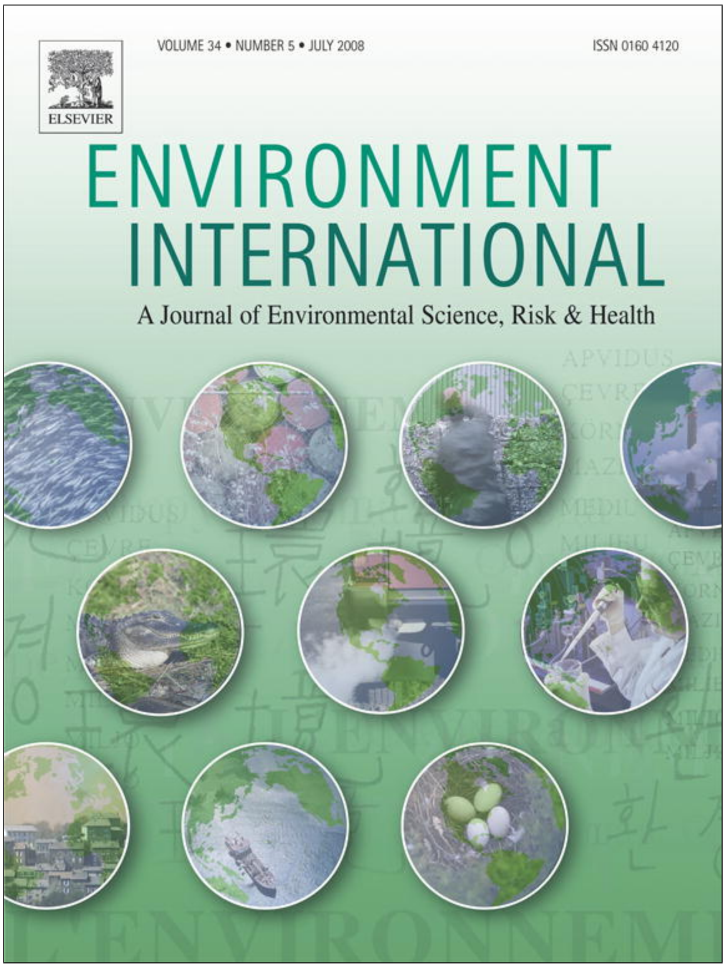

VOLUME 34 • NUMBER 5 • JULY 2008
ISSN 0160 4120
ELSEVIER
ENVIRONMENT INTERNATIONAL
A Journal of Environmental Science, Risk & Health

Available online at www.sciencedirect.com
ScienceDirect
Environment International 34 (2008) 635–647
ENVIRONMENT INTERNATIONAL
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Sudden high concentration of TSP affected by atmospheric boundary layer in Seoul metropolitan area during duststorm period

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Abstract

Hourly concentrations of TSP, PM_{10}, $PM_{2.5}$ near the surface at Seoul city were examined from March 20 to March 25, 2001 (duststorm event) in order to investigate the effect of a duststorm generated in China on the local aerosol concentration in Korea, The ratios of fine to coarse particles such as TSP to PM_{10}, TSP to $PM_{2.5}$ and PM_{10}–$PM_{2.5}$ to $PM_{2.5}$ showed that a great amount of dust transported from the origin of the duststorm was remarkable with a maximum ratio of 9.77 between TSP and $PM_{2.5}$. Back trajectories every 6 h showed the movement of dust particles in the lower atmosphere near 500 m to 1500 m (atmospheric boundary layer), which implied transport from Baotou in inner Mongolia of northern China to the direction of Seoul city in Korea and then the back trajectories passed near the southern border of Mongolia and Baotou through Zengzhou in the midlevels (3000 m) and low levels (500 m) of China, finally reaching Seoul city. So, the TSP concentration at Seoul city was partially influenced by the duststorm, under the prevailing westerly wind and the transported aerosols could influence high concentrations of pollutants of TSP, PM_{10} and $PM_{2.5}$ in Seoul. The sudden high concentrations of TSP and PM_{10} were found for a few hours, especially at 1500 to 1800 LST, March 22. At 1200 LST, before the passage of a cold front through the Korean peninsula, the convective boundary layer (CBL) near Seoul was not shallow, but at 1500 LST, under the frontal passage, the CBL was remarkably thinner (less than 300 m), due to the compression of the boundary layer by the intrusion of cold air. This resulted in the increase of the TSP concentration, even though the mixed layer above maintained almost the same depth. At 1800 LST shortly after the frontal passage, that is, near sunset, the nocturnal cooling of the ground caused air parcels to cool, thereby enhancing the shallower nocturnal surface inversion layer and producing the maximum concentration of TSP of 1388 $\mu g/m^3$ near Seoul city.

Keywords: TSP; PM_{10}; $PM_{2.5}$; Dust storm; Convective boundary layer; Frontal passage

1. Introduction

In the past ten years, dust storms termed ‘Asian Dust’, ‘Yellow Sand’ and ‘KOSA’ have frequently and periodically occurred under strong winds blowing topsoil in the arid area of northern China including the five provinces of Xinjiang, Inner-Mongolia, Ningxi, Shanxi, Gansu and Gobi desert in Mongolia (Chon, 1994; Xuan and Sokolik, 2002; Zhang and Arimoto, 1993). The resulting storms have transported a great amount of dust to eastern China, Korea, Japan, and recently even to the western coast of North America (David et al., 2001; Fei and Qing, 1998; Jungder, 1999; Lin, 2001; McKendry et al., 2001; Qian and Hu, 1997; Natsagdorj et al., 2002; Wang et al., 2000, 2003). A duststorm can remove several hundred thousand tons of sand and dust from dried or desert areas such as in western and northern China (Chung et al., 2001, 2003; Chung and Yoon, 1996; Middleton, 1986; Natsagdorj and Jugder, 1992).

The transported dust is not only significantly harmful to health, causing eye diseases, asthma and allergies, but also to the ecological environment, suppressing plant growth by blocking plant pores and disrupting photosynthesis. During the dust period or immediately after, the reduction of pasture and the delay of its growth for livestock occurred. Even roads were closed, those were covered with dust and sand. As the air turbidity increases with the occurrence of a duststorm, the

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doi:10.1016/j.envint.2007.12.023

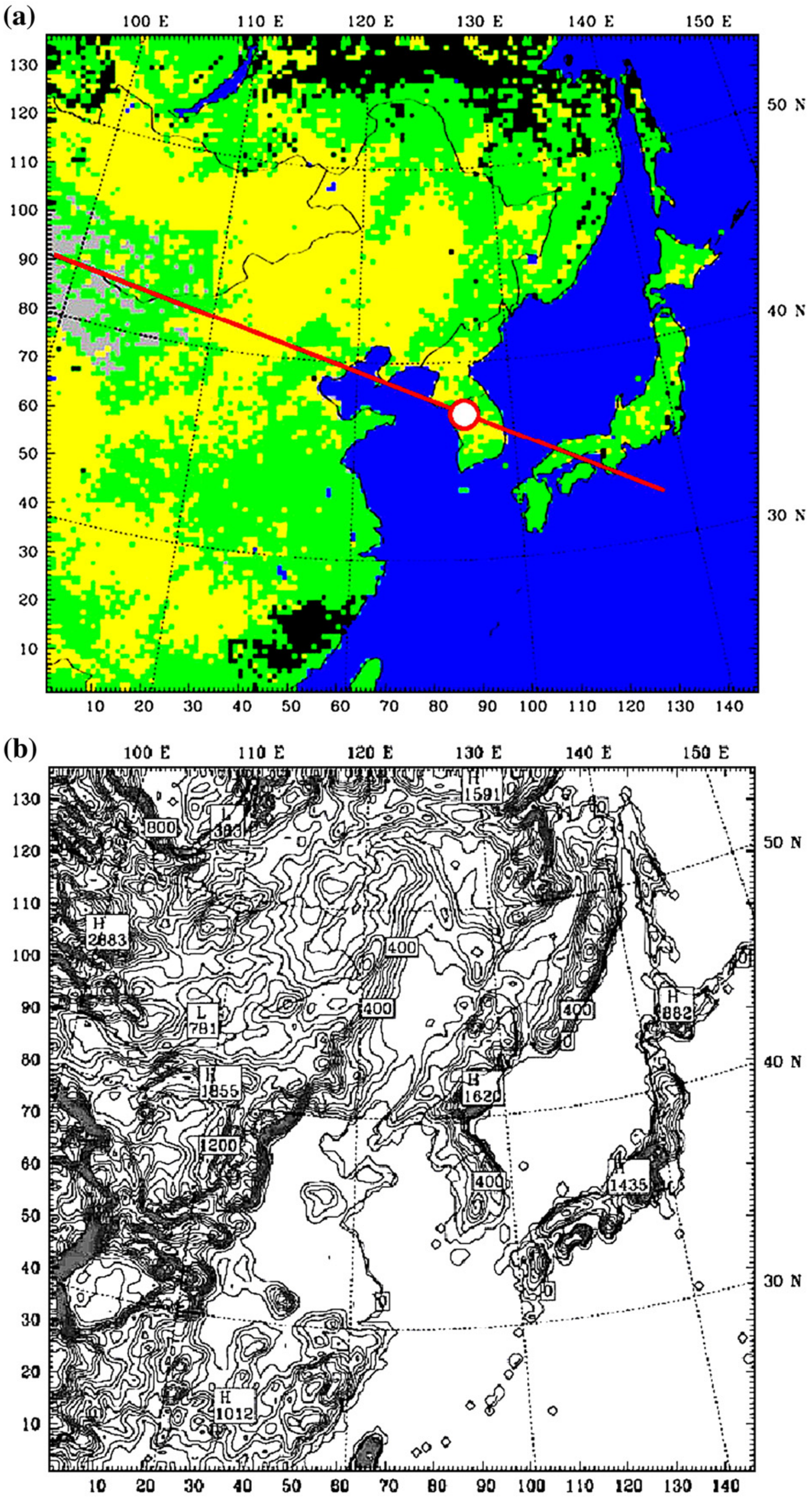

Fig. 1. (a) Land-use data and (b) topography for the coarse domain horizontal grid size 27 km for MM5 model. Circle denotes Seoul city district, Korea.

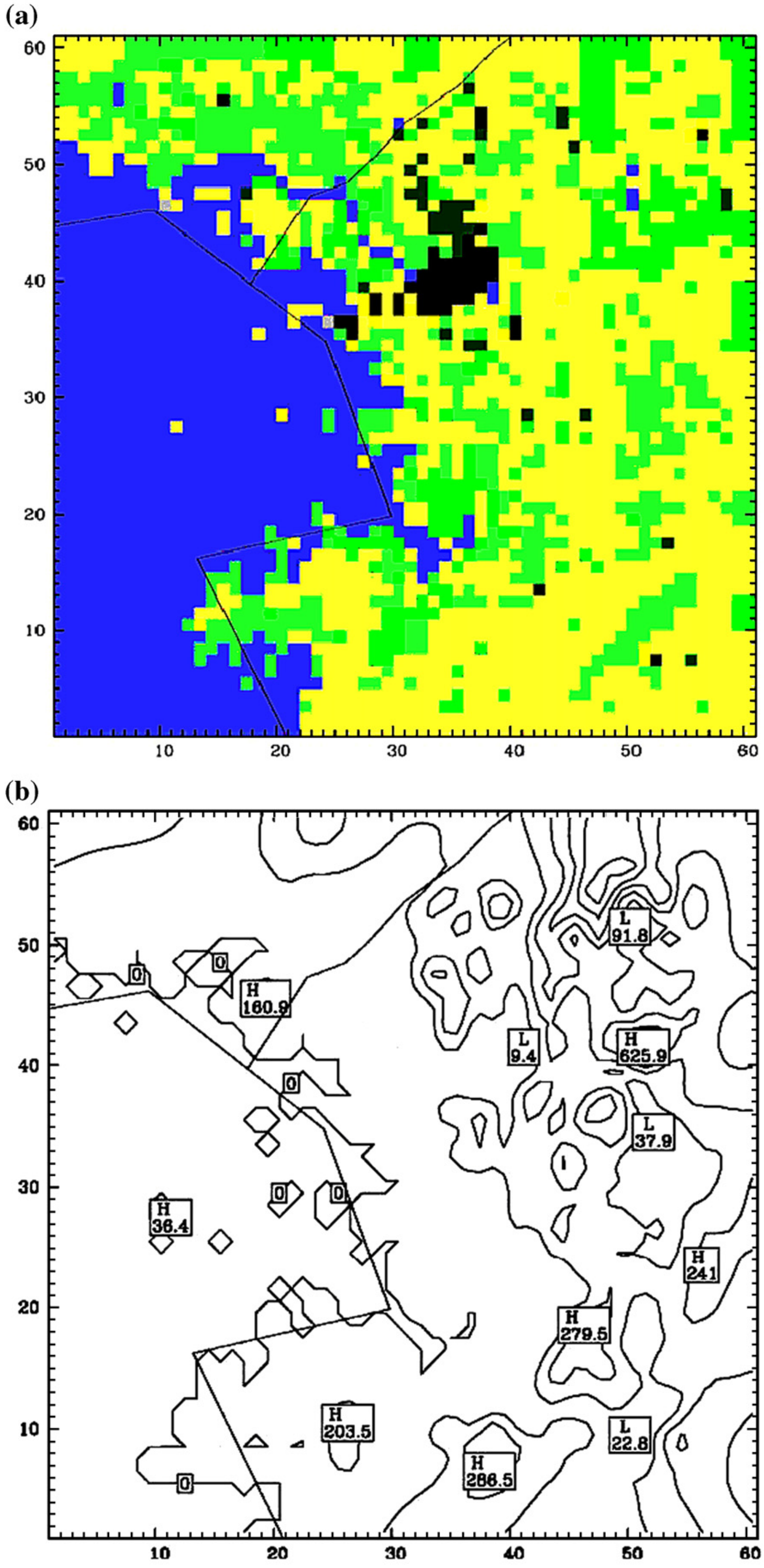

Fig. 2. (a) Land-use data and (b) topography for the fine-mesh domain of horizontal grid size 3 km for MM5 model including Seoul city. Major black part of the figure denotes Seoul metropolitan area.

amount of solar radiation reaching the ground reduces and the reduction of solar radiation can greatly influence climate over the Asian continent (Huebert et al., 2003; Jigjidsuren and Oyuntsetseg, 1998; Kai et al., 1988). The dust causes high concentrations of pollutants lasting several days, even up to one week with extremely high concentrations for a few hours when combined with locally emitted pollutants in dense population and industrial areas.

During the Asian Dust events in 2001 and 2002, dust particles generated from inner Mongolia of China could be transported to Seoul district under a westerly wind speed of about 20 m/s and influenced the chemical components of particulate matters and the number size distribution of aerosol in China and Korea (Carmichael et al., 1997; Chun et al., 2001; Gao and Anderson, 2001; Kim and Kim, 2003; Kim et al., 2001, 2003). Chon (1994) and Zhang and Zhong (1985) estimated that about half the total quantity of particulate matter is deposited near the source area (30%) and re-distributed on a local scale (20%) and the other half is subject to long-range transport from the source region toward other area. This transported dust can serve as one of the major particulate matter sources over the whole of Asia and the Pacific Ocean.

In order to investigate the aerosol cycle, the Aerosol Characterization Experiment in Asia (ACE-ASIA) was carried out by several participating scientific groups in many east Asia locations of Korea, China and Japan in 2001 (Carmichael et al., 1997; Chung et al., 2003; Xiao et al., 1997). During the period of ACE-Asia, major measurement experiments and research were performed at the Gosan Supersite of Jeju island in southern Korea. At other sites, except for Gosan, several scientists personally carried out the measurement of aerosols and of those sites, aerosol data for Seoul city were acquired for use in this study (Kim et al., 2002). Previous research from ACE-Asia experiments has focused on chemical analysis and synoptic scale meteorological influences for the duststorm, usually with Gosan site data, but without a detailed explanation of the effect of frontal passage or the depth of the atmospheric boundary layer on the local pollutant concentration.

Thus, the objective of this study is to investigate precisely the evolution of atmospheric boundary layer influence on the horizontal transportation of the dust and its vertical distribution on the local pollutant concentration and to explain the effect of the frontal passage by considering synoptic and meso-scale atmospheric circulations.

2. Numerical method and aerosol data

2.1. Numerical model and input data

A three dimensional non-hydrostatic meteorological model MM5, V3.5 with an isentropic vertical coordinate was used for investigating meteorological phenomena during the dust storm period from March 18 to 25, 2001 (MM5, 2003). For the numerical model simulation, three-dimensional NCEP data with a horizontal resolution of 2.5° × 2.5° including topography, vegetation, snow cover or water, meteorological elements of wind, temperature, moisture content, heat budget, sea surface temperature in the surface layer and vertical sounding data from the surface to 100 hPa were used as initial data for the coarse-mesh domain (Fig. 1).

Then through an interpolation process, the modified input data were triply nested consisting of 125 × 105 grid points (horizontal resolution 27 km) and 23 vertical levels in the coarse-mesh domain. The next nesting (horizontal resolution 9 km) consisted of 82 × 82 grid points and the third (3 km), 61 × 61 grid points. Terrain data at 2.5° interval was used for the largest domain and 0.9 km interval terrain data was used for fine mesh domain. MRF method was adopted as boundary layer process in the planetary boundary layer (Hong and Pan, 1996) and simple ice physics considering no supercooled water and immediate melting of snow below freezing level was used. After nesting from the large domain to small domain, a west-east cross-section was made on the dust transport route from the dust storm generation area in China toward Seoul, Korea, in order to investigate the vertical structure of the wind, temperature, relative humidity and total cloud mixing ratio distribution of the atmosphere.

In the coarse-mesh domain, a straight line from Mongolia-near Beijing–Seoul–Kyoto–Pacific Ocean with reference latitude/longitude points (10, 90), (130, 40), and in the second domain (60, 70) (100, 55) including Seoul city is shown in (Fig. 2) for investigating both the upper trough of the cold low at 500 hPa and the cold front with low-pressure near the surface in the third domain including Seoul city (10, 41) (55, 41).

2.2. TSP, PM_{10} and $PM_{2.5}$ data in Seoul

Generally, when the hourly TSP (total suspended particulate matter) concentration is greater than 200 µg/m^3, the duststorm affects the local pollutant state in Korea. Before March 19, the concentration of TSP at Seoul was less than 200 µg/m^3 and from March 20, the TSP concentration started to increase to more than 200 µg/m^3 and visibility became very poor (less than 1 km). Thus, The Korean Meteorological Administration announced that the duststorm was affecting the Seoul district.

During the ACE-ASIA experiment period from March to May, 2001, Kim et al. (2002, 2003) performed research measurements at 37°32′N, 127°04′E. The site of collection of particulate matter (PM) samples on the top of the 5th floor, Natural Science Building of Sejong university in the eastern part of Seoul city consists of a moderately developed urban area, surrounded by a large-scale public park in the east, residential area in the north and west and commercial area in the south. Permission was granted to use some of the hourly-data between March 19–25, 2001 in this study. Detailed explanation on how to treat the measured data is given by Kim et al. (2003).

3. Result and discussion

3.1. Local concentration of aerosol in Seoul: duststorm period

In the past 10 years, Asian Dust events have averaged a few days or less per year, but the Asian Dust event days in 2001 had an unexpectedly high frequency of 27 days from January to May. The measurements on duststorm and non-duststorm days were made only over the weekday period, such that, for example, there were 11 days from March 19 to 31. Hourly concentrations of TSP, PM_{10}, $PM_{2.5}$ near the ground surface revealed important information on the different concentrations of coarse versus fine particles between duststorm and non-duststorm periods. According to the report of Korean Meteorological Administration, duststorm event was detected from March 20 through March 25 in the Seoul district of Korea (Figs. 3 and 4).

In general, the concentrations of TSP and $PM_{2.5}$ during duststorm periods were twice as high as the concentrations during non-dustorm period. Maximum concentrations of TSP and $PM_{2.5}$ were also found with values of 1388 μg/m^3 and 142 μg/m^3 at 1600 LST (LST = 9 h + UTC), March 22, 2001 with a ratio of 9.77 and at 1800 LST, with a ratio of 10.04. For this period until 1200 LST March 23, the measurement of PM_{10} was not possible due to some mechanical problems with the measuring instrument. Then the measurement of PM_{10} continued until 0000 LST on April 1. The ratios of TSP to PM_{10}, TSP to $PM_{2.5}$ and PM_{10}–$PM_{2.5}$ to $PM_{2.5}$ were about 2, 6 and 2, respectively.

During the period of duststorm event, relative humidity was low around 50% with a minimum of 41%, but those values measured by Korean meteorological Administration. The ratios of TSP to PM_{10} (T/10), TSP to $PM_{2.5}$ (T/2.5) and PM_{10}–$PM_{2.5}$ to $PM_{2.5}$ (C/F) were examined in order to investigate the effect of the duststorm on the local aerosol concentration. The duststorm transported a great quantity of dust from its origin. The ratios between fine and coarse particles were remarkable. In general, since small size particles are observed in Korea for non-duststorm periods, the Korean Government Ministry of Environment has measured PM10 concentration instead of TSP in recent years.

3.2. Local concentration of aerosol in Seoul: non-duststorm period

During the non-duststorm period, the ratios of TSP to PM_{10} (T/10), TSP to $PM_{2.5}$ (T/2.5) and PM_{10}–$PM_{2.5}$ to $PM_{2.5}$ (C/F) were found to be approximately 2, 4 and 0.5, respectively, but on March 26, the ratios reached 16.37, 3.4 and 3.81 (Fig. 5). On March 26, the aerosol concentration was still affected by the duststorm, even though visibility was much improved over the previous days and the Korean Meteorological Administration reported that the effect of the duststorm had disappeared at Seoul city. Thus, we classified March 26 as a duststorm day.

Through a comparison of TSP, PM_{10} and $PM_{2.5}$ between non-duststorm period and duststorm period, it was found that coarse particles made a large contribution to the increase in total suspended particulate concentration for the period of duststorm at Seoul city, and the ratio of coarse particle to fine particle defined as (PM_{10}–$PM_{2.5}$)/$PM_{2.5}$ (C/F) during the duststorm period was approximately twice that during the non-duststorm period. This means that although a large amount of dust during duststorm period was transported into the Seoul area reaching three times as much as that during non-duststorm periods, the amount of coarse particles increased only twice as much.

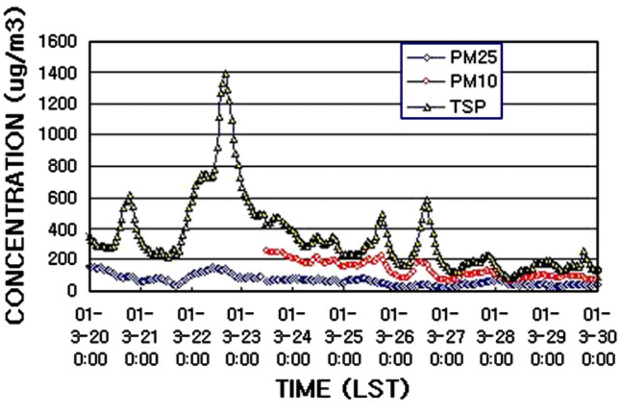

Fig. 3. Hourly based concentration of $PM_{2.5}$, PM_{10} and TSP from March 20 to 30, 2001, including duststorm and non-duststorm periods.

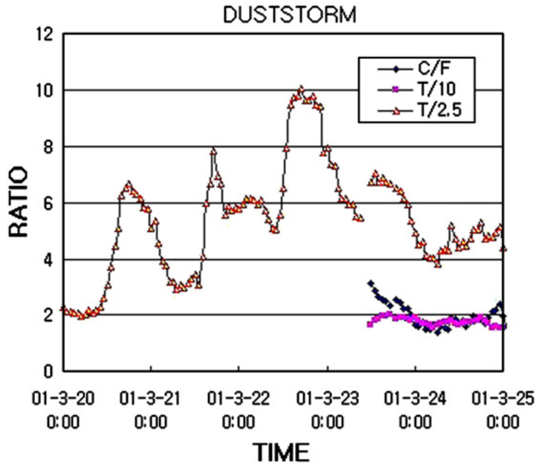

Fig. 4. Ratios of TSP to PM_{10} (T/10), $PM_{2.5}$ (T/2.5) and PM_{10}–$PM_{2.5}$ to $PM_{2.5}$ (C/F) during duststorm period from March 20 to 25, 2001 at Seoul city, Korea.

3.3. Origin of air masses during duststorm and non-duststorm periods

In order to investigate the effect of the dust transported from China on the concentrations of TSP and PM_{10} at Seoul city, back trajectories every 6 h were calculated for the duststorm the period from March 20 to 25, 2001, including its generation stage. The backward trajectories are seen separately in Fig. 6. Three levels from near the ground to 10 km, namely, 500 m to 1500 m (approximate height of boundary layer), 3000 m to 4500 m (mid-troposphere) and 5000 m to 6000 m (upper troposphere including the effect of stratosphere), were considered.

On Fig. 6, trajectories in the upper part of each figure indicate the movement on each level and trajectories below in each figure indicate vertical movement. Air trajectories at the start of the duststorm on March 19 before the detection of its effects at Seoul city, indicate that air in the upper and middle troposphere at 3 km and 5 km in height passed over the middle to north-eastern part of Mongolia.

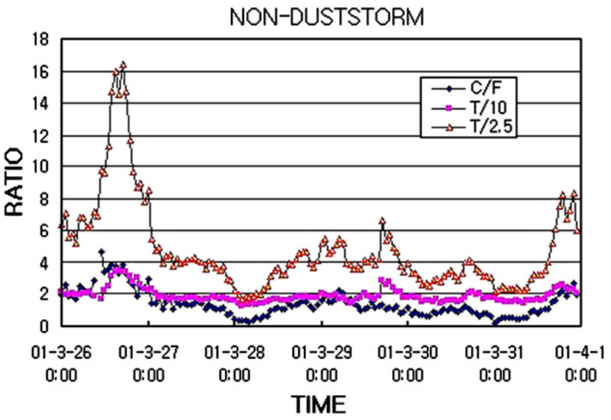

Fig. 5. Ratios of TSP to PM_{10} (T/10), $PM_{2.5}$ (T/2.5) and PM_{10}–$PM_{2.5}$ to $PM_{2.5}$ (C/F) from March 26 to March 31, 2001. March 26 was classified in non-duststsorm period, as KMA declared it a non-duststorm day.

This means that air parcels reflecting the environmental conditions in the steppes of Siberia in Mongolia can be assumed clear be clean and these air parcels are transported into the Seoul area. Air in the lower troposphere from 500 m to 1500 m (boundary layer) are also transported from Baotou in the Nei Mongo (the border of northern China) towards Seoul city, with a different pattern evident in the upper levels compared to lower levels. After the back trajectories in the middle and lower tropospheric levels passed near the southern border

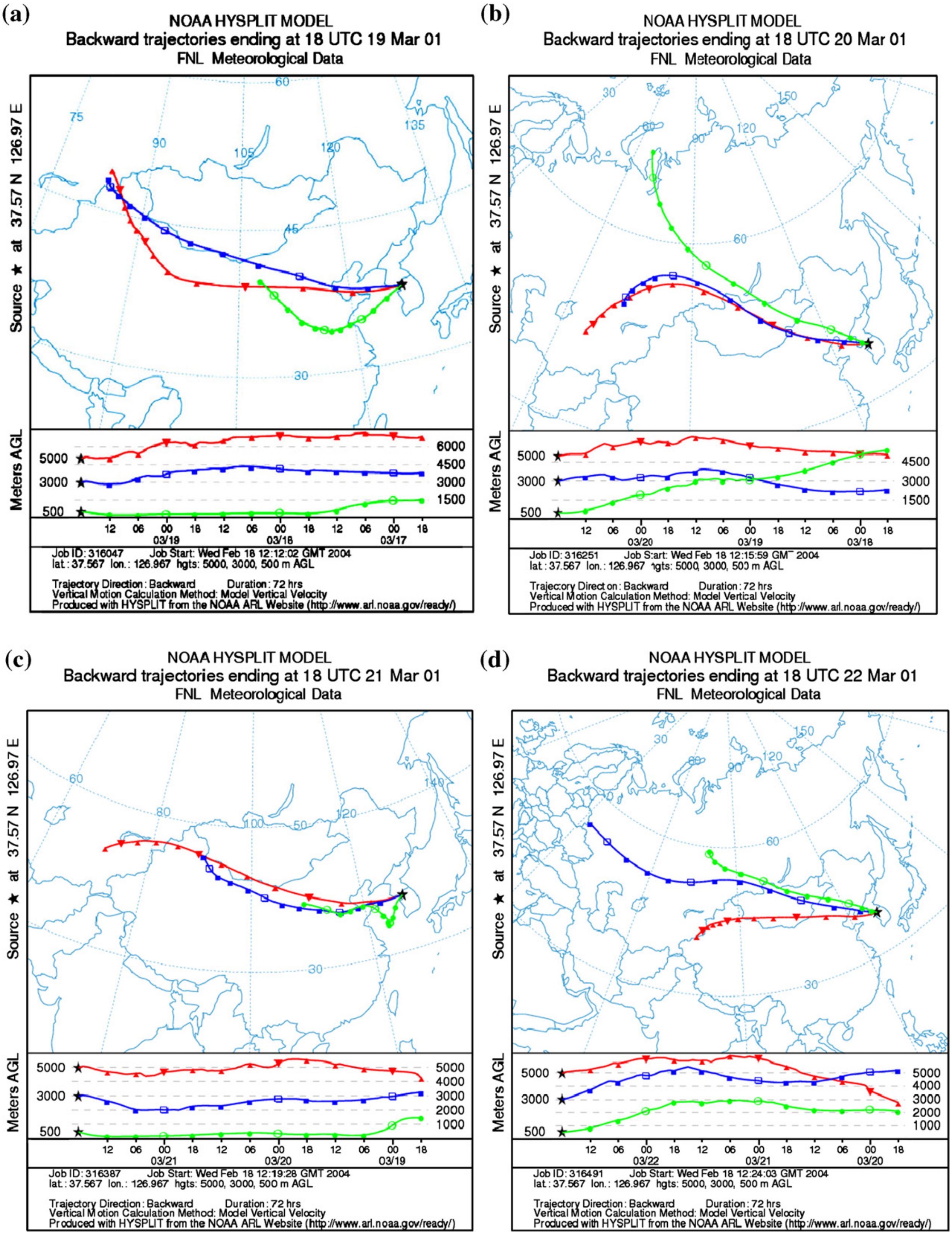

Fig. 6. (a) Back trajectory every 6 h on 3 levels-5000 m (high level; red), 3000 m (middle level; blue) and 500 m (low level; green) above ground at Seoul on March 19, 2001(b) March 20, (c) March 21 and (d) March 22.

of Mongolia and Baotou, through Zengzhou and Xuzhou, finally reaching Seoul city, it can then be concluded that the TSP concentration at Seoul city was being partially influenced by the duststorm.

Through March 20 to 25 during the main stage of the duststorm event over Korea air at the 3 km and 5 km levels, which came from Ximiao, Ningxia and Lang Shan near Nei Mongo in northern China below the southern part of Mongolia, passed right across the northern part of China, reaching the Seoul district. The dust was lifted horizontally off the ground by the strong surface wind to at least 3 km above ground and was transported across the Beijing area and to Seoul under the prevailing westerly wind (Fig. 7). The aerosol transport could influence high concentrations of pollutants of TSP, PM_{10} and $PM_{2.5}$ in the city. From back trajectories, we can partially trace the path of air parcels and from which level the air parcel descended to the ground, and vice versa. Since back trajectories do not directly reflect all directions of moving parcels but only their main direction, it is an indirect and qualitative method for determining the transport of dust to the area of interest.

As a result of this study, sudden high concentrations of TSP and PM_{10} were found for a few hours, especially at 15 to 18 LST, March 22, 2001. It is important to find out why such a sharp concentration of the TSP took place, even though dust transport was assumed to be at the same rate for several hours. From the back trajectories, it is difficult to explain why such a sudden high concentration of TSP occurred at 1800 LST, March 22. The driving mechanism is explained in detail in the next section.

From March 26, although there was no detection of duststorm effect at Seoul, back trajectories still showed that air in the upper troposphere near 5000 m and 3000 m passed over southern Monoglia and Nei Mongo, and the lower level trajectory had a similar path, even though it deviated slightly from the upper path. Sometimes their trajectories lay over eastern Mongolia, and persisted until March 26. TSP concentration at Seoul was still high, although visibility was not bad, while good visibility occurred from March 26 until March 31.

3.4. Atmospheric boundary layer effect

In general, during the day, thermal convection at the ground of a flat area such as the Seoul city basin occurs due to solar heating, and then heated air parcels from the soil gain buoyancy and are uplifted in the convective boundary layer (CBL). The emitted pollutants from the ground source reach the top of the CBL and merge together, resulting in a low concentration of pollutant close to the ground. Conversely, nocturnal cooling of the ground produces a nocturnal surface inversion layer (NSIL). A shallow surface inversion layer slowly moves down toward the land surface and air parcels inside the NSIL also descend to the surface, resulting in calm or very weak wind conditions, under a stable surface layer of air. The uplifted pollutants during the day also descend and the nocturnally emitted pollutants do not rise as they are constrained by the NSIL. The pollutants should merge near the surface, indicating an increase in pollutant concentration at night.

In the coastal region of Seoul city a westerly sea breeze develops during the day owing to higher air temperature (left side of Fig. 2) than over the inland basin, Seoul city. The city is surrounded by mountains and sea and its western outlet is associated with a valley wind due to higher air temperature than over the mountain surface (right side of Fig. 2a,b), resulting in a sea-valley wind from sea toward the top of the mountain, which drives the onshore wind. The emitted pollutant or particulate matter from the surface and pollutants transported from the sea should all rise toward the top of the city CBL and then rise further toward the top of the mountain, resulting in the high concentration of TSP at the mountain top, while the TSP concentration is low near the ground over the city. Since Seoul city is surrounded by mountains and sea, its western outlet has characteristics of coastal and urban

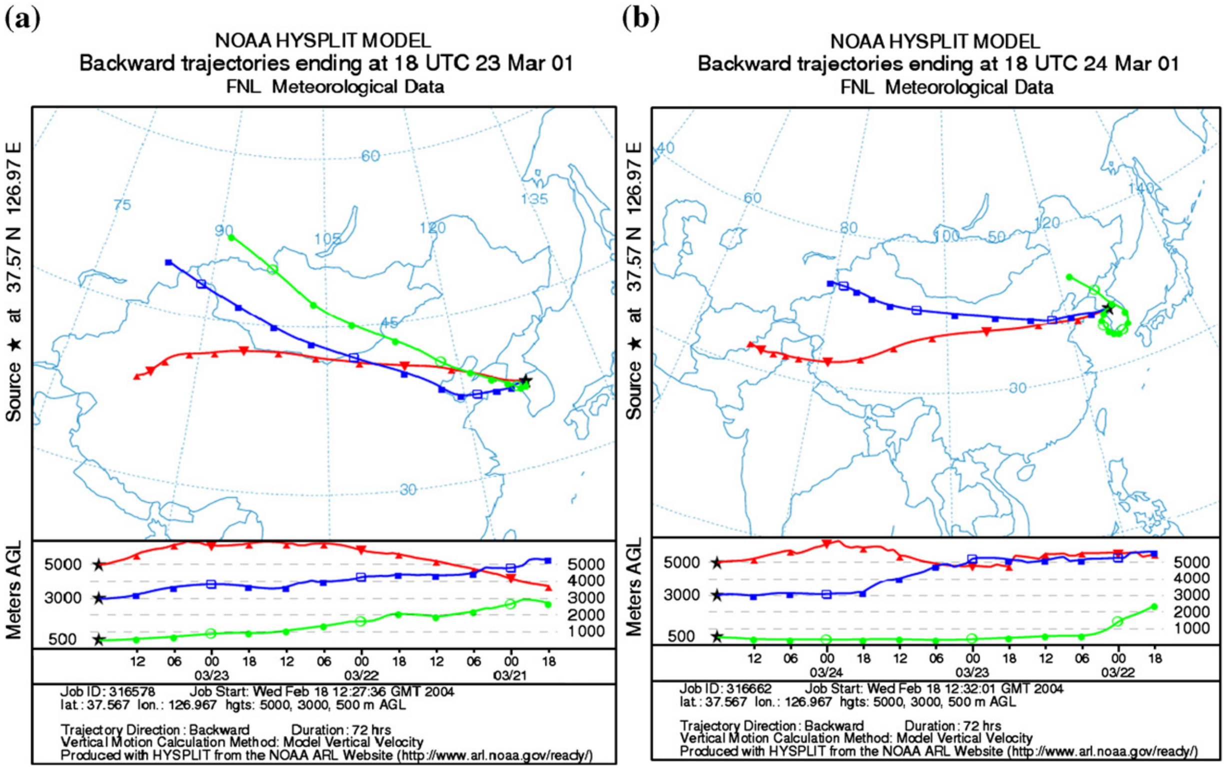

Fig. 7. As shown in Fig. 6, except at Seoul on March 23 and 24, 2001.

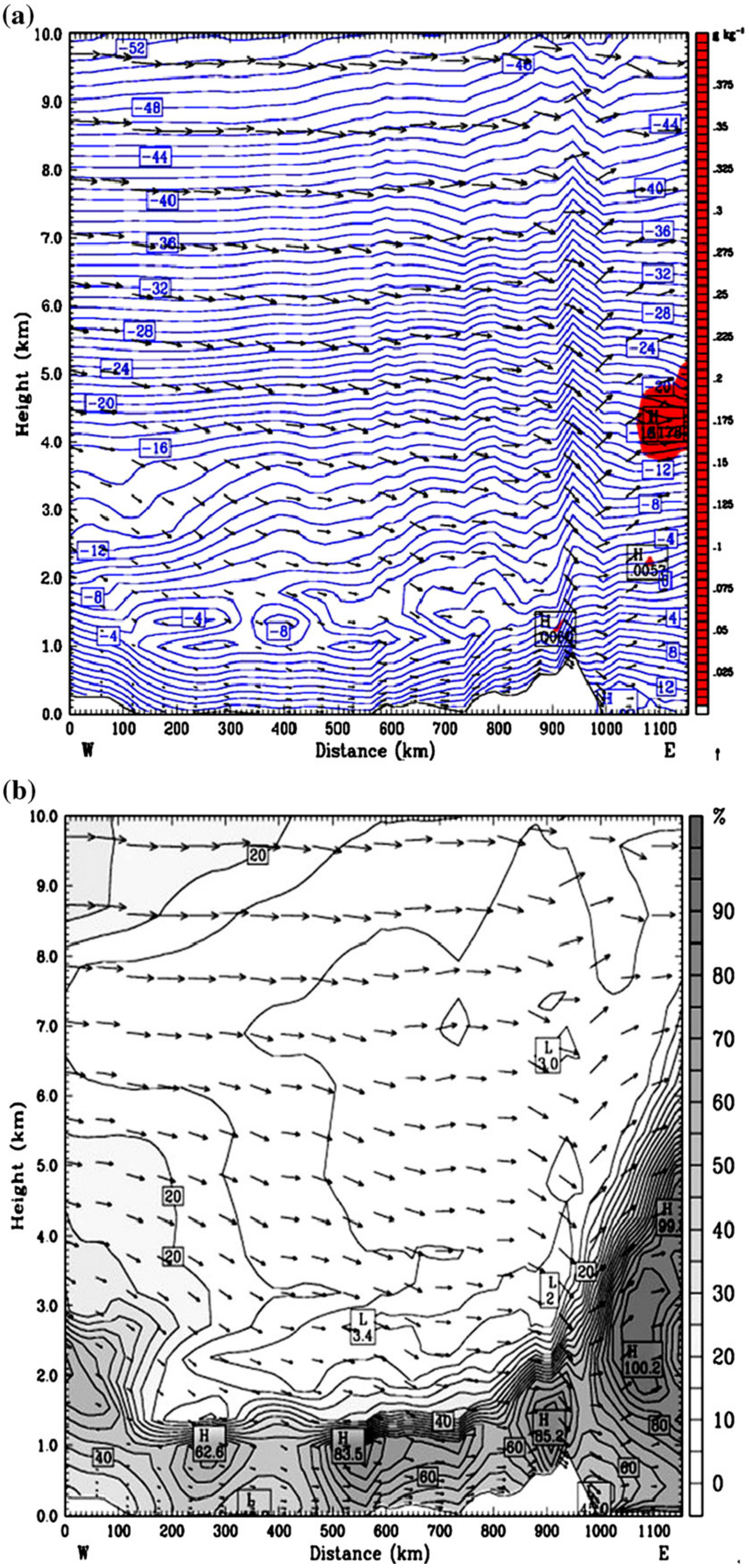

Fig. 8. (a) Vertical distribution of air temperature (°C)-cloud mixing ratio (g/kg)-wind vectors (m/s) on the path of the duststorm from China to Seoul city, (b) relative humidity (RH; %)-wind vectors (m/s), (c) Ertel potential vorticity (PVU-a function of diabatic and frictional terms. Bottom white-unstable layer, gray-mixed layer, dark black-stable layer) and (d) horizontal air temperature (°C)-relative humidity in Seoul city at 1200 LST, March 22. In Fig. (c), unstable layer (white color near the surface of 50 to 1000 on *x*-axis; Seoul city (700 to 750)) is shallow.

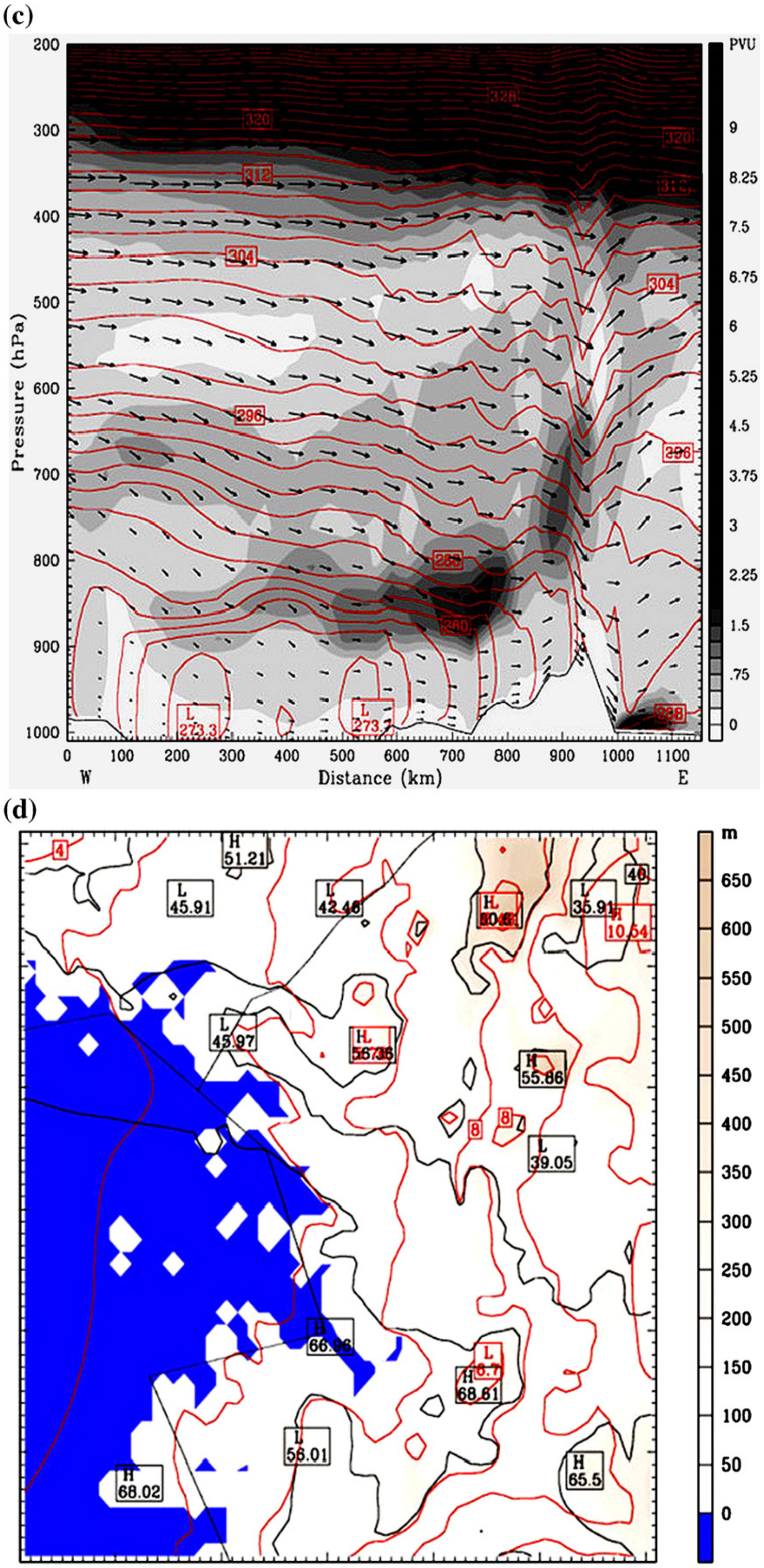

Fig. 8 (*continued*).

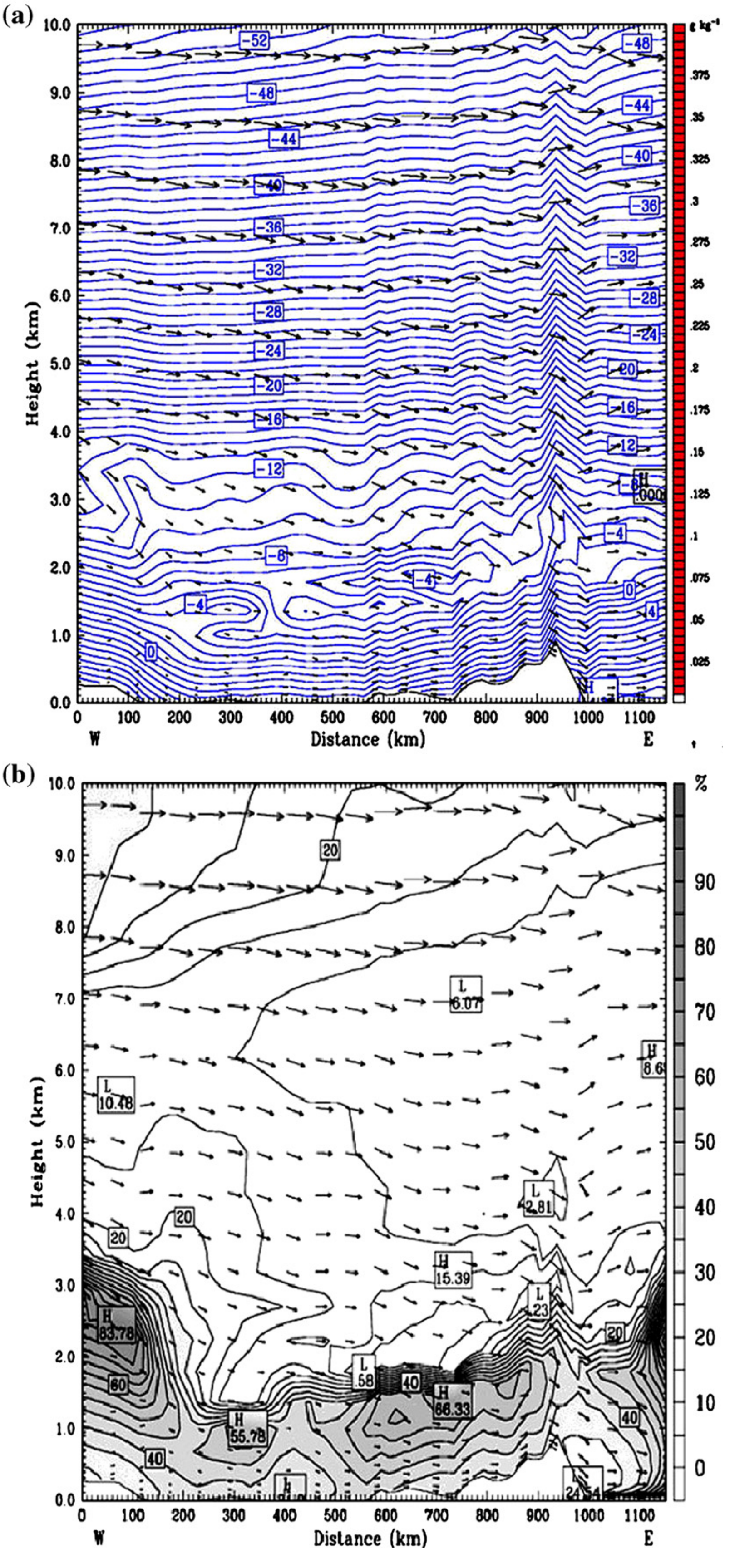

Fig. 9. As shown in Fig. 8, except for 1500 LST, March 22 and (d) geopotential height at 500 mb level and mean sea surface pressure (red line-surface cold front). In (c), unstable layer (white color near the ground between 400 and 750 on *x*-axis; Seoul city (between 700 and 750) is much shallower than that at 1200 LST (before frontal passage). In (d), Seoul (red circle) is located above the trailing end of the cold front.

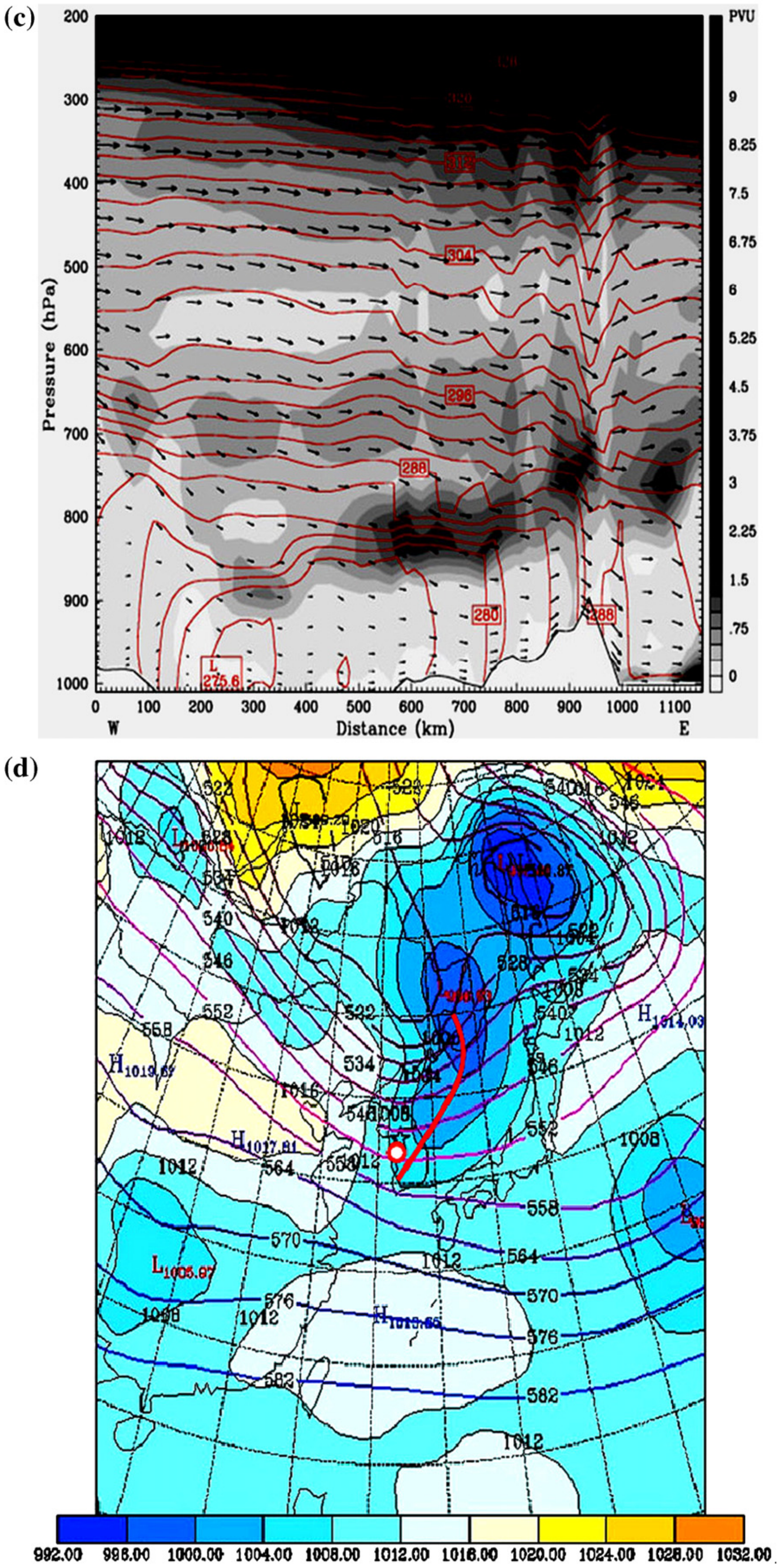

Fig. 9 (*continued*).

topographical effects, and its TSP concentration is generally low (Choi and Speer, 2006; Choi et al., 2004).

However, at night, a land breeze is directed from inland toward the sea due to cooler air temperature over the land surface than the sea surface. Simultaneously, cooler air over the mountain than that over the inland basin at the same altitude produces a mountain wind directed from the mountain top toward the basin. Then the mountain wind combined with the land breeze produces a land-mountain breeze in the city and results in an offshore wind directed over Seoul and the further coast.

In addition, we have to consider the effects of the atmospheric boundary layer. For example, between 0900 LST and 1200 LST, March 22, there was a cold frontal passage through the Korean peninsula. Before the passage of the cold front, the CBL (here white color area in the vertical distribution of baroclinic potential vorticity (Bluestein, 1993; Holton, 1992)) near Seoul was not shallow, but during the passage of the front, the CBL was remarkably shallow, resulting in the compression of the boundary layer and the increase in the TSP concentration (Fig. 8). Normally, small size particles float and are easily suspended in the CBL, because their settling velocity is too small, but in the case of a duststorm, a large amount of the coarse dust particles were observed in the study area (Figs. 3 and 4). Thus, the dust particles also descend to the ground, even inside the CBL.

On the figures of vertical distribution of air temperature at 1200 LST and 1500 LST, March 22, 2001, the air temperature was different on the coastal side of Seoul city compared to the mountain side. The relative humidity was noticeably much lower on the coastal side compared to the mountain side, owing to the temperature contrast. The intrusion of cold air could cool the ground more, resulting in the shallower nocturnal surface inversion layer near Seoul city and the maximum concentration of TSP (Fig. 9). Accompanying the frontal passage, the depth of CBL is less than 300 m, even though the mixed layer above maintained almost the same depth. Thus, the thinner CBL may make a large contribution to the increase in the TSP concentration of Seoul city.

At this time, the dust transport from the duststorm generation area was almost the same at Seoul, including the whole Korean peninsula according to the numerical simulation by Uno et al. (2003), but the TSP concentration according to the high volume sampler measurements was much higher after the frontal passage than before it (Fig. 9).

4. Conclusion

Shortly after a cold frontal passage over Seoul city, an extremely high concentration of TSP occurred at 1600 LST, even though dust transport was reducing in quantity from the southern part of Mongolia toward Seoul city. During and after the cold frontal passage through the Seoul area, the atmospheric boundary layer, especially the CBL, became much thinner than before its passage, with the depth of the CBL reducing to less than 300 m, even though the mixed layer above maintained almost its same depth. Thus, the thinner CBL can make a large contribution to the increase in TSP concentration. Simultaneously, the positive effect of the large scale meteorological circulation together with boundary layer forcing can also greatly contribute to the high concentration of TSP locally and even on the larger scale.

Acknowledgements

The authors thank very much the College of Environmental Sciences, Peking University, China and Department of Atmospheric Environmental Sciences, Kangnung National University, Korea for using computer system and analysis, and Prof. K. H. Kim, Sejong University, Korea for the use of aerosol data from the March 2001 Asian Dust event. This work was partially funded by the Korea Meteorological Administration Research and development Program under Grant CATER 2006-2308 — “Generation mechanism and prediction of windstorm in the mountainous coast-for 2006-2008 year”.

References

Bluestein HB. Synoptic-dynamic meteorology in mid-latitudes. Principles of kinematics and dynamics. Oxford University Press; 1993.

Carmichael GR, Hong MS, Ueda H, Chen LL, Murano K, Park JK, Lee H, Kim Y, Kang C, Shim S. Aerosol composition at Cheju Island, Korea. J Geophys Res 1997;102(5):6047–61.

Choi H, Speer MS. Effects of atmospheric circulation and boundary layer structure on the dispersion of suspended particulates in the Seoul metropolitan area. Meteorol Atmos Phys 2006;92(3):239–54.

Choi H, Zhang YH, Takahashi S. Recycling of suspended particulates by the interaction of sea-land breeze circulation and complex coastal terrain. Meteorol Atmos Phys 2004;87:109–20.

Chon H. Historical records of yellow sand observations in China. Res Environ Sci 1994;7–6:1–11.

Chun YS, Kim JY, Choi JC, Boo KO, Oh SN, Lee MH. Characteristic number size distribution of aerosol during Asian dust period in Korea. Atmos Environ 2001;35:2715–21.

Chung YS, Yoon MB. On the occurrence of yellow sand and atmospheric loadings. Atmos Environ 1996;30:2387–97.

Chung YS, Kim HS, Natsagdorj L, Jugder D, Chen SJ. On yellow sand occurred during 1997–2000. J Korean Meteorol Soc 2001;37:305–16.

Chung YS, Kim HS, Jugder D, Natsagdorj L, Chen SJ. On sand and duststorms and associated significant dustfall observed in Chongju–Chongwon, Korea. Water Air Soil Pollut Focus 2003;3:5–19.

David MT, Robert JF, Douglas LW. April 1998 Asian dust event: a southern California perspective. J Geophys Res 2001;106(D16):18371–9.

Fei J, Qing Y. The numerical simulation on dust-storm over east Asia II: A case analysis. (J). Acta Sci Nat Univ Pekinensis 1998;34(5):639–45.

Gao Y, Anderson JR. Characteristics of Chinese aerosols determined by individual particle analysis. J Geophys Res 2001;106(D16):18037–45.

Hong SY, Pan HL. Nonlocal boundary layer vertical diffusion in a medium-range forecast model. Mon Weather Rev 1996;124:2322–39.

Holton JR. An introduction to dynamic meteorology. 3rd Ed. Academic Press; 1992.

Huebert BJ, Bates T, Russell PB, Shi G, Kim YJ, Kawamura K, Carmichael G, Nakajima G. An overview of ACE-Asia: strategies for quantifying the relationships between Asian aerosols and their climate impacts. J Geophys Res 2003;108(D23):8633. doi:10.1029/2003JD003270.

Jigjidsuren S, Oyuntsetseg S. Pastureland utilization problems and ecosystem. Ecological sustainable development. Ulaanbaatar 1998;2:206–12.

Jungder, D., Hydrodynamic statistic model for prediction of wind, snow storms and dust storms over the territory of Mongolia. The thesis presented for the Ph.D. in mathematics and physics. National University of Mongolia, Ulaanbaatar 1999;3–30.

Kai K, Okada Y, Uchino O, Tabata I, Nakamura H, Takasugi T, Nikaido Y. Lidar observation and numerical simulation of a Kosa (Asian dust) over Tsukuba, Japan during the spring of 1986. J Meteorol Soc Jpn 1988;66:457–71.

Kim HK, Kim MY. The effects of Asian dust on particulate matter fractionation in Seoul, Korea during spring 2001. Atmos Environ 2003;51:707–21.

Kim HK, Kim MY, Kim J, Lee G. The concentrations and fluxes of total gaseous mercury in a western coastal area of Korea during the ate March period of 2001. Atmos Environ 2002;36(21):3413–27.

Kim KW, Kim YJ, Oh SJ. Visibility impairment during Yellow Sand periods in the urban atmosphere of Kwangju, Korea. Atmos Environ 2001;35:5157–67.

Kim KH, Choi GH, Kang CH, Lee JH, Kim JY, Youn YH, Lee SR. The chemical composition of fine and coarse particles in relation with the Asian dust events. Atmos Environ 2003;37:753–65.

Lin TH. Long-range transport of yellow sand to Taiwan in spring 2000: observed evidence and simulation. Atmos Environ 2001;35:5873–82.

McKendry IG, Hacker JP, Stull R, Sakiyama S, Mignacca D, Reid K. Long-range transport of Asian dust to the lower Fraser Valley, British Columbia, Canada. J Geophys Res 2001;106(D16):18361–70.

Middleton NJ. A geography of dust storms in southwest Asia. J Climate 1986;6:183–96.

MM5. PSU/NCAR mesoscale modeling system tutorial class notes and user's guide: MM5 modeling system version 3; 2003.

Natsagdorj L, Jugder D. Statistics method for prediction of dust storms over the Gobi and steppe area in Mongolia in spring. Ulaanbaatar: Scientific report; 1992. p. 83.

Natsagdorj L, Jugder D, Chung YS. Analysis of dust storms observed in Mongolia. J Korean Meteorol Soc 2002;38(3):209–23.

Qian Z, Hu Y. Survey and analysis for "93.5.5." strong dust storm, dust storm research in China. Beijing: Meteorology Press; 1997. p. 37–43.

Uno I, Carmichael GR, Streets DG, Tang Y, Yienger JJ, Satake S, Wang Z, Woo JH, Guttikunda S, Uematsu M, Matsumoto K, Tanimoto H, Yoshioka K, Iida T. Regional chemical weather forecasting using CFORS: analysis of surface observations at Japanese island stations during the ACE-Asia experiment. J Geophys Res 2003;108:8668. doi:10.1029/2002JD002845.

Wang Z, Ueda H, Huang M. A deflation module for use in modeling long-range transport of yellow sand over East Asia. J Geophys Res 2000;26:947–56.

Wang X, Ma Y, Chen H, Wen G, Chen S, Tao Z, Chung Y. The relation between sandstorms and strong winds in Xinjiang, China. Water Air Soil Pollut Focus 2003;3:67–79.

Xiao H, Carmichael GR, Durchenwald J. Long-range transport of SOx and dust in East Asia during the PEM B Experiment. J Geophys Res 1997;102:28589–612.

Xuan J, Sokolik IN. Characteristics of sources and emission rates of mineral dust in Northern China. Atmos Environ 2002;36:4863–76.

Zhang Y, Zhong Y. The simulation and diagnosis for a strong wind associated with northeast low. Acta Meteorol Sin 1985;43:97–105.

Zhang X, Arimoto R. Atmospheric trace elements over source regions for Chinese dust: concentrations, sources and atmospheric deposition on the losses plateau. Atmos Environ 1993;27A(13):2051–67.