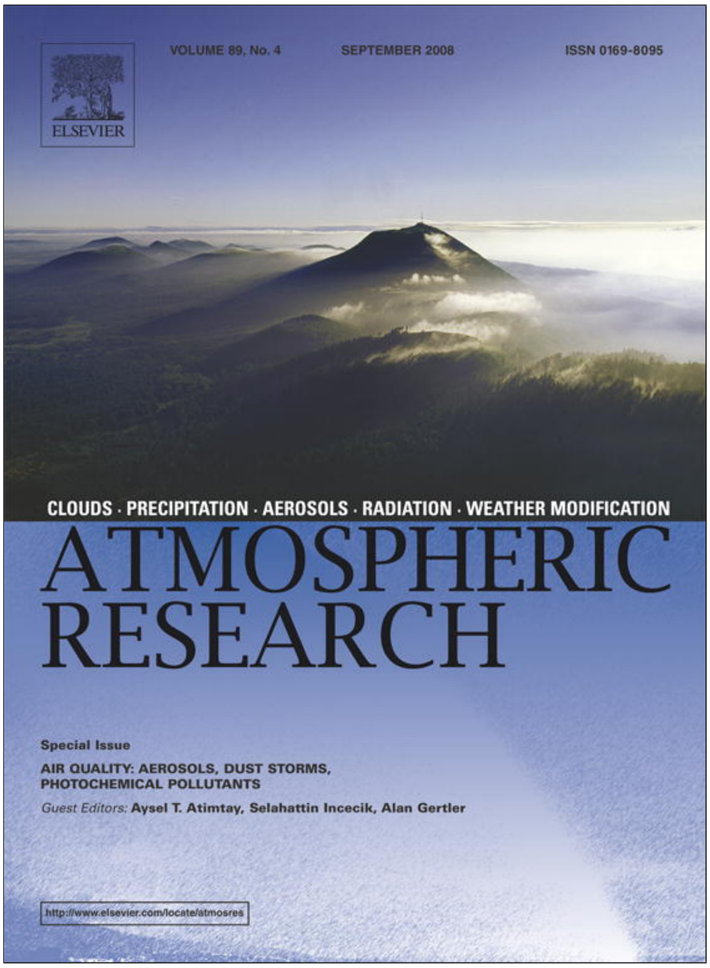
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Research Article

Concentrations of PM_{10}, $PM_{2.5}$, and PM_1 influenced by atmospheric circulation and atmospheric boundary layer in the Korean mountainous coast during a duststorm

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A R T I C L E I N F O

Keywords:
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A B S T R A C T

Particle size concentrations of 100 ng m^{-3} to 20 μg m^{-3} were measured at two sampling points over the eastern coastal region of Korea by two GRIMM aerosol samplers from March 7–17, 2004. One sampling point was located on the western upwind side of the mountains, and the other sampling point was located in the city of Kangnung in the coastal basin downwind and adjacent to the East Sea. Concentrations of PM_{10}, $PM_{2.5}$, and PM_1 were measured near the ground in Kangnung on March 8, 2004, until 1200 LST before the passage of a duststorm. Values of about 40, 35, and 30 μg m^{-3}, respectively, were detected indicating little variation among sample concentrations. Before the duststorm, maximum concentrations for PM_{10} occurred around 0800 and 1700 LST due to increased fuel combustion from road vehicles. From the afternoon of March 10–16 when the largest amount of dust from China had passed over Kangnung under the influence of a westerly wind, PM_{10} concentration reached 340 μg m^{-3}, and $PM_{2.5}$ and PM_1 concentrations reached 105 μg m^{-3} and 60 μg m^{-3}, respectively, indicating double the PM_{10} concentration as compared to $PM_{2.5}$. Most of the dust transported from China consisted of particle sizes larger than $PM_{2.5}$ and PM_1. Dust transported from the western, upwind side of the mountains combined with the particulates emitted from road vehicles and industrial and residential boilers in the city after sunrise under the influence of westerly winds resulted in a high particulate concentration at 0900 LST. However, a low concentration of particulates in the city was detected near 1200 LST due to changes in the structure of the atmospheric boundary layer, while a high concentration over the mountains occurred due to a stable layer. High-particulate concentrations in the city occurred again after 1700 LST owing to increased fuel combustion from road vehicles and residential boilers, as well as transport of dust particles from China. Particulate from China was transported through the upwind side of the mountains by westerly, land–mountain breezes directed toward the city and a decreased depth in the boundary layer over the city with a maximum concentration at 2200 LST. Particulate matter concentrations of all sizes were generally higher over the mountains than in the city due to a much shallower boundary layer.

1. Introduction

An Asian duststorm, locally referred to as Yellow Sand or KOSA, has different characteristics compared to duststorms occurring in other regions of the world, such as in the Sahara and Australian deserts (Reiff et al., 1986; Middleton, 1986). Asian duststorms have occurred frequently and periodically under the influence of strong winds raising soil in the arid areas of northern China and the Gobi deserts in Mongolia and transporting large amounts of dust to eastern China, Korea, and Japan, even to North America (Chon, 1994; Chung et al.,

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2001; Chun et al., 2001; Chung and Yoon, 1996; Huang and Wang, 1998; Jigjidsuren and Oyuntsetseg, 1998; Middleton, 1986; Natsagdorj and Jugder, 1992a; Lin, 2001). The dust causes low visibility and decreased air quality during the spring in northern Asian countries and even the USA (Carmichael et al., 1997; Choi and Song, 1999; Chung et al., 2003; David et al., 2001; Gao and Aderson, 2001; Kim et al., 2001; McKendry et al., 2001; Murayama, 1988). In recent years, newspapers and television have reported that livestock diseases in China, Taiwan, Korea, Japan, and Thailand were influenced greatly by duststorms, which may have brought various bacilli bacteria and germs to the countries along the duststorm path, thereby causing thousands of livestock to die due to bacterial disease (KBS TV, 2004; Joong-ang, 2004).

Kim and Kim (2003) and Kim et al. (2003) explained that particulate matter (PM) during Asian dust events in 2001 and 2002 could have be transported toward Seoul, Korea, by a strong westerly wind of about 20 m s^{-1}. Zhang and Zhong (1985) claimed that about half the total quantity of PM was deposited near the source area (30%) and re-distributed locally (20%), while the other half was subjected to long-range transport. The transported dust may serve as one of the major PM sources across the whole Asia/Pacific region. An aerosol experiment was performed in 2004 that included several scientific groups in many locations of east Asia including Korea, China, and Japan. Most measurements and related research in Korea was associated with the Gosan Supersite of Jeju Island in southern Korea. Apart from Gosan, some scientists have conducted aerosol measurements in western parts of Korea, but no measurements have previously been taken in the mountainous coastal region of the Korean peninsula.

Thus, the objective of this study was to investigate diurnal aerosol concentrations, especially PM_{10}, $PM_{2.5}$, and PM_1, and to explain the occurrence of high PM concentrations due to atmospheric circulation flow and boundary layer depth from the mountains in the west to Kangnung, Korea, in the coastal basin of the east.

2. Measurement of aerosol and topography

2.1. Instrument

Concentrations of particle sizes 100 ng m^{-3} to 20 μg m^{-3} have been measured by GRIMM aerosol samplers over the eastern coastal region of Korea from March 7–17, 2004, during the spring duststorm in China. One aerosol-sampling instrument was installed at an elevation of 896 m on Mt. Taegulyang in the western, upwind side of the mountains and the other at Gangwon Regional Meteorological Administration in the coastal city of Kangnung, which is adjacent to the East Sea.

The GRIMM Model 1107 is an extremely small and portable particle analyzer and is specifically designed for PM_{10}, $PM_{2.5}$, and PM_1 environmental ambient air analysis using laser-light-scattering technology. This technology enables the Model 1107 to make very precise "cut points" for all three PM size classifications. This patented system allows the user to collect all three PM fractions simultaneously without changing sampling heads or weighing filters.

The Model 1107 is the only PM monitor to offer dual technology consisting of both optical and gravimetrical analysis. It incorporates a removable 47-mm PTFE (polytetrafluoroethylene) filter, which allows the user to verify the optical analysis gravimetrically, as well as providing the option for other chemical analyses on the collected residue. The Model 1107 environmental particulate monitoring system measures particulates via laser-light scattering. Air containing multiple particle sizes passes through a flat laser beam produced by a precisely focused laser and several collimator lenses. The scattered light is then detected by a 15-

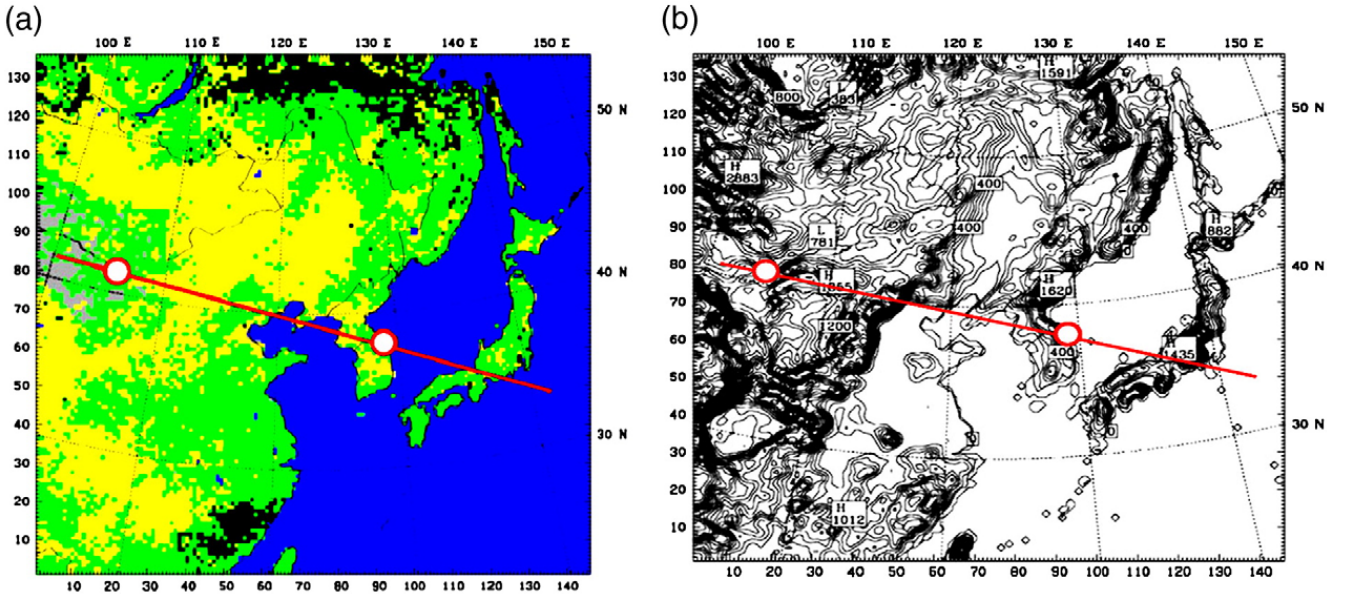

Fig. 1. Land-use data in a coarse domain on a 27-km horizontal grid. Yellow and green areas denote bare and grass areas, respectively, (a). Circles denote duststorm area in China (left) and Kangnung coastal city of Korea (right). Topography near Kangnung city, (b).

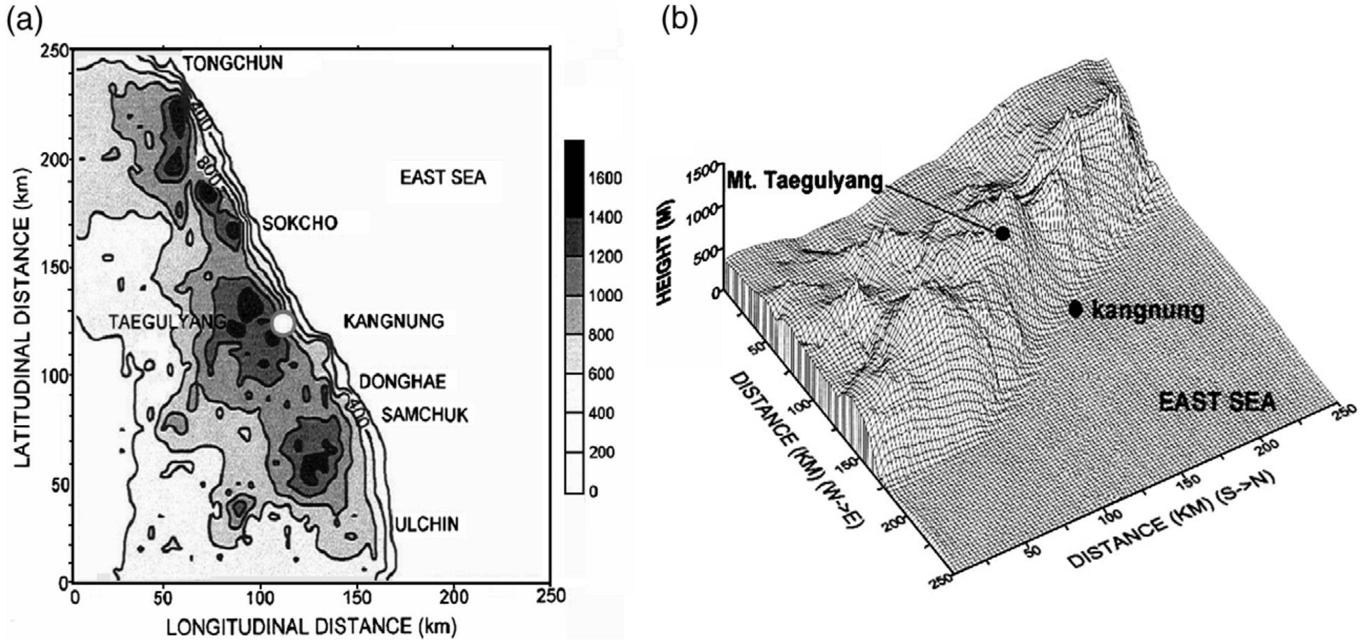

Fig. 2. Two-dimensional (left) and three-dimensional (right) topographies (circle area shown in Fig. 1b) with horizontal grid sizes of 5 km near Kangnung city (20 m above mean sea level; 10 km wide) and Mt. Taegulyang (896 m), Korea.

channel, pulse-height analyzer for size classification. The counts from each size classification are then converted to mass by a well-established equation. The data are then presented as PM_{10}, $PM_{2.5}$, and PM_1. As a stand-alone system, Model 1107 can be operated directly at all times in the field. No sample pipe heating is needed and no loss of volatile organic compounds. Auto-zero, self-diagnostic, and continuous performance recording are invoked after each start.

2.2. Topography in study area

The study area was located in a mountainous coastal region of the eastern Korean peninsula where two GRIMM aerosol samplers were set up, one on Mt. Taegulyang (896 m above mean sea level) and another at Gangwon Regional Meteorological Administration in Kangnung city (20 m above mean sea level) adjacent to the East Sea.

Terrain data with a horizontal resolution of 2.5° were used for the largest domain, and 1-km horizontal resolution data were used for the fine-mesh domain. A vertical cross-section along a straight line oriented west–east through Mongolia, Beijing, Seoul, and Kyoto to the Pacific Ocean was selected for analysis. This path was the major transport route from the area in China where the duststorm originated.

2.3. Numerical model and input data

A three-dimensional, non-hydrostatic, mesoscale model (MM5) (V3.5) was used to investigate the development of the atmospheric boundary over Kangnung city during the duststorm period from March 10–11, 2004, in order to explain how the atmospheric boundary layer influences high PM concentrations. Three-dimensional NCEP (US National Weather Service, National Centers for Environmental Predictions) data with a horizontal resolution of 2.5°×2.5°, including topography, vegetation, snow cover or water, meteorological elements of wind velocity, temperature, moisture content, heat budget, sea surface temperature, and sounding data from the surface to 100 hPa, were used as initial conditions for the coarse-mesh domain. Interpolated input data were triply nested first at 27 km (125×125 grid points) with 23 vertical levels, then at 9 km (82×82 grid points), and finally at 3 km (61×61 grid points). The 2.5° resolution terrain data were used for the coarse-mesh domain, and then 0.9-km resolution terrain data were used for the fine-mesh domain near Kangnung.

The medium-range forecast scheme for cumulus parameterization was adopted in the planetary boundary layer, and a simple ice scheme with no supercooled water and the melting of snow below freezing level was also used (Hong and Pan, 1996). After the nesting process from a large to small domain, a west–east cross-section along the dust transport route was made from the dust generation area in western China to Japan in order to investigate the vertical structure of wind, temperature, relative humidity, total cloud-mixing ratio, and vertical velocity. In the large domain, a line was drawn through locations of Neimongo, Beijing, Seoul, Kyoto, and the Pacific Ocean from the latitude and longitude coordinates of (10, 85) to (130, 50) (Figs. 1 and 2).

3. Results and discussion

3.1. Aerosol concentrations over Kangnung and Mt. Taegulyang

Concentrations of PM_{10}, $PM_{2.5}$ and PM_1 near the ground in Kangnung were very low until 1200 LST, March 8, 2004. Before the duststorm passed values were around 40, 35, and 30 $\mu g\ m^{-3}$, respectively, with little variation between them. On March 7, 2004, before the duststorm, the maximum concentration of PM_{10} occurred around 0800 LST and again around 1700 LST. Dust transported from China over the Korean peninsula from March 8 until 1200 LST, March 10, doubled the

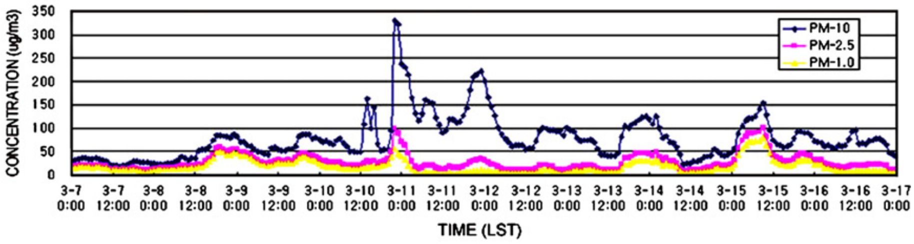

Fig. 3. Hourly-based concentrations (μg m^{-3}) of PM_{10}, $PM_{2.5}$, and PM_1 collected at an aerosol-sampling point of the Gangwon Regional Meteorological Administration in Kangnung, Korea, during March 7–17, 2004. Particulate matter concentrations at 1200 LST were low due to a deep convective boundary layer. A high PM_{10} concentration at 1500 LST was affected by the transport of dust trapped in the left basin of Mt. Taegulyang on the upwind side, atmospheric boundary layer increases as shown in Fig. 7a and b). The maximum PM concentration at 2200 LST occurred under the shrunken atmospheric boundary layer at night as shown in Fig. 7c and d.

concentrations of PM_{10}, $PM_{2.5}$, and PM_1 to 50–95 μg m^{-3}. During March 10–16 when a large amount of dust passed over Kangnung, PM_{10} concentration reached 340 μg m^{-3}, and $PM_{2.5}$, and PM_1 concentrations reached 105 μg m^{-3} and 60 μg m^{-3}, respectively, indicating the PM_{10} concentration has doubled the $PM_{2.5}$ concentration (Figs. 3, 5, and 6).

Concentrations of PM $_{2.5}$ and PM_1 on Mt. Taegulyang were very similar to those over Kangnung, but the concentration of PM_{10} on Mt. Taegulyang was slightly higher than over the city, although the temporal distribution was similar (Figs. 3 and 4).

The concentration of PM_{10} was higher over the mountain than over the city, particularly on March 11. This was due to a much shallower boundary layer or no boundary layer at all over the mountain as compared to a deep boundary layer over the city, as shown in Fig. 7.

Most dust transported from China consisted of particle sizes larger than $PM_{2.5}$, except during the period from 1800 LST, March 10, through 0300 LST, March 11, when the maximum concentrations for PM_{10}, $PM_{2.5}$, and PM_1 were still very low and similar to concentrations before the period of dust transport. This means that dust transport from China to Kangnung, as shown on streamlines at the 850-hPa level (approximately 1.5-km height) in Fig. 5, could lead to increased PM_{10} concentrations locally but not have much influence on $PM_{2.5}$ and PM_1 concentrations. Particulate matter concentrations at Kangnung on March 10 were affected by the transport of dust from China over Mt. Taegulyang as shown in Figs. 6a,b,c,d and 7, but concentrations over the city on March 11 were directly affected by transport of dust particles from China rather than over Mt. Taegulyang.

It is important to note that the highest PM concentrations occurred first at 0900 LST, around the beginning of office hours, and then again at 1700 LST, around the end of office hours, to 2200 LST. Dust transported from the western, upwind side of Mt. Taegulyang by westerly winds blowing toward Kangnung combined with particulates generated by the wind and those emitted by fuel combustion from road vehicles and residential boilers in the city after sunrise. This resulted in a high particulate concentration that coincided with the beginning of office hours (0900 LST).

The low PM concentration over Kangnung at 1200 LST on March 10 was due to a deepening of the boundary layer (especially convective boundary layer) near the coastal region to a depth of about 1 km (Fig. 7a). Generally, in daylight hours, particles emitted at the street level rise to the top of the convective boundary layer due to diurnal heating of the surface. Upslope winds combined with easterly sea breezes and easterly valley winds drive dust particles and PM in the city westward where it dissipates over the western side of the mountain thus resulting in a decrease in PM near the coast at about 1200 LST (Choi, 2003; Choi et al., 2004). However, the wind direction on March 10 for the duststorm period was southwesterly on the mountain and a weak southwesterly in Kangnung. Thus, the low concentration of PM at 1200 LST in the city was due mainly to particles rising from close to the surface over the city to the top of a thick, convective boundary layer thereby resulting in a low PM concentrations near ground level in the city.

However, the depth of the boundary layer over Mt. Taegulyang on the western, upwind side was relatively shallow or nonexistent, resulting in a high PM concentration at 1200 LST (Fig. 7a). After 1200 LST, a westerly wind continuously drove particulates from Mt. Taegulyang toward Kangnung, and 2–4 h later at 1400 and 1600 LST, PM_{10} concentration at Kangnung reached a very high value of

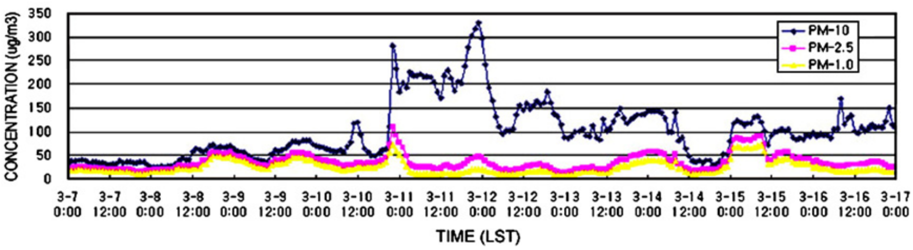

Fig. 4. A high PM concentration at 1200 LST on the mountain was affected by a lid on a stable layer as shown in Fig. 7a. The concentration at 1500 LST became low due to the increase in the depth of boundary layer. As the nocturnal boundary layer was very shallow (Fig. 7d) and a large amount of dust particles were transported from China (Fig. 5), an increase in PM concentrations can occur. The higher PM concentration over the mountain than over the city, particularly on March 11, from the transport of dust particles from China was due to a much shallower boundary layer.

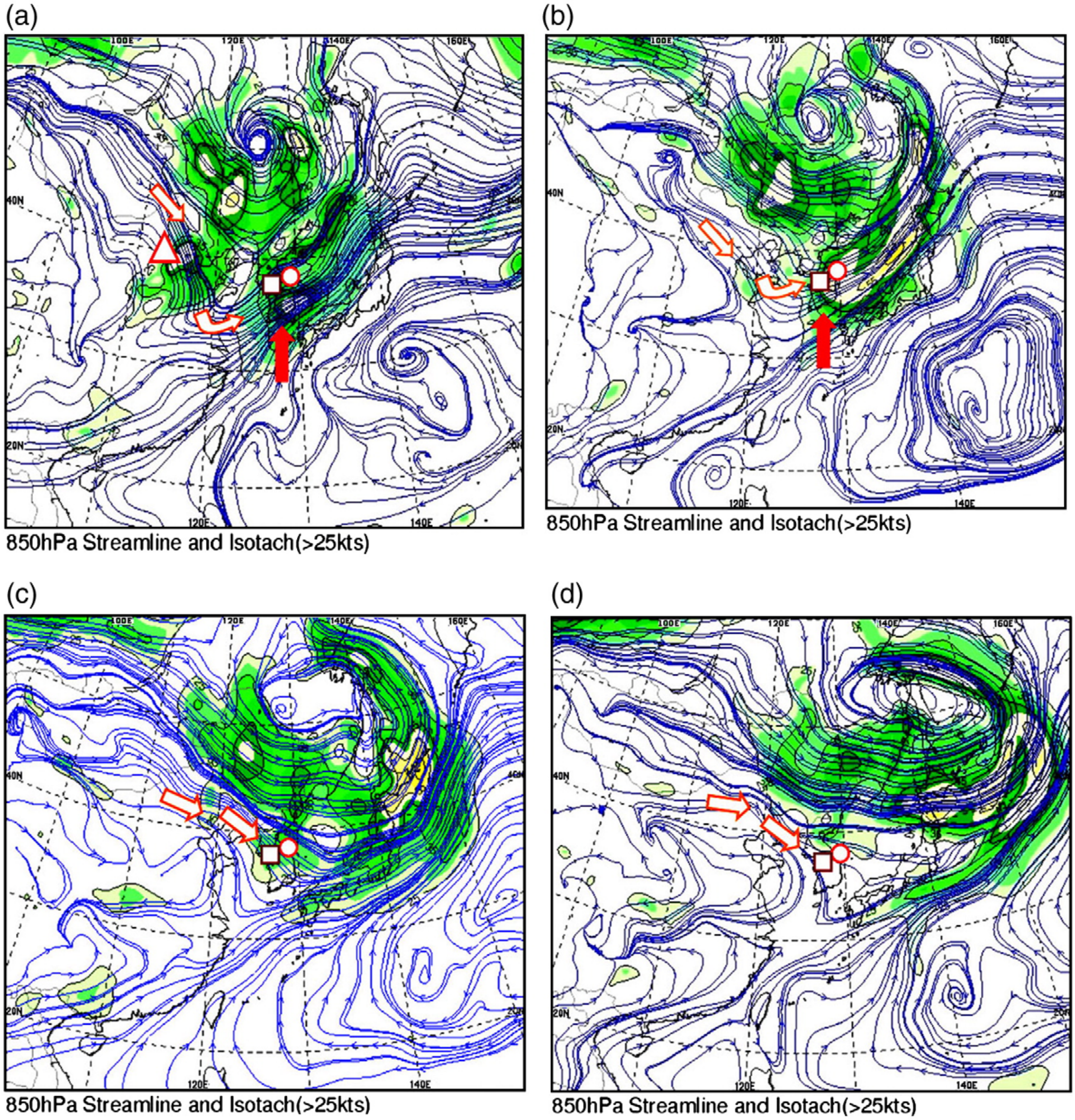

Fig. 5. Streamline and isotach (>25 kts) at the 850-hPa level (1.5 km) simulated by MM5 model at 0900 LST, (a); 2100 LST, March 10, 2004, (b); 0900 LST, (c); and 2100 LST, March 11, 2004, (d). Triangle, open arrow, thick arrow, box, and red circle denote duststorm generation area in China, dust transport route, Korean Peninsula, Mt. Taegulyang, and Kangnung, respectively. Particulate matter concentrations at Kangnung are affected by transport of dust from China over Mt. Taegulyang in (a) and (b), but PM concentrations in the city are affected directly by transport of dust particles from China rather than Mt. Taegulyang.

280 μg m^{-3} due to transport of trapped dust particles on the mountainside moving downslope toward Kangnung. Particulate matter concentrations on the mountains at 1500 LST became lower due to transport of dust particles downslope toward Kangnung and an increased boundary layer depth to about 200 m over the mountains (Fig. 7b).

From 1800 LST (just after sunset), the wind direction was still westerly. The high PM concentration occurred again due to increased fuel combustion of road vehicles and residential boilers at the end of office hours. High PM concentrations gradually increased before midnight to a maximum at 2200 LST due to decreased depth in the boundary layer from reduced surface heating of the ground (Fig. 7c) and nocturnal cooling of the ground, which formed a shallow nocturnal surface inversion layer over the city (Fig. 7d). After sunset, the nocturnal surface inversion layer was much shallower than the daytime convective boundary layer. Thus, the PM concentration in the boundary layer should have been increased in the evening as compared to the daytime and further enhanced by dust transport from China under the influence of westerly winds.

From 2300 LST, high PM gradually decreased until 0900 LST the next day. The decrease was due to a prevailing westerly synoptic wind that combined with mountain wind after sunset becoming a strong, downslope surface wind directed toward Kangnung and the coast. This westerly surface wind was further enhanced by a westerly land breeze directed toward the East Sea, resulting in particles being driven over the coast and East Sea and a reduced PM concentration of 110 μg m^{-3} in Kangnung at 0600 LST on March 11, 2004.

From 0600 LST on March 11, 2004, transported dust from the western, upwind side of the mountains directed toward Kangnung, combined with the particulates generated by surface winds, road vehicles, and residential boilers after sunrise, led to the high PM concentration by 0900 LST. After 0900 LST, a developing sea breeze and valley wind drove particulates back over the western side of the mountains, resulting in a low PM concentration of 80 μg m^{-3} close to 1200 LST. After the duststorm period, diurnal PM concentrations generally showed a high concentration around 0900 LST and a maximum concentration around 2100 or 2200 LST.

The $PM_{2.5}$ and PM_1 concentrations on Mt. Taegulyang during the duststorm period were very similar to those in Kangnung. However, PM_{10} concentrations on Mt. Taegulyang were slightly higher than over the city but had a similar temporal distribution, as shown in Fig. 4. The PM concentration on Mt. Taegulyang on March 11, 2004, were higher than

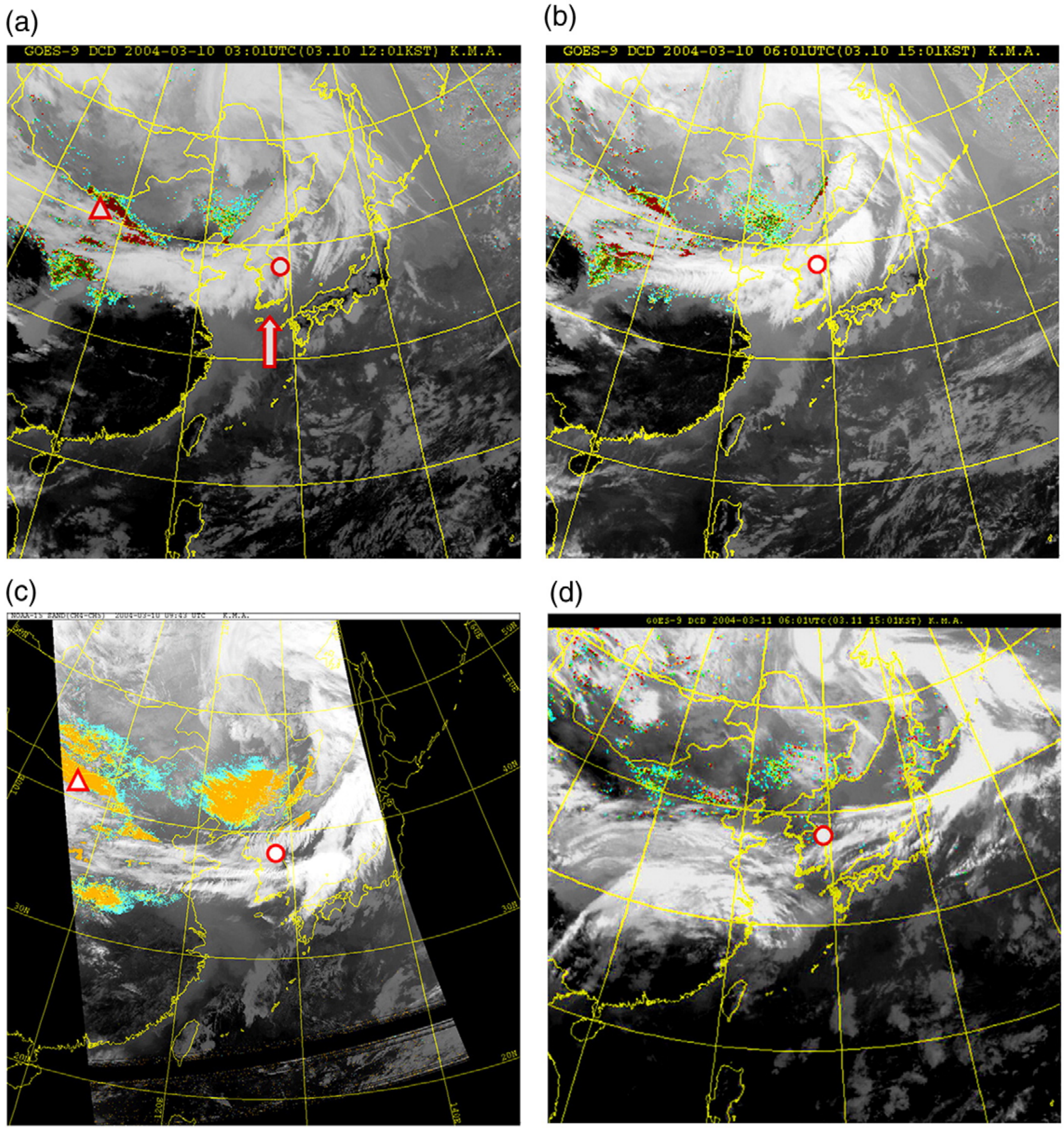

Fig. 6. GOES-9 satellite pictures on March 10, 2004, at (a) 0300 UTC (1200 LST), (b) 0600 UTC (1500 LST), and (c) 0943 UTC (1843 LST) and on March 11, 2004, at (d) 0300 UTC (1200 LST). Dark red and blue areas on GOES images indicate dust generation and dispersion areas with high-density dust. Yellow areas on NOAA image denote high-density dust, and blue areas indicate dust dispersion areas. Triangle, arrow, and circle denote dust generation areas in China, Korea, and Kangnung, respectively.

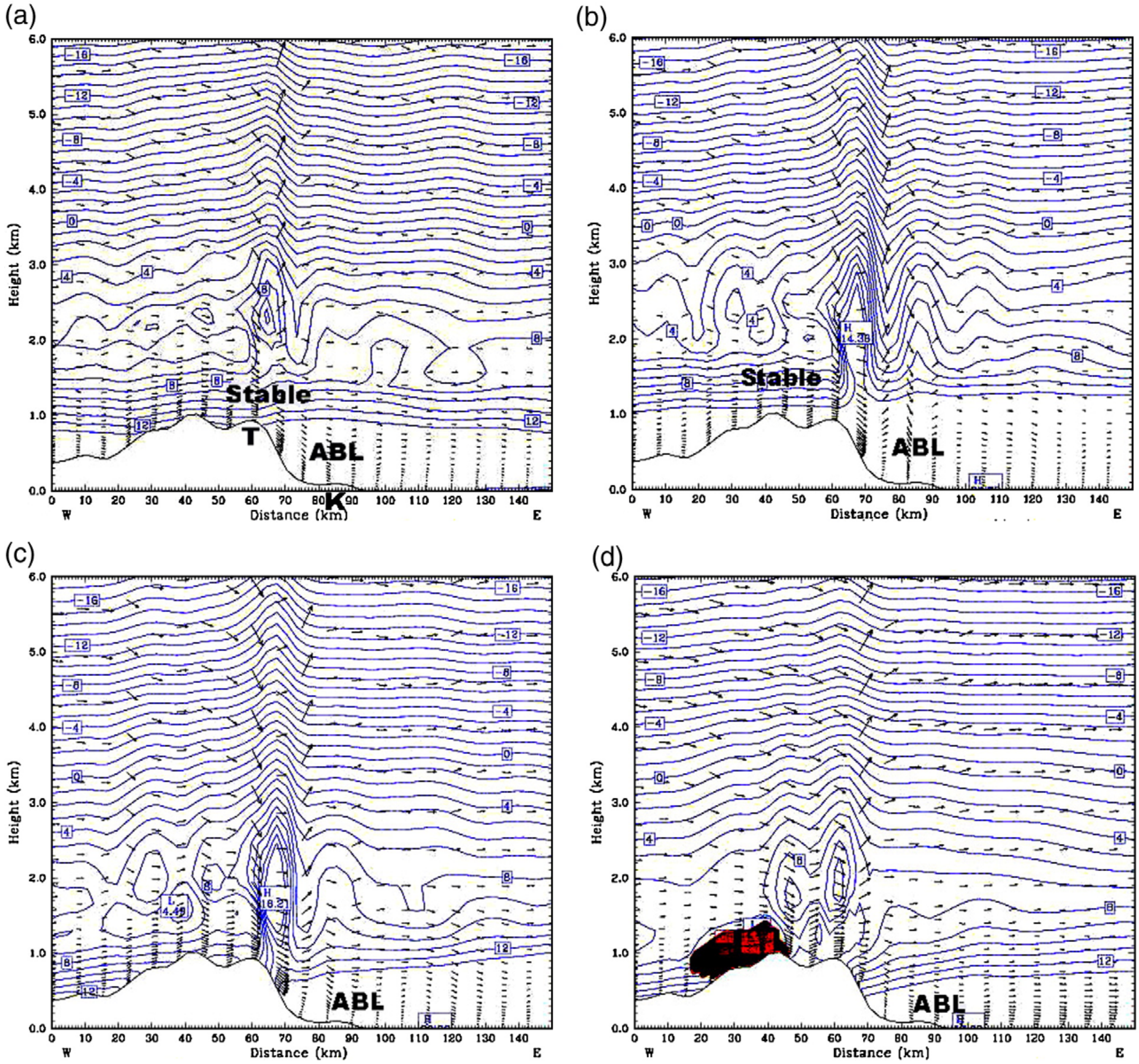

Fig. 7. Vertical profiles of air temperature (°C) and wind speed (ms^{-1}) on March 10, 2004, at (a) 1200 LST (b) 1500 LST, (c) 1800 LST, and (d) 2100 LST. T, K, and ABL denote Mt. Taegulyang, Kangnung, and atmospheric boundary layer. Thick red parcel on the mountain denotes a cloud as upper-stable layer over ABL acts as lid at the top of Mt. Taegulyang and traps a large amount of dust particles. Particulate matter concentration at 1200 LST is very high. At 1500 LST, ABL expands over mountain top and concentration gradually decreases, while PM concentration at Kangnung increases due to transport of a large amount of dust particles trapped in the mountain side and downslope toward Kangnung city. As the depth of ABL decreases in the evening and at night, PM concentrations increase (see Figs. 3 and 4).

in the city. A boundary layer up to 200 m in depth over the mountain could induce higher PM_{10} concentrations than a boundary layer 1–1.2 km in depth over the city, as shown in Fig. 7.

4. Conclusion

During a duststorm occurring from March 10–16, 2004, a large amount of dust passed over the coastal city of Kangnung, Korea, due to a westerly wind influence. Concentrations of PM_{10} reached 340 μg m^{-3}, and $PM_{2.5}$ and PM_1 concentrations reached 105 and 60 μg m^{-3}, respectively, indicating double the PM concentration for PM_{10} as compared to $PM_{2.5}$. Most of the dust transported from China consisted of particle sizes larger than $PM_{2.5}$ and PM_1.

A high concentration of particulates was detected at 0900 LST, just before office hours, and again from 1700–2200 LST. Transported dust from the western, upwind side in the mountain area under the influence of a westerly wind was directed to the downwind side (Kangnung). This dust combined with fuel combustion particulates emitted from road vehicles and residential boilers in the city after sunrise and resulted in the high PM concentrations by 0900 LST. Low PM concentrations occurring around 1200 LST near the ground surface were due mainly to particles rising to the top of a thick convective boundary layer. However, PM concentrations on the mountains were very high due to the entrapment of dust particles in a very shallow boundary layer.

High PM concentrations occurred again in the city after sunset due to increased fuel combustion of road vehicles and residential boilers after 1700 LST and a decrease in boundary layer depth. Particle emissions from vehicles and boilers combined with transported dust particles from the mountains producing a maximum PM concentration at 2200 LST in a decreased boundary layer depth.

Acknowledgements

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