Trapping Effect of a Calm Zone by Lee Side-Internal Gravity Waves and Cyclonic Winds on Sudden High Concentrations of Particulate Matters combined with the Yellow Dusts from Gobi Desert in the Korean Eastern Coast

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Abstract

Sudden high particulate matter concentrations of PM_{10}, $PM_{2.5}$ and PM_1 measured by a GRIMM-1107 aerosol sampler in the Korean eastern mountainous coast, Gangneung city were investigated on October 23 ~ 27, 2003. Until 18:00LST, October 24, before a Yellow Dust period under the transportation of dust particles to the city, PM_{10}, $PM_{2.5}$ and PM_1 concentrations were lower than 40 $\mu g/m^3$, 25 $\mu g/m^3$ and 23 $\mu g/m^3$ respectively. Backward trajectories of air by NOAA- HYSPLIT model and wind fields by numerical simulation by 3D-WRF-3.3 model indicated the transportation of dusts from Gobi Desert and the northern China toward the Korean coastal city from 1800 LST October 24 to 1900 LST October 25 (dust period).

Under the combination of dust particles transported from China and local pollutants like gases and particulate matters emitted from vehicles and flying dusts on the road and additionally from heating boilers in the resident area, maximum concentrations of PM_{10} with 104.38 $\mu g/m^3$ occurred at 07:00LST around the time to go to the office and maxima of $PM_{2.5}$ and PM_1 were at 09:00LST. Similarly, secondary maxima of PM_{10}, $PM_{2.5}$ and PM_1 were detected at 17:00LST around the time to come from the office.

After cold front passed by the Korean eastern mountainous coastal region, synoptic-scale north-westerly wind was more intensified which blew over the top of Mt. Taegulyang and moved down along its eastern slope toward the city, resulting in a strong downslope wind storm. The downslope wind storm caused the propagation of lee side-internal gravity waves along the eastern slope bounding up and down with a hydraulic jump motion of air and the gravity waves produced a cavity of calm or weak wind under wind shift by a cyclonic circulation in the coastal basin. Thus, as westerly downslope wind was prohibited from easterly wind from the sea toward the inland coast, the dusts transported from Gobi Desert combined with particulate matters or gases emitted from vehicles on the road of the city could be trapped and merged within a calm cavity in the coastal basin, resulting in maximum particulate matter concentrations in the city at 07:00LST, October 25.

Keywords: Particulate matter, Yellow Dust period, NOAA-HYSPLIT model, WRF-3.3 model, internal gravity waves.

Introduction

Yellow Sand Storm called Asian Dust Storm or KOSA originated from mainly Taklamakan Desert, Gobi Desert, Ordos Deserts and Loess plateau in Nei-Mongo surrounding the southern Mongolia in dry spring, when strong winds over than about 10m/s under less than 40% of relative humidity near the ground surface remove a great amount of sand and dust from the ground surface of the desert or the dried area into the lower atmosphere[1, 2]. Chon[3] indicated that during a dust storm period, huge amount of dust and sand particles move to the long distances of several thousand kilometers, resulting in the reduction of the visibility less than 1km and severe pollutant concentration in the areas on the dust path of northern Asian countries and even U.S.A.[4- 7]

Most of dust particles which influenced upon the occurrence of a high particulate matter concentration in Korea came from Gobi Desert, Xinjiang province of China and Inner-Mongolia (Nei-Mongo) of Ningxi, Shanxi and Gansu provinces[8-10]. On the other hand, the dust effect in Korea has been still detected in autumn and winter with a relatively smaller particulate matter concentration than in spring[11-14]. Major researches on the Asian Dust Storm have been focused on the generation of dust and sand particle from the dried ground surface and local loading and chemical component analysis of dusts on its transportation route from the dust origin toward the down wind sites, using measurement by aerosol sampler and observation by lidar, remote sensing by satellite images and synoptic-scale meteorological analysis by weather chart and numerical model[15, 16].

However, Choi et al[17] presented merging processes of total suspended particulates locally emitted from the ground surface of the Seoul metropolitan area toward the ground surface at night and their recycling process in the morning using a three dimensional random walk model of particles.

Uzen and Alpert[18] showed that the highest air pollution events in the eastern Mediterranean coast occur during summer at 12:00~15:00 LST through the drop of atmospheric boundary layer height to 450 m above the ground. During the Asian Dust Storm period, Choi et al[19] described a sudden high concentration of total suspended particulates affected by shrunken daytime atmospheric boundary layer in Seoul metropolitan area under the cold front passage during Chinese dust storm period, using a MM5 numerical model. On the other hand, Choi et al[10] also explained the occurrence of abrupt high particulate matter concentration of PM_{10}, $PM_{2.5}$ and PM_1 in the nocturnal surface inversion layer in the eastern mountainous coastal region of Korea.

In this study, author focuses on the explanation of the formation of sudden high concentrations of particulate matters for few hours, related with the trapping of dusts inside a calm cavity generated by internal gravity waves in the lee side of the mountain and cyclonic winds in the coastal basin, reverse to prevailing westerly wind accompanying dust particles from the northern China toward the Korean eastern coast during a Yellow Dust period.

Topographical Feature of Study Area

The study area around Gangneung city ($37^0$45’ N, $128^0$54’ E) indicating a fine-mesh domain (box) in fig. 1 covers an eastern coast of Korean peninsula as a basin which includes high mountains in the west and sea in the east. Daily weather of the city is affected by not only steep mountains, but also by the East Korea Warm Current (EKWC) as branch currents of Kuroshio Warm Current, bound for north, following the eastern coast of Korea. Gangneung is a clean coastal city where there is no special industry and its population is about 230,000[20].

In this city, main air pollution sources are vehicles on the road and heating boilers in the residential area, especially apartment. As high mountainous area in the west of the city are strongly heated during the day, upslope wind combined with valley wind from inland basin to the mountain top and sea breeze from the coastal sea to the inland basin is generally developed while nocturnal downslope wind combined with mountain and land breezes is dominant in the coastal inland and sea. However, synoptic-scale westerly and easterly winds in the eastern coastal region of Korea always response positively or negatively to both meso-scale sea-valley breeze during the day and mountain-land breeze at night.

Numerical Model

Measurement of particulate matters: Concentrations of particle sizes of 0.3 ~ 20 μm have been measured by German aerosol sampler of GRIMM-1107 in the eastern coastal city of Korea from October 23 ~ 27, 2003 when local particulate matter concentrations (PM) were greatly affected by dust transportation from China during a Yellow Dust period. Aerosol sampling instrument was installed in an instrument shelter at Gangwon Regional Meteorological Administration (20 m height above mean sea level) in the downtown of Gangneung city adjacent to the East Sea of Korea.

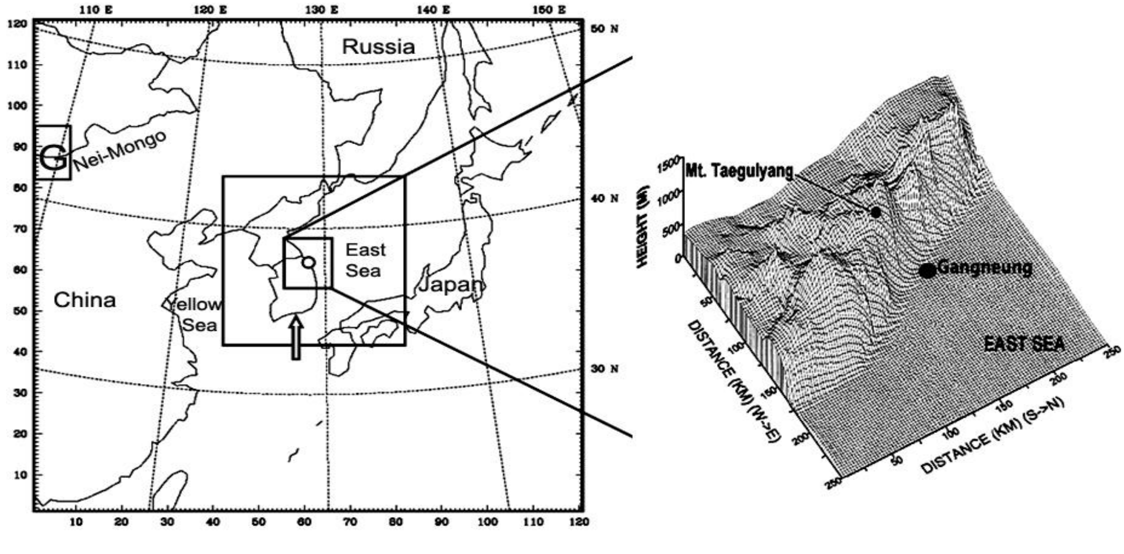


Figure 1: Topographical features in the northeastern Asia including Gangneung city (a small circle in the center) in the Korean eastern coast ($37^0$45’ N, $128^0$54’ E; 20 m height) in which an aerosol sampler was equipped.[21] G in a left square in the left figure denotes Gobi Desert and two inner squares near the center of the figure denote the 2nd and 3rd domains with each 9 km and 3 km horizontal grid in WRF model simulation. A three dimensional figure in the vicinity of Gangneung city, Korea turns to a 90^0 degree right from the 3rd domain of WRF model in the left.

The Model 1107 is a portable particle analyzer and also a PM monitor to offer dual technology consisting of both optical and gravimetrical analysis[10]. This 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 channel, pulse-height analyzer for size classification. The counts from each size classification are then converted to mass by a well established equation which 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. Then the data are presented as PM_{10}, $PM_{2.5}$ and PM_1.

Numerical model and input data: For depicting backward trajectories of dust particles with time, NOAA-HYSPLIT model (hybrid single particle Lagrangian integrated trajectory) from the Air Resources Laboratory (ARL) using FNL meteorological data was adopted and the heights of dust particle trajectories were set up at 2000 m, 1000 m and 500 m, considering dust floating level for investigating their transportation routes from a dust origin toward Gangneung city in the Korean eastern coast respectively (Fig. 3).

This model showed very detailed information on temporal transportation routes of dust particles and their flowing height and major spreading area. Thus, back trajectories of air with a time-step of 6 hour interval over a period of 120 hours using the HYSPLIT model were depicted at 500 m, 1000 m and 2000 m above ground level in order to detect possible links between diurnal variation of PM concentrations and pathway of dust particles transported from both Gobi Desert and Nei-Mongo in the northern China toward a Korean eastern coastal city.

For the numerical simulation on the generation of meteorological phenomena, a three-dimensional, non-hydrostatical grid point model called Weather Research and Forecasting Model (WRF)-3.3 with a terrain following coordinate system was adopted on the route of dust transportation from China to Gangneung city in the eastern coast of Korea from 00:00 UTC (Local Standard Time (LST) = 9h + UTC; 09:00 LST), October 23 through 00:00UTC, October 27, 2003 (left of Fig. 1). In the numerical simulation, one way, triple nesting process from a coarse-mesh domain to a fine-mesh domain was performed using a horizontal grid spacing of 27 km covering a 120 x 120 grid square in the coarse mesh domain. The second and third domains also consist of the same grid square of 120 x 120 with 9 km and 3 km horizontal grid intervals respectively.

As meteorological input data to the model, National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis-Final Analyses (FNL) 1.0^0 x 1.0^0 resolution data were used and were vertically interpolated onto 36 levels with sequentially larger intervals increasing with height from the surface to the upper boundary level of 100 hPa.

In the WRF model, WSM 6 scheme was used for microphysical processes for the heat and moist budgets in the atmospheric boundary layer and the YSU PBL scheme for the planetary boundary layer. The Kain-Fritsch (new Eta) for cumulus parameterization, the five thermal diffusion model for land surface and the RRTM long wave radiation scheme and dudhia short wave radiation schemes were also used[10].

In using a three dimensional numerical WRF-3.3 model to generate meteorological phenomena, input terrain data with a horizontal resolution of 1° were used for the first domain and 1 km horizontal resolution data were used for second domain and third domain. These domains cover the major transport route from both Gobi Desert in the southern Mongolia and Nei-Mongo in the northern China where dust storms originated. Meteorological elements such as wind were evaluated horizontally and vertically in northeastern Asia sequentially in the three-mesh domains of WRF model. Hourly archived wind data measured by Gangwon Regional Meteorological Administration in Gangneung city were used for the verification of numerical results of the meteorological elements.

Results and Discussion

Aerosol concentration before Yellow Sand period: Fig. 2 indicates hourly distribution of PM_1, $PM_{2.5}$ and PM_{10} concentrations at Gangneung city from 00:00 LST October 23 to 17:00 LST October 24, 2003. No special industry exists at the city in the eastern mountainous coast of Korea. Main air pollution sources of the city are vehicles on the road and heating boilers in the residential area especially apartment complex, which greatly affect local PM concentrations. Due to the effects of mountain and sea, daytime air temperature is in the range of 10 ~ 20 ^{0}C in October, but night time one is much lower with the range of 5 ~ 10 ^{0}C, showing a big diurnal temperature difference, larger than 5 ^{0}C. Thus, heating boilers work for generally a few hours in the resident area around sunset and sunrise.

Until 17:00LST, October 24, before the transportation of dust particles from Gobi Desert in the southern Mongolia and Nei-Mongo in the northern China where dust storm originated, PM_{10}, $PM_{2.5}$ and PM_1 concentrations at Gangneung city were lower than 40 μg/m^3, 25 μg/m^3 and 23 μg/m^3 respectively. Their distributions had similar tendencies on their occurrence times of maximum and minimum concentrations with very small time deviations.

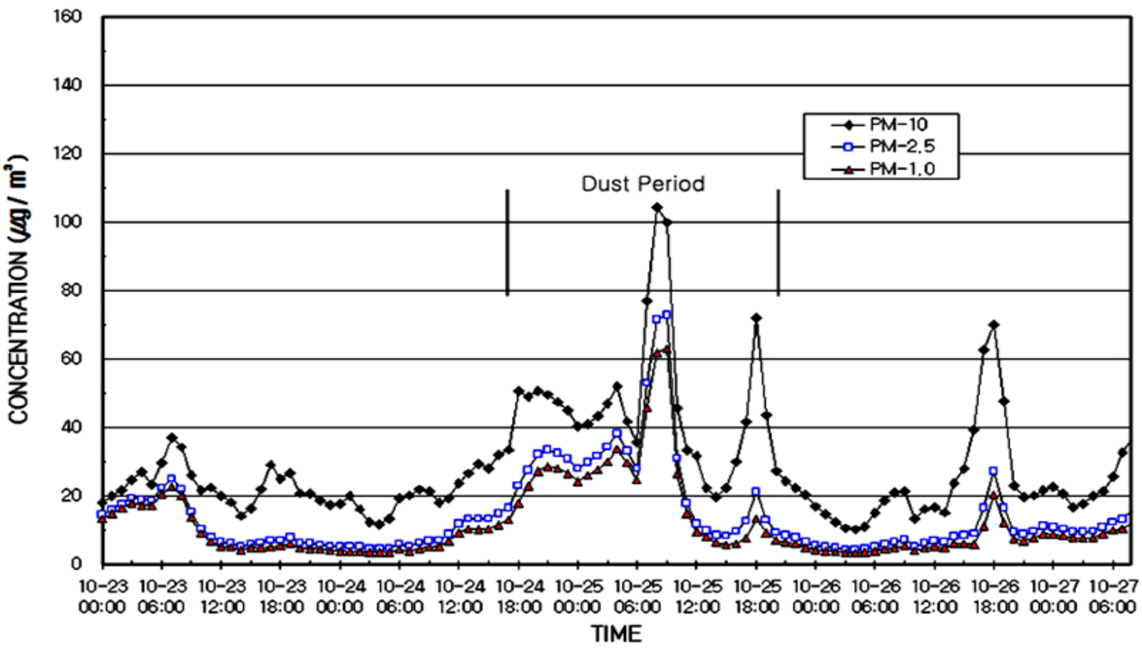


Figure 2: Hourly distributions of PM_{10}, $PM_{2.5}$ and PM_1 concentrations at Gangwon Meteorological Administration located in the downtown of Gangneung city from October 26 ~ 29, 2003.

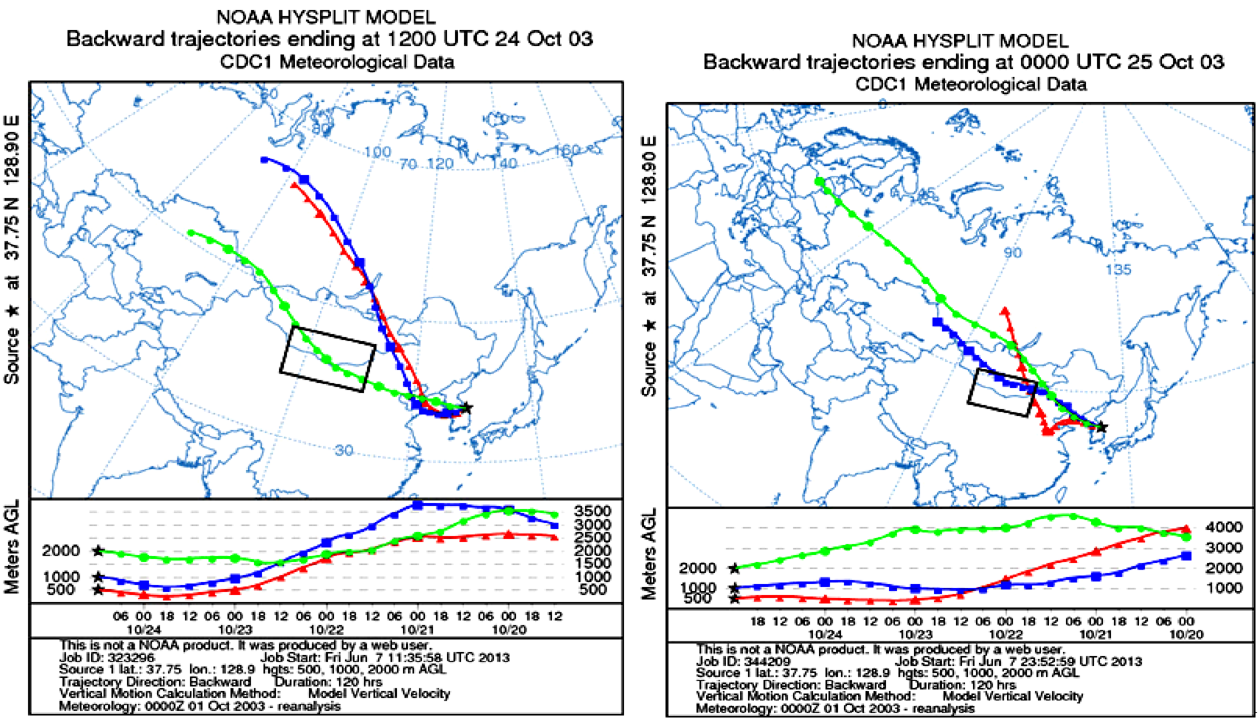
Maximum concentration of PM_{10} with 37.34 ug/m^3 occurred at 07:00 LST around time going to the office due to a larger amount of pollutants such as particulate matter and gases emitted from vehicles on the road, flying dusts from the road and particulate matter and gases emitted from heating boilers near sunrise in the residential area. Maxima of $PM_{2.5}$ with 24.93 $\mu g/m^3$ and PM_1 with 22.58 $\mu g/m^3$ were detected at 07:00 LST at the same time in case of PM_{10}.

Secondary maximum of PM_{10} occurred 17:00 LST around the time coming from the office near sunset due to the similar conditions to the morning case, but maxima of $PM_{2.5}$ and PM_1 occurred 19:00 LST on October 23 with two hours delay. The magnitudes of maximum PM_{10}, $PM_{2.5}$ and PM_1 concentrations around 07:00 LST in the morning on October 23 and 08:00 LST on October 24 were larger than ones 17:00 LST in the evening, except for October 24 with an increasing trend of particulate matters under a little influence of transported dust particles from Gobi Desert to the city.

Aerosol concentration during Yellow Sand period: From 18:00 LST, October 24 until 20:00 LST, October 25, as dusts were transported from Gobi Desert toward Nei-Mongo by westerly wind and from the north-eastern China toward the Korean peninsula by north-westerly wind, PM_{10}, $PM_{2.5}$ and PM_1 concentrations rapidly increased with time. Maximum PM_{10} concentration of 104.38 $\mu g/m^3$ occurred at 08:00 LST and its magnitude reached about 2.8 times larger than one on October 23 and 24 before the dust period. Similarly, maxima of $PM_{2.5}$ of 72.72 $\mu g/m^3$ and PM_1 of 62.87 $\mu g/m^3$ occurred at 09:00 LST and their magnitudes were 2.9 times larger than ones before the dust period. It means that dusts transported from Gobi Desert, regardless of particle sizes, greatly influenced upon the local PM concentrations of the city.

Especially, after cold front passed by Gangneung city at 06:00 LST, October 25, northerly and north-westerly winds generated by a high pressure system should transport a large amount of dust particles from Gobi Desert to Nei-Mongo in the northern China and then the transported dusts moved toward the Korean peninsula including Gangneung city (Fig. 5a). At 09:00 LST, October 25, maximum concentrations of PM_{10} with 104.38 $\mu g/m^3$ occurred at 08:00 LST (around the time going to the office) and maxima of $PM_{2.5}$ and PM_1 were detected at 09:00 LST, under the combination of dust particles transported from Mongolia and China with both gases and particulate matters emitted from vehicles, flying dusts on the road and additionally from heating boilers in the resident area of the city. Similarly, secondary maxima of PM_{10} with 71.94 $\mu g/m^3$, $PM_{2.5}$ with 21.12 $\mu g/m^3$ and $PM_1$with 13.33 $\mu g/m^3$ were detected at 18:00 LST (around the time coming from the office).

Trapping effect of a calm zone by lee side internal gravity waves and reverse cyclonic wind on high PM concentration: For investigating their transportation routes from dust origin toward Gangneung city in the Korean east coast, dust particle trajectories were set up at 2000 m, 1000 m and 500 m considering dust floating level respectively (Fig. 3). This model showed very detailed information on temporal transportation routes of dust particles and their flowing height and major spreading area but giving whole spreading area of dust particles.



(a) (b)

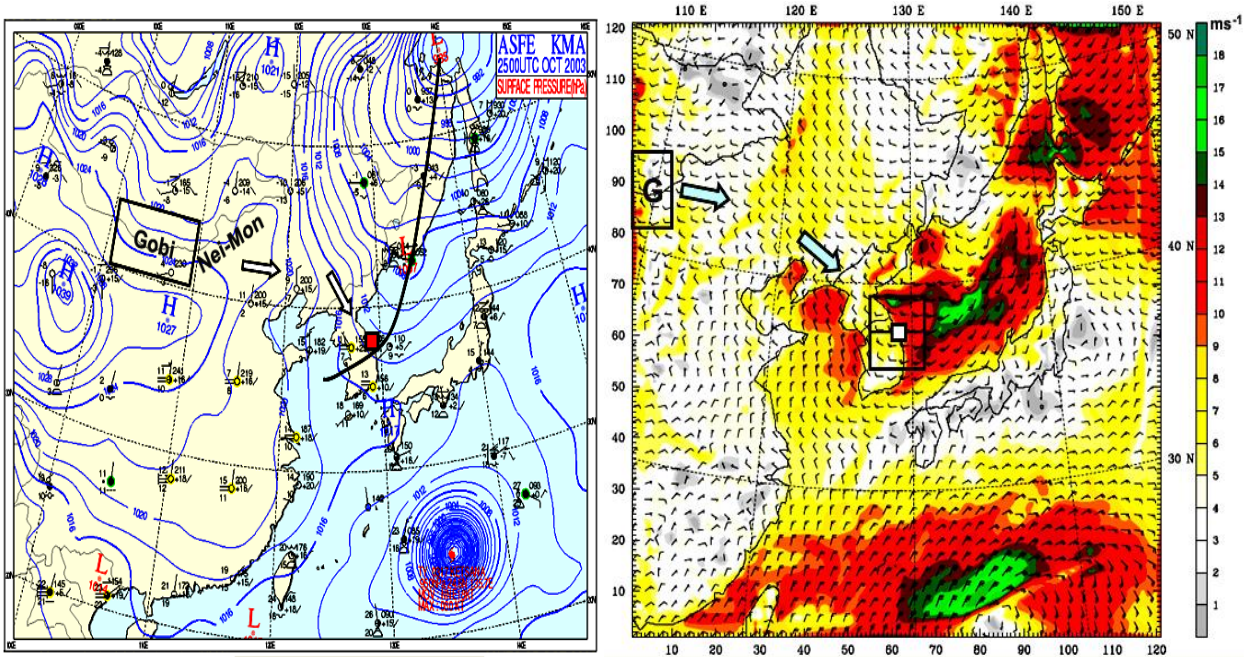
Figure 3: (a) Backward trajectories of air masses at 2000 m, 1000 m and 500 m heights of Gangneung city, Korea by NOAA-HYSPLIT model ending at 21:00 LST (12:00 UTC) on October 24, 2003, (b) at 0900LST (00:00 UTC) on October 25. In (a), dust particles floated from the desert reached about 2000 m height of the city and partially influenced on the increase of PM concentration of the city, but dust particles transported from the heights less than 1000m over Gobi Desert and Nei-Mongo reached at 1000m and 500m heights at Gangneung city of Korea, resulting in maximum PM concentrations.

The dusts floated from Gobi Desert were moved by synoptic-scale wind and some of heavy dust particles during their transportation processes fell down to the ground and were prohibited by obstacles near the ground surface or mountains. Thus, dust particles at least over 500 m height level of the dust origin could be freely transported to Gangneung city and the transported dusts at this level of the Korean city could influence upon the increase of particulate matter and gases concentrations locally emitted from the city.

In fig. 3a, dust particles floated at 2000 m height of Gobi Desert on October 22 and 23 reached 2000 m height of Gangneung city and some amounts of the transported dusts could make a little influence upon the increase of PM concentration as shown in the rapid increase of PM concentrations from 18:00 LST to 21:00 LST, October 24. The increase trend of PM concentrations continued to be on October 25. Air parcels at 1000 m and 500 m height of Nei-Mongo in the west of Mongolia on October 22 and 23 might contain some amounts of dusts transported from Gobi Desert under the westerly wind in figs. 4a and 4b and finally reached 1000 m and 500 m of the city, resulting in the increase of local PM_{10}, $PM_{2.5}$ and PM_1 (PM) concentrations.

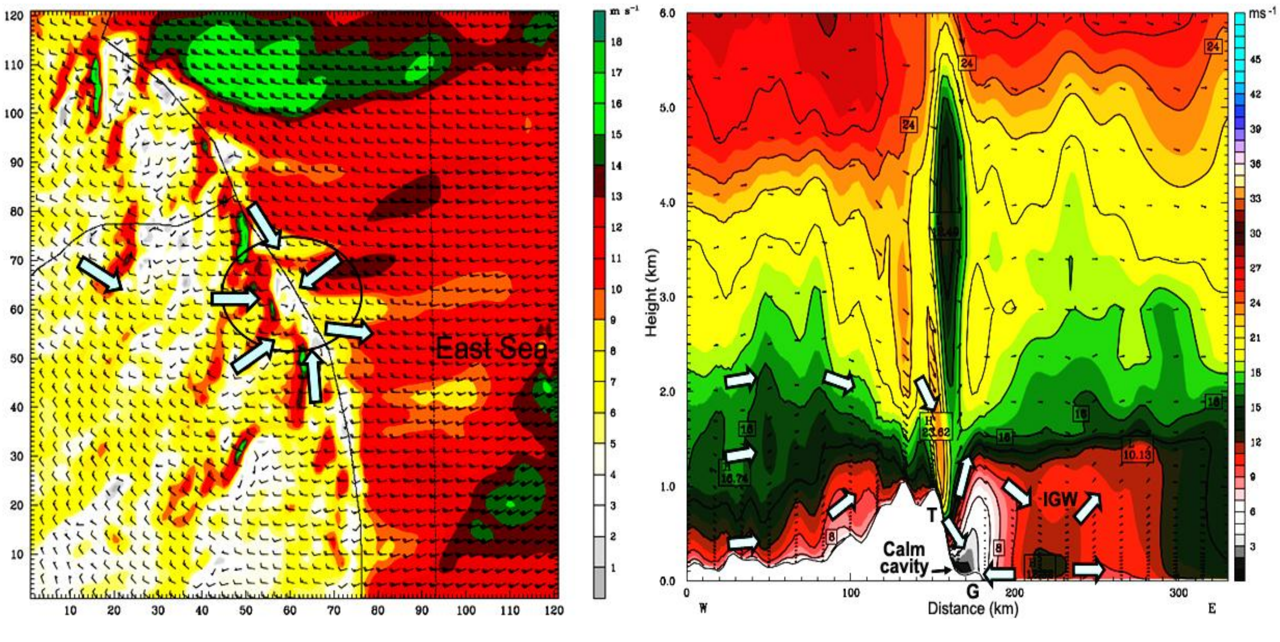
On synoptic weather map at 09:00 LST, October 25 in fig. 4a, as a low pressure system of 1007 hPa was located near Vladivostok, Russia and a high pressure system of 1021 hPa was also located in the region of the south of Gobi Desert to the northern China (Fig. 4a). The high pressure produced northerly wind near Gobi Desert which caused the dusts generated in Gobi Desert to move toward Manchuria in the north-eastern China. Then, under a passage of cold front by Gangneung city (a small square), relatively strong north-westerly wind drove the dusts toward the Korean peninsula, further reaching the city. Under this situation, the transported dust particles could move down to the ground surface of the city (Fig. 4b).

In 3b, dust particles floated at 1000 m and 500 m heights of the desert from October 22 to 24 reached 1000 m and 500 m heights of Gangneung city respectively. Under westerly wind, the dusts transported from the desert also passed by 2500 m height of Nei-Mongo on October 24 and reached at 2000 m height of the city by north-westerly wind as shown in figs. 3b, 4a and 4b. Thus, as a huge amount of the dusts originated from Gobi Desert reached the Korean eastern city at 09:00 LST, October 25, the dusts combined with pollutants such as particulate matter and gases emitted from vehicles on the road, flying dusts from the road and additionally pollutants from heating boilers in the major residential apartments, resulting in maximum PM concentrations at this time.



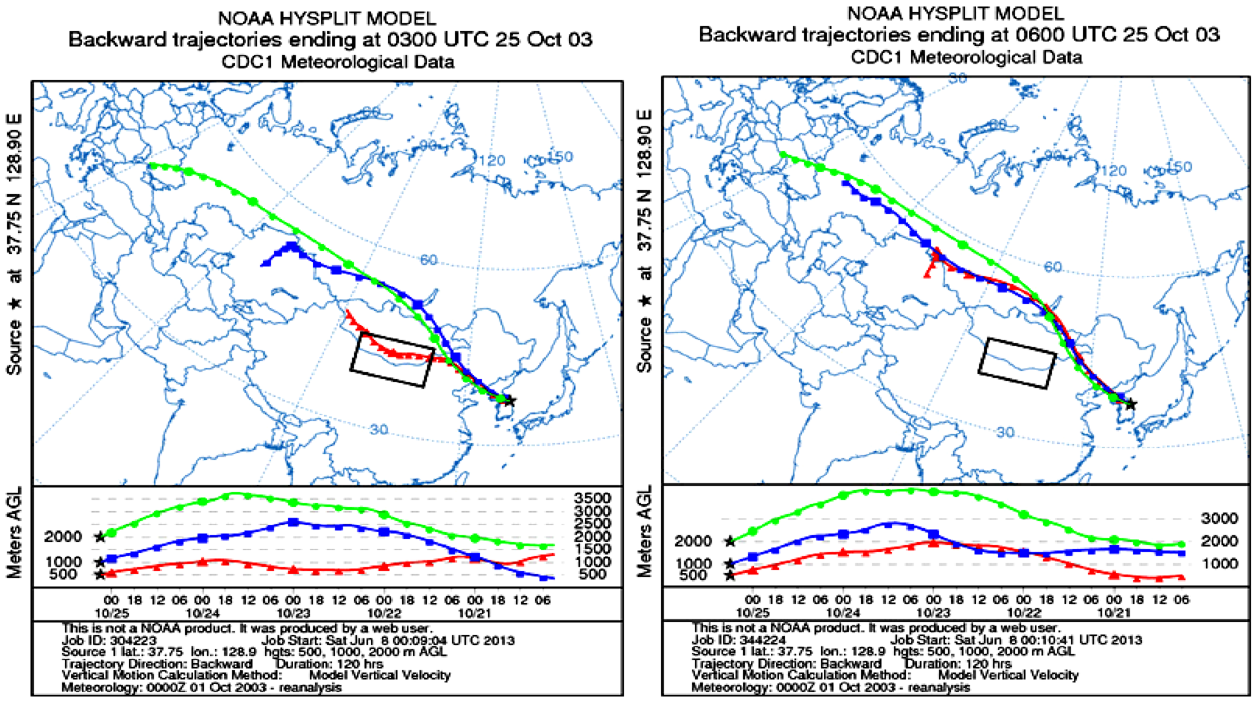
(a) (b)

Figure 4: (a) Surface weather map at 09:00 LST (00:00 UTC), October 25 and (b) simulated surface wind (m/s) at the occurrence time of maximum PM concentrations. A square in the left in (a) denotes Gobi Desert and small and big squares in the center of (b) are Gangneung city and the 3rd domain of WRF model.



(a) (b)

Figure 5: (a) Surface wind (m/s) near Gangneung city in the 3rd domains of WRF model in fig. 5(b) at 09:00 LST, October 25, 2003 and (b) vertical profile of horizontal wind (m/s) on a straight cutting line (y=60) from west to east in (a) Arrows in (a) and (b) and T and G in (b) denote air flow, Mt. Taegulyang and Gangneung city, respectively. Internal gravity waves in (b) and reverse easterly wind near Gangneung city (x=60, y=60) in (a) and (b) could generate a cavity of calm wind or very weak wind where dust particles transported from the desert should combine with local pollutants emitted from the city and be trapped, resulting in the mergence of dust particles near the ground surface of the city and maximum PM concentrations at 08:00LST.



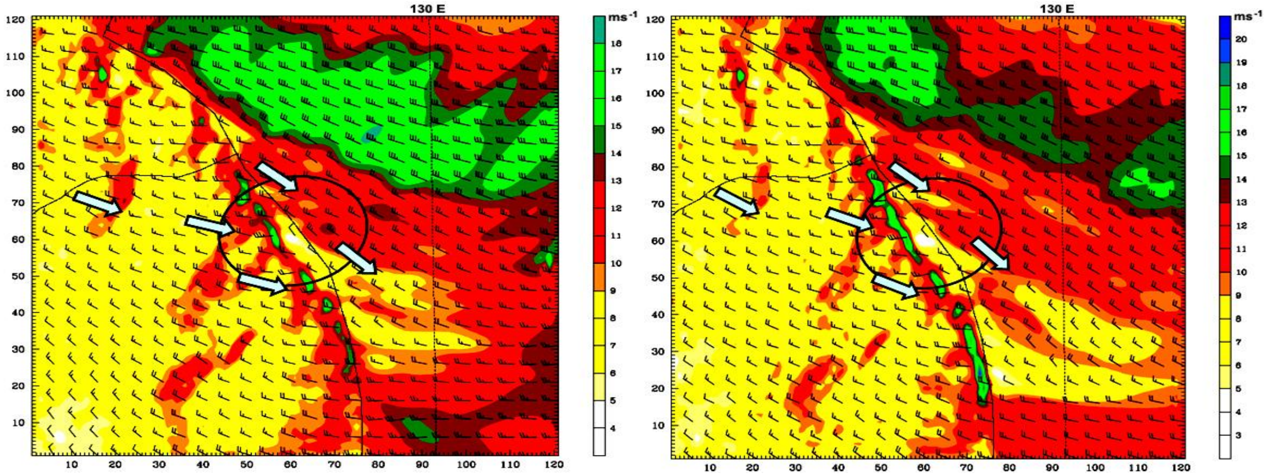
(a) (b)

Figure 6: (a) Backward trajectories of air masses at 2000 m, 1000 m and 500 m heights of Gangneung city, Korea by NOAA-HYSPLIT model ending at 12:00 LST (03:00 UTC) on October 25, 2003 and (b) at 15:00 LST (06:00 UTC). A square denotes Gobi Desert. Dusts uplifted from Gobi Desert were transported by westerly wind to the eastern Mongolia and Nei-Mongo in the northeastern China and the dusts by north-westerly wind reached a 500 m height of Gangneung city, Korea at 12:00 LST. Air parcels passing by no Gobi Desert, but Manchuria made little contribution to high PM concentrations of the city.

After cold front passed by the study area at 06:00 LST, synoptic-scale north-westerly wind was more intensified into westerly wind in figs. 4a and b. The intensified westerly wind blew over the top of a steep mountain called Mt. Taegulyang and moved down along its eastern slope toward the coastal basin (Gangneung city), resulting in a strong downslope wind storm of 23.62 m/s (Fig. 5b). The strong downslope wind storm caused the propagation of lee side-internal gravity waves along the eastern slope toward the East Sea, bounding up and down, resulting in a cavity of calm wind. Simultaneously the downslope westerly wind was prohibited from easterly wind from the sea toward the inland coast (Fig. 5a). The dusts transported from China by north-westerly wind toward the city could combine with particulate matters or gases emitted from vehicles on the road of the city. The combined dusts could be merged within a calm zone in the coastal basin (Gangneung city) and trapped by reversal marine easterly like a cyclonic wind, resulting in maximum particulate matter concentrations at 08:00LST, October 25.

Dust particles floated at about 500 m height of Gobi Desert on October 22 and 23 moved toward Nei-Mongo area by westerly wind and then passed by north-eastern China (Manchuria) by north-westerly wind, finally reaching at 500 m height of the Korean eastern coastal city at 12:00 LST (03:00 UTC), October 25, as the high pressure moved eastward (Figs. 6a and 7a). On the other hand, air parcels reaching about 2000 m and 1000 m heights of the city might contain some amounts of dusts floated at about 1000 ~ 2000 m heights of Nei-Mongo which were transported from 500 m height of Gobi Desert. The transported dusts in Manchuria moved to the city by north-westerly wind, resulting in making a little contribution to the increase of the ground based particulate matter concentrations to some extent. Major contribution to the local PM concentrations of the city was made by dusts transported from a 500 m height of Gobi Desert and minor contributions were by 1000 m and 2000 m heights of the desert.

As shown in fig. 7a, wind fields in the inland basin and coastal sea of Gangneung city indicated relatively strong north-westerly wind over than 5 m/s. Thus, all of dusts transported from the northern China combined with local pollutants rapidly moved toward the East Sea without any sustenance in the coastal basin, resulting in low PM concentrations. As daytime goes on, especially, around noon, strong thermal convection by the daytime heating of ground surface should uplift air parcels including locally emitted particulate matters and gaseous to the top of the convective boundary layer extended vertically in the inland basin or similarly the thermal internal boundary layer (TIBL) in the coastal basin, resulting in very low PM concentrations near the ground surface around 12:00LST. However, very high PM concentrations could be at the top of the TIBL[10].



(a) (b)

Figure 7: (a) Surface wind (m/s) at 12:00 LST (03:00 UTC), October 25, 2003 and (b) a5 15:00 LST (06:00 UTC) in the vicinity of Gangneung city (x=60, y=60). The combined dusts from the northern China with ones locally emitted from the city rapidly moved by strong north-westerly wind toward the sea without their sustenance in the coastal basin.

Thus, low PM concentrations at 12:00 LST, October 25 might be also attributed to the uplifting of some amount of transported dusts with locally emitted particulate matters to the top of the thermal internal boundary layer and furthermore no operation of heating boilers in the residential area for daytime hours.

On the other hand, all of air parcels reaching 2000 m, 1000 m and 500 m heights of Gangneung city at 15:00 LST, October 25 passed by no Gobi Desert but Nei-Mongo and Manchuria (north-eastern China). Even though air parcels originally started from the southern Russia in Europe, they might contain a little amount of dusts passing by Manchuria (Fig. 6b). However, they were basically clean air masses. The air parcels reaching the city might make a little contribution to the increase of PM concentrations at this time. Similarly to the case of 12:00 LST, October 25, the development of daytime thermal internal boundary layer in the coastal basin caused the vertically extension of atmospheric boundary layer which uplifted dust particles toward its top and resulted in very low PM concentrations near the ground surface as shown in fig. 2

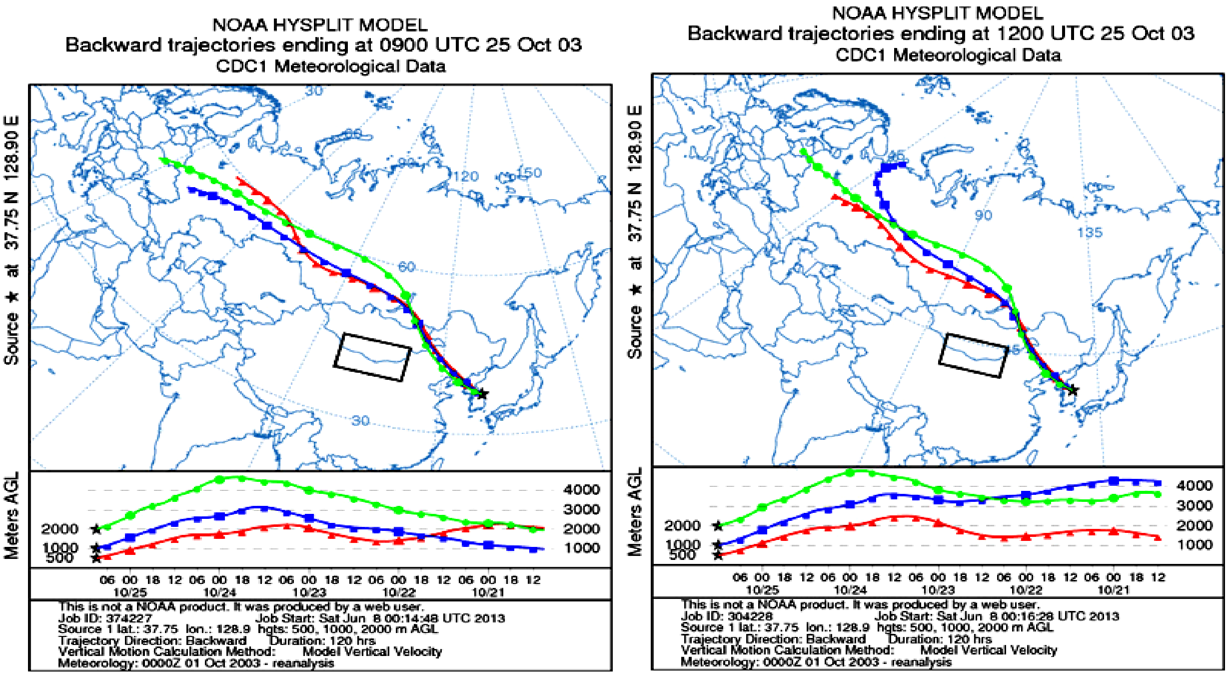
Differently from 09:00 LST, wind near Gangneung city at 12:00 LST was north-westerly in both the coastal inland and sea (Fig. 7a). The transported dusts from the Gobi Desert could combine with ones emitted from the coastal city, they were rapidly drove by relative strong north-westerly wind toward the sea, resulting in no longer sustenance in the coastal basin and low PM concentrations near the ground surface in the city.

All of air parcels reaching 2000 m, 1000 m and 500 m heights of Gangneung city at 18:00 LST around sunset and 21:00 LST in the evening on October 25 passed by no Gobi Desert, but Nei-Mongo and Manchuria (north-eastern China). Basically clean air parcels originally started from the southern Russia in Europe and then passed by Nei-Mongo and Manchuria on October 24 and reached Gangneung city in the afternoon of October 25 (Fig. 8a). They might still contain a little amount of dust dispersed from Gobi Desert in the north-eastern China.

As wind was westerly in Gobi Desert, Nei-Mongo and Manchuria and north-westerly in the Korean peninsula including Gangnung city, the transported dusts reaching the city could make a little contribution to the increase of PM concentrations (Figs. 9a, 9b, 10a and 10b). Thus, high PM concentrations at 18:00 LST were due to the increase of particulate matter concentrations by the combination of dusts transported from Gobi Desert and Nei-Mongo with local particulate matter and gases from the increase of vehicle number on the road around the end time of office hour and the operation of heating boilers in the residential area. Many tourists coming from Seoul (capital city of Korea) and other cities drove their cars to Gangneung city on Sunday afternoon and the increase of vehicles coming from the outside cities with ones inside city could also influence upon the high PM concentrations, compared to normal working days.

Furthermore, near the sunset, nocturnal surface inversion layer due to the cooling of ground surface under no sun radiation should be much shrunken than the daytime boundary layer[10]. The shrunken stable nocturnal surface inversion layer (NSIL) should cause particulate matters to be merged into the ground surface, resulting in a high concentration of PM_{10} with similar trends in $PM_{2.5}$ and PM_1

at 18:00 LST.



(a) **(b)**

Figure 8: (a) Backward trajectories of air masses at 2000 m, 1000 m and 500 m heights by NOAA-HYSPLIT model ending at 18:00 LST (09:00 UTC) on October 25, 2003, (b) at 2100LST (12:00 UTC). A square in the figure denotes Gobi Desert.

At 21:00 LST in the evening, all of air parcels reaching 2000 m, 1000 m and 500 m heights of Gangneung city passed by no Gobi Desert (Figs. 8b and 9a). As basically clean air parcels originally started from the southern Russia in Europe and passed by Nei-Mongo and Manchuria on October 24 and 25, the parcels might contain little amount of dust particles this region. The transported dusts reaching the city under westerly and north-westerly winds could make little contribution to the increase of PM concentrations.

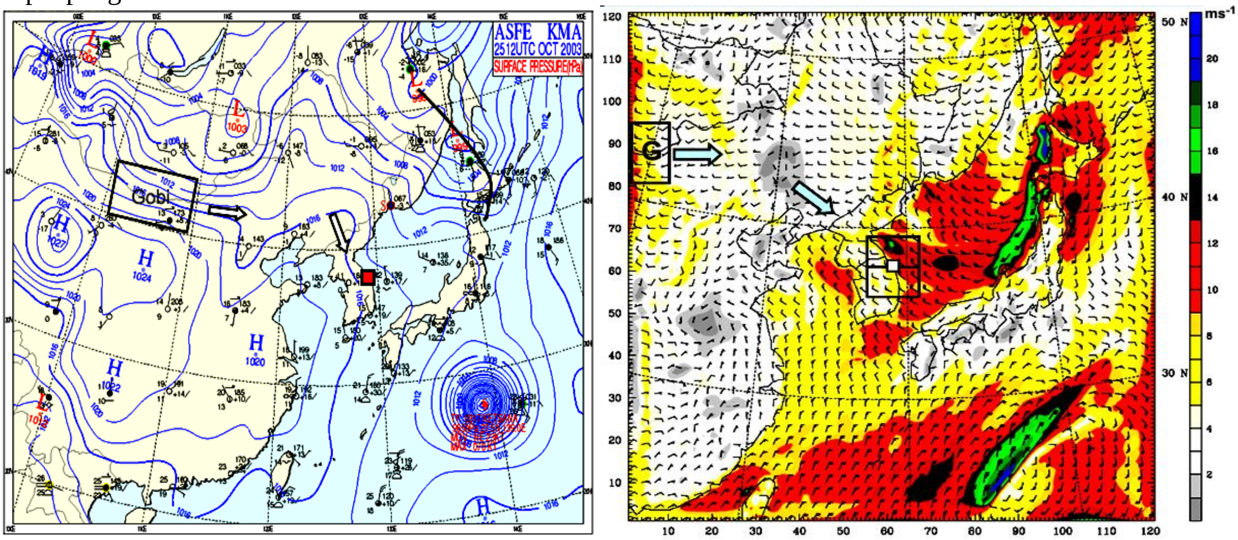
After 18:00 LST, the number of vehicles on the road rapidly decreased and the amounts of particulate matters emitted from vehicles and flying dusts on the road of the coastal city could also decrease. In general, the operation of heating boilers in the residential area is limited to a few hours around sunset due to not much cold weather in October under the influence of the East Korea Warm Current in the coastal sea and only a little emission amount of particulate matter and gases from the residential area was expected. Even though nocturnal surface inversion layer was shrunken, PM concentrations near the ground surface of the city were very low, similar to common state before the dust period.

Since 21:00 LST, October 25, PM concentrations rapidly decreased and continued to be in the morning of October 26. The distribution of PM10, PM2.5 and PM1 concentrations showed their high concentrations at 09:00LST and 18:00 LST and low concentrations were near noon. As October 26 is Sunday and a few numbers of vehicles were detected on the road, due to little movement of residents of the city, the emission amounts of particulate and gases were much smaller than one on the normal working day.

On the other hand, most vehicles drove by tourists moved toward their cities and number of vehicles on the road also increased again around 18:00 LST and some amounts of dusts transported from the northern China were detected in the Korean east coast again. Thus, the combination particulate matter and gases locally emitted from the city by tourist and residential cars, heating boilers and further dusts transported from China could cause high PM concentrations at 18:00LST, under relatively shallower nocturnal surface inversion.

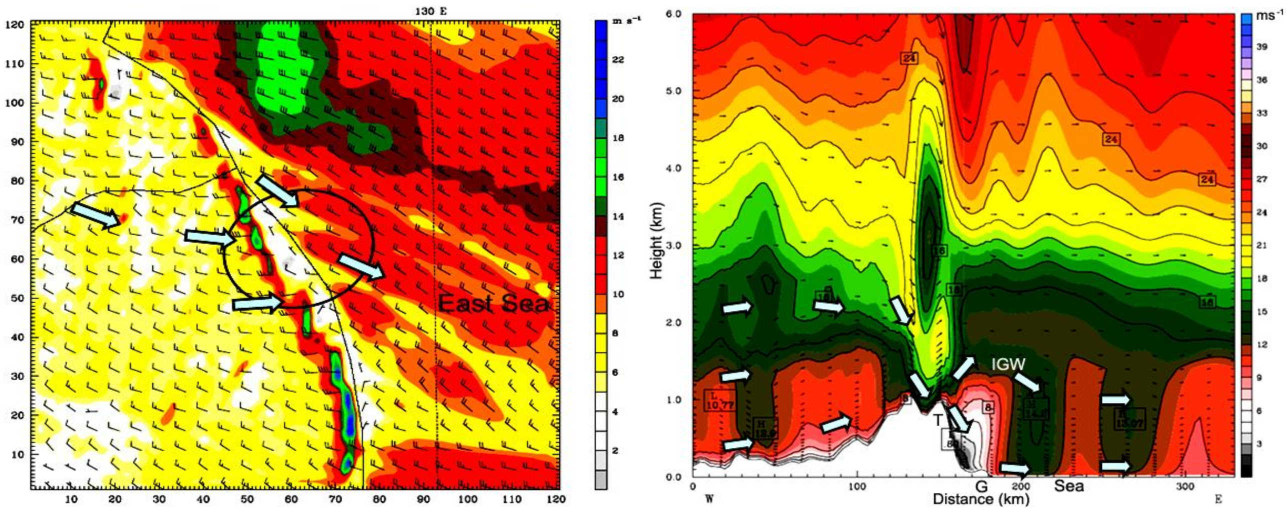
Conclusion

Sudden high particulate matter concentrations of PM_{10}, $PM_{2.5}$ and PM_1 in the Korean eastern coastal city were investigated using a backward trajectory model and a three-dimensional numerical model for a dust transportation period from Gobi Desert towards the city. Before the transportation of dust particles to the city, PM_{10} ($PM_{2.5}$ and PM_1) concentrations were very low, showing its first maximum concentration at 07:00 LST (09:00 LST) and second maximum at 17:00 LST. Maximum concentrations of PM_{10} ($PM_{2.5}$ and PM_1) occurred at 08:00LST around the time when people go to the office.



(a) (b)

Figure 9: (a) Surface weather map at 21:00LST, October 25 and (b) simulated surface wind (m/s) at 18:00 LST at the occurrence time of maximum PM concentrations. A square in the left in (a) denotes Gobi Desert and small and big squares in the center of (b) are Gangneung city and the 3rd domain of WRF model.



(a) (b)

Figure 10: (a) Simulated surface wind (m/s) near Gangneung city in the 3rd domains of WRF model at 18:00 LST, October 25, 2003 and (b) vertical profile of horizontal wind (m/s) on the straight cutting line (y=60) from west to east in (a). Arrow in (a) and (b) denote air flow and T and G in (d) denote Mt. Taegulyang and Gangneung city respectively. In (b), Dust particles were partially trapped inside a cavity of very weak wind generated by internal gravity waves in the lee-side of the mountain, resulting high PM concentrations at the city.

As cold front passed by the study area, intensified westerly wind blew over the top of the mountain in the west of the city and moved down along its eastern slope toward the city, resulting in a strong downslope wind storm. The wind storm caused lee side-internal gravity waves bounding up and down with a hydraulic jump motion of air and the gravity waves produced a cavity of calm or weak wind in the coastal basin by reverse easterly win near the ground. Thus, the dust particles transported from Gobi Desert combined with particulate matters or gases emitted from the city could be trapped and merged within a calm zone in the coastal basin, resulting in maximum particulate matter concentrations in the city at 08:00LST, October 25.

Daytime PM_{10} ($PM_{2.5}$ and PM_1) concentration was still low due to the uplifting dust particles towards the top of thermal internal boundary layer in the coast. Another highest PM concentration at 18:00 LST was due to the increase of vehicle number by tourist and civilian cars and the operation of heating boilers in the residential area under the shrunken nocturnal surface inversion.

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