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Role of coarse and fine mode aerosols in MODIS AOD retrieval: a case study

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Abstract

In the present study we have compared the MODIS (Moderate Resolution Imaging Spectroradiometer) derived aerosol optical depth (AOD) data with that obtained from operating sky-radiometer at a remote rural location in South India (Gadanki, 13.45° N, 79.18° E). While the comparison between total (coarse mode + fine mode) AOD shows R^2 value of about 0.71 with a negligible bias of 0.01, if one separates the AOD into fine and coarse mode, the comparison becomes very poor, particularly for fine mode with an R^2 value of 0.44. The coarse mode AOD derived from MODIS and sky-radiometer compare better with an R^2 value of 0.74 and also the seasonal variation is well captured by both measurements. It is shown that the fine mode fraction derived from MODIS data is more than a factor of two smaller than that derived from the sky-radiometer data. Based on these observations we argue that the selection of aerosol types used in the MODIS retrieval algorithm are not appropriate particularly in the case of South India. Instead of selecting a moderately absorbing aerosol type (as being done currently in the MODIS retrieval) a more absorbing type aerosol is better suited for fine mode aerosols, while reverse is true for the coarse mode aerosols, where instead of using "dust aerosols" which is relatively more absorbing, usage of coarse sea-salt particles which is less absorbing is more appropriate.

1 Introduction

Detailed knowledge on atmospheric aerosols is necessary as they play very important role in determining Earth's radiation budget by scattering and absorbing incoming solar radiation and can modify cloud microphysical properties (Haywood and Boucher, 2000; Ramanathan et al., 2001). Their ability to influence Earth's radiation budget as well as their effects on health, air quality and clouds significantly depends on their size (Ruzer and Harley, 2004; Dusek et al., 2006). Aerosol size distribution in turn depends on their production mechanism e.g. particles formed by gas-to-particle conversion are small

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particles whereas particles formed by mechanical actions such as wind lifting of dust, wave-breaking, etc. are bigger in size. Particles which are produced as a result of human activities are in-general smaller in size and the naturally produced particles are in general bigger in size. Hence ability to differentiate particles with respect to their size can provide a mean to quantify the influence of human activities on the abundance of atmospheric aerosols. Separating contributions from smaller and bigger particles to aerosol optical depth (AOD) is a step forward in this direction and can serve as a proxy to study many of the effects discussed above (Kosmopoulos et al., 2008; Lee et al., 2010; Kaskaoutis et al., 2012; Sinha et al., 2012).

Separating contributions from smaller and bigger particles to AOD requires knowledge on size distribution (number concentration as a function of particle radius) and bulk refractive index of particles. There exist methods that can derive these two parameters from spectral observation of AOD and sky-radiances from ground-based sky-radiometer (Nakajima et al., 1996; Dubovik and King, 2000). However, both the size distribution and the refractive index of aerosol are highly variable in space and time. Hence, space borne platforms are necessary to observe aerosol properties over global or continental scale. A considerable progress has been made to estimate AOD from space-borne platforms in past two decades (Martonchik et al., 1998; Ignatov et al., 2004; Remer et al., 2005; Kokhanovsky et al., 2007; Laszlo et al., 2008; Remer et al., 2008; Livingston et al., 2009; Kahn et al., 2010; Tanré et al., 2011; Hsu et al., 2012). However, retrieval of other aerosol properties like size distribution, single scattering albedo or refractive-index remains to be a challenging task. MODIS (Moderate Resolution Imaging Spectroradiometer) on-board Terra and Aqua, MISR (Multi-angle Imaging Spectroradiometer) on-board Terra and OMI (Ozone Monitoring Instrument) on-board Aura satellites are currently operational satellite sensors which provide estimates of AOD over land (Torres et al., 2007; Remer et al., 2008; Kahn et al., 2010). Besides, AOD, there are several other atmospheric parameters that are retrieved from MODIS, of which fine mode fraction of AOD is of particular interest in the present context. However, the fine mode fraction from MODIS is still an experimental product and it is been advised that discretion must be exercised to use it for scientific purpose (Levy et al., 2010).

Algorithm to retrieve fine mode fraction is described in Levy et al. (2007). Inversion of MODIS radiances to AOD requires assumption regarding aerosol type and size distribution. The columnar aerosol size distribution is assumed to be bimodal which is a combination of one fine mode and one coarse mode aerosol. One of the three aerosol types namely "non-absorbing type", "absorbing type" and "moderately absorbing type" is selected for fine mode aerosol based on place and season of the measurement and "dust type" is selected for coarse mode aerosols. Proportion of two aerosol models (types) in terms of AOD at 0.55 µm is selected such that difference between calculated reflectances and the reflectances measured by MODIS at 0.47 µm are zero and the difference at 0.66 µm is minimum. The weighting parameter thus obtained between fine mode and coarse mode aerosols is fine mode fraction of AOD at 0.55 µm (Levy et al., 2007).

There are several factors that affect the retrieval accuracy of fine mode fraction. The weighting parameter (or fine mode fraction) is not determined as a continuous variable but a value from the set of 11 discrete values between 0.1 and 1. There are only four (three fine mode and one coarse mode) aerosol models to select from on a global scale. Inaccuracies in spectral surface reflectance estimates have bearing on spectral AOD retrieval. These are a few of various factors that affect accuracy of MODIS fine mode fraction. There has been a few studies to validate the fine mode fraction using ground-based sky-radiometer data. Here, we mention only those which pertains to latest (C05) collection of MODIS data. Levy et al. (2007) have shown using 780 pairs of collocated data of fine mode fraction spread over 200 AERONET (AErosol RObotic NETwork; Holben et al., 1998) sites that the linear least square fit for MODIS vs. AERONET has slope 1.051, intercept −0.347 and R^2 0.248. An interesting feature of their comparison has been a better match for absolute values of fine mode AOD implying poor determination of coarse mode AOD. The linear least square fit between MODIS vs. AERONET fine mode AOD has slope 0.95, intercept −0.023 and R^2 0.781.

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Possibly Levy et al. (2007) might have used only one or two sites of AERONET in India that existed after 2002 and before 2006. Hence, their result cannot be generalized for South India. Levy et al. (2010) mention that the fine mode fraction (referred as weighting parameter ETA in their article) have little physical validity and primarily reflect algorithm assumption about particle type. This is an important attribute of this parameter and its importance in-spite of less physical validity stands-out as a variable that could be used to diagnose the problem and improve the AOD retrieval. Lee and Chung (2013) have compared the AERONET, MODIS and MISR fine mode fraction and have suggested a method to integrate ground-based observations with MODIS data to improve the accuracy of MODIS fine mode fraction. They also find comparison of MODIS vs AERONET fine mode fraction poorly correlated ($R^2 = 0.19$) if the improvement as one suggested by them not applied. Similar observations have been made for MISR fine mode fraction over land (Lee and Chung, 2013).

Objective of the current study is to examine the dynamics of aerosol size-distribution in terms of fine mode fraction of AOD over a tropical continental and remote location and to validate MODIS derived fine mode fraction with ground-truth data obtained using a sky-radiometer.

2 Site-description and instrumentation

Observations of AOD, columnar size-distribution and column integrated refractive-index are regularly being carried out using a sky-radiometer (Model: POM-01, Prede Co. Ltd., Japan) from a rural and remote site in South India (Gadanki; 13.45° N, 79.18° E). The place has in general a tropical wet climate. It is strategically located in peninsular India where it experiences two entirely different airmass, from south–west during summer (June to August) and north–east during winter (December to February). Climatological mean relative humidity and wind stream lines over South Asia are shown in Fig. 1 for January and July months using NCEP re-analysis data (Kalnay et al., 1996). Location of Gadanki is shown with a white star on the map. Airmass coming from north–east

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direction via Bay of Bengal are expected to be rich in anthropogenic aerosols whereas the airmass coming from Indian Ocean are expected to be rich in natural aerosols (Corrigan et al., 2006; Jayaraman et al., 2006; Suresh Babu et al., 2007; Rajeev et al., 2010).

2.1 Sky-radiometer

The sky-radiometer measures direct solar radiation at one minute interval and sky-radiances at fixed angles with respect to sun at 10 min interval. While direct and the sky-radiances can be used to retrieve AOD in the present study, we have used AOD retrieved using sky radiances only as the AOD retrieval from sky-irradiances does not depend on absolute radiation measurements and hence suitable for long-term studies (Nakajima et al., 1996). The AOD observations are made at 5 wavelengths viz. 400, 500, 675, 870 and 1020 nm. SKYRAD.PACK (Henceforth referred as SKYRAD) software which is used to retrieve AOD and other aerosol optical properties is based on Nakajima et al. (1996). Though the algorithm takes care of cloud contamination using in-built threshold checks, in the present study, all data points are also manually inspected for consistency using log-book entries on cloud conditions. Overall error in AOD retrieval is estimated to be 6 % based on estimates of errors in inputs and their forward propagation in the algorithm. AOD observations over Gadanki are available from April 2008 to March 2011. Same algorithm is used to retrieve columnar size distribution and refractive indices. Kim et al. (2004) using sensitivity analysis have shown that the SKYRAD algorithm is highly accurate for retrieving volume concentration of particles in size range 0.1 to 10 µm. Estellés et al. (2012) have compared columnar volume size distribution by SKYRAD and AERONET and found that on an average they differ by about 13 % for particle radius between 0.15 to 5 µm.

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2.2 MODIS data

The MODIS data used in this study are Level 3 Collection 5 data downloaded from NASA GIOVANNI web-site (http://disc.sci.gsfc.nasa.gov/giovanni last accessed on 25 March 2013). MODIS Level 3 data are quality checked and globally gridded over $1^{\circ} \times 1^{\circ}$ grid resolution. Expected error over land in MODIS AOD is characterised as $\Delta\tau = \pm 0.05 \pm 0.15\tau$, where τ is aerosol optical depth at 550 nm (Levy et al., 2007). There are certain inherent limitations of comparing ground-based AOD retrieval with satellite based AOD retrievals for example a typical sky-radiometer has narrow field of view and hence represents a smaller area, whereas satellite retrievals represent average over large foot print. This limitation can be partly compensated by time averaging ground-based data for a characteristic time for spatial resolution of satellite data (Ichoku et al., 2002). In this study we have compared MODIS $1^{\circ} \times 1^{\circ}$ AODs with sky-radiometer AODs which are averaged over interval of one hour around satellite overpass time. There have been several validation exercises world-wide using ground-based data including our own (Ichoku et al., 2002; Hauser et al., 2005; Remer et al., 2005; Tripathi et al., 2005; Jethva et al., 2007, 2010; Misra et al., 2008; El-Metwally et al., 2010; Levy et al., 2010; Kiran Kumar et al., 2013) and majority of them report that the MODIS AOD compares with ground-based data within the above stated expected error. However, we have reported a significant underestimation of AOD over South India by MODIS (Kiran Kumar et al., 2013). Since our last study, we have collected more data using the sky-radiometer and a comparison of MODIS AODs with ground-truth data is shown in Fig. 2. Regression relationship between MODIS Terra and Aqua is nearly same ($y = 0.75 \cdot x + 0.01$ for Terra and $y = 0.72 \cdot x + 0.026$ for Aqua) with R^2 values 0.71 and 0.77 for Terra and Aqua respectively. We suggest that the underestimation could be because of wrong aerosol model for absorbing properties. MODIS aerosol model for South Asia and particularly for South India does not have sufficiently low single scattering albedo (ratio of scattering to scattering+absorption). It is important to know whether it is a problem with fine mode or coarse mode aerosol model since there are two aerosol models which have significant absorption in visible region but with different size distribution. These are soot and dust aerosols, while soot particles are fine mode aerosols, dust particles are predominantly coarse mode aerosols. This aspect is examined in detail as reported below.

3 Results and discussion

Monthly median values of AOD at 400 and 1020 nm from sky-radiometer are shown in Fig. 3. Lower wavelength AOD values are more sensitive to smaller size particles and higher wavelength AOD values are more sensitive to coarse mode particles and forms the basis for retrieving columnar aerosol size distribution. A systematic seasonal variation of AOD at 1020 nm can be seen with high values close to 0.4 during May to August and low during October to February with values close to 0.1. AOD at 400 nm also has seasonal variation but not as systematic as that observed for 1020 nm. The difference between the 400 and 1020 nm AODs become minimum during June, July and August and maximum during November, December, March and April indicating that there are changes taking place in columnar aerosol size distribution.

As noted earlier columnar size distribution is retrieved from the sky-radiometer measured direct and sky radiances and SKYRAD algorithm in case of ground-based observations. The algorithm is based on Nakajima et al. (1996). Median columnar size distributions obtained for summer and winter periods are shown in Fig. 4. The volume size-distribution is found to be predominantly bi-modal for most seasons with a clear dip between the two modes. Sinha et al. (2012) have studied aerosol size distribution from Hyderabad (17.47° N, 78.58° E) – a major city in South India and have also reported bi-modal size distribution using hand-held sun-photometer. The size distribution ideally should be split into two parts from centre of the dip. However, we have used a fixed radius 0.6 µm to separate fine mode and coarse mode AOD as 0.6 µm is the closest to the dip for most seasons and also it is the convention followed for AERONET data (O'Neill et al., 2003). AODs are re-calculated for each part separately using Mie

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algorithm (Bohren and Huffman, 1983), and the refractive indices and size-distribution retrieved by SKYRAD. Fine mode fraction is calculated as ratio of fine mode AOD divided by total (fine + coarse) AOD. Time series of fine mode fraction by sky-radiometer and MODIS are shown in Fig. 5. A prominent seasonal cycle in fine mode fraction values is evident from the figure. Fine mode fraction from sky-radiometer is as high as 0.9 during winter and never goes less than 0.4. The minimum fine mode fraction observed is during July. High fine mode fraction values are linked to airmasses coming from Indian subcontinent and low values of fine mode fraction are linked to airmasses coming from Northern Indian Ocean. MODIS fine mode fraction also captures the seasonal cycle but systematically underestimates the values by more than a factor of two compared to sky-radiometer results.

Seasonal changes in fine mode fraction can take place when anyone of the two AODs (fine mode AOD or coarse mode AOD) is changing, or both AODs are changing with two different seasonal pattern. In Fig. 6a, time-series of monthly mean coarse mode AOD from MODIS and sky-radiometer are compared and in Fig. 6b, time-series of monthly mean fine mode AODs are compared. Coarse mode AOD has well defined seasonal variation with low values around 0.05 during January and high values between 0.3 and 0.4 from May to July. Peak coarse mode AOD is found decreasing during the three years period from 2008 to 2011 which is an interesting observation, but beyond the scope of the present study. There is a good match between sky-radiometer and MODIS for coarse mode AODs, though the MODIS coarse mode AOD is high in most cases. The decrease in peak coarse mode AOD during three years from 2008 to 2011 is also observed in MODIS data. A scatter plot of daily coarse mode AOD from sky-radiometer and MODIS-Terra is shown in Fig. 7a. There is a good correlation ($R^2 = 0.74$) but the slope of linear square fit is 1.3 with a positive bias of 0.1 which imply a significant overestimation of coarse mode AOD in MODIS data. The match between MODIS and sky-radiometer fine mode AOD is rather poor ($R^2 = 0.44$; Fig. 7b). This is in contrast to the findings of Levy et al. (2007) who have found in general a better correlation for fine mode AODs between AERONET and MODIS data. In the present case

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MODIS significantly underestimates the fine mode AOD and it is the main cause for overall underestimation of AOD as shown in Fig. 2. MODIS fine mode AOD for a large part of the time-series close to 0.05 and barely reaches 0.1 during winter, whereas sky-radiometer fine mode AOD never goes below 0.2. Another difference between MODIS fine mode AOD and sky-radiometer fine mode AOD as evident from Fig. 6b is that a systematic maximum in fine mode AOD in case of sky-radiometer is observed during April–May which is absent in MODIS fine mode AOD. The correlations between sky-radiometer and MODIS coarse mode and fine mode AODs are season dependent. Their seasonal correlations along with un-separated MODIS-Terra AOD are shown in Table 1. The highest correlation (R^2) in case of coarse mode AODs is found during summer with value 0.75 and lowest correlation is found during Autumn with value 0.4. In case of fine mode AODs, the highest correlation is during winter with value 0.56 and nearly zero correlation (−0.07) during summer. Whereas in case of total (fine + coarse) AOD, the highest correlation is found during winter (0.9) and lowest during autumn (0.6). In-spite of good correlation in winter for total (fine + coarse) AOD, relatively poor correlation in coarse mode and fine mode AODs imply that error or mismatch between sky-radiometer and MODIS fine mode and coarse mode AODs are complementary to each other that is cancelling each other effect on total AOD.

Earlier we suggested that cause of error or underestimation of AOD is due to selection of "less absorbing type" of aerosol model in MODIS look-up table for South India (Kiran Kumar et al., 2013). MODIS uses moderate absorbing type of aerosol model and it is same for all seasons in case of South Asia. Here we suggest that both aerosol model that is moderately absorbing type for fine mode and dust type for coarse mode are not the appropriate models for South India. MODIS algorithm uses the radiances measured from the top of the atmosphere to compare with calculated radiances which in turn rely on aerosol type. When a wrong aerosol type is assigned, for example when real aerosols are highly absorbing type but model uses moderate absorbing type of aerosol then the calculated radiances will require less AOD in order to match with observed radiances. Reverse is also true that is if the real aerosol are scattering type

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but model uses absorbing type then model will need higher values of AOD in order to match with observed radiances. Dust is an absorbing type of aerosols whereas region like South India which is far from desert and having ocean on three side will have more sea-salt particles than dust particles. Overestimation of coarse mode AOD by MODIS seems to confirm this fact.

4 Conclusions

MODIS derived AOD values have found significant usage from the aerosol science community as it provides unprecedented spatial and temporal coverage required for a variety of studies. Attempts were also made regularly to compare the MODIS derived aerosol products with the ground-truth data wherever available. In the present study we have compared the MODIS derived AOD data with that obtained from operating a sky-radiometer from a remote rural location in South Asia. While the comparison between the total AOD shows an R^2 value of about 0.71 with a small bias of 0.01, if one separates the AOD into fine and coarse mode, the comparison becomes very poor, particularly for the fine mode, with an R^2 value of 0.44. The coarse mode AOD derived from MODIS and sky-radiometer compare better with an R^2 value of 0.74 and also the seasonal variation is well captured by both measurements. It is shown that the fine mode fraction derived from MODIS data is more than a factor of two less than that derived from the sky-radiometer data. Based on these observations we argue that the selection of aerosol types used in the MODIS retrieval algorithm is erroneous particularly in the case of South India. Instead of selecting a moderately absorbing aerosol type (as being done currently in the MODIS retrieval) a more absorbing type aerosol is better suited for fine mode aerosols, while reverse is true for the coarse mode aerosols, where instead of using “dust aerosols” which is relatively more absorbing, usage of coarse sea-salt particles which is less absorbing is more appropriate.

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Table 1. Coefficient of determination between sky-radiometer and MODIS-Terra.

	MODIS-Terra Unseparated AOD		MODIS-Terra Coarse mode and fine mode AOD		
Seasons	N	R^2	N	R_C^2	R_F^2
Spring (Mar, Apr, May)	153	0.661	142	0.59	0.43
Summer (Jun, Jul, Aug)	61	0.721	58	0.75	−0.07
Autumn (Sep, Oct, Nov)	70	0.622	66	0.40	0.37
Winter (Dec, Jan, Feb)	97	0.899	88	0.47	0.56
Overall	381	0.712	354	0.74	0.44

R^2 – for unseparated AOD R_C^2 – for coarse mode AOD R_F^2 – for fine mode AOD AOD values are at 550 nm.

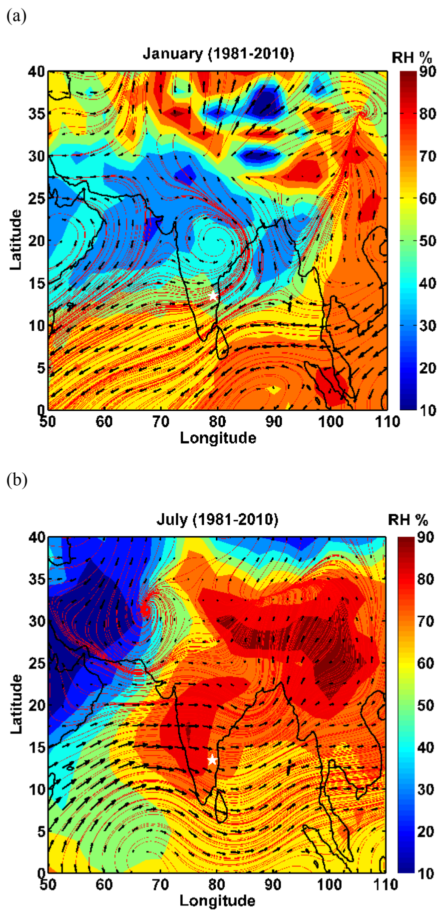

Fig. 1. Climatological wind stream line overlaid over climatological relative humidity over South Asia based on NCEP reanalysis data.

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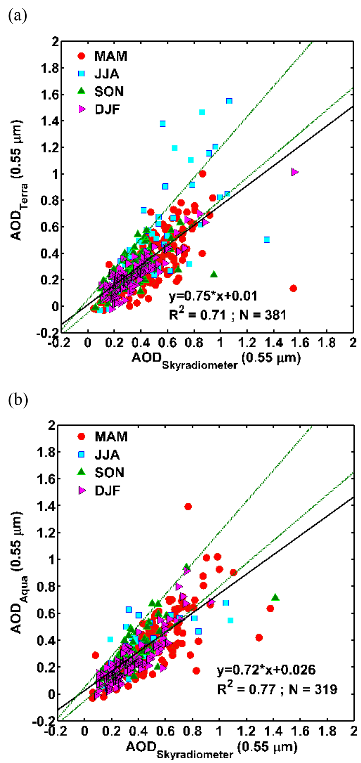

Fig. 2. Scatter plot **(a)** between MODIS-Terra and sky-radiometer AOD and **(b)** between MODIS-Aqua and sky-radiometer AOD over a rural location in South India (Gadanki 13.45° N, 79.18° E). Sky-radiometer AODs are averaged for one hour around satellite overpass time. Satellite AODs are averaged over 1° × 1° grid-box over Gadanki. Black line in both the figures show the linear fit for which the equation is shown while green lines show the boundary of expected errors in MODIS AOD over land (Levy et al., 2007).

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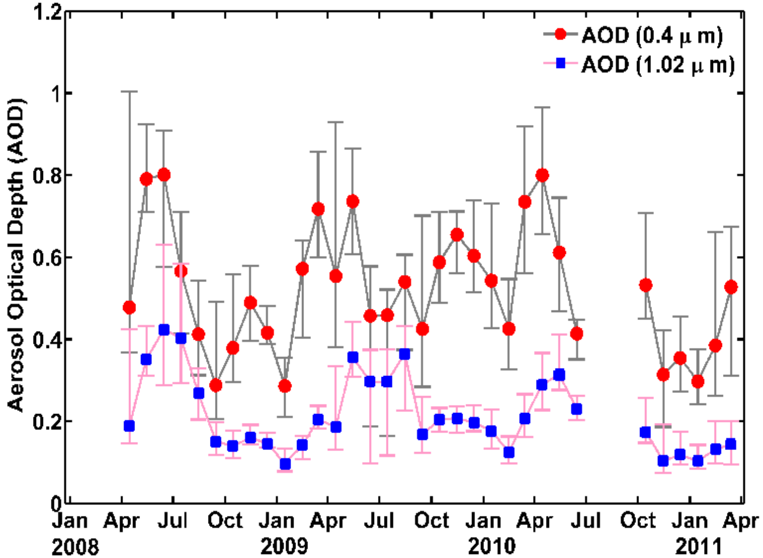

Fig. 3. Monthly median aerosol optical depth at 400 nm and 1020 nm derived from sky-radiometer data. Vertical bars are interquartile range.

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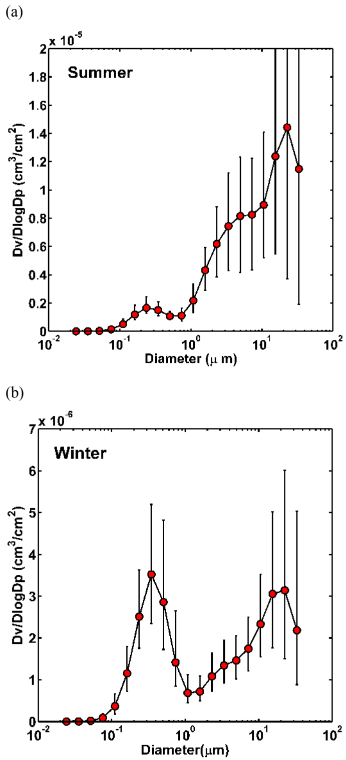

Fig. 4. Median columnar volume-size-distribution over Gadanki for **(a)** summer and **(b)** winter derived from the direct and sky-radiance measurements using the sky-radiometer. Vertical bars are interquartile range. Values of bar in summer plot going beyond y-axis range are 3.27×10^{-5}, 8.21×10^{-5} and 1.11×10^{-4} for radii 7.73, 11.31 and 16.54 µm.

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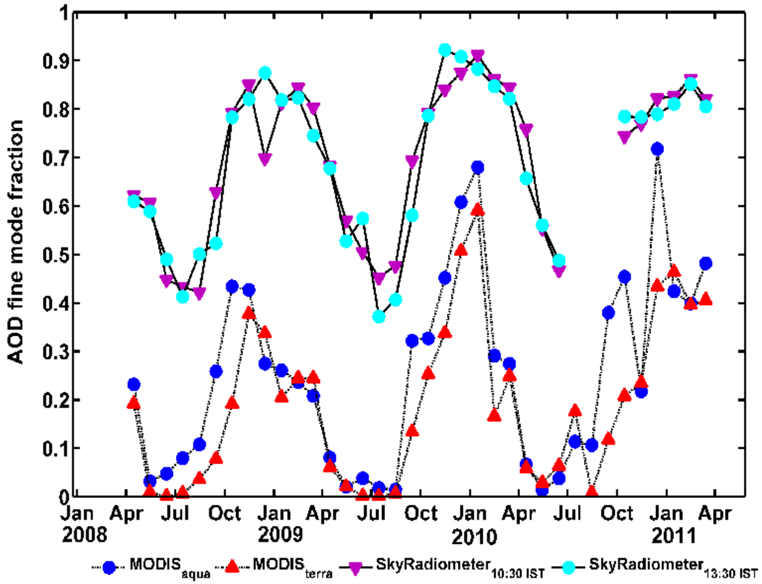

Fig. 5. Time series of monthly mean fine mode fraction over Gadanki derived using sky-radiometer data are compared with that given by MODIS Terra and Aqua payloads.

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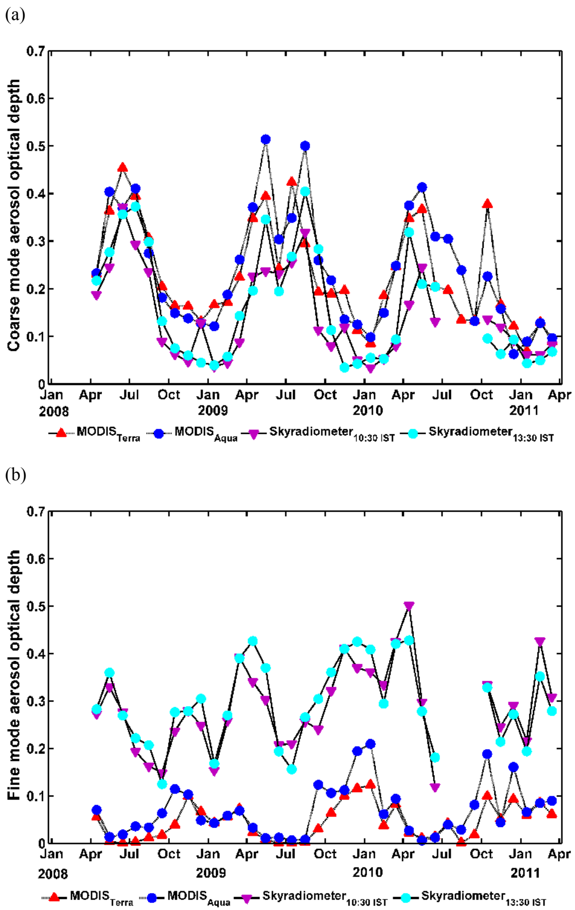

Fig. 6. Time series of monthly mean fine mode and coarse mode AODs obtained from sky-radiometer data over Gadanki are compared with that from MODIS Terra and Aqua payloads.

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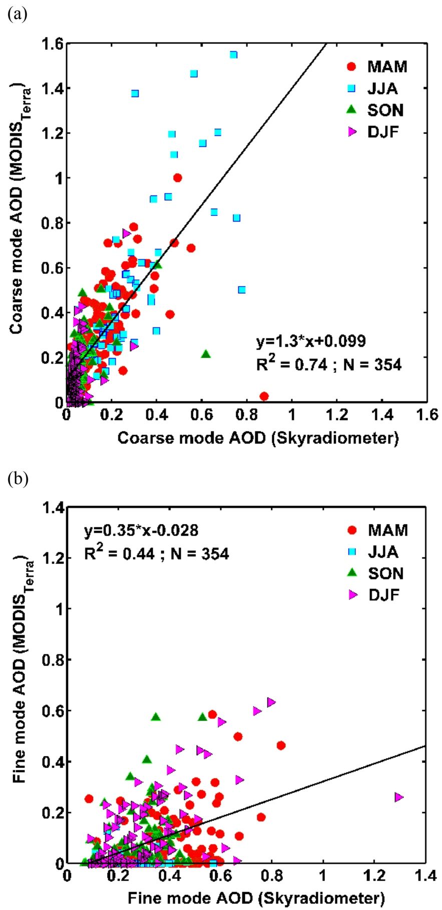

Fig. 7. Scatter plot of MODIS vs sky-radiometer AOD for **(a)** coarse mode and **(b)** fine mode.

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