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Meteorological Mechanisms Associated with Long-range Transport of Asian Dust Observed at the West Coast of North America in April 2001

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Abstract

Meteorological mechanisms in association with long-range transport of Asian dust in April 2001 have been investigated using weather maps, satellite images, TOMS and surface PM_{10} data, backward trajectories, plus modeling output results (geopotential heights, horizontal wind vectors, potential temperatures, and streamlines). The results indicated that long-range transport of Asian dust to the west coast of North America was associated with strong westerlies between the Aleutian low and the Pacific high acting as a conveyor belt. Accelerating westerly flows due to cyclogenesis at the source regions over East Asia transported pollution from the continent to the central Pacific. When the system reached the Aleutian Islands, the intensity of troughs and the westerlies were amplified in the North Pacific. Thereafter the winds between the Aleutian Islands and the Pacific Ocean were more intensified from the air flow transport of the conveyor belt. Consequently, the strong wind in the conveyor belt enhanced the dust transport from the Pacific Ocean to the west coast of North America. This was evidenced by PM_{10} concentration (maximum of about $100\,\mu g\,m^{-3}$) observed in California. Further evidence of the dust transport was found through the observation of satellite images, the distribution of TOMS aerosol index, and the analyses of streamlines and backward trajectories.

Key words : Long-range transport, Upper-level trough, Surface cyclone, Conveyor belt, Strong wind

1. INTRODUCTION

Long-range transport of atmosphere substances including dusts and air pollutants such as aerosols, ozone, carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) occurs from the Asian continent to the surrounding regions by the mid-latitude westerlies. Therefore, the transboundary transport of air pollutants is a significant environmental problem in East Asia because of a very rapid increase of pollutant emissions due to fast economic growth. The long-range transport of dusts originated from source regions of inland Asia affects downwind regions such as Korea, Japan, and North America across the Pacific (Kim *et al.*, 2003; Hacker *et al.*, 2001; Husar *et al.*, 2001; Jaffe *et al.*, 1999; Krits, 1990; Merrill *et al.*, 1989).

In the last 20 years many attempts have been undertaken to investigate dust sources, their transport

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and deposition mechanisms, their optical properties, and their physical characteristics (Murayama *et al.*, 2001; Wang *et al.*, 2000; Xiao *et al.*, 1997; Gao *et al.*, 1992). These studies have used meteorological parameters, optical thickness, and aerosol chemistry or mineral composition derived from satellite images, lidar and other ground-based instruments in East Asia, North Pacific, and North America. According to Merrill *et al.* (1989), the temporal variation in mineral aerosol concentrations common to all North Pacific network stations was caused by the seasonality of dust storms in Asia. Kritz (1990) found that the Asian boundary-layer air can be transported to the upper troposphere over California in 2-4 days. Gao *et al.* (1992) presented that the Asian dust to the open ocean was influenced not only by conditions in or near the source regions but also by the large-scale atmospheric circulation patterns. More recently, Jaffe *et al.* (1999) observed Asian air pollution being transported to the surface of North America in the spring of 1997, and in the following year, they reported a visible plume of dust from a strong April Asian dust storm was carried over North America. Jaffe *et al.* (2001) have again detected Asian pollution off the coast of Washington State in the spring of 1999. Recently an Asian dust episode from the Asian continent to Japan and North America which occurred in April 1998 was simulated with the Regional Atmospheric Modeling System (RAMS) (Uno *et al.*, 2001) and the Mesoscale Compressible Community (MC2) model (Hacker *et al.*, 2001). In particular, Husar *et al.* (2001) insisted that Asian dust appeared over the North Pacific Ocean on 21 April reached North America on 23-25 April. Many researcher reported that long-range transport of Asian dust played an important role in determining the optical properties and the biogeochemical cycles of air pollutants in Korea, Japan, and North Pacific Ocean (Mckendry *et al.*, 2001; Tratt *et al.*, 2001; Okada *et al.*, 1990).

Such approaches for examining dust transports helped us to understand the features and origins of dust generation and the effects of desert dusts on climate at a global scale. However, most of previous studies hardly discussed synoptic meteorological processes that lead to long-range transport mainly due to the limited observational data. The purpose of the present study is to analyze meteorological mechanisms associated with the dust event transported to the west coast of North America in April 2001, and to clarify the long-range transport process of Asian dust with a modeling simulation.

2. DATA AND METHODS

The data used in the present study are weather maps, satellite images, aerosol index and hourly PM_{10} data, the backward trajectories, and meteorological variables obtained from Meteorological mesoscale model (MM5) and Read/Interpolate/Plot (RIP) of NCAR graphic program for specific days of April 2001.

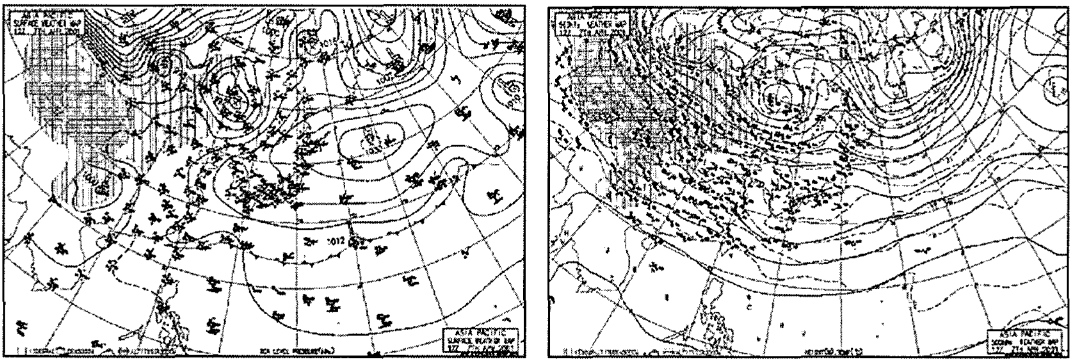
In order to detect the spatial distribution of the dust clouds and plumes, we used satellite remote sensing data measured by Sea-viewing Wide Field-of-view Sensor (SeaWiFS). Daily spectral images obtained from the sensor provided detailed spatial and spectral patterns of the dust at about local noon each day. The resulting spectral reflectance values represented the combined reflectance from the land, clouds, and the aerosol. Further, in order to analyze the origin and intensity of long-range transport from the Asian continent to the west coast of North America, we analyzed the aerosol index data from Total Ozone Mapping Spectrometer (TOMS, http://toms.gsfc.nasa.gov/aerosols/aerosols. html) and the hourly PM_{10} data observed by the beta-ray absorption method at Seoul (37.57° N, 126.97° E, 27 sites), Busan (35.10° N, 129.03° E, 9 sites), Kwangju (35.17° N, 126.88° E, 4 sites), Daegu (35.88° N, 128.62° E, 6 sites), and Daejeon (36.30° N, 127.40° E, 3 sites) of the Korean peninsula, and Glenn (39.5° N, 122.7° W), Nevada (39.5° N, 122.6° W), and Kern (35° N, 118° W) in California of North America.

The geopotential heights, horizontal wind vectors, and potential temperature obtained from MM5 V3 model with National Centers for Environmental Prediction/Climate Data Assimilation System (NCEP/CDAS) input data (2.5° × 2.5°) were analyzed. The resolution of MM5 data is 80 km × 80 km in a domain of 10° N to 70° N and 100° E to 110° W for 17 standard pressure levels between 1000 hPa and 5 hPa. The origin of Asian dust might be identified by constructing the backward trajectory analysis (http://gus.arlhq.noaa.gov/ready/hysplit4.html) using HYSPLIT_4 (Hybrid Single-Particle Lagrangian Integrated Trajectory) model (Draxler and Hess, 1998).

3. OVERVIEWS OF ASIAN DUST PHENOMENON IN APRIL 2001

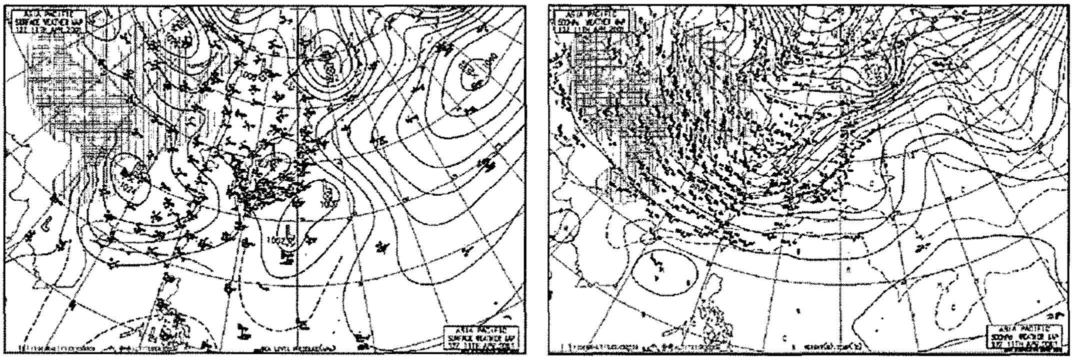
3.1 Synoptic features associated with the dust transport

Fig. 1 shows weather maps on 1200 UTC of 7 and 11 April 2001. These figures indicate a surface level (left figures) and 500 hPa level (right figures), respectively. The synoptic conditions in Fig. 1 are mainly associated with the upper-level trough in connection with surface low system over the northern part of Korea. On the surface level of 7 April, a surface low-pressure system was located at 50° N and 122° E. A high-pressure circulation occurs in the eastern subtropical Pacific producing the southeasterly tropospheric trade winds of the tropical Pacific. On the 500 hPa level of 7 April, a high-latitude cyclonic circulation with the weak trough occurs over eastern Siberia, which is located northwest of the Korean peninsula, and a mid-latitude westerly flow can pass across the North Pacific in the middle/upper troposphere. Owing to the strong zonal wind, the slope of a trough within the westerly would be small. Further because the isoline of geopotential height was formed parallel to 45-50° N of latitude, the horizontal motion of zonal wind tends to occur near Korea without downward flow due to cold advection (500 hPa weather map of 7 April).



Surface level/7 April

500 hPa level/7 April



Surface level/11 April

500 hPa level/11 April

Fig. 1. Weather maps at 1200 UTC on 7 April and 11 April 2001.

The synoptic conditions on 7 April were continuous on 8 and 9 April (not shown). Therefore, although the dust event was reported in Korea, we could expect that the influence of the dust on the Korean peninsula would be small for 7-9 April.

However, on the surface and 500 hPa level of 11 April, the upper-level trough in connection with surface low system already passed from the northwestern part to the central part of Korea and moved into the North Pacific, compared to weather maps of 7 April. At that moment, the strong trough was developed around the Korean peninsula with the downward motion of cold air to the western part of the trough axis. That is, loft pollution of the dust into the free troposphere at the source regions under the upper-level trough passage and surface low system where it then may be carried rapidly across the North Pacific. As the upper-level trough with the low-pressure system moved eastward, there were dust event reports behind the cold front at near the Korean peninsula. A large amount of the dust was reported and then continuously moved eastward.

3.2 Spatial distributions of the dust plumes using satellite image

Fig. 2 depicts the spatial distribution of the dust plumes obtained from 1 km resolution SeaWiFS satellite images on 7, 11, and 14 April 2001. The spectral reflectance images provide a rich visual context, including surface reflectance and the position of white cloud systems relative to the Asian dust. The dust plume followed a northern route toward central

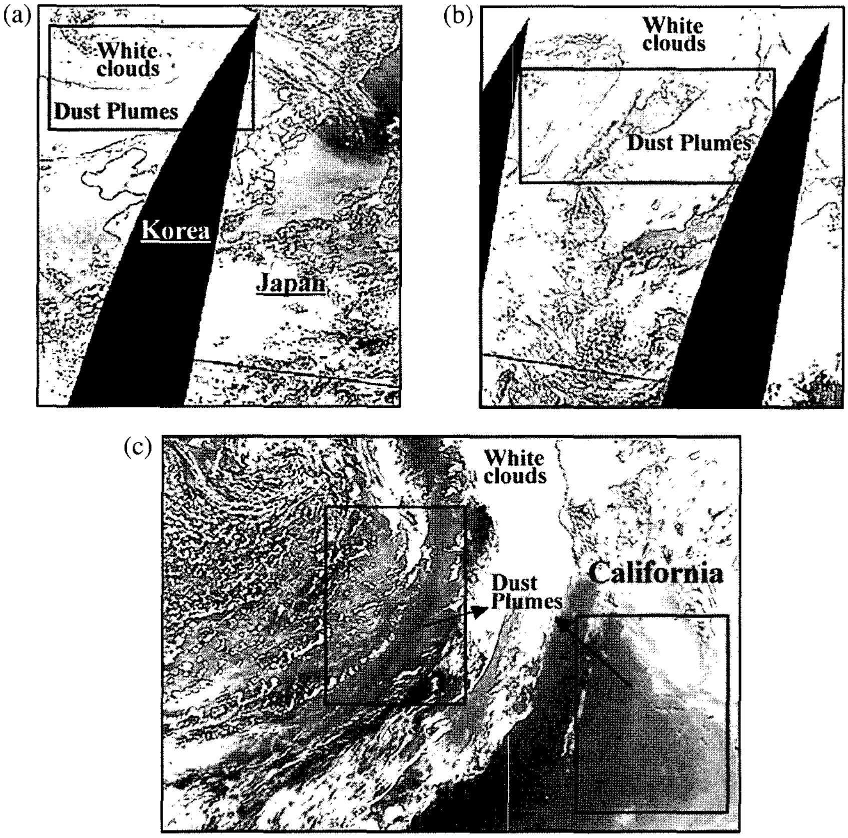


Fig. 2. SeaWiFS satellite images on (a) 7 April, (b) 11 April, and (c) 14 April 2001. The Asian dust plumes are distinguishable from the white clouds and dark land surfaces. The above images were adopted from SeaWiFS Global Area Coverage (GAC) images (http://seawifs.gsfc.nasa.gov/SEAWIFS.html).

and eastern China (Fig. 2a) and subsequently began to turn toward the central of Korea from west to east (Fig. 2b). In the first image (Fig. 2a), from 7 April 2001, the bright yellowish-brown cloud near Inner Mongolia is the center of the dust storm, being pushed by a short wave trough and a low-pressure system located at the 50° N and 122° E on the weather map of 7 April (Fig. 1). In the subsequent images from April 11 (Fig. 2b), the atmospheric circulation around a low-pressure system (see surface weather map of 11 April in Fig. 1), which is located to the east of Korea, entrains the dust plumes from the storm and can carry them over the North Pacific Ocean (Fig. 2b). On April 14, dust from this event reached the west coast of North America, and this image shows the arrival of airborne dust from the source regions of China. Dust plumes are visible south (below) of the coast, and mixed with clouds further west over an open ocean (the left part of Fig. 2c). Therefore we found that there was close correlation between the movement of the low-pressure system and that of the dust plume.

3.3 Spatial distribution of aerosol index of TOMS

Using TOMS aerosol indexes for the period 4-14 April 2001 (not shown), we can find that most dust storms in East Asia occur in the major source regions from Takla-Makan desert (38.5-41.5° N, 78-90° E) in northwestern China to northern Inner Mongolia (41.5-43.5° N, 112.5-117.5° E) across Gobi (37.5-42.5° N, 100-110° E) desert. The location of three regions was chosen by quoting the paper of Kwak and Jhun (2002).

In the present study, we displayed daily images of aerosol indexes produced by Earth Probe TOMS measurements on 7, 9, 11, and 13 April 2001 as shown in Fig. 3. Light gray of aerosol index (+0.7) indicates the smallest amount of dust/smoke in the atmosphere, with black color indicating the largest amount. On 7 April, high value of aerosol index greater than about +4 is shown the northwestern part of the Korean peninsula (Fig. 3a). Thereafter, it progressively moves eastward across the northern part of the Korean peninsula for next two days (Fig. 3b). The dust phenomenon appeared over the North Pacific Ocean (50-55° N, 155-160° E) and Alaska (55-60° N, 150-160° W) on 11 April (Fig. 3c). In particular, we found that the dust continued to be present over the North Pacific Ocean and Alaska and

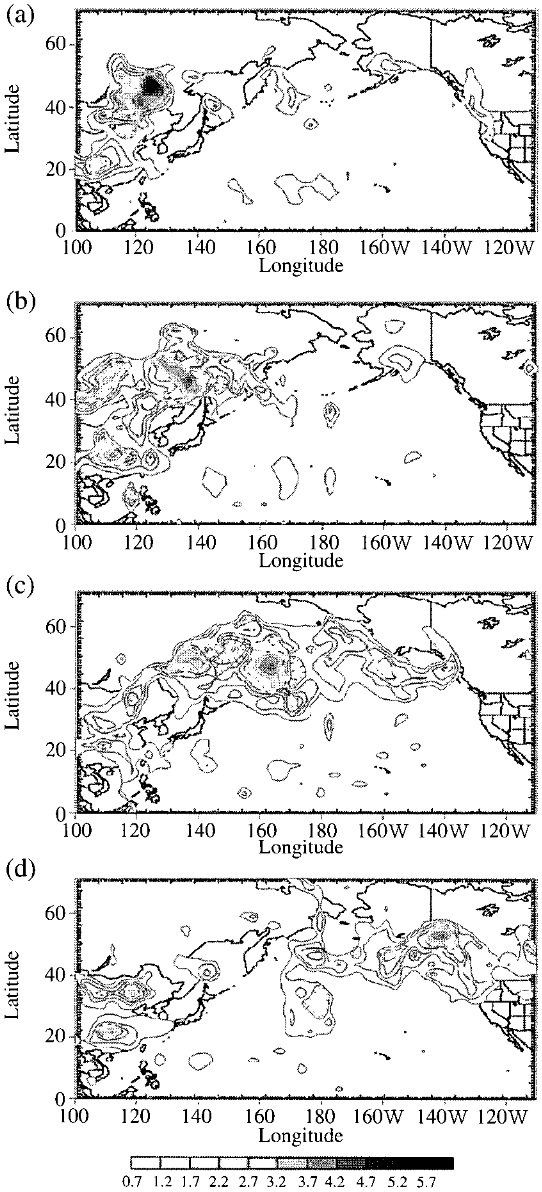


Fig. 3. Horizontal distribution of aerosol indexes from TOMS. (a)-(d): at 1500 LST on 7, 9, 11, and 13 April 2001 (http://toms.gsfc.nasa.gov/aerosols/aerosols.html).

then the high dust concentration arrived at the North America on 13 April. At the same day, Asian dust was detected in the Gobi desert, and the Chinese Loess Plateau and southeastern China (Fig. 3d).

Although the distribution of TOMS aerosol index was similar to that of SeaWiFS images, the superposition of the SeaWiFS and TOMS data in Figs. 2 and 3 revealed that the dust pattern from TOMS and SeaWiFS did not coincide geographically. This is an indication that the fresh dust layer was near the ground where the TOMS sensor is less sensitive to dust (http://toms.gsfc. nasa.gov/aerosols/aerosols.html).

3.4 Variations of PM_{10} concentration observed in Korea and North America

In order to confirm the Asian dust enhancement over Korea and North America, we analyzed hourly mean PM_{10} concentration observed at 5 cities of Korea for 5-15 April 2001 (Fig. 4) and at 3 counties in California of North America for 10-20 April 2001 (Fig. 5). All of the PM_{10} concentrations shown in Figs. 4 and 5 are the averaged values observed in several sites each county.

The observed PM_{10} concentration does not increase for the first 3 days after the Asian dust event (ADE, 7-13 April 2001) being reported by KMA (Korea Meteorological Administration). However, it starts to increase from 10 April and to exceed a maximum of 500 $\mu g\ m^{-3}$ in Seoul on 11 April. This is about 5 times higher than the averaged value of 100 $\mu g\ m^{-3}$ on non-dust days in most cities. The trough with cold core passed through the central part of Korea from the northwest to the southeast as shown in Fig. 1. This well explains the dust enhancement in the downwind regions. Thereafter it slowly decreases for 12-14

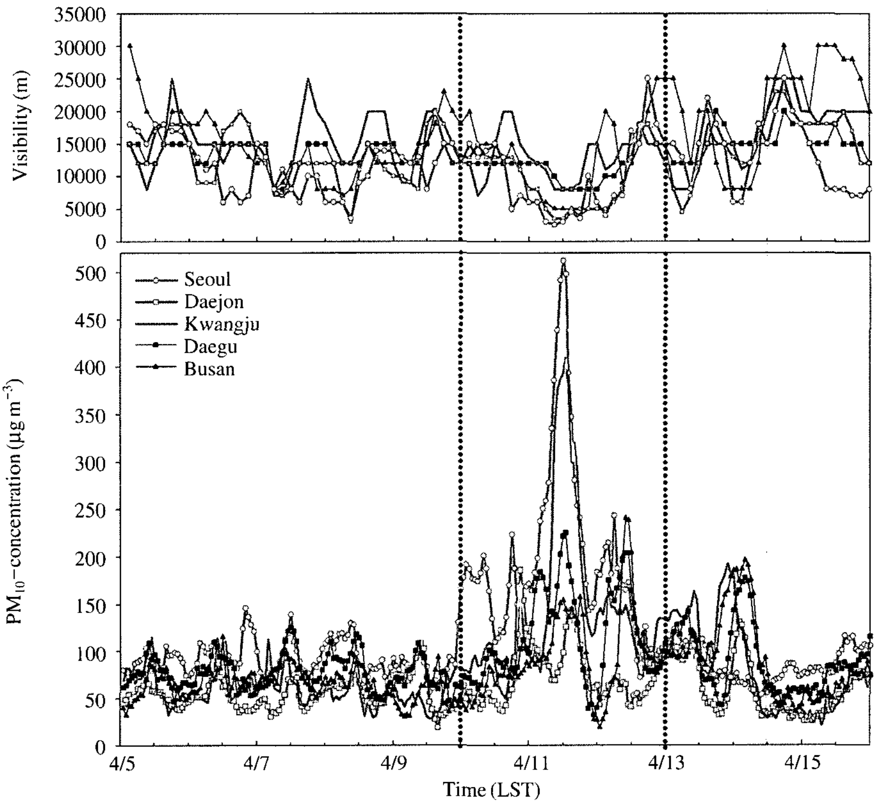


Fig. 4. Visibility (3 hourly) and hourly surface concentrations of particulate matter (PM_{10}) observed at monitoring sites in five cities supported by Ministry of Environment in Korea for 5-15 April 2001.

April and the dust event begins to disappear on 15 April. Nevertheless the Asian dust phenomenon over Korea observed between 7 and 13 April, PM_{10} concentration shows the lower value (about 100 $\mu g\ m^{-3}$) during the dusty days except for 10-12 April. This was caused by attenuating the downward motion of air flow in the central part of Korea because of the movement of the upper-level trough observed at the northern part of the Korean peninsula (see Fig. 1).

Compared between a top and bottom figure in Fig. 4, we found that there was nearly negative correlation between PM_{10} concentration and visibility at most cities except for Kwangju and Busan during this event. In particular, visibility was increased for 5-6 April and was severely degraded due to highly increased PM_{10} concentration during the dusty days, particularly on 10-13 April. The visibility at noon on 11 April indicated a minimum value ($\leq$ 2000 m) at most cites.

Fig. 5 shows hourly PM_{10} concentration averaged at 3 counties, which is Glenn, Nevada, and Kern, in California, North America for 10-20 April 2001. The concentrations show a strong and consistent diurnal cycle throughout the dust event in California from the noon on 13 April to the early afternoon on 18 April. From afternoon on 13 April, PM_{10} concentration increases and reaches about 60 $\mu g\ m^{-3}$. The maximum concentration shows as nearly 100 $\mu g\ m^{-3}$ on 16 April, compared to the other days. For 17-18 April, the concentration shows around 60 $\mu g\ m^{-3}$, and then it slowly decreases until the end of the ADE. Mean PM_{10} concentration during one month, April 2001, is 24.28 $\mu g\ m^{-3}$ at 3 counties and this is about 4 times lower than the averaged value of 60-90 $\mu g\ m^{-3}$ during the dusty days. The present analysis of PM_{10} concentration transported toward North America across the Pacific is consistent with the results (PM_{10} concentration exceeding 60 $\mu g\ m^{-3}$ during the ADE) of Husar *et al.* (2001). Therefore these figures provide a good example of the Asian dust phenomenon transported toward the western part of North America during the ADE.

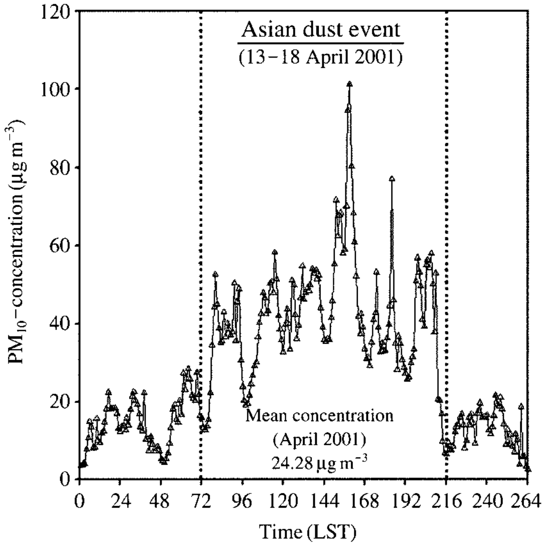


Fig. 5. Hourly PM_{10} concentration averaged at 3 counties (Glenn, Nevada, and Kern) in California, North America for 10-20 April 2001 (http://www.arb.ca.gov/adam/welcome.html).

4. ANALYSIS OF METEOROLOGICAL MECHANISMS ASSOCIATED WITH THE DUST TRANSPORT

4.1 Meteorological conditions associated with the dust transport in the North Pacific

The meteorological conditions of the source regions 2-3 days before are generally important in long-range transport of Asian dust (Chun, 1997; Chung and Park, 1995). In particular, trans-pacific dust transport is also associated with the meteorological conditions, which are pressure patterns, wind erosion, and the distribution of meteorological variables (horizontal wind, potential temperature, and streamline), over the North Pacific Ocean as well as the Asian continent. According to Jaffe *et al.* (2001), the strongest pollution episode, the enhancement of CO transported from East Asia, observed at Cheeka Peak Observatory (CPO) with the strong westerlies due to the air flow movement through conveyor belt in which flow is accelerated in a straight and narrow band between the Aleutian low (55° N, 160° E) and the Pacific high (40° N, 160° E). However they did not study the meteorological mechanisms in connection with the conveyor belt. Therefore, we are to confirm the acceleration of horizontal wind in association with the conveyor belt, plus the analysis of horizontal distributions of wind velocity, geopotential heights, and potential temperature (Figs. 6c and 7c), and are to analyze the flow of air parcel including the dust near the Aleutian Low with streamlines and backward trajectories (Figs. 8c and 9).

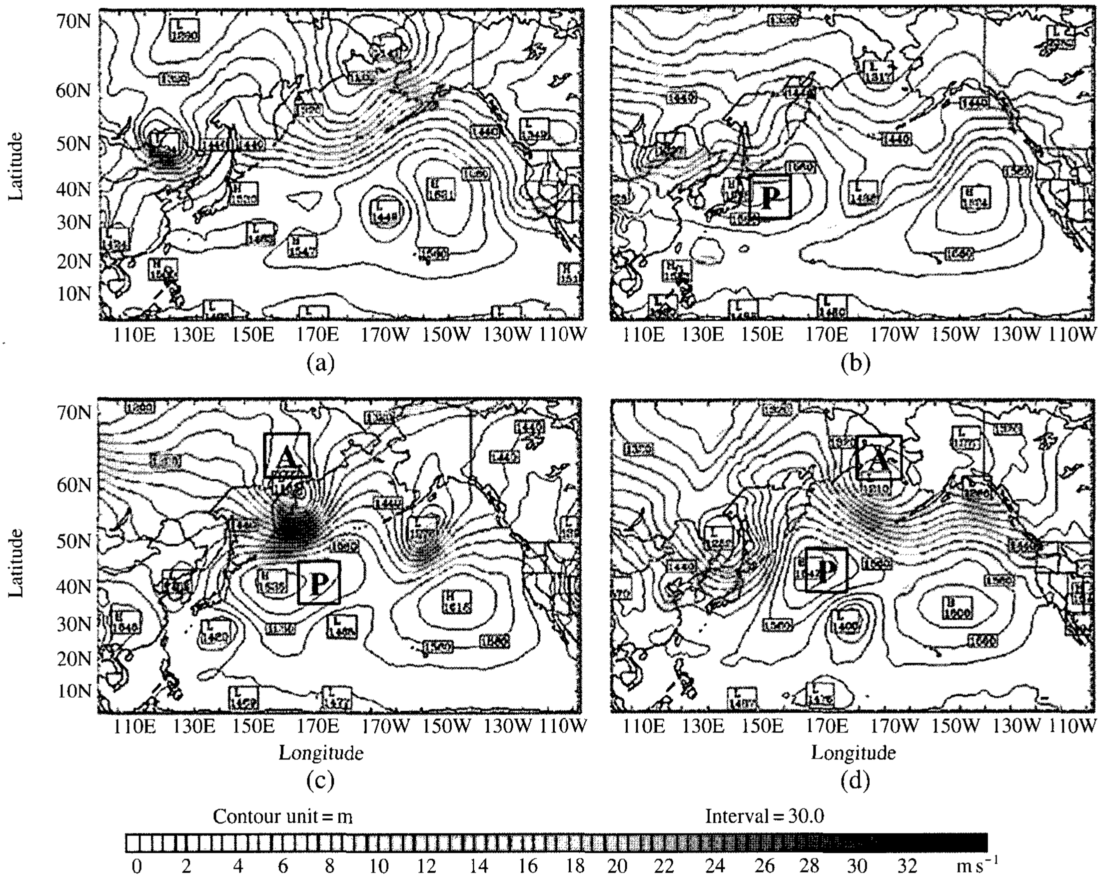
Besides, Stone *et al.* (1999) insisted that the strongest ADEs over North America were often associated with amplifying troughs in the North Pacific, an area of frequent cyclogenesis known as the Pacific storm track. These systems loft the boundary layer air into the free troposphere on the ridge part of the baroclinic wave, and cause clean air to descend on the trough part of the wave. When cyclogenesis at the source regions over East Asia is followed by strong amplification in the storm track, accelerating westerly flows can move pollution from the continent to the central Pacific in a few days. When the system reaches the Aleutian Islands, a dust plume extends virtually across the Pacific Ocean from East Asia. Therefore the strong wind velocity between the Aleutian Islands and the Pacific Ocean was more intensified from the air flow transport of the conveyor belt.

4.2 Analysis of meteorological variables associated with the dust transport

In this section we will discuss the analysis of meteorological variables to better understand long-range transport of Asian dust to the western part of North America. Generally, the upstream part of the conveyor belt being mentioned in the present study is a broad air stream that often appears as the low-level jet and the maximum wind in the low-level jet is about 1 km above the earth's surface (Dusan, 1994). Therefore we are to analyze the characteristics of geopotential heights, wind velocity, streamlines, and potential temperature in the 850 hPa level.

Fig. 6 shows the horizontal distributions of geopotential heights and isotach in the 850 hPa level at 1200 UTC (2100 LST) on 7, 9, 11, and 13 April 2001 from the MM5 modeling. The formation, transport, and deposition of Asian dust for the period of 7-13 April 2001 are correlated with geopotential heights and wind velocity in the 850 hPa level. The long-range transport of Asian dust toward the North Pacific Ocean and North America can be also related with the strong westerlies in the high latitude in association with the strong upper-level trough. On 7 April 2001 (Fig. 6a), the distributions of goepotential heights were developed and deepened in the northern part of Korea with the trough in connection with a surface low-pressure system (the weather map on 7 April in Fig. 1). The dust transport from the source regions of China is due to the strong westerlies with the development of a surface low-pressure system. On 9 April, the zonally distributed geopotential heights in the northern part of Korea and Japan give rise to the dust transport zonally (Fig. 6b). When the strong westerly due to the development of the upper-level trough passes through over the source regions such as Takla-Makan and Gobi desert, Inner Mongolia, and Loess plateau, the dust storm can be entrained and partially deposited in the vicinity of the source regions, and partially transported to the downwind regions. It is indicated that the strong dust storm in the source regions is mainly affected by the development of surface anticyclone in higher latitudinal location between the upper-level ridge and trough, and is trapped within high mountains or is transported eastward. Above all, it is important to understand the distributions of geopotential heights with the development of the upper-level trough to find out the transport path of Asian outflow.

While, the dust moves horizontally along the long-wave upper-level trough from the northwestern China to the North Pacific Ocean on 11 April, because the strong wind passes through the source regions of the dust storm in the northern and northwestern China (Fig. 6c). Thereafter, the development of the deepening trough in connection with surface cyclone and their eastward motion play a role in the transport and deposition of Asian dust not only in East Asia but also in the North Pacific area. The more accelerated wind due to the air flow transported from the conveyor belt results in the fast movement of air flow ($\geq$ 20 m s^{-1}) at the southern part (50° N, 160° E) of the Aleutian Islands, compared



(a) (b) (c) (d)

Fig. 6. Horizontal distribution of geopotential heights (solid lines) and isotach contours (shaded) in the 850 hPa level obtained from MM5. (a)-(d) at 1200 UTC (2100 LST) on 7, 9, 11, and 13 April 2001. Aleutian Low are denoted "A", while Pacific High are denoted "P".

to the mean wind velocity (about 12 m s^{-1}) for 1990-2000 year (not shown), presented by the more accelerated wind due to the air flow transported from the conveyor belt. At this time, Asian dust can fast move along the horizontal wind distribution due to the intensified wind. Such analyses also show that the air streams near the center of the deep trough in connection with the surface cyclone tend to move parallel to geopotential contours without much vertical motion. These pressure patterns are shown in the long-range transport of Asian dust from China to the west coast of North America.

On 13 April, the surface cyclone with the trough was elongated and stretched eastward of the Pacific. The dust continued to be present over the North Pacific Ocean and Alaska and most of the dusts reached the west coast of North America (Fig. 6d). At last, the high concentration of dust arrived at the west coast of North America. As the strong wind could induce the dust transport from the Pacific Ocean to the west coast of California, and the PM_{10} concentration reached a maximum of about 100 $\mu g\ m^{-3}$ (Fig. 5). At the same day, Asian dust can be generated continuously in the Takla-Makan and Gobi desert, the Chinese Loess Plateau, and southeastern China.

Fig. 7 displays the horizontal distribution of potential temperature and wind vectors in the 850 hPa during this April event. The wind vectors at the north of Korea (50° N, 125° E) were converged as a cyclone system, and the distributions of potential temperature were also shown a strong gradient (about 15 K from 270 K to 285 K) on both parts of the border of 50° N in latitude and 140° E in longitude (Fig. 7a). The front occurs frequently at this region, and the air flow is found wrapped around the trough. The dusts transported through the westerly could be also deposited into the lower level of Korea caused by the vertical motion along the frontal zone, but the influence of the dust on the center of Korea was very slight. We confirmed the low effect of PM_{10} concentration as seen by Fig. 4. On 9 April, the downward motion of air flow was very weak because the gradient of potential temperature and wind vectors were weaker than that of 7 April at the north of Korea. The dust deposition must be also small (Fig. 7b). For 11-13 April, the gradient of potential temperature developed between the Aleutian Low and the Pacific High, and the wind vectors were stronger at this region. The wind velocity was accelerated with the air flow transported from the conveyor belt (Figs. 7c and 7d). It was obvious that the dust transport from the Pacific Ocean to the west coast of North America was well reflected as the synoptic patterns and the distribution of geopotential heights (see Figs. 1 and 6).

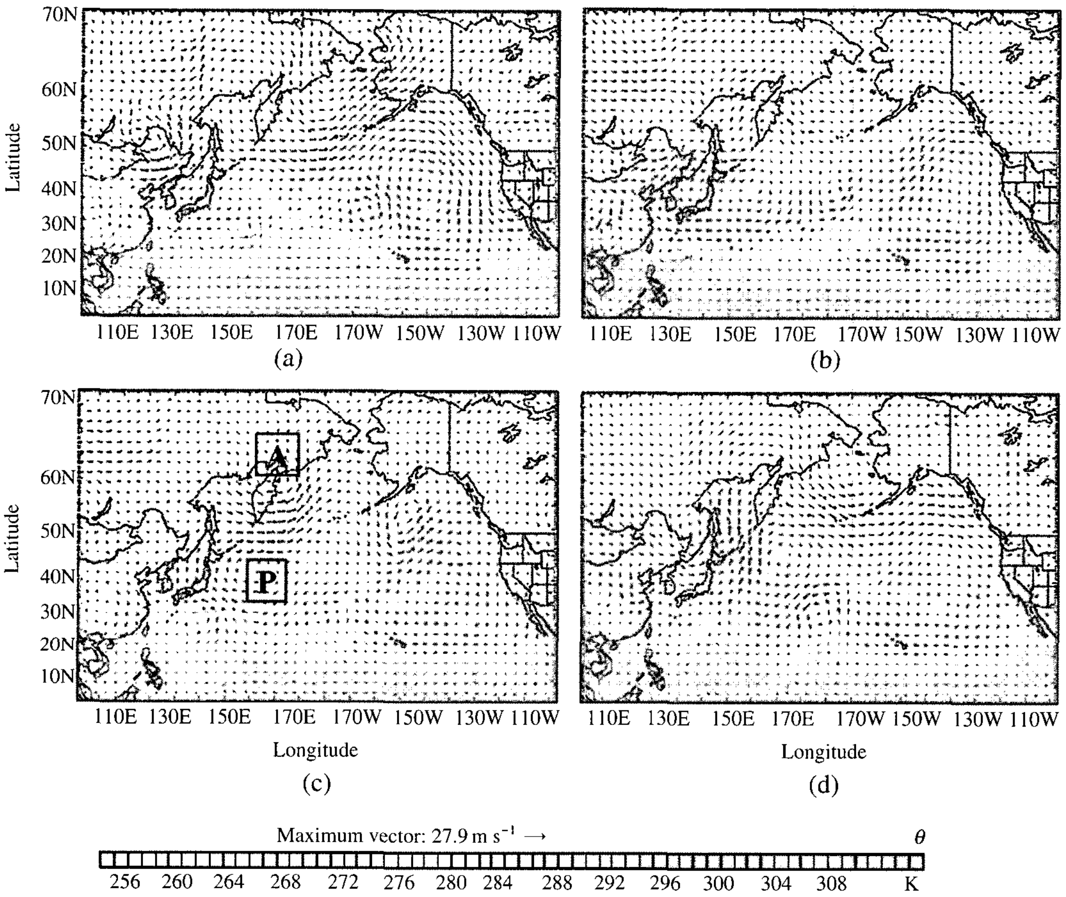


Fig. 7. Horizontal distribution of potential temperature and wind vectors in the 850 hPa level on 1200 UTC (2100 LST) (a) 7, (b) 9, (c) 11, (d) 13 April 2001. Shown are potential temperature (K, contour) and horizontal wind vectors (m s^{-1}, arrow). Aleutian Low are denoted "A", while Pacific High are denoted "P".

Fig. 8 shows the horizontal distribution of streamlines in the 850 hPa level on 1200 UTC (2100 LST). Anticyclonic centers are denoted "A", while cyclonic centers are denoted "C". Typical flow patterns on 7 April are dominated by the strong air flows showed at the northern part of the Korean peninsula (Fig. 8a). The westerly flows of the streamlines were continuous on 9 April (Fig. 8b), and the dust transport was also shown from the northern part of the Korean peninsula to the northern Pacific (see Fig. 3b). On 11 April, the streamlines show a major anticyclone (40° N, 155° E) dominating the northern Pacific. Strong subsidence associated with this anticyclone occurs over the subtropical northeastern Pacific (not shown). Thereafter the subsidence (including the dust) with streamlines can be transported from the subtropical region to the ending of Aleutian Low, and it might be again moved into the west coast of North America (Fig. 8c). On 13 April, the accelerated air flow from the effect of conveyor belt reached the western part of North America by accompanying with the cyclone in high latitude and the anticyclone in the subtropical region (Fig. 8d).

Fig. 9 shows ten-day backward trajectories of the air mass arrived at 3 counties (Glenn, Nevada, and Kern) along the isentropic surface on 2100 UTC of 13 April 2001. The top figure shows a horizontal perspective of the trajectories, while the lower figure is a plot of pressure altitude versus longitude. Open circles along the trajectory paths indicate the air mass arrived at Glenn (39.5° N, 122.7° W), grey stars denote it arrived at Kern (35° N, 118° W), and small arrows indicate it arrived at Nevada (39.5° N, 122.6° W). The air parcels were transported from a

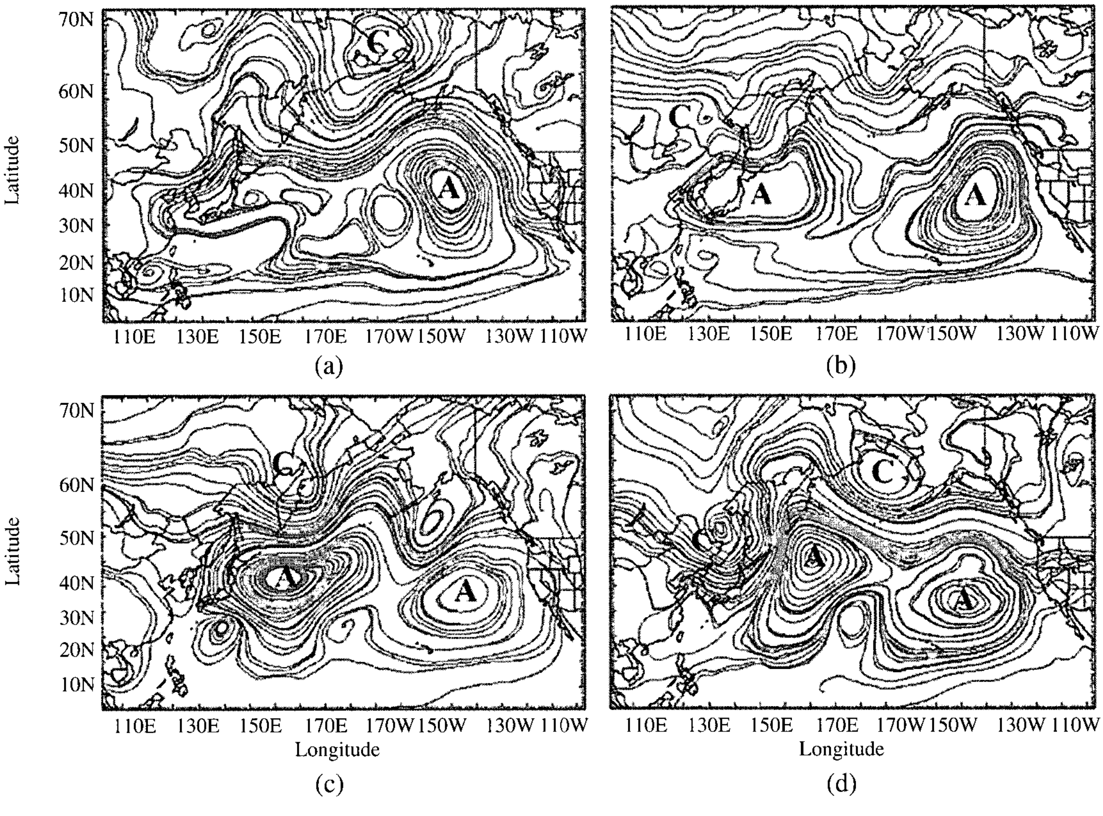


Fig. 8. Horizontal distribution of streamlines in the 850 hPa level on 1200 UTC (2100 LST) of (a) 7, (b) 9, (c) 11, and (d) 13 April 2001. Anticyclonic centers are denoted "A", while cyclonic centers are denoted "C".

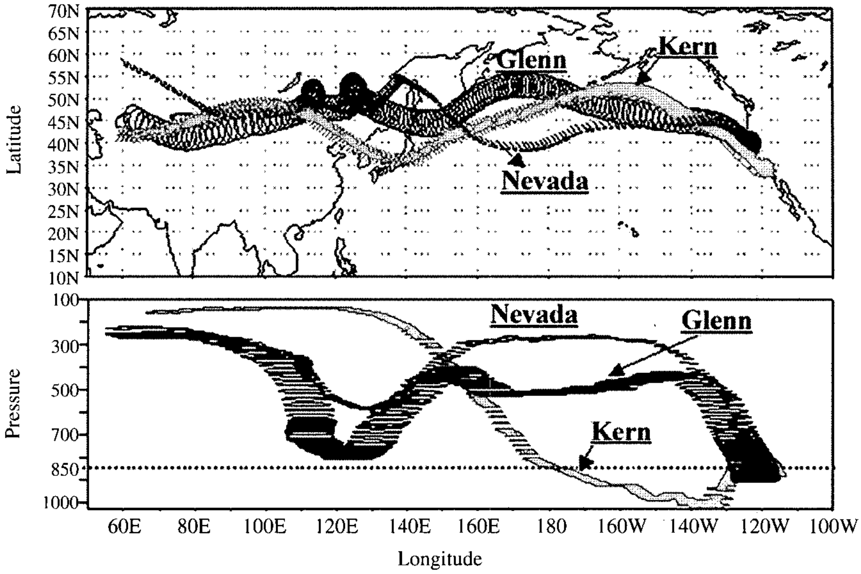


Fig. 9. Ten-day backward trajectories of the air mass arrived at 3 counties, Glenn (open circles; 39.5° N, 122.7° W), Nevada (small arrows; 39.5° N, 122.6° W), and Kern (grey stars; 35° N, 118° W) along the isentropic surface on 1200 UTC (2100 LST) of 13 April 2001. AGL; above ground level (http://arlhq.noaa.gov/ready/hysplit4.html). 850 hPa level is denoted as the dotted lines.

Takla-Makan and Gobi desert of China, Japan, and then passed through a series of midlatitude wave cyclones as they progress eastward across the Aleutian Islands. The current trajectories started in the upper troposphere at first, and then most of trajectories except for Kern passed through the mid and low troposphere. We could know that the air flows corresponding to the top figure arrived at the west coast of North America after rapid transport across the Pacific. In particular, the 1000-m profile of the downwind deposition region indicated that the air flow including Asian dust was intruded from an elevation of approximately 5 km. Therefore we can also know that the long-range transport of April 2001 event is originated from Takla-Makan and Gobi desert, and is related to the strong westerlies caused by the accelerated air flow from the conveyor belt.

Consequently, we found that trans-pacific dust transport has been related to the meteorological mechanisms (the accelerated horizontal wind and the distribution of potential temperature and streamline associated with the conveyor belt) and synoptic conditions (the upper-level trough, surface low- and high-pressure system) over the North Pacific Ocean. For example, such cases occurred in the spring of 1998 and 2001 (Kim *et al.*, 2002, 2003; Hacker *et al.*, 2001; Husar *et al.*, 2001).

5. SUMMARY AND CONCLUSIONS

The meteorological mechanisms of Asian dust to North America are related to various synoptic conditions, which is the high-latitude distribution of the strong westerlies with the upper-level trough and surface cyclones. The characteristics on the meteorological mechanisms associated with Asian dust transport in April 2001 were analyzed by using weather maps, satellite images, TOMS and surface PM_{10} data, backward trajectories, plus modeling output results (geopotential heights, horizontal wind vectors, potential temperatures, and streamlines). The spatial distribution of satellite image and TOMS aerosol index indicated that the dust storms generated in Takla-Makan and Gobi desert before 7 April were transported to the west coast of North America for 13-14 April. PM_{10} concentration showed around 60 $\mu g\ m^{-3}$ for 13-18 April, particularly it reached a maximum of about 100 $\mu g\ m^{-3}$ on 16 April 2001.

The dominant meteorological features associated with long-range transport of Asian dust are also summarized as follows. The westerlies passed through the source regions of dust storms in the northern and western China, causing Asian dust to move horizontally eastward with the long-wave trough to North America. The development and motion of the deepening trough connected with a surface cyclone therefore played a role in the transport and deposition of Asian dust not only in East Asia but also in the North Pacific. In particular, the dust transport from the Asian continent to the west coast of North America is associated with the strong wind velocity between the Aleutian low and the Pacific high. The strong wind velocity was more intensified with the fast and strong air flow through the conveyor belt. When the westerlies reached the Aleutian Islands, dust plumes extend across the Pacific Ocean from East Asia. At that moment, the strong wind induced continuously the dust transport from the Pacific Ocean to the west coast of North America.

From the modeling results of the meteorological variables, we concluded that the fast movement of the air flow induced the trans-Pacific dust transport between the Aleutian low and the Pacific high as shown in the horizontal distribution of geopotential heights and streamlines in the 850 hPa level. The distributions of potential temperature and wind vector illustrated a strong gradient (from 270 K to 285 K) on the border of the region. It was evident that the warm air flow was transported through the conveyor belt and the air flow was more accelerated the westerlies at the North Pacific. Finally, these features well show the long-range transport of Asian dust from China to the west coast of North America.

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