

Influence of Long-Range Transport Dust Particles on Local Air Quality: A Case Study on Asian Dust Episodes in Taipei during the Spring of 2002

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(Manuscript received 3 September 2003, in final form 23 April 2004)

ABSTRACT

In the spring of 2002, an intensive field measurement campaign was conducted to investigate the impact of Asian dust transport on local air quality in Taipei, Taiwan. The mass concentration, size distribution and chemical composition of the atmospheric aerosols were measured. Air quality data collected by the Taiwan EPA during this period were also analyzed. It was found that the content of crustal elements in aerosols could drastically increase on the arrival of air masses transported from the desert areas in Northwestern China and Mongolia. Time series analysis of aerosol measurements, air quality data, and meteorological conditions identified six Asian dust transport episodes occurring in the spring of 2002. In order to apportion the ambient aerosol burden between local and long-range sources, nitrogen oxides (NO_x) was chosen as a local pollution tracer and a simplified algorithm based on the NO_x and PM_{10} correlation was proposed. It was estimated that long-range transported aerosols contributed as much as 87% to the PM_{10} in Taipei on Feb. 11, the most intense dust event in 2002. A weak event that occurred on Mar. 23 contributed 35% to the PM_{10} . Our results indicate that the air quality impact due to Asian transport dust is still important even during weak dust events.

**(Key words: Asian dust; Aerosol composition;
Long-range transport; Air quality)**

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1. INTRODUCTION

In the springtime, extreme weather conditions such as intense fronts and strong surface winds are induced frequently over Northwestern China and Mongolia. Mineral particles can be lifted up by the surface winds over the desert and loess areas in this region and injected into the troposphere following intense convection. The mineral particles are then transported to Northeastern Asia and usually result in serious deterioration in local air quality (e.g., Iwasaka et al. 1983; Hursar et al. 2001; Murayama et al. 2001; Kim et al. 2003). Sometimes, Asian dust transport can even be observed in the North Pacific Ocean and North America (e.g., Duce et al. 1980; Shaw 1980; Uematsu et al. 1983; Jaffe et al. 1999; Mckendry et al. 2001; Tratt et al. 2001; VanCuren and Cahill 2002). Although the Asian dust particles are carried mostly by westerly winds and spread over the mid-latitudes, a portion of the dust particles can also be transported to Taiwan under the prevailing northeasters of the winter monsoon.

Public concern regarding the long-range transport of Asian dust has arisen in Taiwan due to its impact on the local air quality and, consequentially, public health. It was recorded that the PM_{10} concentration (particulate matter with aerodynamic diameter less than $10 \mu m$) increased to a level higher than $400 \mu g m^{-3}$ in an intense dust event that occurred in April 2000 (Lin 2001). Recently, this concern has increased due to the co-transport of anthropogenic pollutants and dust in the Asian outflows. To evaluate this health hazard, it is critical to determine the amount of particulate pollutants transported from the Asian continent during these dust events. This is not an easy task, because there are substantial local sources of air pollutants, particularly in urban areas.

To assess the impact of Asian dust on local air quality, an intensive aerosol experiment was implemented in Taipei during the spring of 2002. In this paper, we use the aerosol measurements made during the campaign and the gaseous pollutant mixing ratios measured concurrently at the Taiwan-EPA's air-quality monitoring stations to estimate the contribution from long-range transport to the atmospheric aerosol burden for each dust episode. We used mineral elements as tracers for the Asian dust, while NO_x was selected as the tracer for local pollution. The latter was selected because, in an analysis of temporal variations in air pollutants during Asian dust events, Lin et al. (2004) noticed that NO_x tended to represent local pollution the best as relatively little NO_x came from long-range transport.

2. FIELD CAMPAIGN AND DATASET

The campaign period of this study was from February to May in 2002. The Taiwan Air Quality Model (TAQM) was used to simulate Asian dust transport and forecast the occurrence of a dust episode in Taiwan (Liu et al. 2004). Aerosol sampling for PM_{10} and $PM_{2.5}$ started one day before the forecast "dust day" and lasted one week for each dust event. In addition, for comparison purposes, a non-dust experiment was arranged from May 27 to 31 to collect aerosol samples for "normal" days. The sampling equipment was located on the main building of the Central Weather Bureau (CWB) in Taipei, Taiwan. Figure 1 shows the geographical location of the sampling site. The sampling period for each sample set was 12 hours. Daytime

samples were collected from 0800LST to 2000LST and nighttime sampling was from 2000LST to 0800LST the next day. Aerosol mass concentrations were determined by gravimetric measurement of the PTFE membrane filters before and after the sampling activities. The PTFE filter samples were also used for ionic species and crustal element analyses. The details of the chemical analyses are presented in separate papers in this special issue (Hsu et al. 2004; Lung et al. 2004). Besides, a redundant sample set was collected on pre-fired quartz filters for analyzing carbonaceous species (i.e., organic carbon and elemental carbon) in aerosols. The analysis method for the carbonaceous species was following the thermal/optical reflectance (TOR) protocol (Chow et al. 1993).

In addition to the measurements described above, data from the Taiwan Air Quality Monitoring Network (TAQMN), which belongs to the official air quality monitoring system of the Taiwan EPA, were analyzed to examine potential Asian dust episodes. The TAQMN consists of 72 air-quality monitoring stations and provides highly time-resolved air quality data from all over the island. All instruments in these stations are maintained and periodically calibrated according to the TAQMN Quality Management Plan. In this work, data sets from the Wan-Li and Ku-Tin stations were analyzed: Wan-Li is a remote station located near the northern tip of Taiwan and is upwind from Taipei under the northeastern monsoons. Ku-Tin is a representative downtown station in Taipei. The geographical locations of the two TAQMN stations are also shown in Fig. 1.

3. RESULTS AND DISCUSSION

3.1 Identification of Asian Dust Episodes

The daily average PM_{10} concentrations over downtown Taipei are generally around 40 - 60 $\mu\text{g m}^{-3}$ in the spring. Figure 2 shows the time series of hourly PM_{10} levels at the Wan-Li and Ku-Tin stations between Feb. 1 and Apr. 30, 2002. One can see that several "peaks" over 100 $\mu\text{g m}^{-3}$ occurred concurrently at Wan-Li and Ku-Tin. These high PM_{10} episodes are usually attributed to Asian dust transport. However, the increase in aerosol concentration is not necessarily related to dust storms. Either long-range transport of particulate pollutant or pollution from local sources can also result in a high PM_{10} event.

Lin et al. (2004) developed an objective method to distinguish long-range transport air masses from local pollution. They reported that the diurnal cycle of local pollutants would disappear when a long-range transported air parcel arrived and dominated the local air quality. Accordingly, a high PM_{10} episode will be identified as a "suspected Asian dust transport case", if

- a drastic increase in the PM_{10} concentration occurs within a few hours after the arrival of a cold front that originated in the Asian continent, and
- local pollutant (like NO_x and CO) concentrations decrease to a low and steady level at the same time.

Following these rules, eight of the PM_{10} peaks in Fig. 2 (which occurred on Feb. 9 - 11, Mar. 6, Mar. 18, Mar. 23, Apr. 9 - 10, and Apr. 18) were suggested as results of Asian dust

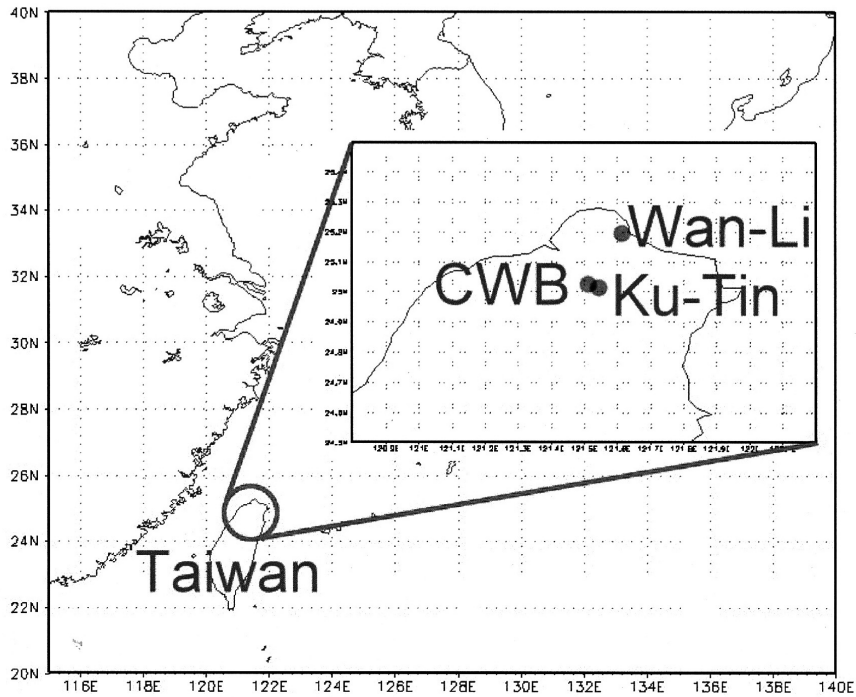


Fig. 1. Geographic locations of the sampling site (CWB) and the air-quality monitoring stations (Ku-Tin and Wan-Li) of Taiwan EPA.

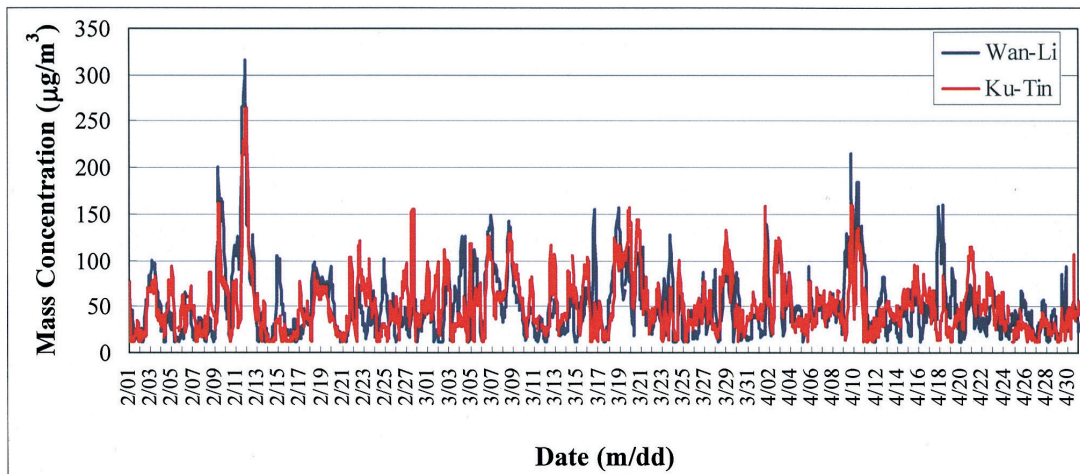


Fig. 2. Variations in PM₁₀ concentrations at the EPA's Ku-Tin and Wan-Li stations during spring 2002.

transport. Figures 3 and 4 show the temporal variations in air pollutants during those periods at Wan-Li and Ku-Tin, respectively. The pattern of the time series plots for the Wan-Li's air quality data agrees well with the results from Lin *et al.* (2004). However, that for the Ku-Tin's data shows some inconsistent points. First, when air parcels with dust arrived and increased the PM_{10} level at Wan-Li, air pollution from local sources in Taipei was still obvious, as indicated by the high levels of NO_x at Ku-Tin. Given that the Wan-Li station is located near the northern tip of Taiwan, the strong and prevailing northeaster associated with frontal passage can sweep the local pollutants away with the arrival of a cold front. However, due to the geographical features of Taipei, the surface wind in the Taipei basin is significantly weaker and can only blow a portion of the local pollutants out. Thus, it is rather difficult to identify a dust episode using the time series pattern of air pollutant concentrations in the Taipei downtown area if the dust event is not strong enough to dominate the air quality. Second, changes in air quality patterns at Ku-Tin on Mar. 23 and Apr. 18 were likely due to local pollution, whereas the air quality patterns at Wan-Li clearly show dust transport characteristics. The differences show that the dust signals can be masked by heavy pollution in the downtown area in a weak dust event. A particular case occurred on Mar. 8. A "dust parcel" came with a cold front on Mar. 6 and resulted in a typical dust event. The PM_{10} levels declined at both Wan-Li and Ku-Tin on Mar. 7 and then concurrently increased on Mar. 8. The air quality data from the Wan-Li station on Mar. 8 showed signs of local pollution; however, relatively low CO and NO_x mixing ratios occurred at Ku-Tin, suggesting the high PM_{10} episode was an Asian dust transport case. Figures 3b and 4b show that the increase in PM_{10} on Mar. 8 followed a change in wind direction from a southwesterly to an easterly. Thus, a possible explanation for this case is that, as the center of the high-pressure system moved to the east of Taiwan, its circumfluence brought some dust back and generated a mixture of dust and local pollutants.

Information concerning the aerosol chemical compositions is essentially the best evidence of a dust event. In general, the Taipei aerosols are composed mostly of ionic and carbonaceous species. Figure 5 illustrates the chemical compositions of aerosol samples collected during the Asian dust episodes and the non-dust period in this work. The ionic species (NH_4^+ , SO_4^{2-} , and NO_3^-) and total carbon (TC) accounted for 24 and 22% of the average PM_{10} concentration during the dust episodes. Both were significantly lower than their non-dust counterpart (36 and 29%). The change in the abundance of crustal elements (e.g., Al, Ca, Fe, Mn, etc.) in the ambient aerosols was quite obvious. It increased from about 5% on the normal days to 22% for dust episodes.

Figure 6 shows the time series for the PM_{10} and aluminum concentrations (in PM_{10}) measured during our field campaign. A detailed discussion on all the crustal elements is presented in a separate paper in this issue (Hsu *et al.* 2004). Comparing our elemental measurement with the PM_{10} concentrations, six of the PM_{10} peaks in Fig. 2 (occurring on Feb. 11, Mar. 6, Mar. 8, Mar. 18, Mar. 23 and Apr. 9) were identified as dust events, because the PM_{10} concentration increased coincidentally with the increase in the aluminum level. We validated this rule by applying it to the data for the non-dust experiment: PM_{10} showed a typical diurnal variation between May 27 and 31, whereas aluminum stayed at a low and steady level in the same period. Dust transport episode identification using aluminium abundance was used to check the suspected episodes suggested by the air quality method. The high level of crustal

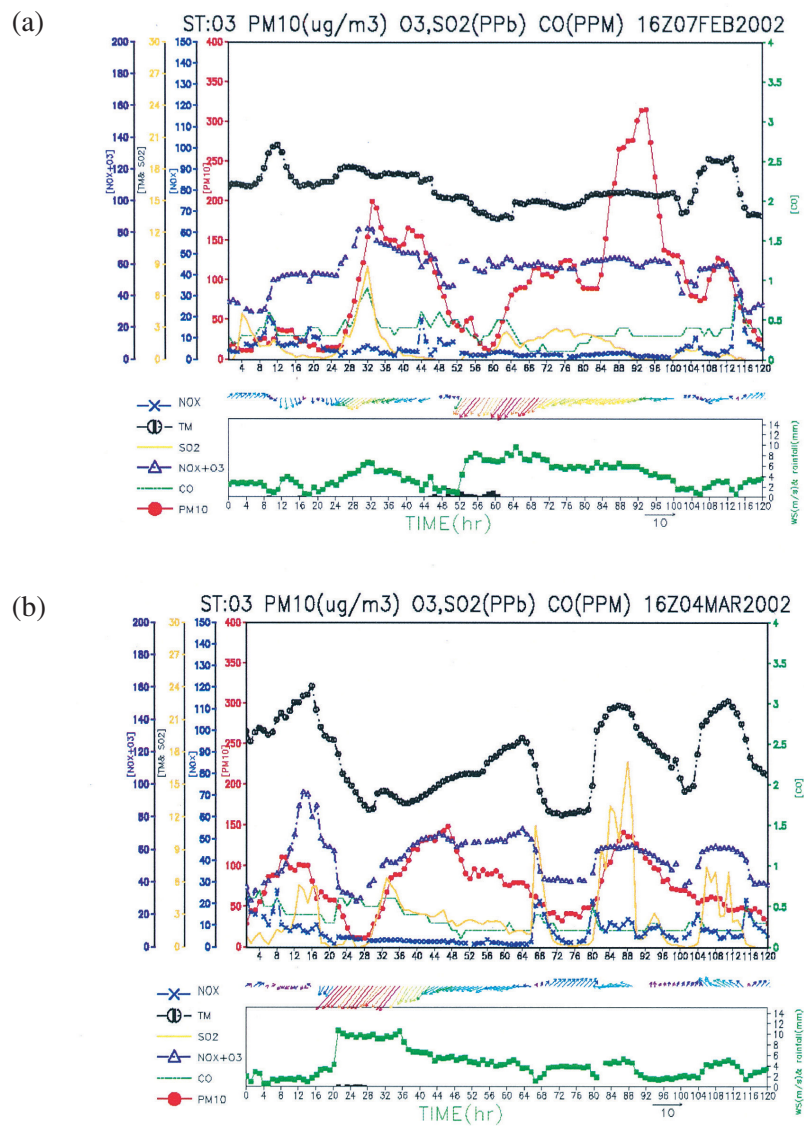


Fig. 3. The time series of hourly PM₁₀ (red closed circles), CO (dashed line), SO₂ (solid line), NO_x + O₃ (triangle), NO_x (cross), surface temperature (open circle with vertical line), wind speed (closed squares, bottom panel), and rainfall (black bar, bottom panel) measured at EPA's Wan-Li station during six high PM₁₀ periods. The surface wind is presented using wind vector: (a) 0100LST Feb. 8 to 2400LST Feb. 12; (b) 0100LST Mar. 5 to 2400LST Mar. 9; (c) 0100LST Mar. 16 to 2400LST Mar. 20; (d) 0100LST Mar. 21 to 2400LST Mar. 24; (e) 0100LST Apr. 8 to 2400LST Apr. 12; (f) 0100LST Apr. 17 to 2400LST Apr. 20.

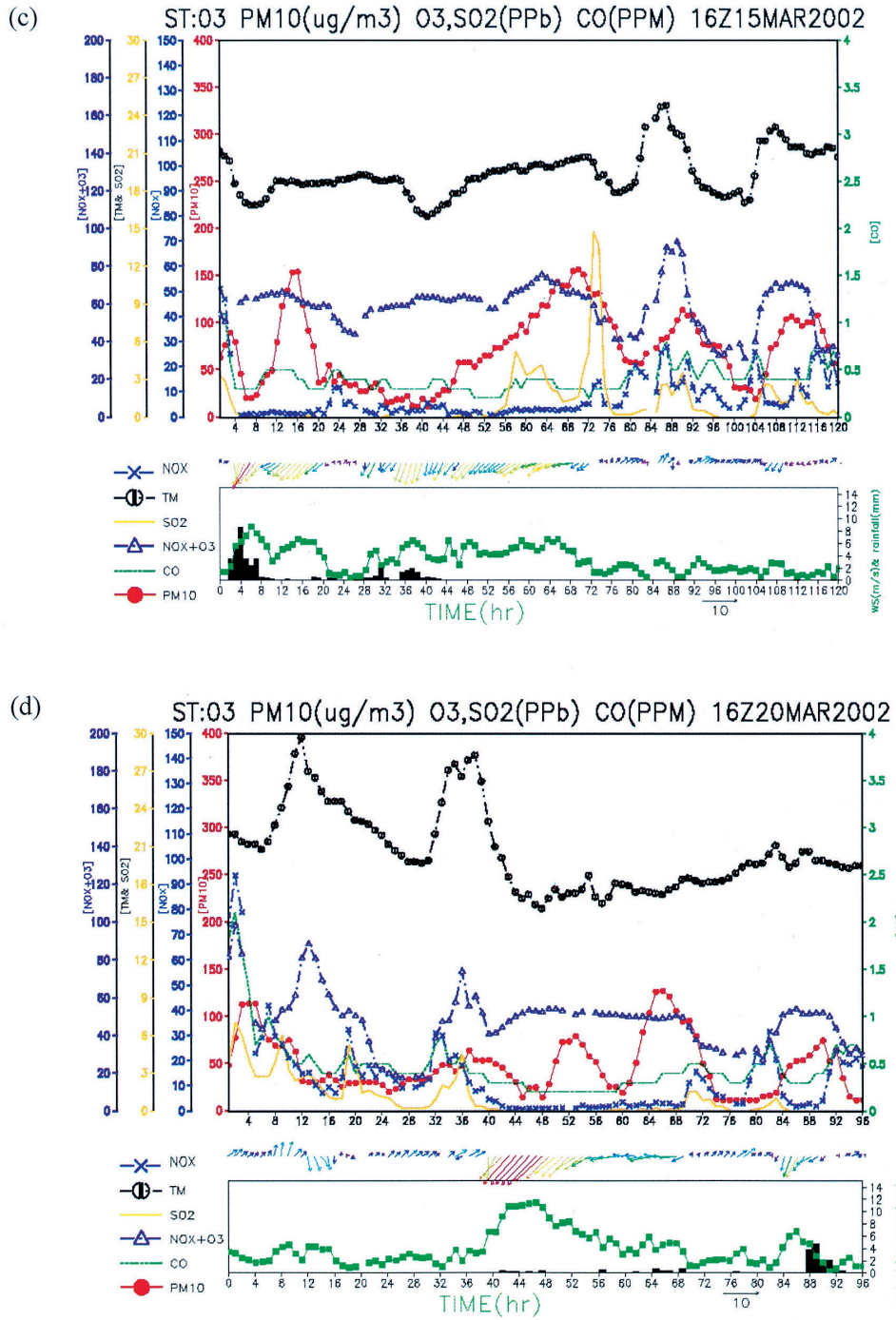


Fig. 3. Continued.

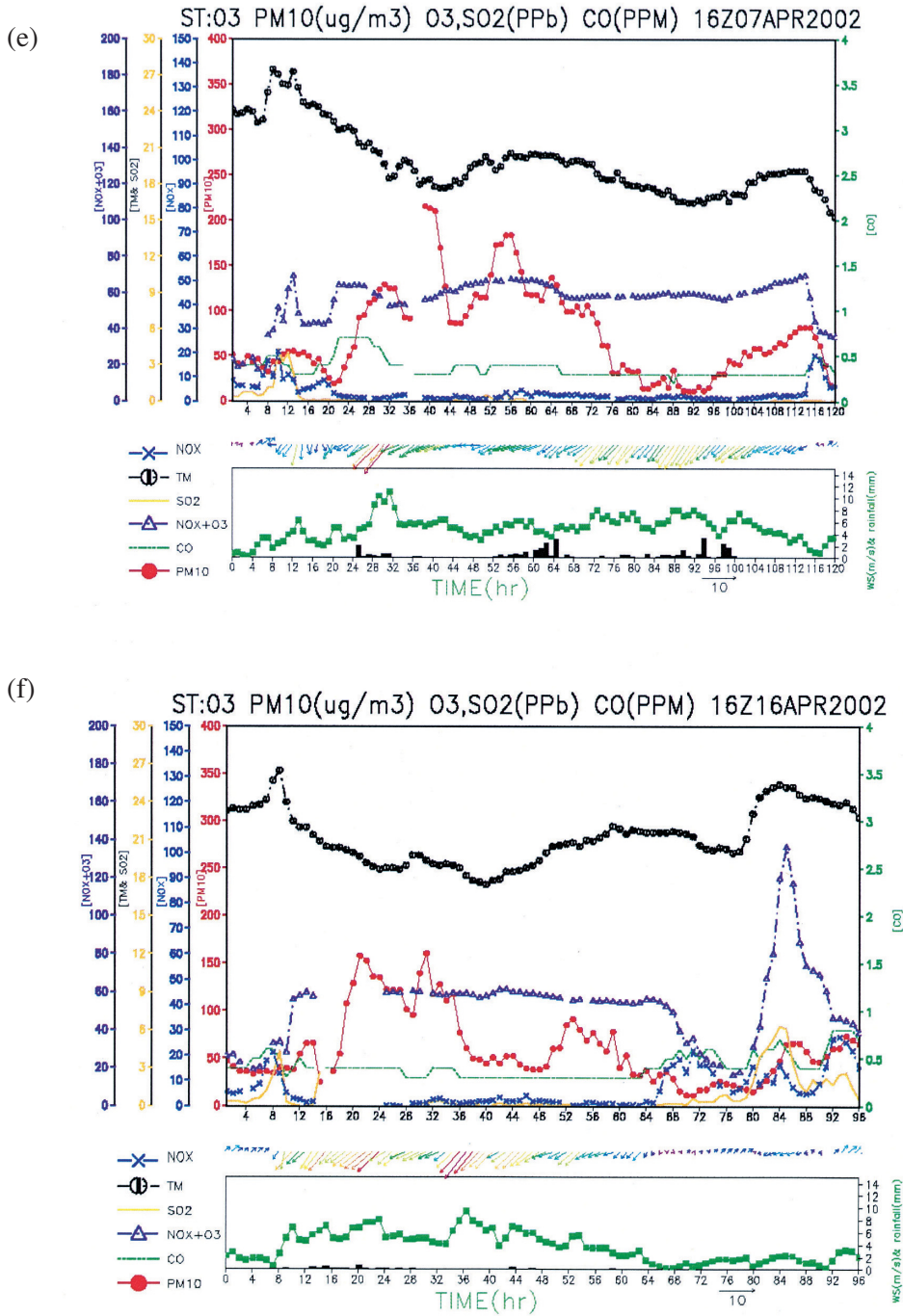


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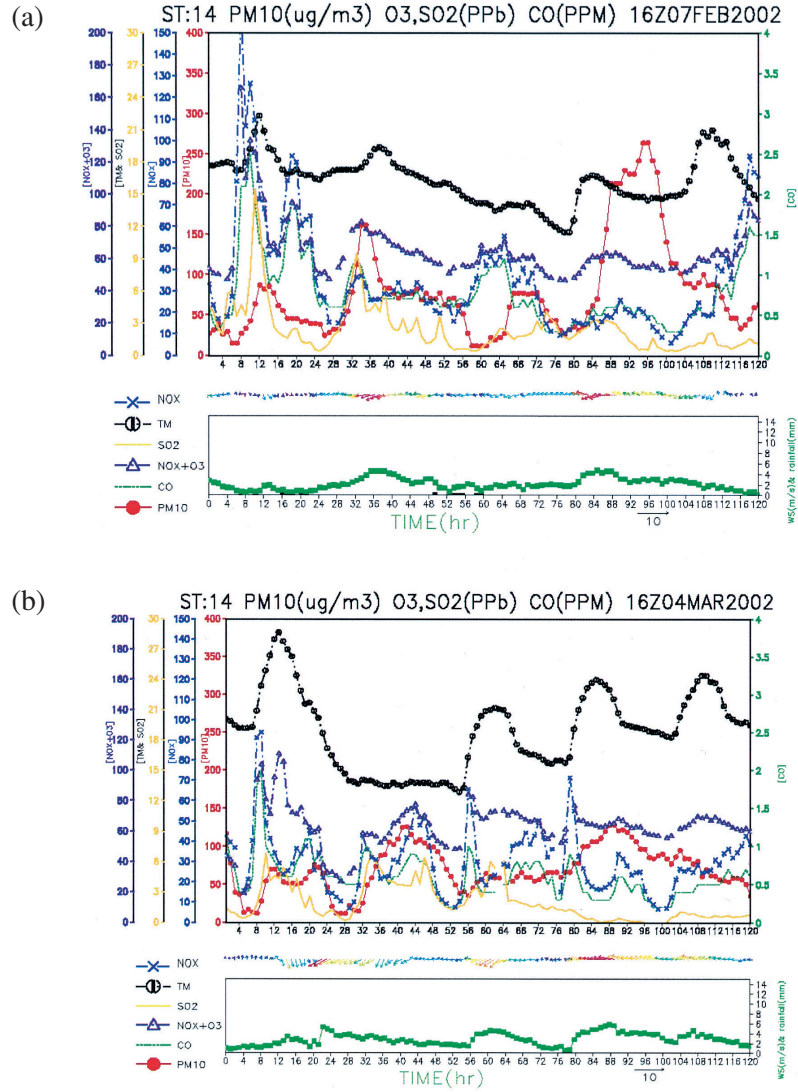


Fig. 4. The time series of hourly PM_{10} (red closed circles), CO (dashed line), SO_2 (solid line), $NO_x + O_3$ (triangle), NO_x (cross), surface temperature (open circle with vertical line), wind speed (closed squares, bottom panel), and rainfall (black bar, bottom panel) measured at EPA's Ku-Tin station during six high PM_{10} periods. The surface wind is presented using wind vector: (a) 0100LST Feb. 8 to 2400LST Feb. 12; (b) 0100LST Mar. 5 to 2400LST Mar. 9; (c) 0100LST Mar. 16 to 2400LST Mar. 20; (d) 0100LST Mar. 21 to 2400LST Mar. 24; (e) 0100LST Apr. 8 to 2400LST Apr. 12; (f) 0100LST Apr. 17 to 2400LST Apr. 20.

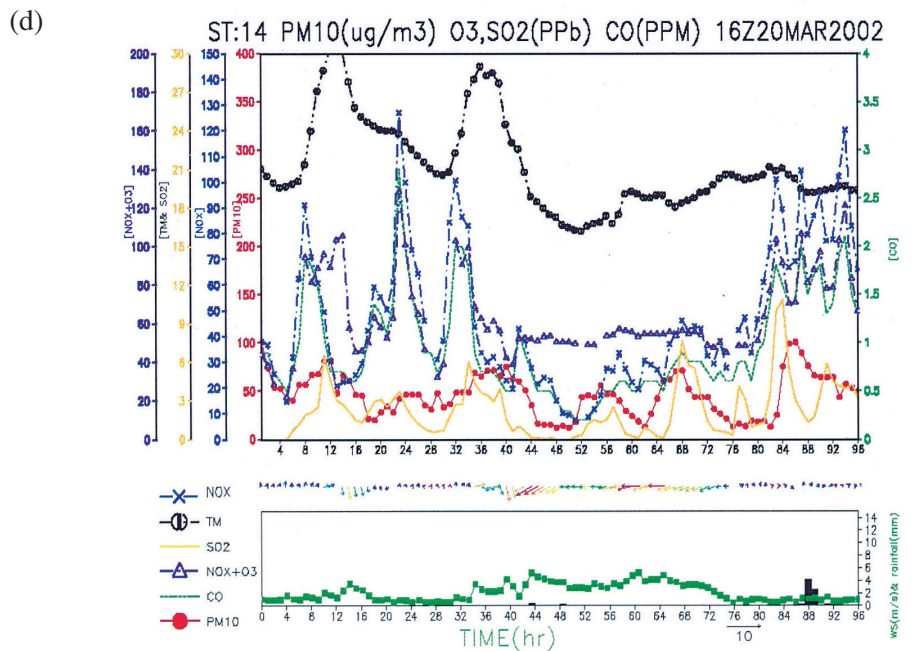
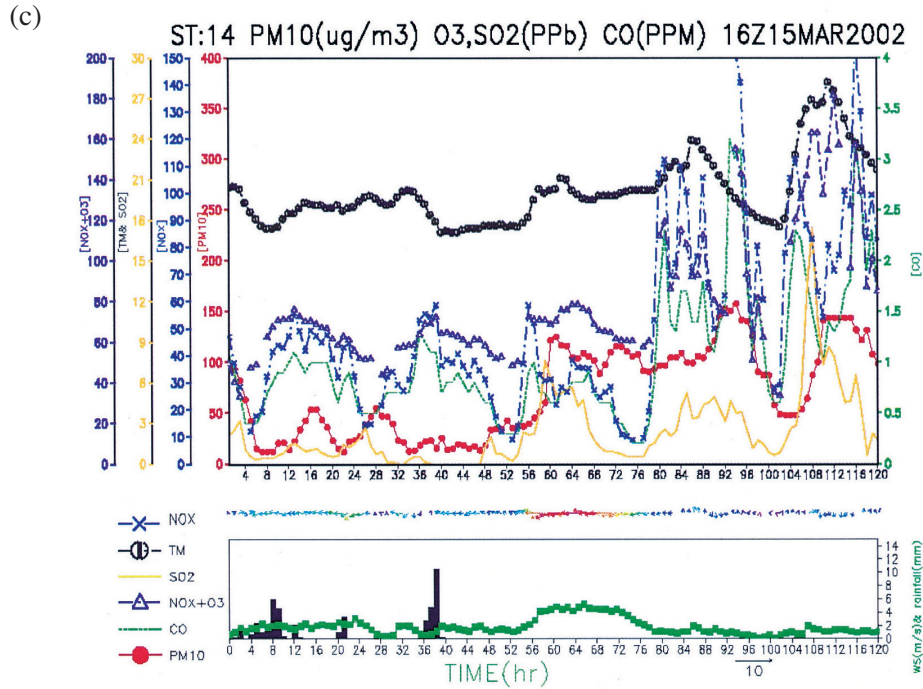


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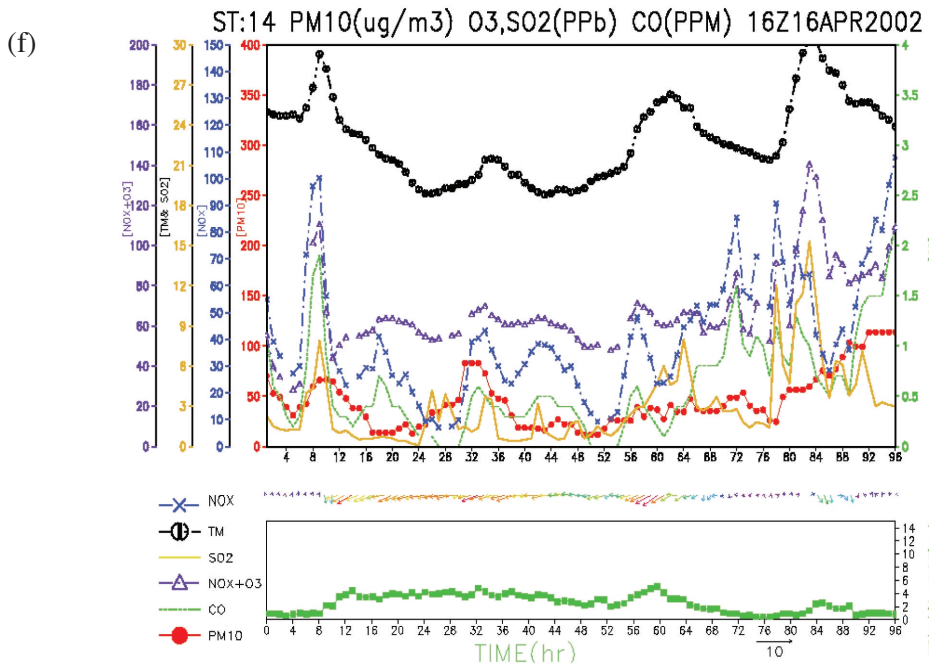
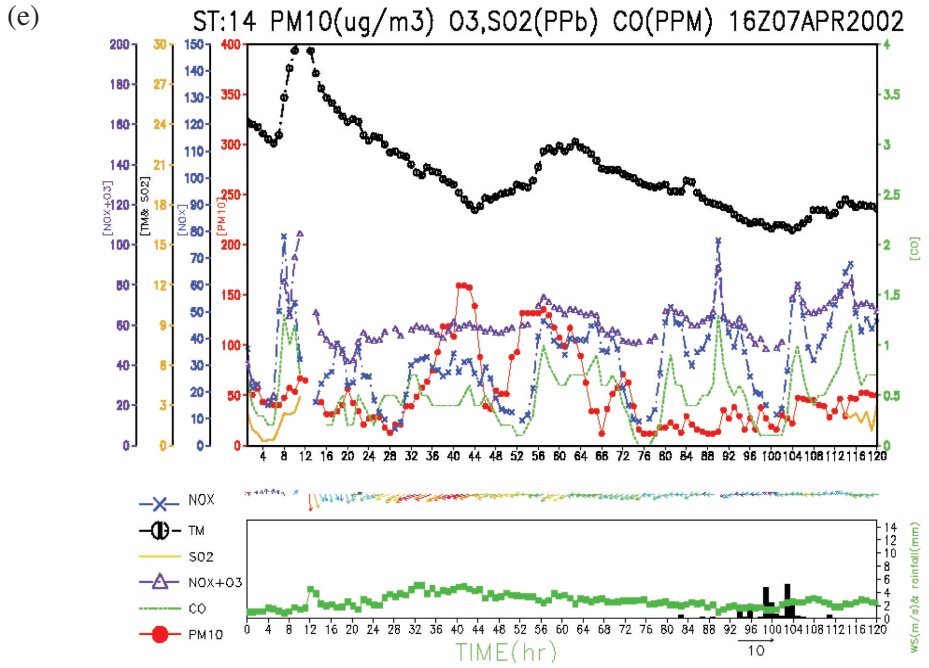


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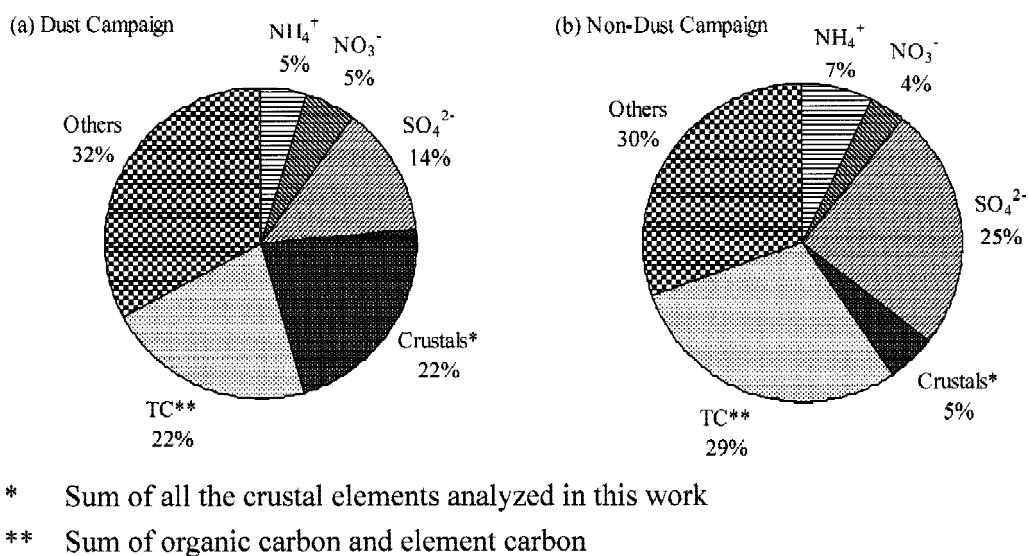


Fig. 5. Average chemical compositions of aerosol samples collected during (a) the dust episodes and (b) the non-dust experiment period.

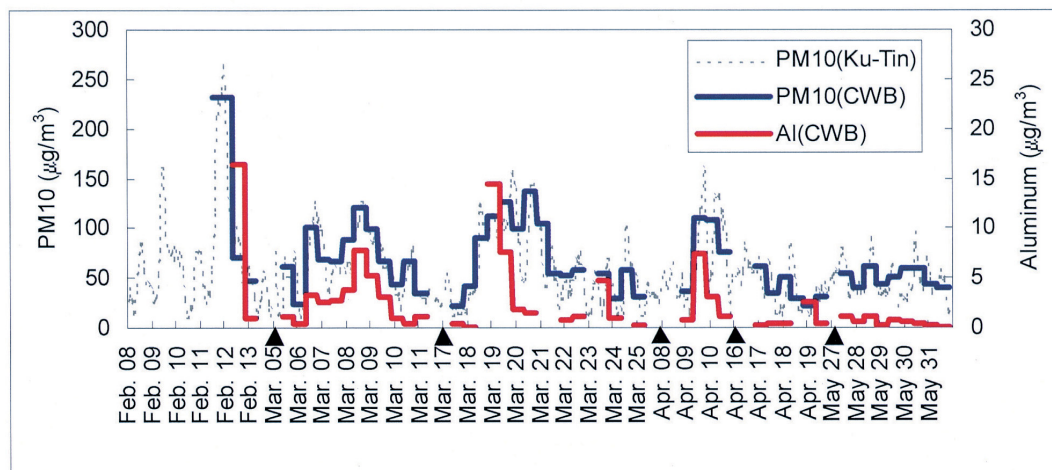


Fig. 6. Time series for the PM₁₀ and aluminum concentrations at CWB, Taipei over the field campaign. The hourly PM₁₀ concentration measured at EPA's Ku-Tin station is also plotted for comparison. The black triangles indicate the break points on the time axis.

elements in the aerosols confirmed the suspected cases on Mar. 8 and Mar. 23, whereas the low aluminum content showed that the Asian dust contribution to Taipei's aerosols was low on Apr. 10 and Apr. 18. However, the high PM_{10} episode on Feb. 9 remained a suspected case, because we do not have aerosol composition measurements to confirm it as a dust event.

In summary, five Asian dust episodes and one suspected case were identified according to the general meteorological conditions, time series pattern of air pollutant concentrations, and the abundance of aluminum in the aerosols. Unfortunately, our intermittent aerosol composition measurements left the origins of some high PM_{10} episodes uncertain. Table 1 lists the periods of respective identified dust episodes in Taipei in the spring of 2002. The maximum hourly PM_{10} concentrations at the Wan-Li and Ku-Tin stations are also listed. Note that the features of weak dust events could be masked by local pollution in the downtown area, and therefore, we cannot rule out the possibility that some weak cases occurred beyond the periods listed here.

3.2 Asian Dust Contributions to the Local Aerosol Concentrations

After establishing the dust event periods, we tried to estimate the contribution of Asian dust to the aerosol burden, which is important for a quantitative assessment of the environmental impact. To address this issue, a local pollution tracer was needed. The first characteristic of a good tracer is a robust correlation with PM_{10} in the local pollution air mass. With this feature, the tracer can be used to estimate local contribution to the ambient aerosols during a dust event. Figures 7a, b and c show the correlations between PM_{10} and the gaseous pollutants (NO_x , CO, and SO_2) in their monthly average concentrations at Ku-Tin in 2002. PM_{10} correlates strongly with NO_x , moderately with CO, and weakly with SO_2 . Good correlations suggest the similar source processes between the pollutants: PM_{10} , NO_x , and CO come mainly from vehicular exhaust emissions in Taipei, whereas SO_2 comes mostly from industrial sources (e.g., power plants). Despite the emission sources, the atmospheric lifetime of a pollutant can affect its temporal variation pattern and, consequently, its correlation with other species. The lifetime of NO_x is comparable to that of PM_{10} , while CO can survive longer in the troposphere. Hence, NO_x is expected to track the variation in PM_{10} more closely and with a better correlation than CO. The second characteristic that a good tracer for local pollution must have is a relatively low mixing ratio in long-range transported air masses. If the dust storm air masses originate in remote clean regions, they should not contain high levels of urban pollutants. When the air parcels pass through Northern and Eastern China, they may pick up some air pollutants via vertical mixing in the boundary layer and then carry the pollutants together with the dust. Among the air pollutants regularly monitored at the TAQMN stations, NO_x is the most reactive species with a lifetime of only around 1 day in urban areas (Seinfeld and Pandis 1998). Thus, the mixing ratio of NO_x in aged air masses should be significantly lower than that in urban areas. This expectation is consistent with the observations shown in Fig. 3: The mixing ratio of NO_x remained at a level of only a few ppb during the periods with strong and prevailing northeasters at Wan-Li. In addition to coming from a clean area, heterogeneous reactions between the NO_x and the alkali dust particles can further reduce the mixing ratios of NO_x in the air parcels. It has been proven that nitrate can be formed via heterogeneous reac-

Table 1. Periods and particulate measures for identified Asian dust episodes in Taipei.

Episode	Event Period ^{(a), (b)} (Starting Time/Date ~ Ending Time/Date)	Peak ^(c) (Time/Date)	Max. Hourly PM ₁₀ (µg/m ³)	
			Wan-Li	Ku-Tin
Confirmed episode				
C1	9:00/Feb. 11 ^(d) ~ 19:00/Feb. 12	23:00/Feb. 11	315	264
C2	6:00/Mar. 6 ~ 5:00/Mar. 10	16:00/Mar. 8	136	128
C3	4:00/Mar. 18 ~ 6:00/Mar. 20	12:00/Mar. 18	156	125
C4	1:00/Mar. 23 ~ 3:00/Mar. 24	19:00/Mar. 23	127	71
C5	3:00/Apr. 9 ~ 22:00/Apr. 9	17:00/Apr. 9	216	159
Suspected episode				
S1	1:00/Feb. 9 ~ 10:00/Feb. 10	10:00/Feb. 9	200	161

- (a) The starting point is defined by the time PM₁₀ begins to continuously increase to the PM₁₀ peak during a dust episode, confirmed by the abundance of aluminum in the aerosols and from the air quality inspection.
- (b) The ending point is defined using the time PM₁₀ stops decreasing from the peak and both the air quality inspection and aluminum abundance show that the episode has passed.
- (c) The peak point is defined at the time both PM₁₀ and the aluminum concentrations reach their maximum.
- (d) Because the aerosol sampling was started at 1200LST, Feb. 11, the starting time for this episode was determined solely using the results of time series analysis of air quality data.

tions between NO_x and mineral particles (Mamane and Gottlieb 1989; Zhang et al. 2003). Consequently, using NO_x as the local pollution tracer during Asian dust episodes was justified.

Figure 8 shows the variations in the monthly average concentrations for PM₁₀ and NO_x at the Ku-Tin station in 2002. The consistency between PM₁₀ and NO_x is quite obvious. With this fact in mind, it is accepted that a temporary source must be in effect if the correlation between PM₁₀ and NO_x deviates far from the long-term track when viewed over a short

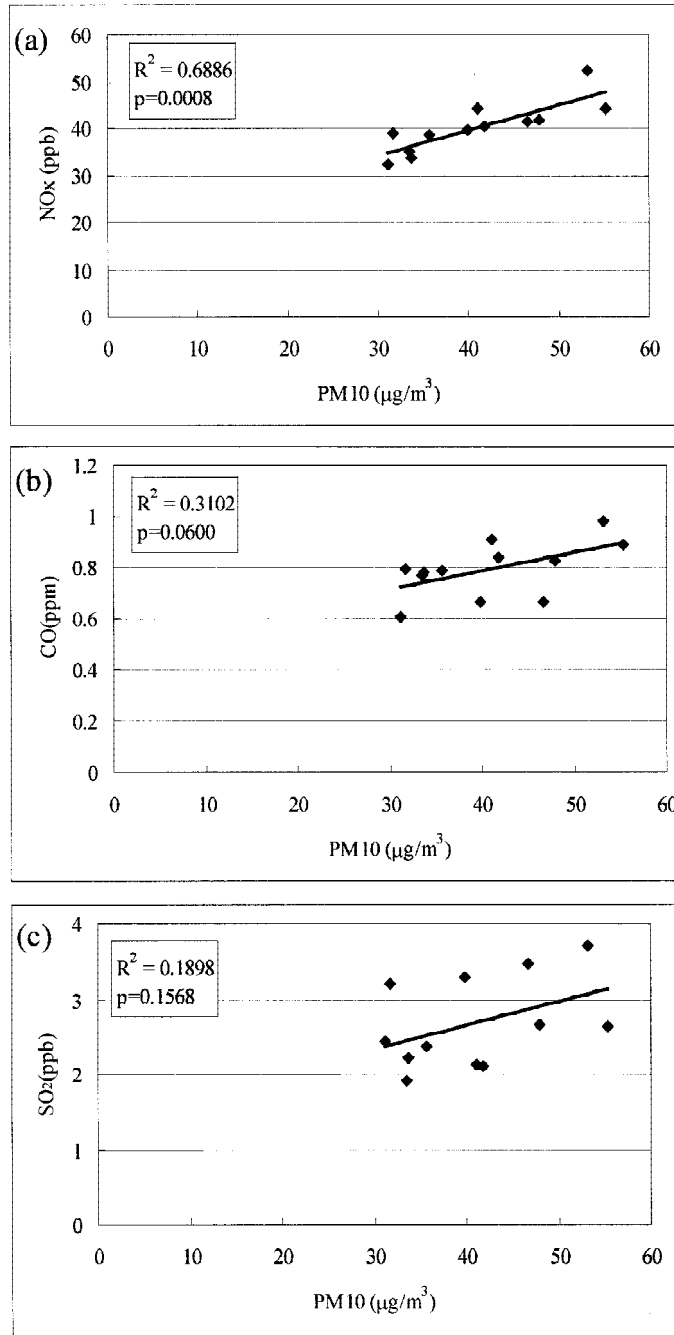


Fig. 7. Correlations between the PM₁₀ concentration and the mixing ratios of critical gaseous pollutants monitored at the Ku-Tin station in 2002: (a) PM₁₀ vs. NO_x; (b) PM₁₀ vs. CO; (c) PM₁₀ vs. SO₂.

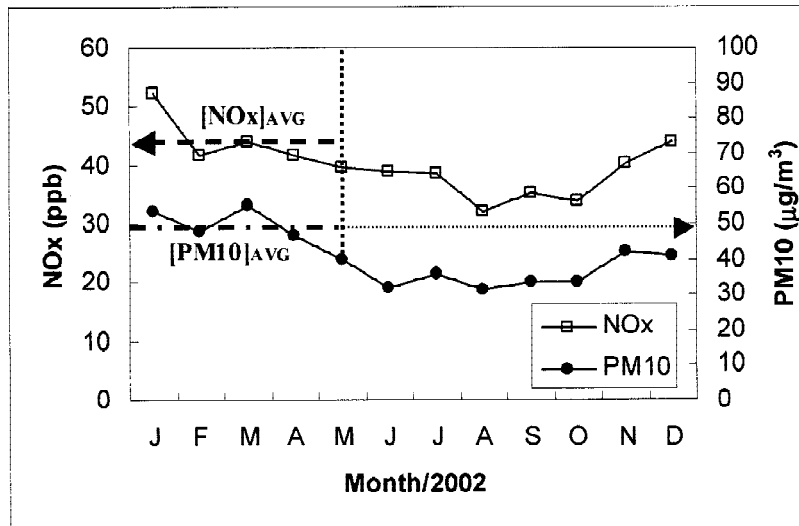


Fig. 8. Variations in monthly average PM_{10} and NO_x concentrations at the Ku-Tin station in 2002. The average concentrations over the first five months were taken as the basis for estimating the local PM_{10} contribution.

period. The time series plots in Fig. 3 clearly show that the NO_x concentration decreased to a very low and steady level after a frontal passage, whereas PM_{10} increased sharply due to the presence of dust in the same period. To quantify the temporary source contribution to PM_{10} , we defined “ PM_{10} Anomaly” and “Anomaly Ratio” based on the long-term correlation between PM_{10} and NO_x as follows:

$$PM_{10} \text{ Anomaly} = [PM_{10}] - [PM_{10}]_{AVG} \times \left\{ \frac{[NO_x] - [NO_x]_{Wan-Li}}{[NO_x]_{AVG}} \right\}, \quad (1)$$

and

$$\text{Anomaly Ratio} = PM_{10} \text{ Anomaly} / [PM_{10}], \quad (2)$$

where $[PM_{10}]$ and $[NO_x]$ are the PM_{10} and NO_x concentrations in Taipei, respectively. $[NO_x]_{Wan-Li}$ is the simultaneous NO_x concentration at Wan-Li, assumed to be the NO_x concentration brought by the air parcel from the Asian continent. $[PM_{10}]_{AVG}$ and $[NO_x]_{AVG}$ are the average PM_{10} and NO_x concentrations in Taipei over the spring-months in 2002, respectively.

Table 2 summarizes the daily PM_{10} Anomaly Ratio, calculated from the air quality data from Ku-Tin station, during each previously identified dust event. The Anomaly Ratio reached a high level of 86.8% on Feb. 11, the most intensive dust case in 2002. The long-range trans-

port of Asian dust is surely not the only factor resulting in the PM_{10} Anomaly. In practice, a high PM_{10} Anomaly can also be found on a significant number of days besides the dust periods. Nevertheless, given that dust transport is the strongest factor affecting the PM_{10} concentration during the dust event periods, it is reasonable to attribute the PM_{10} Anomaly to Asian dust and assume the Anomaly Ratio as a maximum estimate for the contribution from Asian dust transport to the aerosol burden on the dust days. For the other three significant dust events, the estimated Asian dust contributions were 75.8, 62.5, and 62.5% on Mar. 8, Mar. 18, and Apr. 9, respectively. The air quality impacts due to weak dust events were usually considered negli-

Table 2. Asian dust contributions to the local aerosol burden in Taipei during the identified Asian dust episodes.

Event ID	Date	PM_{10} ($\mu\text{g}/\text{m}^3$) ^(a)	NO_x (ppb) ^(a)	Anomaly Ratio of PM_{10} ^(b)
Confirmed episode				
C1	Feb. 11	123	16.8	0.868
	Feb. 12	95	34.2	0.675
C2	Mar. 6	71	30.0	0.574
	Mar. 7	58	30.1	0.513
	Mar. 8	95	28.8	0.758
	Mar. 9	71	25.7	0.718
C3	Mar. 18	78	28.8	0.625
	Mar. 19	115	70.8	0.445
C4	Mar. 23	40	26.7	0.352
C5	Apr. 9	72	24.2	0.625
Suspected episode				
S1	Feb. 9	79	28.2	0.672
	Feb. 10	51	33.5	0.336

(a) Daily average monitored at EPA's Ku-Tin station.

(b) The PM_{10} anomaly is attributed to Asian dust during the given dust event periods.

gible in relevant studies because of the relatively low PM_{10} levels on those days. However, the results from this study show some different aspects. On Mar. 23, for instance, the daily average PM_{10} concentration was only around $40 \mu\text{g m}^{-3}$, whereas the results of our analysis show that the Asian dust contribution to PM_{10} was noticeable. It reached 35.2%, a level of about $14 \mu\text{g m}^{-3}$ in terms of the PM_{10} concentration. This is consistent with the relatively high aluminum content in the aerosol samples collected at that time (see Fig. 6). Thus, according to the results described above, long-range transport dust has important implications for local air quality during a dust episode, even if the dust event is not intense and overall PM_{10} levels are not high the contribution from Asian transport dust can still be significant.

4. CONCLUSIONS

Asian dust episodes identified using time series analysis of air quality data was compared with those identified using aerosol compositions. The observations show that high levels of aluminum in the ambient aerosols are usually associated with the suspected Asian-dust episodes identified by air quality inspection. The consistent results from two independent methods confirmed five Asian dust episodes in Taipei in the spring of 2002. Furthermore, we estimated the contribution of long-range transported aerosols to the ambient PM_{10} using a simplified method based on the observed correlation between NO_x and PM_{10} in Taipei. Our results showed that the contribution of long-range transported aerosols to the local aerosol burden reached as high as 86.8% in the most intensive dust event that occurred on Feb. 11, 2002. For the weakest event on Mar. 23, 2002, the contribution was still at a noticeable level of 35%, even it is not so obvious in terms of the PM_{10} concentration. With the fact that dust is the predominate aerosol species in the long-range transported air parcels during a dust episode, the PM_{10} Anomaly Ratio reported above was suggested as the maximal estimate of the Asian dust contribution to the local aerosol burden on a "dust day". Many more scientific insights regarding the long-range transport of natural material and anthropogenic pollutants can be obtained from extreme dust cases, although long-range Asian dust transport is a natural phenomenon, increasing industrial production over Eastern China undoubtedly necessitates more investigations into this issue.

Acknowledgments We are very grateful to the Reviewers for their constructive comments. This work was supported by Academia Sinica theme project "Particulate Matter and its Environmental Impacts in Taiwan", National Science Council grant NSC-92-2111-M-001-002 and Environment Protection Agency under contract EPA-91-FA11-03-A062.

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