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Asian Dust Transport during Blocking Episode Days over Korea

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Asian dust(or yellow sand) occurs mainly in spring and occasionally in winter in east Asia, when the weather conditions are under an upper trough/cut-off low and surface high/low pressure system during blocking episode days associated with the stationary patterns of the upper level jet stream. The transport mechanism for Asian dust during the blocking episode days in spring 2001 was analyzed using the TOMS aerosol index and meteorological mesoscale model 5(MM5). Based on the E vector, an extension of an Eliassen-Palm flux, the blocking episode days were found to be associated with the development of an upper cut-off low and surface cyclones. Concurrently, the occurrence of dust storms was also determined by strong cold advection at the rear of a jet streak, which exhibited a maximum wind speed within the upper jet stream. As such, the transport mechanism for Asian dust from China was due to advection of the isentropic potential vorticity(IPV) and isentropic surfaces associated with tropopause folding. The transport heights for Asian dust during the blocking episode days were found to be associated with the distribution of the isentropes below the IPV. At the same time, lee waves propagated by topography affected the downward motion and blocking of Asian dust in China. The Asian dust transported from the dust source regions was deposited by fallout and rain-out with a reinforcing frontogenesis within a surface cyclone, as determined from satellite images using TOMS and GMS5. Accordingly, these results emphasize the importance of forecasting jet streaks, the IPV, and isentropes with geopotential heights in east Asia.

Key words : Asian dust, the upper trough/cut-off low, blocking episode, E vector, isentropic potential vorticity, surface front, and cyclone

1. Introduction

The long-range transport of Asian dust from China and its surrounding regions plays an important role in determining the optical properties and biogeochemical cycles of air pollutants, such as aerosols, ozone, CO, NO_x, SO_x, and other trace gases in Korea, Japan, and North America[1~8].

Asian dust(or yellow sand) occurs mainly in spring in east Asia and its distribution is determined by the related weather systems. Sun *et al.*[9] indicated that dust storms in China were highly associated with frontal systems and the Mongolian cyclonic depression, the major sources for which are the Gobi desert in Mongolia and northern China and the Takla-Makan desert in western China. Murayama *et al.*[10] and Uno *et al.*[11] reported that Asian dust was observed in Japan under a high-pressure system behind a cold front of a traveling cut-off low. Carmichael *et al.*[12] also observed large amounts of dust entrained into a cut-off low based on NOAA/AVHRR data. Chun *et al.*[13] concluded that the synoptic conditions for dust emission over Korea were high surface winds and a baroclinic instability at a level of 1.5 km. They also found

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that the meteorological conditions in spring in east Asia were mainly characterized by a periodic alternation between synoptic scale high and low pressure systems. Kim *et al.*[7] proposed that the enhancement of aerosols(or yellow sand) over Korea during Asian dust events occurred under weather conditions of upper trough/cut-off low and surface high pressure systems associated with tropopause folding. They found that the enhancement of aerosols and ozone above and to the west of cyclones was caused by strong meandering advection entering the region from the west and partly by air sinking under such a weather system. Furthermore, Merrill *et al.*[3] reported that the long-range transport of mineral aerosols over the North Pacific was expected in the upper level jet stream and a cold front system.

Recently, the current authors observed that Asian dust occurs mainly in spring and occasionally in winter during blocking episodes of the upper level jet stream. Accordingly, the current study considers whether the Asian dust occurring on blocking episode days is associated with stationary patterns of the upper trough/cut-off low or upper level jet stream. Blocking episodes occur in the winter and spring seasons, and reach a maximum frequency in springtime[14]. The role of synoptic/planetary-scale interactions during the onset of a blocking episode involves four elements : a quasi-stationary planetary-scale ridge at 500 hPa ; a developing precursor cyclone on the surface located upstream of the block ; an associated amplifying short-wave ridge at 500 hPa; a strong jet maximum on the flank of the developing short-wave ridge[15~17]. As such, the development of surface cyclones would appear to play an important role in forming and maintaining a block with tropopause folding[18~21]. Blocking episodes may also maintain the long-range transport of Asian dust over east Asia and north Pacific. Therefore, the current study analyzed the formation, transport, and deposition mechanisms of Asian dust during blocking episode days in the spring of 2001 in east Asia using TOMS satellite images and the mesoscale meteorological model 5(MM5) with NCEP reanalysis data.

2. Data and methodology

To understand the transport mechanism for Asian dust during blocking episode days, the geopotential height, ageostrophic and vertical wind velocity, air and potential temperature, isentropic potential vorticity, and E vector were all simulated using MM5 with NCEP/CDAS input data(2.5 °× 2.5 °). The resolution of the MM5 data used a 30 km latitude from 20 °N to 70 °N and 30 km longitude from 50 °E to 170 °E for 17 standard pressure surfaces between 1000 hPa and 5 hPa. The time step was 30 seconds. Based on isobaric coordinates, the ageostrophic wind speed was calculated as the difference between the geostrophic wind(v component) and the horizontal wind speed. The isentropic potential vorticity(IPV) is useful as an indicator of the air parcel transport related to the tropopause folding movement, even when the IPV distribution is changed by convection and synoptic-scale mixing. Plus, Ertel's isentropic potential vorticity acts a dynamic tracer for distinguishing between stratospheric and tropospheric air, and is defined as

$$IPV = -g \cdot (f + \xi) \cdot \partial\theta/\partial p \quad (1)$$

where $(f + \xi)$ and $\partial\theta/\partial p$ are the absolute vorticity on the isentropic surface and the static stability, respectively. The tropopause values of IPV are generally 1-2 potential vorticity units(1 IPV = $10^{-6}\ m^2\ s^{-1}\ K\ kg^{-1}$).

The E vector technique provides information on wave structures, propagation, and the net forcing of time-mean flows by transient eddies during blocking episodes. The vector is an extension of Eliassen-Palm flux vectors for zonal mean flows. Following Trenberth[22], the horizontal components of a zonal flow E vector are given by :

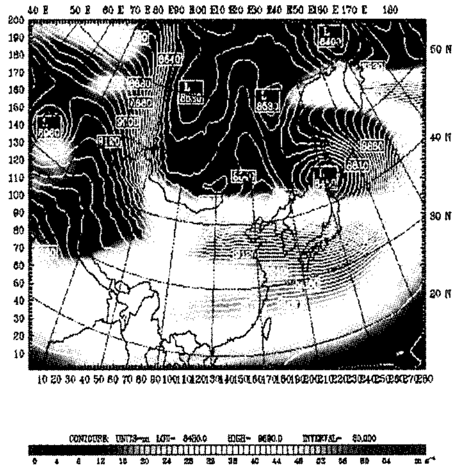
$$E = [(v'^2 - u'^2)/2 - u'v'] \quad (2)$$

where u and v are the zonal and meridional flow components, and primes denote departures from the time-mean values. The arrows in the E vector, directed from the weak to the strong values of the zonal velocity, indicate a positive net growth of the eddy energy. The divergence of the E vector implies a positive net(eastward) forcing of the mean flow.

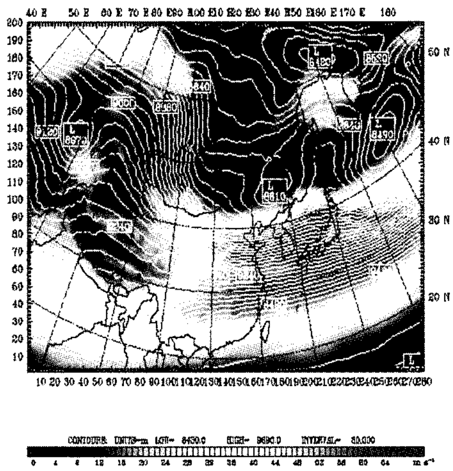
To confirm the enhancement of Asian dust over Korea, the blocking episode days that occurred on March 5-7, 2001 were selected, and hourly PM_{10} data observed by the beta-ray absorption method at monitoring sites in Daegu, Busan, and Seoul was analyzed from 1 to 10 March 2001. To simulate the long-range transport of Asian dust toward North America, specific episode days that occurred on April 7 - 13, 2001 were selected. In addition, aerosol index data from the Total Ozone Mapping Spectrometer(TOMS, http://toms.gsfc.nasa.gov/aerosols/aerosols.html) and Lidar data obtained by the National Institute for Environmental Studies at Tsukuba in Japan(http://info.nies.go.jp:8094/kosapub/rsltko01/index.html) was also used to detect the temporal and spatial distribution of Asian dust.

3. Meteorological conditions during blocking episode days in east Asia

Enhanced aerosols(or yellow sand) at the ground monitoring sites in Korea mainly occurred in the springtime under weather conditions of an upper trough/cut-off low and surface high/low pressure system during dust episode days, as shown in Table 1. Fig. 1 shows the geopotential heights and isotach contours at 300 hPa on March 5 & 6, 2001, as simulated using MM5. Two polar and subtropical jet streams approached each other at the longitudes of the semipermanent troughs of the middle-latitude westerlies. The formation or enhancement of a strong upper tropospheric jet streak occurred along the longitudes of the upper trough. At this point, cold advection occurred in the left exit region, while warm advection occurred in the right entrance region of the jet streak in the middle and upper troposphere[14]. Dust storms in China mainly occurred in the left exit region of a strong jet streak, as shown in Fig. 1 (a), which may have been due to the cold advection associated with an upper jet streak. Therefore, the location of a strong jet streak



(a)



(b)

Fig. 1. Geopotential heights(lines) and isotach contours(shaded) at 300 hPa simulated by MM5. At 1200 LST on March 5, 2001 (a) and 1400 LST on March 6, 2001 (b).

Table 1. Asian dust days associated with weather maps of upper trough/cut-off low and surface high pressure over Korea for last 7 years from 1995 to 2001

	Jan.	Feb.	Mar.	Apr.	May
1995	-	-	2, 12	7-9, 23-25	4.27-5.3
1996	-	-	8	17-18	2, 8-9
1997			3-4	-	-
1998		-	28-30	14-22 (L), 27-28	-
1999	25-28	27	-	5	1-2
2000	-	-	7, 23-24, 27-28	7-8, 12	-
2001	2-3	-	3-7, 20-25	7-14 (L), 24-26	3, 16-19

L : long-range transport toward North America relative to the upper trough/cut-off low in spring time in China played an important role in the formation of dust storms. The longitudes of the mean polar troughs were also locations for a jet streak, the strongest mean west wind.

In particular, it was found that the speed of the movement of the upper trough was very slow during Asian dust storms. Thus it would appear that the wave patterns at 300 hPa during Asian dust storms were stationary from blocking according to the definition by Tsou and Smith[16], who stated that blocking patterns are subject to retardation or retrogression in their eastward motion due to the greater influence of the transition from a zonal to a azonal flow as a result of the non-linear interaction of smaller waves with larger ones, such as a cyclone-scale disturbance. Fig. 2 shows the E vector at 250 hPa for a period of 6 days(March 1 - 6, 2001). The E vector over East Asia indicates that eddies tended to weaken the westerlies in China and the Pacific region. The eddies became meridionally elongated as they moved into the area of the upper large-scale flow over east Asia. In this event, it was found that the synoptic patterns of the cut-off low and surface cyclone affected the growth of the eddy energy. Accordingly, blocking seemed to be related to realistic surface boundary conditions, such as topography and synoptic scale disturbances, in China and the Pacific area. Synoptic-scale cyclones were also found to play an important role in forming and maintaining the block.

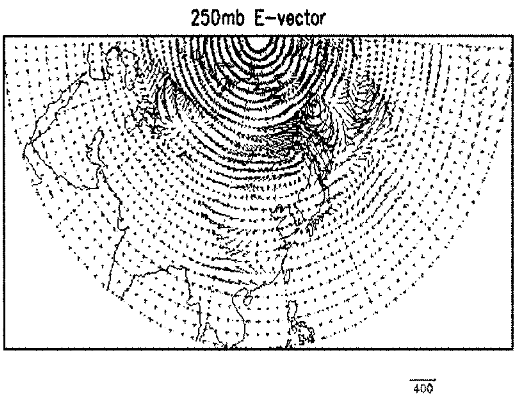
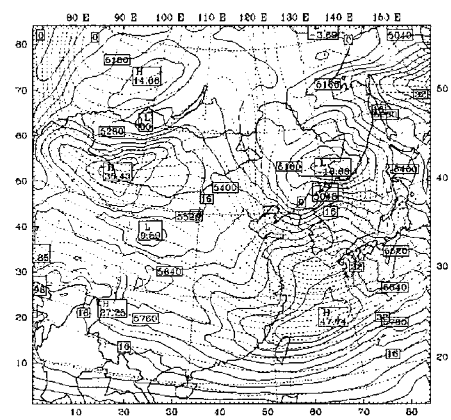


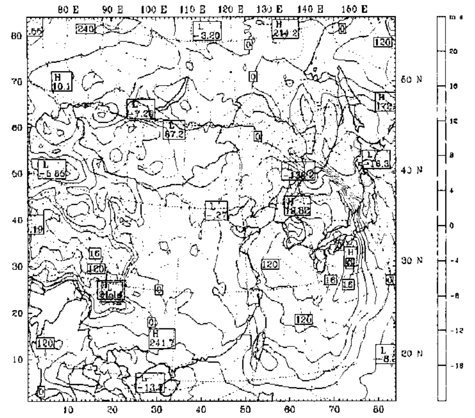
Fig. 2. E vectors at 250 hPa over east Asia for period of 6 days(March 1-6, 2001).

Fig. 3 shows the geopotential heights at 500 hPa and 1000 hPa on March 7, 2001. The approach of the upper trough/cut-off low toward a low-level baroclinic zone and a preexisting weak surface cyclone acted to focus and enhance the effects of the warm air advection, sensible heat fluxes and moisture fluxes in the Planetary Boundary Layer (PBL), and latent heat released above the north and east of the surface cyclone. The net effect between the upper trough and ridge was to warm the lower and middle troposphere near the axis of the upper ridge and increase the divergence between the upper trough and the ridge axes. This increased upper level divergence then deepened the cyclone even further and the self-development of rapid cyclones slowed the eastward progression of the upper-level ridge[23~24]. Fig. 3 (b) shows the self-development cyclone. The propagation of the jet streak into the downstream trough also accompanied a deepening of the downstream trough. That is, the decrease in the wavelength between the trough and the ridge axes with the development of the upper cut-off low, the increase in the diffluence corresponding to the spread of the geopotential height lines of the trough axis, and the increase in the maximum wind speeds of the upper-level jet streak all combined to enhance the divergence in the upper troposphere above the surface cyclone. Therefore, the development of such a surface cyclone with a surface front appeared to play an important blocking role for Asian dust. Thereafter, the Asian dust disappeared as a result of sedimentation and precipitation in the vicinity of the surface cyclone.

Subsequently, the storm track in east Asia during



(a)



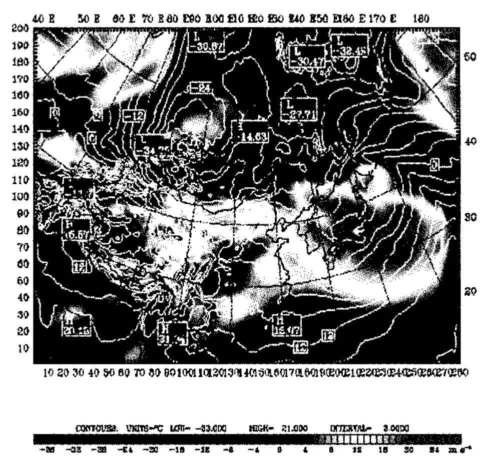
(b)

Fig. 3. Geopotential heights(dotted line) and isotach (shaded line) at 1200 LST on March 7, 2001, at 500 hPa (a) and 1000 hPa (b).

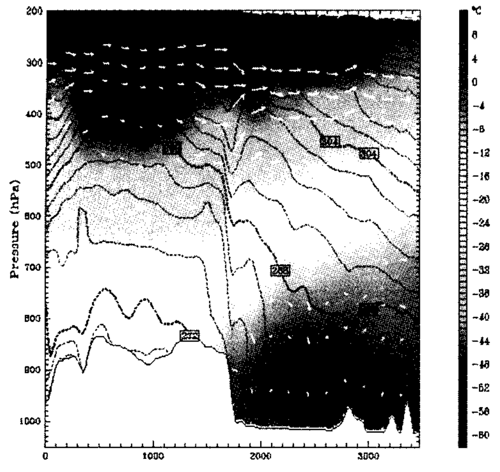
the Asian dust storms was determined as the block developed a wave with a strong jet streak. Blocking during Asian dust episodes is more frequent during the winter and spring months, and reaches a maximum frequency in springtime under weather conditions of an upper trough/cut-off low and surface cyclone. This mechanism appears to be a combination of baroclinic and barotropic instability. Accordingly, the weather maps are accompanied with a strong jet streak on the developing trough, amplifying short-wave trough at 500 hPa with a developing cut-off low, and developing cyclone at the surface. Consequently, Asian dust transported from China is deposited by the blocking of a deepening cyclone. It would also appear that the existence of semipermanent troughs and a jet streak is of considerable importance for both the divergence of a deepening surface cyclone and the occurrence, transport, and deposition of aerosols and trace gases, such as ozone.

4. Mechanism of formation, transport, and deposition of Asian dust during blocking episode days

Most dust storms in China occur in spring, when the synoptic systems over China are under the upper trough/cut-off low and surface cyclonic depression and frontogenesis, and under the blocking patterns of the upper jet stream. The upper trough/cut-off low patterns and jet streams not only provide a divergence for deepening surface cyclones, but also contribute to the intensity of upper-level fronts and the related distribution of the potential vorticity, which has a significant impact on the spin-up of dust storms through the descent and horizontal advection of stratospheric air toward the cyclogenetic region[21]. Fig. 4 shows the isotach at 850 hPa and vertical cross section of the air and potential temperature at 1200 LST on 5 March 2001. The episode on this day was associated with the formation of dust storms in China. The upper trough/cut-off low induced a cold advection in the rear of the upper jet streak, as in Figs. 1a and 4b. A cold dome, represented by an upward bulge in the isentropic surface, was evident near the dust source regions. When the warm air from the low levels was brought into juxtaposition with the cold air masses from the higher latitudes and upper levels, the dust storm occurred over the deserts of northern and northwestern China or the Loess Plateau. Consequently, the meridional and vertical temperature gradients during the blocking episode days were enhanced because the westerly flow in the upper troposphere was roughly proportional to the baroclinity of the atmosphere. Then, the cold frontal system was enhanced by a Mongolian cyclone as a deepening cyclonic depression connected with the upper cut-off low. At the same time, a strong meandering wind due to the upper jet streak occurred mainly in the dust source regions just south of the Mongolian cyclone at 850 hPa(see Fig. 4a). This result indicates that the dust storms occurred when the strong cold and dry air due to the upper



(a)



(b)

Fig. 4. Geopotential heights(lines) and isotach contours(colors) at 850 hPa(a), and vertical cross-section of potential temperature(lines) and air temperature(colors) at 1200 LST on March 5, 2001 (b).

jet streak and upper trough/cut-off low arrived at the dust source regions in northern and north-western China or the Chinese Loess Plateau.

Fig. 5 shows vertical cross-sections of the isentropes(K), ageostrophic wind(m s^{-1}) and vertical wind(103 m s^{-1}) velocity, and potential vorticity(1 PVU = 10^{-6} m^2 s^{-1} K kg^{-1}) between (32 °N, 135 °E) and (43 °N, 95 °E) simulated by MM5. In particular, it appeared that the transverse associated with tropopause folding(TF) along the axis of an upper-level jet/front system was the mechanism that displaced the stratospheric air down towards the 700 hPa layer25) The downward motion of aerosols and trace gases due to tropopause folding can be depicted based on the principle of the conservation of the isentropic potential vorticity(IPV). As stratospheric air descends into the troposphere, the air mass is stretched and the static stability($-\partial\theta/\partial p$) decreases significantly. Consequently, the absolute vorticity($\xi_\theta + f$) increases with respect to parcel trajectories as long as the stratospheric values of the IPV are preserved. As such, high IPV values are due to a strong absolute vorticity in the troposphere and significant static stability in the stratosphere. The advection of a high IPV at middle levels towards the cyclone center was consistent with the advection of an absolute vorticity at 500 hPa. The TF process was seen at the rear of the jet streak based on the presence of shallow tongues of IPV and deeply sloped potential temperatures, as shown in Fig. 5. High IPV values descended down the frontal zone into the middle and lower troposphere. The movement of stratospheric air along the isentropic surfaces from near the tropopause to the vicinity of the surface cyclone resulted in the intrusion of high absolute vorticity values upstream from the flow. This also indicates a probable connection between the upper frontogenesis or tropopause folding due to jet streak transverse circulation patterns and the development of surface cyclones. The upper level IPV anomaly just arrived over a region with a significantly low-level baroclinity. A low level IPV anomaly was also found to induce a cyclonic circulation that acted to reinforce the circulation pattern induced by the upper level IPV anomaly. At this point, the flow of relatively cold air over a warm region under tropopause folding forward surface cyclones developed a strong storm. This result is consistent with the fact that all dust storms occur in a surface cyclonic depression and frontogenesis in China[9]. It was also found that strong storms occurred in surface cyclones near Japan(see Fig. 3b). Within a day or so the jet streak and developing tropopause fold then migrated eastward with the development of the upper trough/cut-off low and surface cyclone. Initially, the system was quite weak, however, on March 5 the folding process and stationary wave amplification became dramatically evident in the upper troposphere over China. Then, by March 7 the cyclone was very deep, at which point the jet streak lay close to the surface cyclone. Thereafter, both the trough and the surface cyclone began to weaken. During this process the isentropes in the middle and lower troposphere became distorted with the advection of the IPV anomaly due to tropopause folding.

If it is considered that Asian dust moves along an isentropic surface from the source region, the vertical structure of isentropes then plays an important role in the transport mechanism of Asian dust. On March 5, a dust storm due to the strong jet streak occurred in the dust source regions in northern China. The Asian dust stayed within northern China along the lower tropospheric isentropes below the blocking of the upper IPV

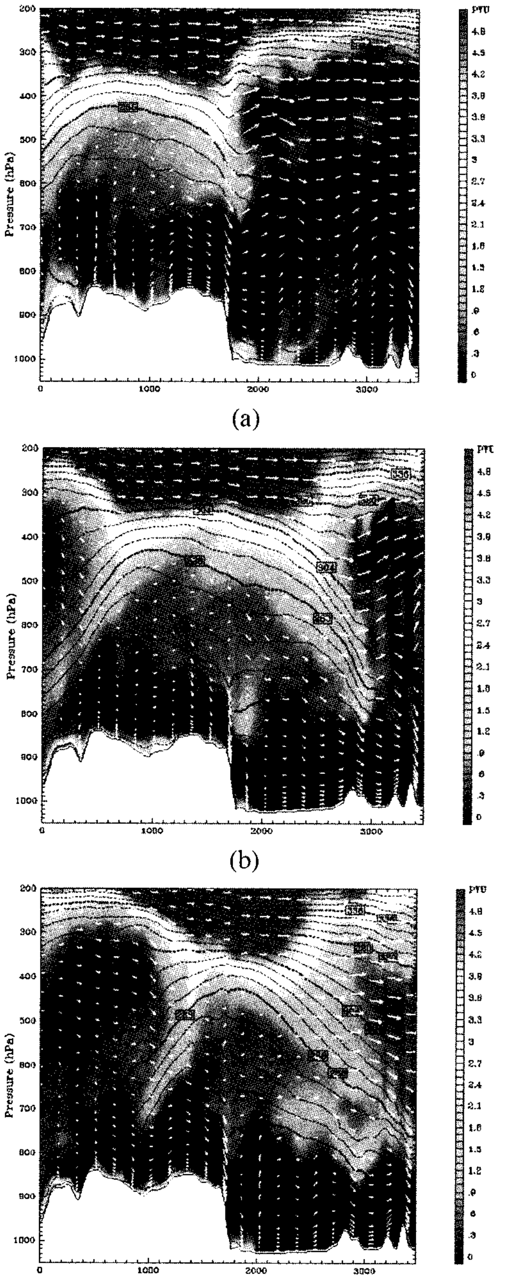


Fig. 5. Vertical cross-section of isentropes(K, lines), ageostrophic wind(m s^{-1}) and vertical wind (10^{-3} m s^{-1}) velocity(arrows), and potential vorticity(1 PVU = 10^{-6} m^2 s^{-1} K kg^{-1}, shaded) between(32 ° N, 135 ° E) and (43 ° N, 95 ° E) simulated by MM5. At 1200 LST on March 5, 2001 (a), at 1400 LST (b), and 2000 LST on March 6, 2001 (c).

anomaly due to TF. At this point, lee waves generated by the topography in China also acted to block the transport of Asian dust. Lee waves propagated to the upper troposphere induced both the strong downward motion of Asian dust and the blocking of the upper jet stream during the Asian dust episode days from March 5 to 7, 2001. On March 6, as the IPV anomaly moved eastward, TF occurred in Korea and Japan. Then, the enhancement of Asian dust was detected by the ground monitoring sites, as seen in Figs. 6 and 7. The dust storm in China was also stopped by the movement of the upper jet streak and development of the upper trough/cut-off low. On March 8, as the reinforced IPV anomaly approached a surface cyclone, the Asian dust disappeared due to sedimentation and precipitation in the vicinity of the surface cyclone. The transport of Asian dust was thus determined by the vertical structure of the isentropes below the IPV anomaly due to the jet streak and upper trough/cut-off low. Although the transport altitude of Asian dust was determined using lidar intensity, the primary altitude was also estimated at near 800 hPa using MM5 isentropes. This result is in agreement with images of the lidar intensity observed at Tsukuba, Japan, as shown in Fig. 7.

Fig. 6 shows the enhanced aerosols(PM_{10}) measured at the ground monitoring sites in Korea on March 6 & 7, 2001. The peak aerosol concentration for Seoul occurred at night on 6 March, while the peak concentrations for Busan and Daegu(more than 500 μg m^{-3}) occurred in the day on March 7, 2001. This indicates a time lag in the peak aerosol concentration relative to the TF movement. The dust reached the surface based on the intersection

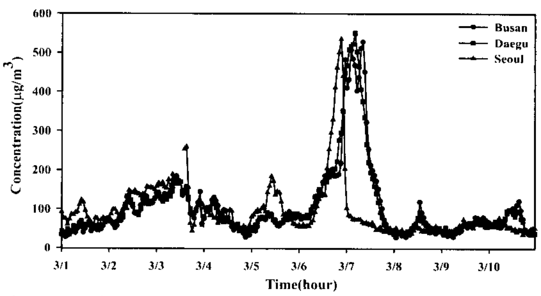


Fig. 6. Diurnal variation of aerosols(PM_{10}) at each monitoring site in Korea for period March 1 to 10, 2001.

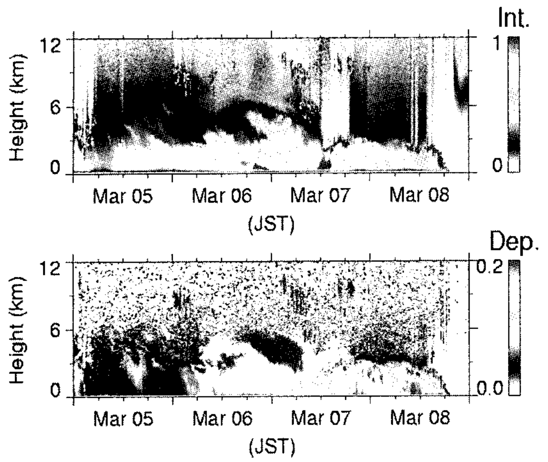
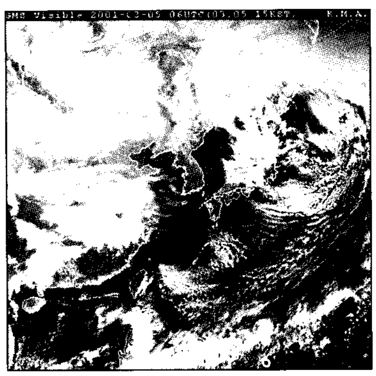


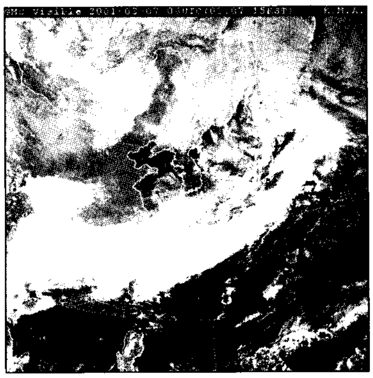
Fig. 7. Intensity and Depolarization Ratio derived from Lidar at Tsukuba, Japan during Asian dust episode days from March 5 to 8, 2001 (http://info.nies.go.jp:8094/kosapub/rsltko01/index.html).

of the descending anticyclonic air stream with strong advection from China or by fallout and rain-out near the surface cyclone and front below the eastern side in the upper trough axis, as in Fig. 8b.

Figs. 8 and 9 show satellite images from the Korean Meteorological Agency(KMA) taken on March 5 & 7, 2001 and the aerosol index using TOMS on March 6, 2001. A surface high/low pressure system related to the upper trough/cut-off low determined the range of the Asian dust. The enhancement of Asian dust was expected within or at the rear of the surface high pressure system following the upper jet streak and surface cold frontogenesis. High winds and dust clouds were



(a)



(b)

Fig. 8. Satellite images from KMA taken at 1500 LST on March 5 (a) and 7 (b), 2001.

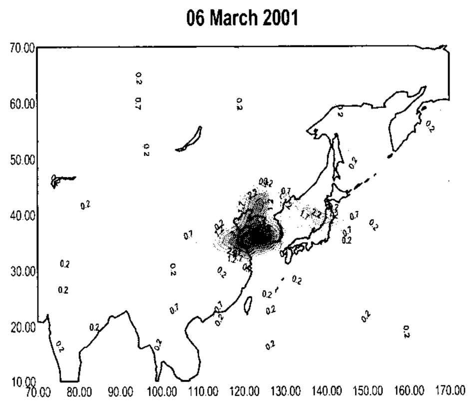


Fig. 9. Aerosol indexes using TOMS on March 6, 2001.

found along the cold frontogenesis, and north and west of the cyclone. In particular, it would appear that surface frontogenesis played an important role in blocking Asian dust, then the sedimentation or deposition of Asian dust occurred through precipitation. These results were detected in many satellite images of Asian dust, as provided by GMS5 and Meteosat.

Accordingly, the long-range transport of Asian dust was associated with the longitudinal location of a strong jet streak and development of large upper trough/cut-off lows and surface cyclones under stationary and high amplitude blocking patterns.

5. Conclusions

Asian dust mainly occurs in springtime and sometimes in wintertime under an upper level trough/cut-off low and surface high/low pressure system during blocking episodes. Blocking during dust episode days follows the formation of an intense surface cyclone and development of a trough/cut-off low at 500 hPa. Blocking cycles can be re-established every one to four weeks before a zonal flow in springtime. A particular blocking episode occurring in east Asia in spring or winter then determines the weather characteristics of Asian dust days. The meteorological situation during the dust episode days in spring 2001 was analyzed using vertical cross sections of the potential temperature, isentropic potential vorticity, and ageostrophic and vertical velocity to the upper trough/cut-off low using MM5. These simulations may help in future estimates of how much aerosol and trace gases, such as ozone, NO_x, SO_x, and CO, are irreversibly transported into the troposphere through folding and advection. As such, the formation, transport, and deposition of Asian dust during blocking episode days were found to result from a strong meandering stream(or cold advection) due to the upper jet streak, the downward and horizontal movement of the IPV due to tropopause folding, the gradients of the isentropes in the lower troposphere under such a system, the development of lee waves due to topography, and the location of the surface front due to the development of an upper cut-off low and surface cyclone.

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