Asian Dust Storms and Their Impact on the Air Quality of Taiwan

Shaw Chen Liu*[1 2] and Chein-Jung Shiu[3]

1 Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, ROC

2 Also at Department of Atmospheric Sciences, National Central University, Chungli, Taoyuan, Taiwan, ROC

3 Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan, ROC

Measurements of aerosols (PM10) and other air pollutants at stations of the air quality monitoring network of Taiwan Environmental Protection Administration (EPA) from 1993 to 2000 are analyzed to evaluate the impact of Asian dust storm events on the air quality of Taiwan. Enhancements of PM10 at Yangming mountain station in northern Taiwan as well as coastal stations to the north and northeast turn out to be the key indicators in identifying unambiguously the major Asian dust storm events and to estimate the impact of these events on the PM10 over Taiwan. Our analysis shows that the major increases of PM10 at Yangming station occur in March, April, and May. They are clearly associated with the Asian dust storm events. On a yearly basis, the impact ranges from about 3% in southwestern cities to about 12% for Yangming station. On the monthly basis, the enhancements can be as large as 150% for a clean station such as Hengchun hear the southern tip of Taiwan. Although the major component of the observed PM10 enhancements is mineral dust, we estimate that sulfate and nitrate ions contribute to about one quarter of the enhancements. The corresponding enhancements for other air pollutants (i.e. CO, O_3, NO_2, and SO_2) can be identified only occasionally because of high ambient values, large variability in concentrations, and other reasons.

1. Introduction

Asian dust storm events over northern China have a long history. They were recorded in the literature as early as the fourth century (Zhang, 1984). The events transport a large amount of dust over long distance and can reach almost the entire northern Pacific Ocean. Their large spatial impact in the spring can be readily detected from satellites (e.g. Husar et al., 1997). Ground-based samplings and optical (lidar in particular) observations as well as modeling investigations have rendered vast amount of information on the genesis, transport, distribution, and other physical and chemical properties of the dust storm events (Rex et al., 1969; Mizohata and Mamuro, 1978; Duce et al., 1980; Zhou et al., 1981; Wang et al., 1982; Iwasaka et al., 1983; Uematsu et al., 1983; Chen and Chen, 1987; Prospero et al., 1989; Merrill et al., 1989; Bodhaine, 1995; Murayama et al., 1998). These investigators have demonstrated that the genesis of the dust storm events includes a combination of factors: dry soil conditions near the end of the dry season, strong surface winds, and the unstable or turbulence atmospheric conditions in the spring. These factors are most prevalent in the spring months, namely March, April, and May. Obviously, transport of dust to high altitudes is essential in the long-range transport of Asian dust storms (Chen and Chen, 1987). Some of these factors also lead to long-range transport of other air

*Corresponding author:
Tel.: +886-2-2783-9910 ext. 407
Fax: +886-2-2788-0332
E-mail address: shawliu@earth.sinica.edu.tw

pollutants from Asian Continent and Pacific Rim countries to the Pacific Ocean (e.g. Hoell et al., 1997).

Chen and Chen (1987) made a comprehensive investigation of the large-scale features of Asian dust storm events. They found that strong surface winds and dry lower tropospheric conditions associated with a cold front passage or strong anticyclone at a proper location over the Asian Continent in the spring are the necessary conditions for dust storm genesis. More importantly, they found that the dust storm events affecting Taiwan tend to be those dust storms reaching the middle troposphere, while those storms reaching significantly higher altitude are usually carried eastward toward the mid- and eastern Pacific, including Hawaii and even the North American continent. A recent lidar observation of a major dust storm (03/05/2001) at the National Central University in Chungli, Taiwan found that the dust layer topped at about 4 km (J-B. Nee, private communication, 2001), consistent with the finding of Chen and Chen (1987).

In the following, we use measurements of aerosols with diameters less than 10 μm (i.e. PM10) and other air pollutants made at stations of the air quality monitoring network of Taiwan EPA from 1993 to 2000 to identify the Asian dust storm events and to evaluate the impact of these events on the air quality of Taiwan. Because Asian dust storm events encountered in Taiwan are associated with northeasterly winds of the winter monsoon, we expect that the coastal stations along the north and northeast of Taiwan would show the largest impacts of the dust storm events. This indeed turns out to be the case. In particular, enhancements of PM10 at Yangming mountain station (826 m altitude) in northern Taiwan are extremely valuable. They can be used to unambiguously identify the major Asian dust storm events over Taiwan. This is done in the following section. In addition, the enhancements identified at Yangming station as well as at coastal stations in the north and northeast of Taiwan are used as a guide for evaluating the impacts of Asian dust storm events on other stations, particularly for stations in southwestern Taiwan that otherwise would be difficult to evaluate because of high ambient values caused by large local sources of PM10 and great seasonal variability as a result of large seasonal change in mixing height.

2. Data and Analysis

Monthly averages of measurements of PM10 and other air pollutants made at stations of the air quality monitoring network of Taiwan EPA from September 1993 to February 2001 are used as the primary source of data in our analysis. As stated above, we start with the Yangming station to identify the major Asian dust storm/Asian continental outflow events over Taiwan. This is illustrated in Figure 1, which shows unambiguously the spring enhancements/spikes of PM10 for all eight years with complete seasonal cycles. The spikes are easiest to identify at this station because of two factors: one is that the station has very low ambient concentrations of PM10 as it is located at a relatively high altitude in a national park away from direct pollution sources, the other is that the station is in northern Taiwan, i.e. upwind for encountering dust storms sweeping southwestward by the northeasterly winds of the winter monsoon. Most of the peaks occur in April, in some years the peaks occur in March or May. This is consistent with previous investigations of the long-range transport of Asian dust storms to the Pacific Ocean (e.g. Duce et al., 1980; Prospero et al., 1989). Beside the eight enhancements in the spring, there are only three other prominent enhancements, i.e. the ones in Nov/93, Feb/94, and Sept/95. We believe that they are not Asian dust storm events because there are no concurrent enhancements at coastal stations in the north and northeast of Taiwan (e.g. Ilan and

Keelung). Their origins have not been determined except that the Feb. 1994 spike could be one of those secondary spikes (in average only about 15% of the sizes of spring spikes) occurring consistently in January and/or February just before the onset of Asian dust storm events. The secondary spikes could be due to a minor continental outflow process. On the other hand, they could also be a result of near surface inversion layers that frequently form in the winter under clear sky conditions. These inversion layers trap effectively air pollutants emitted near the surface and are known to be responsible for winter maximum concentrations of air pollutants in many industrialized areas. More discussion on this point will be made later.

Figures 2 and 3 depict the corresponding plots for Keelung (Renai) and Ilan. With the guidance from the Yangming station, the enhancements due to Asian dust storm events can be readily picked out. On the other hand, one can notice that there are more and larger secondary enhancements in Keelung (Renai) and Ilan, making the identification of the Asian dust storm events significantly harder, especially if there were no guidance from the Yangming station. Other stations along the east coast also have similar features.

As expected, the ambient concentrations of PM10 are substantially greater at Keelung (Renai) and Ilan stations than that at Yangming station. The ambient values are even greater for urban stations as well as rural stations in the western plain (see Figures 4, 5, 6, and 7 for Taipei (Sungshan), Taichung (Jungming), Kaohsiung (Nantz), and Meinon, respectively). The rural stations in southern and central Taiwan of which Meinon is a representative station suffer high levels of PM10 and many other air pollutants because of emissions from wide spread factories and traffics. Furthermore, the relatively long residence time of PM10 (several days) allows effective transport of PM10 over the entire western plain of Taiwan. As a result, there is little difference in the ambient levels of PM10 between rural and urban stations. The large ambient concentrations have two effects on our analysis. One is to make the identification of the Asian dust storm events more difficult, particularly for stations with winter maximums (Figures 6 and 7, and to a lesser extent Figure 5), which are a result of frequent near surface inversion layers as discussed earlier. This type of stations are mostly located in southern Taiwan, and to a lesser extent in central Taiwan, where clear sky conditions usually prevail in the winter. Because the spring Asian dust storm events tend to occur at the decreasing side of the winter peaks of PM10, they usually appear as minor peaks and sometimes even as small shoulders. This phenomenon is most obvious in southern Taiwan (e.g. Kaohsiung (Nantz) and Meinon) where clear sky conditions occur consistently in the winter. The other effect has to do with the secondary spikes mentioned earlier during the discussion of the three northern stations. Their sizes obviously increase with the ambient concentrations. Furthermore, they become larger at the stations with larger winter maximums and practically coincide with the winter peaks. In fact, at Kaohsiung (Nantz) and Meinon the "secondary" spikes are greater than those of Asian dust storm events, a drastic contrast to the situation at the Yangming station. Given the fact that the winter enhancements of PM10 and other primary pollutants in the western plain is a result of wintertime near surface atmospheric inversions, we have to conclude that the major cause of the secondary spikes is the winter atmospheric inversion also. Thus, the secondary spikes are not due to any minor continental outflow process mentioned above. In other words, other than the Asian dust storm events there is no significant secondary Asian continental outflow of pollutants reaching Taiwan.

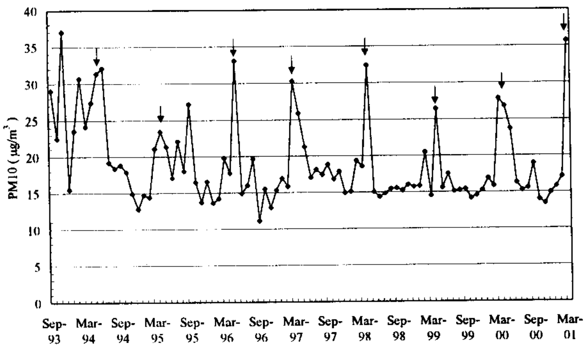

Figure 1 Monthly average concentrations of PM10 at Yangming station. The arrows indicate the months in which Asian dust storms occurred.

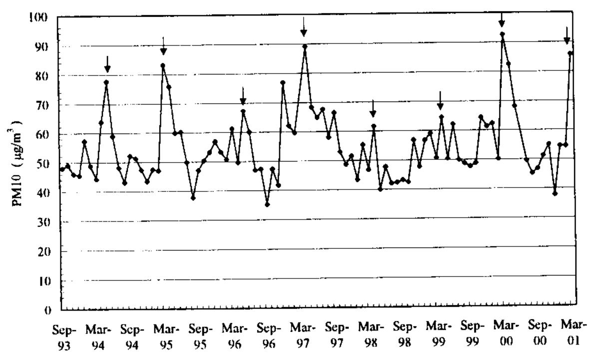

Figure 2 As Fig. 1 except for the case of the Keelung (Renai) station.

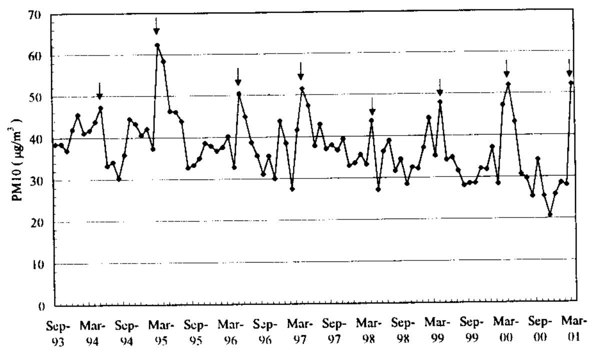

Figure 3 Same as Fig. 1 except for the case of the Ilan station.

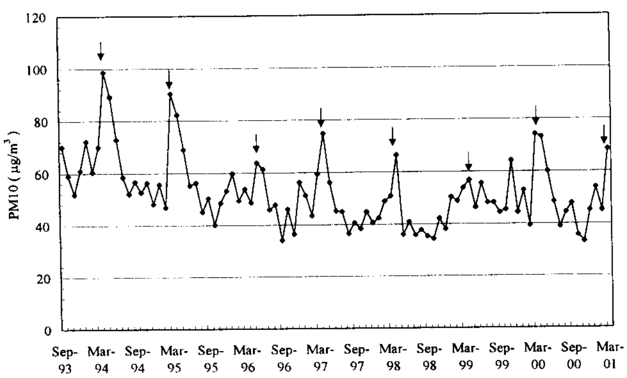

Figure 4 As Fig. 1 except in the case of the Taipei (Sungshan) station.

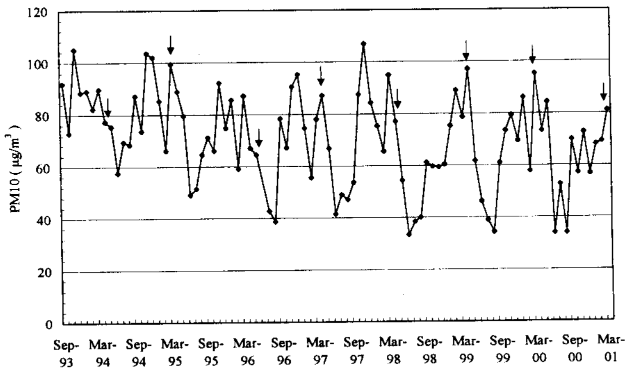

Figure 5 As Fig. 1 except in the case of the Taichung (Jungming) station

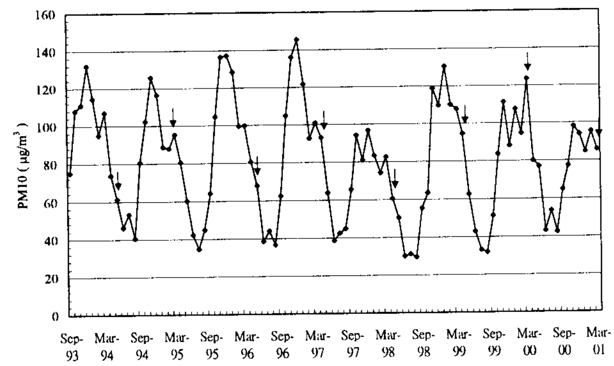

Figure 6 As Fig. 1 except in the case of the Kaohsiung (Nantz) station.

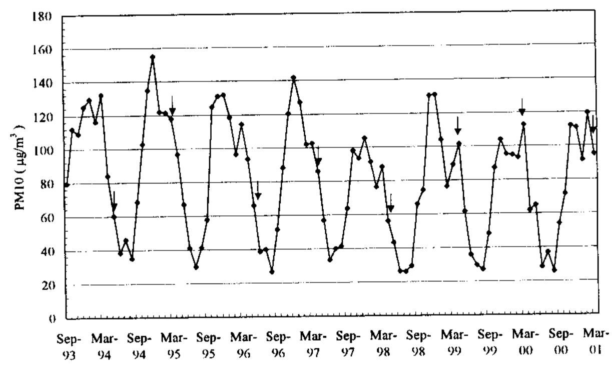

Figure 7 As Fig. 1 except in the case of the Meinon station.

3. Impact on air quality

In principle, the impact of the Asian dust storm events on the PM10 concentration at each of the stations in Taiwan can be estimated by a straightforward integration of all the spikes/ enhancements due to the events (i.e. the increases above the base/ambient value). The integral can then be divided by the average of ambient PM10 value (i.e. values after removing the spikes) to obtain the impact. In practice, the method can be carried out easily for stations like Yangming for which the spikes can be identified unambiguously. This is done for the Yangming station and the result is shown in Table 1. On the yearly basis, the impact averaged over eight years is about 12%, i.e. aerosols from the Asian dust storm events add 12% to the total PM10 loading at the Yangming station. In the month of April, the impact can be as large as 120%, i.e. more than double the ambient concentration. For stations along the north and east coasts (Keelung (Renai), Ilan, Haulein, and Taitung), with the guidance of Yangming station the method can still be performed without introducing too much ambiguity. The results are again shown in Table 1.

For other stations, especially for the stations in the southwestern plain, a quantitative determination of the spikes is difficult because of the problems mentioned above. As an alternative, we use the Asian dust storm events of Ilan station as the surrogate. This probably is an overestimate because Ilan station is at the upwind side of the winter monsoon, while the stations in the western side of Taiwan are protected by the Central Mountain range which has a 2.5 km average altitude. On the other hand, the spikes of Ilan station have one of the smaller average values among the northeast and east coast stations. Table 1 lists the degrees of impact calculated this way for a selection of representative stations west of the Central Mountain range, including Taipei. On the yearly basis, the impact ranges from about 3% in southwestern cities (and the rural station Meinon) to about 8% for Hengchun. On the monthly basis, the enhancements can be as large as 150% for a clean station such as Hengchun. This is expected because of the low ambient value in Hengchun.

There is little doubt that the major component of the observed PM10 enhancements during the Asian dust storm event is mineral dust. Mineral dust is natural and thus should not be considered as a serious health hazard. However, elevated levels of sulfate and nitrate ions have also been observed consistently during the Asian dust storm events (Duce et al., 1980; Uematsu et al., 1983; Prospero and Savoie, 1989). Most of the non-sea-salt sulfate (NSS-sulfate) and nitrate ions have been shown to be anthropogenic in origin (Prospero and Savoie, 1989; Arimoto et al., 1997). As a matter of fact, we noticed that the ratio of NSS-sulfate to nitrate (about 1.5) measured during the Asian dust storm events in the above studies was fairly consistent with the emission ratio of sulfate to nitrate over Asia. This ratio and the ratio between nitrate and mineral dust (about 0.1) measured by Prospero and Savoie (1989) can be used to calculate fractions of NSS-sulfate (15%) and nitrate (10%) in the PM10 enhancements during the Asian dust storm events. These ratios imply that NSS-sulfate and nitrate ions contribute to about one quarter (i.e. 15% + 10%) of the enhancements. This is highly significant to the air quality of Taiwan on the monthly basis. On the event basis, the enhancement of NSS-sulfate and nitrate ions can be a serious health hazard.

Table 1 Impacts of Asian dust storms at some representative stations

Station	Average Yearly Impact	Maximum Monthly Impact
Yangming	12%	120%
Keelung (Renai)	8%	90%
Ilan	7%	85%
Taipei (Sungshan)	9%	90%
Taichung (Jungming)	6%	50%
Kaohsiung (Nantz)	3%	40%
Meinon	3%	25%
Hualien	8%	100%
Taitung	7%	80%
Hengchun	8%	150%

The corresponding enhancements for other species (CO, O_3, NO_2, and SO_2) during the Asian dust storm events can be identified only occasionally. As a result, their impact on the air quality of Taiwan cannot be evaluated without additional information. There is no clear single reason that can explain why their enhancements could not be consistently detected. For CO, relatively poor instrument sensitivity is an obvious reason. Meanwhile, O_3 enhancements are probably masked by its large seasonal variation that also has its maximum in the spring. For NO_2 and SO_2, high ambient values due to large local sources, short photochemical lifetimes and/or large variability in concentrations are all likely the contributing factors for failing to detect their enhancements.

4. Conclusions

Our analysis of the measurements of PM10 and other air pollutants at the stations of air quality monitoring network of Taiwan EPA from September 1993 to February 2001 suggests that Asian dust storm events have a significant impact on the air quality of Taiwan. The analysis shows that the major increases of PM10 due to Asian dust storm events occur in March, April, and May. This is consistent with previous studies of long-range transport of Asian dust storms to the Pacific Ocean. On the yearly basis, we estimate that the impact ranges from about 3% in southwestern cities to about 12% for the Yangming station. On the monthly basis, the enhancements can be as large as 150% for a clean station such as Hengchun because of its low ambient concentration. On the event basis, the impact is even greater. Although the major component of observed PM10 enhancements is mineral dust, we estimate that sulfate and nitrate ions contribute to about one quarter of the enhancements. On the event basis, the enhancement of NSS-sulfate and nitrate ions can be a serious health hazard for the people in Taiwan. The corresponding enhancements for other species (CO, O_3, NO_2, and SO_2) can be identified only occasionally because of high ambient values, large variability in concentrations, and other factors.

5. Remaining Issues and Future Studies

Why the Asian continental outflow of air pollutants reaching Taiwan seems to be limited to the period of Asian dust storm events, i.e. the spring? The period with the strongest and most frequent northeasterly winds of the winter monsoon is in the months of December, January, and February. In this period there must be substantial outflow of air pollutants from the Asian continent as well as the Pacific Rim countries to the Pacific Ocean whenever cold fronts sweep out of northern China, at least in the boundary layer. But there is no significant enhancement of air pollutants due to Asian continental outflow over Taiwan in the winter (assuming the secondary spikes are local events as discussed above). One likely explanation is that most of the air pollutants carried in the Asian continental outflow are trapped in the boundary layer (i.e. lack of vertical transport) and thus efficiently removed by wet and dry deposition over the ocean before reaching Taiwan. This suggests that transport of air pollutants as well as dust from the surface layer to the middle and upper troposphere is a critical process in the long-range transport of trace species from the Asian continent.

We have noticed that the enhancements associated with the Asian dust storm events tend to increase with the ambient levels of PM10. The cause(s) is not clear. One possibility is that increased volume of dust particles enhances the condensation of gas phase pollutants such as HNO_3 and NH_3 on the dust (Cheng et al, 2001; Lee et al., 2001). In addition, the oxidation of SO_2 to sulfate may be enhanced by the dust particles. If these enhancements occur, it would be more difficult to distinguish the contribution of Asian dust storms to the observed PM10 in Taiwan from that of local sources.

There is a tendency for the enhancements to be greater over the western part (or downwind side) of Taiwan than the north and eastern part (upwind side). This probably requires that the concentration of dust increases with height and downward mixing on the lee side of the Central Mountain range. Lidar measurements by Prof. Jen-Bei Nee (private communication, 2001) did show a peak around 2 to 3 km.

Some of the questions and issues raised above obviously can be addressed by examining individual events of Asian dust storms recorded by the EPA air quality monitoring stations. We plan to make a careful study of those events. However, there is a severe limitation in regard to this type of study because the measurements made at the stations do not include some key parameters and chemical species. For example, the size distribution and chemical composition of aerosols are not measured. Furthermore, as the measurements at the stations are designed for monitoring purpose, they usually do not have enough precision to meet the stringent standard required in scientific research projects.

In order to make effective investigations of the impact of Asian dust storms on Taiwan's air quality, there is a great need to make reliable measurements of the composition of aerosols as a function of their size distribution. Measurements of other air pollutants also need to be improved. In addition, aircraft and lidar observations are essential in understanding the vertical transport and distributions of the dust storms and air pollutants. Finally, a well-designed experiment that incorporates modeling and field measurements of the key trace species and meteorological parameters from both aircraft and strategically placed ground stations is needed to give a definitive answer to the questions and issues raised in this study.

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