Atmospheric Environment 44 (2010) 3728–3738

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Transport of dusts from East Asian and non-East Asian sources to Hong Kong during dust storm related events 1996–2007

Y.C. Lee [a], Xun Yang [b], Mark Wenig [b,*]

[a] Guy Carpenter Asia-Pacific Climate Impact Centre, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China
[b] School of Energy and Environment, City University of Hong Kong, Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China

ARTICLE INFO

Article history:
Received 16 July 2009
Received in revised form
25 March 2010
Accepted 26 March 2010

Keywords:
Desert dust transport
Hong Kong
Non-East Asian sources
Seasonality
Estimated contribution

ABSTRACT

Over a twelve year period from 1996 to 2007, 76 dust storm related events (as days) in Hong Kong were selected for study, based on Aluminium and Calcium concentrations in PM_{10}. Four of the 76 events reach episodic levels with exceedances of the Hong Kong air quality standards. The purpose of the study is to identify and characterize dust sources impacting Hong Kong.

Global distribution of aerosols in NASA's daily aerosol index images from TOMS and OMI, are compared to plots generated by NRL(US)'s Navy Aerosol Analysis and Prediction System. Possible source areas are assigned by computing air parcel backward trajectories to Hong Kong using the NOAA HYSPLIT model. PM_{10} and elemental data are analyzed for crustal mass concentrations and element mass ratios.

Our analysis reveals that 73 out of the 76 dust events (96%) involve non-East Asian sources-the Thar, Central/West Asian, Arabian and Sahara deserts (Saharan influence is found in 63 events), which are previously not known to affect Hong Kong. The Gobi desert is the most frequent origin of dust, affecting 68 dust events while the Taklamakan desert impacts only 30 of the dust events. The impact of the Gobi desert in March and December is apparently associated with the northeast monsoon in East Asia.

Our results also show a seasonal pattern in dust impact from both East Asian and more remote sources, with a maximum in March. Dust event occurrences are conspicuously absent from summer. Dust transport to Hong Kong is commonly associated with the passage of frontal low-pressure systems.

The coarse size fraction of PM_{10} concentrations were, as indicated by Al, Ca and Fe concentrations, about 4–8 times higher during dust events. The mean Ca/Al ratios of sources involving the Taklamakan desert are notably higher than those for non-East Asian sources owing to a higher Ca content of most of the East Asian deserts. The Fe/Al ratios follow a similar trend.

Contributions from the desert sources are grossly estimated where possible, by using the average Al abundance of 8% in the upper continental crust to convert the Al mass in the PM_{10} to dust concentrations. This is done for the six events identified with air mass purely of non-East Asian origin and the two events related only to the Thar/Arabian/Sahara deserts. Results reveal that the average contribution from the non-East Asian sources (including C/W Asia) is approximately 10% and, that from the Thar/Arabian/Sahara deserts is about 8%.

1. Introduction

1.1. Desert dust transport

Arid and hyperarid regions, approximating the boundaries of deserts (Fig. 1), occupy almost 20% of the earth's surface (UNEP, 2006). Large amounts of dusts are often transported over long distances from these regions to different parts of the world. According to Liu et al. (2008), about 12% of the area between 0 and 60°N is influenced by desert dust about 50% of the time. There are concerns that the deposition of dusts not only causes air pollution, but also heats up the atmosphere and contributes to climate change (Han et al., 2008).

Long range transport of dusts has long been documented, especially for sources like the Sahara desert, the Arabian desert, both of which are prolific dust sources (Liu et al., 2008), and the Gobi and Taklamakan deserts in East Asia. Sahara dust is not only transported across northern Africa into Europe, westward to the Caribbean and West Indies, but has also been reported to be carried eastward to Korea and Japan (Park et al., 2005; Tanaka et al., 2005;

* Corresponding author at: School of Energy and Environment, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China. Tel.: +852 2784 4676.
E-mail address: mark.wenig@cityu.edu.hk (M. Wenig).

1352-2310/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.atmosenv.2010.03.034

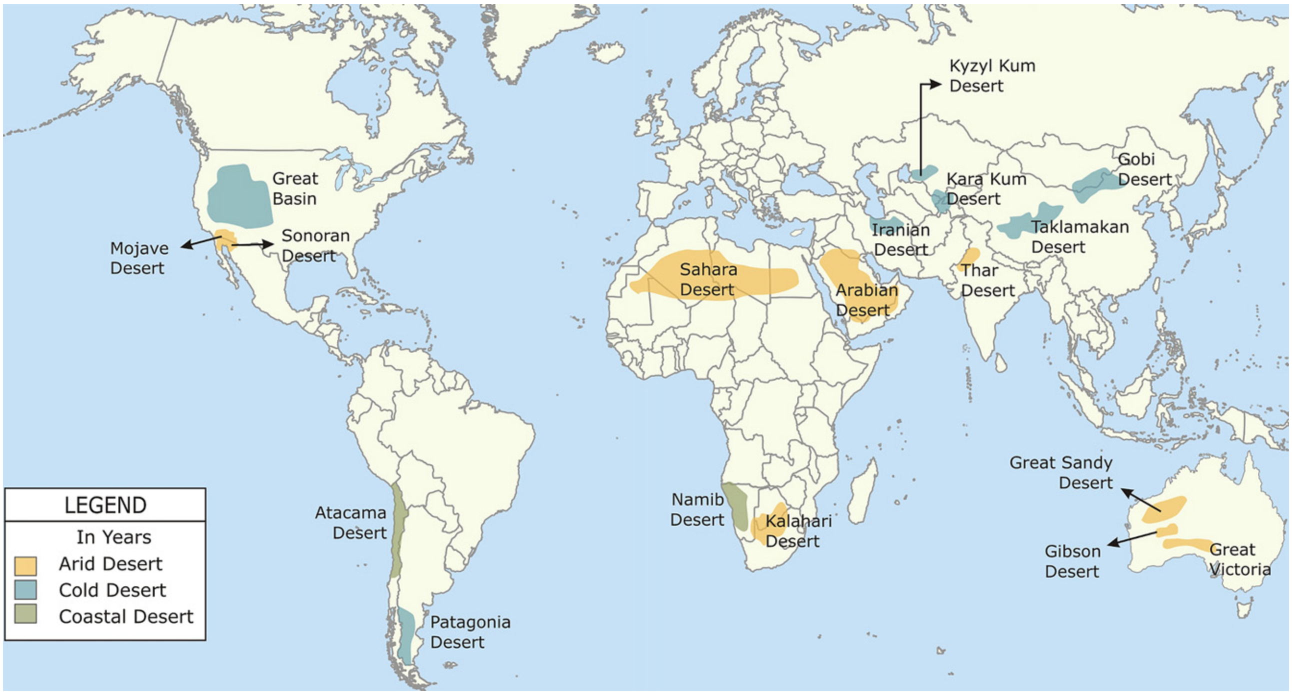

Fig. 1. World deserts (source:www.mapsofworld.com).

Lee et al., 2006). The transport of dusts from East Asian deserts to Korea (Chung and Yoon, 1996; Kim, 2008), Japan (Zhou et al., 1996) are well reported. Researchers have shown that the Asian dusts reached as far east as the North Pacific (Merrill et al., 1989) and North America (Husar et al., 2001).

The occurrence of dust storms depends on the intensities of surface cyclonic systems and migratory anticyclones, the passage of cold fronts and the horizontal gradients of the surface air pressure in the cold frontal zone (Dulam, 2005). Rising warm air associated with the passage of weather fronts and systems is believed to lift Saharan sand to altitudes of several kilometers (Morales, 1986). Most dust events in the desert regions in the southwestern United States are caused by similar meteorological conditions (USEPA, 2004) associated with the passage of fronts and troughs or the down mixing of upper level winds.

In other cases, when the blowing winds are strong and persistent, dust from deserts can also ascend into the upper atmosphere. In North Africa, the Saharan dust is lifted to 3000 m when the northeasterly winds (the "Harmattan") in winter converge with the southwest monsoon forming a front. The tops of Saharan dust plumes were observed or estimated to be from 1500 m to above 6000 m (Morales, 1986).

Discontinuous bands of relatively strong westerly winds called jet streams found just under the tropopause, are believed to play a dominant role in the long range transport of desert dust. The subtropical jet stream, generally found within the subtropics, has been found to have a strong wave guide effect (Watanabe, 2004; Hong et al., 2009) through which wave activity forced in the Mediterranean-Sahara region could be transmitted to East Asia. Asian dust was observed in Korea and Japan behind a cold front of a travelling cut-off low associated with the upper westerly jet. Dust transport over the North Pacific was also believed to be related to upper level jet streams (Moon and Lee, 2008). Jet streams may similarly be responsible for the eastward transport of Saharan dust in an elevated layer. Jet streams often form as a result of the meeting of two air masses of different temperatures, causing high pressure difference. They are located above areas of strong temperature gradients, e.g. frontal zones.

1.2. Desert dust deposition

The Gobi and Sahara desert storms have been found to have a higher impact on dust deposition in Japan than the arid loess region and Taklamakan desert storms (Lee et al., 2006). Among other studies, Kubilay et al. (2000) have shown that trajectories arriving at the Turkish coast of the eastern Mediterranean at upper barometric levels (700 or 500 hPa) mostly originate from Africa and dusts from these sources contribute significantly to peak dust events. Kubilay et al.'s study includes ground based aerosol samples and deposition (wet) measurements. The transported North African and Middle East desert dust particles generally constitute a sizable fraction of the annual atmospheric deposition in the eastern Mediterranean.

1.3. Seasonal variations of dust impact

The incidence of dust storms and their impact vary seasonally. The transitional season of spring is usually the most active dust season. Data from 18 key stations reveal that dust events around the Taklamakan desert occur mainly in spring (53.4% of observations) and summer (34%) and in northeast China mainly in spring (65%) and winter (22%) (Wang et al., 2004). According to Kurosaki (2005) vegetation cover begins to suppress dust emission from May in the Gobi Desert.

While also occurring in winter and autumn, the incidence of dust storms in the Sahara peaks from March to May. The transport of Saharan dust from North Africa to the Eastern Mediterranean has been found to occur predominantly in spring (Kubilay et al., 2000) and is commonly associated with the eastward passage of frontal low-pressure systems (Guerzoni and Molinaroli, 2005). Dust storms over Israel are usually associated with a cold front and a significant downward flowing jet stream (Goudie and Middleton, 2001). The passage of fronts has been considered a precursor of a dust event in Taiwan (Liu et al., 2009), and fronts and sometimes frontal rain are found on dust event days in Hong Kong.

Similarly, Borbély-Kiss et al. (2004) found that the seasonal distribution of the Saharan dust related events in the Hungarian region exhibit spring and autumn maxima around March and November. Similar double peaked periodicity has been observed in the atmosphere over Tel Aviv (Israel) (Ganor, 1994). Thirty-three years of measurements in Israel indicate more frequent transport of desert dust in spring and autumn (Kubilay et al., 2000). However, the most intense dust events occur between March and May.

1.4. Elemental mass ratios of dust

Mineral dust mainly consists of a mixture of silicates (clay minerals, feldspar, quartz) associated with carbonates. Guerzoni and Molinaroli (2005) suggest that the abundance of these minerals in dust reflects the source composition and its evolution during transport. Variations in the proportions of different clay minerals, e.g. ratios of illite-to-kaolinite, derived from different source areas have therefore been used to indicate sources. However, Silicon is not measured in Hong Kong, so similar comparisons cannot be made.

Concentration ratios of elemental constituents have been considered as signatures of desert areas in many transport studies. The use of the average X/Al ratio (where X = an element), for instance, eliminates the variability owing to different mineralogical compositions (Guieu et al., 2002). Different Ca content of dust sources e.g. African and Asian, has made Ca/Al a good tracer.

Ti as Ti/Ca, Ti/Fe ratios (Nicolás et al., 2008; Borbély-Kiss et al., 2004) has been used as typical marker of Saharan dust outbreaks. Ti/Ca and Ti/Fe were found by Borbély-Kiss et al. (2004) to be a good signature of the transport of Saharan dust to Northern Italy. However, Ti was not analyzed for the particulate filters in Hong Kong. On the other hand, the Al/Ca ratio has been used successfully in tracing aerosol plumes from distant Saharan dust sources in Illinois, U.S. (Gatz and Prospero, 1996), Eastern U.S. and Virgin Islands (Perry et al., 1997), the Amazon Basin and Israel (Formenti et al., 2001) while the Ca/Fe ratio has been used for tracing dust plumes transported from Saharan and Taklamakan sources to the U.S. and Japan (Gatz and Prospero, 1996; Makra et al., 2002).

"Episodes" in this paper involve exceedances of the Hong Kong Air Quality Objectives found at http://www.epd-asg.gov.hk/english/backgd/hkaqo.php. The first dust storm related episode reported in Hong Kong occur on 10 May 1996 and has been attributed to dust transport from the Gobi desert (Fang et al., 1999). Account on a later two day episode in 2000 was given by Lee and Hills (2003). The episode on 16 March 2006 has not yet been documented. There are indications that the sources of dusts in the episodes and events may go far beyond the East Asian deserts. It is the purpose of this paper to investigate, identify, gain insight into and characterize as far as possible the possible sources, whether East Asian or more remote sources.

2. Methods of tracing air mass origins of dust storm related events in Hong Kong

Altogether 76 dust storm related events in Hong Kong are included for analysis in this paper over the period 1996–2007 (Table 1). Dust event days, including the episode days of 10 May 1996, 17 April 1998, 28/29 March 2000 and 16 March 2006 with exceedance(s) of the Hong Kong Air Quality Objectives, are selected for study based on criteria pertaining to crustal elemental concentrations: that Aluminium and Calcium concentrations are equal to or greater than 1000 and 2000 ng m^{-3} respectively. Compared with a criterion of 3000 ng m^{-3} Al used in other work (Liu et al., 2009), the criterion adopted in this study has permitted the inclusion of small dust events.

2.1. Satellite images and NAAPS plots

The global distribution of aerosols is observed in NASA's daily aerosol index images from Earth Probe Total Ozone Mapping Spectrometer (TOMS) from 1996 to end of 2005 and the Ozone Monitoring Instrument (OMI) from October 2004 which represent the absorbing aerosol particles as they cross the land/sea boundary. Using these data it is possible to observe the phenomena of desert dust transport.

The TOMS aerosol index images are compared with plots generated by the US Naval Research Laboratory (NRL)'s Navy Aerosol Analysis and Prediction System (NAAPS), a global aerosol model using global meteorological fields from the Navy Operational Global Atmospheric Prediction System (NOGAPS). It analyzes and forecasts on a 1° × 1° grid, at 6-h intervals and 24 vertical levels (beginning September 2002) reaching 100 mb. The model has presumed eight dust-producing categories, including low sparse grassland, bare desert, sand desert, semi-desert shrubs, semi-desert sage, polar and alpine desert, salt playas, sparse dunes and ridges. The source regions in the Sahara, Middle East, Arabia, and Australia have been further refined by NRL in June, 2000 using an analysis of TOMS AI data.

Table 1
Dust event dates of Hong Kong 1996–2007.

	Dust event[a] dates, Hong Kong 1996–2007(nil for July–September)							
	Jan	Feb	Mar	Apr	May	Oct	Nov	Dec
1996	25				10		20, 23	2, 14, 17
1997	2							
1998				16, 17				
1999	8	3–4, 19, 20		7, 8				
2000			25–31		5, 21			
2001	15	17	3–6, 9, 10	13–15			14	29
2002	23	12–13	6–8, 9			7		
2003								19–20, 26
2004	2, 30		6, 7			8, 26		3, 8
2005	4						30	21–22
2006	9		16, 30, 31	21				17
2007	9, 28–30						13, 27	6, 30–31

[a] Aluminium ≥ 1000 ng m^{-3}, Calcium ≥ 2000 ng m^{-3} (in PM_{10}).

2.2. Backward trajectories generated by HYSPLIT

The HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model of the US National Oceanic and Atmospheric Administration (NOAA) is used to assign possible source areas. Air parcel backward trajectories to Hong Kong at 00 UTC are computed for altitudes at 500 m intervals up to 6.5 km, and for up to 315 h. The Windows-based version 4.9 of the model is used. Vertical motion is provided by the meteorological model's vertical velocity fields. The National Centers for Environmental Prediction (NCEP) reanalysis data is used as model input (Draxler and Rolph, 2003).

The slope of the vertical component of trajectories shown in the lower panel of the backward trajectory plots, provides information on prevailing meteorological conditions during the transport.

2.3. Analysis of chemical species of PM_{10}

The PM_{10} and elemental data were obtained from the Hong Kong Environmental Protection Department (EPD). PM_{10} is known to be collected by the Graseby Andersen PM_{10} high-volume sampler for 24 h for chemical analysis of the quartz filters. Concentrations of PM_{10} and $PM_{2.5}$ and crustal species which are abundant in the earth's crust, are analyzed and element mass ratios computed. Analysis is by the multi-element Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP) with minimum detection limits at 13.5, 22.7 and 7.5 ng m^{-3} for Al, Ca and Fe respectively (USEPA, 1999). Elemental data for $PM_{2.5}$, however, is not yet available from the EPD.

2.4. Aerosol size distribution

A PREDE POM-01 sun-sky radiometer installed on the main campus of the City University of Hong Kong (Kowloon) is used to measure direct and scattered solar radiation. By applying an inversion algorithm, columnar aerosol optical properties such as size distribution can be obtained (Yang and Wenig, 2009).

3. Dust sources identification

Results of the analysis using the methods outlined in 2.1 and 2.2 reveal the following origins of desert dust for the episodes/events. Very different origins of the air masses arrive at Hong Kong at different barometric levels in the multilayered transport. The trajectories at lower altitudes (900 hPa) usually identify air masses coming from North China as shown in Fig. 2 while the trajectories arriving at higher barometric levels (700 or 500 hPa) indicate origins of the Sahara, which is also evident from Fig. 2.

3.1. The Gobi and Taklamakan deserts

Apparently the Gobi desert is the most frequent origin of air mass (see Fig. 3), affecting as many as 68 of the total of 76 dust events. On two days, Gobi's influence coincides with that of the Taklamakan desert with no other sources. Notably on only one day is the impact coming solely from Gobi. Actually for most of the time Gobi influences Hong Kong concurrently with non-East Asia sources, with or without the Taklamakan. It is interesting to note the smaller influence of the Taklamakan desert on Hong Kong as compared with the Gobi desert. Taklamakan affects Hong Kong in 30 of the dust events.

The significant impact of the Gobi desert in March and December is believed to be associated with the winter monsoon path in East Asia as Hong Kong is downwind of the Gobi desert in this season. Interactions between the northeast monsoon and the mid-latitude westerly jet are likely. On the other hand, troughs may occasionally move through the Tibetan Plateau and initiate cold surges over southern China and cause cold air (which may carry dust) to reach Hong Kong in 12–24 h (Cheng, 1988). Anticyclones

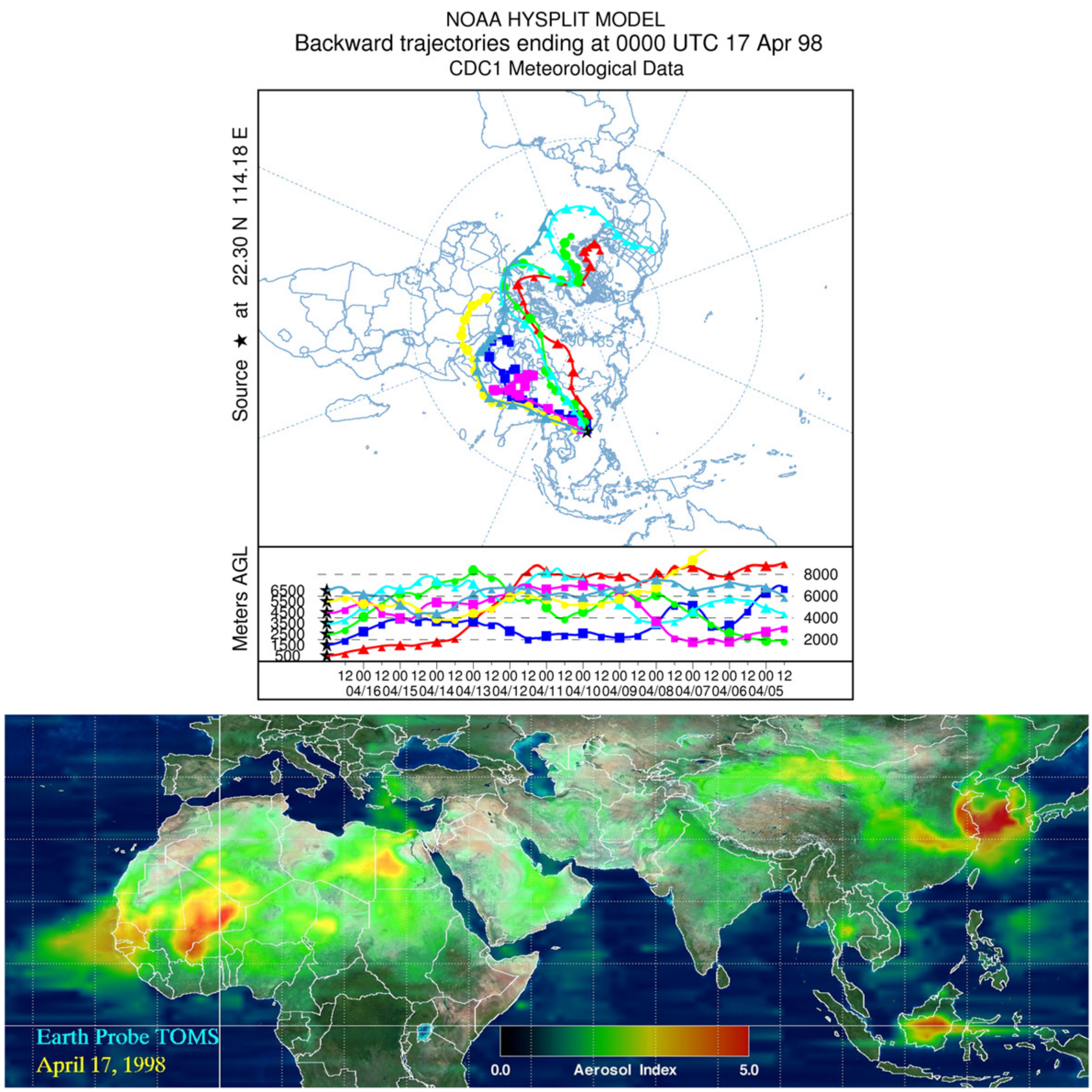

Fig. 2. HYSPLIT trajectories and TOMS aerosol images of dust episode days in Hong Kong, 1998–2007 (The 10 May 1996 episode is not shown as no TOMS image is available).

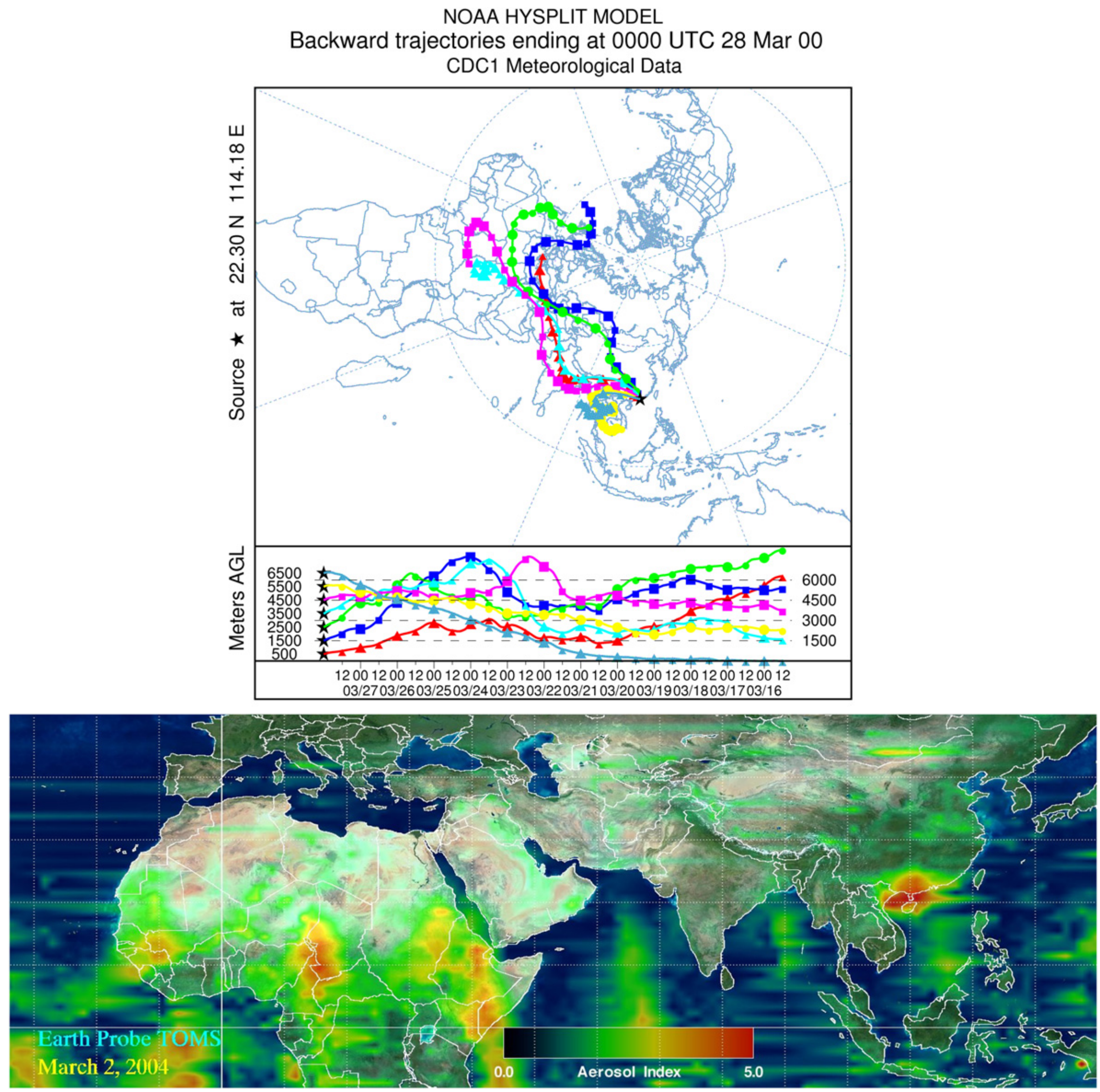

Fig. 2. (*continued*).

developing over the Tibetan Plateau are not common and usually happen in the first half of winter (Thompson, 1951).

3.2. The Thar, Central/West Asia, Arabian and Sahara deserts

Backward trajectories plotted for higher altitudes in Fig. 2 illustrate the three dust storm related dust episodes in Hong Kong that involve dusts from non-East Asian sources, a fact which has been unknown before our study. These sources include the Sahara (West, North, Central and East) as well as the Arabian desert, Central/West Asia and the Thar desert in India and Pakistan. It is interesting to note that the 2006 March 16 episode may have a contribution from the continental scale Sahara dust outbreak of 5–9 March in 2006 (Kerkmann, 2006). As many as 73 of the total dust events, or 96%, involve contributions from non-East Asian sources.

In respect of the frequency of impact, the Thar desert affects as many as 65 of the dust events, followed by the Sahara desert and the Arabian desert impacting 63 and 62 events respectively. The number of days which are also expressed as percentages of the total number of dust events, are shown in Fig. 3. Trajectory analysis indicate that six of the dusty days in Hong Kong solely involve non-East Asian sources, with maximum Al and Ca concentrations reaching 1300 and 3500 ng m^{-3}. Backward trajectory and the TOMS aerosol index image for a similar day affected by non-East Asian sources but with lower Al and Ca concentrations are shown in Fig. 4.

4. Seasonality of dust impact

The annual distribution of dust events in Hong Kong from 1996 to 2007 is shown in Fig. 5. The monthly influence of the individual sources is also shown. March records 21 out of a total of 76 events. All dust storm related episodes in Hong Kong have occurred in spring i.e. March, April and May. December comes second after March in regard to the number of dust events. Then they come in the order of January, February, April, and November. By contrast, only a small number of events occur in May and October. Dust events are prominently absent from summer, and September. Dust impact from both the East Asian deserts of Gobi and Taklamakan, as well as the Thar, Central Asian, Arabian and Sahara deserts seem to follow a similar seasonal pattern.

As reported for other places (see Section 1.3), dust transport from non-East Asian sources is commonly associated with such meteorological events as the passage of frontal low-pressure

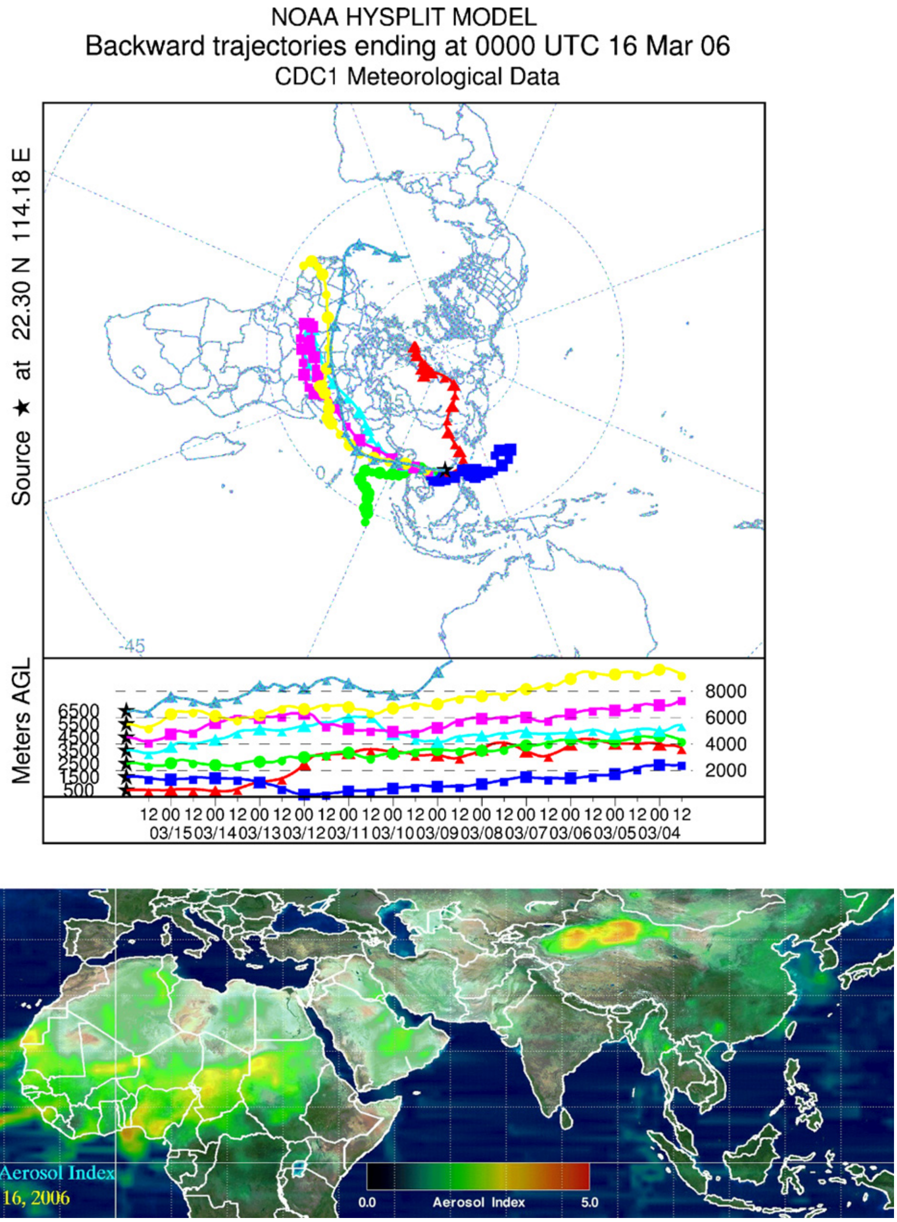

Fig. 2. (*continued*).

systems (with warm air ahead of the front being lifted up and over). The vertical component of the trajectories indicates temporal variations of the altitudes of the air masses. Dusts are entrained into the cut-off low (of uplifted warm air). Synoptic scale high and low-pressure systems are known to alternate in spring in East Asia. As an illustration, the vertical component of the trajectories plotted for 16 March 2006 show the air mass with Saharan dust travelling at 3000–6000 m. It appears to be brought down by frontal systems in Hong Kong at about 4000 m after about 10 days' travel.

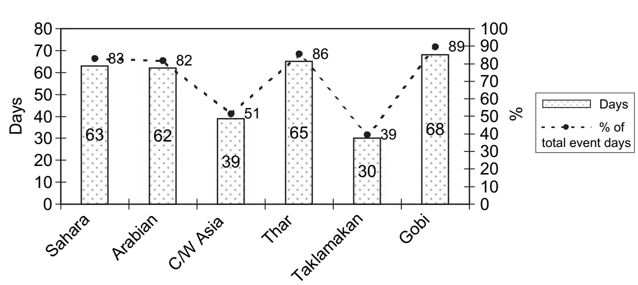

Fig. 3. Impact of various dust sources on Hong Kong (as number of days affected by each source and percentage of total number of dust event days), 1996–2007.

Evaluating the synoptic weather charts together with the precipitation data for the events can be useful. Trace amount of rainfall, believed to be frontal rain, was found on the episode day of 16 March 2006.

5. Characterization of dust storm related events

5.1. Mineral dust composition

PM_{10} concentrations during the dust episode were higher than those before, as shown in Fig. 6 (i) for the month of March 2006, in which the major dust episode of 16 March 2006 occurred. It appears that a slightly more pronounced increase is found in the

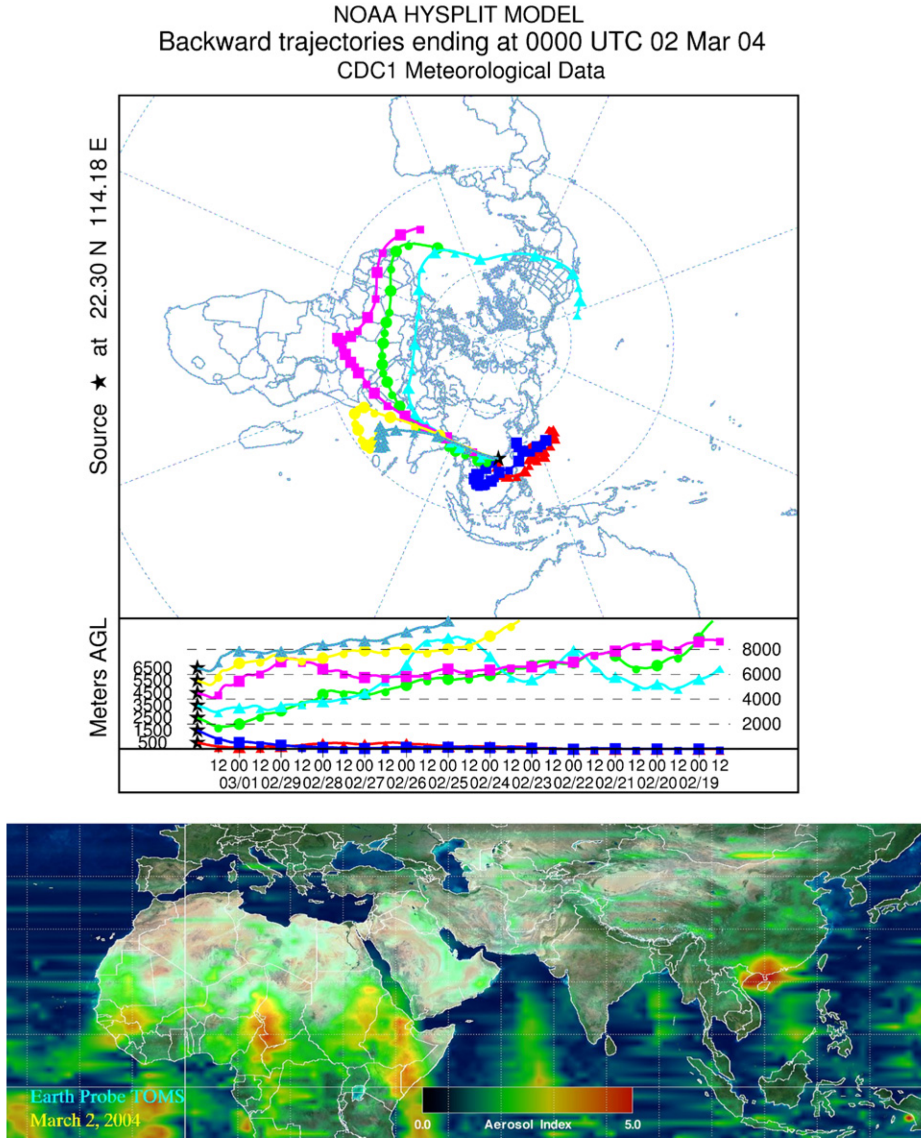

Fig. 4. HYSPLIT trajectory and TOMS aerosol image on 2 March 2004: Hong Kong affected by only non-East Asian sources (Al, Ca & Fe concentrations are lower than the "dust event" criteria. This day is selected to show impact on the south China region).

coarse size fraction for the background site of Tap Mun than for the urban site of Tsuen Wan.

Aluminium and Calcium are known indicators of mineral dust or crustal weathering. Their concentrations (Al, Ca, Fe), like the PM_{10} concentrations, significantly increase on event days as shown in Fig. 6 (ii) for the monthly distribution and Fig. 7 for the episode days. Increment factors for Al, Ca, Fe comparing event day

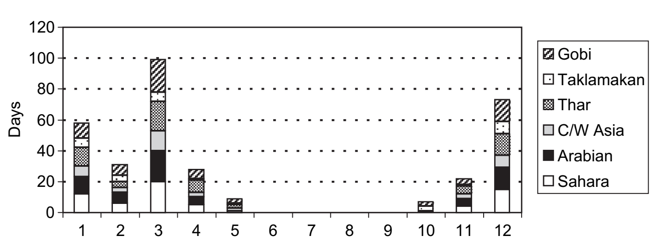

Fig. 5. Annual distribution of frequency of dust sources for dust events in Hong Kong, 1996–2007.

concentration and the pre-event 10 day mean (Al and Ca concentrations <800, 1000 ng m^{-3} respectively) vary from 4 to 8 times.

5.2. Volume particle size distribution

An aerosol event on 6 and 7 March 2004 shown by backward trajectories to be affected by air masses from the Gobi desert, is studied in greater detail. The mean aerosol size distributions before (4, 5 March), during (6, 7 March) and after (8, 9 March) the dust event are shown in Fig. 8. The mean distributions are found to be within the interval of 0.01–20 μm with a typical bimodal size distribution. The fine mode has a radius ranging from 0.01 to 0.6 μm while the coarse mode ranges from 0.6 to 20 μm.

The columnar aerosol concentrations obtained by integrating the size distribution, are 0.179, 0.129, 0.156 $\mu m^3\ \mu m^{-2}$ respectively for the fine mode aerosol for the periods before, during and after the dust event. The corresponding coarse mode aerosol concentrations for the same three periods are 0.208, 0.255, 0.209 $\mu m^3\ \mu m^{-2}$. The concentration fractions of coarse to fine aerosol are hence 1.17, 1.96,

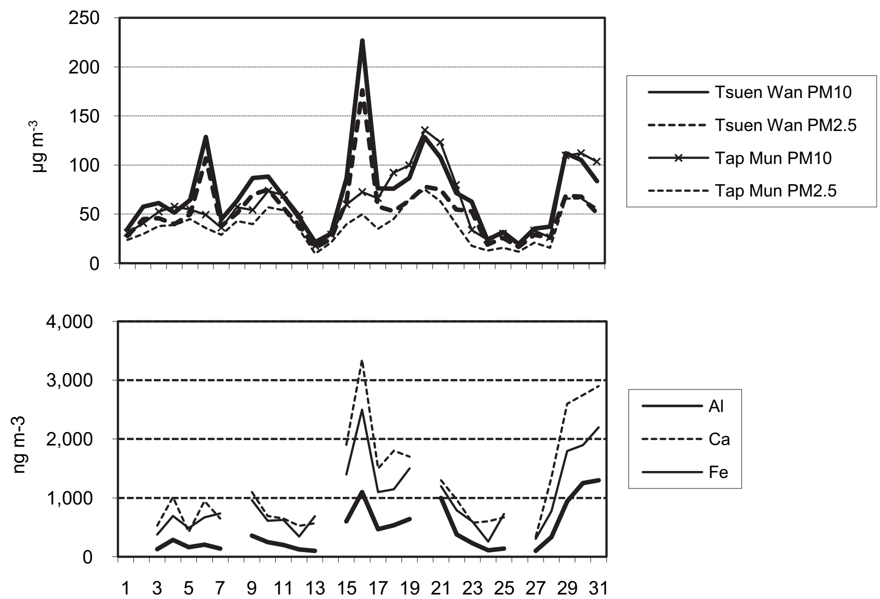

Fig. 6. (i) PM_{10} & $PM_{2.5}$ concentrations at Tsuen Wan (urban) and Tap Mun (background) in March 2006 (ii) Crustal elemental concentrations (Al, Ca, Fe) (ng m^{-3}) (average of urban Yuen Long and Tsuen Wan) in March 2006 indicating dust events.

1.39. About 79% of the mass concentration of PM_{10} dust is due to the presence of the coarser fraction (2.5–10 µm). Therefore the size distribution evolution clearly indicates that the coarse mode aerosol is enhanced during the dust period, despite likely scavenging of coarse particles by frontal rain. The size distribution generally depends on the point of origin, and on how the dust is picked up. It is probably modified in the initial stages of transport, but after injection into the upper atmosphere, it is not much changed (Murdin, 1986). Annual variations of desert dust size distribution are likely (Israelevich et al., 2003).

5.3. Element mass ratios

Sandy soils in the arid part of China, especially the Taklamakan, have high Calcium content (Carmichael et al., 1998) while soils in the southern part of China has a higher percentage of Aluminium, an indicator for aluminosilicate mineral particles (Uematsu et al., 1983).

Element mass ratios are known to differ according to source regions. To make use of these source markers of mineral dust, Ca/Al and Ca/Fe are calculated for the different air mass origins as identified by the backward trajectories. They are (i) non-East Asian sources (ii) Gobi and Taklamakan, (iii) Gobi + non-East Asian sources (iv) Gobi + Taklamakan + non-East Asian sources respectively. No ratio computation is performed for the Gobi desert as no

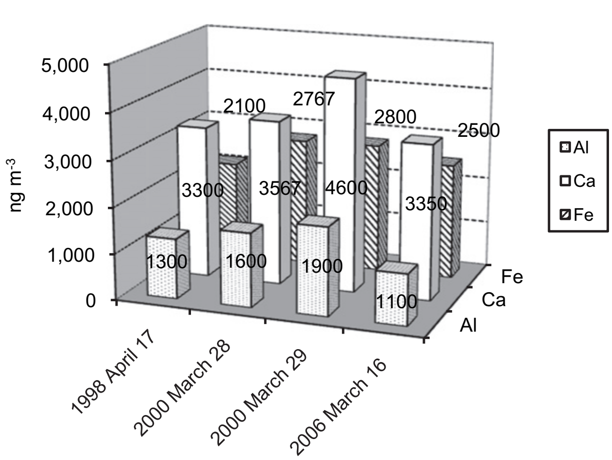

Fig. 7. Al, Fe and Ca concentrations (ng m^{-3}) on dust episode days 1998–2007 (elemental data is not available for the 1996 May 10 episode).

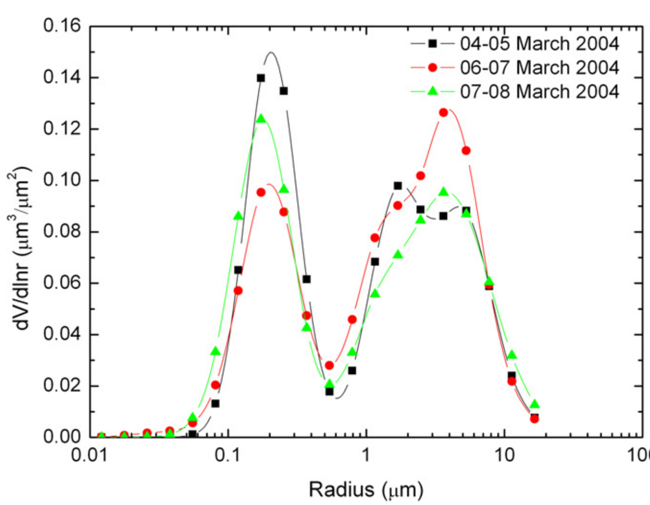

Fig. 8. Aerosol size distribution for the dust event of 6, 7 March 2004, Hong Kong.

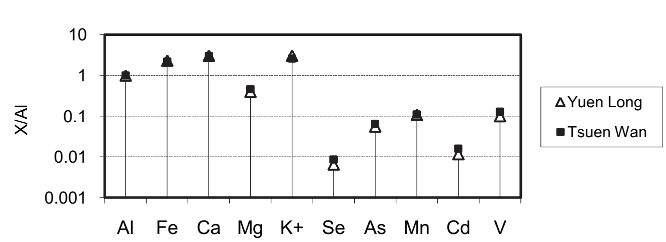

Fig. 9. X/Al ratios (X = an element) of airborne species of PM_{10} on the dust episode day of 16 March 2006, Hong Kong (Yuen Long and Tsuen Wan).

Table 2
Ca/Al, Fe/Al ratios for different dust sources 1996–2007.

	Non-East Asian	Gobi + Takla	Gobi + non-E Asian	Takla + non-E Asian	Gobi + Takla + non-E Asian	UCC[a]	Gobi soil[b] (<100 μm)	China loess[c] PM_{10}
Ca/Al	1.5	2	1.5	2.2	1.9	0.37	1.17	1.08
Fe/Al	0.7	1.6	1	1.3	1.2	0.4	0.4	0.5

The + sign means plus (other sources).
Takla = Taklamakan.
[a] UCC : Upper continental crust (Wu et al., 2009; Taylor and McLennan, 1995).
[b] Ta et al. (2003).
[c] Cao et al. (2008) (China Loess Plateau is south of the Gobi desert).

chemical species data is available for the one event solely under Gobi influence. Elemental concentrations and deduced element ratios represent near-ground level conditions.

The difference in X/Al (where X = an element) is shown in Fig. 9 for crustal as well as other elements for the episode day of 16 March 2006 for two sites in Hong Kong (Yuen Long and Tsuen Wan). It is apparent that the X/Al ratios for the crustal elements Al, Fe and Ca are ten times or more higher than ratios for the non crustal species. Mean mass ratios calculated for the marker elements Ca/Al and Fe/Al for the different dust sources are shown in Table 2. The Ca/Al ratios for the Taklamakan desert are apparently higher than those for non-East Asian sources. According to Cao et al. (2008) the Ca/Al ratios in source regions of Asian dust (0.74–2.7) are one order of magnitude higher than those in African dust (0.15–0.38). Sandy soils in arid parts of China, especially the Taklamakan (Makra et al., 2002) and the loess plateau (south of the Gobi desert) have high Ca content of about 17% on average. However, Ca/Al ratios in Hong Kong may be slightly altered owing to reactions between dust and other pollutant aerosols and the depletion of Ca during the transport.

Mineral dust from the Sahara desert is known to have low Ca content, averaging about 2% (Krueger et al., 2005). However, coastal Saudi dust, usually has large amounts of Ca (average ~15%) compared with inland dust (Kumar et al., 2008) owing to the mixing in of sea salt aerosols. Both the Saharan and the China loess dusts contain approximately similar amounts of Al of about 15–17% (Krueger et al., 2005).

Table 3
Estimated mean contributions of (i) non-East Asian (ii) Thar/Arabian/Sahara deserts to PM_{10}, 1996–2007 (limited samples).

Sources of dust	Mean Al (ng m^{-3})	Mean dust conc (μg m^{-3}) derived from Al	Mean PM_{10} (μg m^{-3})	% of PM_{10}
Non-East Asian (6 days)	1116.7	14	143	9.8
Thar/Arabian/Sahara (2 days)	1100	13.75	166	8.3

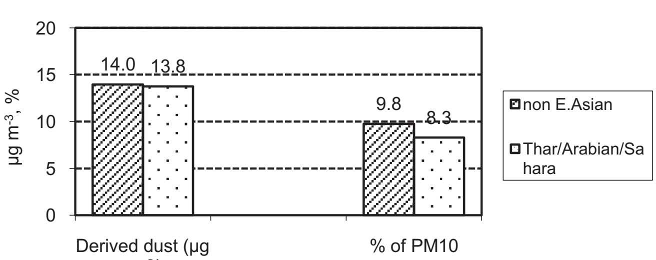

Fig. 10. Mean contributions of (i) non-East Asian deserts (ii) Thar/Arabian/Sahara to PM_{10}, 1996–2007 (limited samples).

Regarding Fe/Al, the non China Fe/Al ratios (see Table 2) are significantly lower than those for the Gobi and the Taklamakan deserts. This is despite the fact that inland dust from Saudi Arabia has been reported to have high Fe content. Ca/Al and Fe/Al ratios for the upper continental crust (UCC) (Wu et al., 2009; Taylor and McLennan, 1995) are listed in Table 2 for comparison.

Air masses may touch different dust or pollution sources along the transport path. Contribution by different sources along the trajectory will vary and depend on such factors as transport time, meteorological conditions, chemical processes and nature of emission sources touched along the path. Thus element mass ratio for air mass from the same origin, for instance from the Sahara, may differ to a varying extent at different places of arrival, e.g. Tel Aviv and Hong Kong. For dust transport involving multiple sources, as in most cases of Hong Kong, it is even more difficult to differentiate the individual sources.

6. An estimation of contributions by non-East Asian sources

Use is made of the six (out of a total of 76) dusty days identified with air mass of non-East Asian origin and the two days entirely under the influence of the Thar/Arabian/Sahara deserts. A gross estimate of contributions from the non-East Asian sources has been performed based on method used by Liu et al. (2009).

Aluminium is released to the environment mainly by natural processes with some anthropogenic contributions. On the assumption that crustal influence dominates on dusty days, an average Al abundance of 8% (Taylor, 1964; The encyclopedia of earth) in the upper continental crust is used to convert Al mass in the PM_{10} to dust concentrations. 8% tends to be on the low side when compared with Krueger et al.'s estimate (2005) that both the Saharan and the China loess dusts contain 15–17% Al. On the basis of the average of 8%, results of the estimation are given in Table 3 and Fig. 10. While the average contribution from non-East Asian dust sources (including C/W Asia) is about 10%, that from the "Thar, Arabian and Sahara deserts" is 8.3%.

For the purpose of comparison, the average daily Al concentrations for summer which is the non dusty season, is 113 ng m^{-3} (mean of 2006 and 2007) from which the calculated Al derived dust concentration is only 1.4 μg m^{-3}. Al concentration is lowest in June, 74, 69 ng m^{-3} in 2006 and 2007 respectively. Under the influence of southwesterlies in June Al contribution in Hong Kong is low.

7. Conclusions

A total of 76 dust storm related events in Hong Kong over the period 1996–2007 have been selected for source identification and characterization in this paper, on the basis of crustal elemental concentrations of Aluminium and Calcium in PM_{10} being equal to or greater than 1000 and 2000 ng m^{-3} respectively. The episode days of 1996 May 10, 1998 April 17, 2000 March 28/29, and 2006 March

16 with exceedance(s) of the Hong Kong Air Quality Objectives, are included in our study.

The methods of study include:

- Observation of the global distribution of aerosols in NASA's daily aerosol index images from Earth Probe Total Ozone Mapping Spectrometer (TOMS) and the Ozone Monitoring Instrument (OMI). The TOMS images are compared with plots generated by NRL's global aerosol model of Navy Aerosol Analysis and Prediction System (NAAPS) regarding aerosol coverage and concentrations.
- Assigning possible source areas by using the HYSPLIT model of the NOAA. Air parcel backward trajectories to Hong Kong are computed for selected altitudes up to 6.5 km, and for up to 315 h.
- The PM_{10} and elemental data obtained from the Hong Kong Environmental Protection Department are analyzed for crustal mass concentrations and element mass ratios.
- Aerosol size distribution for a dust event is obtained by using a PREDE POM-01 sun-sky radiometer installed in the main campus of the City University of Hong Kong (Kowloon). Columnar aerosol concentrations are obtained to verify coarse mode levels.

Results of the analysis reveal remote origins of desert dust for the events in Hong Kong, other than East Asian deserts. Trajectories of the multilayered transport at lower altitudes (900 hPa) usually identify air masses coming from North China while the trajectories arriving at higher barometric levels (700 or 500 hPa) indicate origins of the Sahara. During three of the four dust episodes in Hong Kong during the study period, the Thar, Central/West Asian, Arabian and Sahara deserts also contribute, in addition to dusts from the East Asian deserts. This non-East Asian influence is prevalent, and is found in 73, or 96% of all dust events.

The Gobi desert is found to be the most frequent origin of dust for Hong Kong, affecting 68 dust event days. For a small number of events (2), Gobi's influence coincides with that of the Taklamakan desert, and only in one event is the impact coming solely from Gobi. As a matter of fact, Gobi influences Hong Kong mostly concurrently with non-East Asian sources. The Taklamakan desert affects Hong Kong on only 30 of the dust event days. The significant impact of the Gobi desert in March and December is apparently associated with the winter monsoon in East Asia. In regard to the frequency of impact, the Thar, Sahara and Arabian deserts affect 65, 63 and 62 dust events respectively.

A seasonal pattern is found in the dust impact from both East Asian and non-East Asian sources for the study period. March records 21 events out of a total of 76. Dust storm related episodes have occurred in March, April and May in Hong Kong. Contrary to expectation, December comes second after March in terms of the number of dust events. Then come January, February, April, November, May and October. Dust events are conspicuously absent from summer, and September. The East Asian deserts of Gobi and Taklamakan, as well as the Thar, Central/West Asia, Arabian and Sahara deserts seem to follow a similar seasonal pattern. Dust transport from remote sources to Hong Kong is commonly associated with meteorological events such as the passage of frontal low-pressure systems.

The concentrations of PM_{10} during the dust episode were much more elevated than those before, particularly for the coarse size fraction. Increment factors for the crustal elements Al, Ca and Fe vary from about 4 to 8 times. The mass ratios of Ca and Al are known to differ according to source regions. Owing to the higher Ca content of the deserts of China, the mean Ca/Al ratios related to the Taklamakan desert are higher than those for non-East Asian sources. The Fe/Al ratios follow a similar trend.

A gross estimate of contributions from the non-East Asian sources (including C/W Asia) and the Thar/Arabian/Sahara deserts is made based on concentrations of the crustal marker Al. Use is made of the six events identified with air mass of non-East Asian origin and two events with influence coming from the Thar/Arabian/Sahara deserts. The average Al abundance of 8% in the upper continental crust is used to convert the Al mass in the PM_{10} to dust concentrations. Results indicate that the average contribution from the non-East Asian sources is approximately 10% and about 8% from the Thar/Arabian/Sahara deserts.

Acknowledgements

The work described in this paper was supported by a grant from City University of Hong Kong (Project No. 7002322). Thanks are due to the Guy Carpenter Asia-Pacific Climate Impact Centre of the City University of Hong Kong for research grant support, as well as the Environmental Protection Department of the Hong Kong Special Administrative Region for the provision of air quality data. The authors also gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model used in this publication, and Dr Dave Larko of NASA Goddard Space Flight Center for the provision of high quality TOMS/OMI images.

References

Borbély-Kiss, I., Kiss, Á.Z., Koltay, E., Szabó, Gy., Bozó, L., 2004. Saharan dust episodes in Hungarian aerosol: elemental signatures and transport trajectories. Journal of Aerosol Science 35, 1205–1224.

Cao, J.J., Chow, J.C., Watson, J.G., Wu, F., Han, Y.M., Jin, Z.D., Shen, Z.X., An, Z.S., 2008. Size-differentiated source profiles for fugitive dust in the Chinese Loess Plateau. Atmospheric Environment 42, 2261–2275.

Carmichael, Gregory R., Guttikunda, Sarath K., Wang, Jing, Streets, David, Waldhoff, Stephanie, Levy II, Hiram, 1998. China Map: Emissions Activity, Progress Report – update, at: http://www.cgrer.uiowa.edu/people/carmichael/ChinaMap10-98/index.html.

Cheng, T.S., 1988. Synoptic patterns leading to cold surges over South China, WMO Selected Workshop on Asian Winter Monsoon, Kuala Lumpur, 27 June–1 July 1988.

Chung, Yong-Seung, Yoon, Ma-Beong, 1996. On the occurrence of yellow sand and atmospheric loadings. Atmospheric Environment 30, 2387–2397.

Draxler, R.R., Rolph, G.D., 2003. HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model Access via NOAA ARL READY Website. NOAA Air Resources Laboratory, Silver Spring, MD. http://www.arl.noaa.gov/ready/hysplit4.html.

Dulam, Jugder, 2005. Discriminate analysis for dust storm prediction in the Gobi and Steppe Regions in Mongolia. Journal Water, Air, & Soil Pollution: Focus 5 (3–6), 37–49.

Fang, M., Zheng, M., Wang, F., Chim, K.S., Kot, S.C., 1999. The long range transport of aerosols from northern China to Hong Kong – a multi-technique study. Atmospheric Environment 33, 1803–1817.

Formenti, P., Andreae, M.O., Andreae, T.W., Galani, E., Vasaras, A., Zerefos, C., Amiridis, V., Orlovsky, L., Karnieli, A., Wendisch, M., Wex, H., Holben, B.N., Maenhaut, W., Lelieveld, J., 2001. Aerosol optical properties and large-scale transport of air masses: observations at a coastal and a semiarid site in the eastern Mediterranean during summer 1998. Journal of Geophysical Research 106 (D9), 9807–9826. doi:10.1029/2000JD900609.

Ganor, E., 1994. The frequency of Saharan dust episodes over Tel Aviv, Israel. Atmospheric Environment 28, 2867–2871.

Gatz, D.F., Prospero, J.M., 1996. A large silicon-aluminum aerosol plume in central Illinois: North Africa desert dust. Atmospheric Environment 30, 3789–3799.

Goudie, A.S., Middleton, N.J., 2001. Saharan dust storms: nature and consequences. Earth-Science Reviews 56, 179–204.

Guerzoni, Stefano, Molinaroli, Emanuela, 2005. Input of Various Chemicals Transported by Saharan Dust and Depositing at the Sea Surface in the Mediterranean Sea. The Handbook of Environmental Chemistry, vol. 5, Part K, pp. 237–268.

Guieu, C., Loÿe-Pilot, M.-D., Ridame, C., Thomas, C., 2002. Chemical characterization of the Saharan dust end-member; some biological implications for the western Mediterranean. Journal of Geophysical Research 107 (D15), 4258. doi:10.1029/2001JD000582.

Han, Y., Dai, X., Fang, X., Chen, Y., Kang, F., 2008. Dust aerosols: a possible accelerant for an increasingly arid climate in North China. Journal of Arid Environments 72 (8), 1476–1489.

Hong, Chi-Cherng, Hsu, Huang-Hsiung, Chia, Hsin-Hsing, 2009. A study of East Asian cold surges during the 2004/05 winter: impact of East Asian jet stream and subtropical upper-level Rossby wave trains. Terrestrial, Atmospheric and Oceanic Sciences 20 (2), 333–343. doi:10.3319/TAO.2008.02.04.01(A).

Husar, R.B., Tratt, D.M., Schichtel, B.A., Falke, S.R., Li, F., Jaffe, D., Gassó, S., Gill, T., Laulainen, N.S., Lu, F., Reheis, M.C., Chun, Y., Westphal, D., Holben, B.N., Gueymard, C., McKendry, I., Kuring, N., Feldman, G.C., McClain, C., Frouin, R.J., Merrill, J., DuBois, D., Vignola, F., Murayama, T., Nickovic, S., Wilson, W.E., Sassen, K., Sugimoto, N., Malm, W.C., 2001. The Asian dust events of April 1998. Journal of Geophysical Research – ATM 106 (D16), 18317–18330.

Israelevich, P.L., Ganor, E., Levin Z., Joseph, J.H., 2003. Annual variations of desert dust size distribution over Israel. EGS – AGU – EUG Joint Assembly, Abstracts from the Meeting Held in Nice, France, 6–11 April 2003, abstract #1869.

Kerkmann, Jochen, 2006. Continental-scale Sahara Dust Outbreak (5–9 March 2006). EUMETSAT, at: http://oiswww.eumetsat.org/WEBOPS/iotm/iotm/20060308_dust/20060308_dust.html.

Kim, J., 2008. Transport routes and source regions of Asian dust observed in Korea during the past 40 years (1965–2004). Atmospheric Environment 42, 4778–4789.

Krueger, B.J., Grassian, V.H., Cowin, J.P., Laskin, A., 2005. Erratum to "Heterogeneous chemistry of individual mineral dust particles from different dust source regions: the importance of particle mineralogy". Atmospheric Environment 39, 395.

Kubilay, Nilgün, Nickovic, Slobodan, Moulin, Cyril, Dulac, Francois, 2000. An illustration of the transport and deposition of mineral dust onto the Eastern Mediterranean. Atmospheric Environment 34, 1293–1303.

Kumar, Ashwini, Sarin, M.M., Su, A.K., 2008. Mineral and anthropogenic aerosols in Arabian Sea–atmospheric boundary layer: sources and spatial variability. Atmospheric Environment 42, 5169–5181.

Kurosaki, Y., 2005. Characteristics of dust event in East Asia: focus on the Gobi desert, and Mongolia regions. In: Proceedings of the 11th CEReS International Symposium on Remote Sensing, Chiba, Japan.

Lee, H.N., Igarashi, Y., Chiba, M., Aoyama, M., Hirose, K., Tanaka, T., 2006. Global model simulations of the transport of Asian and Sahara Dust: total deposition of dust mass in Japan. Water, Air, and Soil Pollution 169, 137–166.

Lee, Y.C., Hills, P.R., 2003. Cool season pollution episodes in Hong Kong, 1996–2002. Atmospheric Environment 37, 2927–2939.

Liu, Dong, Wang, Zhien, Liu, Zhaoyan, Winker, Dave, Trepte, Charles, 2008. A height resolved global view of dust aerosols from the first year CALIPSO lidar measurements. Journal of Geophysical Research 113, D16214.

Liu, Tsun-Hsien, Tsai, Fujung, Hsu, Shih-Chieh, Hsu, Che-Wei, Shiu, Chein-Jung, Chen, Wei-Nei, Tu, Jien-Yi, 2009. Southeastward transport of Asian dust: source, transport and its contributions to Taiwan. Atmospheric Environment 43, 458–467.

Makra, L., Borbely-Kiss, I., Koltay, E., Chen, Y., 2002. Enrichment of desert soil elements in Takla Makan dust aerosol. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 189 (1), 214–220 (7).

Merrill, J.T., Uematsu, M., Bleck, R., 1989. Meteorological analysis of long range transport of mineral aerosols over the North Pacific. Journal of Geophysical Research 94 (D4), 8584–8598.

Moon, Yun-Seob, Lee, Seung-Hwan, 2008. Meteorological guideline for forecasting Asian dust using WRF (Weather Research Forecasting version 2.2) in the Korean peninsula. Extended abstracts and workshop presentations for the 8th WRF Users' Workshop, June 11–15, 2007.

Morales, Christer, 1986. The airborne transport of Saharan dust: a review. Climatic Change 9, 219–241.

Murdin, Paul, April 1986. Geology and Meteorology of Saharan dust. Royal Greenwich Observatory/La Palma Technical Note No. 41.

Nicolás, Jose, Chiari, Massimo, Crespo, Javier, Orellana, Isabel, Garcia, Lucarelli, Franco, Nava, Silvia, Pastor, Yubero, Eduardo, 2008. Quantification of Saharan and local dust impact in an arid Mediterranean area by the positive matrix factorization (PMF) technique. Atmospheric Environment 42, 8872–8882.

Park, Chan Bong, Sugimoto, Nobuo, Matsui, Ichiro, Shimizu, Atsushi, Tatarov, Boyan, Kamei, Akihide, Lee, Choo Hie, Uno, Itsushi, Takemura, Toshihiko, Westphal, Douglas L., 2005. Long-range Transport of Saharan Dust to East Asia Observed with Lidars. SOLA, vol. 1, pp. 121–124.

Perry, K.D., Cahill, T.A., Eldred, R.A., Dutcher, D.D., Gill, T.E., 1997. Long-range transport of North African dust to the eastern United States. Journal of Geophysical Research 102 (D10), 11,225–11,238.

Ta, W.Q., Zheng, X., Qu, J.J., Yang, G.S., Wang, T., 2003. Characteristics of dust particles from the desert/Gobi area of northwestern China during dust-storm periods. Environmental Geology 43, 667–679.

Tanaka, T.Y., Kurosaki, Y., Chiba, M., Matsumura, T., Nagai, T., Yamazaki, A., Uchiyama, A., Tsunematsu, N., Kai, K., 2005. Possible transcontinental dust transport from North Africa and the Middle East to East Asia. Atmospheric Environment 39, 3901–3909.

Taylor, S.R., 1964. Abundance of chemical elements in the continental crust: a new table. Geochimica et Cosmochimica Acta 28, 1273–1285.

Taylor, S.R., McLennan, S.M., 1995. The geochemical evolution of the continental crust. Reviews of Geophysics 33, 241–265.

The encyclopedia of earth, at: http://www.eoearth.org/article/Aluminum.

Thompson, B.W., 1951. An essay on the general circulation of the atmosphere over Southeast Asia and the West Pacific. Quarterly Journal of the Royal Meteorological Society 77 (334).

Uematsu, M., Duce, R.A., Prospero, J.M., Chen, L., Merrill, J.T., McDonald, R.L., 1983. Transport of mineral aerosol from Asia over the North Pacific Ocean. Journal of Geophysical Research 88, 5343–5352.

United Nations Environment Programme: Global Deserts Outlook, 2006.

U.S. Environmental Protection Agency, 1999. Compendium of Methods for the Determination of Inorganic Compounds in Ambient Air. Compendium Method IO-3.4 Determination of Metals in Ambient Particulate Matter Using Inductively Coupled Plasma (ICP) Spectroscopy. Center for Environmental Research, Information Office of Research and Development. EPA/625/R-96/010a.

U.S. Environmental Protection Agency, 2004. The Particle Pollution Report: Current Understanding of Air Quality and Emissions Through 2003.

Wang, Xunming, Dong, Zhibao, Zhang, Jiawu, Liu, Lichao, 2004. Modern dust storms in China: an overview. Journal of Arid Environments 58 (4), 559–574.

Watanabe, M., 2004. Asian jet waveguide and a downstream extension of the North Atlantic oscillation. Journal of Climate 17, 4674–4691.

Wu, Guangjian, Xu, Baiqing, Zhang, Chenglong, Gao, Shaopeng, Yao, Tandong, 2009. Geochemistry of dust aerosol over the Eastern Pamirs. Geochimica et Cosmochimica Acta 73 (4), 977–989.

Yang, X., Wenig, M., 2009. Study of columnar aerosol size distribution in Hong Kong. Atmospheric Chemistry and Physics 9, 6175–6189.

Zhou, M., Okada, K., Qian, F., Wu, P., Su, L., Casareto, B., Shimohara, T., 1996. Characteristics of dust-storm particles and their long-range transport from China to Japan—case studies in April 1993. Atmospheric Research 40, 19–31.