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Cool season pollution episodes in Hong Kong, 1996–2002

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Abstract

Seven serious pollution episodes occurred in Hong Kong during the winter and spring seasons of 1996–2002 with NO_2 and/or PM_{10} concentrations exceeding the Hong Kong Air Quality Objectives. Analyses were made with respect to general meteorological and synoptic conditions, air mass back trajectories, satellite images and PM_{10} chemical species characterization. Six of the episodes are related to continental anticyclonic systems in the cool season, with one believed to be caused by cyclogenesis over southwestern China. Episodic conditions were usually associated with protracted weak northeast monsoon conditions, but one of the episodes was caused by a surge of easterly monsoon. On seven out of nine of the episode days, interactions are observed between the anticyclonic system and/or dust events with coastal sea breezes. Coupled with intense low level inversions, pollutants accumulated to episodic levels. Long range transport of pollutants from mainland China by the northeast monsoon is evident from the analyses. It is remarkable that all the three episodes in the spring season are also traceable to dust storm events originating in deserts in north or northwestern China. High concentrations of As, Mn, V, non-sea-salt sulphate and ammonium_N on the episode days indicate the significant impact of fossil fuel burning, while enhanced Al, Ca, Fe and Mn concentrations show the effect of mineral dusts and crustal materials.

Keywords: Hong Kong winter and spring episodes; Monsoon system; Dust storm; Pollutant transport

1. Introduction

Hong Kong (Fig. 1) is a city on the southeastern coast of China. It has a subtropical climate. Local air quality occasionally reaches an episodic scale of pollution with the hourly reported Air Pollution Index exceeding 100. This signifies a very high pollution level with air quality worse than both short-term and long-term Air Quality Objectives of Hong Kong. While summer air pollution episodes are found to be related to tropical cyclones (Lee et al., 2002), winter and spring episodes, as shown in this paper, are associated with anticyclonic systems which prevail in the Asian continent from mid-October to late March, occasionally extending from September to May.

This paper focuses on territory-wide air pollution episodes during the winter and spring seasons. There were seven such episodes spanning 9 days during the winters/springs of 1996–2002. While the transport of desert dusts to Hong Kong leading to episodic conditions on 10 May 1996 has been reported by Fang et al. (1999), the relationship between the winter episode in 1999 and boundary layer dynamics and sea-land breezes has recently been described by Liu and Chan (2002a, b). In this paper, all the cool season episodes are grouped together and analyzed to differentiate spring and winter episodes in terms of their different sources of pollution, though effects of environmental factors do overlap. Meteorological factors for the winter and spring episodes will be described, together with an analysis of air mass back trajectories, web-based satellite images and source characterization by chemical species.

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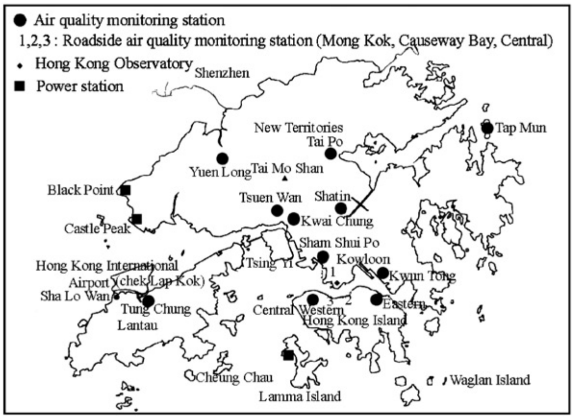


Fig. 1. The map of Hong Kong.

2. Environmental factors related to pollution episodes in the cool season

2.1. The northeast monsoon in Asia

In winter, small depressions resulting from a divergence of air at upper levels (Chin, 1969) give rise to monsoon surges to Hong Kong on average two or three times a month. These depressions form over northeast China, and sometimes farther west, and deepen over the East China Sea and Yellow Sea. As a result, the continental high pressure system intensifies. When the anticyclone in the north is intense enough the cold air will penetrate through the Nanling Ranges in south China and arrive in Hong Kong as a northerly wind. The Himalayas causes the southward flow of cold air to be channelled over this region. Troughs may also occasionally move through the Tibetan Plateau and initiate cold surges over southern China causing cold air to reach Hong Kong in 12–24 h (Cheng, 1988). Anticyclones developing over the Tibetan Plateau are not common and usually occur in the first half of winter and often give clear conditions (Thompson, 1951).

The weather associated with a monsoon surge varies with the depth of cold air, and the intensity and the extent of the surge (Thompson, 1951). As it flows south the cold air usually shrinks in depth; for example, cold air initially 9 km deep at 60°N can be less than 3 km deep by the time it reaches 22°N—the latitude of Hong Kong (Bell and Fong, 1981). The subsiding air is warmed and dried, reaching very low relative humidity.

The concentration of dust carried south in the air increases as a result of the shrinking and the long passage over land, resulting in much higher local background pollutant concentrations in winter. This is most readily seen in the seasonal variations of particulate concentrations in rural areas of Hong Kong, where there are negligible anthropogenic activities. The mid-season PM_{10} time series for the rural site of Tap Mun for the year 2000 in Fig. 2 clearly shows the daily average PM_{10} concentrations are much more elevated in winter than in summer when wind directions reverse to southerly (the occasionally elevated summer concentrations result from the influence of tropical storms near Hong Kong). However, the higher pollutant concentrations in cool seasons may also be related to the generally stable atmospheres which limit the volume of air into which emissions from the local power stations and motor vehicles are dispersed. A recent publication on the December 1999 episode (Liu and Chan, 2002a) suggests that the effect of local emissions dominate, recognizing that it was difficult to identify the winter monsoon effect. Evidently, more in-depth studies are needed to ascertain the relative contributions which will vary under different meteorological conditions. For comparison between rural and urban situations, PM_{10} concentrations are also plotted in Fig. 2 for Tsuen Wan, an urban area in Hong Kong.

One of the seven episodes (10 May 1996) is related to an easterly monsoon surge which occurs when the southward penetration of cold air falls short of the Nanling Ranges in south China, resulting in cold air taking an easterly route. In the process, small high pressure cells may detach from the main anticyclone (Morrice, 1973). Due to the Wuyi Mountain along the coast of southeast China (highest peak at 2120 m) and the Yushan (highest peak at 3997 m) of Taiwan, the air is channelled and accelerates in the Taiwan Strait, resulting in much stronger winds than that over land on the two sides. This funnelling effect enhances the formation of a ridge of high pressure extending along the southeast coast of China (Chang, 1989; Lee and Zhang, 1992). The easterly monsoon occurs with increasing frequency as winter progresses and reaches its maximum frequency in March. Since the easterly monsoon involves the anticyclone moving eastward across the sea, the air arriving at Hong Kong is generally less polluted than from a northerly wind. It would be an exception if the easterlies carried large amounts of dust originating from dust storms.

2.2. Dust storms in China

Dust storms are a major environmental problem in China. The number of dust storms has increased from five in the 1950s to 22 in the 1990s (Liu, 2000). Like the episode on 10 May 1996 which was found to be related to the transport of desert dusts to Hong Kong (Fang et al., 1999), all other spring episodes in Hong Kong in the period of 1996–2000 seem to have a similar origin.

The transport of dusts in spring from dust storms occurring in the Gobi and Taklamakan deserts in China and the loess plateaus to the south are well documented (Duce et al., 1980; Uematsu et al., 1983; Chung and

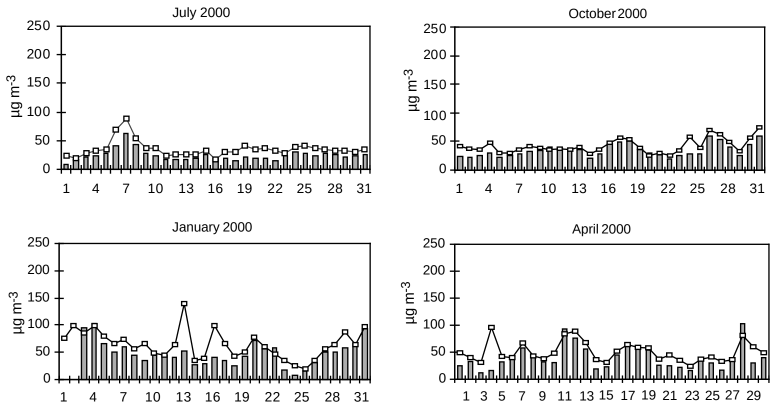
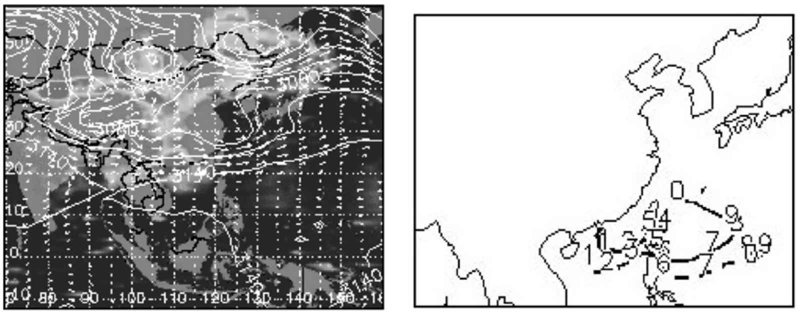


Fig. 2. Seasonal variations of PM_{10} concentrations at a rural site Tap Mun (TM, as indicated by grey columns) and an urban site Tsuen Wan (TW, as indicated by linked markers) in mid-seasons in Hong Kong, 2000.



(a) (b)

Fig. 3. (a) TOMS aerosol index with wind and geopotential height superimposed at 700 mb, 8 April 2001 (http://hyperion.gsfc.nasa.gov/Missions). (b) Back trajectory arriving at Hong Kong 8 April 2001 (http://wwwsrv.cmdl.noaa.gov/ozwv/).

Yoon, 1996). The transport of dust to Korea (Chung and Yoon, 1996), Japan (Zhang et al., 1993; Zhou et al., 1996; Fan et al., 1996), the North Pacific (Duce et al., 1980; Darzi and Winchester, 1982; Uematsu et al., 1983; Merrill et al., 1989) to as far east as North America (Husar et al., 2001) have also been reported. Atmospheric concentration of aluminium at North Pacific stations have been compared with the frequency of dust storm reports (Uematsu et al., 1983). Dust clouds have been observed in aircraft and satellite images (Chung and Yoon, 1996) and tracked (Iwasaka et al., 1983).

It has been suggested that the occurrence of yellow sandstorms has increased due to the desertification of Mongolia and northwest China (Chung and Yoon, 1996). The year 2000 saw the most sandstorms in the past 50 years (People's Daily, 2001), and some Chinese scientists have attributed them to droughts, warm weather and El Niño (People's Daily, 2002). Desertification is intensifying at an alarming rate of about 2460 km^2 per year, with desert and desertified land constituting about 16.7% of the country's total area (Guang Ming Daily, 2000).

It is obvious that dusts are carried southward to Hong Kong from the source centres in the mainland by the continental high pressure systems. However, it is noted that dust storms do not necessarily lead to elevated pollutant levels in Hong Kong. This depends very much on whether the northeast monsoon is prevailing. In spring the continental pressure system will weaken, so interruptions of the northeast monsoon become more and more frequent. A good illustration is observed on 8 April 2001 when an incoming maritime airstream spared Hong Kong the influence of dust plumes from north China (Fig. 3a and b). This dust storm, originating around 6 April from the Gobi and Takla Makan deserts, is in fact reported to be the largest in the Northern Hemisphere since 1979 in terms of the area covered. It actually drifted across the Pacific Ocean, and traversed North America from Alaska to Florida before finally dissipating in the mid-Atlantic (Naval Research Laboratory, 2001) (NASA, 2001). Another severe dust storm originated in China on 17 March 2002 (NASA, 2002) and a dust plume was observed as far east as the northwestern shores of North America. However, it had only a slight influence on Hong Kong.

2.3. Coastal sea breezes

The sea breeze is the most significant coastal wind in the tropics (Atkinson, 1981). They are most frequent in winter and late autumn in Hong Kong (Zhang and Zhang, 1997). It is usually a closed circulation and does not in itself transport pollutants over long distances. Warm temperatures, high solar radiation and light gradient winds promote the development of sea breezes.

Simulation of sea breeze under light synoptic wind in Hong Kong by Yeung et al. (1991) using a three-dimensional hydrostatic model shows that, as sea breeze sets in, local winds change to southeasterly in the eastern part of the territory and turn westerly in the western part. The model results were found to compare favourably with observations. Later use of a mass model by Zhang and Zhang (1997) clearly shows that the local sea breeze system consists of three parts: (i) westerly wind in the northern and western parts of Hong Kong, (ii) easterly in the eastern and northern parts, and (iii) southerly wind to the south.

The highly irregular coastline of Hong Kong enhances the convergence of sea breezes. Lines of convergence have been shown to be formed locally (Zhang and Zhang, 1997) in: (i) the central part of the New Territories, the Kowloon Peninsula and Hong Kong Island due to the meeting of the westerly and easterly winds, (ii) Lantau, and (iii) from Castle Peak to Tai Mo Shan, the latter two due to westerly and southerly winds converging. Modelling results by Liu et al. yield similar confluence zones (Liu et al., 2001). The formation of the confluence zones favours the accumulation of pollutants. The depth of the sea breeze in Hong Kong has been shown to be about 500 m in August 1996 on western Lantau (Chang, 1997), making it likely to affect the dispersion of the power station (with stack heights of up to 250 m) plumes.

3. Pollution episodes

3.1. Pollutant levels

The maximum concentrations of the major pollutant levels of NO_2 and PM_{10} recorded on the episode days are given in Table 1. Hourly and 24-h maxima are presented for these parameters which have exhibited exceedances of the Hong Kong Air Quality Objectives. Such exceedances are marked with an (*).The recording hour and the station recording the maxima are given in brackets. Locations of the monitoring stations are shown in Fig. 1.

As shown in Table 1, the maximum 1-h PM_{10} concentration measured in Hong Kong from 1996 to 2002 was 446 $\mu g\,m^{-3}$ recorded on 30 December 1999 at Tung Chung New Town on Lantau Island, which has a new monitoring station commencing operation in 1999. Time series plots for NO_2 and PM_{10} are given in Fig. 4. A concurrent rise in SO_2 was notable for all episode days except for the windy day of 10 May 1996, which was dominated by a late season easterly surge.

Table 1
Maximum pollutant concentrations on winter and spring episode days, Hong Kong, 1996–2002

Date	Maximum concentration ($\mu g\,m^{-3}$)			
	NO_2		PM_{10} (Teom)	
	1 h	24 h	1 h	24 h
Winter episode				
3 Jan 1996	265 (0800, Sham Shui Po)	168* (Sham Shui Po)	279 (0900, Yuen Long)	155^{+} (Yuen Long)
17 Dec 1997	237 (0900, Kwun Tong)	178*(Kwun Tong)	294 (2000,Kwun Tong)	162^{+} (Kwun Tong)
29 Dec 1999	344* (1700,Tsuen Wan)	189*(Tung Chung)	316 (1300, Tung Chung)	193$^{*,+}$ (Tung Chung)
30 Dec 1999	383*(1300, Tsuen Wan)	199* (Tung Chung)	446 (1100, Tung Chung)	200$^{*,+}$ (Tung Chung)
1 Jan 2002	230 (2000, Kwun Tong)	170* (Kwun Tong)	243 (1400, Tsuen Wan)	145 (Tsuen Wan)
Spring episode				
10 May 1996	136 (1800,Sham Shui Po)	87 (Sham Shui Po)	279 (0700, Yuen Long)	182$^{*,+}$ (Kwun Tong)
17 April 1998	215 (1300, Tsuen Wan)	157* (Sham Shui Po)	267(1000, Kwai Chung)	174^{+} (Tsuen Wan)
28 Mar 2000	326*(2000, Central Western)	211* (Kwai Chung)	327 (1700, Kwai Chung)	200$^{*,+}$ (Central Western)
29 Mar 2000	259 (0000, Central Western)	146 (Sham Shui Po)	349 (0900, Central Western)	185$^{*,+}$ (Sham Shui Po)

Notes:
*Exceedance of Hong Kong Air Quality Objectives: NO_2: 300 $\mu g\,m^{-3}$ (1 h), 150 $\mu g\,m^{-3}$ (24 h); PM_{10}: 180 $\mu g\,m^{-3}$ (24 h).
$^{+}$Exceedance of USEPA NAAQS for PM_{10} (150 $\mu g\,m^{-3}$).
() Hour and station of maximum concentration.
Teom: "Tapered element oscillating microbalance" sampler.

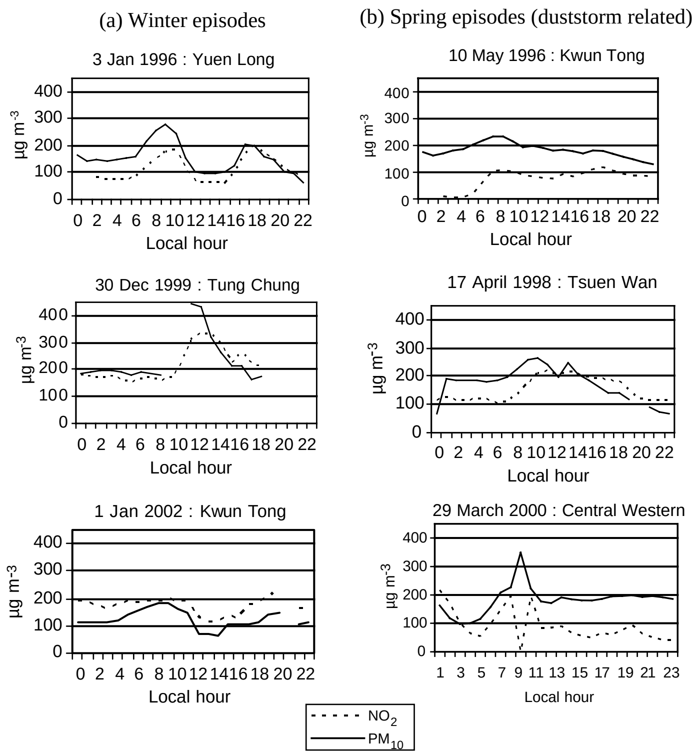


Fig. 4. Time series plots for NO_2 and PM_{10} on (a) winter episode (b) spring episode days.

3.2. Meteorological factors

3.2.1. General conditions

The general meteorological conditions on the episode days are listed in Table 2. All days except 10 May 1996 are characterized by low wind speeds of less than $4.5\,s^{-1}$ at the hours of maximum PM_{10} concentration. Air temperatures are warm, ranging from 20.1°C on 29 December 1999 to 30.8°C on 17 April 1998. Cloud cover (except for 10 May 1996) varies from 0% to 64% with generally adequate solar radiation. Since there was an easterly surge on 10 May 1996, the cloud cover (with low clouds characteristic of easterly surges) was as high as 93% while the wind speed at the hour of maximum PM_{10} concentration was $13\,m\,s^{-1}$, which was double the average wind speed of Hong Kong.

With the exception of 10 May 1996 and 17 December 1997, all episode days are associated with an intense, unusually low level inversion besides the higher level anticyclone-related double inversions. The low level radiation inversions were at about 110 m (1000 hPa), and apparently started to form during the night preceding the episode day. The ground based inversion of 17 December 1997 is believed to have given rise to the particularly high PM_{10} concentrations during the late evening of that day. Extracts of tephigrams for the two most recent episodes are shown in Fig. 5, portraying clearly the stable atmosphere, especially near ground level. It is possible that inversion(s) on the episode day mornings were low enough to have merged with the overnight inversions, thus further restricting vertical pollutant dispersion.

3.2.2. Synoptic conditions

The winter episodes of 3 January 1996, 29/30 December 1999, 1 January 2002 and the spring episodes of 28/29 March 2000 are associated with a weakening ridge of high pressure over southeast China. The synoptic conditions for the episodes are shown in Fig. 6. A weak northerly wind is believed to have resulted from the backing of winds following the weakening of the ridge. However, the episode on 17 April 1998 was related to a weak northerly surge arriving at the south China coast, replacing the original easterly flow. The mean dew point dropped from 12.3°C on 16 April 1998 to 8.5°C on 17 April 1998, indicating a weak surge of the northeast monsoon. By contrast, a strong continental easterly monsoon prevailed during the episode on 10 May 1996 with a maximum pressure centre observed over east China, as is characteristic of easterly monsoon surges.

Table 2
Meteorological data for winter/spring episode days

Date	At hour of max PM_{10}[a]		Max air temp. (°C)	Mean R.H. (%)	Cloud cover (%)	Total bright sunshine (h)	Solar radiation (MJ/m^2)	Visibility at hour of max PM_{10} (km)
	WD (deg)	WS (m/s)						
Winter episode								
3 Jan 1996	10	4.4	22.3	56	0	9.2	13.37	4.5
17 Dec 1997	220	1.5	24.8	76	–	8.1	11.44	2.5
29 Dec 1999	50	4	20.1	78	64	1.7	8.22	9
30 Dec 1999	70	2.5	22.3	72	8	9.6	14.66	6
1 Jan 2002	80	1.7	22.5	63	23	8.6	12.4	5
Spring episode								
10 May 1996	80	13	24.9	72	93	1.4	14.51	9
17 April 1998	30	1	30.8	54	39	10.6	22.09	2.9
28 Mar 2000	210	4.5	27.7	68	22	9.9	20.40	6
29 Mar 2000	80	3.0	25.3	67	20	9.9	21.25	5

[a] Wind data obtained from Waglan Island on the SE part of Hong Kong.

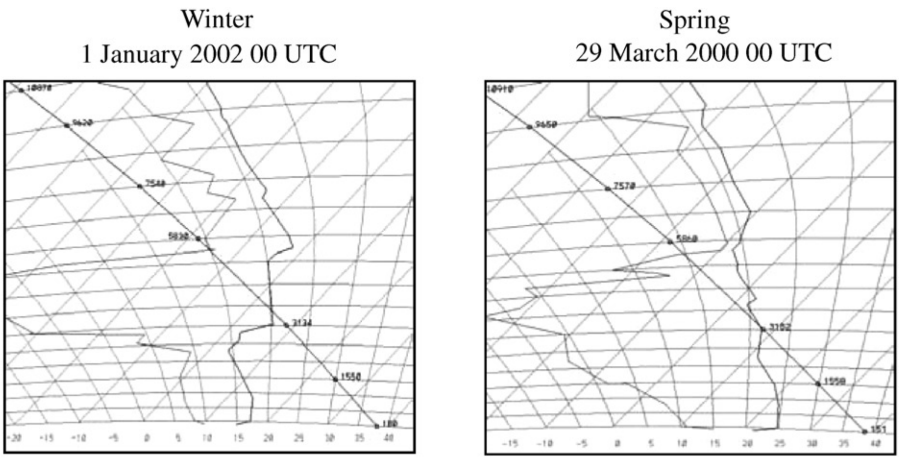


Fig. 5. Temperature profile showing low level inversion on most episode days.

Owing to the effect of the northeast monsoon, streamline analysis charts of all episode days except 10 May 1996, show land-based air flow to Hong Kong across southeastern China which is a potential pollution contributor. On 10 May 1996 the air flow, however, originated from a high pressure cell which broke away from the main anticyclone with the air subsequently channelled in the Taiwan Strait, resulting in the easterly surge. The air flow patterns on the two most recent episode days are shown in Fig. 7. The charts are obtained from the NOAA Air Resources Laboratory (http://www.arl.noaa.gov /ready/).

The 17 December 1997 episode may be related to cyclogenesis over southwestern China (Chan, 1989) which is one of the three regions favourable for cyclogenesis in East Asia, the other two being the East China Sea near the estuary of the Yangtze river, and near Mongolia (Sheng and Tao, 1988). The westerly wind in southwestern China is believed to have split into two streams which eventually meet on the lee side to form a divergence field favourable for the formation of winter cyclones downwind of the Tibetan Plateau (Sheng and Tao, 1988).

3.2.3. Sea breeze convergence

Besides the presence of inversions, the severity of the episodes on 3 January 1996, 17 April 1998, 29/30 December 1999, 28/29 March 2000 and 1 January 2002 are also attributed to a convergence of sea breezes which have been found to occur most frequently in December

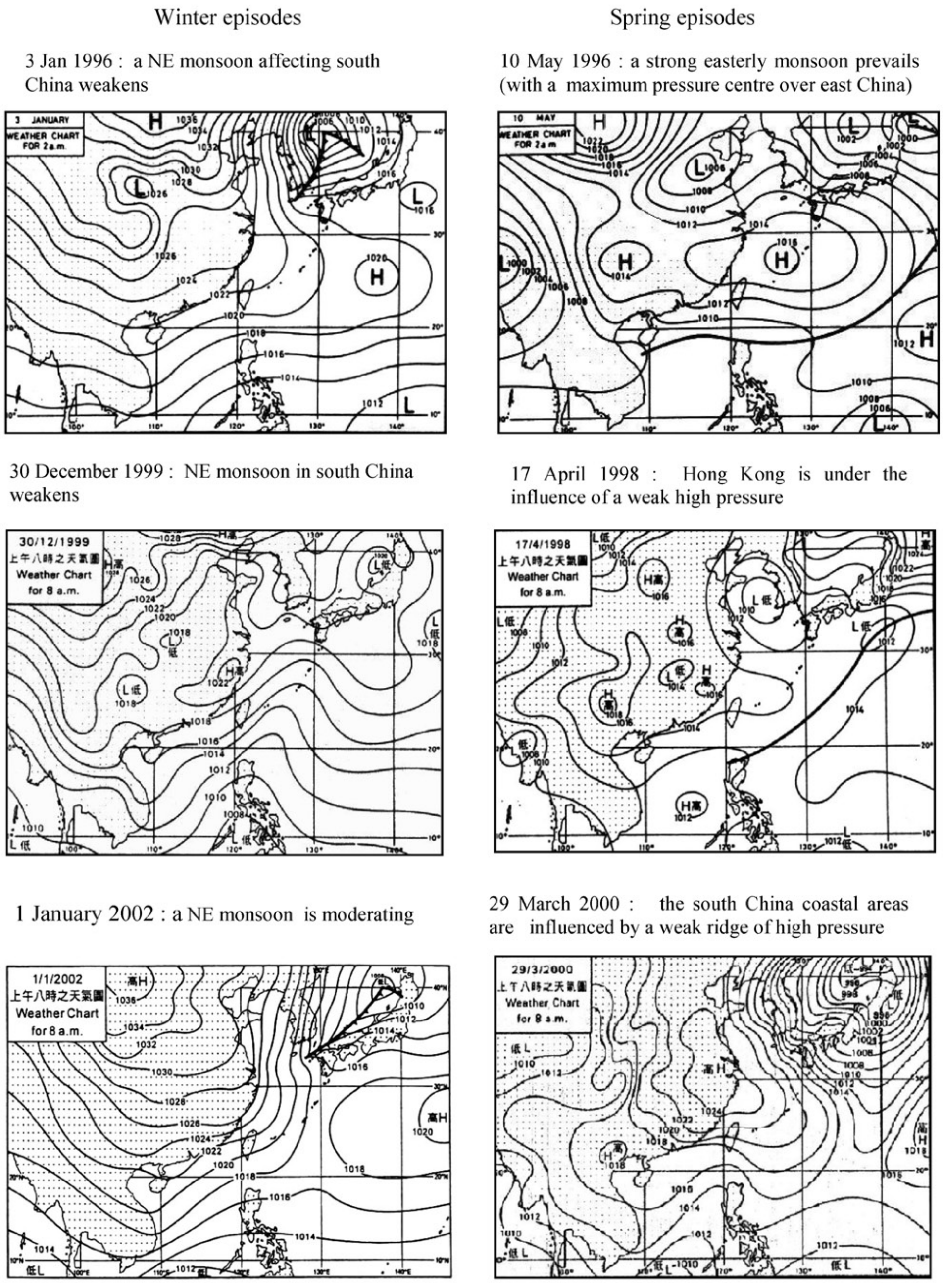


Fig. 6. Synoptic charts for the episode days.

and January in Hong Kong, on days when a weak northeast monsoon prevails with clear skies and stable atmospheres. The air temperatures on these episode days are warm, usually with fairly strong solar radiation and low percentage cloud cover, as shown in Table 2. The sea breezes cause an inland airflow from the South China Sea and the Pearl River Estuary in late morning and it intensifies in the day. The impact of sea breeze circulations on the 29/30 December 1999 episode has been described in two recent publications (Liu and Chan, 2002a, b).

Fig. 8 shows the opposing directions of the sea breezes, with the northerly wind in the morning changing to easterly at Waglan Island, and to westerly wind on the western part of Hong Kong at Sha Lo Wan or the Chek Lap Kok International Airport in the late

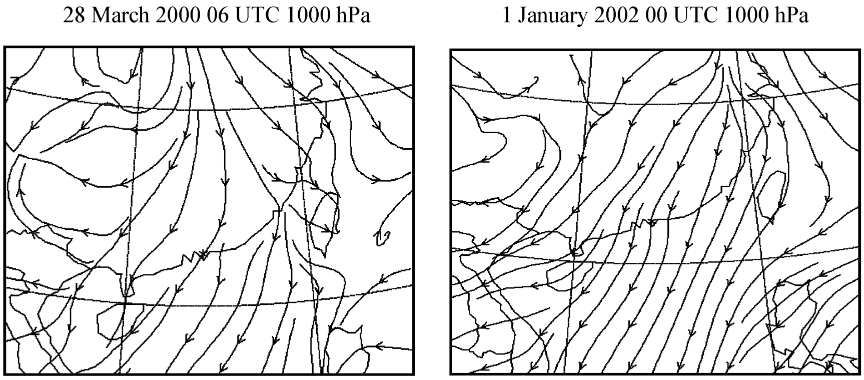


Fig. 7. Streamline charts to show air flow to Hong Kong on two episode days.

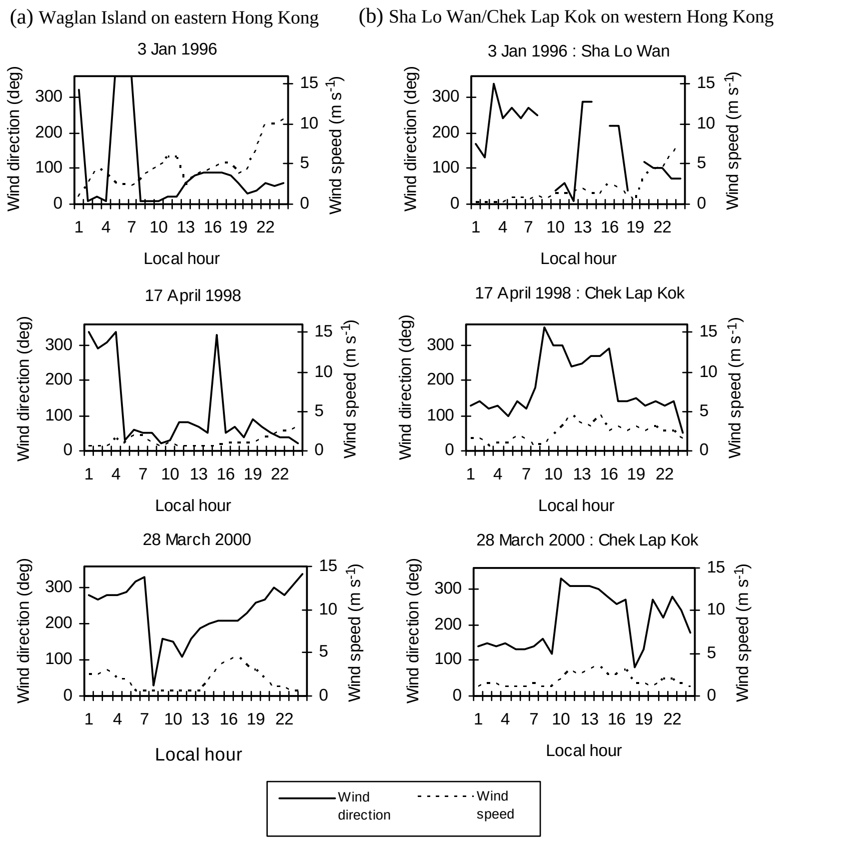


Fig. 8. Wind speed and directions on episode days at Waglan Island and Sha Lo Wan/Chek Lap Kok.

morning or at about noon time. At the hours of maximum PM_{10} concentrations, wind directions at the major Hong Kong Observatory weather stations also indicate a confluence of sea breezes on the aforementioned dates.

The weak northerly wind which prevails on the episode days aggravates the convergence effect. This wind convergence, together with the intense low level temperature inversion virtually prevent pollutant dissipation. Monitoring stations at or close to the lines of convergence, including Tung Chung (in Lantau), Tsuen Wan, Sham Shui Po in Kowloon, and the Central/Western station on the Hong Kong Island, have recorded the highest pollutant levels.

4. Analysis, results and discussion

4.1. Air mass back trajectories

Air mass back trajectories characterize source-receptor relationships. Back trajectories of up to 10 days in time to Hong Kong are obtained from the Climate Monitoring and Diagnostics Laboratory of the US National Oceanic and Atmospheric Administration (NOAA). They are calculated by the CMDL Isentropic Transport model in 3-h time steps, and trajectories for the two most recent episodes are presented in Fig. 9, showing the passage of air parcels before arriving at Hong Kong at 00 and 12 Universal Coordinated Time (UTC). Pressure levels for the arrival of the trajectories are 850 hPa, or 900 hPa/950 hPa.

Results indicate pollutant transport into Hong Kong from remote upwind sources in the mainland. This is in addition to the locally produced emissions from motor vehicles and power stations. With the exception of 17 December 1997 which is mainly confined to the south-western part of China, all other episodes involve continental scale transport, as previously reported by Lee et al. (1987).

4.2. Web-based satellite images showing dust storms

Satellite image analyses indicated that the 17 April 1998 episode can be traced back to a dust storm which started on 15 April 1998 in the Gobi desert, with dust plumes first observed on both sides of the Mongolia–China border. The dust plume was reported to reach eastern China on 16 April (Husar et al., 2001). The NAAPS (US Navy Aerosol Analysis and Prediction System) analyses of dust optical depth for 17 April 1998 (Naval Research Laboratory, 2000) and the total ozone mapping spectrometer (TOMS) absorbing aerosol index both prominently indicate the aerosol plume. These two images are reproduced in Fig. 10.

The 28 and 29 March 2000 episode is similarly associated with a dust storm originating in the Gobi desert and later reported in Beijing on 27 March 2000. The aerosol plume was detected in eastern China on 28 March, recording an extinction coefficient never

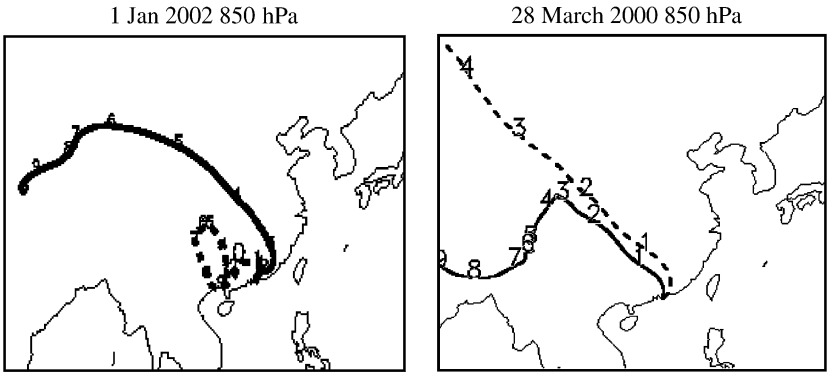
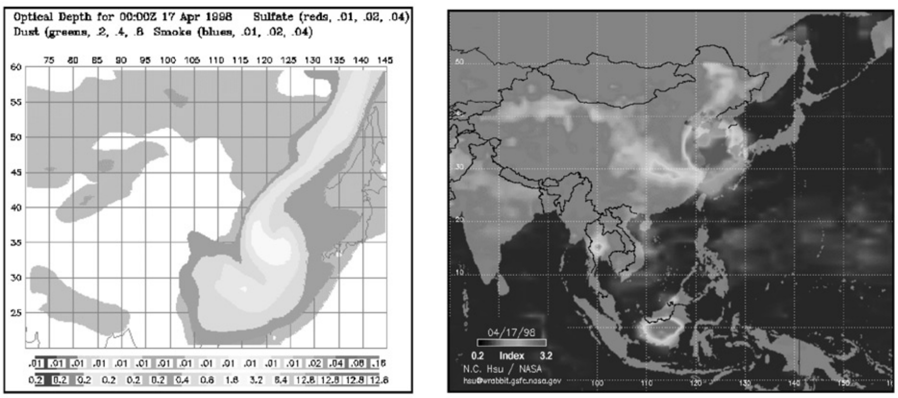
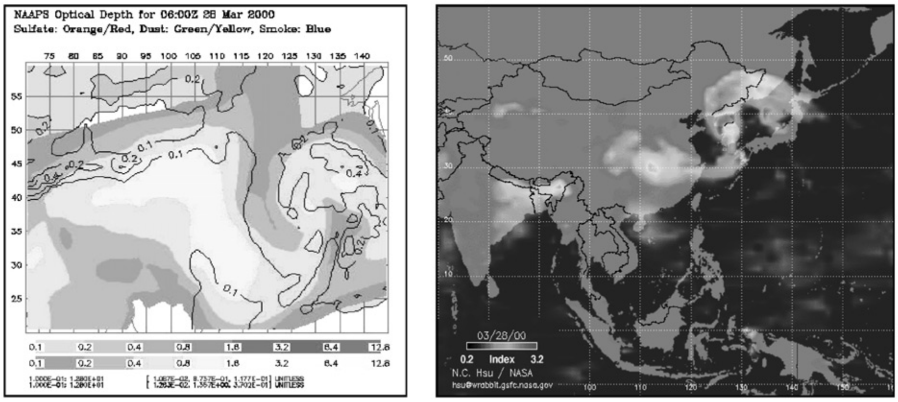


Fig. 9. Back trajectories arriving at Hong Kong on episode days (00UT—solid, 12UT—dashed).



(a) (b)

Fig. 10. Dust storm of 15 April 2000: (a) NAAPS optical depth analysis for 17 April 1998 (Naval Research Laboratory) (b) Earth Probe TOMS aerosol index on 17 April 1998 (courtesy of Dr. Christina Hsu of Goddard Space Flight Centre, NASA).



(a) (b)

Fig. 11. Dust storm of 27 March 2000: NAAPS analysis of optical depth (courtesy of Dr. D. Westphal, Naval Research Laboratory) and Earth Probe TOMS aerosol index (courtesy of Dr. Christina Hsu of Goddard Space Flight Centre, NASA) for 28 March 2000.

measured before (Anhui Institute of Optics and Fine Mechanics, 2000). The presence is also well illustrated by the NAAPS dust optical depth analyses and the TOMS absorbing aerosol index of 28 March 2000 (Fig. 11).

4.3. Source characterization

Chemical species are useful tracers for different sources. Such data are available only for two spring episodes and three winter episodes, totaling 7 days. They are shown in Fig. 12. Notably many species indicative of likely sources can be seen to be enhanced to different degrees. This includes Arsenic (As) from coal combustion (Ondov, 1989) and non-ferrous metal industries (Pacyna et al., 1989), as well as the species of Mn, Fe, Ca and Al which arise from coal combustion as well as crustal weathering. Vanadium, also enhanced, is derived mainly from residual oil combustion (Rahn, 1981). There is, however, no major residual oil combustion plant in Hong Kong. The local power plants use mainly coal but are also gas-fired, while petroleum makes up about 20% of China's energy consumption.

The maximum episodic concentrations of As, Mn and V shown in Fig. 12, all recorded (from ten monitoring stations) on 28 March 2000, are respectively about eight, six and four times the corresponding annual averages for the year 2000.

Sulphate, which arises mainly from sulphur in fossil fuel, generally has episode day concentrations about double that of the cool season median value. Ammonium_N which originates from a variety of anthropogenic (Bauer, 1985) and natural sources other than coal burning, also reached high concentrations on the episode days. As earlier shown in Fig. 2, generally higher pollutant concentrations are found in the cool seasons in Hong Kong.

The elements of Mg, Al, Si, K, Ca and Fe have been found to form a major fraction of aerosol particles collected in China during dust storms (Fan et al., 1996). Calcium and aluminium are known indicators of mineral dust or crustal weathering. Chemical species data available for the dust storm-related episodes of 17 April 1998 and 28/29 March 2000 are included in Fig. 12. As shown, the Ca concentration is conspicuously higher on 29 March 2000 than the previous day of 28th. This is consistent with the trend of Al. All these suggest a higher crustal impact on 29 March 2000 than the previous day. Compared to the winter episode days, it is clear that the concentrations of Ca, Al, Fe, Mg as well as Mn are conspicuously higher for the spring episodes. The episodic concentrations of Ca, Al and Fe are respectively about six, eight and five times the corresponding annual averages (from 10 monitoring stations) for the year 2000.

5. Conclusion

Seven pollution episodes spanning 9 days with NO_2 and/or PM_{10} concentrations exceeding the Hong Kong Air Quality Objectives occurred in the winter and spring seasons of 1996–2002. Analyses were conducted with respect to general meteorological and synoptic conditions, air mass back trajectories, satellite images and PM_{10} chemical species characterization. Six of the episodes are related to the continental northeast monsoon system, and one (on 17 December 1997) is believed to be caused by cyclogenesis over southwestern China.

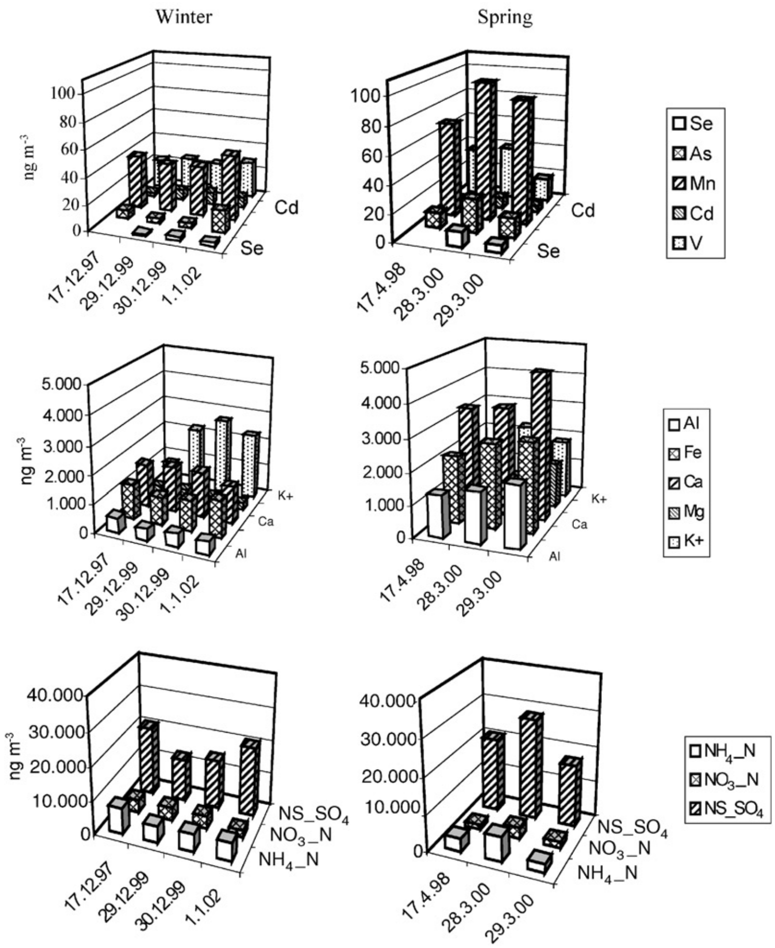


Fig. 12. Concentrations (24 h) of airborne species on four winter and three spring episode days (ng m^{-3}).

Episodic conditions were usually associated with protracted weak northeast monsoon conditions, but one of the episode days (10 May 1996) was caused by a surge of easterly monsoon. On seven of the nine winter and spring episode days, interactions are observed between the northeast monsoon system and/or dust events with coastal sea breezes. In the weak prevailing background wind on warm clear days, sea breezes are strongly established and are found to converge on different parts of Hong Kong, restricting pollutant dispersion. Coupled with intense low level inversions, pollutants accumulated to episodic levels.

Long range transport of pollutants from the mainland by the northeast monsoon is evident from the analyses. It is remarkable that all the three episodes in the spring season in the period are also traceable to dust storm events originating in deserts in north or northwestern China. Concentrations of chemical species for PM_{10} were available for three winter episodes, and two spring episodes. High concentrations of As, Mn, V, non-sea-salt sulphate and ammonium_N indicate the significant impact of fossil fuel burning, while enhanced Al, Ca, Fe and Mn concentrations show the effect of mineral dusts and crustal materials. The particularly high concentrations of the chemical fingerprints of Al, Fe, Ca, Mn and Mg for the spring episodes of 17 April 1998 and 28/29 March 2000 demonstrate well the dust storm relationship of the spring episodes and the very substantial contribution of dust from this source.

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