Kong episode day.

TABLE 3. Comparison of the API/AQI breakpoint concentrations among Hong Kong, Macau, and China (with regard to PM_{10}, SO_2, NO_2, and O_3); CO is omitted from this table for simplicity. The main disparities between Hong Kong and the region are in italics.

	Concentration (μg m^{-3})											
	PM_{10}			SO_2			NO_2			O_3		
Index	Macau	Mainland China	Hong Kong	Macau	Mainland China	Hong Kong	Macau	Mainland China	Hong Kong	Macau	Mainland China	Hong Kong
0	0	0	0	0	0	0	0	0	0	0	0	0
50	100	50	55[a]	60	50	*80*[a]	80	80	80[a]	80	120	120
100	150	150[b]	*180*[c]	150	150[b]	*350*[c]	150	120[d]	*150*[c]	160	200[d]	240
200	350	350	350	800	800	800[e]	280	280	*300*[e]	350	400	400
300	420	420	420	1600	1600	1600	565	565	565	600	800	800
400	500	500	500	2100	2100	2100	750	750	750	800	1000	1000
500	600	600	600	2620	2620	2620	940	940	940	1000	1200	1200

[a] Annual average.
[b] China national air quality standard Grade II.
[c] 24-h average.
[d] China national air quality standard Grade III.
[e] Hourly average.

and Guangdong Province cities. Furthermore, contrary to the generally practiced midnight-to-midnight measurements, the calculation period for Macau's daily AQI goes from noon of the previous day to noon of the day of concern. For these reasons, adjustments have to be made if precise comparisons are intended. Many of the discrepancies are expected to be resolved when a collaborative monitoring effort begins in 2005, with 16 monitoring stations collecting data from various parts of the Pearl River Delta (Hong Kong Government Information Services Department 2004).

c. *Pollution trend in the Pearl River Delta in 2003–04 in comparison with Hong Kong*

Macau is located in the western part of the Pearl River estuary across from Hong Kong, and records elevated pollutant levels, for example, PM_{10} particulate (Fig. 4), when Hong Kong, on the eastern part of the estuary, is affected by an episode scale of pollution.

For the rest of the Pearl River Delta, Table 2 indicates that air pollution in Hong Kong in 2003 and 2004 correlates with that of the Pearl River Delta region. Out of 10 episode days occurring in Hong Kong in the period, 3 of them coincided with the most polluted day in Guangdong for the particular month. This occurred on 2 November 2003 at Hong Kong and Guangzhou, and 14 February and 18 August 2004 at Hong Kong and Shenzhen on both days. Two other local episodes—19 January 2003 and 14 September 2004—occurred within 2 days of the provincial episodes. To investigate the relationship between pollution in Hong Kong and the region, monthly pollution trends in Hong Kong and the PRD cities are examined with respect to seasons.

1) AUTUMN

On 2 November 2003 the entire region, including Hong Kong, was affected. The pollution in Macau on the western part of the Pearl River Delta region soared to high levels, recording a maximum PM_{10} concentration of 289 μg m^{-3} (at Taipa). The rest of the Pearl River Delta region also reported very high API values, which well exceeded 100 in Guangzhou, Foshan, Jiangmen, Zhaoqing, and Shaoguan, with Guangzhou reaching a maximum of 303, the highest API value for the province for the whole year of 2003.

The air pollution trend of November 2003 for cities of the Pearl River Delta region shown as API values in Fig. 5 portrays a similar pattern of pollution in Hong Kong and the Guangdong Province cities. They notably share the worst polluted day of 2 November. The MODIS images in Fig. 6 clearly indicate the haze trapped in the valleys of the Pearl River Delta, extending to Hong Kong and the nearby coastal region.

A photochemical event was also found in the Pearl River Delta region on 14–16 September 2004, with a maximum API for the month of 118 recorded in Shenzhen on the 16th. This apparently correlates with the most polluted day in Hong Kong history, which occurred on 14 September 2004 when the thick smog covering up the city pushed the API at Tung Chung to an all-time record of 201. The smog continued into 15 September, but then moderated. The general trend for September 2004 in Hong Kong and Guangdong is shown in Fig. 5.

2) SUMMER

The pollution trends in Hong Kong, Macau, and the Guangdong Province cities are found to be comparable

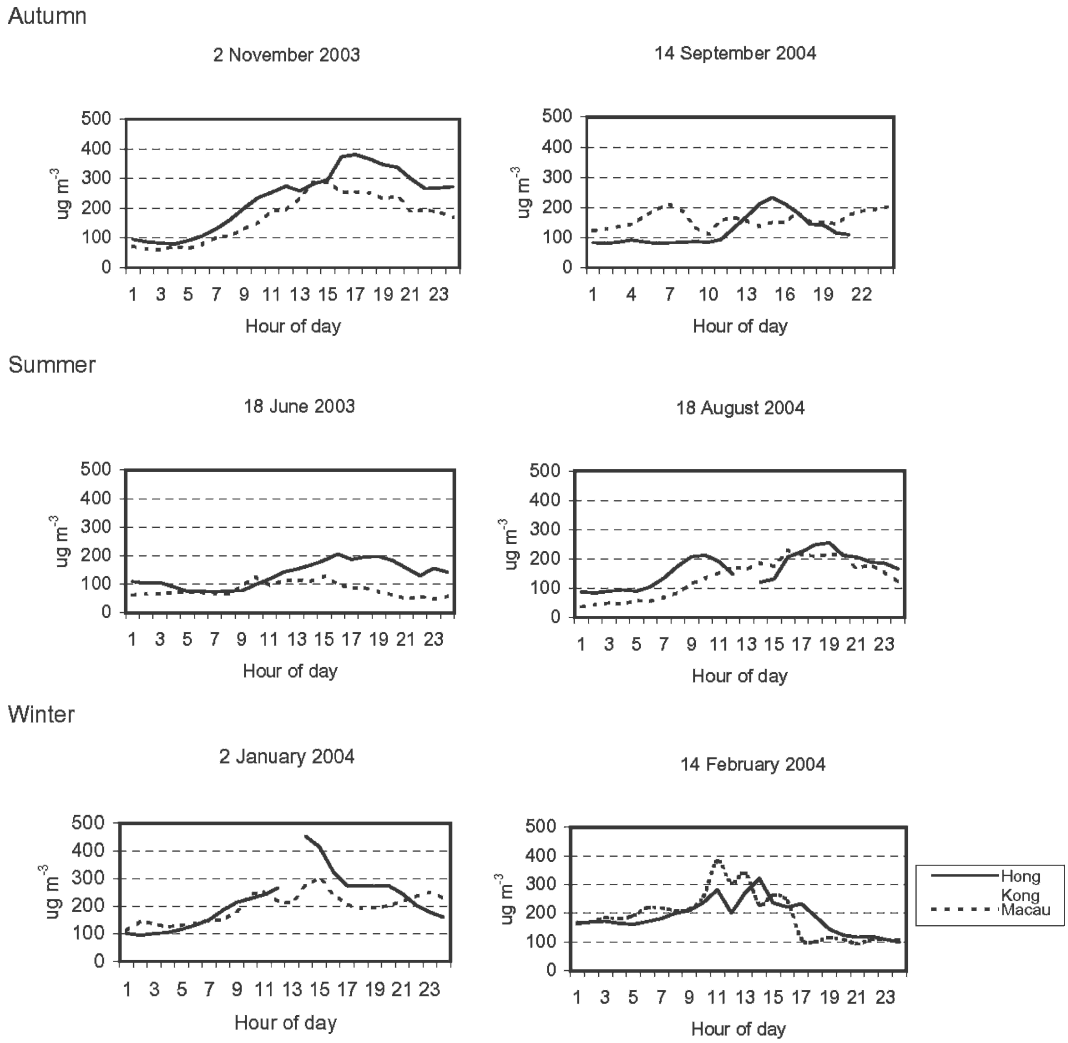

FIG. 4. PM_{10} concentrations in Hong Kong and Macau on episode days.

in June 2003 though the maximum API in Guangdong for the month occurred 5 days earlier than that in Hong Kong, measuring 100 in Foshan on 13 June (Table 2). The movement of pollutants offshore over Hong Kong on 18 June is also illustrated by the MODIS image in Fig. 6. This movement is consistent with the northwesterly airflow pattern prevailing in the region.

In comparison, the API trends for June and August 2004 in Hong Kong and Guangdong do not correspond closely. The Hong Kong photochemical episode on 29 June 2004 saw elevated pollutant levels in Guangdong Province cities, but the worst pollution in the province had occurred much earlier in the month. Similarly, the episode on 18 August corresponds to a provincial maximum at Shenzhen for the day, but the monthly provincial maximum occurred earlier in the month (Fig. 7).

The lower resemblance between the API trends of Hong Kong and the Pearl River Delta region in 2004 June and August is believed to be due to the positions of the tropical storms in the months, as explained in section 4a.

3) WINTER

As shown in Table 2, high API values for the winters of 2003 and 2004 occurred on the same day as Hong Kong, or within up to 6 days from the Hong Kong episode day. The trend is illustrated in Fig. 8, which shows the API values for January 2003.

It is evident from Fig. 8 that, although the whole PRD is simultaneously under the influence of a northeast monsoon, the pollution trend in Hong Kong and the other PRD cities bear less resemblance to each

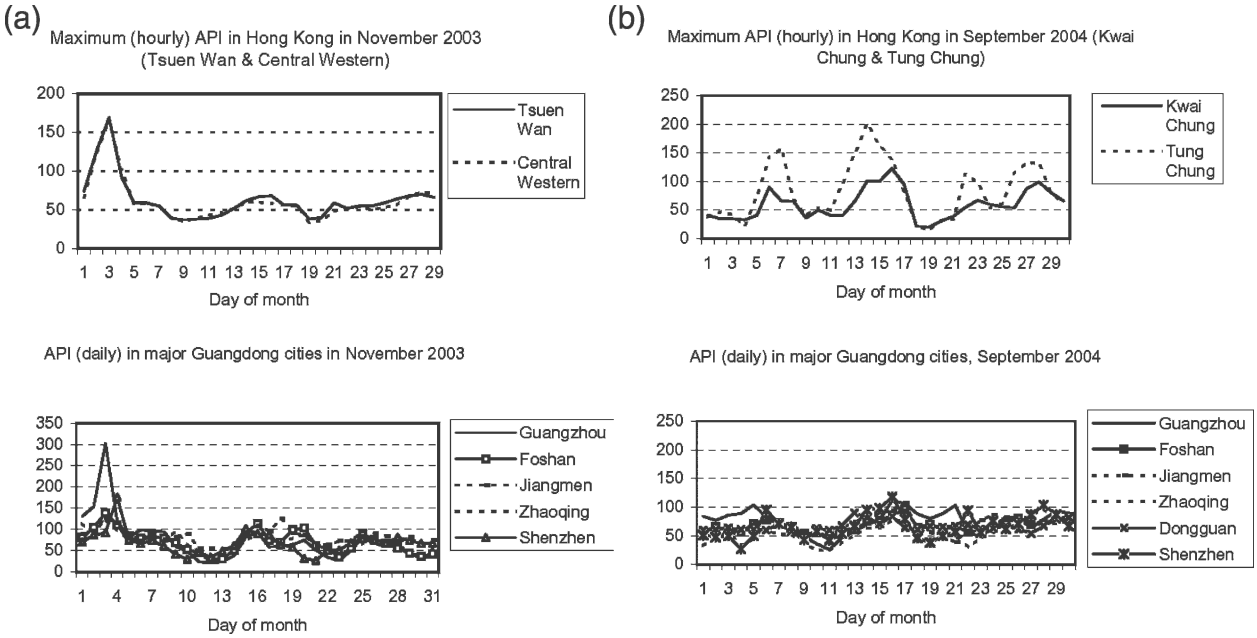

FIG. 5. API trends in Hong Kong and Guangdong in autumn: (a) November 2003 and (b) September 2004.

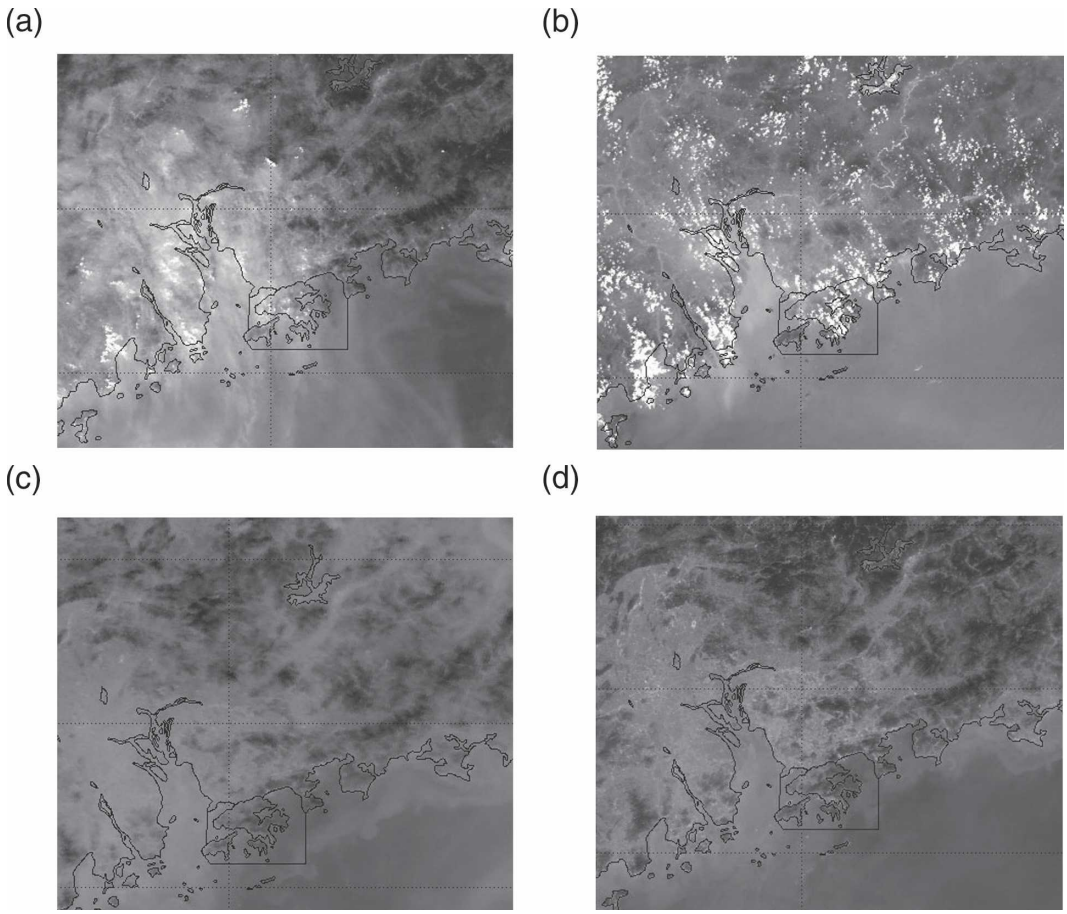

FIG. 6. MODIS image for the Pearl River Delta region on episode days: (a) 2 Nov 2003, (b) 18 Jun 2003, (c) 31 Dec 2003, and (d) 14 Feb 2004.

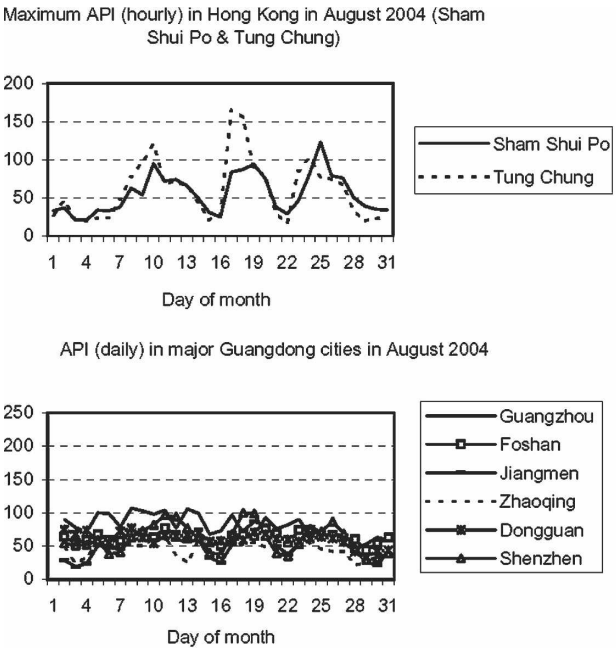

FIG. 7. API trends in Hong Kong and Guangdong in summer: August 2004.

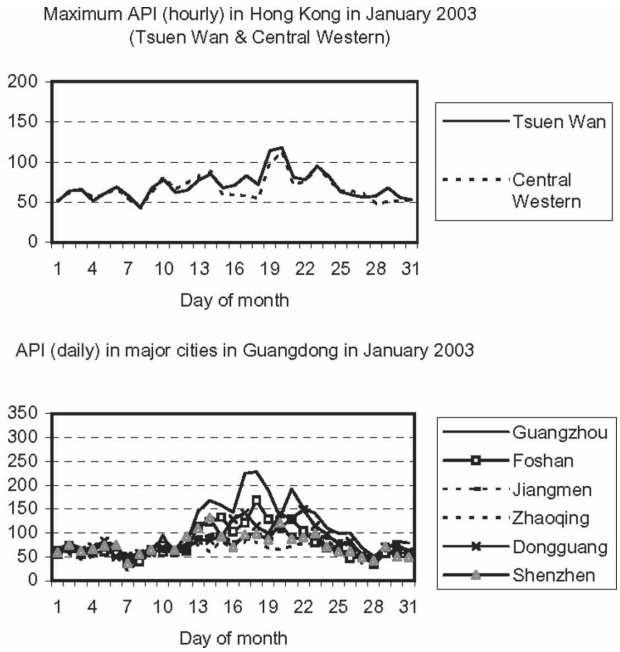

FIG. 8. API trends in Hong Kong and Guangdong in winter: January 2003.

other in winter than in other seasons. This may suggest that, apart from differing source characteristics, factors, other than regional ones (most probably localized meteorological factors), may impose a greater influence in winter. Such likely factors are presented and explained in section 5. The regional haze problem on the winter episode days is also vividly demonstrated by the MODIS images in Fig. 6 for 31 December 2003 and 14 February 2004.

4. Meteorological patterns in the region during episodes

All the episode days are associated with specific synoptic conditions as shown in Fig. 9 and summarized in Table 2. Broadly, three types of seasonal patterns can be distinguished, (i) autumn with a tropical storm (or sometimes only a trough of low pressure, as on 14 September 2004) and an anticyclone, (ii) summer with a tropical storm, which may be at different locations from the PRD, and (iii) winter with a weak anticyclone.

a. Tropical cyclones

During the 2 November 2003 episode, a broad ridge of high pressure was prevailing over southeast China when severe Tropical Storm Melor entered the Luzon Strait. As a result, both the cyclone and the anticyclone influenced the region. However, the airflow to Hong Kong shown in the streamline chart of Fig. 10 [from the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory; see information online at http://www.arl.noaa.gov/ready/], is mainly northwesterly wind. This is an anticlockwise flow typically induced by a storm. This direction of airflow is also indicated in Fig. 11, showing wind directions at the Hong Kong Observatory weather stations at the hours of maximum PM_{10} concentrations. Apparently the northwesterly flow has replaced the original northeasterly flow that is prevalent on anticyclonic days, and persists as the dominating influence. It causes pollutants to be transported across the region (Lee et al. 2002).

By contrast, the September 2004 episode occurred without a tropical storm but with only a trough of low pressure that covered part of the Pearl River Delta. Most of China was mainly under the influence of a weakened continental airstream.

Regarding summer episodes, the synoptic pattern is typically characterized by the presence of tropical storms (Fig. 9 and Table 2). On all summer episode days of 2003 and 2004, like the autumn 2 November 2003 episode that was under the influence of a storm, background northwesterly flow was found across the Pearl River Delta region. The regional airflow pattern is shown in Fig. 10.

The extent and degree of tropical storm impact on the Pearl River Delta and South China Sea region are apparently dependent on the relative position of the cities with respect to the center of the storm, as well as

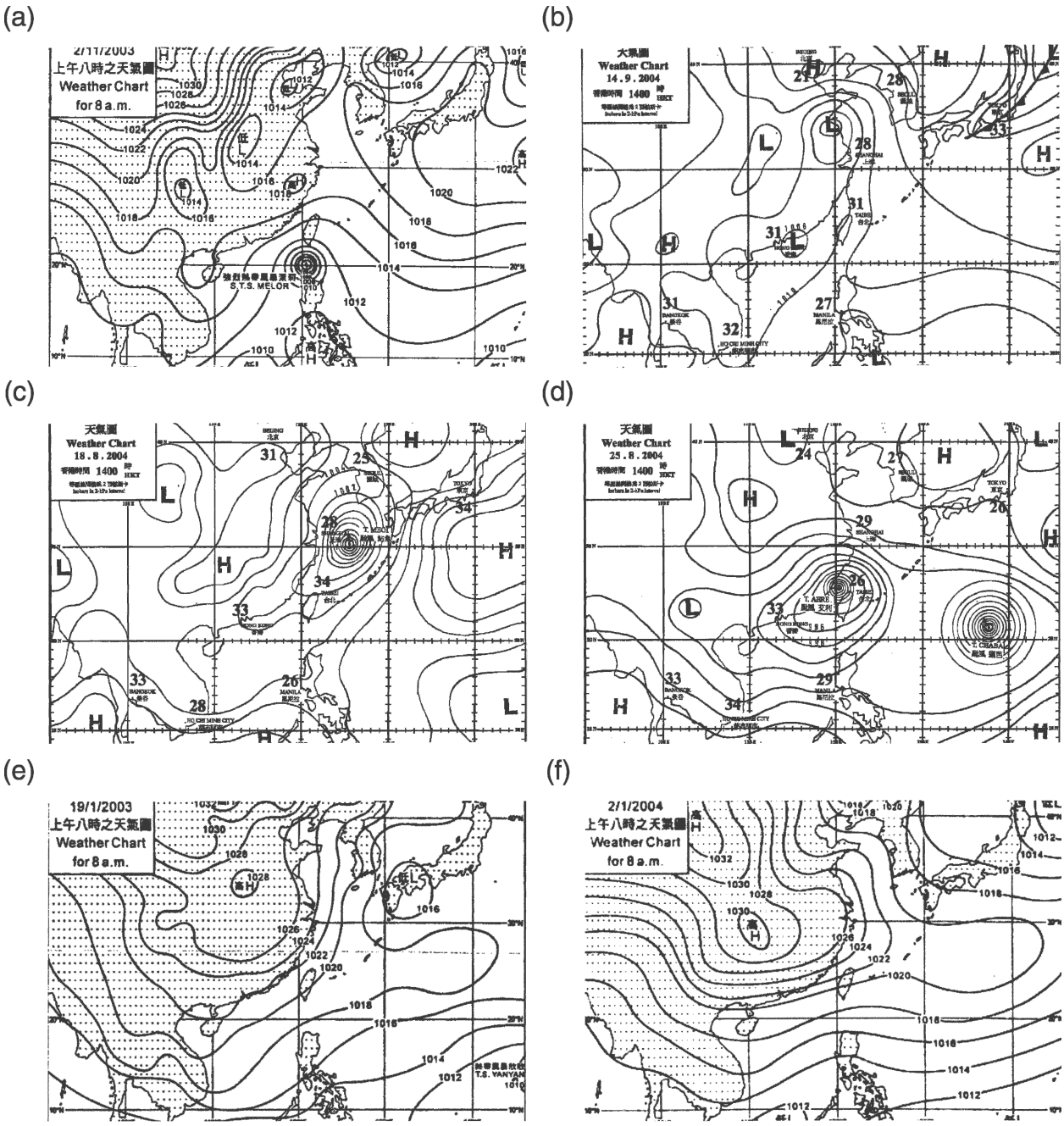

FIG. 9. Synoptic charts for the episode days for autumn [(a) 2 Nov 2003; (b) 14 Sep 2004], summer [(c) 18 and (d) 25 Aug 2004], and winter [(e) 19 Jan 2003; (f) 2 Jan 2004].

the intensity of the storm. The impact of storms on Hong Kong air quality has been shown to be most significant when the storms reach the Bashi Channel (south of Taiwan) or the Balintang Channel (north of the Philippines) (Lee et al. 2002). That also appears to be the position of the storm for which most of the cities upwind of Hong Kong are also affected.

While the 2 November 2003 episode was influenced by a storm at the Luzon Strait between Taiwan and Luzon in the Philippines, the storms on all of the summer episode days in 2003 and 2004 were at other more distant positions. On 18 June 2003 Typhoon Soudelor was crossing the East China Sea (Hong Kong Observatory 2003b). During the episode on 29 June 2004, Typhoon Mindulle was northeast of Luzon. On 18 August 2004, Typhoon Megi was in East China Sea, and on 25

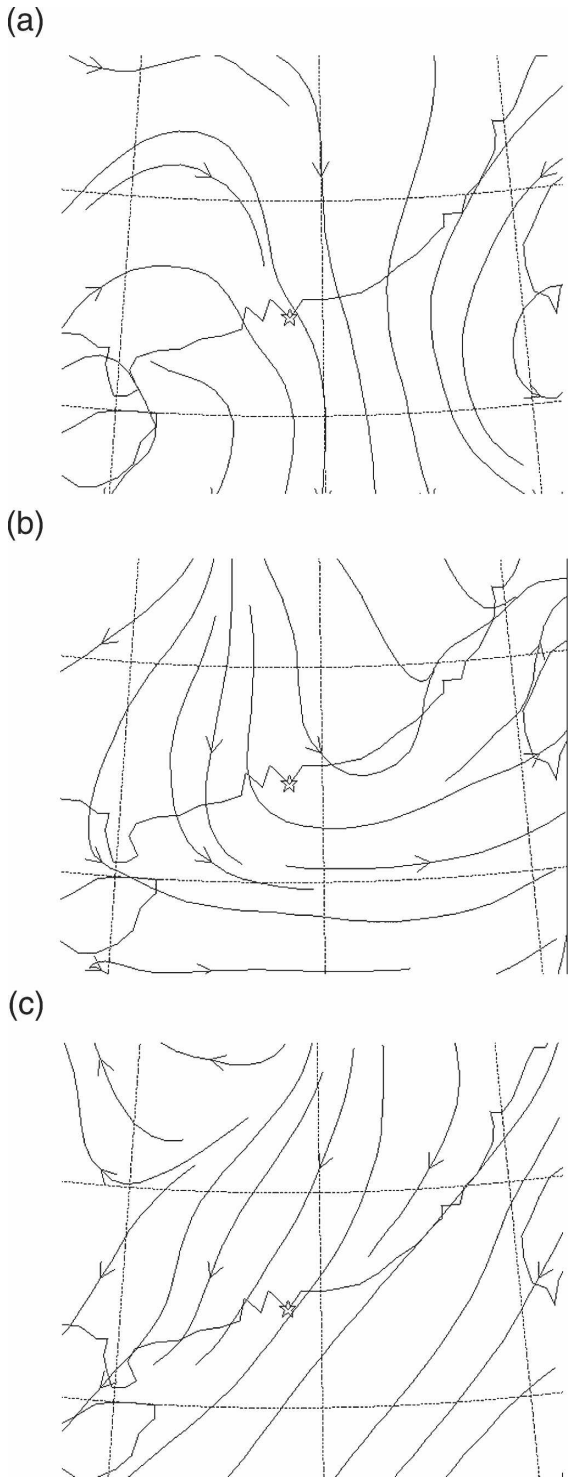

FIG. 10. Streamline charts to show airflow to Hong Kong on episode days: (a) 2 Nov 2003, (b) 18 Aug 2004, and (c) 31 Dec 2003.

August Typhoon Aere was at northwest Taiwan. With the storms at positions other than the Luzon Strait, the influence appears to be greater on the eastern part of the PRD than on the western part. The eastern part includes nearby Shenzhen, which shared a common episode with Hong Kong on 18 August 2004. On 25 August, elevated pollutant concentrations were also found in the PRD though the API values stay within 100.

b. Weak anticyclonic system

All four winter episodes described are associated with weakening anticyclonic systems that generate weak northeasterly airflows over the continent, as shown in Fig. 10 for 31 December 2003. This is similar to previous winter episodes (Lee and Hills 2003). While the stagnating air masses move slowly over the continent to southeast China, they bring about fine and dry weather. However, the light wind and stable atmospheric condition are conducive to pollutant accumulation and episodic conditions.

5. Influence of local meteorological factors

In addition to synoptic-scale systems, local meteorological factors are believed to contribute significantly to the temporal differences in the monthly pollution peaks in Hong Kong and the rest of the PRD. This is probably most relevant to the winter season under weak anticyclonic conditions. The factors are (i) sea-breeze convergence and (ii) inversions.

a. Sea breezes

Sea breezes, a local wind effect most significant in the Tropics, have a significant effect on coastal urban environments like Hong Kong. The convergence of sea breezes is found by local studies to occur most frequently in the winter months of December and January (Zhang and Zhang 1997), when most of the winter episodes occur (Lee and Hills 2003). The highly irregular coastline of Hong Kong particularly favors this convergence. Especially on fairly warm days with clear skies and light gradient winds, typical of the winter episode days, lines of wind convergence are found to form in different parts of the territory (Zhang and Zhang 1997). Observations at the automatic weather stations at the maximum particulate hour on the episode days shown in Fig. 11 well illustrate this convergence effect, which leads to pollutant buildup. The weak northerly wind that prevails on those days aggravates the convergence effect.

b. Inversions

Small-scale local systems are generated during the passage of synoptic- and mesoscale systems over land, causing the micrometeorology of the atmospheric layer adjacent to ground to vary from place to place. The mixing height (depth), especially its inner surface

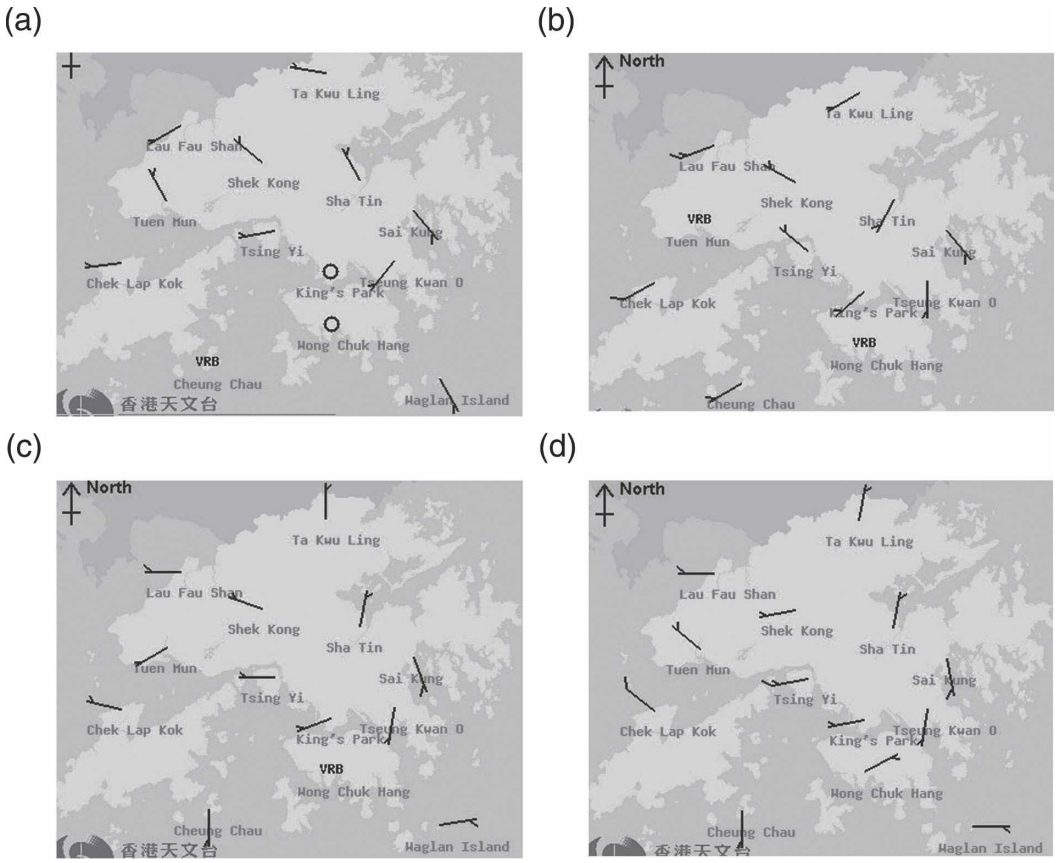

FIG. 11. Wind barb charts showing wind directions at the Hong Kong Observatory weather stations at the hour(s) of maximum PM_{10} concentrations: (a) 2 Nov 2003, (b) 18 Jun 2003, (c) 31 Dec 2003, and (d) 2 Jan 2004.

boundary layer, and their vertical temperature gradients will vary spatially as a result of such factors as the rate of heating or cooling of the surface, strength of winds, vertical motions, horizontal advections of heat and moisture, change of roughness/topography of the underlying surface, and different land uses (Arya 1988; McIntosh and Thom 1978). Inversion is one of the local systems with varying influence over different parts of the PRD.

Low-level inversions may be formed as a result of air subsidence associated with tropical storms or anticyclones. Storm-related inversion is found during the local episode of 2 November 2003 (Fig. 12) but not on the summer episode day of 18 June 2003.

Cool-season inversions found with anticyclonic weather in Hong Kong include upper inversions as well as low-level inversions caused by radiative cooling of air near the ground surface, resulting in very stable atmospheres. Intense ground inversions are found on the episode days of 19 January 2003, 31 December 2003, and 14 February 2004, as observed in Fig. 12. While upper-level inversions limit the volume of air into which emissions are dispersed, the unusually low-level inversions accumulate pollutant emissions close to the ground surface.

The episode of 14 February 2004 illustrates the combined influence of intense inversions and sea-breeze influence. On that day, intense inversions (Fig. 12) resulted in high levels of pollution all over Hong Kong in the morning hours of 0900–1000 LT. Shenzhen, just north of and sharing a common border with Hong Kong, also recorded the highest API of 148 of all of the Guangdong Province cities on this day. Obviously, conditions of atmospheric stability in these two highly urbanized cities are very similar, though Shenzhen has much shorter coastlines and therefore less of a sea-breeze influence. The setting in of sea breezes later in the day pushed the pollutant levels in Hong Kong to maxima at about 1400 LT at Tung Chung (Table 1), located at the mouth of the Pearl River estuary. In February, local sea breezes have been demonstrated to start in the early afternoon (at about 1300 LT), which is a few hours later than in the warm months (Zhang and Zhang 1997).

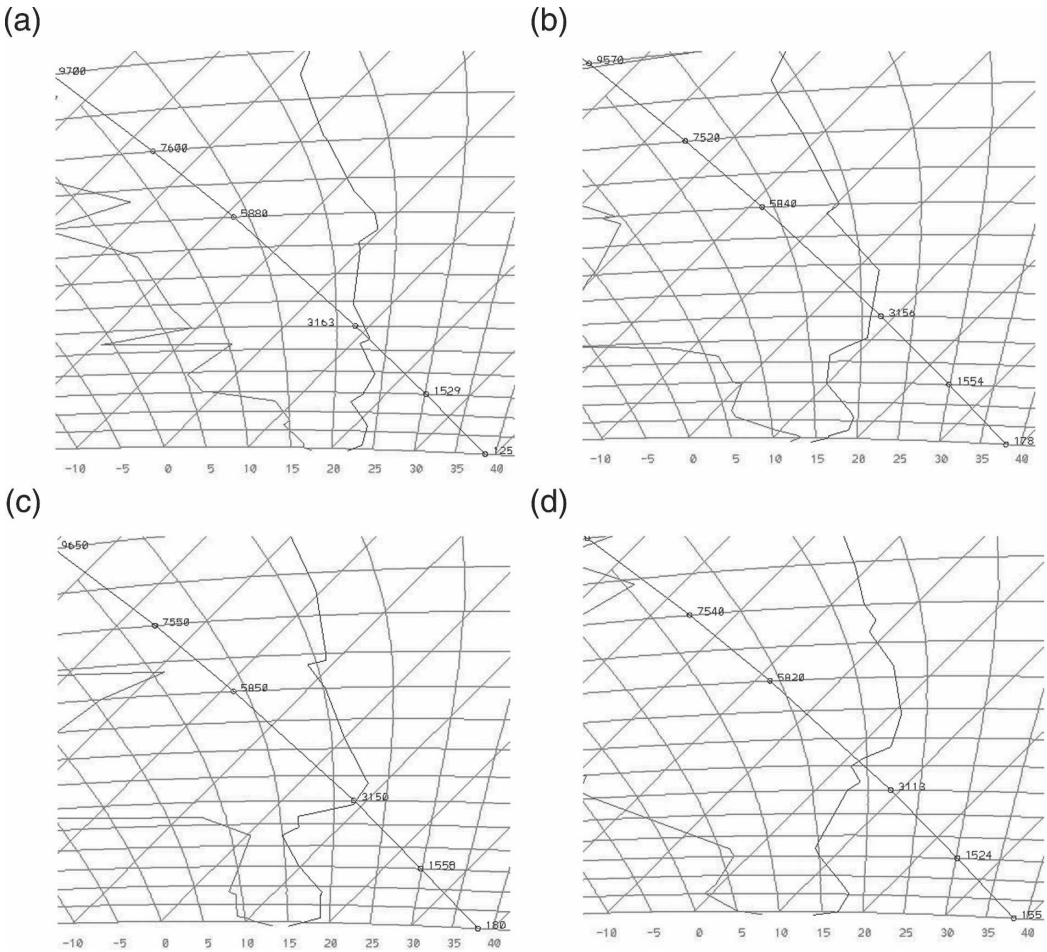

FIG. 12. Temperature profile showing low-level inversion on episode days at 0000 UTC: (a) 2 Nov 2003, (b) 19 Jan 2003, (c) 31 Dec 2003, and (d) 14 Feb 2004.

6. Conclusions

In 2003 and 2004, 10 territory-wide air pollution episodes occurred in Hong Kong. Contrary to previous years, the worst pollution of 2003 and 2004 was found in autumn. The episode in November 2003 had a record low visibility of 1000 m, whereas the September 2004 episode recorded both the highest ever API of 201 and an O_3 concentration of 403 μg m^{-3} in Hong Kong. The summer episodes (18 June 2003, and 29 June and 18 and 25 August 2004) were photochemical events. Regarding the four winter episode days (in January and December 2003, and January–February 2004), the January 2004 episode measured the highest ever hourly PM_{10} concentration of 452 μg m^{-3}.

Air pollution in Hong Kong is found to correlate with that of the Pearl River Delta region of the Guangdong Province of south China, which encompasses municipalities experiencing rapid industrial and urban growth, and is known to be one of the four regions in China heavily afflicted by haze. It is noted that of the 10 local episode days occurring in 2003 and 2004, 3 of them coincided with the most polluted days of the month in Guangdong Province, with one involving Guangzhou, the capital of Guangdong and two in nearby Shenzhen. They fell on 2 November 2003, with a record API of 303 in Guangzhou, and 14 February and 18 August 2004, with maximum API measured at Shenzhen at 148 and 100. On two other episode days, including the most serious local episode day of 14 September 2004, the most polluted days in Guangdong occurred within 2 days of the Hong Kong episodes.

Particulate concentrations in Hong Kong and Macau, on the eastern and western part of the Pearl River estuary, respectively, are found to be elevated on the same days. Regarding the rest of the PRD, air pollution there is compared with that of Hong Kong, by making use of API/AQI values because air pollution data are not yet available. It is however noted that definitions for the 100 index points for SO_2 and PM_{10} are different

between Hong Kong and mainland China, and ozone is not yet reported on the mainland.

The air pollution trends of the Pearl River Delta region of Hong Kong and the Guangdong Province cities resemble each other more under certain meteorological conditions than others, notably when a tropical storm passes the Luzon Strait between Taiwan and Luzon in the Philippines, affecting most cities of the PRD. In the tropical cyclone season, the level of pollution in Hong Kong and different cities of the PRD is impacted by storms to a degree that depends on the relative positions of the storm centers and the cities, as well as the strength of the storm. During the episode of 2 November 2003, when the tropical storm was located in the Luzon Strait and the influence of a cyclone dominated over an anticyclone, almost the entire region was equally affected. At other positions of the storms, quite often the eastern part of the PRD, including Hong Kong and Shenzhen, is affected more significantly than the western part, such as during the 18 August 2004 episode, when the tropical cyclone was located in the East China Sea.

In winter episodic conditions when weak anticyclonic air masses stagnate over the south China region, local micro- and mesoscale meteorological factors appear to contribute to the temporal difference of the pollution peaks in Hong Kong and the rest of the PRD. In addition to intense inversions found with anticyclonic weather, sea-breeze convergence, typical of the coastal environment of Hong Kong, is a major factor leading to local pollution peaks in winter.

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