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Short-cut transport path for Asian dust directly to the Arctic: a case study

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Abstract

Asian dust can be transported long distances from the Taklimakan or Gobi desert to North America across the Pacific Ocean, and it has been found to have a significant impact on ecosystems, climate, and human health. Although it is well known that Asian dust is transported all over the globe, there are limited observations reporting Asian dust transported to the Arctic. We report a case study of a large-scale heavy dust storm over East Asia on 19 March 2010, as shown by ground-based and space-borne multi-sensor observations, as well as NCEP/NCAR reanalysis data and HYSPLIT trajectories. Our analysis suggests that Asian dust aerosols were transported from northwest China to the Arctic within 5 days, crossing eastern China, Japan and Siberia before reaching the Arctic. The results indicate that Asian dust can be transported for long distances along a previously unreported transport path. Evidence from other dust events over the past decade (2001–2010) also supports our results, indicating that dust from 25.2% of Asian dust events has potentially been transported directly to the Arctic. The transport of Asian dust to the Arctic is due to cyclones and the enhanced East Asia Trough (EAT), which are very common synoptic systems over East Asia. This suggests that many other large dust events would have generated long-range transport of dust to the Arctic along this path in the past. Thus, Asian dust potentially affects the Arctic climate and ecosystem, making climate change in the Arctic much more complex to be fully understood.

1. Introduction

The Arctic is especially affected by global warming, which causes ice retreat and leads to exposure of absorbing Arctic Ocean water in the region (Zábori *et al* 2012). There is evidence to support substantial warming in the Arctic since the mid-20th century, with climate models predicting much greater warming in the region than the global average (Arctic Climate Impact Assessment (ACIA) 2004). The annual mean sea ice extent in the Arctic has rapidly decreased since 1979, with a rate of decline ranging from 3.5 to 4.1% every decade (IPCC 2013). Moreover, ice-free conditions lasted nearly 3 months in some areas of the Arctic, such as the East Siberian Sea and the western Beaufort Sea. The Arctic sea ice cover is likely to continue shrinking and thinning due to global warming (Serreze *et al* 2007). It has been demonstrated that aerosols may significantly influence the Arctic climate (Garrett and Zhao 2006). Light absorbing aerosols (e.g., dust aerosols and black carbon) deposited on the ice or snow surfaces could further reduce surface albedo thereby accelerate the snow or glacier melting (Huang *et al* 2011, Yasunari *et al* 2011, Wang *et al* 2013).

Model simulations have shown that about 400 Tg of Asian dust are subjected to long-range transport to downwind regions by westerly winds (Zhang *et al* 1997). More dust aerosols may be injected into the atmosphere as a result of accelerated dryland expansion under climate change (Huang *et al* 2015). The long-range transport path of Asian dust from northwest China to the Pacific Ocean is well understood (e.g., Uno *et al* 2001, Takemura *et al* 2002, Huang *et al* 2008a, Wang *et al* 2010a, Sugimoto and Huang 2014), as is the route to North America along two main transport pathways (Jaffe *et al* 1999, Zhao *et al* 2006); furthermore, even a transport route of more than one full circuit around the globe has been documented (Uno *et al* 2009). Mineral dust particles not only adversely impact human health, they also have a large impact on the Earth's radiation budget by scattering and absorbing solar and terrestrial radiation due to their spectral characteristics and large optical depth (Haywood *et al* 2003, Huang *et al* 2010, 2014, Hayasaka *et al* 2007, Bi *et al* 2010, Chen *et al* 2013 and 2014). Mineral dust mixed with air pollution in the atmosphere can lead to a brownish haze, which absorbs and scatters solar radiation and thus decreases solar irradiance at the surface (Ramanathan *et al* 2001). Furthermore, if the mineral dust particles contain carbonaceous components, they can have a proportionately stronger impact on atmospheric heating than does sub-micrometer black carbon, and their residence time is greater (Seinfeld *et al* 2004). Dust particles could play a role in regional cloud formation because they are generally known as active ice nuclei (IN) inducing ice formation and cloud condensation nuclei (CCN) forming liquid cloud droplets, depending on ambient temperature (Huang *et al* 2006a and 2014, Zhao *et al* 2008, Wang *et al* 2015). When combined with sulfur dioxide or nitric acid, dust particles become more hygroscopic due to its surface property modifications with hydrophilic material (Clarke *et al* 2004, Huang *et al* 2006b, Wang and Huang 2009, Wang *et al* 2010b). It has also been shown that Asian dust can mix with organic matter and bioaerosols (Sugimoto *et al* 2012). Dust particles experience morphological change and become more spherical during long- range transport (Zhang and Iwasaka 2004, Tobo *et al* 2010).

Long-range transport of Asian dust has been documented in ice and snow cores in the Arctic region. Previous studies have reported that Asian dust can be long-range transported to Alaska (Rahn *et al* 1981) and has significant impact on regional radiation (Stone *et al* 2007). Based on a comparison of clay mineralogy and chemical fingerprints, Biscaye *et al* (1997) reported that dusts deposited in a Greenland ice core probably originated from East Asia during several intervals in the last glacial period. Mineral dust extracted from snow and firn deposited over the last decade at the North Greenland Ice Core Project (NorthGRIP) ice camp has confirmed an East Asian origin for central Greenland dust (Bory *et al* 2003). Until now, very few studies investigated the long-range transport path of Asian dust to the Arctic. In the Arctic, anthropogenic aerosol may influence the radiation budget and generate positive forcing at the surface (McFarquhar *et al* 2011), but top-of-the-atmosphere (TOA) forcing is thought to be negligible. Atmospheric aerosols (such as dust) can affect the microphysical characteristics of cloud, consequently influence the amount of radiation that heats or cools the surface ice and snow (Sharma *et al* 2006) and the effects that Arctic mixed-phase clouds can have on surface cooling (Morrison *et al* 2012). Mineral dust may also affect the characteristics and chemical reactions of polar stratospheric clouds (PSC), which play an essential role in the springtime chemical depletion of ozone at high latitudes (Solomon 1999). Therefore, both dust aerosols and black carbon (Koch and Hansen 2005, McConnell *et al* 2007) may have an impact on the Arctic environment and climate change, as well as its hydrology and biogeochemistry cycles.

Here, we report a case study of the long-range transport of Asian dust directly toward the Arctic, as shown by ground-based and space-borne multi-sensor observations. We focus on a heavy dust storm that occurred from 19 to 22 March 2010. We examined 10 years of Asian dust events that were observed by lidar during 2001–2010 and validated by SKYNET sky-radiometer observations and/or dust reports. The Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT) was also used to check whether dust from Asian dust events was transported to the Arctic. Finally, the mechanism of Asian dust long-range transportation to the Arctic was investigated.

2. Instruments and data

2.1. Ground-based and space-borne CALIPSO lidars

The ground-based lidar system used in this study was a two-wavelength (532 and 1064 nm) Mie-scattering polarization lidar developed by the National Institute for Environmental Studies (NIES) in Japan for continuous network observations (Sugimoto *et al* 2008). It uses a flash-lamp-pumped, second-harmonic Nd: YAG laser and a receiver telescope with a diameter of 20 cm. The transmitted laser (532 nm) was linearly polarized (Sugimoto *et al* 2003). The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on board the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite is designed to acquire vertical profiles of elastic backscatter at two wavelengths (532 and 1064 nm), providing profiles of linear depolarization at 532 nm (Winker *et al* 2007). Its high-resolution vertical profiling ability and accurate depolarization measurements make it a superb platform for the study of dust aerosols (Liu *et al* 2008, Chen *et al* 2010, Liu *et al* 2015). Ground-based lidar has a unique advantage of charactering the evolution of atmospheric aerosol properties in the troposphere, especially within boundary layer (Gao *et al* 2011). Four NIES lidar sites include Sendai, Tsukuba, Chiba as well as the Semi-Arid Climate and Environment Observatory of Lanzhou University

(SACOL). In addition, measurements from a high spectral resolution lidar (HSRL) built by the Wisconsin University lidar group in Eureka at the North Pole (Eloranta and Razenkov 2006, Bourdages *et al* 2009) were used. CALIPSO product Level 1 (version 3.01) on 22 March 2015 is used in this study. Three ground-based lidars (at SACOL, Sendai and Eureka) and space borne CALIPSO lidars were simultaneously used to trace dust aerosols along the transport path for the case study. Ground-based NIES lidars (at Tsukuba and Chiba) and CALIPSO lidar were used to investigate 10-year analysis of Asian dust transported to the Arctic.

2.2. AERONET sun-photometer and SKYNET sky-radiometer

The AERONET sun photometer automatically measures direct solar radiation with spectral interference filters (10 nm FWHM) centered on specific wavelengths, e.g., 440, 670, 870, and 1020 nm, to determine the Aerosol Optical Thickness (AOT), and another channel (at 940 nm) was used for the retrieval of water vapor content. More details of this instrument have been described by Holben *et al* (1998). The SKYNET sky radiometer, which was designed by Nakajima *et al* (1996), measures direct and diffuse solar radiation in almucantar mode at several wavelengths, e.g., 315, 400, 500, 675, 870, 940, and 1020 nm. The 315 and 940 nm channels are designed to retrieve the column content of ozone and water vapor, respectively. Other channels are used for aerosol retrieval (Takamura and Nakajima 2004). In this study, AERONET (Xianghe and the Polar Environment Atmospheric Research Laboratory (PEARL)) and SKYNET (Chiba and Sendai) measurements were used to study the optical properties of dust aerosols subjected to long-range transport. Moreover, SKYNET measurements in Chiba were used to identify Asian dust events for climatological analysis during 2001–2010, combing lidar observations.

2.3. NCEP/NCAR reanalysis data

The joint National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis project performs global data analysis using data from 1948 to the present. The quality and utility of the reanalysis data are effectively ensured by quality control, high vertical resolution, and the output of numerous meteorological fields (Kalnay *et al* 1996). In this study, daily geopotential height data, with 2.5 × 2.5° global grids, were used to clarify the dynamic process of dust aerosol transport during the dust event and the mechanism of the long-range transport of Asian dust to the Arctic. The dates for the case study are 19–24 March and range for the climatological analysis is 2001–2010. We used atmospheric levels at 850 mb both for the case study and climatological analysis. But only 500 mb was used for the last day of the case study because dust aerosols was lifted up to higher altitude.

2.4. HYSPLIT trajectory model

The National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory's Hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) model is a complete system for computing both simple air parcel trajectories and complex dispersion and deposition simulations using previously gridded meteorological data. The model calculation method is a hybrid of the Lagrangian and Eulerian approaches (Draxler and Hess 1998). We used HYSPLIT trajectories to show the transport path of dust aerosols for the case study, and extended to the climatological approach of investigating 10 years-worth of Asian dust transported to the Arctic. Key input information, such as exact times and altitudes of dust aerosol layers, were obtained from ground-based lidar observations. We conducted normal trajectories for the case study selecting Chiba lidar site as starting location. But for 10-year analysis trajectories matrix was conducted for 131 Asian dust events during 2001–2010, and the size of matrix is 30–40°N and 135–142°E. One trajectory can be initiated in every 1-degree grid spacing, and total 88 trajectories are obtained for each matrix. All air mass trajectories, both for the case study and 10-year analysis, were reasonably combined from 72 h backward trajectory and 96 h forward trajectory. Probability density function (PDF), defined as ratio of number of trajectories in each latitude/longitude grid (1° × 1°) and total trajectories, is calculated.

3. Results

From 19 to 22 March 2010, a serious large-scale dust storm occurred over East Asia that had widespread impacts on human health (such as inducing respiratory problems) (Li *et al* 2011). The long-range transport path of dust aerosol during the event was identified by simulations from the HYSPLIT trajectory model, as shown in panel a of figure 1. To improve the reliability of HYSPLIT simulation, key input information (such as time and location) is needed and shorter trajectories are recommended due to aerosols removal process (Stein *et al* 2009). Therefore, the long-range transport path reasonably consists of a 72 h backward trajectory and a 96 h forward trajectory. The starting time and altitude of these two trajectories are 13 LST and 700 m respectively, based on lidar measurements on 21 March in Chiba. It can be clearly seen that air masses traveled eastward over a long distance from their origin in the Gobi Desert of northwest China to eastern China, Korea, and Japan. Subsequently, they were transported across the Pacific Ocean to North America, as reported in previous studies (McKendry *et al* 2008, Huang *et al* 2010). However, during this dust storm, some dust aerosols were transported in a

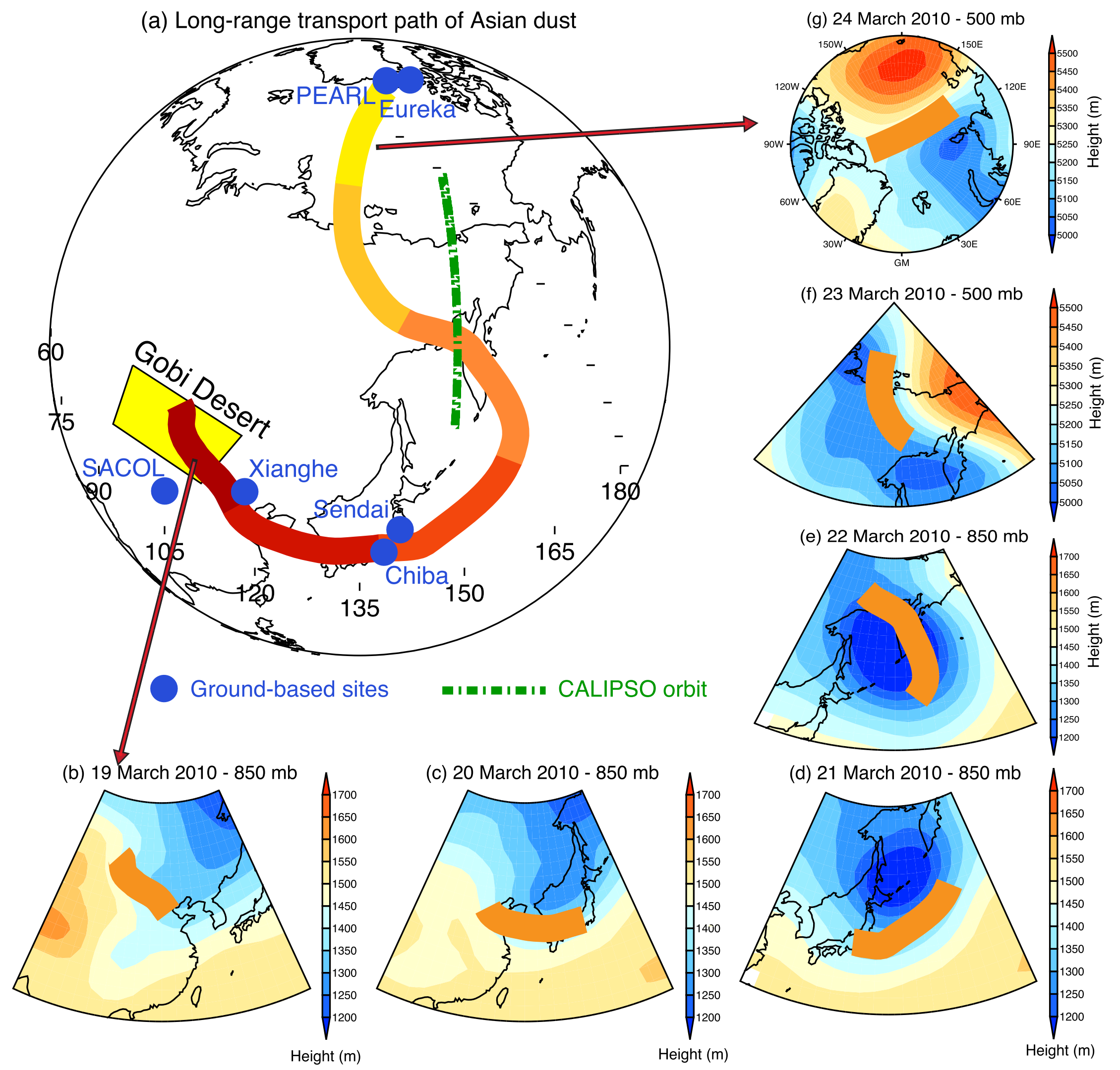

Figure 1. (a) Long-range transport path of Asian dust from the Gobi Desert to the Arctic during the dust event on 19 March 2010 over East Asia. (Panels (b)–(g)) The contour colors represent the geopotential height from NCEP/NCAR daily reanalysis data for 19–24 March. The solid line in panel a shows the transport path based on HYSPLIT trajectory data, and the color segments represent the path on each day. The locations of ground-based sites and space-borne CALIPSO tracks are shown by the blue solid points and green line, respectively.

different direction over the northwest Pacific and advanced northward to the Arctic. Synoptic charts of geopotential height fields over the Northern Hemisphere during dust period based on NCEP/NCAR reanalysis data were used to validate and describe the dust storm. A low-pressure system located over Northeast Japan moved northward on 21 March and grew much stronger over Siberia the next day. The direction of transport of the dust aerosols changed, and they were lifted up to the free troposphere by the cyclone. In the following days, dust aerosols were transported northward, arriving in the Arctic on 24 March.

The vertical structure of Asian dust from the Gobi Desert to the Arctic was traced by ground-based and space-borne lidars along the long-range transport path, as shown in figure 2. On 19 March, a thick dust layer (~3 km) was observed by a ground-based lidar at SACOL, located in northwest China near the dust source region (Huang *et al* 2008b). The dust event was also observed from other ground-based lidar measurements in Sendai on 21 March. CALIPSO lidar observations were used to fill in the gaps in ground-based observations. A distinct dust layer with an average depolarization ratio (DR) of about 0.2 at around 4–6 km above ground level (AGL) was apparent from CALIPSO lidar observations over Siberia (57.50°N/155.21°E) around 16 UTC on 22 March. In subsequent days, it became more difficult to detect dust aerosols from observations near the polar region. Fortunately, a HSRL system in Eureka also observed a clear aerosol layer with high DR at a height of 7 km on March 24. In general, the attenuated backscatter coefficient decreased gradually with the transport distance of the dust aerosols. The high DR implied that the aerosol layer was a dust layer with non-spheroid coverage (Hu *et al* 2007, Zhou *et al* 2013, Tian *et al* 2015). Therefore, the results indicated that the concentration

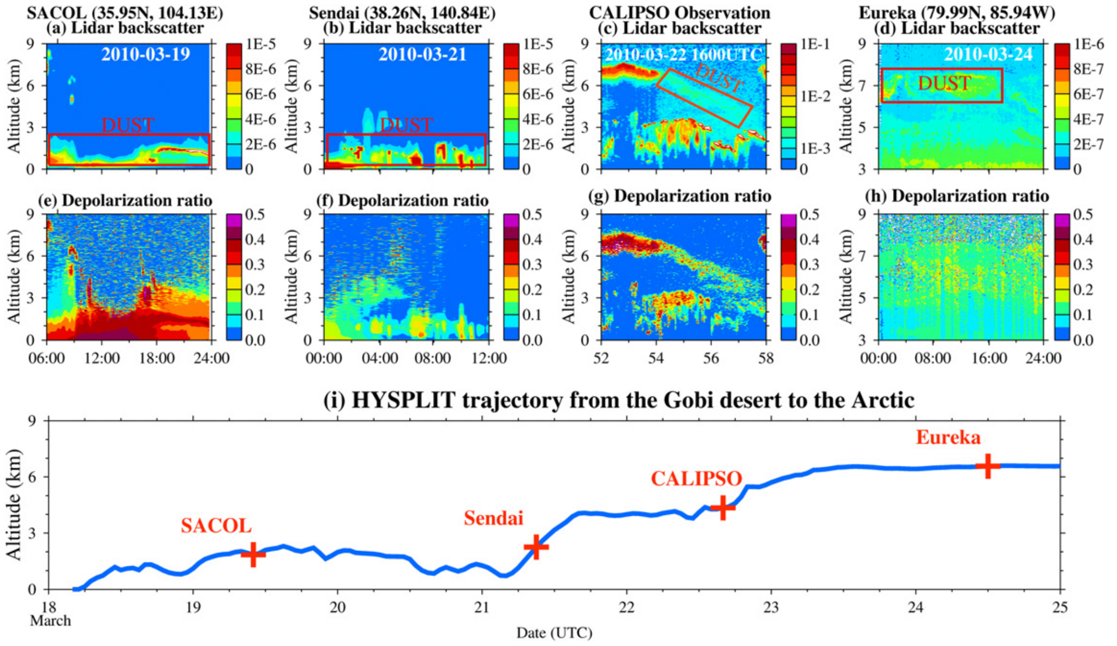

Figure 2. Characterization of the vertical structure of Asian dust (a)–(h) traced by lidars along the long-range transport path and (i) generated from the HYSPLIT model. The red plus signs show the height and time of dust layers observed by lidars, indicating good agreement between lidar observations and the trajectory analysis.

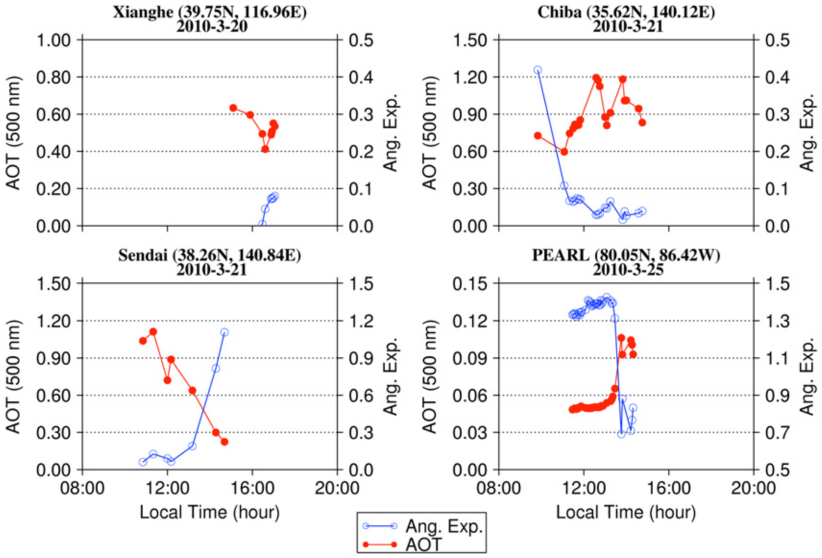

Figure 3. Columnar optical properties of Asian dust subjected to long-range transport from near the dust source region to the Arctic. Red lines with filled circles and blue lines with unfilled circles represent the AOT and AE from AERONET (Xianghe and PEARL) and SKYNET (Chiba and Sendai) observations. Locations of four sites are labeled in figure 1.

of dust aerosols decreased as some of them were deposited. Moreover, dust aerosols became more spherical during long-range transport in the atmosphere. The lower panel of figure 2 was obtained from a HYSPLIT trajectory (same as in figure 1) and shows the vertical movement of air masses (or dust aerosol). Good agreement between lidar observations and the HYSPLIT trajectory results can be seen, especially for the height and transport time of dust aerosol.

The columnar optical properties of the Asian dust were studied using observations from the AERONET and SKYNET sun photometers. AOT and Angström exponent (AE) are useful quantities to assess dust optical properties. Small AE (<1) indicate size distributions dominated by coarse mode aerosols (radii >0.5 um) that are typically associated with dust and sea salt, and large AE (>2) indicate size distributions dominated by fine mode aerosols (radii <0.5 um) that are usually associated with urban pollution and biomass burning (Ogunjobi *et al* 2008, Bi *et al* 2014). Diurnal variations in AOT and AE for four sites along the long-range transport path of the Asian dust are shown in figure 3. The dust arrived at the Xianghe site in the afternoon (around 15:00 LST) of 20 March, creating a maximum AOT (about 0.63) and a small AE value (nearly zero). Li *et al* (2007) showed that the large range of AE (from less than 0.2 to close to 2.0) suggests that different types of aerosol were present (from very fine-mode pollution to large coarse-mode dust) at Xianghe. AOT increased sharply after 11:00 LST on 21 March at Chiba, Japan, with the initial peak (about 1.19) at 13:00 LST. However, AE decreased dramatically at the same time. A peak AOT value (about 1.11) was also detected in Sendai when the AE was 0.13. An AERONET sun photometer provided successive aerosol measurements at PEARL over the Arctic. During 24–26 March, there was a peak in the afternoon of 25 March, when aerosols from the dust storm may have arrived in the Arctic. In the morning, the AOT and AE were around 0.05 and 1.33, respectively. However, by afternoon, the AOT had increased more than twofold (to about 0.11), and the AE had decreased to 0.69. This indicates that some adventitious coarse particles altered the local conditions and disturbed the clean air in the region. Independent measurements from AERONET and SKYNET also agreed well with the lidar observations and HYSPLIT trajectory analysis.

More evidence was required to confirm the long-range transport path of Asian dust to the Arctic. We therefore identified all of the Asian dust events that had occurred over the past 10 years. Firstly, all probable dust events were recognized based on lidar measurements if there was dust layer with high DR, strong backscattering signals as well as long duration (>3 h). Then certain dust events were further validated by co-located sky-radiometer observations and/or surface-based dust reports. Dust events were identified in Tsukuba (36.05°N/140.12°E) for 2001–2006 and in Chiba (35.62°N/140.12°E) for 2007–2010. The exact times and heights of dust aerosol layers were detected from these ground-based lidar observations. Although we had to use data from two sites because no lidar observations were conducted at Chiba before 2007, this did not affect our investigation because the distance between Chiba and Tsukuba is only about 50 km. The trajectories matrix of air masses (or dust aerosols) for all dust events was obtained from HYSPLIT simulations. Among the 131 Asian dust events that occurred over the past decade, 33 (about 25.2%) resulted in direct transport of dust toward the Arctic. When expressed as a percentage of dust from dust events reaching the Arctic every year, a minimum of 16.7% in 2005 and a maximum of 40.0% in 2003 were found. The size of matrix is 30–40°N, 135–142°E. Probability density function (PDF), defined as ratio of number of trajectories in each latitude/longitude grid ($1^\circ \times 1^\circ$) and total trajectories, is calculated. Finally the general transport pathway was clearly seen as shown in figure 4. The results conclusively show that Asian dust was transported directly over long distances from northwest China (Gobi and Taklimakan deserts) to the Arctic during the past decade. This suggests the existence of a fast, short-cut path for Asian dust transport directly from dust sources to the Arctic.

To further investigate the mechanism of the long-range transport of Asian dust, the pressure systems during dust events were compared for Asian dust transported to the Arctic and North America. A mean daily geopotential height of 850 hPa was composited from the NCEP reanalysis dataset, as shown in figure 5. This shows that the pressure system when Asian dust was transported to the Arctic was abnormally lower than when dust was transported to North America. Moreover, the mean Arctic Oscillation (AO) index, defined as the leading mode of the Empirical Orthogonal Function (EOF) analysis of the monthly mean 1000 mb height during 1979–2000, was −0.18 for dust transported to the Arctic, but only 0.05 for that transported to North America. The daily AO index is constructed by projecting the daily 1000 mb height anomalies poleward from 20°N onto the loading pattern of the AO (Higgins *et al* 2002). When the AO index is negative, stronger meridional and weaker zonal winds tend to occur (Thompson and Wallace 1998), along with an enhanced cyclonic flow at 850 hPa and an enhanced East Asia Trough (EAT) over Northeast Asia (Chen and Zhou 2012). This pattern of atmospheric circulation forces the long-range transport of Asian dust to the Arctic along the flank of the enhanced EAT. However, an increased pressure gradient over the North Pacific causes stronger westerlies when the AO index is positive, thus transporting Asian dust to North America.

4. Conclusions and discussion

In this study, we investigated a large-scale dust storm that occurred over East Asia in spring 2010 using ground-based and space-borne multi-sensor observations, including lidar, and the SKYNET sky-radiometer/AERONET sun photometer, as well as NCEP/NCAR reanalysis data and a HYSPLIT trajectory analysis. Our study suggests that Asian dust aerosols were rapidly transported from northwest China to the Arctic within 5 days, crossing eastern China, Japan, and Siberia before reaching the Arctic. Lidar observations along the transport path of the dust agreed well with the corresponding HYSPLIT trajectory analysis.

Previous studies have demonstrated that Asian dust can be transported from northwest China to Greenland (e.g., Biscaye *et al* 1997) and can even make more than one full circuit around the globe (Uno *et al* 2009). However, Biscaye *et al* looked at dust mineralogy in the ice and were not able to determine the transport path or length of transport of Asian dust to Greenland. Therefore, our findings that long-range transport path of Asian dust directly from northwest China to the Arctic within 5 days have not been previously reported. Evidence from other dust events over the past decade

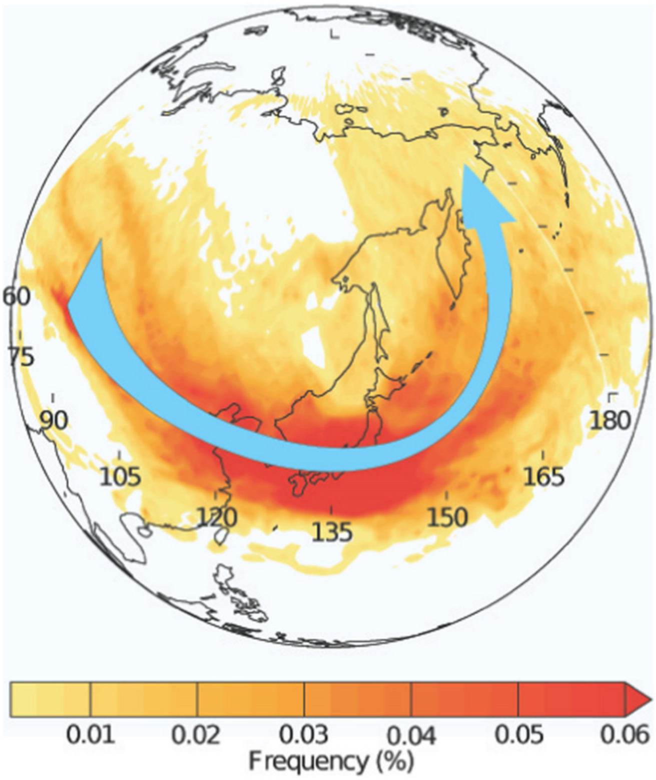

Figure 4. Probability density function (PDF) calculated for approximately 3000 single trajectories obtained from the HYSPLIT model for 33 Asian dust events that dust aerosols can long-range transported to the Arctic during 2001–2010. The resolution of each latitude/longitude grid is 1° × 1°.

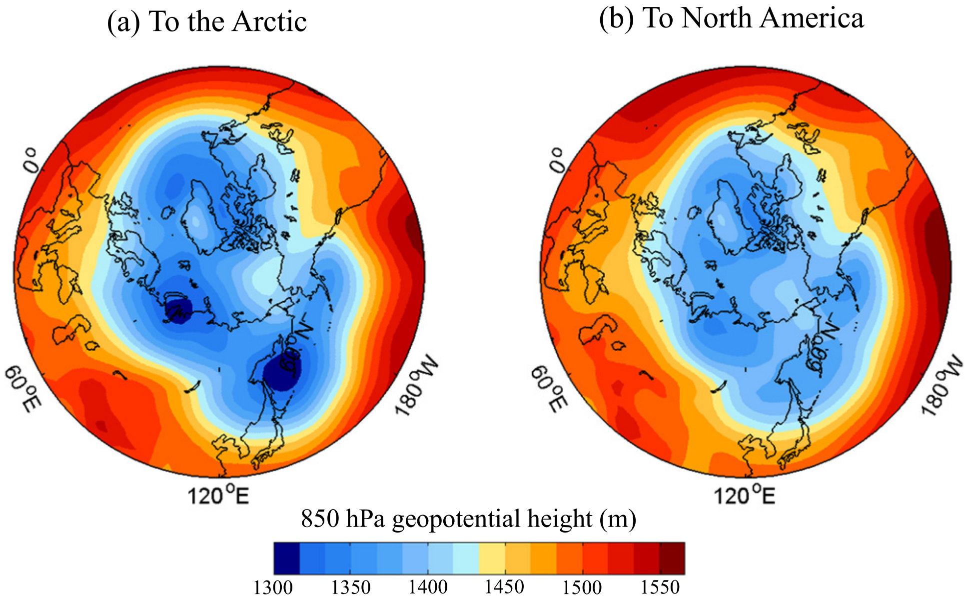

Figure 5. Comparison of the mean geopotential height from the NCEP/NCAR reanalysis datasets when Asian dust is transported (a) to the Arctic and (b) to North America for all dust cases during 2001–2010.

(2001–2010) from lidar measurements and HYSPLIT trajectories also supported our results, showing that dust from 25.2% of Asian dust events generated during this period has potentially been transported directly to the Arctic. The results also show that the long-range transport of Asian dust to the Arctic is due to cyclones and an enhanced EAT, which are very common synoptic systems over East Asia, implying that many dust events could have transported Asian dust to the Arctic along this path in the past.

An anthropogenic contribution to the very substantial Arctic warming during the past 50 years has been identified (Brock *et al* 2011, IPCC 2013) as a result of the acceleration in warming in the polar region. Such a rapid short-cut transport of Asian dust may have a significant impact on the Arctic environment, climate, and ecosystems. The evaluation of these effects is beyond the scope of this study. Thus, a more detailed study of this region and these issues is required from the climate science community in the future.

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