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Spatiotemporal analysis of absorbing aerosols and radiative forcing over environmentally distinct stations in East Africa during 2001–2018

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Highlights

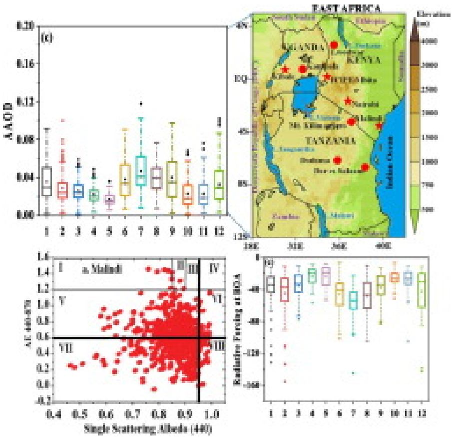
- We have investigated the impact of absorbing aerosols on radiative forcing over East Africa.
- Volume size distribution exhibited a bimodal pattern over the study sites.
- We have studied spatiotemporal changes of DARF observed over the domain.
- DARF was found to be associated with AOD, with the two having direct relation.

Abstract

East Africa (EA) suffers from the inadequate characterization of atmospheric aerosols, with far-reaching consequences of its inability to quantify precisely the impacts of these particles on regional climate. The current study aimed at characterizing absorption and radiative properties of aerosols using the long-term (2001–2018) AErosol RObotic NETwork (AERONET) and Modern-Era Retrospective analysis for Research and Applications (MERRA-2) data over three environmentally specific sites in EA. The annual mean absorption aerosol optical depth ($AAOD_{440\ nm}$), absorption Angstrom Exponent ($AAE_{440-870\ nm}$), total effective radius (R_{Eff}), and total volume concentration ($\mu m^3/\mu m^2$) revealed significant spatial heterogeneity over the domain. The study domain exhibited a significant contribution of fine-mode

aerosols compared to the coarse-mode particles. The monthly variation in $SSA_{440\ nm}$ over EA explains the strength in absorption aerosols that range from moderate to strong absorbing aerosols. The aerosols exhibited significant variability over the study domain, with the dominance of absorbing fine-mode aerosols over Mbita accounting for ~40 to ~50 %, while weakly absorbing coarse-mode particles accounted for ~8.2 % over Malindi. The study conclusively determined that Mbita was dominated by AAOD mainly from biomass burning in most of the months, whereas Malindi was coated with black carbon. The direct aerosol radiative forcing (DARF) retrieved from both the AERONET and MERRA-2 models showed strong cooling at the top of the atmosphere (TOA; −6 to −27 Wm^{-2}) and the bottom of the atmosphere (BOA, −7 to −66 Wm^{-2}). However, significant warming was noticed within the atmosphere (ATM; +14 to +76 Wm^{-2}), an indication of the role of aerosols in regional climate ch
The study contributed to understanding aerosol absorption and radiative characteristics over EA
form the basis of other related studies over the domain and beyond.

Graphical abstract



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Introduction

Atmospheric aerosols have posted significant uncertainty by affecting the global radiation budget directly and indirectly (Twomey et al., 1977; Rosenfeld, 2000; IPCC, 2021). They affect climate directly by scattering and absorbing both incoming shortwave solar radiation and outgoing longwave terrestrial radiation (Charlson et al., 1992; Ramanathan et al., 2001; Myhre, 2009). Aerosols modify cloud quantity, formation, and lifetime, and indirectly change the Earth's outgoing radiation (Albrecht, 1989; Twomey et al., 1977). Additionally, they are known to have detrimental effects on human health and cause visibility degradation (Gauderman et al., 2002; Liao et al., 2015; Yu et al., 2016).

Aerosols have distinct microphysical and optical properties that vary intensely with space and time (Mkoma and Mjemah, 2011; Kumar et al., 2013; Khamala et al., 2018, Khamala et al., 2022). Their microphysical and optical properties are of ultimate significance as they determine their radiative characteristics, and hence information on these properties can be used to assess the Earth's climate at varying scales (Omar et al., 2009; Eck et al., 2010; IPCC, 2013; Che et al., 2018; Moreno et al., 2019; Khan et al., 2020, Khan et al., 2021). On this account, several studies based on ground observations have been carried out to enhance the understanding of their variations and effects on Earth's climate in different domains (Holben et al., 2001; Kaufman et al., 2002; Li et al., 2016).

Ground-based networks have been established worldwide to monitor spatiotemporal aerosol distribution and direct aerosol radiative forcing (DARF). They include the China Aerosol Remote Sensing NETwork (CARSNET; Che et al., 2009); the SKYrad Network (SKYNET; Takamura and Nakajima, 2004); the European aerosol Lidar Network (EARLINET; Pappalardo et al., 2014); the Global Atmosphere Watch Programmer-Precision Filter Radiometers Network (GAW-PFR; Wehrli, 2002; Estelles et al., 2012) and the Aerosol Robotic Network (AERONET; Holben et al., 1998, Holben et al., 2001). Among key ae inversion parameters provided by the AERONET include absorption properties (absorption aeros optical depth (AAOD), Absorption Angstrom Exponent (AAE), single scattering Albedo (SSA), an parameters such as Fine- and Coarse-mode AOD), extinction Angstrom exponent (EAE), volume concentration and effective radius (R_{Eff}, Total, Fine and Coarse).

Extensive efforts have recently been dedicated to monitoring atmospheric aerosols using various techniques ranging from ground-based measurements to satellite remote sensing, and aerosol modeling. For instance, Russell et al. (2010) established that AAE was close to 1 for urban/industrial aerosols over the United States in the East Coast, 1.45 for the biomass-burning type of aerosols, and 2.27–2.34 for the dust aerosols in the Sahara Desert and Asia. Giles et al. (2012) suggested that a combination of Angstrom Exponent (AE) and AAE distinguishes aerosols more effectively than when AAE was used alone. Qin and Mitchell (2009) combined SSA, AOD, and asymmetry factor to identify four episodic aerosol types over the Australian continent and reported that aerosols significantly varied over different AERONET sites. In other related studies, Che et al. (2018) indicated a greater heterogeneity in absorbing particle composition over the CARSNET sites in China, while in terms of sizes, they reported a bimodal size distribution over the study site.

Further, Lee and Chien Wang (2020) determined the impact of biomass-burning on convective systems over the Maritime Continent using the Weather Research and Forecasting model coupled with a chemistry module (WRF Chem). They indicated a significant negative impact on rainfall. Khan et al. (2020) identified key aerosol types from six AERONET sites over Southeast Asia, with biomass-burning and urban/industrial aerosol types as significant contributors to the total AOD. Over South Africa, Kumar et al. (2014) showed the existence of large fractions of fine-mode aerosols during spring that is majorly caused by local anthropogenic pollution or biomass aerosol; while in summer, the study suggested a more significant influence of coarse-mode aerosols that are transported from the Indian Ocean over the region. Boiyo et al. (2018) noted remarkable seasonal heterogeneity in aerosol size distribution over Mbita (in East Africa), significantly influencing various aerosol types.

On the other hand, several studies on radiative characteristics of aerosols at various domains have been outlined to reduce uncertainties in DARF (Sokolik and Toon, 1999; Lyamani et al., 2009; El-Metwally et al., 2011; Esteve et al., 2014; Kumar et al., 2015, Kumar et al., 2016, Kumar et al., 2017; Bibi et al., 2016, Bibi et al., 2017; Adesina et al., 2017; Khan et al., 2020). For instance, Kumar et al. (2016) indicated that DARF over specific AERONET sites in India varied from 21.2 Wm^{-2} to 56.6 Wm^{-2} for clean and polluted environments, respectively. Studies by Esteve et al. (2014) reported mean ARF values of -17 ± 1.0 Wm^{-2} and -2.2 ± 1.3 Wm^{-2} at the bottom (BOA) and top of the atmosphere (TOA), respectively over Spain. Additionally, Bibi et al. (2017) reported significant seasonal heterogeneity in ARF over Pakistan, attributed to seasonal cycles of emission sources and meteorological variables. Whereas Che et al. (2018) observed annual mean DARF over different CARSNET sites of East China as -93 ± 44 to -79 ± 39 Wm^{-2} at

BOA and ~−40 Wm^{-2} at the TOA. At the regional scale, Adesina et al. (2017) and Kumar et al. (2017) indicated significant heating within the atmosphere (ATM) over specific sites in South Africa caused by absorbing aerosols. While related studies by Makokha and Angeyo (2013) used the Coupled Ocean and Atmospheric Radiative Transfer (COART) model and reported invariant DARF over three AERONET sites in Kenya. Recently, Boiyo et al. (2018) reported that an averaged DARF at the Kenyan rural AERONET sites showed a strong cooling at the BOA and significant warming within the ATM.

Several studies over the current domain have reported the existence of fine- and coarse-mode aerosols (de Graaf et al., 2010; Ngaina et al., 2014; Khamala et al., 2018) at monthly and seasonal scales. F[illegible] studies have reported atmospheric warming of varied magnitude (Makokha and Angeyo, 2013; Bo[illegible] al., 2019) at different spatiotemporal scales. However, most of these studies reported their findin[illegible] on total aerosol properties alone, despite a lack of basic knowledge on aerosol absorption properties (e.g., AAOD, AAE, and SSA) and AAOD classification. Also, the investigation of aerosol inversion properties (e.g., Extinction Ångström exponent (EAE), aerosol effective radius (R_{eff}) for total, fine, and coarse aerosols, and volume concentration) is crucial in reducing uncertainties in aerosols is mainly missing (Cheng et al., 2015; Kang et al., 2016; Kumar et al., 2017; Adesina et al., 2017; Bibi et al., 2016, Bibi et al., 2017; Khan et al., 2020).

The present study, therefore, investigated the absorption characteristics of aerosols and estimated the DARF using the optical and microphysical measurements obtained from the AERONET during 2001–2018. The assessment of these properties was evaluated to ascertain the temporal characteristics and discrimination of dominant absorbing aerosol types over distinct locations in East Africa. For this purpose, the temporal changes of DARF (TOA, BOA, and ATM), AAOD, SSA, Total, fine and coarse-mode aerosols were plotted, with the classification of absorbing aerosols from the scatter plots of SSA versus AE. The rest of the present paper is structured as follows: Section 2 gives a brief description of the study area and meteorology, data, and methodology, while results and discussion are provided in Section 3. Finally, the main conclusions from this study are presented in Section 4.

Section snippets

Study domain and meteorology

The study was carried out at selected sites in East Africa (EA), bounded by latitudes (12°S, 5°N) and longitudes (28°E, 42°E). Ethiopia and Sudan border the domain to the North, Somalia and the Indian Ocean to the East, Rwanda, Burundi, and the Democratic Republic of Congo (DRC) to the West, and Mozambique and Zambia to the South. The domain has a multifaceted landscape that spans glaciated mountains, plateaus, and the coastal plain, ranging from sea level to the highest altitude of 5895 m (Mt …

Absorption aerosol optical depth

The annual mean $AAOD_{440}$ measured at the three AERONET sites was analyzed and presented in Fig. 2 and Table 1. A large number of absorbing aerosols were widely distributed throughout the study domain, consistent with the earlier studies by Boiyo et al. (2018), Kumar et al. (2020), Khan et al. (2021). In terms of aerosol loading, $AAOD_{440\ nm}$ was found high over Mbita (0.27±0.17) and Malindi (0.25±0.10), but relatively low over Nairobi (0.15±0.07), with the three sites experiencing large …

Summary and conclusion

In the present study, aerosol optical absorption properties (i.e., single scattering albedo, absorpti aerosol optical depth, and absorption Angstrom exponent), microphysical properties (EAE, Effective radius, and volume concentration), and radiative characteristics (DARF at TOA, BOA, and ATM) have been investigated over three specific AERONET sites located in East Africa. The conclusions drawn from the present study are listed as follows:

1. The $AAOD_{440\ nm}$ generally indicate extensive …

…

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CRediT authorship contribution statement

All the authors have contributed to shaping the ideas and revising the paper.

Geoffrey W. Khamala: Formal analysis, Methodology, Visualization, Investigation, Writing-Original draft preparation. **John W. Makokha**: Conceptualization, Resources, Supervision, Writing-review and editing. **Richard Boiyo**: Validation, Supervision, Writing-review and editing. **Kanike Raghavendra Kumar**: Validation, Funding acquisition, Project administration, Writing-review and editing. …

Declaration of competing interest

The authors declare that there is no conflict of interest in the publication of this work. …

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