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Retrieval uncertainty and consistency of Suomi-NPP VIIRS Deep Blue and Dark Target aerosol products under diverse aerosol loading scenarios over South Asia☆

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ABSTRACT

Retrieval accuracy and stability of two operational aerosol retrieval algorithms, Deep Blue (DB) and Dark Target (DT), applied on Visible Infrared Imaging Radiometer Suite (VIIRS) on-board Suomi National Polar-orbiting Partnership (S-NPP) satellite were evaluated over South Asia. The region is reported to be highly challenging to accurate estimation of satellite-based aerosol optical properties due to variations in surface reflectance, complex aerosol system and regional meteorology. Performance of both algorithms were initially evaluated by comparing their ability to retrieve aerosol signal over the complex geographical region under specific air pollution emission scenario. Thereafter, retrieval accuracy was investigated against 10 AERONET sites across South Asia, selected based on their geography and predominance aerosol types, from year 2012–2021. Geospatial analysis indicates DB to efficiently retrieve fine aerosol features over bright arid surfaces, and for smoke/dust dominating events whereas DT was better to identify small fire events under dark vegetated surface. Both algorithms however, indicate unsatisfactory retrieval accuracy against AERONET having 56–59% of valid retrievals with high RMSE (0.30–0.33) and bias. Overall, DB slightly underpredicted AOD with −0.02 mean bias (MB) whereas DT overpredicted AOD (MB: 0.13), with seasonality in their retrieval efficiency against AERONET. Time-series analysis indicates stability in retrieving AOD and match-up number for both algorithms. Retrieval bias of DB and DT AOD against AERONET AOD under diverse aerosol loading, aerosol size, scattering/absorbing aerosol, and surface vegetation coverage scenarios revealed DT to be more influenced by these conditions. Error analysis indicates at low AOD ($\leq$0.2), accuracy of both DB and DT were subject to underlying vegetation coverage. At AOD$>$0.2, DB performed well in retrieving coarse aerosols whereas DT was superior when fine aerosols dominated. Overall, accuracy of both VIIRS algorithms require further refinement to continue MODIS AOD legacy over South Asia.

1. Introduction

Atmospheric aerosols are multi-component system of solid and liquid particles suspended in air having wide range of sources and properties. Aerosols are essentially quantified by means of Aerosol Optical Depth (AOD), a column-integrated measure of solar extinction by airborne particulates at a given wavelength (Kaufman et al., 2002). Measuring accurate AOD is therefore, extremely pertinent to assess particle pollution and in assessing aerosols' interaction with cloud and radiation (Sayer et al., 2019). Among many techniques, ability to measure airborne particulates using remote sensing data has appeared to be very useful and efficient tool for atmospheric research community (Jethva et al., 2018; Bourgeois et al., 2018; Sorek-Hamer et al., 2020; Singh et al., 2022). Aerosol remote sensing has diverse applications including measuring geospatial distribution of aerosols (Mehta et al., 2018; Mhawish et al., 2021), identifying sources (Zhang et al., 2009), quantifying emissions and to relate atmospheric abundance of aerosols with many of the Earth system processes (Feng and Zou, 2019; Jin et al., 2021; Xin et al., 2023). Once initiated simply for identifying haze pollution during late 1970s from GOES and Landsat satellite retrievals, sensing techniques have evolved significantly in the last two decades. Specific improvements are achieved in two contexts, firstly, sensing

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technology which enable a sensor to measure particle extinction at multiple angles and wavelengths; secondly, maturity in signal retrieval and processing algorithm (Lyapustin et al., 2011a,b; Hsu et al., 2013; Kim et al., 2018; Hsu et al., 2019). Undoubtedly, this led to increase access to many of the quality aerosol products while exposing the complexity of the aerosol-cloud-radiation interaction within the Earth system.

Due to rich diversity in Earth-observing satellites, many aerosol retrieval algorithms were simultaneously developed and are being used to retrieve aerosol optical and microphysical properties from space. Exemplifying, four independent operational aerosol retrieval algorithms like Dark Target (DT) over land (Levy et al., 2013), DT over ocean (Tanré et al., 1997), and Deep Blue (DB) for global land surfaces except snow/ice (Hsu et al., 2004; Hsu et al., 2013) and Multiangle Implementation of Atmospheric Correction (MAIAC, Lyapustin et al. (2011a,b) were developed for Moderate Resolution Imaging Spectrometer (MODIS) sensors on board Earth Observing System (EOS) Terra and Aqua satellite. Retrieval accuracy and contextual biases of these algorithms were periodically reviewed against ground-truth observation or data based on field campaigns. This has subsequently led to refinement in retrieval algorithm and secure accuracy. Likewise, MODIS Dark Target (DT) and Deep Blue (DB) AOD retrieval algorithms have been evaluated globally by Remer et al. (2008), Li et al. (2007) and Sayer et al. (2014) and regionally by Bilal et al. (2016), Mhawish et al. (2017, 2019) and Su et al. (2021, 2022). Attempts were also made to evaluate MODIS 3 km DT AOD over different land covers by Remer et al. (2013) and Munchak et al. (2013). Recently, MAIAC 1 km AOD was extensively validated over diverse geographical regions like in South Asia by Mhawish et al. (2019), South America by Martins et al. (2017), North America by Superczynski et al. (2017) and across North Africa, California and Germany by Falah et al. (2021). Besides, retrieval algorithm for sensors like CALIOP, MISR, OMI were also periodically evaluated (Torres et al., 2013; Kim et al., 2018; Garay et al., 2020; Mhawish et al., 2021). This has helped to fine tune retrieval uncertainty of optically sensitive aerosol properties over diverse land surfaces and environmental scenarios. Surely, accuracy estimation and intercomparison of aerosol retrieval algorithms are integral and imperative step in aerosol remote sensing that boosts confidence in aerosol data products used both in observational and modelling exercises.

In continuation of the legacy of polar-orbiting MODIS and MISR sensors that extends two decades of Earth observation, next generation polar-orbiting operational environmental satellite system is now being functional in active cooperation between NASA and NOAA (Goldberg, 2013). Suomi National Polar-orbiting Partnership (S-NPP) is the first within this Joint Polar Satellite System (JPSS) program that carries Visible Infrared Imaging Radiometer Suite (VIIRS). VIIRS is a next generation scanning radiometer designed to continue delivering time-series of multi-spectral observation at visible and infrared channels (Jackson et al., 2013). It has many identical features of MODIS including similar orbit, major spectral coverage in visible/infrared spectral channels, wide swath and common retrieval processing algorithms. MODIS retrieval has been extensively studied and validated by Remer et al. (2008), Levy et al. (2010) and He et al. (2017), and there are reports of effect of aerosol layering, aerosol types and surface reflectance on MODIS aerosol retrieval accuracy (Mhawish et al., 2017, 2019; Rogozovsky et al., 2021; Su et al., 2022). Retrieval accuracy of VIIRS V1 AOD products is yet to be explored in contrasting geographical and environmental scenarios. Initial findings however, reveal consistency in VIIRS retrievals against AERONET and MODIS AOD (Huang et al., 2016; Superczynski et al., 2017; Sayer et al., 2019; Sawyer et al., 2020; Su et al., 2021; Osgouei et al., 2022). Sayer et al. (2019) in an extensive validation study concluded DB on MODIS and VIIRS retrievals has a stability of 0.005–0.01 AOD per decade. Su et al. (2022) reported DB on VIIRS retrieval has highest accuracy (77%) and consistency (0.027 decade^{-1}) among AVHRR, SeaWiFS, MODIS, and VIIRS over parts of Asia. Sawyer et al. (2020) concluded that DT applied on MODIS Aqua and SNPP VIIRS has lower offset compared to that of MODIS Aqua and MODIS Terra, possibly due to common daytime Equatorial crossing time. Nonetheless, majority of the researchers reported consistency in VIIRS AOD retrievals to continue MODIS legacy till late 2030s (Sayer et al., 2019; Sawyer et al., 2020). However, VIIRS AOD retrievals is also reported to be affected by surface reflectance, model selection and prevailing aerosol types (Jackson et al., 2013; Huang et al., 2016; Su et al., 2021; Sayer et al., 2019). Likewise, Sayer et al. (2019) reported VIIRS DB AOD tend to fall below expected level of error (EE) at AOD >1 with large negative bias for dust dominated region. This necessitates a comprehensive analysis of VIIRS aerosol retrieval algorithm over South Asia (Fig. 1), a highly complex geographical region in terms of surface reflectance and prevailing aerosols (Jethva et al., 2005, 2010; Mhawish et al., 2017; Gautam et al., 2011; Banerjee et al., 2021, 2022). There are many reports of complexity that exists in aerosol system over South Asia which are direct function of associated sources (Singh et al., 2017, 2021; Jethva et al., 2019), meteorology (Upadhyay et al., 2020) and vertical stratification due to tropical convection and boundary layer height (Vinjamuri et al., 2020; Banerjee et al., 2022). Retrieval of AOD over South Asia is often challenging considering the robust spatial-temporal-vertical diversity of aerosols, varying sources and types, especially over the Indo-Gangetic Plain (IGP; Dey and Di Girolamo, 2011; Sayer et al., 2014, 2019; Mhawish et al., 2017, 2019, 2021). Besides, surface reflectance is also sensitive to modify due to land cover changes causing additional uncertainty in retrieval of aerosol optical properties (Gupta et al., 2016; Mhawish et al., 2018).

This research provides first comprehensive analysis of stability and consistency of over-land VIIRS V1 Dark Target (DT) and Deep Blue (DB) retrieval algorithm against AERONET. Initially, intercomparison of AOD retrieval abilities of both VIIRS algorithms were made against MODIS MAIAC C6 retrievals under diverse air pollution scenarios over complex geographical regions. Thereafter, performance accuracy of both VIIRS DT and DB algorithms were evaluated against AERONET retrievals using collocated observations for 10 years. Ten AERONET stations across South Asia were selected considering varying background aerosols types and loading to ascertain representation of aerosol diversity. Retrieval uncertainty was also explored under varying seasons, vegetation coverages, prevailing aerosol loading and types scenarios. Clearly, our analysis would build confidence in aerosol products as retrieved by VIIRS, will assure quality, and extend potential applications of VIIRS AOD retrievals in diverse research fields over South Asia.

2. Study domain, data set and methods

2.1. Description of the study domain

Among globally recognized aerosol hotspots, South Asia is one of the most unique and complex geographical regions having many sources of aerosols and co-emitting species (Sayer et al., 2014; Mhawish et al., 2021). Fig. 1 shows the geographical region of South Asia considered for aerosol retrieval and analysis, including locations of all AERONET stations and outline of the IGP. Within South Asia, major proportion of aerosol mass do exist over IGP (Gautam et al., 2011; Giles et al., 2011; Jethva et al., 2005; Mhawish et al., 2017, 2019; 2021), a long-stretch flat river-basin spanning across from Pakistan, northern India and Bangladesh. The IGP is also a climate sensitive region as many studies depict the greater sensitivity of the IGP to regional climate with associated implications from regional aerosols (Sarangi et al., 2015; Kumar et al., 2017; Srivastava et al., 2019; Jin et al., 2021).

2.2. VIIRS aerosol retrieval algorithms

Suomi National Polar-orbiting Partnership (S-NPP) launched in late 2011 is the first satellite under JPSS program that carries five different sensors to measure Earth system essentially related to radiation balance, air quality (ozone and aerosols) and atmospheric water vapor. Out of

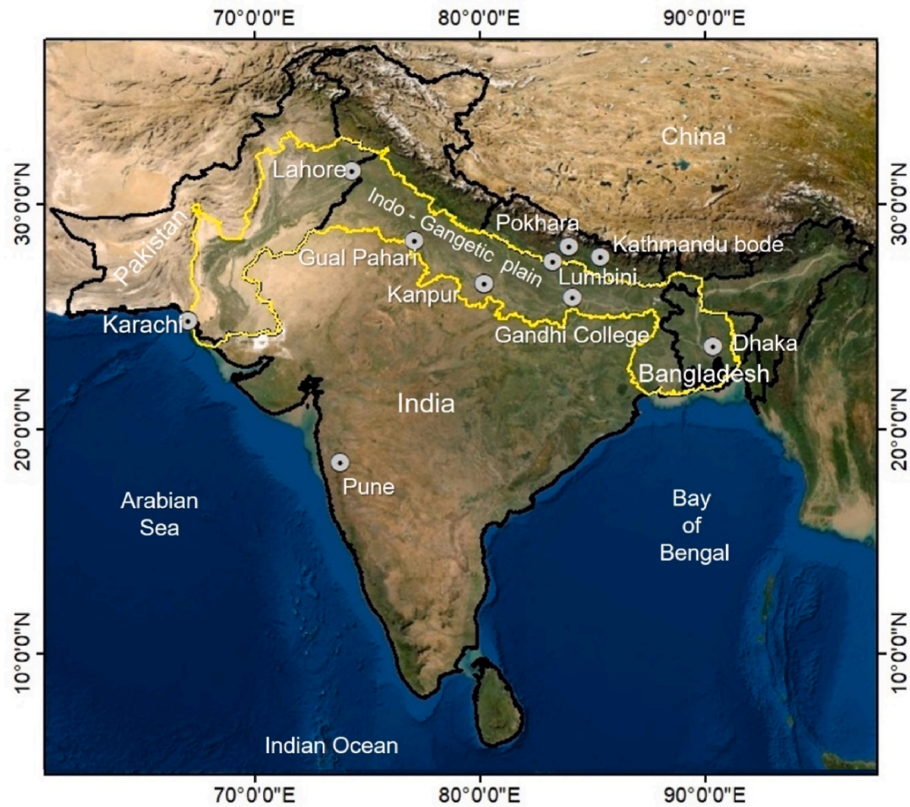

Fig. 1. South Asia study domain selected for aerosol retrieval and spatial analysis including location of AERONET stations (grey bullet) and boundary of Indo-Gangetic Plain (in yellow shade). The background image is a true colour image. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

these, one of the sensor onboard S-NPP and now also in NOAA-20 and NOAA-21, and will possibly be in future JPSS missions is Visible Infrared Imaging Radiometer Suite (VIIRS). VIIRS, a multispectral passive imaging radiometer, is designed and expected to continue the heritage of MODIS/MISR observation for wide range of applications. A detail description of the payload, capability, sensor calibration and algorithm may be found in the works of Jackson et al. (2013) and Cao et al. (2013).

Briefly, VIIRS is a cross-track single-angle scanning radiometer capable of measuring reflected and emitted radiation at 22 spectral bands ranging from 412 nm to 12.488 μm. It has a wide swath (~3000 km), an on-board pixel trimming algorithm to reduce "bowtie" effect, and pixel aggregation and geometric strategy to reduce pixel distortion at swath edge. Among the three types of VIIRS bands, aerosol properties are retrieved from M-band records in 402–1250 nm range. VIIRS AOD is retrieved and processed by many algorithms. Likewise, environmental data records (EDR) is the official L2 product (Jackson et al., 2013), Enterprise Processing System (EPS) algorithm by Laszlo and Liu (2016), VIIRS V1 Deep Blue (DB) AOD (Hsu et al., 2019) based on advanced MODIS based DB algorithm by Hsu et al. (2013), and more recently VIIRS Dark Target (DT) algorithm (Sawyer et al., 2020) that was originally developed for MODIS by Remer et al. (2008) and Levy et al. (2013). In this manuscript, considering the possibility of extending two decades of MODIS aerosol database over South Asia, retrieval accuracy of DB and DT algorithms on VIIRS retrievals was evaluated.

2.2.1. VIIRS V1 deep blue AOD and AE

Initially developed to retrieve aerosol only over bright surfaces like desert and urban landscape using blue wavelength (~412–490 nm) and later extended to vegetated and dark surfaces, VIIRS DB algorithm is capable of providing AOD across globe except over snow and ice (Hsu et al., 2013). VIIRS employs a polarized Vector Linearized Discrete Ordinates (VLIDORT) radiative transfer model (Spurr, 2006) to assess reflected intensity at top of the atmosphere (TOA). It initially measures surface reflectance constraining land cover type and retrieve AOD based on lookup tables (LUT) generated by VLIDORT for different viewing geometry and aerosol scenarios (Hsu et al., 2019). VIIRS DB algorithm is capable of providing AOD both over land and water. It also holds several important enhancements in terms of better estimation of surface reflectance, dust optical model and smoke mask. VIIRS V1 DB AOD has been validated against AERONET AOD by Hsu et al. (2019) and Sayer et al. (2019). Both have reported approx. 80% of retrieval falling within the EE with spatial coverage depending on cloud/snow and polar night. Osgouei et al. (2022) compared MODIS DT, DB and MAIAC AOD, and VIIRS DB AOD against AERONET AOD over Eastern Mediterranean and the Black Sea. Overall, MAIAC and VIIRS retrieval correlate well over land with 81–89% of retrieval falling within EE. Over East China, VIIRS DB algorithm appeared superior over Terra/Aqua MODIS DT and DB retrieval, especially over the vegetated land cover (Su et al., 2021). For this experiment, AOD at 550 nm and ÄngstrÖm exponent (AE) at 412–490 nm following surface data base method was extracted to indicate columnar aerosol loading and qualitative indication of prevailing aerosol types, respectively. VIIRS V1 L2 pixels (AERDB_L2_VIIRS_SNPP) with QA $\geq$ 2 with prefiltered dataset for AOD and AE having 6 km nominal horizontal resolution at nadir was retrieved from 2012 to 2021 (all inclusive). This is to be noted that retrieval accuracy of VIIRS AOD during monsoon was not accounted here for uncertainty related to increase in AOD owing to hygroscopic growth of aerosols under high moisture content (Kim et al., 2007; Altaratz et al., 2013; Mhawish et al., 2019, 2021).

2.2.2. VIIRS dark target AOD

The basic approach in DT algorithm is to retrieve relatively bright aerosols in visible and infra-red wavelength against darker surface. A detail description of the generic DT algorithm is included in Remer et al.

(2008) and Levy et al. (2013). Briefly, DT selects dark pixels within a retrieval window before removing unqualified pixels based on predefined masking and extremity. Spectral reflectance was then corrected for Rayleigh scattering before comparing it with predefined TOA reflectance in LUT, resulting AOD at 550 nm. Surely, there are few exceptions in between MODIS and VIIRS DT algorithm in terms of cloud masking and selection of minimum number of pixels, which is articulately explained in Sawyer et al. (2020). Here, quality-filtered (3) VIIRS DT AOD (AERDT_L2_VIIRS_SNPP) at 550 nm was retrieved over entire South Asia from 2012 to 2021 and over each AERONET station, and was compared against AERONET and corresponding DB retrievals over South Asia.

2.3. AErosol RObotic NETwork (AERONET) aerosol products

AERONET is a sun-photometer network distributed globally and provides consistent post-deployment calibrated and quality-controlled point measurements of spectral AOD and ancillary parameters with a frequency of 5–15 min at several wavelengths in between 340 and 1640 nm. It employs two different algorithms, direct-Sun and Inversion, to infer AOD and its spectral dependence including other aerosol optical properties. AERONET direct-Sun AOD is extensively used as benchmark to evaluate satellite retrievals and model predictions. Direct-Sun AOD has an uncertainty of ~0.01 in the mid-visible range (Eck et al., 1999) while retrieval accuracy varies from ±0.01 (for longer wavelength) to ±0.02 (for shorter wavelength, Holben et al., 1998).

This analysis utilizes latest AERONET Version 3 Level 2.0 direct-Sun AOD at 500 nm over 10 AERONET sites across South Asia for years 2012–2021. AERONET AOD at 500 nm was later interpolated spectrally to 550 nm using AE at 440 nm and 675 nm wavelength pair. Besides, AERONET Angstrom Exponent at 440–675 nm and single scattering albedo (SSA) linearly interpolated at 550 nm. Considering the availability of AERONET and VIIRS collocated aerosol dataset, ten AERONET stations across South Asia were selected (Table S1), namely Karachi (24.87°N, 67.03°E), Lahore (31.54°N, 74.32°E), Kanpur (26.51°N, 80.23°E), Gual Pahari (28.42°N, 77.15°E), Gandhi College (25.87°N, 84.13°E) and Dhaka (23.73°N, 90.40°E), Pune (18.54°N, 73.81°E), Kathmandu Bode (27.68°N, 85.39°E), Pokhara (28.15°N, 83.97°E) and Lumbini (27.49°N, 83.28°E).

2.4. Data processing and evaluation matrices

To compare point based AERONET AOD against spatial AOD measured by VIIRS over ten AERONET stations across South Asia, we followed the satellite-AERONET matchup criteria as discussed in Ichoku et al. (2002). For a scientifically valid matchup, a threshold on number of satellite and AERONET retrievals was considered over an area. Here, a single collocation between VIIRS and AERONET indicate to have a minimum one VIIRS pixel in the retrieval window and at least one AERONET data in temporal scale. A 27.5 km circle centered over each AERONET station was selected as spatial window for VIIRS AOD retrieval. Correspondingly, temporal resolution of AERONET AOD retrieval was computed for a 1-h window (±30 min of VIIRS overpass) for the same collocation. Only the best and quality assured VIIRS retrievals were averaged within the selected window and included for analysis.

Geospatial comparison of AOD retrieval capability of VIIRS DB and DT algorithm was made considering two approaches. Initially, spatial variations in AOD retrieved by two aerosol retrieval algorithms were compared. Further, monthly mean AOD time-series of two algorithms were compared against AERONET AOD to identify consistency between two data sets. Daily retrievals of VIIRS DB and DT AOD were further compared with daily AERONET AOD to measure events when largest discrepancy occurred. Capability of VIIRS DB and DT algorithm to retrieve aerosol signal in few distinct pollution episodes namely intensive smoke aerosols, dust storm, crop-residue burning and forest fire events was explored. Retrieval uncertainty in satellite measurement against AERONET was also evaluated under different aerosol loading (AOD: ≤0.2 and > 0.2) and dominating aerosol sub-type (Angstrom Exponent, α: <0.7; 0.7–1.25; >1.25) scenarios. Further, effect of surface reflectance on VIIRS retrieval accuracy was evaluated considering VIIRS DB daily NDVI product at 6 km resolution as a proxy of the surface cover types (NDVI: <0.2, 0.2–0.4, 0.4–0.6, >0.6). Several statistics were used as evaluation matrices to measure retrieval accuracy of both the algorithms against AERONET. Both mean and median bias was considered to explore synergy between VIIRS AOD and AERONET AOD. Besides, other statistical measures like root mean square error (RMSE), mean absolute error (MAE), mean bias (MB), and the expected error (EE) were also taken into consideration. Here, EE indicate the number of satellite retrieval that falls within one-standard-deviation-confidence interval of AERONET observation, considered to be within the retrieval's expected level of error. For both algorithms, EE of ±(0.05 + 20%) relative to AERONET AOD was considered following Hsu et al. (2013), Sayer et al. (2019) and Sawyer et al. (2020).

3. Results and discussion

3.1. Intercomparison of VIIRS DT and DB AOD

To evaluate the stability, consistency and accuracy of both working VIIRS AOD retrieval algorithms, two mechanisms were followed. Initially, spatial intercomparison of VIIRS DB and DT AOD were made for four pre-identified specific atmospheric events viz. predominance of dust aerosols, smoke in extreme biomass burning days and during winter haze period, and forest fire over complex geographical region. For the spatial intercomparison, VIIRS DB and DT were also compared with Collection 6 Multiangle Implementation of Atmospheric Correction (MAIAC) algorithm applied on Aqua-Terra MODIS retrieval (MCD19). MAIAC has been reported to perform well to distinguish fine aerosol features with high spatial resolution, and has better retrieval accuracy over South Asia compared to MODIS C6 DB and DT products (Mhawish et al., 2019). Secondly, intercomparison of VIIRS DB and DT AOD was explored against ground-truth AERONET AOD across South Asia. Both temporal and location specific comparisons were made following the procedures as mentioned in Ichoku et al. (2002), Sayer et al. (2019) and Mhawish et al. (2017, 2019).

3.1.1. Spatial intercomparison during high air pollution events

South Asia frequently encounters diverse air pollution events, either in short-term or long-term. These events are influenced individually or in combination of conventional aerosol sources like industrial and vehicular emissions, large-scale burning of agriculture residues, burning of municipal waste and forest fire (Banerjee et al., 2021; Singh et al., 2017). To compare VIIRS DB and DT AOD, four specific air pollution scenarios were considered, all under clear-sky condition with quality assured retrieval. Fig. 2 includes VIIRS true-colour images of mineral dust storm (as in June 13, 2018), smoke aerosols emitted from forest fire over complex geographical region having dark background (May 21, 2018), atmospheric haze having thick smoke aerosols across IGP (November 9, 2020), and prevalence of very thick smoke aerosols originating from burning of agriculture residues (October 30, 2016). Both MODIS MAIAC and VIIRS DB algorithms were capable to retrieve AOD over the bright surfaces (Fig. 2a) covered with mineral dust while DT failed to retrieve AOD for high dust aerosols. Presence of mineral dust reduces TOA reflectance at 2.13 μm whereas DT algorithm assumes atmosphere to be transparent at 2.13 μm leading poor VIS-SWIR surface reflectance relation. For small scale forest fire over dark vegetated areas in mountain (Fig. 2b), clearly MAIAC performed better to retrieve fine attributes of aerosol loading due to its superior estimation of surface reflectance and higher spatial resolution (Mhawish et al., 2019). The DT also retrieve AOD successfully with much coarser resolution while DB failed to retrieve minute detail of aerosol emission.

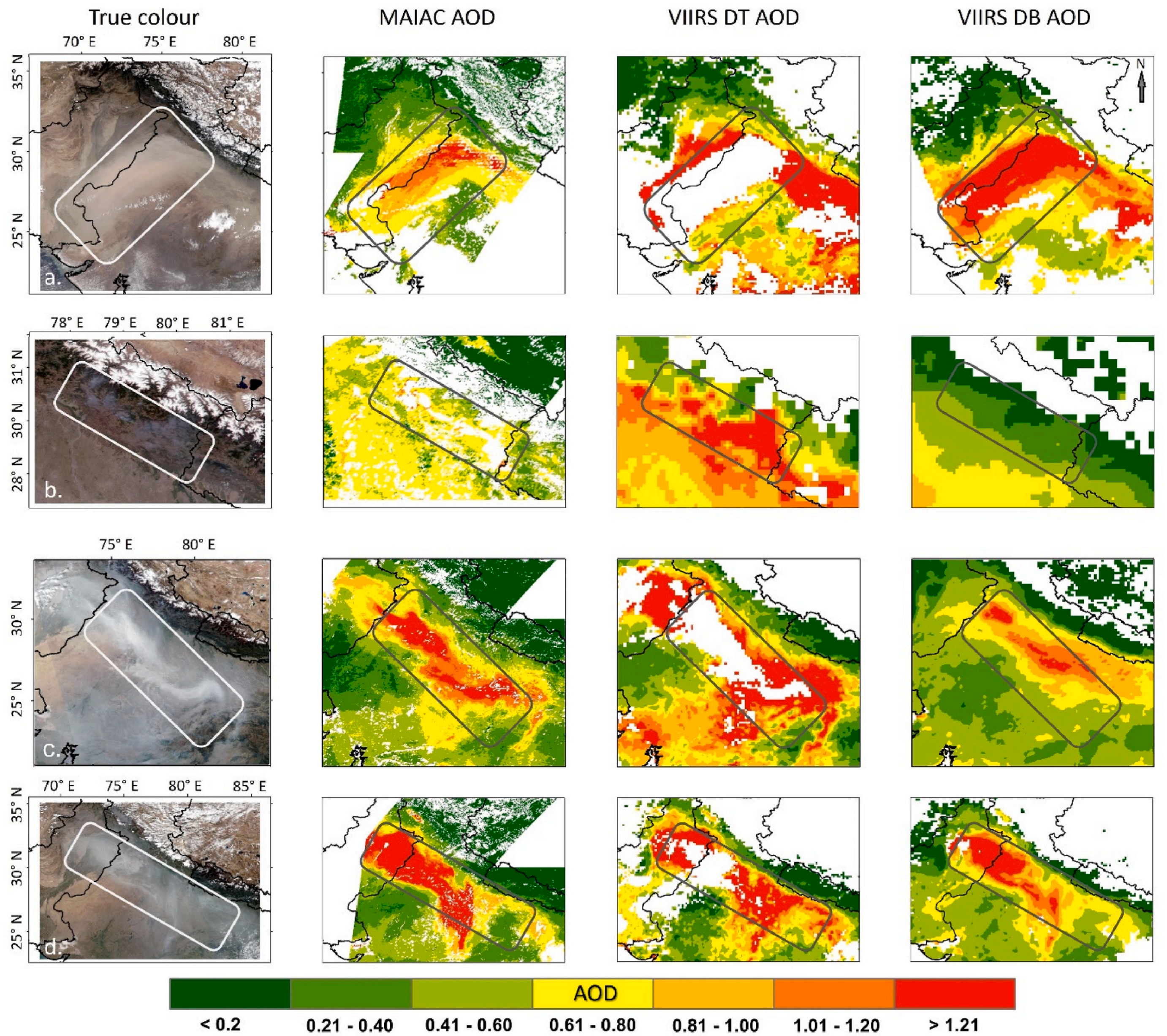

Fig. 2. Spatial comparison between MODIS MAIAC, VIIRS DT and VIIRS DB AOD retrievals for specific events (white/grey enclosure): (a) dust, June 13, 2018, (b) forest fire, May 21, 2018, (c) smoke aerosols, November 9, 2020, and (d) biomass burning, October 30, 2016.

During predominance of smoke aerosols, in both the cases of atmospheric haze events (Fig. 2c) and in extreme biomass burning days (Fig. 2d), both MAIAC and DB were able to retrieve AOD. In contrast, DT failed to retrieve AOD over heavy smoke dominated region which could be attributed to its bright surface or cloud mask. Overall, clear discrepancy was noted on the AOD retrieval ability among the three algorithms. Besides, there was strong variation in the absolute AOD value retrieved by each algorithm as in Table S2, which demand comparative analysis against AERONET .

3.1.2. *Spatio-temporal variations of VIIRS AOD*

A detail analysis was carried out to ascertain regional reliability and discrepancy between VIIRS DT and DB AOD retrieval algorithms using 10-years area-weighted mean AOD over South Asia. Fig. 3(a–b) shows both annual and seasonal mean AOD computed as spatial average of daily mean AOD across South Asia from 2012 to 2021. This section also compares the differences in season specific mean AOD as retrieved by these two algorithms (Table S3). The VIIRS DB owing to its ability to retrieve both over dark and vegetated surfaces has better spatial coverages compared to VIIRS DT which is originally developed to retrieve bright aerosol signal in VIS-NIR band contrasted with dark underlying surface.

Overall, both the algorithms resemble in identifying comparatively high AOD over the Northern India, part of Pakistan and Bangladesh, typically covering the IGP. Area-weighted annual average AOD (±SD) as retrieved by DT over South Asia was 0.47 (±0.19), 27% higher than the DB AOD (0.37 ± 0.16). Among the seasons, both algorithms indicate highest area-weighted mean AOD during pre-monsoon (DB: 0.39 ± 0.14; DT: 0.51 ± 0.18; Table S3). High AOD during pre-monsoon over South Asia are typically associated to re-suspension of mineral dust which remain further suspend in the atmosphere by strong convective wind over the tropics (Banerjee et al., 2022; Eck et al., 2010; Giles et al., 2011; Mhawish et al., 2017). In contrast, aerosol optical depth during post-monsoon and winter primarily regulated by the extent of biomass burning activities over Northern India and Pakistan, local energy practises and meteorology (Singh et al., 2018, 2022; Schnell et al., 2018;

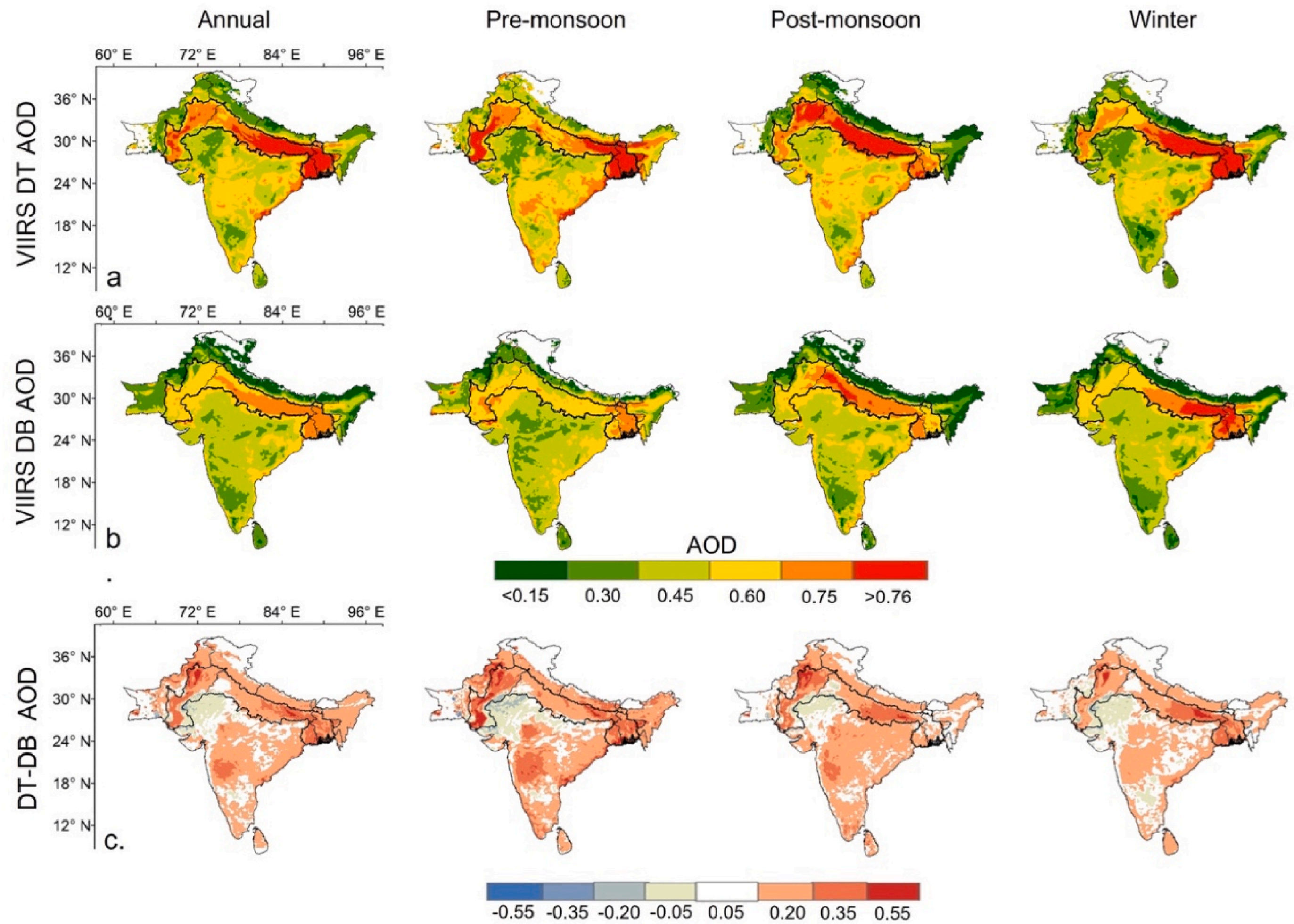

Fig. 3. Spatial distribution of seasonal and annual mean DT (a) and DB AOD (b) over South Asia, retrieved from year 2012–2021. The spatial difference ($\tau_{DT} - \tau_{DB}$) in daily mean AOD is also included (c).

Vinjamuri et al., 2020). Both DB and DT recorded minimum variation in mean AOD between post-monsoon (DB: 0.37 ± 0.18; DT: 0.47 ± 0.22) and winter (DB: 0.37 ± 0.18; DT: 0.45 ± 0.24). Spatial nature of DB-DT agreement also matches well as both algorithms recognize the IGP, especially the lower IGP having highest AOD during majority of the year. The highest positive disagreement (DT-DB > 0.4) was noted over the Indus plan in Pakistan and at lower IGP, regions having dominance of absorbing aerosols, be it fine (smoke) or coarse (dust) particles. Whereas, negative difference (DT-DB > −0.10) was noted especially over the arid region of Thar desert having very high surface reflectance.

Characteristic variation in seasonal AOD was however, different over the IGP having highest AOD during post-monsoon (DB: 0.58 ± 0.14; DT: 0.73 ± 0.17) and winter (DB: 0.58 ± 0.15; DT: 0.72 ± 0.24) compared to pre-monsoon season (DB: 0.52 ± 0.11; DT: 0.68 ± 0.16). Interestingly, VIIRS AOD over the IGP was comparatively low in pre-monsoon compared to post-monsoon and winter, a trend also reported when MODIS- MAIAC, C6 Aqua_DB and C6 Aqua_DT were compared by Mhawish et al. (2019). Overall, a large discrepancy in mean spatial AOD by DB and DT was recorded across South Asia, IGP in particular, which was seasonally consistent and possibly influenced by assumptions in surface reflectance and/or selection of aerosol model. Fig. 3c indicate the geo-spatial deviation in mean VIIRS AOD ($\tau_{DT} - \tau_{DB}$) with respect to seasons. Clearly, positive deviation can be noted over most part of South Asia. In contrast, negative deviation is noted exclusively over western arid region and lower part of Decan plateau, the region having bright surface reflectance.

3.2. Collocation statistics with AERONET

Retrieval accuracy and consistency of VIIRS DB and DT AOD was compared against version 3 Level 2.0 direct-Sun AERONET AOD, spectrally interpolated to 550 nm over 10 sites across South Asia. To collocate VIIRS AOD against each AERONET sites, quality assured DT and DB AOD was retrieved over a 27.5 km circle centered over each AERONET station constraining ±30 min of satellite overpass time. A valid matchup was considered when at least one collocated observation was available for both VIIRS and AERONET. The number of AERONET matchup for both the algorithms did not vary considerably with DB recorded slightly higher retrieval (N, DB: 6310, DT: 6255), especially during pre-monsoon season (DB: 2502, DT: 2422).

3.2.1. Summary statistics over South Asia

Fig. 4 indicates the summary statistics and overall stability of VIIRS-AERONET collocation considering retrievals from all the AERONET stations. Descriptive statistics of VIIRS-AERONET collocation for individual station is included in Table S4. DB (DT) recorded 59% (56%) of retrieval that fall within one-standard-deviation confidence interval of AERONET AOD, accounting unsatisfactory retrieval accuracy over South Asia considering the minimum threshold value of 68%. Retrieval accuracy however, varied slightly with prevailing seasons discussed in the preceding section. Both algorithms come with a modest agreement with AERONET (R; DB: 0.70; DT: 0.78) as correlation (Pearson) varied from 0.53 to 0.82 among the seasons. The Spearman's rank correlation,

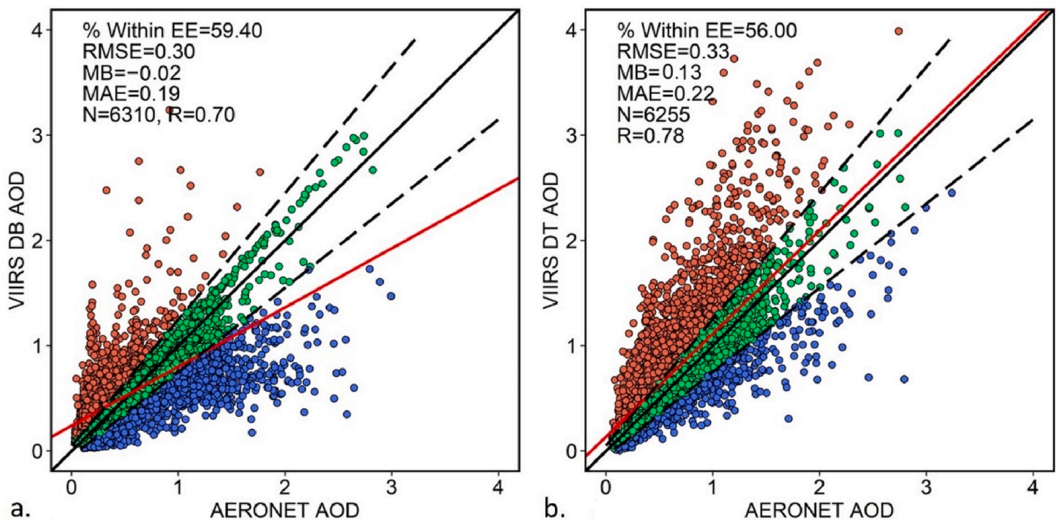

Fig. 4. Evaluation of VIIRS DB and VIIRS DT AOD against AERONET AOD for all sites across South Asia. The solid red line is the regression line, the dash lines are the EE boundary, and the black solid line is the 1:1 line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

which is less sensitive to extreme outliers was also measured. For DB, Spearman's rank correlation varied from 0.58 to 1.00 (overall: 0.68) among the AERONET stations whereas for DT, the range varied from 0.47 to 0.98 (overall: 0.79). Nonetheless, performance accuracy of VIIRS DB algorithm differs significantly from the reported 74% of retrieval within EE by Sayer et al. (2019), although with much lower number of matchups (N: 4410). Su et al. (2022) also explored retrieval uncertainty of VIIRS DB AOD over a part of India and reported ~68% of EE for VIIRS DB. This ambiguity in retrieval accuracy may possibly due to consideration of greater matchups, selection of AERONET stations and retrieval window selected for analysis.

Overall, DB was found to slightly underestimate AOD (MB: 0.02) with high RMSE (0.30) and MAE (0.19) against AERONET retrievals which was in line of the findings of Sayer et al. (2019) and Su et al. (2022). As such, DB algorithm is reported to perform poor over Asia owing to very high aerosol loading and limitations in estimating surface reflectance and aerosol SSA (Sayer et al., 2014; Bilal et al., 2016; Mhawish et al., 2017, 2019). On a separate analysis by Mhawish et al. (2017, 2019) over South Asia, DB applied on MODIS C6 retrievals is reported to have lower EE (Aqua_MODIS: 49%; Terra_MODIS: 53%) with significant underestimation of AOD (RMB: 0.8) and high RMSE (0.2). However, it appears that DB on VIIRS has slight improvement on its performance due to recent adjustments in surface and aerosol models which is however, yet to be implemented in MODIS C6.1.

Incidentally, retrieval accuracy of VIIRS DT AOD has not been extensively investigated over the land surface both on global and regional scale. Over South Asia, DT algorithm on VIIRS retrievals shows high RMSE (0.33) and positive bias (MB: 0.13) indicating significant overestimation of AOD against AERONET. Overestimation of AOD, particularly at low AOD condition, indicate underestimation of the surface reflectance while at high AOD this possibly attributed to uncertainty in selection of aerosol model. Overall agreement of DT AOD with AERONET remained positive (R: 0.78) and significant for almost all the AERONET stations except in Karachi (R: 0.61), Lumbini (R: 0.59) and Pune (0.44) (Figs. S1 and S2). This is perhaps due to relatively small number of matchups over Pune (N: 9) and Lumbini (N: 359) whereas in Karachi, a poor correlation (N: 600; R: 0.61) is indication of underestimation of surface reflectance over bright land surfaces, and uncertainty in aerosol model selection. Nonetheless, DT algorithm on VIIRS retrievals did not achieve satisfactory retrieval accuracy (EE: 56%) over South Asia, in identical to its previous application on MODIS retrievals (Aqua_MODIS: 65%; Terra_MODIS: 64%) over the same geographical region (Mhawish et al., 2019). Globally, a similar trend is reported by Sawyer et al. (2020) for VIIRS DT, having higher bias (RMB: 0.04) compared to MODIS Aqua DT especially at high AOD scenario. A significant correlation with AERONET AOD (R: 0.91) is also reported by Sawyer et al. (2020) with 70% of retrieval falling within EE over land.

3.2.2. Temporal variations in retrieval accuracy

Both VIIRS DB and DT has a spatial and temporal pattern on their retrieval accuracy over South Asia. South Asia experiences seasonal reversal of wind and monsoon which characteristically regulates the local and transboundary air pollution, and associated sources (Banerjee et al., 2021; Mhawish et al., 2021). Meteorology-air pollution interaction is however, much complex over the IGP which results from large heterogeneity in aerosol sources, their contribution and resultant aerosol profile (Jethva et al., 2005; Henriksson et al., 2011; Singh et al., 2017, 2018; Mhawish et al., 2020). Fig. 5 illustrates the seasonal variation of error statistics in VIIRS DB and DT AOD against AERONET AOD whereas descriptive statistics is included in Table S5.

Both algorithms indicate seasonal deviation in their performance with varying trend. Likewise, in terms of retrievals falling within the EE bracket, DB performed best during post-monsoon (62%) and pre-monsoon (60%) seasons whereas, DT was having highest retrieval accuracy (60%) in winter. Retrieval accuracy, bias and RMSE did not change much for DB among the seasons whereas it did indicate a seasonal variation in matchup points mainly due to months considered within each season. The lowest number of DB-AERONET collocation (N: 1599) was noted during post-monsoon with underestimation of AOD (MB: 0.05) due to slight overestimation of surface reflectance and aerosol SSA. While DB underestimated AOD also in winter (MB: 0.04), it slightly overpredict AOD during summer (MB: 0.004) mainly due to underprediction of SSA for prevailing coarse aerosols. Considering all the performance accuracy estimates, it can be stated that DB was the best to retrieve AOD during pre-monsoon and post-monsoon seasons. In contrast, DT performed poorly for both pre-monsoon (EE: 53%; MB: 0.14) and post-monsoon (EE: 54%; MB: 0.12) with high RMSE and overestimation of AOD, referring underestimation of surface reflectance, especially over the dry and bright surfaces. Conversely, its performance accuracy improved during winter (EE: 60%) having strong association with AERONET (R: 0.82) and relatively low mean bias (MB: 0.10), indicating it was winter when DT performed its best. Results matches well with the previous reports of seasonality in DT and DB algorithms on MODIS retrievals over South Asia (Mhawish et al., 2017, 2019; 2021),

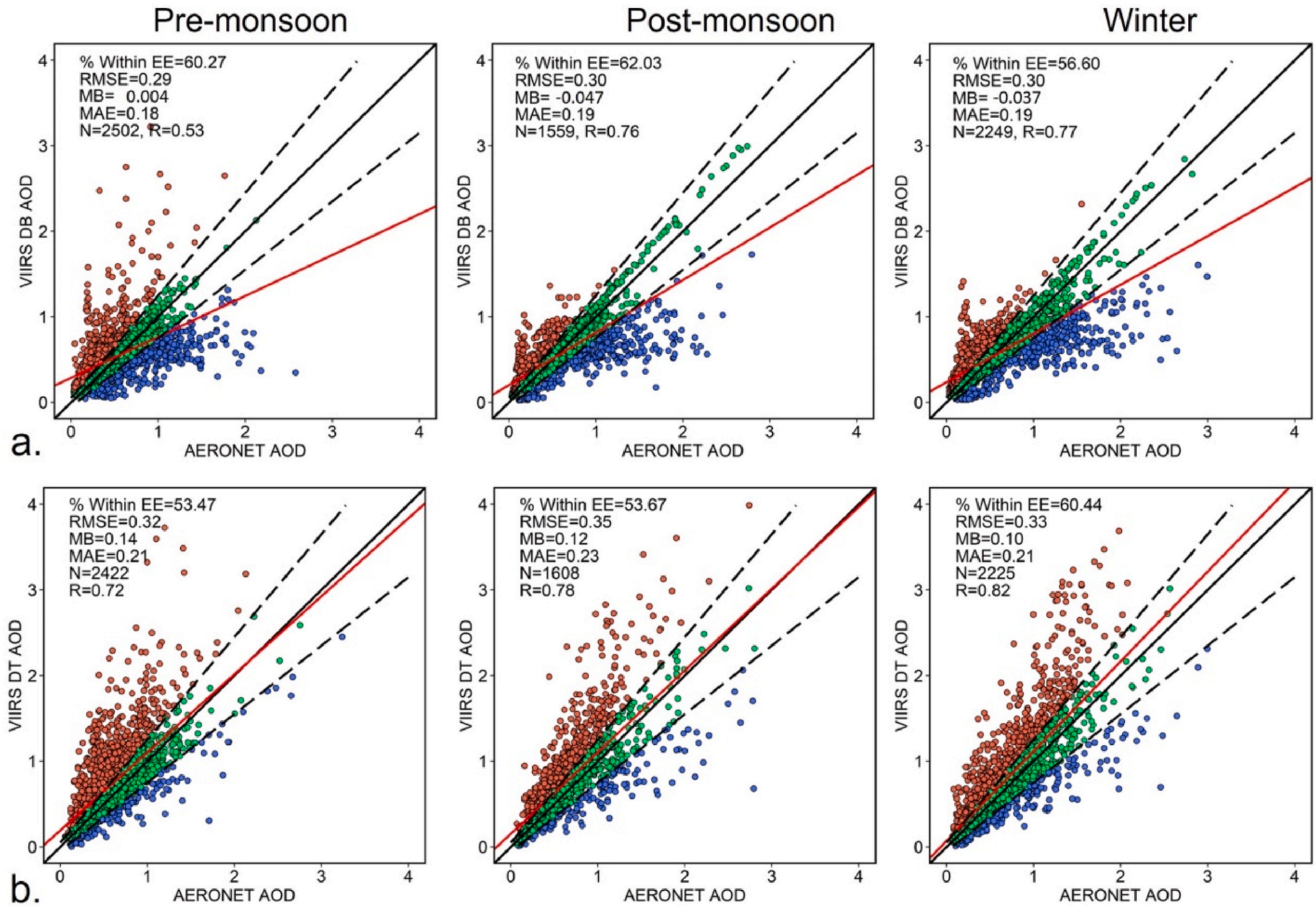

Fig. 5. Seasonal variations of retrieval accuracy of VIIRS DB and DT AOD against AERONET AOD over South Asia. The solid red line is the regression line, the dash lines are the EE boundaries, and the black solid line is the 1:1 line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

indicating importance in considering seasons before selecting an algorithm to retrieve AOD over South Asia.

3.3. Time series analysis

Fig. 6 indicates time-series variation in DT and DB AOD and their departure (DT-DB bias), average RMSE against AERONET AOD, variation in VIIRS-AERONET matchups, and season-specific mean bias in DT and DB AOD against AERONET AOD, all averaged site-by-site thereafter, split into three seasons. Its noteworthy that time-series refer the spatial average of satellite retrievals that falls within the retrieval window centered over each AERONET station and may not necessarily resemble the aerosol climatology based on geospatial mean as in section 3.1.2.

It can be noted that overall DT and DB time series remain fairly smooth as both resemble in identifying seasonal trend in AOD over South Asia. Irrespective of seasons, DT AOD was high compared to DB AOD while the distinction between the two remained maximum (minimum) in pre-monsoon season (winter). The time-series of RMSE (Fig. 6b) was however, has large variations particularly in RMSE for DB AOD which varied from 0.21 to 0.61 (median: 0.32). Incidentally, all the high RMSE values (top 10%) were noted beyond year 2016 among which majority were during post-monsoon and winter owing to small number of extreme AOD values. In contrast, seasonal variations in DT AOD RMSE were less prominent (range: 0.22 to 0.47; median: 0.30), except few comparatively high values (>0.35), without having any specific seasonal trend.

Time series of collocation between VIIRS and AERONET is shown in Fig. 6c. Average season specific matchups did not differ considerably in between DB (∼184) and DT (∼198) while DT indicate a corresponding high median (207) compared to DB (159). Of course, overall retrieval capability of DT algorithm on VIIRS retrieval has increased over South Asia compared to DT applied on MODIS C6, as evident by Mhawish et al. (2017, 2019). The mean bias time series of both algorithms was also explored against AERONET. No particular seasonal trend in mean bias was noted except a high negative bias for DB (MB: 0.37) during post-monsoon and a single instance of high bias for DT (MB: 0.32) in pre-monsoon, possibly influenced by extreme AOD. Clearly, for majority of the period, DB underpredicted AOD except very few cases when slight overestimation of AOD (MB: 0.03–0.08) was noted, all during pre-monsoon season. Conversely, DT always overpredicted AOD without much seasonal deviation in mean bias. This indicate a consistent error in surface reflectance estimation and in assessing aerosol types by both algorithms which is required to be updated over South Asia.

3.4. Consistency of VIIRS AOD under varying aerosol loading, type and surface coverage scenarios

Retrieval uncertainty and consistency in VIIRS DT and DB AOD was further explored under varying aerosol loading, type and land cover scenarios, considering susceptibility of both algorithms applied previously on MODIS C6 (Mhawish et al., 2017, 2019) and VIIRS V1 retrieval (Sayer et al., 2019). In Fig. 7a–b, daily deviation in VIIRS AOD from

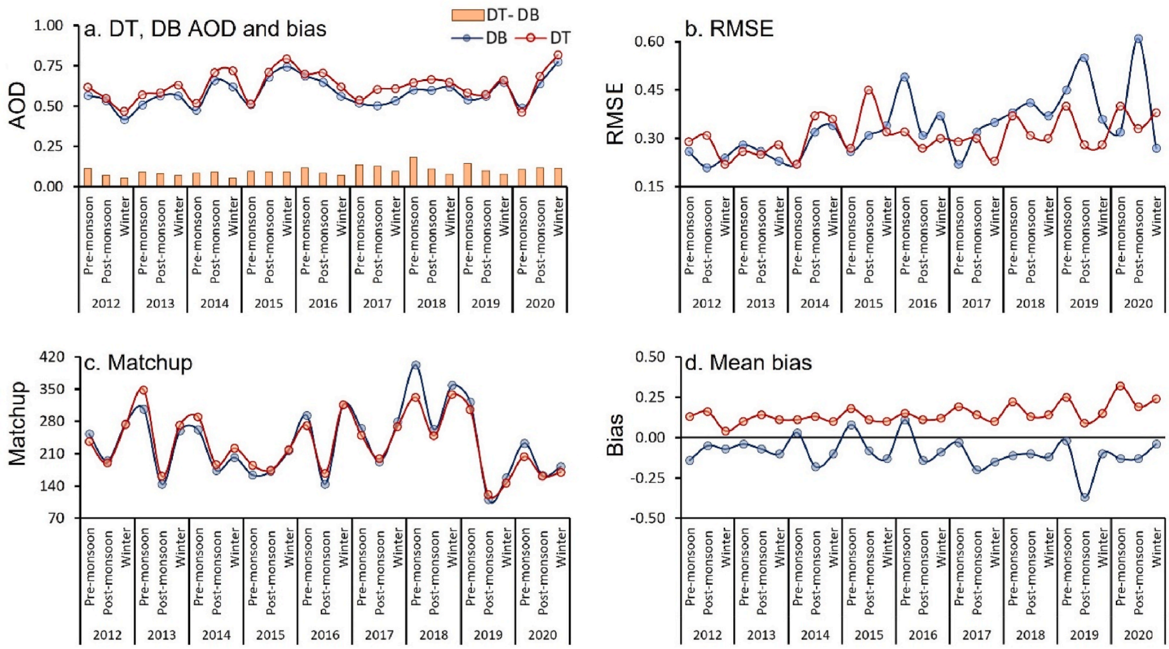

Fig. 6. Time series of (a) mean DT and DB AOD with their deviation, (b) RMSE for 550 nm AOD, (c) number of VIIRS-AERONET collocation and (d) MB against AERONET AOD. Each data is the mean of respective season for the period of 2012–13 to 2020–21.

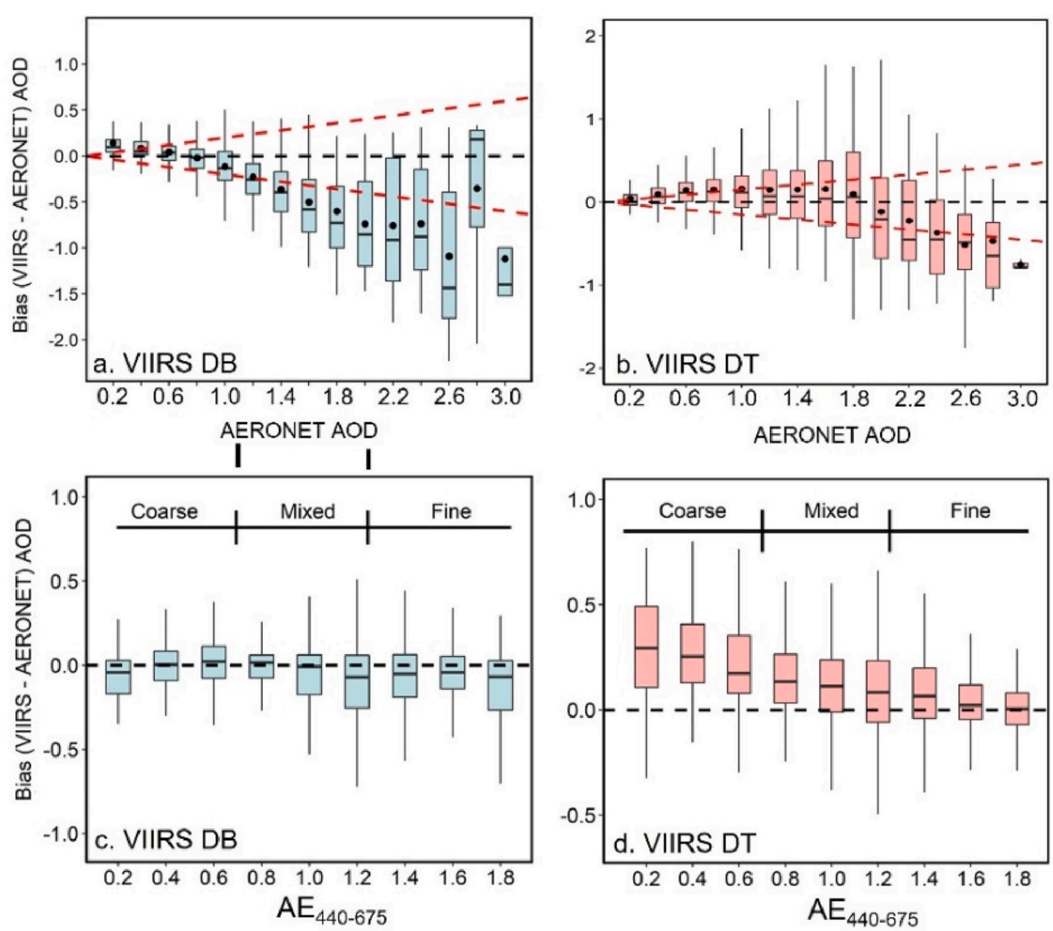

Fig. 7. Consistency of VIIRS DB and DT AOD retrieval bias with respect to aerosol loading (AERONET AOD, a-b) and aerosol size (AERONET $AE_{440\text{-}675}$, c-d). The black horizontal dashed line represents zero bias and the red dotted lines represent the EE. For each box, the middle line, dot, and upper and lower hinges represent the median, mean, and 25th and 75th percentiles, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

AERONET AOD over each station was averaged and plotted against AERONET AOD, each binned into size of 0.2. For AOD <0.5, DB indicates very low positive median bias which however, decreased consistently to a negative as AOD increased above 0.6. The median DB AOD bias was negative in all the scenarios when AERONET AOD was >0.6 while it increased consistently from −0.1 to −1.2 with increase in AERONET AOD. At low AOD scenario, DB bias was negligeable but at high AOD, the assumption related to aerosol properties (like SSA) and overestimation of surface reflectance induced underestimation of AOD. Similarly, for AERONET AOD <1.0, DT median bias remained positive and consequently increased with increasing aerosol loading. For AERONET AOD 1.0 to 2.0, bias remained within the EE bracket but at high AOD (>2.0), DT significantly underestimated aerosol loading possibly due to uncertainty in selection of aerosol model and assumption related to aerosol properties.

The VIIRS DB and DT bias against AERONET was further explored with respect to prevailing aerosol size considering AERONET $AE_{440\text{-}675}$ as a first-order indicator of the optical dominance of aerosol particles (Fig. 7c–d). Prevailing aerosols were classified into three size ranges: coarse e.g. mineral dust (AE≤0.7), mixed i.e., a mixture of both fine and coarse particles (0.7 < AE < 1.25) and fine e.g. primarily anthropogenic including smoke (AE≥1.25). VIIRS DB AOD indicated very low bias varying from −0.1 to 0.1 for both coarse and fine mode aerosols. For fine mode dominated environment, VIIRS DB however underestimated AOD but systematic negative bias did not exceed −0.2. In contrast, VIIRS DT retrievals exhibited large dependence on prevailing aerosols as it showed considerable positive bias for all the aerosol types. Relative bias was significantly positive for coarse-mode dominated environment and gradually reduced as the proportion of fine mode aerosols increased. Overall, DB AOD outperformed DT for both coarse and mixed aerosol types while for fine particles, both DB and DT algorithms exhibited relatively small bias against AERONET.

The effect of heterogenous land surfaces on the retrieval of aerosol optical properties was further evaluated considering NDVI as a proxy for vegetation coverage. Fig. 8a-b indicates the relative bias for both the algorithms against AERONET AOD. It is clear that both algorithms suffered from the error in measuring surface reflectance over South Asia. For arid surface, VIIRS DB was found to slightly overestimate AOD which further reduced to underestimation of AOD as NDVI increased >0.3. However, variation in relative bias for DB AOD was less significant against changing NDVI as it was for DT AOD. VIIRS DT AOD indicated systematic bias against AERONET AOD with changing NDVI, with maximum bias over arid surface (0.23) before decreasing to nil over dense vegetation. This indicates DT measured surface reflectance well over moderate to dark surfaces compared to DB while for relatively bright surfaces, DB performed better.

Prevailing aerosol types and their UV absorption potential is reported to influence retrieval capability of satellite (Su et al., 2022; Mhawish et al., 2019, 2021). Here, existing aerosols were classified based on AERONET SSA and AE, considering their representation to scattering potential of aerosol and aerosol size, respectively (Fig. 8c–d). For AOD<0.2 scenario, aerosols were considered as clean background where accuracy in estimating surface reflectance induce highest uncertainty in measuring aerosol optical property. DB indicated comparatively high positive bias against AERONET when background aerosol dominated, referring error in measuring surface reflectance. VIIRS DB

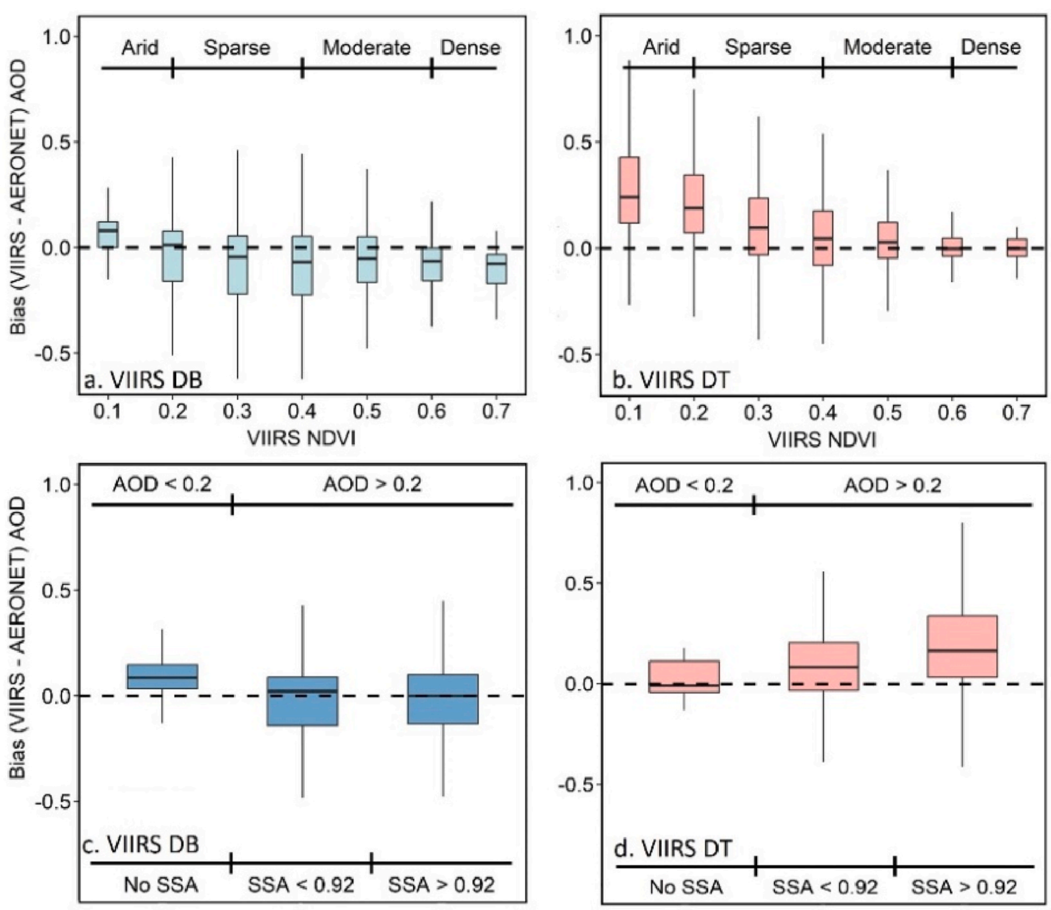

Fig. 8. Consistency of VIIRS DB and DT AOD retrieval bias with respect to surface vegetation coverage (NDVI, a-b) and aerosol type (c–d). The black horizontal dashed line represents zero bias and the red dotted lines represent the EE. For each box, the middle line, and upper and lower hinges represent the median, and 25th and 75th percentiles, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

however, performed well in retrieving aerosol optical depth under absorbing and scattering-dominated aerosol conditions, as also reported by Su et al. (2022). DT was however, found to significantly overestimated AOD for both scattering and absorption-dominated aerosols with consequent increase in relative bias with increase in aerosol SSA. This indicates more systematic error in selection of aerosol model in VIIRS DT algorithm over South Asia and needs updation.

3.5. Accuracy of VIIRS AOD retrievals under varying aerosol type and surface coverage scenarios

To compare the accuracy of both VIIRS AOD retrieval algorithms, VIIRS-AERONET collocated matchups of VIIRS AOD were evaluated against AERONET AOD under different aerosol size and surface vegetation coverage scenarios. Initially, error statistics of both algorithms were assessed under two AOD-AE stratifications: (1) at low AERONET AOD (≤0.2) to assess error associated with measuring surface reflectance, and (2) at relatively high AOD (>0.2) dominated by different sizes of aerosol particles to recognize error in aerosol model selection. In continuation to this, retrieval accuracy of DB and DT AOD was assessed under diverse surface vegetation coverage scenarios considering NDVI as a proxy of surface vegetation in both low (AOD ≤0.2) and high AOD (>0.2) conditions.

Retrieval uncertainty of two VIIRS AOD algorithms reveals contrasting results as shown in Table 1. At low AOD (≤0.2), VIIRS DB indicated poor retrieval accuracy having 35% of retrievals within the expected level of error with low mean bias and high RMSE. In contrast, DT indicated satisfactory retrieval accuracy with 69% of collocations failing within the expected error having high positive bias and low RMSE. Results clearly indicates that at low AOD when surface reflectance primarily contributes to TOA signal compared to aerosols, DB performed poorly while DT underestimated surface reflectance resulting significant overestimation of AOD over South Asia. At high AOD (>0.2), clearly having more matchups, retrieval accuracy of DB improved considerably (EE: 59–72%) but achieved satisfactory accuracy only when coarse particulate dominated (AE<0.7). Relative bias of DB AOD remained low at high AOD conditions with better correlation and moderate RMSE particularly when coarse to mixed aerosols dominated. In contrast, retrieval accuracy of DT was poor for all aerosol types, especially when mixed and coarse aerosols dominated. Although DT did not achieve satisfactory retrieval accuracy at AOD>0.2, its accuracy improved gradually with increase in proportion of fine aerosols with subsequent decline in mean bias and RMSE. Nonetheless, retrieval accuracy of VIIRS DB appeared better at AOD>0.2 for coarse and mixed aerosols dominating scenarios which otherwise indicated error in estimating surface reflectance at low AOD or error in selecting aerosol model at high AOD condition. In contrast, DT performed superior during low AOD, although with relatively high bias, and exhibited better accuracy compared to DB at AOD>0.2 for fine aerosol dominating scenario.

Table 1
Error statistics of VIIRS DB and DT -AERONET comparison of AOD stratified by aerosol type and vegetation coverage.

	AE/NDVI class	N	R	RMSE	MB	EE%
AOD≤0.2	No class	770 (458)	0.38 (0.29)	0.23 (0.14)	0.14 (0.44)	34.7 (69.0)
AOD>0.2	AE<0.7	693 (585)	0.78 (0.67)	0.17 (0.40)	0.00 (0.25)	71.7 (39.7)
	0.7 < AE<1.25	3019 (3057)	0.72 (0.76)	0.31 (0.35)	−0.08 (0.13)	63.3 (52.7)
	AE>1.25	1828 (2141)	0.53 (0.78)	0.33 (0.31)	−0.01 (0.10)	58.7 (62.2)
AOD≤0.2	NDVI<0.2	58 (175)	0.06 (0.34)	0.14 (0.14)	0.11 (0.02)	43.1 (75.4)
	0.2<NDVI<0.4	84 (174)	0.18 (0.24)	0.15 (0.15)	0.05 (0.07)	60.7 (63.8)
	0.4<NDVI<0.6	241 (103)	0.31 (0.41)	0.11 (0.10)	−0.03 (0.04)	65.2 (65.1)
	NDVI>0.6	30 (2)	0.31 (1.00)	0.15 (0.05)	−0.01 (0.05)	83.3 (100.0)
AOD>0.2	NDVI<0.2	1844 (2046)	0.79 (0.75)	0.25 (0.34)	−0.04 (0.11)	70.9 (59.7)
	0.2<NDVI<0.4	2607 (2007)	0.65 (0.75)	0.36 (0.33)	−0.14 (0.13)	58.8 (52.3)
	0.4<NDVI<0.6	1358 (1613)	0.64 (0.77)	0.25 (0.36)	−0.08 (0.15)	52.4 (53.2)
	NDVI>0.6	52 (106)	0.42 (0.79)	0.28 (0.33)	−0.12 (0.20)	44.2 (38.7)

NOTE. Values within the parenthesis indicates DT and outside is for DB.

The sensitivity of VIIRS aerosol retrieval algorithms over heterogenous land surface reflectance was also investigated considering both high (AERONET AOD>0.2) and low (AERONET AOD≤0.2) aerosol loading. VIIRS DB daily NDVI product at 6 km resolution was used as a proxy of underlying surface vegetation and to classify surface coverage into four classes: arid surface (NDVI≤0.2), light/-sparse vegetation (0.2 < NDVI <0.4), moderate vegetation cover (0.4≤NDVI <0.6), and dense vegetation cover (NDVI≥0.6). Table 1 indicates variation in VIIRS AOD retrieval error as a function of NDVI and AOD. Interestingly, in low AOD condition (AOD≤0.2), retrieval accuracy of both VIIRS AOD algorithm increased with increase in vegetation coverage having single exception of DT also registering satisfactory retrieval over arid surface. For almost all the cases, mean bias against AERONET AOD remained minimum (<0.11) with low RMSE (<0.15) and poor correlation. Accuracy of VIIRS DB increased with increase in NDVI with highest accuracy (83%) noted over dense vegetated area. VIIRS DT in contrast, exhibited satisfactory performance both in arid (75%) and dense vegetated surface (100%). At high AOD (>0.2), both algorithms performed poorly as their retrieval accuracy declined with increase in NDVI. Among all, only DB achieved satisfactory retrieval at NDVI<0.2 with high matchups, low negative mean bias and high correlation coefficient. This entails accurate estimation of aerosol optical properties by DB algorithm over arid surface which reduced gradually as vegetation coverage increased. Coarse aerosols are also common over the arid surface which could also result into better performance of DB. In contrast, DT performed poorly (EE<40%) over the vegetated surface (NDVI>0.6), overestimating AOD (MB: 0.20), quite similarly as it performed for MODIS C6 AOD over South Asia (Mhawish et al., 2019).

4. Conclusions

A detail investigation on the performance and accuracy of two operational VIIRS AOD retrieval algorithms were made over South Asia. Both spatial and temporal matrices were used to evaluate retrieval accuracy with emphasis on exploring algorithms' capability to retrieve aerosol optical property during specific pollution events. Retrieval accuracy was also evaluated under varying aerosol loading, aerosol size and surface vegetation scenarios. Spatial intercomparison indicates DB was able to retrieve fine aerosol features over the bright arid surfaces with coarse mineral dust, and over the regions having thick haze and/or smoke aerosols. In contrast, DT was superior to retrieve AOD at small scale forest fire over dark vegetated surface. Both algorithms however, able to reproduce similar trend in spatial AOD across South Asia and the IGP. Discrepancy within DB and DT AOD was lowest in post-monsoon and winter season but increased over the region dominated with absorbing aerosols, and/or with high surface reflectance.

Both VIIRS DB and DT algorithms were unable to satisfactorily retrieve AOD within one-standard-deviation-confidence interval of AERONET AOD. Like its previous applications on MODIS C6, DB on VIIRS retrievals slightly underestimated AOD across South Asia, owing to its limitations in overestimating surface reflectance and aerosol SSA. DT in contrast, overpredicted AOD with high RMSE but with better correlation coefficient over most of the AERONET stations except on arid surface. Overall, DB performed better in pre- and post-monsoon whereas DT outperform DB during winter. DB also indicated low positive median bias for AERONET AOD<0.5 for underpredicting surface reflectance but at AOD>0.6, assumption related to aerosol properties, like SSA, led to considerable underestimation of AOD. Relative bias of DB AOD against AERONET under varying prevailing aerosol sizes and vegetation coverages was comparatively low against DT retrievals. DB indicated low positive bias for clean background aerosols while remained neutral both for scattering- and absorption-dominated aerosol types. Consistency in DT AOD was however, largely dependent on aerosol loading and sizes as it indicates deviation in relative bias with changing AOD, and overestimation when coarse and mixed type aerosols dominated. A systematic positive bias was also noted in DT AOD for all the cases when NDVI was less than 0.5. For scattering and absorption-dominated aerosol types, relative bias in DT AOD increased with SSA indicating systematic error in selection of aerosol model.

Retrieval accuracy of both VIIRS algorithms was also evaluated using VIIRS-AERONET collocated observations under diverse aerosol loading, aerosol type and vegetation coverage scenarios. At low AOD, DB accounted a poor retrieval accuracy possibly due to error in measuring surface reflectance whereas DT performed well achieving satisfactory accuracy but with high bias. At AOD>0.2, accuracy of DB improved gradually as the proportion of coarse aerosol increased whereas DT retrieved its best only when fine aerosol dominated. Both algorithms indicate large uncertainty in selecting aerosol model and measuring optical property, however with varying degrees. We note that at low AOD, accuracy of both algorithms decreased with decrease in vegetation coverage. However, error in assessing surface reflectance over arid surface at AOD≤0.2 was high in DB resulting poor retrievals. At AOD>0.2, retrieval accuracy of both algorithms declined gradually with increase in vegetation coverage, indicating associated error in aerosol model and estimating aerosol optical property.

To conclude, we note error in both VIIRS operational aerosol retrieval algorithms over the South Asia with both DB and DT performing unsatisfactorily in terms of retrieval accuracy, systematic error and mean bias against AERONET. Clearly, both algorithms represent dependence, although with varying degree, on prevailing aerosol size and type while exhibiting uncertainty in estimating surface reflectance and selecting aerosol model. Considering the potential applications of VIIRS sensor in Earth System Science as a successor of MODIS, efforts should be made to improve the retrieval capability and stability of both VIIRS operational algorithms over South Asia. This could potentially help both climate and air quality researchers to explore long-term air quality and relate aerosols feedback on many of the Earth system processes.

Authors contributions

KA: Data curation, formal analysis and interpretation; AS: formal analysis; TB: conceptualization, methodology & interpretation, funding as well as writing & editing manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Link to access data is included in text.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2023.121913.

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