Variations of Dust Extinction Coefficient Estimated by Lidar Observations over Japan, 2007–2016

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Abstract

Dust extinction coefficients, a fundamental product of the Asian Dust and Aerosol Lidar Observation Network, were analyzed to evaluate climatological variations of Asian dust in Japan. Dust optical depth (vertically integrated dust extinction coefficients) from the network displayed peaks similar to those in the official Japan Meteorological Agency reports in spring, and in other seasons they were more responsive signals of moderate dust events. Between 2007 and 2016, dust optical depth decreased by 2.5% per year in Japan, and by 0.7% per year in Mongolia, a major source region of Asian dust. Relative to Mongolia, then, Japan has displayed a stronger negative trend in dust extinction coefficients, which is attributed to the meteorological field between continental Asia and Japan, including wind and rainfall during transportation. This negative trend of Asian dust in Japan was stronger in the middle troposphere (5–6 km altitude) than in the planetary boundary layer.

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1. Introduction

Episodes of aeolian dust transport, or Kosa, are common atmospheric phenomena in Mongolia, China, Korea, and Japan during springtime that are referred to as Asian dust events. Strong winds in arid and semi-arid areas in the source region (mainly the Gobi Desert in Mongolia and the Inner Mongolia province in China) mobilize small soil particles, and westerly winds transports them to downwind regions including Japan and the North Pacific Ocean. The arrival of Asian dust in Japan is marked by increases in the concentration of airborne particles, such as suspended particulate matter (SPM) or $\text{PM}_{10}$, and decreased visibility. Given its impact on human health, Asian dust is being intensively studied, and quantitative estimation of the amount of Asian dust is of growing interest to researchers. For example, Ueda et al. (2012) detected a correlation between Asian dust measured by lidar and ambulance dispatches in Nagasaki, Japan. Kanatani et al. (2016) detected the impacts of Asian dust particles on allergy symptoms of pregnant women by using lidar observations.

The emission of Asian dust in its source region is influenced by many factors, including surface conditions and weather. For example, vegetation in semi-arid regions is related to the friction velocity, which determines the threshold wind speed for severe dust mobilization (Mao et al. 2013). Snow cover and wet ground conditions inhibit the emission of dust (Kurosaki and Mikami 2004; Ishizuka et al. 2005). Meteorological conditions including horizontal wind speed and direction affect the transportation of Asian dust to downwind regions, and rainfall controls the wet deposition process during transportation (Osada et al. 2014). Thus the amount of Asian dust in a given place is dependent on changes in both dust emission and meteorological conditions.

In this study we analyzed the dust extinction coefficient, a quantitative representation of atmospheric dust concentration measured by the Asian Dust and Aerosol Lidar Observation Network (AD-Net), to clarify the changes in the Asian dust phenomenon over Japan in the previous decade. Although Osada et al. (2017) have discussed seasonal variations in elevated Asian dust layers detected by the AD-Net station in Toyama and by optical particle counter measurements in Tateyama (2450 m a.s.l.) between 2004 and 2014, this paper presents the first comprehensive analysis of data from the whole lidar network in Japan, encompassing the decade 2007–2016.

2. Lidar observation and data analysis

The AD-Net network of elastic scattering lidar instruments is maintained by the National Institute for Environmental Studies (NIES) of Japan and collaborating organizations in East Asia. Polarization sensitive, dual-wavelength lidar instruments are operated at 14 locations in Japan, 3 in Korea, 3 in China, and 3 in Mongolia. This study mainly relied on observations from 11 stations in Japan with high-quality records, and observations from two stations in Mongolia were used to characterize the dust emission from source regions (Fig. 1).

Lidar stations employ a Nd:YAG laser firing at 10 Hz as a light source, and atmospheric observations are recorded every 15 min as the average of 3000 laser shots (5 min). Observations consist of backscatter intensities at 532 nm and 1064 nm and volume depolarization ratios at 532 nm. Dust extinction coefficients ($\alpha_{d}$) and spherical particle extinction coefficients ($\alpha_{d}$) are derived from these data based on the method described by Shimizu et al. (2017). A sensitivity analysis of $\alpha_{d}$ was presented in Shimizu et al. (2011).

The extinction coefficients have a vertical resolution of 30 m. Aerosol optical depth ($\tau_{a}$), the vertically integrated extinction coefficient of aerosols, is a common index for columnar aerosol density. We defined dust optical depth ($\tau_{d}$) as...
where $Z_i$ is the cloud base height from lidar observations (or 6 km during fine conditions) and $\alpha_d$ is obtained from lidar polarization data. Although Hara et al. (2011) have utilized $\tau_d$ as an index of spherical (anthropogenic) aerosol loading, $\tau_d$ values derived from AD-Net have not previously been analyzed. Figure 2, displaying values of $\alpha_d$ and $\tau_d$ obtained at the Matsue station in May 2011, shows that $\tau_d$ is an efficient gauge of the intensity and duration of Asian dust events. A strong relationship has been confirmed between $\alpha_d$ near the surface in Nagasaki and the mass concentration of iron (Fe) in PM$_{2.5}$ sampled at the surface in Fukuoka, 100 km from Nagasaki, during 2009–2011 (Kaneyasu et al. 2012). Local dust events detected by AD-Net lidar in Japan were almost limited to Kanto region (e.g. Sugimoto et al. 2016). Thus, $\alpha_d$ and $\tau_d$ are considered to be proxies of the intensity of Asian dust.

In Japan, Asian dust is officially recognized in meteorological reports of the Japan Meteorological Agency (JMA). Trained officers at each JMA meteorological observatory determine the sky condition every 3 h based on visual observations and auxiliary information. Although historically determinations of Asian dust events required visibility less than 10 km, this condition was relaxed in 1989 and Asian dust may be reported even when visibility exceeds 10 km. JMA maintains a daily database of the number of JMA stations reporting Kosa events (hereafter NK, http://www.data.jma.go.jp/gmd/env/koasap/en/koasa_shindan_e.html). In this study we compared lidar results from AD-Net with the monthly totals of NK from JMA.

3. Comparison with JMA official record

We compared the characteristics of $\tau_d$ as determined from lidar data, to monthly NK values derived from the official JMA records of Asian dust (Fig. 3). Peaks in NK occur in spring, and year-to-year variation is great. The lidar data are presented as the records of Asian dust (Fig. 3). Peaks in NK occur in spring, and lidar data, to monthly NK values derived from the official JMA station in that month. The condition during fine conditions) and $\tau_d$ exceeds 0.1 divided by the total hours of lidar observations by the station in that month. The condition in which $\tau_d > 0.1$ corresponds to, for example, a dust layer of $\alpha_d = 0.07/km$ that is 1.4 km deep. A value of $\alpha_d$ of 0.07/km was used as a threshold criterion by Ueda et al. (2012) for detection of Asian dust by near-surface lidar observations.

The NK and PHT data have a strong resemblance; for example, both records show relatively weak spring peaks in 2015 and 2016 compared to the rest of the decade. However, the two records have differences. High NK values are more common in spring, and high PHT values are distributed more widely across other seasons, displaying subsidiary peaks in 2009 and 2013. In winter PHT had slightly higher values in 2008–2009 and 2013–2014. As NK and PHT have differing definitions, these discrepancies are reasonable, and the differences between them may also depend on the threshold used for PHT ($\tau_d > 0.1$ in this case). However, neither NK nor PHT is suitable for evaluating the long-term trend of Asian dust. Instead, we employed monthly mean dust optical depth $\tau_d$ as an index of dust intensity measured by lidar observations.

4. Evaluation of monthly mean dust optical depth

Values of monthly mean $\tau_d$ were determined for each lidar station in Japan and a nationwide average was then calculated. This average $\tau_d$ was fitted to the following combination of a linear trend and a sinusoidal curve with a 1-year period and a linearly changing amplitude:

$$\tau_d(t) = A + Bt + (C + Dt) \sin (2\pi t/12 + E)$$

where $t$ is measured in months. The nonlinear least-squares Marquardt-Levenberg algorithm, implemented in the gnuplot graphing utility, was employed to fit the data.

As indicated in Fig. 4, the network lidar measurements documented a decrease in $\tau_d$ of 2.5% per year in Japan, such that it fell by one-fourth its magnitude during the study decade. This quantitative result was obtained solely on the basis of $\tau_d$ determined from AD-Net data. Linear fitting analysis on seasonal data (not shown) revealed the negative trend was stronger in spring (~4.3% per year for Mar/Apr/May) compared with other seasons (~1.1% per year for Jun/Jul/Aug, ~2.9% per year for Sep/Oct/Nov, and ~1.7% per year for Dec/Jan/Feb).

For further insight into this tendency, we repeated this analysis of $\tau_d$ on a vertically resolved basis using six layers from 0–1 km to 5–6 km altitude (Fig. 5). The results show that the magnitude of the decadal decrease was dependent on altitude, changing from ~0.8% per year near the surface to ~6.8% per year in the middle troposphere (5–6 km). It is noteworthy that the highest layer displayed the greatest decrease, but had the lowest value of $\tau_d$. The fact that the decadal decrease in the lower atmosphere was smaller suggests that the impact of Asian dust on humans and the environment has not changed greatly. The results also suggest that estimating the time variation of radiative forcing by Asian dust on the basis of total (altitude integrated) $\tau_d$ is problematic because radiative effects depend on the vertical distribution of the dust.
extinction coefficient $\alpha_d$.

As Japan is located in the downwind region of Asian dust transport, $\tau_d$ is influenced by weather conditions along the transportation path as well as changing emissions in the source region. To investigate the source region, we conducted a similar analysis of data from Mongolian lidar stations in Sainshand and Zamyn-uud in the eastern Gobi Desert. The results show relatively large fluctuations, but the negative trend in monthly mean $\tau_d$ (0.7% per year) is much smaller than the decrease in Japan (Fig. 6). This finding suggests that the negative trend in Japan cannot be entirely attributed to changing dust emission in the source region. Therefore, the explanation for the difference in trend between Japan and Mongolia must consider variations in the transportation path from the source region to Japan. Also, the discrepancy between observed $\tau_d$ and the fitted sinusoidal curve was large in autumn, a feature that was not evident in Japan (Fig. 4). This difference suggests that Asian dust is not efficiently transported from the Gobi Desert to Japan in Autumn.

Another question raised by Fig. 5 is the cause of the stronger negative trend of $\tau_d$ in the upper layers over Japan. Mineral dust in the free troposphere conveyed from the Taklimakan desert or other regions is recognized as “background dust” (Iwasaka et al. 1988; Uno et al. 2009). Figure 5 suggests a possible decadal variation in background dust over Japan, which could be analyzed with data from the GALION world-wide federation of lidar networks (Bösenberg and Hoff 2008), or satellite-borne lidar instruments.

5. Concluding remarks

AD-Net reports quantitative dust concentrations in terms of dust extinction coefficient $\alpha_d$ or dust optical depth $\tau_d$. Although the periods of high $\tau_d$ (PHT) in the AD-Net data product generally agree with the official NK record from JMA, neither of these quantities is well suited for monitoring long-term variations in Asian dust. In a simpler approach, we fitted values of monthly mean $\tau_d$ to a sinusoidal curve, and we found that the decadal negative trend of $\tau_d$ in Japan (~2.5% per year) is not directly linked to the decrease in Mongolia, the source region (~0.7% per year). To better interpret the results from AD-Net, the meteorological field, including wind and precipitation, during the dust outbreak period must be analyzed. The combination of meteorological parameters and dust loading in the atmosphere can be investigated using chemical transport models, such as MASONGAR (Tanaka and Chiba 2005) or CFORS (Uno et al. 2003). Song et al. (2016) simulated spring dust emissions in northern China and found a slight negative trend from 1982 to 2011. Such an analysis covering the whole East Asian region is indispensable to account for the dif-

![Fig. 4. Time series of $\tau_d$ at each lidar station (thin lines), average $\tau_d$ for all lidar stations in Japan within 1 km thick layers from 0–1 km to 5–6 km altitude (black) and fitted sinusoidal curve based on Eq. (2) (bold purple line).](image-url)

![Fig. 5. Time series of average $\tau_d$ for all lidar stations in Japan within 1 km thick layers from 0–1 km to 5–6 km altitude (black) and fitted sinusoidal curve for each layer (purple). The amplitude of the sinusoidal curve ($C + Dt$) for January 2015 is indicated at the top of each panel.](image-url)

![Fig. 6. Time series of $\tau_d$ at two lidar stations in Mongolia (thin lines), average $\tau_d$ for both lidar stations in Mongolia (bold black line), and fitted sinusoidal curve based on Eq. (2) (bold purple line).](image-url)
ference in trends in Japan and Mongolia found in this study. Also, continued observations of dust in this region are important to confirm these trends over the long term. Recently the Himawari-8 geostationary satellite gained the ability to detect Asian dust in the day time (Bessho et al. 2016), and CALIPSO (Winker et al. 2009) has observed the globe with spaceborne polarization lidar for more than 10 years. Continuous measurements from space and the ground will help us better understand the mechanisms of the emission and transportation of Asian dust.

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