

Satellite and ground observations for large-scale air pollution transport in the Yellow Sea region

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Abstract Large-scale air pollution transport (LSAPT) in the Yellow Sea region and their inflow onto the Korean Peninsula were observed through satellite images and ground measurements. LSAPT includes regional continental air-masses saturated with pollutants originating from China and subsequently landing on or passing through the Korean Peninsula. It is also possible to identify the distribution and transport patterns of LSAPT over the Yellow Sea. The ground concentrations for PM₁₀, PM_{2.5} and CO measured at Cheongwon, located in the centre of south Korea, were compared with NOAA satellite images. Notably, the episodes observed of the LSAPT show a PM_{2.5} to PM₁₀ ratio of 74% of the daily maximum concentrations. However, cases of duststorms were clearly distinguished by much higher PM₁₀ concentrations and a ratio of 30% of PM_{2.5} to PM₁₀ for daily maximum concentrations. For the episode on January 27, 2006, the inflow of a regionally polluted continental air-mass into the central and southwestern regions of the Korean Peninsula was observed sequentially at various ground observatories as well as by satellite. The north airflow dissipated the clouds over Mt. Halla on Jeju Island and further downwind, reducing air pollution and creating a von Kármán vortex.

Keywords Large-scale air pollution transport (LSAPT) · Satellite observations · Ground observations · PM₁₀ · PM_{2.5} · Von Kármán vortex

1 Introduction

With the East Asian region emerging as one of the world's three major industrial regions, intensive atmospheric observation campaigns have been conducted in recent years (Hoell et al. 1996, 1997; Huebert et al. 2003; Jacob et al. 2003). Air pollution spreads not only

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regionally but can also transform into other toxic pollutants during transport over long distances. The concentrations of sulphate and O₃ produced photochemically by stationary large-scale polluted air-masses passing through the Yellow Sea were observed to be higher than their corresponding background concentrations caused by the north-northwest airflow (Chung and Kim 1991; Kim and Chung 2005). Furthermore, the concentrations of CO demonstrate an extensive distribution due to the high level of emissions in the East Asian region along with lifetimes of several months (Novelli et al. 1998). The Tae-ahn Peninsula, on the western coast of Korea, displays the highest CO concentration levels in East Asia (Kim and Chung 2008).

Haziness is a measure of light scattering and absorption by aerosols, that is closely related to the concentration of air pollutants (Husar et al. 1981). Meteorological satellites are capable of measuring the characteristics of radiation; thus, satellite data are useful in the detection of forest fires and the resulting smoke plumes (Chung and Le 1984; Fraser et al. 1984). Duststorms and associated dustfalls are also detectable by satellite analysis (Chung et al. 2003a, 2005). Satellite observations of LSAPT of anthropogenic origins were investigated in earlier studies (Chung 1986; Chung et al. 2003c).

Anthropogenic air pollution originating from China affects the Korean Peninsula and Japan as well (Chung et al. 2001, 2003c; Kim and Chung 2005). Therefore, continual impact assessments of the air pollution in the Yellow Sea region are necessary. It is also necessary to observe and analyze episodes of the large-scale transport of air pollution. In this study, NOAA satellite images are analyzed and PM₁₀, PM_{2.5} and CO concentrations are measured at Cheongwon in south Korea.

2 Observation and analysis methods

2.1 Satellite observation

NOAA Advanced Very High Resolution Radiometer (AVHRR) data has six channels: visible (channel 1), near-infrared (channel 2), short-wave infrared (channel 3a), mid-infrared (channel 3b), and two thermal-infrared (channel 4 and 5). Images are made using a false color composite technique based on channels 1, 2, and 4 in the AVHRR data in order to observe the LSAPT (Chung and Le 1984; Chung 1986; Chung et al. 2003a, b, c). Channel 1 (0.58~0.68 μm) is located in the red region, Channel 2 (0.725~1.00 μm) in the green, and Channel 4 (10.30~11.30 μm) in the blue.

A false color composite image displays the sea and lakes in blue, typically without air pollution due to their low reflection rate. The clouds appear as white and the land as green. Industry-produced LSAPT images of the sea or of lakes appear as magenta, and smoke plumes as either magenta or as a purplish-yellow hue. These false color composite analysis criteria show that the LSAPT over the Yellow Sea originating from China is detectable. This study analyzed the LSAPT from July 2005 to January 2006, during which records of NOAA satellite observations were available.

2.2 Ground observation of air pollutants

Air pollutant monitoring was conducted at a rural site in Cheongwon (127.22° E, 36.34° N, 93 m), which is located in the central area of south Korea (Fig. 1). The Cheongwon observatory is located approximately 120 km south of Seoul and 120 km east and downwind of the west coast of the Tae-ahn Peninsula; with moderate winds, it roughly 3 to

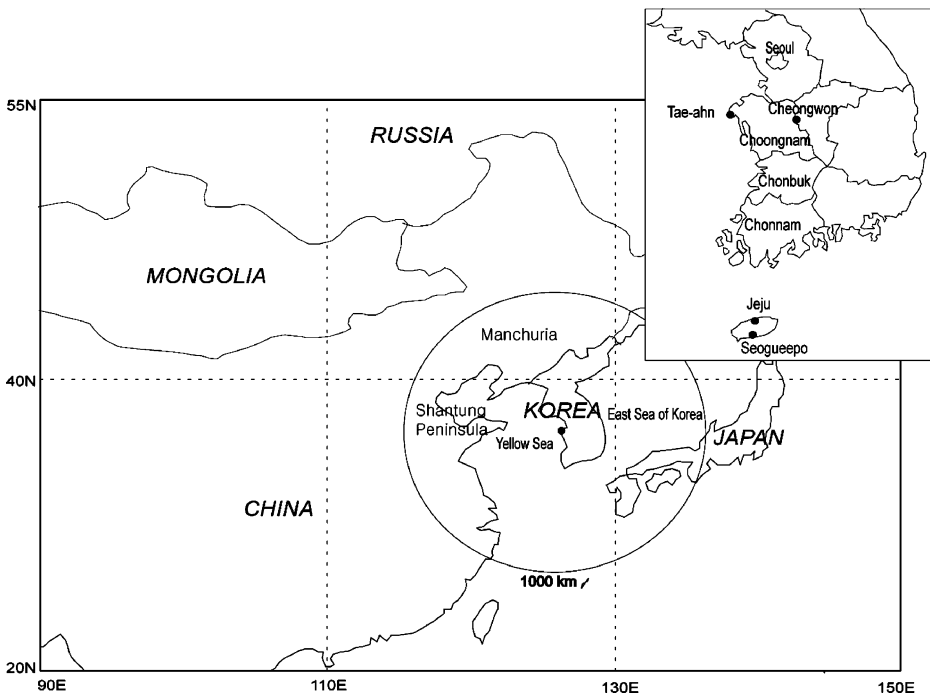


Fig. 1 Map of the Yellow Sea region and the Korean Peninsula, which are represented with cities and provinces

5 h is required for the airflow from Tae-ahn to reach Cheongwon. There are no cities or industrial complexes that measurably contribute to large-scale air pollution on the path from Tae-ahn in the upwind direction from Cheongwon.

Hourly concentration data of PM₁₀, PM_{2.5} and CO measured at the Cheongwon observatory over the period of July 2005~January 2006 were used to analyze the LSAPT. TEOM (Tapered Element Oscillating Microbalance) Series 1400a instruments from Rupprecht and Patashnick were used for observation of the concentrations of PM₁₀ and PM_{2.5}. With these equipments, the dust mass collected in the filter can be measured directly by means of the TEOM method. An equipment (Model 48C) from Thermo Environmental Instruments was used to measure the CO value.

2.3 Analysis of the large-scale transport path of air pollutants

The LSAPT across the Yellow Sea is affected by synoptic-scale atmospheric movement (Kim and Chung 2005). To analyze the transport of air pollution according to the synoptic scale, 925 hPa height and wind charts from the Korea Meteorological Administration were used.

The HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) model (Draxler and Rolph 2003) was used to track the large-scale transport path of air pollution in the East Asian region. The HYSPLIT model is a system for computing simple air parcel trajectories to complex dispersion and deposition simulations. This model includes improved advection algorithms, updated stability and dispersion equations, and the option to include modules for chemical transformations. The isentropic backward trajectory of the airflow that arrives at Cheongwon was calculated at 00 UT (Rolph 2003).

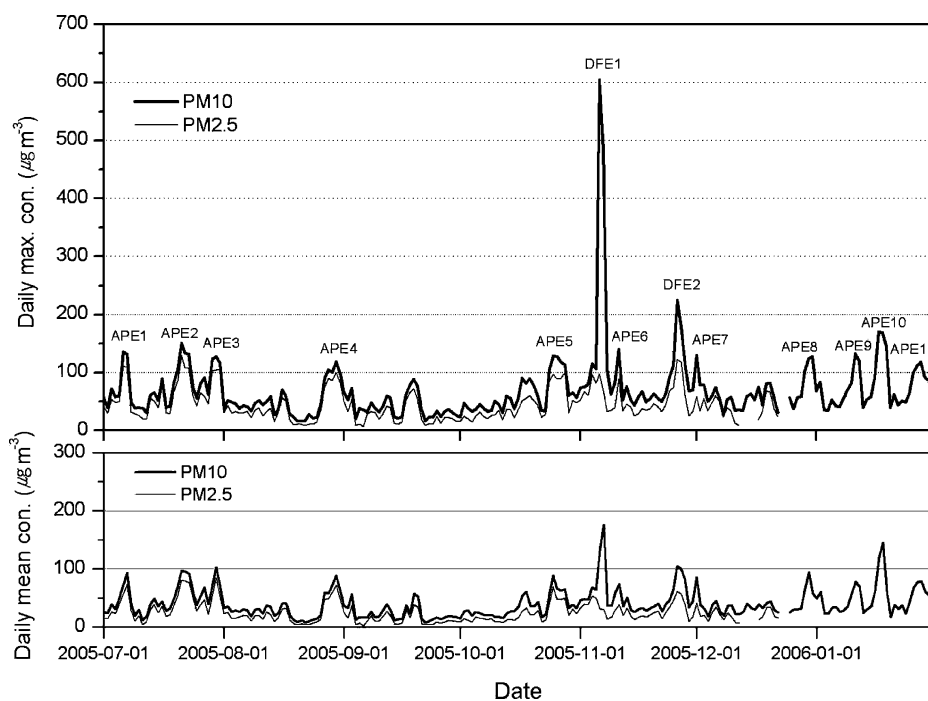


Fig. 2 Day-to-day variations of daily maximum and mean PM10 and PM2.5 concentrations from July 2005 to January 2006

Table 1 PM10 and PM2.5 concentrations during dustfall episodes (DFE) and regional air pollution episodes (APE) in 2005 and 2006

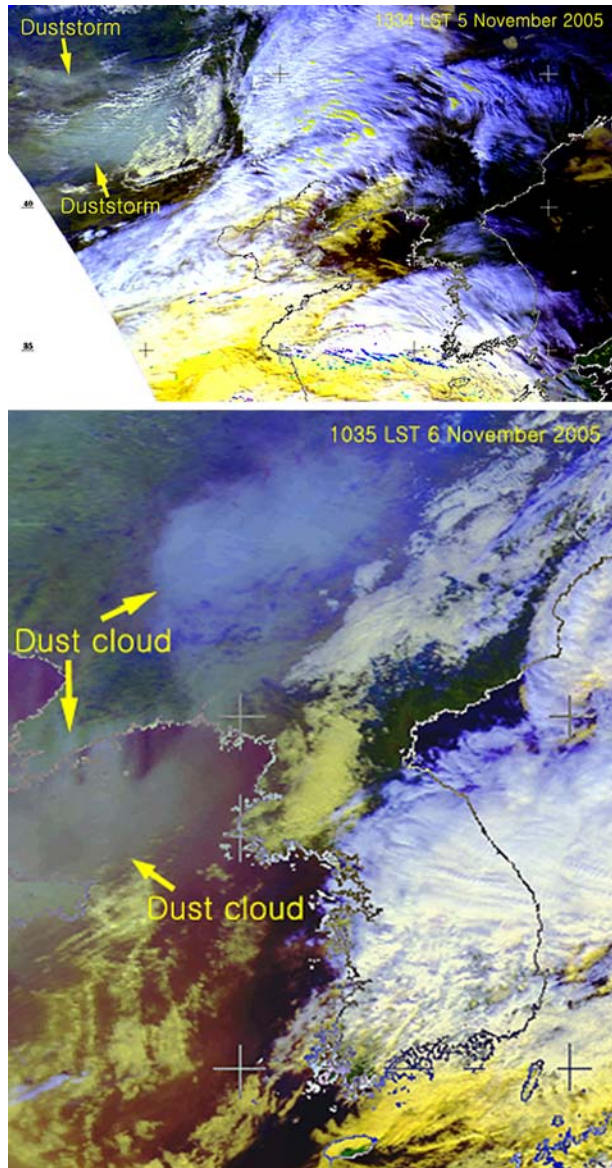
Case	Date	PM10 ($\mu\text{g m}^{-3}$)	PM2.5 ($\mu\text{g m}^{-3}$)
DFE1	6–7 November	154±171	31±25
DFE2	26 November	105±49	62±24
Average		138±144	41±29
APE1	6–7 July	82±33	65±30
APE 2	20–23 July	89±25	73±23
APE 3	29–31 July	82±31	64±30
APE 4	28–30 August	73±21	60±18
APE 5	24–28 October	68±33	51±27
APE 6	11 November	74±27	39±19
APE 7	1 December	86±28	42±10
APE 8	29–31 December	73±31	–
APE 9	11–12 January	74±29	–
APE 10	17–19 January	109±53	–
APE 11	27–28 January	78±17	–
Average		80±34	59±27

3 Results and discussion

3.1 Day to day variation

The day-to-day variations of the daily mean and maximum concentrations of PM₁₀ and PM_{2.5} at Cheongwon from July 2005 to January 2006 are shown in Fig. 2. The averages of PM₁₀ and PM_{2.5} measured at Cheongwon were $41 \pm 27 \mu\text{g m}^{-3}$, $25 \pm 18 \mu\text{g m}^{-3}$, respectively. They were compared with the PM₁₀ average at $57 \pm 44 \mu\text{g m}^{-3}$ at Cheongju, 10 km to the east, and the results suggest that there are fewer local and anthropogenic sources of emissions at Cheongwon. Dust generated in Korea and transported (~ 100 km) to

Fig. 3 Satellite images showing a large-scale duststorm occurrence in the Gobi Desert and associated dustfall over the Yellow Sea and the Korean Peninsula for 5~6 November 2005



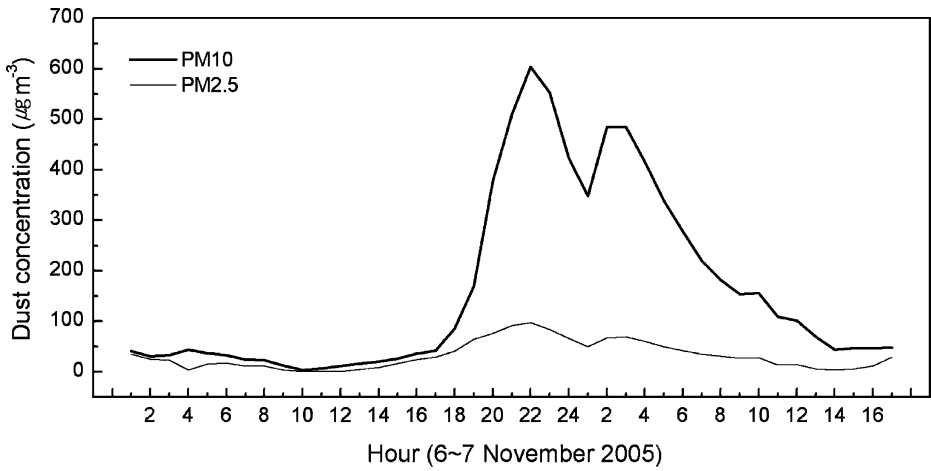


Fig. 4 Variations of PM10 and PM2.5 concentrations observed at Cheongwon during 6–7 November 2005

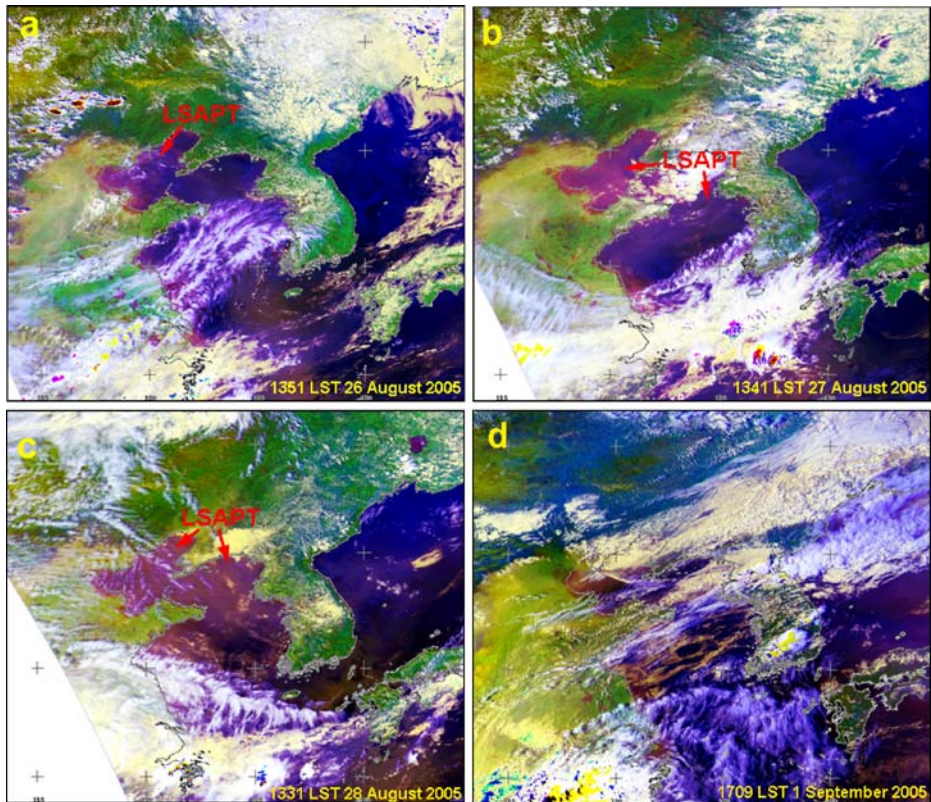


Fig. 5 a–d Satellite images showing a large-scale air pollution transport (LSAPT) over the Yellow Sea and the Korean Peninsula from 26 August to 1 September 2005

Cheongwon can affect the day-to-day variations of the PM₁₀ and PM_{2.5} concentrations. However, satellite observations have been made of many cases of LSAPT, as this crosses the Yellow Sea and moves over the Korean Peninsula. LSAPT can affect the PM₁₀ and PM_{2.5} concentration build-up and air quality on the downwind side, the Korean Peninsula.

An upward spike in the dust concentration within the day-to-day variation at Cheongwon is influenced by two different types of airflows. Significant high dust concentrations can be caused by dustfall episodes (DFE). In a source region such as the desert or semi-arid environments of northern China and Mongolia, dust and sandstorms occur throughout the year (Chung et al. 2003a). Intense duststorms occur mainly in spring after the ground surface has thawed. However, an intense sandstorm occurred in the Gobi Desert even in November 2002 and influenced the dust loadings on the Korean Peninsula, downwind side, as a result of dustfall (Chung et al. 2003b). Moreover, greatly increased PM₁₀ and PM_{2.5} concentrations at Cheongwon can be influenced strongly by regionally polluted airflows (air pollution episodes, APE).

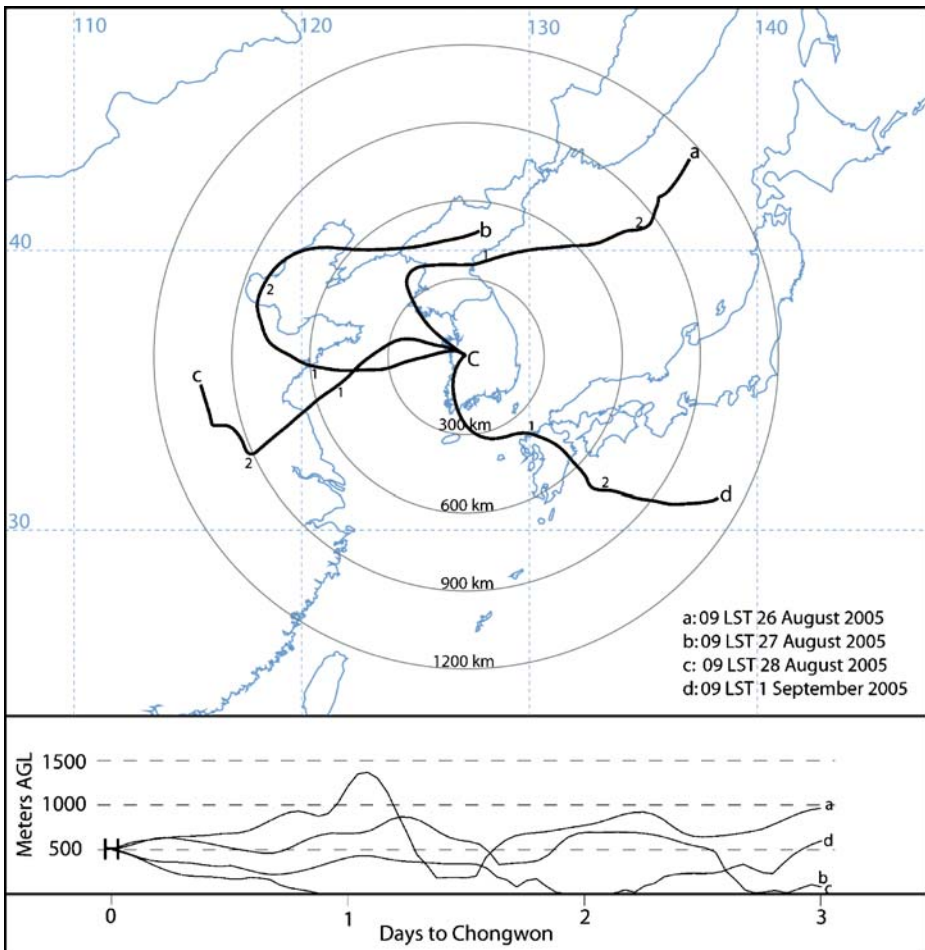


Fig. 6 Backward trajectories arriving at Cheongwon (C) produced with NOAA HYSPLIT Model (<http://www.arl.noaa.gov/ready>)

Table 1 shows the PM₁₀ and PM_{2.5} concentrations for the cases of DFE and APE observed at Cheongwon over the period of July 2005–January 2006. NOAA satellite composite images enable the observation of large-scale duststorms in the northern part of China and Mongolia and associated dustfalls over the Yellow Sea region. The observation also showed the anthropogenic air masses that had built up in the eastern part of China drifting toward the central part of the Korean Peninsula past the Yellow Sea.

Two cases of DFE and 11 cases of APE were observed. The DFE observations showed that PM₁₀ concentrations were higher compared to those of APE, with a PM_{2.5}/PM₁₀ ratio standing at 30%. On the other hand, observations of APE by means of LSAPT show that the PM_{2.5} concentrations increased, with a PM_{2.5}/PM₁₀ ratio of 74%.

3.2 Episodes of 6–7 November 2005

Figure 3 presents satellite images showing that a duststorm that had developed in the Gobi Desert on November 5 was approaching the Korean Peninsula on November 6 at 1035 LST. The dust clouds over the Yellow Sea represent a case in which clouds that had developed in Gobi Desert, in Mongolia, had reached the Yellow Sea in one day due to the winds at 25–30 ms⁻¹ at an altitude of 1,500–3,000 m. A duststorm accompanied by strong north-west winds under a high pressure and behind a cold front at 09 LST on November 5, reached the eastern part of Mongolia and the western part of Inner Mongolia at 15 LST on November 5. It subsequently reached the Yellow Sea and north Korea past the Bohai Bay at 09 LST, on November 6.

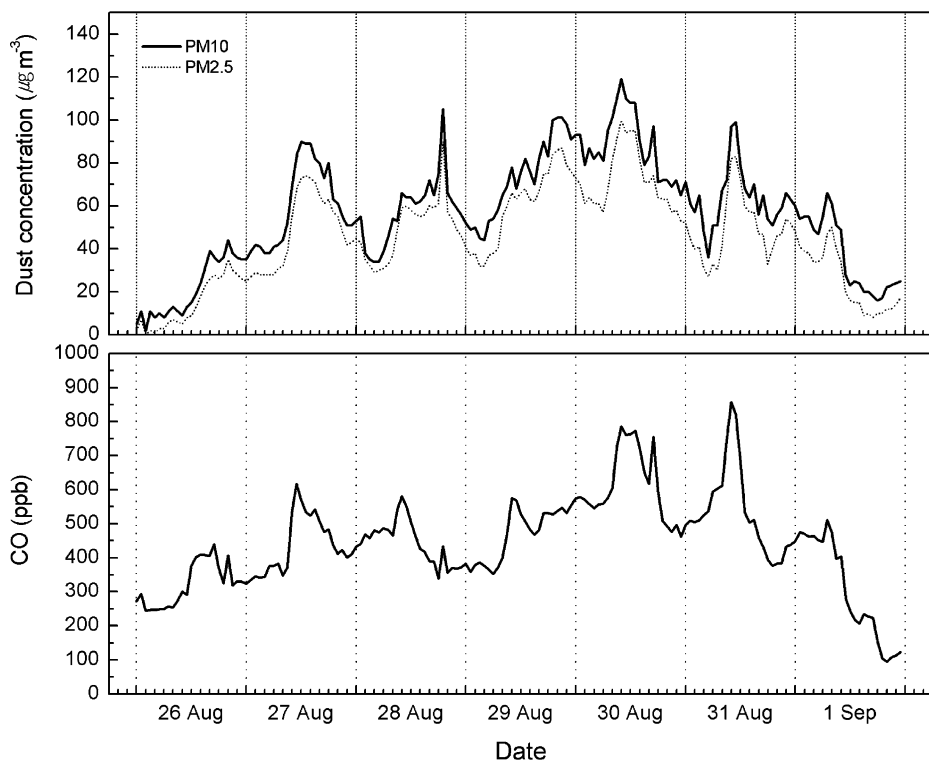


Fig. 7 Variations of PM₁₀, PM_{2.5} and CO concentrations observed at Cheongwon during 26 August–1 September 2005

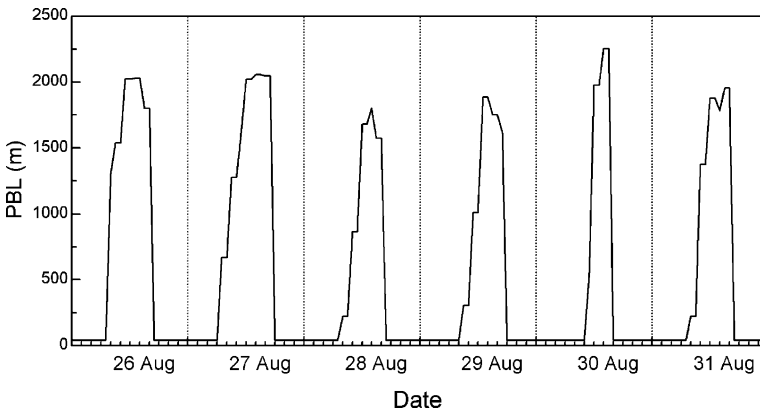


Fig. 8 Diurnal variations of planetary boundary layer (PBL) height at Cheongwon during 26–31 August 2005. PBL heights in prognostic meteorological fields are generated using the PSU/NCAR mesoscale model (MM5). Initial and boundary data utilized the three hourly Regional Data Assimilation and Prediction System (RDAPS) provided by the Korea Meteorology Administration (KMA)

Figure 4 shows the PM10 and PM2.5 concentrations observed at Cheongwon over the period of November 6–7, 2005. There were two bi-modal maximum values, the PM10 concentration of the first standing at $604 \mu\text{g m}^{-3}$, and that of the second at $485 \mu\text{g m}^{-3}$ 6 h later. The ratio of the maximum values of PM10 and PM2.5 stood at 16% with an extremely low PM2.5 level.

3.3 Episodes of 27–31 August 2005

Figure 5 shows NOAA satellite images from August 26, 2005 that depict large-scale air pollution spread across the Yellow Sea. This is an analysis of typical satellite images

Fig. 9 Satellite image of NOAA 18 (1435 LST, 27 January 2006) showing large-scale air pollution transport (LSAPT) over the Yellow Sea moving to SW Korea and crossing to Jeju Island (Mt. Halla) producing von Kármán vortices

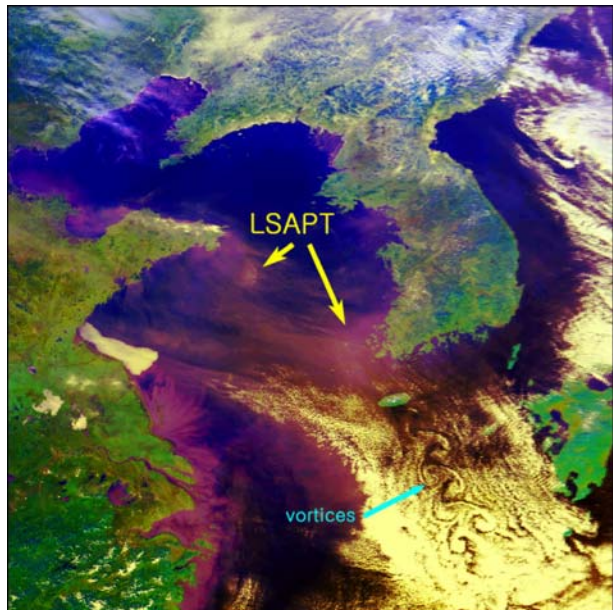


Table 2 Hourly dust concentrations ($\mu\text{g m}^{-3}$) of PM10 measured in Cheongwon, Choongnam, Chonbuk, Chonnam, Jeju and Seogweepo during 27~28 January 2006

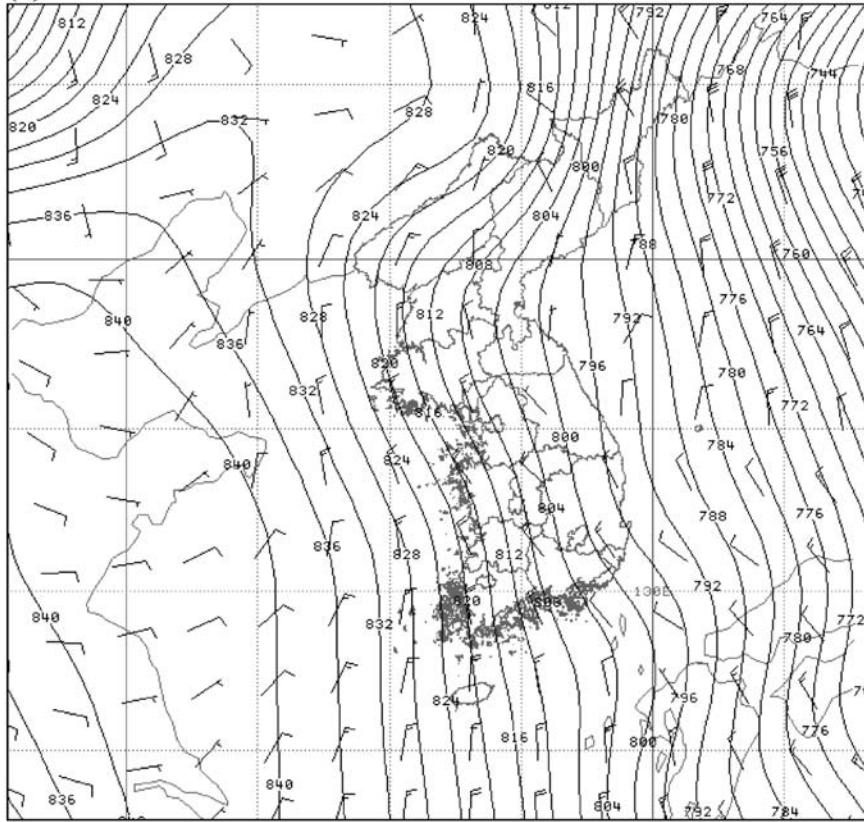
Hour	Cheongwon	Choongnam	Chonbuk	Chonnam	Jeju	Seogweepo
1	70	92	87	80	91	124
2	69	86	92	71	91	112
3	67	84	93	74	90	111
4	71	79	89	79	90	109
5	73	74	95	77	78	114
6	74	67	95	73	87	122
7	74	59	94	78	83	112
8	74	56	102	87	86	114
9	75	65	110	107	99	167
10	78	84	112	125	116	107
11	78	94	116	148	124	86
12	75	97	111	154	132	84
13	74	98	110	137	139	81
14	73	99	100	141	146	101
15	75	108	119	154	166	92
16	61	111	131	151	165	101
17	68	113	131	144	227	93
18	54	92	136	134	184	114
19	78	111	138	122	200	127
20	103	113	145	116	199	137
21	110	118	135	114	165	124
22	103	110	131	115	110	109
23	94	104	126	113	87	101
24	87	91	123	108	93	93
1	84	78	114	105	85	80
2	80	88	131	102	64	58
3	78	89	108	96	61	35
4	70	85	112	92	55	35
5	78	82	112	90	58	23
6	91	84	124	90	57	17
7	93	81	122	85	55	15
8	85	89	118	87	49	17

showing the LSAPT in the direction of the Korean Peninsula. A polluted air mass, measuring 400 km wide, and originated in the north of the Shantung Peninsula in China was sighted on August 26, 2005. Figure 6 shows the back trajectories arriving at Cheongwon from August 26 to September 1, 2005. The Cheongwon area was affected by airflows flowing around the area to the north of the East Sea of Korea and north Korea at an approximate altitude of 500~1,000 m on August 26, 2005. The daily maximum PM10 and PM2.5 values were 44 and 35 $\mu\text{g m}^{-3}$, respectively. The trajectory for this airflow was analyzed to represent the background concentration, as the trajectory did not pass through areas of heavy anthropogenic emissions.

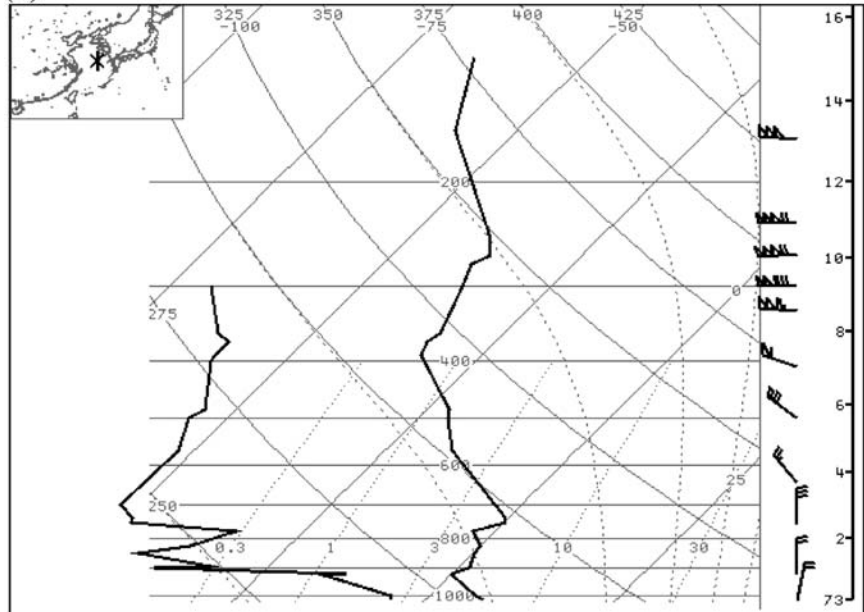
The LSAPT subsequently passed southeastward through the Yellow Sea and occupied most of the southern part of the Korean Peninsula over the period of August 27~31, 2005.

Fig. 10 (a) A 925 hPa height and wind chart and (b) an upper-air sounding chart at Jeju by the Korea Meteorological Administration at 12 UT, January 27, 2006

(a)



(b)



In Fig. 6, the back trajectories of August 27–28, 2005 are shown, having spent 2–3 days over eastern China and the Yellow Sea before reaching Cheongwon. Figure 7 depicts the hourly concentrations of PM₁₀, PM_{2.5} and CO observed at Cheongwon between August 26 and September 1, 2005. The regionally polluted airflows over regions of heavy anthropogenic emissions led to an increase in the PM₁₀ and PM_{2.5} concentrations at Cheongwon. With the LSAPT clouds reaching Cheongwon, the PM₁₀ and PM_{2.5} concentrations gradually increased reaching maximum levels of 119 and 100 $\mu\text{g m}^{-3}$, respectively, on August 30. The PM₁₀ and PM_{2.5} concentrations on August 31 stood at 99 $\mu\text{g m}^{-3}$, 83 $\mu\text{g m}^{-3}$, respectively. Notably, the similarities in the concentrations of PM₁₀ and PM_{2.5} and in the increase in the PM_{2.5} concentrations are attributable to the influence of large-scale air pollution. Additionally, the maximum CO concentration was relatively low on 26 August, at 581 ppb and increased to 857 ppb on August 31.

Daily variations in the PM₁₀, PM_{2.5} and CO concentrations at Cheongwon, particularly over the period of August 27–31, 2005, reached a peak during the daytime. In general, the planetary boundary layer rises high during the daytime when the surface of the earth continues to be heated. In such a case, the vertical diffusion of air pollutants readily occurs, lowering the concentrations on the surface of the earth. However, when the LSAPT remains over Cheongwon as a location with low background values in terms of the concentrations of PM₁₀, PM_{2.5} and CO, the planetary boundary layer rises enough to reach polluted airflows as high as 1,801–2,056 m during the daytime (Fig. 8) and pollutants descend close to the surface of the earth, thereby causing a rapid increase in the concentrations on the surface.

However, the PM₁₀, PM_{2.5} and CO concentrations decreased during the daytime on September 1, 2005. The LSAPT does not appear over the Korean Peninsula in the satellite image of Fig. 5d. The synoptic features of the Korean Peninsula were stationary, and hot weather existed due to the influence of a North Pacific high on September 1. An analysis of the isentropic backward trajectories shown in Fig. 6 depicts airflow from the North Pacific reaching the Korean Peninsula after crossing Kyushu, Japan. The relatively low concentrations of PM₁₀, PM_{2.5} and CO observed in the Pacific airflow at Cheongwon present another background characteristic of the region.

3.4 Episodes of January 27, 2006

Figure 9 shows a NOAA 18 satellite image taken on January 27, 2006. Large-scale air pollution from the Shantung Peninsula in China arrived in the Choongnam Province, Korea, at 1055 LST on January 27 and moved to the Chonbuk and Chonnam Provinces at 1435 LST.

Table 2 depicts the hourly PM₁₀ concentrations observed at Cheongwon, Choongnam, Chonbuk, Chonnam, Seogweepo, and Jeju on January 27–28. The PM₁₀ concentration at Cheongwon increased from 78 $\mu\text{g m}^{-3}$ at 10–11 LST to 110 $\mu\text{g m}^{-3}$ at 21 LST on January 27, and the average PM₁₀ level recorded at the Choongnam observatories of the Ministry of the Environment increased to 108–118 $\mu\text{g m}^{-3}$ from 15 to 21 LST. The highest average PM₁₀ concentration at Chonbuk was 100–145 $\mu\text{g m}^{-3}$ higher than that at Choongnam, and the highest average PM₁₀ concentration at Chonnam was a record 107–154 $\mu\text{g m}^{-3}$.

As the satellite image shows, the highest PM₁₀ concentration at Jeju City, which was heavily polluted, was 200–227 $\mu\text{g m}^{-3}$, figures as high as those during a duststorm. The highest concentration level at Seogweepo on the downwind side was 137–167 $\mu\text{g m}^{-3}$, lower than that at upslope Jeju, reflecting the influence of the stress and vortices. The topographical descending airflow of Mt. Halla (1,950 m) caused a dry convergent airflow and cloud dissipation, and the PM₁₀ measurements were much lower in the lee side than those at Jeju on account of the diffusion and deposition of the pollutants.

On January 27, 2006, a continental high pressure system located in southern Manchuria and a prevailing north wind blew over Jeju Island. The weather in the coastal area of the Yellow Sea was characterized by dense fog and thin mist. Figure 10a shows a chart depicting the 925 hPa height and wind. It shows a constant north wind blowing at the right side of a ridge at 7.5 ms^{-1} . Figure 10b is an upper-air sounding chart at 12 UT, January 27, 2006. In the area under 850 hPa, the north wind was dominant depending on the altitude. As the airflow as a whole was very stable from 925 hPa (1,270 m) to 740 hPa (2,500 m), it can be concluded that vortex clouds formed between these layers.

4 Conclusion

This study observes and confirms the existence of LSAPT in East Asia. NOAA satellite images show the result of a combination of three channels of the visibility range and the infrared range using a false color composite scheme (Chung and Le 1984). The analysis of the NOAA satellite images makes it possible to distinguish distribution and transport of regionally polluted air masses. Moreover, measurements of the PM10, PM2.5 and CO concentrations were shown to have increased along with the LSAPT. Particularly, the differences between the measurements of PM10 and PM2.5 in the episodes discussed here are small while those of PM2.5 are relatively high. Therefore, the episodes presented at Cheongwon demonstrate examples of the large-scale transport of air pollutants caused by pollution emitted from the East Asian continent, mainly from the cities and industrial areas of China.

In particular, a significant and dramatic LSAPT inflow into the central and southwest regions of the Korean Peninsula on January 27, 2006 was observed. The airflow passing over Mt. Halla on Jeju Island not only dissipates the cloud further downwind and reduces the level of air pollution, but also produces von Kármán vortices more than 500 km south.

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