Vol. 64 No 02(250) 2024
DOI: https://doi.org/10.5564/pmas.v64i02.3651
PMAS
Proceedings of the Mongolian Academy of Sciences

ARTICLE

Effect of coal type on aerosol optical properties at Ulaanbaatar city

Narangarav Tumur-Uyal [1,3], Baatarchuluun Tsermaa[1,3,*], Tuvshinjargal Baldorj[2,3], Javzandolgor Bad[1,3] and Daariimaa Badarch[1,3]

[1] Department of Geology and Geophysics, School of Arts and Sciences, National University of Mongolia, Ulaanbaatar, Mongolia
[2] Department of Astrophysics, Institute of Astronomy and Geophysics, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia
[3] Laboratory of Atmospheric Optics, Graduate School, National University of Mongolia, Ulaanbaatar, Mongolia

ARTICLE INFO: Received: 02 May, 2024; Accepted:28 June, 2024

Abstract: In this study, seasonal characteristics of aerosol optical properties at Ulaanbaatar station of the international network of SKYNET are investigated using ground-based skyradiometer from the years extending from 2017 to 2023. The aerosol optical thickness (AOT) at 500nm wavelength and Angstrom exponent (AE) were determined in winter to evaluate the decrease in air pollution in Ulaanbaatar since implementing the government's decision to use coal briquettes for household heating. During the study period, the monthly mean AOT at 500nm varied throughout the year, with the maximum value of 0.178±0.004 obtained in winter due to households burning large amounts of biomass, and the highest AOT (0.183) was obtained in February. The mean AOT was 0.21 in the winter of 2017-2019, which decreased by 15 per cent to 0.18 in the winter of 2019-2023.

Keywords: *atmospheric optical properties; aerosol optical thickness; Angstrom exponent; seasonal variation; Ulaanbaatar city;*

INTRODUCTION

Given the fact that air pollution directly affects the air quality and the health of citizens in urban areas, it is important to determine the amount of air pollution and the source of pollutants. This can be evaluated through optical parameters of aerosols [1-2]. Airborne water vapor, water droplets, snow and ice crystals, salt particles, ash, plant dust, dust and smoke are called atmospheric aerosols. They indicate air pollution in a region and are classified as natural or anthropogenic in origin. Aerosols vary with space and time, as well as the geographical location and the climate of the region. Therefore, the lifestyle of the people living in those areas can influence the type, size and distribution of aerosols [3].

In recent years, air pollution in Ulaanbaatar has increased dramatically, which is directly related to over centralization of the population. About 50 per cent of Ulaanbaatar's total 431,000 households live in houses with ordinary stoves and they burn large amounts of biomass for heating and cooking especially in winter.

***Corresponding author, email**: baatarchuluun@num.edu.mn https://orcid.org/0000-0002-7169-3532*

Vol. 64 No 02(250) 2024
DOI: https://doi.org/10.5564/pmas.v64i02.3651
PMAS
Proceedings of the Mongolian Academy of Sciences

This accounts for 80 per cent of air pollution in Ulaanbaatar, while the remaining 10 per cent comes from vehicles on the road, 6 per cent from the thermal plants operating in the city, 4 per cent from ash deposits of thermal plants, dust blown from roads, open garbage and other sources [4].

Considering the annual change of long-term average concentration of pollutants in the air in Ulaanbaatar city, it increases from October and reaches maximum level in December and January, after which it gradually decreases, and is at a permissible level from April to September. This indicates that city dwellers are breathing more polluted air than the permissible level for 6 months of the year. Researchers have shown in their studies that air pollution has a negative impact on the humans' respiratory system, cardiovascular system, and reproductive system. For example, if we consider only the cases of respiratory system diseases among children under 5 years of age in Ulaanbaatar, 116.3 thousand cases of children with respiratory diseases were registered in 2019, which increased by 29.9 per cent as compared to the average of the last 10 years [5]. Therefore, analyzing the characteristics and evolution of aerosols contained in the atmosphere over Ulaanbaatar is important for improving the air quality and public health of the people as a whole.

The government of Mongolia has implemented numerous measures to reduce air pollution in and around Ulaanbaatar. One of them was the decision to ban the use of raw coal in the six central districts of the city and instead introduce coal briquettes for cooking and heating purposes, and this measure was introduced on 15 May 2019. It was hoped that this measure would reduce air pollution in Ulaanbaatar by at least 50 per cent [5].

Optical properties and temporal variations of aerosols in the atmosphere around Ulaanbaatar have been determined and air pollution have been assessed, studied and the results have been published [6-12]. The atmospheric aerosol optical depth in Ulaanbaatar was evaluated in these studies, and its seasonal and annual changes were shown. Moreover, in the works carried out in recent years, by comparing the relationship between AE and AOT, the particle size of aerosols that dominate in the atmosphere of Ulaanbaatar and the cause of their formation were determined.

In this paper we aimed to characterize the atmospheric aerosol optical properties in Ulaanbaatar and analyze their temporal variability, and also to explain the causes of air pollution. In addition, we focused on how air pollution of Ulaanbaatar city decreased in winter after using coal briquettes.

MATERIALS AND METHODS

Determining some optical parameters of aerosols

The intensity of direct solar radiation penetrating the Earth's atmosphere decreases due to scattering and absorptions of molecules of gases and aerosols in the atmosphere. The attenuation of the direct solar radiation is determined by the Bouguer-Lambert-Beer Law, which is expressed by the following equation [13-14]:

$$I_\lambda = I_{0,\lambda} \cdot e^{-\tau_\lambda \cdot m(h_\Theta)} \tag{1}$$

where, I_λ is the measured direct solar radiation at a certain wavelength of spectrum at groundlevel, $I_{0,\lambda}$ is the solar constant at a certain wavelength of spectrum, τ_λ is the total optical thickness of the atmosphere, and $m(h_\Theta)$ is the atmospheric optical mass.

The total optical thickness of the atmosphere is the sum of the optical thicknesses:

$$\tau_\lambda = \tau_a(\lambda) + \tau_R(\lambda) + \tau_{O_3}(\lambda) + \tau_{mg}(\lambda) + \tau_w(\lambda) \tag{2}$$

Here, $\tau_a(\lambda)$ – aerosol optical thickness, $\tau_R(\lambda)$ – optical thickness of Rayleigh scattering, $\tau_{O_3}(\lambda)$ – optical thickness of ozone, $\tau_{mg}(\lambda)$ – optical thickness of mixed gases, $\tau_{P_w}(\lambda)$ – optical thickness of water vapor.

From the Eq.(1) and Eq.(2), the aerosol optical thickness is determined by the following equation:

$$\tau_a(\lambda) = \frac{1}{m(h_\Theta)}\left(lnI_{0,\lambda} - lnI_\lambda\right) - \left[\tau_R(\lambda) + \tau_{O_3}(\lambda) + \tau_{mg}(\lambda) + \tau_{P_w}(\lambda)\right] \quad (3)$$

The Angstrom exponent is a parameter that describes how the optical thickness of an aerosol typically depends on the wavelength of the light. It depends on the linear dimension of the atmospheric aerosols in the region, i.e., its value represents the size distribution of aerosols. The Angstrom exponent at a certain spectral wavelength is defined by the ratio of AOT and the wavelength as shown below.

$$\alpha = -\frac{ln\left(\frac{\tau_\lambda}{\tau_{\lambda_0}}\right)}{ln\left(\frac{\lambda}{\lambda_0}\right)} \quad (4)$$

where, α is the Angstrom exponent, τ_λ is the AOT at the spectral wavelength λ, and τ_{λ_0} is the AOT at the spectral wavelength λ_0 which is chosen as a reference.

The greater value of α then dominantly distributed are the fine-sized aerosols in the air, and in contrast, the low value indicates that the large-sized aerosols are dominant.

Data

The study to determine the optical indicators of air pollution in Ulaanbaatar has been continuously conducted for the past 50 years at the Department of Geology and Geophysics of the National University of Mongolia

Since 2013, the research has been continued with the Skyradiometer POM-01 instrument of the international SKYNET network.

This ground-based Skyradiometer POM-01 is used to measure the intensity of direct and diffused solar radiation every 10 minutes during day-time when the sky is cloud-free. With the data from direct and diffused solar radiation measurement, it is possible to determine the atmospheric optical characteristics, such as aerosol spectral optical depth, Angstrom exponent (AE), scattering albedo (SA), aerosol volume size distribution (VSD), refractive index (RI), single-scattering albedo (SSA) and asymmetry parameters (g). The Skyradiometer has 7 channels with wavelengths of 315, 400, 500, 675, 870, 940, and 1020 nm, and these channels are intended for aerosol measurements. A long-term record of atmospheric aerosols would provide us with a valuable data to evaluate the air pollution in Ulaanbaatar.

In this work, we used 53643 data of 1665 days, which can be available for analysis of the atmospheric optical properties, measured in cloud-free days at Ulaanbaatar station of the SKYNET network in the years 2017-2023.

RESULTS AND DISCUSSION

The spectral AOT is one of the important parameters for evaluating air pollution and it is primarily related to the atmospheric aerosol size distributions. We measured direct solar radiation at 7 channels with wavelengths of 315, 400, 500, 675, 870, 940, and 1020 nm, and determined the corresponding spectral optical thicknesses. While the ozone is the dominant absorber in mid-ultraviolet (UVB) range (280-320nm), the measurements at 315 nm were used to estimate the optical thickness of ozone. Likewise, water

Vol. 64 No 02(250) 2024
DOI: https://doi.org/10.5564/pmas.v64i02.3651

has strong absorption bands at the near-infrared region (for example, around 970 nm, 1200 nm, 1450 nm, 1950 nm), the measurements at 940 nm were employed to evaluate the optical thickness of water vapor. By using Eq. 3, which uses optical thicknesses of ozone and water vapor, the spectral AOT was calculated at the remaining 5 channels. Therefore, in Fig. 1, we have depicted the yearly variations of the monthly mean values of AOT at the spectral wavelengths of 400, 500, 675, 870 and 1020 nm in Ulaanbaatar site.

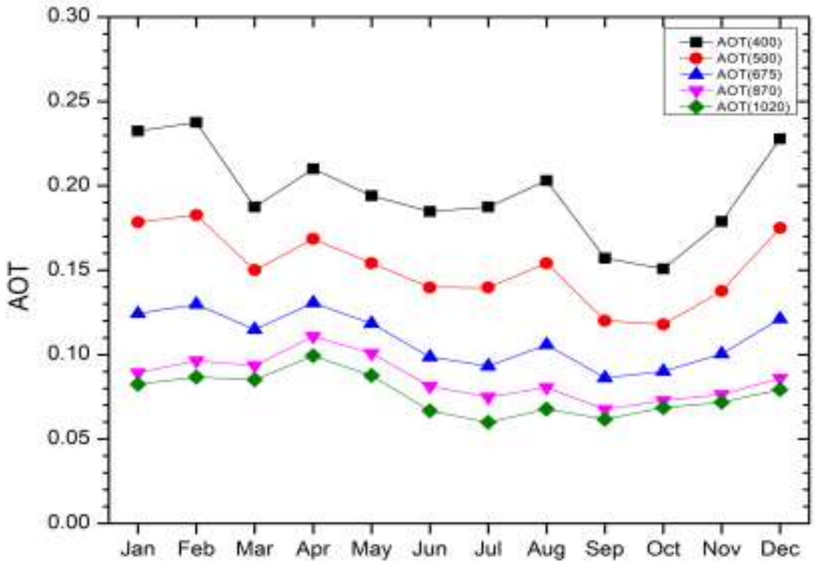

***Figure 1. The annual trends of AOT at 400, 500,* 675, 870 and 1020 nm wavelengths in Ulaanbaatar site**

Coarse-sized aerosols contribute to AOT in both visible (from about 400 to 750 nm) and near-infrared (NIR, from about 750 to 2500 nm) wavelength region, while fine-sized aerosols have more effect on the AOT in the visible region than that of the NIR region [15-16]. Moreover, the AOT at 500nm has been used widely (e.g. *Ma et al., 2012, Wang et al., 2011*) for atmospheric optical studies. Therefore, for the purpose of obtaining the optical properties of aerosol over Ulaanbaatar and comparing our results with other studies, we used the AOT data at 500 nm wavelength.

The two significant parameters for the evaluation of air pollution are the AOT at 500nm wavelength and the AE.

Depending on the season of the year, the causes of air pollution in Ulaanbaatar were different. In this study, annual and seasonal variations of AOT at 500nm wavelength are explored. Moreover, we attempted to define the cause of air pollution using the relationship between AOT and AE. In addition, the main result of this study has shown how air pollution in Ulaanbaatar site decreased since the government’s decision to use coal briquettes for household heating.

Seasons are expressed as *winter* (December-January-February), *spring* (March-April-May), *summer* (June-July-August), and *autumn* (September-October-November).

Vol. 64 No 02(250) 2024
DOI: https://doi.org/10.5564/pmas.v64i02.3651
PMAS
Proceedings of the Mongolian Academy of Sciences

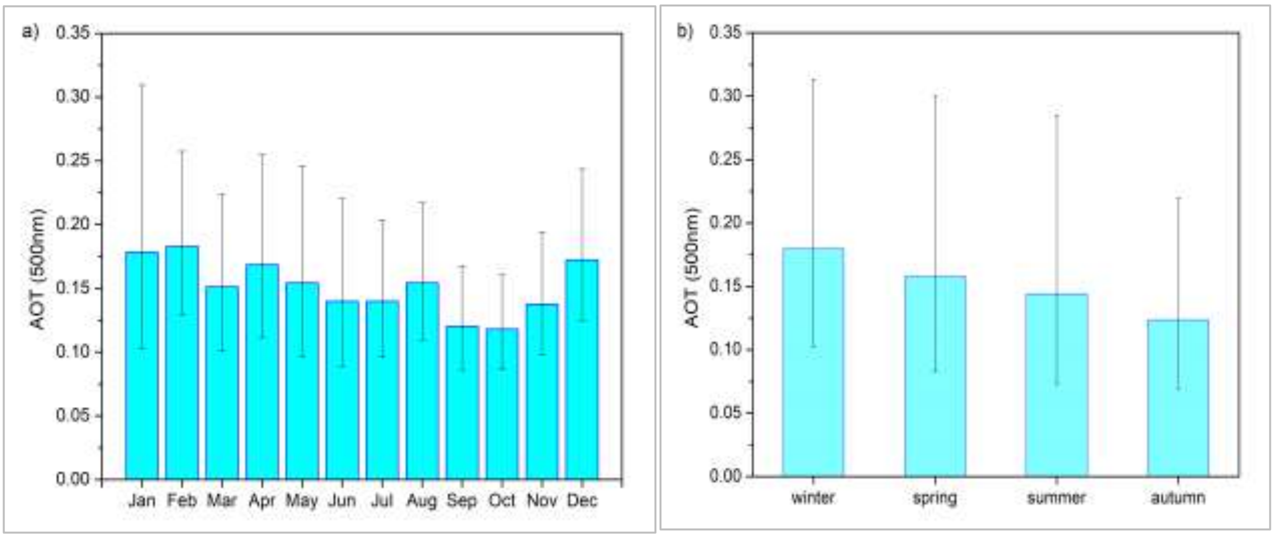

Figure 2. Monthly and seasonal mean values of AOT at 500nm around Ulaanbaatar (from June 2017 to December 2023)

Figure 2 shows monthly (a) and seasonal (b) mean of AOT (500nm) for the study period (June 2017 to December 2023). The maximum monthly mean value of AOT is 0.183 in February, and the minimum monthly mean value of AOT is 0.118 in October.

There is an obvious seasonal routine from the annual variation of AOT (Figure 2a): relative steady in the spring and summer, a decrease to minimum in the fall, and a striking increase to maximum AOT in winter, and again a decrease from spring to autumn. The annual mean value of AOT (500nm) is 0.149, which is about 4 times the minimum daily mean value (0.037) observed at the site during the period of study. A relatively higher value of AOT was observed in April and August than in the other months of spring and summer. Because of the dry climate in spring in Mongolia, coarse-sized aerosols are dominant in the atmosphere due to the dust storm in April in Ulaanbaatar.

In July 2019 and June 2021, forest fires broke out in Siberia, Russia [17]. The smoke from these fires covered some areas of Mongolia and Ulaanbaatar for several days, as a consequence of which a relatively large value of AOT was observed in Ulaanbaatar in the month of August. The seasonal mean values of AOT at 500 nm are shown on Figure 2b. The maximum and minimum values of seasonal means of AOT are 0.180 in winter and 0.124 in autumn, respectively.

The relationship between AOT and AE may afford a probable way to analyze aerosol size and, further, define the sources of aerosol. Figure 3 shows the relationship between the daily mean AOT at 500 nm and the daily mean AE for the winters before and after the use of coal briquette at Ulaanbaatar station. Here, we considered the periods from December 2017 to February 2018, and December 2018 to February 2019 as the winters during which raw coal was used.

Vol. 64 No 02(250) 2024
DOI: https://doi.org/10.5564/pmas.v64i02.3651

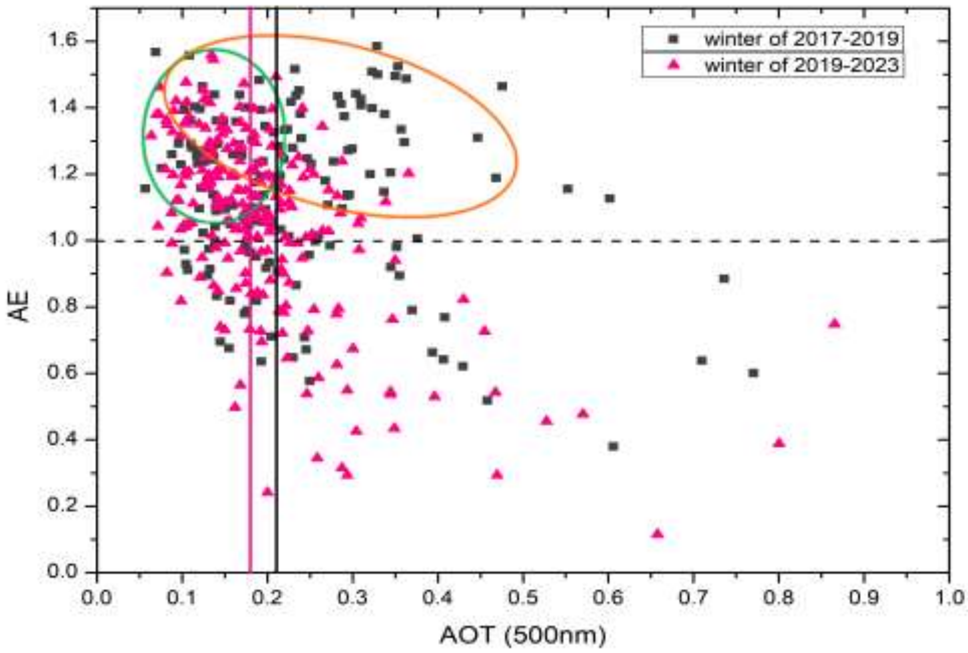

Figure 3. Relationship between daily mean AOT at 500 nm and the daily mean AE for winters before and after the use of coal briquettes in Ulaanbaatar

The periods between December 2019 to February 2020, December 2020 to February 2021, December 2021 to February 2022, and December 2022 to February 2023 were assumed to be the winters during which coal briquettes was used. The mean value of AOT in winter before the use of coal briquettes was 0.21 (depicted as a black line in Fig. 3), and after the use of coal briquettes, the mean value of AOT in winter was 0.18 (shown as a pink line in Fig. 3). This result shows an approximately 15 per cent decrease in AOT of Ulaanbaatar in the winter season due to the use of coal briquettes for household heating. Moreover, this also indicates that when raw coal is used for household heating, the higher value of AE was determined, which indicates the fine-sized aerosols dominant in the atmosphere and it corresponds to the higher AOT (orange circle in Fig.3). On the other hand, after the use of coal briquettes, the higher AE corresponds to the lower AOT (green circle in Fig. 3).

The results of this study are consistent with those in Dunhuang, Northwest China and Hailun, Northeast China in general [18-19]. For example, monthly mean values of AOT at 500 nm in Dunhuang and Hailun tend to increase from winter to spring and decrease from summer to autumn. For both cities, coarse aerosols are dominant due to dust storms in the spring, while fine aerosols are caused by the burning of fossil fuels and biomass for heating in the winter. In addition, Hailun is close to Ulaanbaatar in terms of geographical latitude (47°28'N) and its climate is dry and has cold winters and warm summers. Therefore, the seasonal and annual mean values of AOT at 500 nm in Hailun are approximately the same as those in Ulaanbaatar. As for Dunhuang, it is located in a dry and Gobi desert region, so the seasonal and annual mean AOT are 1.5-2.5 times higher than those of Ulaanbaatar and Hailun.

PMAS
Proceedings of the Mongolian Academy of Sciences
Vol. 64 No 02(250) 2024
DOI: https://doi.org/10.5564/pmas.v64i02.3651

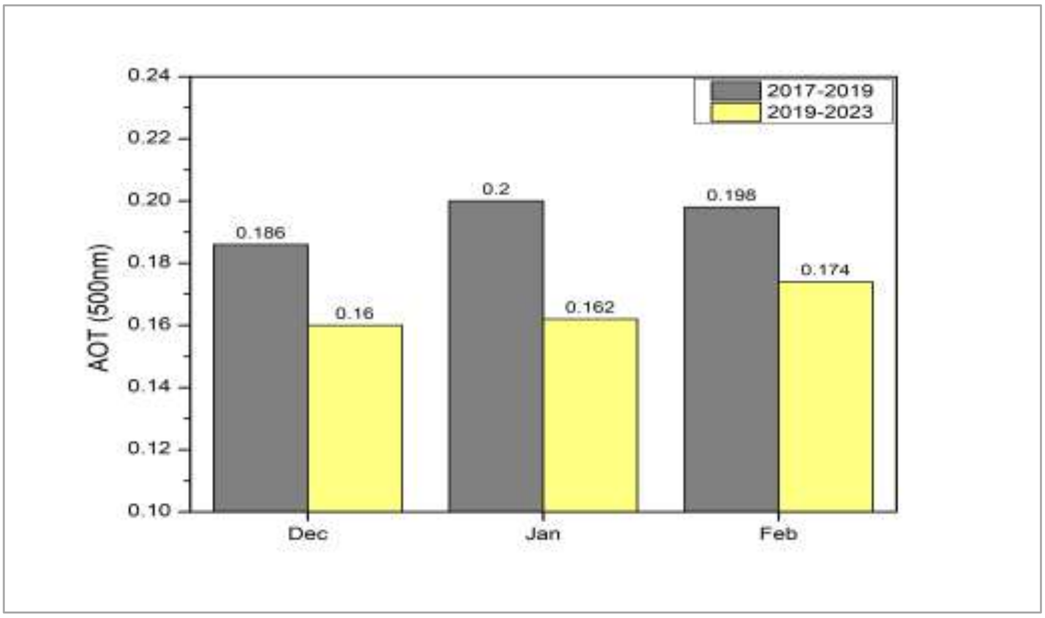

Figure 4. Changes in AOT at 500nm wavelength in the winter months before and after the use of coal briquettes

With the intention of showing how the air quality in Ulaanbaatar site has changed since the use of the coal briquettes, the mean AOT values for the winter months were defined and shown in Fig.4. During the use of raw coal, the mean value of the AOT in Ulaanbaatar in winter was 0.19-0.20, which decreased to 0.16-0.17 after the use of coal briquettes. This indicates that the air pollution caused by the fuel burned by households with ordinary stoves in the city of Ulaanbaatar was reduced by about 1.15 times.

CONCLUSIONS

Using ground-based skyradiometer POM-01 data measured between 2017 and 2023 at the Ulaanbaatar site, the monthly and seasonal AOT at 500nm wavelengths have been studied. The main results are listed below:

- In this region, anthropogenic aerosols are released more during the winter season, which increases air pollution. The annual mean value of AOT at 500nm is 0.15, varying from 0.12 (in autumn) to 0.18 (in winter).
- For the seasons in which the natural aerosols are dominant, a comparatively higher AOT was observed with values of 0.17 in April and 0.15 in August.
- In the winter season, fine-grained aerosols, represented by high values of AE, are prevalent. The mean AOT value at 500 nm for winters using coal briquettes is 0.18, which is approximately a 15 per cent decrease from the mean value of 0.21 for winters, when raw coal was used.
- From the period when the government's passed a decision to use coal briquettes instead of raw coal to reduce air pollution in Ulaanbaatar, the mean value of AOT at 500nm is 0.16, 0.16, and 0.17 in December, January, and February, respectively. This means 18 to 25 per cent decrease as compared to the winter months during which raw coal was used.

Acknowledgement

This study was carried out within the framework of research on the optical state of the atmosphere in Ulaanbaatar, which is being performed at the Laboratory of Atmospheric Optics, Graduate School, National University of Mongolia.

Vol. 64 No 02(250) 2024
DOI: https://doi.org/10.5564/pmas.v64i02.3651

REFERENCES

1. Piracha.A, Chaudhary.M, "Urban Air Pollution, Urban Heat Island and Human Health: A Review of the Literature", Sustainability, 14(15), p.9234, 2022. https://doi.org/10.3390/su14159234
2. Colbeck.I, Lazaridis.M, "Aerosols and environmental pollution", Naturwissenschaften 97, pp.117–131, 2010. https://link.springer.com/article/10.1007/s00114-009-0594-x
3. Kong.L, Hu.M, Tan.Q, Feng.M, Yu Qu, An.J, Zhang.Y, Liu.X, Cheng,N, "Aerosol optical properties under different pollution levels in the Pearl River Delta (PRD) region of China",Journal of Environmental Sciences, Vol. 87, pp.49-59, January 2020. https://doi.org/10.1016/j.jes.2019.02.019
4. "Resident population in Mongolia, by bag/khoroo, urban and rural" https://www2.1212.mn/tables.aspx?TBL_ID=DT_NSO_0300_004V5
5. Report of research on "Impact of air pollution on human health in Ulaanbaatar", 2020. https://www2.1212.mn/BookLibraryDownload.ashx?url=Ub_health_2019.pdf&ln=Mn
6. Nakajima, T., Campanelli, M., Che, H., Estellés, V., Irie, H., Kim, S. W., Kim, J., Liu, D., Nishizawa, T., Pandithurai, G., Soni, V. K., Thana, B., Tugjsurn, N. U., Aoki, K., Go, S., Hashimoto, M., Higurashi, A., Kazadzis, S., Khatri, P., Kouremeti, N., Kudo, R., Marenco, F., Momoi, M., Ningombam, S. S., Ryder, C. L., Uchiyama, A., and Yamazaki, A.,"An overview of and issues with sky radiometer technology and SKYNET", Atmos. Meas. Tech., 13, pp.4195–4218, 2020.https://doi.org/10.5194/amt-13-4195-2020
7. Tuvshinjargal B., Baatarchuluun Ts., Narangarav T., Javzandolgor B., Daariimaa B.,"Results of the correlation and distribution of some aerosol optical properties in Ulaanbaatar (2017-2021)", Geophysics and Astronomy, Vol.9, pp.40-45, 2022.
8. Baatarchuluun Ts., Tuvshinjargal B., Narangarav T., Daariimaa B., Javzandolgor B., Batsukh G.,"Study of the aerosol optical properties in Ulaanbaatar. (2013-2021)", Physics, Vol.32, No.553, pp.56-60, 2021. https://doi.org/10.22353/physics.v32i553.472
9. Baatarchuluun Ts., Batsukh G., Daariimaa B., Javzandolgor B., Narangarav T., Tugjsuren N.,"The study of annual variations of some aerosol optical properties in Ulaanbaatar (2015-2018)", Physics, Vol. 28, No.510, pp.56-61, 2019. https://doi.org/10.22353/physics.v28i510.662
10. Ganbat B., Baatarchuluun Ts., Narangarav T., Daariimaa B.,"Comparative studies on the air pollution of optical parameters in different atmospheric conditions: with smokes from house heating and forest fires", Physics, Vol.24, No. 468, 42-48, 2017. https://doi.org/10.22353/physics.v24i468.637
11. Badrakh L., Baatarchuluun Ts., Daariimaa B., Ganbat B.,"The results of the aerosol optical properties in Ulaanbaatar", Physics, Vol. 19, No. 425, 59-62, 2015. https://doi.org/10.22353/physics.v19i425.358

12. Batsukh G., Baatarchuluun Ts., Daariimaa B.,"General trends on annual and daily

variations of the aerosol optical thickness in Ulaanbaatar", Physics, Vol.17, No. 362, 206-208, 2012. https://doi.org/10.22353/physics.v17i362.729

13. David G. Andrews, "An Introduction to Atmospheric Physics", 2nd edition, Cambridge University Press, 2010.

14. Report of basic research project on "Study of optical parameters of aerosols in the atmosphere of Ulaanbaatar (2015-2017), Ulaanbaatar, 2022.

15. Badarinath, K. V. S., Kharol, S. K., Kaskaoutis, D. G., and Kambezidis, H. D. "Influence of atmospheric aerosols on solar spectral irradiance in an urban area", Journal of Atmospheric and Solar-Terrestrial Physics, Vol. 69, Issues 4-5, pp.589-599, 2007. https://doi.org/10.1016/j.jastp.2006.10.010

16. Schuster, G. L., Dubovik, O. and Holben, B. N. "Angstrom exponent and bimodal aerosol size distributions", J. Geophys. Res.,111, D07207, 2006. https://doi.org/10.1029/2005JD006328

17. Kharuk, V. I.; Dvinskaya, M. L.; Im, S. T.; Golyukov, A. S.; Smith, K. T., "Wildfires in the Siberian Arctic", Fire, 5, 106, 2022. https://10.3390/fire5040106

18. Ma, Y. J., and Coauthors, "Optical properties and source analysis of aerosols over a desert area in Dunhuang, Northwest China", Adv. Atmos. Sci., 34(8), pp.1017–1026, 2017. https://doi.org/10.1007/s00376-016-6224-6

19. Wang, Y., J. Xin, Z. Li, S. Wang, P. Wang, W. M. Hao, B. L. Nordgren, H. Chen, L. Wang, and Y. Sun, "Seasonal variations in aerosol optical properties over China", J. Geophys. Res., 116, D18209, 2011. https://doi.org/10.1029/2010JD015376