Himalayan Physics

A review on aerosol optical properties in the selective parts of Nepal

https://doi.org/10.3126/hp.v13i1.78976

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Abstract: Aerosols, tiny solid or liquid particles suspended in the air, influence the Earth's climate, radiative budget, human health, and air quality by absorbing and scattering the solar radiation. It makes the study of aerosol properties and behavior highly demanding in the present context. Since the aerosol concentration and chemical make-up possess a high level of uncertainty with time and space, continuous observation and monitoring can provide some insight into their microphysical properties. In this regard, this review is based on research articles on aerosol optical depth (AOD) and its optical properties published between 2000 and 2024, covering various parts of Nepal and its immediate periphery. It covers most articles based on AERONET data, validated with satellite data, and a few articles using surface data from low-cost sensors. It is found that AOD shows spectral variation. It decreases with increasing wavelength, showing a strong dependence at shorter wavelengths. This result aligns with findings from various parts of the world. It also shows significant seasonal and geographical variations, with distinct patterns. It means that local environmental factors and anthropogenic activities greatly influence AOD. The review of AE over Nepal shows a predominance of fine mode particles during the post-monsoon season. But, during the remaining seasons, both the fine and coarse mode particles are present in almost all places.

Keywords: Angstrom exponent • Precipitable water • Single scattering albedo • Spectral dependence

Recieved: 2025-04-20 **Revised: 2025-05-24** **Published: 2025-06-02**

I. Introduction

Atmospheric aerosols, characterized as suspensions of minute solid particulates or liquid droplets dispersed within a gaseous medium —predominantly air —show significant spatial and temporal variability in their concentrations and physicochemical properties [1, 2]. This fundamental variability analyzes these aerosols as collective populations rather than as isolated particles [2]. The basic characteristics to define and analyse aerosol populations include size distribution, chemical compo-sition, and morphological characteristics [3]. Based on their heterogeneous sources and formation mechanisms, aerosols play a crucial role in numerous atmospheric processes, exerting significant influences on climate dynamics, air

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quality, and public health. Aerosols can be systematically categorized based on their mechanisms of formation into two principal types: primary aerosols and secondary aerosols. Primary aerosols are directly emitted into the atmosphere from both natural phenomena and anthropogenic activities, such as mineral dust, sea spray, and soot particles pro-duced as a result of the incomplete combustion of fossil fuels. In comparison, secondary aerosols arise from the conversion of gaseous compounds into particulate matter; precursor gases, including sulphur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs), undergo complex chemical reactions followed by condensation, resulting in the generation of secondary aerosols [3, 4]. The chemical composition of aerosols provides essential insights into their sources and the pathways through which they are formed [4]. The particle size and optical properties vary significantly depending upon their emission sources. For example, fine mode aerosols are the result of biomass burning, urban pollution, and biogenic emissions to give higher values of AE (> 1.5 μm). It means that, based on such parameters, the potential source region of origin of various pollutants can be predicted. In contrast, anthropogenic sources result from the combustion of fossil fuels, industrial discharges, vehicular emissions, biomass combustion, and different agricultural activities [5].

The composition of aerosols is significantly influenced by their respective emission sources and the atmospheric processes they undergo. Major categories of aerosols consist of marine aerosols (primarily derived from sea salt), mineral dust (basically from deserts), volcanic aerosols abundant in sulphates, anthropogenic aerosols (which include black carbon, organic carbon, and sulphates orig-inating from industrial activities and vehicular emissions), and aerosols resulting from biomass combustion that comprise both organic and elemental carbon [6]. Particularly in developing na-tions, notable anthropogenic contributions to aerosol formation arise from industrial operations, transportation, residential heating, and cooking practices.

Aerosols exert significant impact on Earth's radiative balance through both direct and indirect mechanisms. The direct effect results the scattering and absorption of solar radiation, which can be quantified utilizing various metrics, including aerosol optical depth (AOD), single scattering albedo (SSA), and the Ångström exponent (AE) [6, 7]. These optical characteristics exhibit regional varia-bility, reflecting differences between emission sources and dominant meteorological conditions. Indirect effects refer to the interactions between aerosols and clouds, whereby aerosols act as cloud condensation nuclei (CCN), thereby influencing cloud formation, properties, and precipitation dynamics [7, 8]. The Terai region of Nepal faces a substantial increase in aerosol concentrations, pri-marily due to transboundary pollution originating in northern India and local anthropogenic emis-sions, as well as agricultural burning practices [6]. Conversely, the mid-hills exhibit a bimodal dis-tribution of particle sizes, influenced by increased aerosol optical depth (AOD) resulting from local emissions and the unique valley dynamics [7]. Traditionally characterized by low aerosol levels, the high Himalayas are now revealing rising concentrations, potentially attributable to upslope aerosol transport and intensified human activity. These alterations

are critically affecting the region's hy-drological processes and glacier albedo [9]. Atmospheric aerosols significantly impact environmen-tal quality, affecting concerns related to visibility and health [10].

Aerosol size distribution

The size of aerosol particles ranges from 0.01 μm to 100 μm. Based on their size, they are termed as ultrafine(>0.1 μm), fine(0.1–1 μm)and coarse (1–100 μm) [2]. Natural aerosols, which are predominantly coarse-mode particles, and combustion-produced particles, which are predominantly fine-mode particles with various mixed relative fractions, are among the most challenging types to characterize [11].

Atmospheric aerosols are mainly found in three size modes. They are Aitken mode, Accumulation mode, and Coarse mode [5]. Particles in Aitken mode range in size from micrometers to nanometers. Since this mode can only be seen when the environment is filled with comparatively recent conflagration aerosols, it is also known as the transitory nuclei pattern. They are the result of processes such as gas-to-particle transformation, heterogeneous nucleation, and combustion. They live for just under an hour, which is a relatively short lifespan. The dimension of the granules in Accumulation mode ranges from 0.1 to 1 micrometer [12]. Aerosol particles that coagulate or condense into this spectrum from lower sizes generally remain in this spectrum while they are in the accumulation phase. They also have the most extended lifespan, which is almost as long as a day. When mechanical mechanisms, such as wind blowing across dusty substrates, or the release of aerosols from huge salt granules from sea spray or mechanically created aerosols, like coal ash, occur, they are said to be in the coarse mode, which is characterized by particles having dimensions larger than 1 micrometer [5, 12]. Due to the speed at which coarse particles settle, both the mass and the maximum size of the large particulates in the atmosphere are likely to vary quite a bit. Anthropogenic sources, such as those from agricultural and mining activities, also produce mechanically coarse particles. They barely last a few hours in the atmosphere due to their immense size, which causes them to settle out or crash onto surfaces easily [12].

Aerosol optical properties

Aerosol optical parameters, including aerosol optical depth (AOD), angstrom exponent (AE), precipitable water vapor (PWV), Aerosol absorption optical depth (AAOD), single scattering albedo (SSA), Asymmetry factor, and some others, are used to evaluate the relationship between particles and radiation [13]. The AOD measures aerosols, such as smoke particles, sea salt, desert dust, urban airborne particles, etc. Aerosol optical depth represents the amount of aerosol present in the atmosphere. Therefore, based on the AOD, we can determine different types of aerosols present in the atmosphere.

If AOD $= 0.2$ (Fairly clean atmosphere)

If AOD $= 0.6$ (Polluted atmosphere)

If AOD $= 1.2$ (Heavy biomass burning or dust event) [14]

Precipitable water vapor gives the amount of water vapor present in the atmosphere. Spectral aerosol optical depth is responsible for determining the size distribution of aerosols based on the wavelength range of 440 nm to 870 nm. The negative slope (or first derivative) of AOD with wavelength in logarithmic scale is known as the angstrom parameter alpha (α). AE can be obtained from two or more wavelengths by using least squares fit [14, 15]. Values of alpha greater than 2.0 indicate fine mode particles (e.g., smoke particles and sulfates) exist, while values of alpha near zero indicate the presence of coarse mode particles such as desert dust [15]. The angstrom exponent represents the wavelength dependence of AOD. It gives the aerosol particle size in the atmosphere; the smaller the aerosol particle, the larger the angstrom exponent [16]. In general, if α is less than 1, it refers to coarse mode particles, and α greater than one refers to fine mode aerosols' dominance.

II. Methodology

This research paper is a review of articles related to aerosol optical properties published between 2000 and 2024. Here, we focused on the trend of aerosol optical properties (AOD, AE, and PWV) at various locations in Nepal and its immediate neighbors, using national and a few international papers related to the topic. The review of available articles is limited to those locations where AERONET stations are installed. Additionally, it encompasses data from low-cost sensors for surface measurements, ground-based networks such as AERONET and ABC, satellite data from MODIS, MISR, CALIPSO, MEERA, and OMI, as well as a few atmospheric models.

III. Results and Discussion

The findings of this study on aerosol optical depth (AOD) reveal notable seasonal variability, shaped by diverse emission sources and meteorological conditions. During the pre-monsoon peri-od, spanning from March to May, AOD reaches its peak levels in Pokhara, with measurements of 0.67 ± 0.14 and 0.75 ± 0.15 attributed to biomass burning and dust storms [13, 17]. These patterns align with trends observed in Beijing, where similar dust transport phenomena are also present [18]. In contrast, the winter months, specifically from December to February, display an elevated AOD of 0.46 ± 0.28, primarily linked to biomass heating, the activities of brick kilns, and the as-sociated winter haze. The monsoon season,

from June to September, is characterized by the lowest recorded AOD at 0.21 ± 0.12, primarily due to heavy rain; however, an exception is observed in Pokhara, where the influence of summer rainfall further diminishes AOD levels [19]. The post-monsoon phase, occurring from October to November, presents a moderate AOD value of 0.33 ± 0.02, reflecting residual emissions from agricultural activities.

Furthermore, trends in the Ångström exponent(AE) indicate a dominance of fine-mode aerosols during both winter and the post-monsoon periods, with values ranging from 1.37 to 1.41, suggesting a significant contribution from anthropogenic sources. In contrast, the monsoon period exhibits a more pronounced coarse-mode influence due to the presence of dust and increased pre-cipitation. Pre-monsoon conditions reveal mixed aerosols with an AE averaging around 1.20 [20]. Additionally, interactions between precipitable water (PW) and aerosols play a crucial role, particu-larly during the monsoon, where high PW levels enhance the hygroscopic growth of aerosols, thereby influencing their scattering properties [21]. Conversely, the lower PW levels during winter contribute to the stabilization of pollution-laden air masses. Regional assessments further indicate that the Indo-Gangetic Plains (IGP) serve as a significant source of pollution, causing elevated AOD in Nepal's Terai region. At the same time, the high Himalayas exhibit lower but gradually increasing AOD due to upslope transport dynamics [19–21]. The principal findings underline that the seasonal patterns of AOD closely correlate with various emission sources, including bio-mass burning, dust, and industrial activities. Shifts in AE reflect variations in aerosol composition [22, 23].

The monthly variation of AOD across various AERONET stations in Nepal reveals that in EVK2 CNR and Jomsom, AOD increased from January to February; however, it was considerably lower from August to December [17, 19]. This is due to the fact that these lo-cations are in the Himalayan region, where winter biomass burning plays a significant role in Jan-uary and February since the village population still uses traditional fuels like wood, straw, and dung for cooking and heating their homes. Because people usually burn organic fuels at relatively low temperatures, which results in incomplete combustion, a high load of particles is released into the atmosphere when this occurs [24]. AOD is lower in these months compared to January and February, as winter begins in December and the days are less cloudy than they are in those months. August saw a decrease in AOD because the month is now mainly characterized by rainy days. Beginning in September marks the end of the monsoon season, when the sky is clear and AOD levels decrease. It was observed that in Pokhara, AOD increases from December to Jan-uary and from January to February. This is the result of traffic and pollution from factories, which also contributes to the winter haze in Pokhara [25]. In Kathmandu, AOD is observed to be increasing in January and December. This is because the maximum of brick kilns is situated in Kathmandu [26]. It is also in these months that the meteorological parameters showed significant fluctuations. A similar pattern is followed in Lumbini. AOD is in increasing order from Febru-ary to April due to land clearing and agricultural fires in various regions of Nepal [27]. AOD was observed to decrease in July due to the

wet days of summer [28]. The summer season in Nepal en-compasses both wet and dry days. On wet days, aerosol is detached due to precipitation. In con-trast, on dry days, the most considerable amount of aerosol is released into the atmosphere due to dry winds and pollution resulting from numerous human activities [29]. The AOD can be seen increasing in Lumbini in May and June because these are the dry months of summer, with no sig-nificant rainfall, and most pollutants are drifted into the atmosphere by this dry wind. However, in Pokhara, AOD is seen to decrease in June because Pokhara is the only city in Nepal where the monsoon starts early and lasts for a long time. As a result, June in Pokhara marks the beginning of the wet summer days.

It has been observed that AOD increases in winter and reaches its maximum in the pre-monsoon season, then drastically decreases during the monsoon. However, it was higher in the post-monsoon season compared to the monsoon in the cases of Pokhara and Lumbini. However, AOD is lower in the post-monsoon period than in the monsoon for EVK2-CNR. These three stations, Pokhara, Lumbini, and EVK2-CNR, were considered for seasonal variation, which encompasses all three geographical regions of Nepal. Lumbini lies in the Terai region, Pokhara lies in the Hilly region, and EVK2-CNR lies in the Himalayan region. From our study, it was observed that Lumbini has the highest aerosol optical depth compared to Pokhara and EVK2-CNR. Also, Pokhara has less AOD than Lumbini but more than EVK2-CNR. The review of the seasonal variation of AOD in EVK2-CNR reveals an increasing trend in winter, which peaks in the pre-monsoon season and drastically decreases in the monsoon, further reducing to a minimum in the post-monsoon season. However, it was higher in the post-monsoon period compared to the monsoon period in the case of Pokhara. This is due to an increase in heating needs, vehicle traffic, and industrial activity, which contributes to winter haze in cities like Pokhara and Lumbini. Pokhara also lies in a region of Nepal where a significant amount of biomass burning occurs, and it is downwind of the Indo-Gangetic plains, contributing to haze during winter and the pre-monsoon season [27]. Brick production in winter also contributes to the emission of aerosols into the atmosphere in Lumbini and Kathmandu. In the case of EVK2-CNR, most of the population relies on traditional fuels, such as wood, straw, and dried dung, for cooking and heating purposes during winter. These organic fuels contribute to a heavy load of particles in the atmosphere.

Additionally, the high Himalayas exhibit higher concentrations during winter and spring (pre-monsoon), minimal concentrations during the summer wet monsoon season, and increasing levels during the post-monsoon [30]. The pre-monsoon season begins with occasional showers, during which the pol-lution contributes to the spring haze. Nepal is considered one of the most polluted countries, with the most degraded air quality. During the pre-monsoon period, AOD was found to be at its maximum in all three stations. Vegetation fires peak in the Himalayan region in April, which has a significant impact on all three sites [27]. It was also observed that during the monsoon, the AOD of Pokhara reaches a minimum because most of the summer months are wet days of the monsoon, and due to heavy rainfall, a

large amount of aerosol is flushed out. However, in the case of Lumbini, summer includes both wet and dry days of the monsoon, due to which only a minimal amount of aerosol is detached, whereas on the wet days. The post-monsoon season begins with the end of the monsoon, resulting in lower AOD compared to other seasons in the context of Nepal [31]. Post-monsoon season is also considered the best season for outdoor activities like trekking, jungle safari, rafting, etc., as you can enjoy lots of green and blue sky Pokhara significantly has lesser AOD than Lumbini but more than ENK2-CNR.

In summary, EVK2-CNR has relatively pristine environments that are occasionally disturbed by pollution episodes. Pokhara and Lumbini, however, are seriously affected by human activities. AOD at Pokhara and Lumbini is much higher than the EVK2-CNR in each month.To acquire a qualitative understanding of atmospheric aerosols and their size distribution, the AOD and Angstrom exponent are often used. The parameter with low and high α values indicates dominance of coarse and fine particles, respectively. During our study period the value of AE is greater than one in all station of Nepal. The greater α may be associated with the secondary fine pollutants generated by photochemical reactions [18].

IV. Conclusion

Finally, it can be concluded that the general trend of AOD with wavelength is inverse. That is, as the wavelength of light increases, the spectral values of AOD decrease, showing a strong dependence at shorter wavelengths and a gradual decline at longer wavelengths. Another interesting fact is that AOD is found to vary with altitude. In general, the value of AOD is found to decrease with increasing height, indicating a comparatively lower influence of anthropogenic activities and other meteorological parameters.

It has been observed that AOD shows substantial seasonal variability, with a maximum value in the pre-monsoon season and a minimum in the Monsoon. A different pattern is observed in the mountainous regions, such as EVK2-CNR and Jomsom, where AOD is at its minimum dur-ing the post-monsoon season. Moreover, the study emphasizes the important role of PW in modu-lating aerosol radiative effects during the monsoon season. The anthropogenic impact is particularly pronounced, driven by emissions from brick kilns, vehicular traffic, and transboundary pollution that contribute to winter peaks. Notably, the unique meteorological conditions in Pokhara serve to highlight localized influences. However, the study is constrained by the limited availability of long-term data and a scarcity of comprehensive investigations that integrate PW with AOD and AE.

References

[1] Prospero J, Charlson R, Mohnen V, Jaenicke R, Delany A, Moyers J, et al. The atmospheric aerosol system: An overview. Reviews of Geophysics. 1983;21(7):1607-29.

[2] Twomey S. Atmospheric aerosols. Elsevier; 1977.

[3] Andreae MO. Climatic effects of changing atmospheric aerosol levels. In: World survey of climatology. vol. 16. Elsevier; 1995. p. 347-98.

[4] Satheesh S, Ramanathan V, Li-Jones X, Lobert J, Podgorny I, Prospero J, et al. A model for the natural and anthropogenic aerosols over the tropical Indian Ocean derived from Indian Ocean Experiment data. Journal of Geophysical Research: Atmospheres. 1999;104(D22):27421-40.

[5] Iqbal M. An introduction to solar radiation. Elsevier; 2012.

[6] Ramachandran S, Rupakheti M. Trends in physical, optical and chemical columnar aerosol characteristics and radiative effects over South and East Asia: Satellite and ground-based observations. Gondwana Research. 2022;105:366-87.

[7] Thapa M, Bhattarai B, Gurung S, Sapkota B, Poudyal KN, Karki NR. Effects of aerosols on the solar radiation in mid-hill of Nepal: a case study in the Kathmandu Valley. International Journal of System Assurance Engineering and Management. 2017;8:54-62.

[8] Regmi KC, Yogendra K, Farias JG, Li L, Kandel R, Yadav UP, et al. Improved yield and photosynthate partitioning in AVP1 expressing wheat (Triticum aestivum) plants. Frontiers in Plant Science. 2020;11:273.

[9] Marinoni A, Cristofanelli P, Laj P, Duchi R, Calzolari F, Decesari S, et al. Aerosol mass and black carbon concentrations, a two year record at NCO-P (5079 m, Southern Himalayas). Atmospheric Chemistry and Physics. 2010;10(17):8551-62.

[10] Menon S, Hansen J, Nazarenko L, Luo Y. Climate effects of black carbon aerosols in China and India. Science. 2002;297(5590):2250-3.

[11] Seinfeld JH, Pandis SN, et al. From air pollution to climate change. vol. 1326; 1998.

[12] Willeke K, Whitby KT. Atmospheric aerosols: size distribution interpretation. Journal of the Air Pollution Control Association. 1975;25(5):529-34.

[13] Jha R, Adhikari B, Singh D. Study of aerosol optical properties at different tourist places of Nepal. Bibechana. 2021;18(1):170-83.

[14] Shaik DS, Kant Y, Mitra D, Babu SS. Assessment of aerosol characteristics and radiative forcing over northwest Himalayan region. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing. 2017;10(12):5314-21.

[15] Eck TF, Holben B, Reid J, Dubovik O, Smirnov A, O'Neill N, et al. Wavelength dependence of the

optical depth of biomass burning, urban, and desert dust aerosols. Journal of Geophysical Research: Atmospheres. 1999;104(D24):31333-49.

[16] Hansen J, Sato M, Ruedy R. Radiative forcing and climate response. Journal of Geophysical Research: Atmospheres. 1997;102(D6):6831-64.

[17] Regmi J, Poudyal KN, Pokhrel A, Gyawali M, Barinelli A, Aryal R. Analysis of aerosol optical depth and angstrom exponents over an AERONET site at Pokhara, Nepal. Bibechana. 2021;18(1):118-27.

[18] Yu X, Zhu B, Zhang M. Seasonal variability of aerosol optical properties over Beijing. Atmospheric Environment. 2009;43(26):4095-101.

[19] Regmi J, Poudyal KN, Pokhrel A, Malakar N, Gyawali M, Tripathee L, et al. Analysis of surface level PM2.5 measured by low-cost sensor and satellite-based column aerosol optical depth (AOD) over Kathmandu. Aerosol and Air Quality Research. 2023;23(1):220311.

[20] Zheng C, Zhao C, Zhu Y, Wang Y, Shi X, Wu X, et al. Analysis of influential factors for the relationship between PM2.5 and AOD in Beijing. Atmospheric Chemistry and Physics. 2017;17(21):13473-89.

[21] Regmi J, Poudyal KN, Pokhrel A, Gyawali M, Tripathee L, Panday A, et al. Investigation of aerosol climatology and long-range transport of aerosols over Pokhara, Nepal. Atmosphere. 2020;11(8):874.

[22] Dumka U, Tripathi SN, Misra A, Giles D, Eck T, Sagar R, et al. Latitudinal variation of aerosol properties from Indo-Gangetic plain to central Himalayan foothills during TIGERZ campaign. Journal of Geophysical Research: Atmospheres. 2014;119(8):4750-69.

[23] Adhikari S. Study of aerosol optical properties at various places of Nepal and a comparison with a region Kanpur in the Indo-Gangetic plain; 2022. Bachelor's thesis, Prithvi Narayan Campus.

[24] Oeder S, Kanashova T, Sippula O, Sapcariu SC, Streibel T, Arteaga-Salas JM, et al. Particulate matter from both heavy fuel oil and diesel fuel shipping emissions show strong biological effects on human lung cells at realistic and comparable in vitro exposure conditions. PloS One. 2015;10(6):e0126536.

[25] Gautam DR. Air pollution: its causes and consequences with reference to Kathmandu metropolitan city. The Third Pole: Journal of Geography Education. 2010:27-33.

[26] Jayarathne T, Stockwell CE, Bhave PV, Praveen PS, Rathnayake CM, Islam RM, et al. Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE): emissions of particulate matter from wood-and dung-fueled cooking fires, garbage and crop residue burning, brick kilns, and other sources. Atmospheric Chemistry and Physics. 2018;18(3):2259-86.

[27] Xu C, Ma Y, Panday A, Cong Z, Yang K, Zhu Z, et al. Similarities and differences of aerosol optical properties between southern and northern sides of the Himalayas. Atmospheric Chemistry and Physics. 2014;14(6):3133-48.

[28] Zhang L, Zhang M, Yao Y. Multi-time scale analysis of regional aerosol optical depth changes in national-level urban agglomerations in China using MODIS Collection 6.1 datasets from 2001 to 2017. Remote Sensing. 2019;11(2):201.

[29] Bhattarai BC, Burkhart JF, Stordal F, Xu CY. Aerosol optical depth over the Nepalese cryosphere derived from an empirical model. Frontiers in Earth Science. 2019;7:178.

[30] Bonasoni P, Cristofanelli P, Marinoni A, Vuillermoz E, Adhikary B. Atmospheric pollution in the Hindu Kush–Himalaya region. Mountain Research and Development. 2012;32(4):468-79.

[31] Marcq S, Laj P, Roger JC, Villani P, Sellegri K, Bonasoni P, et al. Aerosol optical properties and radiative forcing in the high Himalaya based on measurements at the Nepal Climate Observatory-Pyramid site (5079 m asl). Atmospheric Chemistry and Physics. 2010;10(13):5859-72.