Transport of Mineral Dust from Africa and Middle East to East Asia Observed with the Lidar Network (AD-Net)

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Abstract

Mineral dust transported from Africa and Middle East was observed with the Asian Dust and aerosol lidar observation Network (AD-Net). In March 2018, the dense Sahara dust, reported by mass media as that snow in Sochi, Russia stained into orange, was transported to Sapporo in 4 days from Sochi and observed by the lidar. In April 2015, dust from Middle East was transported to Nagasaki passing across the Taklamakan desert. Dust source areas and transport paths were studied with the global aerosol transport model MASONGAR mk-2 separately calculated for different dust sources regions. The results showed that dust from Sahara and Middle East was transported to East Asia and sometimes mixed with dust from the Gobi desert and the Taklamakan desert. The analysis of recent AD-Net data after 2015 showed such long-range transport cases were observed every year in March or April. The transport path often led over the Caspian Sea, Kazakhstan, and Russia. Sahara dust transported north and reached around the Black Sea was transported long range by strong westerly in springtime.

(Citation: Sugimoto, N., Y. Jin, A. Shimizu, T. Nishizawa, and K. Yumimoto, 2019: Transport of mineral dust from Africa and Middle East to East Asia observed with the lidar network (AD-Net). SOLA, 15, 257–261, doi:10.2151/sola.2019-046.)

1. Introduction

Mineral dust is a major aerosol component determining atmospheric radiative characteristics (IPCC 2013). In the East Asian region, dust source areas locate close to industrial and urban areas, and dust is often mixed with anthropogenic aerosols. Dust consequently plays important role in air pollution chemistry (Wang et al. 2017). It is also shown in recent studies that microbes are transported with mineral dust (Maki et al. 2019). To study Asian dust and regional air pollution, we started network observations using ground-based lidars in 2001. The network is named the Asian Dust and aerosol lidar observation Network (AD-Net). Currently, lidars are continuously operated at 20 locations in East Asia (Japan, Korea, China, Mongolia and Thailand) (Shimizu et al. 2017). It is understood with the studies using the network observations and chemical transport models that the major dust source areas in East Asia are the Taklamakan desert in China, the Gobi desert in Mongolia and China, and Loess Plateau in China. Dust from Gobi and Loess Plateau is usually transported near the surface and significantly affect the environment of the lower atmosphere regions (et al. 2003; Shimizu et al. 2004). It is often mixed with air pollution (Pan et al. 2017). Dust from Taklamakan is often uplifted and transported long distance in the free troposphere (Uno et al. 2009).

Dust emitted outside of East Asia is sometimes transported to East Asia. Cases of long-range transport of mineral dust from Africa and Middle East (Tanaka et al. 2005) and soot from oil sphere (Uno et al. 2009). It is often uplifted and transported long distance in the free troposphere (IPCC 2013). In the East Asian springtime., dust source areas locate close to industrial and urban areas, and dust is often mixed with anthropogenic aerosols. Dust consequently plays important role in air pollution chemistry (Wang et al. 2017). In 2015–2016, Leibniz Institute for Tropospheric Research (TROPOS) conducted continuous observation with a multi-wave-length Raman lidar in Dushanbe, Tajikistan (Hofer et al. 2017), and they recently restarted continuous observation. That motivated us to study long-range-transported dust cases using recent AD-Net data. It would be useful if we could observe the same air mass along the transport path to study the change in characteristics of dust. Also, recent studies of bioaerosols (microbes transported with dust) suggest such long-range transport may be important even if the transported amount is small (Maki et al. 2019).

This paper describes the analysis of two long-range transported dust cases. One is the big Sahara dust event in March 2018 where mass media (e.g. BBC, CNN) reported that Sahara dust stained snow at a skiing ground in Sochi, Russia into orange on 22 March 2018. Recently, Kaskaoutis et al. (2019) reported the analysis of radiative effect of the Sahara dust events in March 2018 including this event using satellite observations. We observed the plume of the Sahara dust passed near Sochi on 22 March by the AD-Net lidar in Sapporo on 26 March (Sugimoto et al. 2019). In the same period, there were dust emissions also in the Taklamakan desert and the Gobi desert as reported by Yoon et al. (2019), and the distribution of dust was complicated. We analyzed the source areas of the observed dust plumes using the global aerosol transport model MASONGAR mk-2 (the Model of Aerosol Species in the Global Atmosphere, mark 2) (Yukimoto et al. 2012) calculated separately for different dust source areas.

The other case is the Middle East dust case in April 2015. A lifted dust layer was reported in Dushanbe, Tajikistan (Hofer et al. 2017). The dust was transported across the high mountain in the west of Taklamakan, and it was mixed with dust from Taklamakan and Gobi and transported to Japan. We observed a plume from the same dust event with the AD-Net lidar in Nagasaki. In this paper, we also present a summary of long-range transported dust cases confirmed with the recent AD-Net data after 2015.

2. Method

We used the AD-Net two-wavelength (1064 nm and 532 nm) and polarization sensitive (532 nm) lidar data (https://www.lidar.nies.go.jp/AD-Net/) to identify transported dust plumes (Shimizu et al. 2017). In the analysis, we firstly used archived results of the Navy Aerosol Analysis and Prediction System (NAAPS) of the U.S. Naval Research Laboratory (https://www.nrlmry.navy.mil/aerosol/) to find possible long-range-transported dust cases from Africa or Middle East. We then searched corresponding dust plumes in AD-Net data. When the corresponding dust plumes are found, we performed backward trajectory analysis using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSLIP) of U.S. National Oceanic and Atmospheric Administration (Stein et al. 2015) (https://ready.arl.noaa.gov/HYSPLIT.php). We also confirmed the dust transport paths using the Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) data when available (Winker et al. 2009) (https://www-calipso.larc.nasa.gov). To confirm the dust emission source
areas, we used the results of the global aerosol transport model MASINGAR mk-2 calculated separately for different dust source areas (Sahara, Middle East, Taklamakan, and Gobi). Spatial resolution was TL479 (40 km) for 2018 and TL159 (110 km) for 2015 depending on the version of MASINGAR.

We used the dust extinction coefficient to compare the lidar observations with the model results. In the lidar data analysis, the total extinction coefficient profiles were derived firstly by the backward Fernald method with a constant lidar ratio (here we used $S_1 = 50$ sr), and then the method using the particle depolarization ratio was applied to estimate extinction coefficients for non-spherical (dust) and spherical particles (Sugimoto et al. 2003; Shimizu et al. 2004). We applied the same method also to CALIPSO level 1 data, in the same way as in our previous studies (Uno et al. 2008).

3. Results

3.1 Sahara dust case in March 2018

Figure 1 shows the AD-Net quicklook data in Sapporo from 23 to 27 March 2018. A dust plume is clearly seen in the depolarization ratio plot on 26 March, though the attenuated backscattering coefficient was low. We performed a backward trajectory analysis using HYSPLIT and found that the trajectory passed near Sochi on 22 March as shown in Fig. 2. In Supplement 1a, we show the maps of aerosol optical depth for the Sahara dust calculated by MASINGAR mk-2.

Figure 3 presents time-height indication of dust extinction coefficient in Sapporo from 24 to 27 March 2018 compared with the MASINGAR mk-2 results calculated separately for different dust source areas. The observed dust extinction coefficient was ~0.06 km$^{-1}$ at maximum on 26 March, and the optical depth of the plume estimated from the lidar profile was ~0.3. The particle depolarization ratio and backscattering color ratio ($\beta_{1064nm}/\beta_{532nm}$) (not shown in the figure) were ~0.28 and ~0.4, respectively. The color ratio was low compared to that in major Gobi dust cases (~1.0). This suggests the particle size of the long-range-transported Sahara dust was small, or the plume was mixed with other aerosols such as sulfate and smoke. However, the mixing with other aerosols was not likely from the results of NAAPS. Although it is not possible to estimate the mass concentration of dust without knowing the size distribution and the optical characteristics, in a rough estimation using an empirical conversion factor (Sugimoto et al. 2003), it was about 50 μg/m$^3$. It was high as long-range transported dust. The dust layer stayed for half a day above Sapporo.

The comparison with MASINGAR in Fig. 3 shows the dust plume from Sahara was transported to North America and sometimes to the Arctic.

3.2 Middle East dust cases in 2015

Hofer et al. (2017) reported a lifted dust layer over Dushanbe, Tajikistan on 12–13 April 2015, and they identified the source of the dust as Middle East. We calculated forward trajectories from
the observed dust plume and found that it might reach western Japan. We then searched the corresponding dust plume in the AD-Net data and found a dust plume in Nagasaki on 17 April. Figure 4 shows the time-height indication of the range-corrected lidar signal reported by Hofer et al. (2017) compared with the dust extinction coefficient calculated by MASINGAR mk-2 for Middle East and Sahara. The model reproduced the lifted dust plume, though the height of the modeled dust plume was a bit lower than the observation. The model showed the source area was mostly Middle East. The dust plumes observed in Nagasaki are compared with MASINGAR mk-2 in Fig. 5. The results suggested the plumes was mixture of dust from the Gobi, Taklamakan, Middle East, and Sahara.

The backward trajectory of the plume ending in Nagasaki at 15:00 UTC on 17 April is shown in Fig. 6. Also, the maps of aerosol optical depth for the Middle East dust calculated by MASINGAR mk-2 is presented in Supplement 1b. The trajectory shows that the plume passed near Dushanbe on 13 April and passed across the high mountain in the west of the Taklamakan.

This is probably a rare case, and it was essential that the dust was already lifted in Dushanbe in order to be transported across the high mountain. The heavy dust in Dushanbe in summer reported by Hofer et al. (2017) was not transported to East Asia because it was confined in the lower altitudes.

3.3 Long-range transported dust cases after 2015

Long-range transported African and Middle East dust cases observed with AD-Net are listed in Table 1. Such cases were observed every year in March or April. The transport path from Sahara often led over the Caspian Sea, Kazakhstan, and Russia. Sahara dust transported north and reached around the Black Sea was transported long range by strong westerly in springtime. The transport paths were similar to those reported in the previous papers (Tanaka et al. 2005; Park et al. 2005).

4. Conclusions

This study showed long-range transport from Africa and Middle East to East Asia was not rare. Vertical distribution measurements with the lidars were essential to detect such dust plumes, and the aerosol transport model separately calculated for different source regions was essential to identify the dust source region. In general, the density of long-range transported dust was an order of magnitude lower than that in typical Gobi dust events, and more accurate observations are required to further study optical characteristics in future studies.
Acknowledgements

We thank Teppei J. Yasunari and Dashdondog Batdorj for their contributions in the lidar observations, and Taichu Y. Tanaka and Takashi Maki for their advice.

Edited by: D. Zhang

Supplements

Supplement 1: Maps of dust optical depth calculated by MASINGAR mk-2.
Supplement 2: Comparison of CALIPSO dust extinction coefficient and MASINGAR-mk2.
Supplement 3: Animation of the map of optical depth for dust from Sahara and Gobi calculated separately by MASINGAR mk-2 for the dust event in March 2018.
Supplement 4: The lidar quicklook data in Mongolia and a HYSPLIT trajectory showing that dust from Sahara was transported to Mongolia in April 2017.

Fig. 6. HYSPLIT backward trajectory of the dust plume observed in Nagasaki on 17 April 2015.

Table 1. Major long-range transported dust cases observed with AD-Net after 2015.

| Date       | AD-Net lidar site | Source area |
|------------|-------------------|-------------|
| 2015.04.17 | Nagasaki*         | Middle East |
| 2015.04.27 | Sendai            | Sahara      |
| 2016.03.29 | Sainshand         | Sahara      |
| 2017.04.27-28 | Sainshand, Ulaanbaatar** | Sahara |
| 2018.03.26-27 | Sapporo, Fukue*** | Sahara |
| 2018.03.30-31 | Sapporo         | Sahara      |
| 2019.03.15 | Sainshand         | Sahara      |

* Lifted dust was observed in Dushanbe, Tajikistan (Hofer et al. 2017)
** Dust was taken into the boundary layer in Mongolia (Supplement 4).
*** Heavy Sahara dust was reported in Sochi, Russia.

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Manuscript received 8 October 2019, accepted 11 November 2019

SOLA: https://www.jstage.jst.go.jp/browse/sola/