The Variation in Aerosol Optical Depth over the Polar Stations of Korea

Ja-Ho Koo1*, Taejin Choi2, Yeseul Cho1, Hana Lee1, Jaemin Kim3, Dha Hyun Ahn1, Jhoon Kim1, Yun Gon Lee3

1 Department of Atmospheric Sciences, Yonsei University, Seoul 03722, Korea
2 Korea Polar Research Institute, Incheon 406-840, Korea
3 School Department of Atmospheric Sciences, Chungnam National University, Daejeon 34134, Korea

ABSTRACT

Using NASA’s Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) reanalysis for aerosol optical depth (AOD) and satellite-observed carbon monoxide (CO) data, we examined the basic pattern of AOD variations over the three polar stations of Korea: the Jangbogo and King Sejong stations in Antarctica and the Dasan station in the Arctic. AOD values at the King Sejong and Dasan stations show maximum peaks in spring and appear to be associated with large amounts of atmospheric CO emitted from natural burning and biomass burning. The Jangbogo station shows a much lower AOD than the other two stations and does not appear to be strongly affected by the transport of airborne particles generated from mid-latitude regions. All three polar stations show an increasing trend in AOD in general, indicating that the polar background air quality is becoming polluted.

Keywords: Aerosol optical depth; Arctic; Antarctic; Carbon monoxide.

INTRODUCTION

It is known that the atmospheric environments in the Arctic and Antarctic regions are generally pristine. Since the entire globe has experienced serious air pollution after industrialization, however, the polar atmospheric environments are also influenced by global air pollution issues (Law and Stohl, 2007). For example, there is a common event, Arctic haze (Shaw, 1995), which is usually induced by the accumulation of transported air pollutants from the mid-latitudes. This event can lead to potential changes in solar radiative forcing in the Arctic. Specifically, black carbon (BC), high-radiation-absorbing particles, has a strong influence on the polar climate (McConnell et al., 2007) and can even change the surface albedo when deposited on surface snow. Compared to the Arctic, the Antarctic region is more distant from emission sources of air pollutants in the mid-latitudes. However, influences of mid-latitude air pollutants remain apparent: the plume effect of biomass burning in South America and Africa (Stohl and Sodemann, 2010) and the long-range transport of dust particles toward Antarctica (Li et al., 2008). Thus, it is necessary to investigate the situation of polar atmospheric aerosols.

The most difficult facet in monitoring the extent of aerosol pollution in the Arctic and Antarctic regions is the inconvenience in continuously maintaining ground-based measurement platforms due to harsh weather conditions and their isolated locations. In fact, a number of polar aerosol measurements are usually made in intensive campaigns or in the summertime when observation conditions are better, which results in difficulties when examining long-term properties. Since the available observation sites are not abundant and are sparsely distributed, it is not easy to cover the entire Antarctic area using the ground-based platforms. Satellite measurements from space can reveal optical properties of aerosols, such as the aerosol optical depth (AOD), can show atmospheric turbidity and can move beyond the limitations of ground-based observations in polar regions. However, there are still some limitations because the reflected or emitted radiation from Earth, which is used in AOD retrieval, is strongly biased by the high surface albedo over the bright surfaces in polar areas. To solve these data issues, reanalysis data have been recently established based on data assimilation and statistical techniques using all available ground and satellite measurements and model simulations (Randles et al., 2017) for better analysis of polar...
atmospheric environments.

Two Korean stations in Antarctica (the King Sejong and Jangbogo stations) and one station in the Arctic (the Dasan station) were established and have been operated by the Korea Polar Research Institute (KOPRI). Analyses regarding the spatial distribution of and temporal variation in regional airborne aerosols at these sites have not yet been performed, resulting in a poor understanding of polar aerosol characteristics. In this study, we investigate the spatiotemporal features of AOD at the King Sejong, Jangbogo, and Dasan stations using reanalysis data called the Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2). Also, we compare AOD with carbon monoxide (CO) values obtained from satellite observations to evaluate the contribution of mid-latitude wildfire and biomass burning events to the polar region.

SITE AND DATA DESCRIPTION

Site Information

The locations of all three Korean polar stations are depicted in Fig. 1. For the various kinds of scientific experiments in Antarctica, the King Sejong station (62.13°S, 58.47°E) was first built in 1988 on King George Island, located at the tip of the Antarctic Peninsula, bordering the coast of Maxwell Bay. Recently, the second Korean Antarctic station, the Jangbogo station (74.37°S, 164.14°E), was also built near Terra Nova Bay in southeastern Antarctica. Using measured data from both stations, an analysis of the differences between western and eastern Antarctica can be conducted. In the Arctic, the Dasan station, located in Svalbard (78.55°N, 11.56°E), started its scientific mission in 2002. The monitoring at this station appears to be useful for determining the atmospheric and oceanic properties in the North Atlantic.

Data Description

As previously mentioned, we mainly utilize the MERRA-2 AOD data to observe variations in atmospheric turbidity due to the airborne aerosols in the polar region. MERRA-2 reanalysis data were prepared through the data assimilation process using several in situ and satellite measurements with simulations based on the Goddard Earth Observing System version 5 (GEOS-5) model (Randles et al., 2017). AOD is one of the products of MERRA-2 that is related to air quality and is provided as pixels at a resolution of 0.5 × 0.625°. These data are produced every 3 hours since 0 UTC, and for this study, we use daily averaged AOD for the analyses. For the analysis of long-term aerosol variation in the 21st century, we investigate all AOD values acquired from 2001 to 2016.

Since the transport of air pollutants emitted in the mid-latitude region is considered as a significant factor that influences polar atmospheric pollution, it is necessary to examine the connection between polar and mid-latitude regions. Specifically, the effect of mid-latitude wildfire and biomass burning events appears to be important (Law and Stohl, 2007). CO typically remains in the atmosphere for 4–5 months after it is emitted from the surface, which is appropriate to observe the transport effect from the mid-latitudes. Also, CO can be retrieved using measurements in the infrared channel, which boasts better performance over the polar surface compared to the ultraviolet or visible channels. Thus, the CO pattern is also compared to AODs using the satellite measurements. In this study, we use CO column data obtained from the Atmospheric Infrared Sounder (AIRS) onboard the Aura satellite that was launched in 2002 (Worden et al., 2013). These CO data were retrieved using near infrared channels from 4.58 to 4.50 µm (2183–2220 cm⁻¹).

RESULTS AND DISCUSSION

First, we investigate the decadal mean AOD pattern over the Arctic and Antarctic regions (Fig. 2). AOD over the
Antarctic region is generally low (Fig. 2(a)), but the western Antarctic region shows a slightly higher AOD than the eastern Antarctic region. This difference appears because the western Antarctic region is closer to emission sources in the mid-latitudes, such as South America. Over the Arctic region (Fig. 2(b)), AOD is higher near Eurasia and Siberia and is moderate near North Europe and Canada. Thus, we expect that the AOD at the Dasan station is the highest among the three Korean polar sites.

The monthly and seasonal mean AOD patterns are examined next. Fig. 3 reveals the monthly mean AOD patterns from the Jangbogo, King Sejong, and Dasan stations. The Jangbogo station shows the lowest AOD values of the entire year because the clean polar atmosphere is separated from the polluted mid-latitude air masses due to a strong polar vortex. On average, AOD at the Jangbogo station is high in the austral summer, December and January, but is less than 0.05 at its maximum. AOD at the Jangbogo station is low from March to July, approximately 0.02. This seasonal variation appears to be related to the extent of solar radiation. Thus, the AOD variation at the Jangbogo station is apparently attributable to photochemical activity and is not affected significantly by transport of mid-latitude air pollutants.

AOD at the King Sejong station is almost twice that of AOD at the Jangbogo station. However, the seasonal variation in AOD is similar between the two stations. Mean AOD at the King Sejong station is at a maximum in October but is at a minimum from April to July. Another difference is the standard deviation of monthly AOD, in which there is a larger standard deviation of AOD at the King Sejong station compared to the Jangbogo station. AOD variation at the Jangbogo station is similar through the entire year because of weak external forcing. At the King Sejong station, located at a lower latitude, the influence of external forcing is higher due to the closer proximity of the mid-latitudinal emission source (South America). Accordingly, AOD at the King Sejong station can show a larger change, contingent on the existence of external forcing.

The Dasan station in the Arctic is located at approximately 78.5°N, higher than both the King Sejong and Jangbogo stations considering the absolute degree of latitude. However, AOD at Dasan is higher than at the other two Antarctic stations because the air pollution in the northern hemisphere is generally more severe. AOD at Dasan is the highest in spring (March, April, and May), associated with poor air quality due to the Arctic haze issue (Shaw, 1995). This phenomenon appears to be analogous to recent findings from the analysis of ground-based measurements (Tomosi et al., 2007). AODs rapidly decrease and reach a minimum in October and then increase again in winter. This kind of monthly variation appears to be similar to the variation in total ozone associated with large-scale circulation (Park et al., 2011), implying that it may be necessary to inspect the connection between AOD and atmospheric variation in the future.

As mentioned above, the spatiotemporal variation in AOD in pristine polar regions can be affected by the transport of aerosols that are emitted in low- and mid-latitude regions. Since wildfire and biomass burning events are representative of particle emission sources in the mid-latitudes, we also examine the pattern of CO, which is dominantly produced from fire and combustion processes, for comparison to the AOD variation (Fig. 4). CO over the two Antarctic stations shows similar maximums in September and minimums in the austral summer. This variation is well explained by ground-based CO measurements in the southern hemisphere (Edwards et al., 2006). CO in the Arctic site is high from February to April and is low in June and July, which is consistent with previous findings that show high CO emissions in winter and early spring in the northern hemisphere (Koo et al., 2017).

We further investigate how the relationship between AOD and CO varies seasonally for the periods of March–April–May (MAM), June–July–August (JJA), September–October–November (SON), and December–January–

![Fig. 2. The recent decadal (2007–2016) mean of MERRA-2 AOD over the (a) Antarctic and (b) Arctic.](image-url)
February (DJF). Fig. 5 shows that the seasonal variation of AOD and CO is similar at the Dasan and King Sejong stations. Both sites consistently show a maximum AOD in the springtime (MAM in the northern and SON in the southern hemisphere). Since CO indicates wildfire and biomass burning events, the coincidence of the AOD and CO patterns implies a large contribution by black carbon particles that are emitted in the mid-latitudes to the polar aerosol concentration. In fact, previous studies have shown that black carbon emissions tend to be high in spring (e.g., Bond et al., 2013). In contrast, the AOD at Jangbogo shows the inverse relationship to CO variation (i.e., high AOD during the season characterized by low CO).

Correlations between monthly mean AOD and CO (Fig. 6) better describe the relationship between AOD and CO variation. Similar to the interpretation from Fig. 5, we...
Fig. 4. The monthly mean of carbon monoxide (CO) at the (a) Jangbogo, (b) King Sejong, and (d) Dasan stations. Vertical bars indicate the monthly standard deviation.

can easily see the positive correlation between AOD and CO at the King Sejong and Dasan stations. The highest correlation is observed at Dasan, indicating that the transport of particles emitted from fire and combustion events contributes to the variation in Arctic AOD as previously discussed. At Jangbogo, however, the correlation between AOD and CO is negative (R = –0.47), opposite to cases at the King Sejong and Dasan stations. From this information, we observe that the variation in AOD at Jangbogo is not attributable to the transport of mid-latitude aerosols related to fire and combustion events.

In addition to monthly and seasonal variations, we also investigate the long-term trends in AODs at the three polar stations. Fig. 7 shows the AOD trend at the Jangbogo, King Sejong, and Dasan stations from 2001 to 2016 using annual mean AOD values. Since the average value of AOD can include bias from outlier measurements (e.g., irregular high or low AOD values) or uncertainty/error, a trend
analysis based on percentiles is more accurate. Therefore, we estimate the temporal trends over the past 16 years using the 10th, 50th, and 90th percentiles of MERRA-2 AOD for every year. In general, the trend of the 90th percentile indicates temporal variation in highly polluted cases, and the trend of the 10th percentile describes a change in background air conditions (Yoon et al., 2016).

The median AOD trends at all three sites (Fig. 7) usually tend to increase, which is slightly different from the decreasing trend that occurred until the early 2000s (Tomasi et al., 2007). Basically, the increasing AOD trend indicates recent intensification of polar aerosol pollution. Although the Antarctic sites also show decreasing trends for the 10th and 90th AOD percentiles, the Dasan station in the Arctic shows a consistent increasing trend for the 10th, 50th (median), and 90th AOD percentiles. This characteristic may imply that the general air condition for the entire Arctic region is becoming more polluted because of more frequent emissions with high aerosol concentrations. Since recent trends in northern hemispheric CO emissions show a steady decrease (Worden et al., 2013), other factors that may contribute to the high AOD should be investigated further, instead of aerosol emissions from fire and combustion processes.

Finally, seasonal trend analyses of the 10th, 50th, and 90th AOD percentiles are performed (Fig. 8). Using the trend equal to $10^{-4}$ year$^{-1}$ as a threshold value, strong or weak trends are determined if the absolute value of the AOD
Fig. 7. Trends of the annual 10th (circle), 50th (triangle), and 90th (square) percentiles of AOD at the (a) Jangbogo, (b) King Sejong, and (c) Dasan stations.

trend is higher or lower than the threshold. Therefore, there is a total of four trend patterns: strong increase (SI), weak increase (WI), strong decrease (SD), and weak decrease (WD). Interestingly, all three polar stations generally show a decreasing trend during the MAM and JJA seasons but show an increasing trend during the SON and DJF seasons. We basically focus on the trend of the 50th AOD percentile meaning a standard pattern. As a result, the SI trend is found in DJF, and the SD trend is found in MAM at the Jangbogo station. In the same Antarctic region, however, the King Sejong station commonly shows an increasing trend except during the austral winter season (JJA). Therefore, we
observe a difference in seasonal trends between the two Antarctic stations, which appears to be attributable to the difference in latitude. This feature indicates that the driving forces that explain AOD variation may be different, even in the same Antarctic region.

The Dasan station in the Arctic shows an increasing AOD trend in the SON and DJF seasons as well as a decreasing trend in the MAM and JJA seasons (Fig. 8). The above discussion indicates that the maximum peak for both Arctic AOD and CO appears in spring. Considering this finding in conjunction with the decreasing CO trend in the northern hemisphere (Worden et al., 2013), AOD trends at the Dasan station are not explained by the pattern of wildfire and biomass burning events in the northern hemisphere. Since the SI trend is consistent for the 10th, 50th, and 90th AOD percentiles during the SON period, enhanced anthropogenic activity may increase the extent of Arctic background aerosol pollution. A more detailed analysis is required to better elucidate the long-term trend in AODs.

**SUMMARY AND CONCLUSION**

This study analyzed MERRA-2 reanalysis data to examine AOD variation over two Antarctic stations (Jangbogo and King Sejong) and one Arctic station (Dasan) that are operated by Korea. We observed the maximum peak in AOD during spring at the Dasan and King Sejong stations. The extent of the AOD at the Jangbogo station is smaller than at the other two stations and shows its maximum in summer, with a lower monthly variation than at the other two stations. Although monthly variation in AOD is usually affected by large-scale atmospheric circulation and photochemical activity, which is generally influential in the mid-latitudes, the AOD at Jangbogo is not affected by these factors due to its isolated location at a high latitude. We also performed CO analysis using AIRS satellite measurements to evaluate the influence of mid-latitude regional wildfire and combustion events on AOD variation. The results indicate that AOD variation at the Dasan and King Sejong stations shows a strong positive correlation with CO variation, but AOD variation at the Jangbogo station does not correlate to CO variation.

To elucidate the temporal pattern of aerosol pollution in the polar regions, long-term AOD variations for the past 15 years were also investigated. We consistently observed a general increasing trend of AOD at all three polar stations. In spite of the seasonal relationship between the AOD and the CO, the trend exhibiting the highest AOD was not observed during high AOD and CO emissions, suggesting that wildfire and biomass burning events may not influence the long-term trend of AOD in the polar region. Instead, the increasing trend probably indicates the intensification of polar background aerosol pollution or an increase in industrial and anthropogenic aerosol emissions near the polar region. If this speculation is accurate, the analysis of particle emissions, such as black/brown carbon or gaseous hydrocarbons (e.g., methanol and formaldehyde), will be useful in understanding variations of AOD. This approach can also provide meaningful information for investigating polar climate variability in addition to the air pollution issues that are investigated herein. However, all interpretations and estimations here are based on limited data analysis. Due to the small amount of high-quality data, more detailed studies are necessary in the future to confirm or improve our understanding of polar air conditions.

**ACKNOWLEDGMENTS**

This work was supported by the Korea Polar Research Institute (KOPRI, PE17010). Also, this work was funded by the Korea Meteorological Administration Research and Development Program under Grant KMIPA (KMIPA2015-5010).

**REFERENCES**

Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., DeAngelo, B.J., Flanner, M.G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P.K., Sarofim, S.C., Schultz, M.G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S.K., Hopke, P.K., Jacobson, M.Z., Kaiser, J.W., Klimages, Z., Lohmann, U., Schwarz, J.P., Shindell, D., Storelvmo, T., Warren, S.G. and Zender, C.S. (2013). Bounding the role of black carbon in the climate system: A scientific
Koo et al., Aerosol and Air Quality Research, 18: 3202–3210, 2018

Assessment. J. Geophys. Res. 118: 5380–5552.

Edwards, D.P., Emmons, L.K., Gille, J.C., Chu, A., Attié, J.L., Giglio, L., Wood, S.W., Haywood, J., Deeter, M.N., Massie, S.T., Ziskin, D.C. and Drummond, J.R. (2006). Satellite-observed pollution from southern hemisphere biomass burning. J. Geophys. Res. 111: D14312.

Koo, J.H., Walker, K.A., Jones, A., Sheese, P.E., Boone, C.D., Bernath, P.F. and Manney G.L. (2017). Global climatology based on the ACE-FTS version 3.5 dataset: Addition of mesospheric levels and carbon-containing species in the UTLS. J. Quant. Spectrosc. Radiat. Transfer 186: 52–62.

Law, K.S. and Stohl, A. (2007). Arctic air pollution: origins and impacts. Science 315: 1537–1540.

Li, F., Ginoux, P. and Ramaswamy, V. (2008). Distribution, transport, and deposition of mineral dust in the southern ocean and Antarctica: Contribution of major sources. J. Geophys. Res. 113: D10207.

McConnell, J.R., Edwards, R., Kok, G.L., Flanner, M.G., Zender, C.S., Saltzman, E.S., Banta, J.R., Pasteris, D.R., Carter, M.M. and Kahl, J.D.W. (2007). 20th-century industrial black carbon emissions altered Arctic climate forcing. Science 317: 1381–1384.

Park, S.S., Kim, J., Cho, N., Lee, Y.G. and Cho, H.K. (2011). The variations of stratospheric ozone over the Korean peninsula 1985–2009. Atmosphere 21: 349–359.

Randles, C.A., Da Silva, A.M., Buchard, V., Colarco, P.R., Darmenov, A., Govindaraju, R., Smirnov, A., Holben, B., Ferrare, R., Hair, J., Shinozuka, Y. and Flynn, C.J. (2017). The MERRA-2 aerosol reanalysis, 1980 onward. Part I: System description and data assimilation evaluation. J. Clim. 30: 6823–6850.

Shaw, G.E. (1995). The Arctic haze phenomenon. Bull. Am. Meteorol. Soc. 76: 2403–2413.

Stohl, A. and Sodemann, H. (2010). Characteristics of atmospheric transport into the Antarctic troposphere. J. Geophys. Res. 115: D02305.

Tomasi, C., Vitale, V., Lupi, A., Di Camine, C., Campanelli, M., Herber, A., Treffeisen, R., Stone, R.S., Andrews, E., Sharma, S., Radionov, V., von Hoyningen-Huene, W., Stebel, K., Hansen, G.H., Myhre, C.L., Wehrl, C., Aaltonen, V., Lihavainen, H., Virkkula, A., Hillamo, R. Ström, J., Toledano, C., Cachorro, V.E., Ortiz, P., de Frutos, A.M., Dlindheim, S., Frioud, M., Gausa, M., Zielinski, T., Petelski, T. and Yamanouchi, T. (2007). Aerosols in polar regions: A historical overview based on optical depth and in situ observations. J. Geophys. Res. 112: D16205.

Worden, H.M., Deeter, M.N., Frankenberg, C., George, M., Nichitiu, F., Worden, J., Aben, I., Bowman, K.W., Clerbaux, C., Coheur, P.F., de Laat, A.T.J., Detweiler, R., Drummond, J.R., Edwards, D.P., Gille, J.C., Hurtmans, D., Luo, M., Martinez-Alonso, S., Massie, S., Pfister, G. and Warner, J.X. (2013). Decadal record of satellite carbon monoxide observations. Atmos. Chem. Phys. 13: 837–850.

Yoon, J., Pozzer, A., Chang, D.Y., Lelieveld, J., Kim, J., Kim, M., Lee, Y.G., Koo, J.H., Lee, J. and Moon, K.J. (2016). Trend estimates of AERONET-observed and model-simulated AOTs between 1993 and 2013. Atmos. Environ. 125: 33–47.

Received for review, August 22, 2018
Revised, August 22, 2018
Accepted, September 2, 2018