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A case study on biomass burning aerosols: effects on solar UV irradiance, retrieval of aerosol single scattering albedo

A. Bagheri[1], **B. Kjeldstad**[1], **and B. Johnsen**[2]

[1]Norwegian University of Science and Technology (NTNU), Department of Physics, 7491 Trondheim, Norway
[2]Norwegian Radiation Protection Authority, 1332 Oslo, Norway

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Correspondence to: A. Bagheri (asadollah.bagheri@phys.ntnu.no)

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Abstract

The aerosol optical depth (AOD) from biomass burning aerosols from eastern Europe was measured in Trondheim, Norway (63.43° N , 10.43° E) in May 2006. The event was observed as far as the Arctic. In the first part of this paper, the surface measurements of direct and global UV radiation (and retrieved AOD) are used to simulate the data using a radiative transfer model. Measured and simulated data were used to study the effect of biomass aerosol on the levels of surface UV radiation. We found reductions of up to 31%, 15% and 2% in direct, global and diffuse surface UV irradiance (at 350 nm, SZA=50°±0.5°) as compared to typical aerosol conditions. In the second part of our study, surface measurements of global and direct irradiance at five wavelength in UVB and UVA (305, 313, 320, 340 and 380 nm) were coupled with a radiative transfer model to produce values of aerosol single scattering albedo, ω. The aerosol single scattering albedo for biomass aerosols is compared to ω for background aerosols. The values of ω for biomass aerosols were 0.76 at 305 nm, 0.75 at 313 nm, 0.79 at 320 nm, 0.72 at 340 nm and 0.80 at 380 nm.

1 Introduction

An understanding of the effect of aerosols on UV radiation reaching the Earth's surface is important for many ongoing climate and biological studies. Due to the wavelength dependent scattering and absorption characteristics of aerosols, the effect of aerosols on UV radiation is a complex matter. Moreover, the effects of long-term and short-term changes in atmospheric aerosols should be separated. Earlier studies indicate that the magnitude of the net aerosol effect can be large. Aerosols can reduce the UV flux at the surface by more than 50% (Krotkov et al., 1998) and are highly variable, depending on the number of particles and their physical and chemical properties. Typical values for this reduction associated with biomass burning aerosols range from 15 to 35% (e.g. Latha et al., 2005; Kalashnikova et al., 2007). Usually particles tend to reduce the sur-

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face UV irradiance. However, scattering by non-UV-absorbing particles (background aerosols) can increase the UV exposure on non-horizontal surfaces due to additional scattering from low angles (Dickerson et al., 1997). Liu et al. (1991) estimated that in non-urban areas of the industrialized countries the amount of biologically active solar radiation (UVB, 280 to 315 nm) reaching the surface has decreased in the range of 5 to 18% since the industrial revolution, primarily due to aerosols formed from emissions of sulfur dioxide (SO_2). Kylling et al. (1998) found that surface UV irradiance measured at two sites in Greece under non-cloudy conditions were reduced compared to aerosol-free conditions by 5 to 35%, depending on the aerosol optical depth (AOD) and single-scattering albedo. Very few studies have been done on the effects of different types of aerosols on UV radiation. Balis et al. (2004), using a co-located Raman lidar system and spectral UV-B irradiance measurements, have shown that for the same AOD and ozone column, the surface UV-B irradiance may differ by up to 10%, which was attributed to differences in aerosol type. Modeling studies (Diaz et al., 2000) have suggested that aerosol vertical (height) distribution can also effect surface UV irradiance by 25% for optical depths of 0.5 at visible wavelengths. Due to the combined involvement of different aerosol parameters in controlling UV levels, it is difficult to determine accurately the role of each parameter. Nevertheless, it is important to understand the effects that aerosols have on surface UV irradiance.

The atmosphere in the middle of Norway has a low turbidity ($\beta \sim 0.05 - 0.07$). However, in April and May 2006, a large number of fires occurred in western Russia, Belarus and Ukraine. The biomass aerosols from these fires were transported to the northern part of Norway due to regional-scale transport processes. The event provides the opportunity to investigate the effect of biomass aerosol on UV radiation. Stohl et al. (2007) presented a detailed analysis of this episode using various measurements of air pollution in the European Arctic. Arola et al. (2007) studied the effects of this episode using MODIS and AERONET data. They found reductions up to 35% in noon-time surface UV irradiance (at 340 nm) as compared to typical aerosol conditions in southern Finland.

In this study, we concentrate on the effects of this episode on aerosol optical properties, ω, and surface radiation levels in mid-Norway. First, we investigated the effect of biomass aerosol by combining direct and global surface irradiance measurements at Trondheim, radiative transfer modeling and information on the aerosol conditions. Our analysis includes measurements of direct and global UV radiation and simulated data, spectral data would highlights the wavelength dependence of the aerosol effect. In the second part of this paper, surface measurements of global and direct irradiance at five wavelength in the UVB and UVA (305, 313, 320, 340 and 380 nm) were coupled with a radiative transfer model to produce values of the ω. We use the retrieved aerosol optical depth for investigating the effects of biomass burning aerosols on ω.

2 Methodology

2.1 Experimental setup

The measurement site (63.43°N , 10.43°E, Trondheim, Norway), is a solar platform on the roof of the university building, 70 meters above see level, in a coastal urban region. The solar platform consists of several instruments for the purpose of remote sensing, including one high resolution double monochromator and one multichannel moderate bandwidth filter radiometer (GUV) belonging to the Norwegian UV network. The double monochromator (Bentham DM150 spectroradiometer), measures direct UV irradiance in the range from 290 to 550 nm in steps of one nm. The double monochromator has a spectral response function of 1.0 nm nominal full width at half maximum (FWHM). The spectroradiometer was calibrated against a 1000 W standard lamp traceable back to NIST. Wavelength calibration was performed using emission lines from a low pressure mercury lamp. In addition, further wavelength adjustments were made on all data using the software package for wavelength SHIft and quality Control of solar spectral UV-measurements (SHICrivm, Slaper et al., 1995).

A multichannel, moderate-bandwidth, filter radiometer, GUV, was also used to mea-

sure global irradiance in parallel with the spectral direct measurement. The GUV is manufactured by Biospherical Instruments, USA. It consists of a teflon diffuser, interference filters and photodiodes as detectors. The instrument has 5 channels with central wavelengths at 305, 313, 320, 340 and 380 nm. The bandwidth of the filters is approximately 10 nm (FWHM). Details about the instrument are given elsewhere (Booth et al., 1994; Bernhard et al., 2005). The GUV radiometer was calibrated in units of spectral irradiance using international intercomparison of multiband filter radiometers that was hold at Oslo in 2005 (Johnsen et al., 2007). The methodology used to convert response-weighted GUV measurements to spectral irradiance at the nominal wavelengths and at a bandwidth 1.00 nm is similar to the methodology used for converting broad-band UV measurements to erythemally effective irradiance, and the details of the procedure are described by Webb et al. (2007). Step one involves corrections for tha long-term change in detector responsivity. The second step involves a conversion function based on RT-simulations that accounts for the SZA and total ozone dependent changes in the signal output for a radiometer with a finite bandwidth and a radiometer with 1.00 nm bandwidth. Finally a cosine correction based on the SZA and cloud optical depth is applied.

In this study, the direct solar beam was measured with the direct input optics of the spectrometer and the corresponding channels to GUV's data within one minute average were selected. The instantaneous signals from GUV were one minute averaged to calculate the global irradiance. For the purpose of this study, two special days were chosen, 24th of April as an average normal day in 2006 and 9th of May where the effect from biomass aerosol on AOD are clearly pronounced as reported earlier by Stohl et al. (2007). To ensure cloudless conditions at the given solar zenith angle (SZA), each day's global irradiance was plotted against time of day. If the characteristic bell curve of the irradiance plot was seen as uninterrupted for some time before and after the given SZA for the day, that time and SZA was interpreted as cloudless and usable. Figure 1 (upper pannel) shows the global irradiance for all channels from the GUV for the two days. The smoothness of the global irradiance as function of time of day indicate that

the weather in general was sunny during two days of interest. Thus, uncertainty due to cloud was a minimum.

2.2 Radiative transfer modeling

In order to investigate the effect of biomass burning aerosols on the surface irradiance of UV radiation, we have used retrieved AOD from spectral direct measurements together with the LibRadTran package for radiative transfer modeling (Mayer and Kylling, 2005). Measured data (AOD) from one normal day (24th of April) and a day with high values of AOD due to biomass aerosol (9th of May) were used as input for the radiative transfer modeling. However, to simulate the aerosol effects, one has to make further assumption about the aerosol classes, components and mixing ratio in practical aerosol models (Shettle, 1989; Koepke et al., 1997 and Levoni et al., 1997).

For model calculations, air pressure and temperature profiles were taken from the "subarctic summer" atmosphere. The extraterrestrial solar spectrum used is based on Atlas Plus Modtran and the radiative transfer equation was solved with the Discrete Ordinate method (DISORT, Stamnes et al., 1988). The ozone cross section was taken from Molina and Molina (1986). Other parameters relevant to this study were the solar zenith angle (SZA), total ozone column, ground albedo, and aerosol data (aerosol optical depth AOD, type, season, visibility, asymmetry parameter g, and single scattering albedo ω).

The radiative transfer simulations were performed assuming the standard atmospheric profiles for subarctic summer, and a surface albedo for UV wavelengths. We used the disort solver to solve the radiative transfer equation with 8 streams. When simulating the UV irradiance, the slit function of the spectroradiometer was taken into account. The ozone column value is taken from the TOMS satellite (http://jwocky.gsfc.nasa.gov/teacher/ozone_overhead.html) for each day. All radiative transfer simulations were performed assuming cloudless skies. Atmospheric aerosols are described in the model by means of the wavelength-dependent optical depth, asymmetry factor, and the single scattering albedo. The aerosol vertical distribution is not

measured at Trondheim, thus the default aerosol profile defined in the model (Shettle, 1989) was used. Furthermore the followings were assumed, the aerosol type (volcanic background for above 2 km and urban type for below 2 km), spring-summer season and visibility of 40 km. The aerosol optical depth and its wavelength dependence were scaled according to the Ångström law. According to Ruggaber et al. (1998) the UV irradiance at a specific point is influenced by the albedo of an area with a radius of 20 km. Moreover, a small variation in the ground albedo has little effect on UV irradiance (Weihs and Webb, 1998). The ground albedo of Trondheim has not been measured, thus an assumed value of 0.03 for all wavelengths was taken from Schwander et al. (1998). For summer conditions and ground covered with trees, grass, and fields such as those surroundings the university site, the albedo varies typically between 0.01 and 0.07 (Blumthaler and Ambach, 1998). A more recent study by Kylling et al. (2000) gives a value of 0.08 for a similar ground cover. The asymmetry parameter (g) assigned a value of 0.70, for all wavelengths and altitudes. Madronich (1993) states that g typically falls between 0.6 and 0.8 for the UV wavelengths, and aerosol models defined in the LibRanTran model use g in the region of 0.6 to 0.8 as default (Mayer and Kylling, 2005). The SZA is the major parameter effecting the surface irradiance and hence the AOD. Thus a single SZA and the closest average SZA for both days were chosen for analysis corresponding to 50°±0.5°.

2.3 Retrieval of ω

Herman et al. (1975) first introduced the DDR (Diffuse to Direct Ratio) method to determine the imaginary part of the refractive index for desert dust by comparing measured and calculated DDR. The DDR method is based on the sensitivity of DDR to absorption by aerosols, SZA and ground albedo (King et al., 1979). Once the ground albedo and SZA are known, an unique solution for ω can be found. A similar approach to derive the ω in the UV wavelengths has been adopted by Petters et al. (2003) and Meloni et al. (2006). Our retrieval procedure approach is based on looping over different physically possible values for ω (0.7 to 0.99 in the UV region) until we have a match between

the simulated DDR and the measured DDR. The main model input parameters for the present study were the SZA, aerosol optical depth (AOD), total ozone column, asymmetry parameter (g), ground albedo, and ω. The radiative transfer simulations were performed assuming cloudless skies.

To perform the retrieval procedure of ω, we employed the measured direct and global data from the spectroradiometer (Bentham) and the multichannel filter radiometer (GUV) together with the radiative transfer model "LibRadTran". The global and direct irradiance are measured with two different instruments, and the ratio of the diffuse to the direct components (DDR) is calculated. The measured DDR is then compared to the simulated DDR output from the model. Model output of direct horizontal irradiance was divided by the cosine of the solar zenith angle to give direct normal irradiance to match the direct normal irradiance measurement of the instrument. The DDR is independent of calibration constants and in particular of the extraterrestrial solar spectrum (Halthore et al., 2004). Thus, the DDR is the most appropriate quantity to be compared with radiative transfer simulations.

In order to narrow the effect from biomass aerosol, two specific days were chosen for data analysis. A normal day, 24th of April, and a day which AOD from biomass aerosol showed clear increase, 9th of May. Figure 1 (upper pannel) shows the global radiation for all channels of GUV for the two measurement days.

Keeping the ground albedo at a constant value (see below), the DDR has little dependency on SZA (King et al., 1979), thus a single SZA is chosen for the analysis. The DDR is calculated at SZA of $50^{\circ} \pm 0.5^{\circ}$ for both measurements.

Atmospheric aerosols profile, albedo, asymmetry factor, and ozone data were assumed (as described in the previous subsection).

The radiative transfer model loops over SSA values from 0.7 to 1.0 in 0.01 steps. The DDRs are calculated and compared with the measured DDR within the loop until there is match within 0.05 difference. If a match is found, the SSA value is accepted.

3 Results and discussion

3.1 Effects of biomass aerosols on surface UV irradiance

The global irradiance measuremed by the GUV for 24th of April and 9th of May are depicted in Fig. 1 (upper pannel). Total ozone column for 24th of April and 9th of May were 338 DU and 324 DU respectively (TOMS). Taking the ratio of measured global irradiance for 24th of April and 9th of May (see Fig. 2), we observed reduction of 4.5%, 12%, 14%, 16%, and 15% at 305, 313, 320, 340, and 380 nm, respectively. Considering the 4% reduction in the ozone column from the 24th of April to 9th of May , one would expecting increase in the surface irradiance at the same SZA. However, we see reduction in the surface irradiance. We assume the smaller reduction for 305 nm compared to 313 nm is caused by the change in ozone. From 313 nm to 380 nm a reduction of 15% UV can be observed on average.

Direct solar UV measurements were performed at the same time, and are shown in Fig. 1 (lower pannel) for the same two days. The ratio between the two direct scans performed at same sza shows a reduction of 33% for 320 nm, 31% for 340 nm, 18% reduction for 500 nm (see Fig. 2).

Simulations were done on the same days using LibRadTran model. The input data for modelling were choosen as described in Sect. 2.2. The ratio of the modell results for global and direct spectral irradiance was compared with the ratio of the spectral measurements, and a very good agreement shown in Fig. 2 was achieved. This shows that the simulated spectral data can be compared with the measured data. Thus, information about diffuse radiation can be estimated. The ratio of the simulated diffuse spectra from both days are shown in Fig. 2c. The amount of diffuse radiation is very pronounced, specially in the UVB short wavelength and in the visible reagion, indicating 40% more diffuse radiation at 500 nm when the bloom is passing Trondheim.

The most interesting observations can be summerize as; i) Clear reduction in global radiation, with a reduction of 14% at 320 nm. ii) Decrease of 8.4% at 319 and increase of 40% at 500 for diffuse radiation as well. iii) The largest reduction were observed in di-

rect irradiance, 35% at 315 nm, iv) The aerosol-induced reduction is more pronounced in the UV. v) The effect is less in UVB than in UVA, and we have clear maximum reduction at about 319 nm. vi) Relative difference between diffuse and direct irradiance are largest in visible region.

In the UVB, a maximum reduction in direct irradiance of 35% is seen on 9th of May compared to 24th of April, in agreement with Kylling et al. (1998) for a pollution episode in summer in Greece. Kalashnikova et al. (2007) studied the influence of smoke aerosols on the UV irradiance in Australia. They found that smoke aerosols over Darwin reduced the surface UV global irradiance by as much as 40–50%at 290–300 nm and 20–25% at 320–400 nm near active fires (AOD at 500 nm~0.6). It is emphasized that both Kylling et al. (1998) and Kalashnikova et al. (2007) investigated the aerosol effect on surface irradiance with respect to aerosol-free conditions. Recently, an investigation on the same event that is the subject of this work has been published by Arola et al. (2007). They found that the reduction in global irradiance was about 15% in Finland. Thus, the result of this work agrees with the work from Arola et al. (2007) and Kylling et al. (1998).

3.2 Effects of biomass aerosols on SSA (ω)

To illustrate the effect of biomass aerosol recorded on 9th of May on aerosol single scattering albedo, the result of retrieved SSA for 24th of April and 9th of May are depicted in Fig. 3. The values of ω for biomass aerosols (9th of May) were 0.76 at 305 nm, 0.75 at 313 nm, 0.79 at 320 nm, 0.72 at 340 nm and 0.80 at 380 nm, while for the background aerosol (24th of April), the ω values were 0.87 at 305 nm, 0.75 at 313 nm, 0.8 at 320 nm, 0.74 at 340 nm and 0.94 at 380 nm. Figure 3 shows that ω for the smoke aerosols are lower than the normal day. This can be explained by the fact that the normal aerosol at Trondheim, a mixture of urban and marine aerosol, has a lower absorption in the UV than biomass aerosols. When the sky is dominated by large amount of biomass aerosols, the absorption in the UV increased. It could also be related to the size of the biomass aerosol, a small biomass aerosol will increase

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the ω compared to large stratospheric background aerosol. It should also be noted that, for both days, ω at 340 nm is lower than ω at 320 nm, indicating higher absorption by all type of aerosols at 340 nm. Moreover, taking into account the measurement uncertainty and ozone effects, one could conclude a significant decrease in the ω at 380 nm could be observed.

To compare the result of this study with other works; Meloni et al. (2006) found the SSA for biomass aerosol at Lampedusa (Central Mediterranean) to be 0.82±0.04 at 415.6 nm and 0.80±0.05 at 868.7 nm. Petters et al. (2003) found the SSA at their site (Black Mountain, N. C.) to be 0.80 to 0.99 at 368 nm.

3.2.1 Sensitivity and error analysis

A sensitivity study showed that the retrieved ω's are much more sensitive to changes in Ångström parameter α than changes in the asymmetry factor or ground albedo. Assuming an uncertainty of 5% in α, 7% in asymmetry factor, and 30% for ground albedo, we investigated the effect of errors in α, asymmetry factor, and ground albedo on the retrieved value for ω at each channel. To justify the choice of these uncertainties the following arguments are used, i) even though we know that the uncertainty in α has a wavelength dependence, for simplicity we used an average value, ii) this value is the maximum change which the model is able to produce realistic values for ω. Figure 4 shows the result of the sensitivity run. It can be seen in Fig. 4 that the variation in ω due to changes in asymmetry factor and ground albedo are of the order of 1–3% for all wavelengths, while the variation is much larger (5–9%) due to changes in α. Based on the assumed uncertainties, the total uncertainty in ω ranges from 6.8% to 8% for 9th of May and 5.8% to 9.3% for 24th of April.

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4 Conclusions

The high load of smoke aerosol in May 2006 caused an observed reduction in global irradiance of about 15% at 350 nm, while an increase of about 40% in diffuse radiation at 500 nm. The smoke aerosol in Trondheim has more absorption in the UV than the background aerosol. Biomass aerosol is also a very effective scatterer. Retrieved aerosol single scattering albedo showed that ω was variable, for smoke aerosols ω's showed lower values than for the normal day. The values of ω for biomass aerosols (9th of May) were 0.76 at 305 nm, 0.75 at 313 nm, 0.79 at 320 nm, 0.72 at 340 nm and 0.80 at 380 nm. It should be noted that ω at 340 nm is lower than ω at 320 nm, which could be interpreted as higher absorption at 340 nm than 320 nm for both days.

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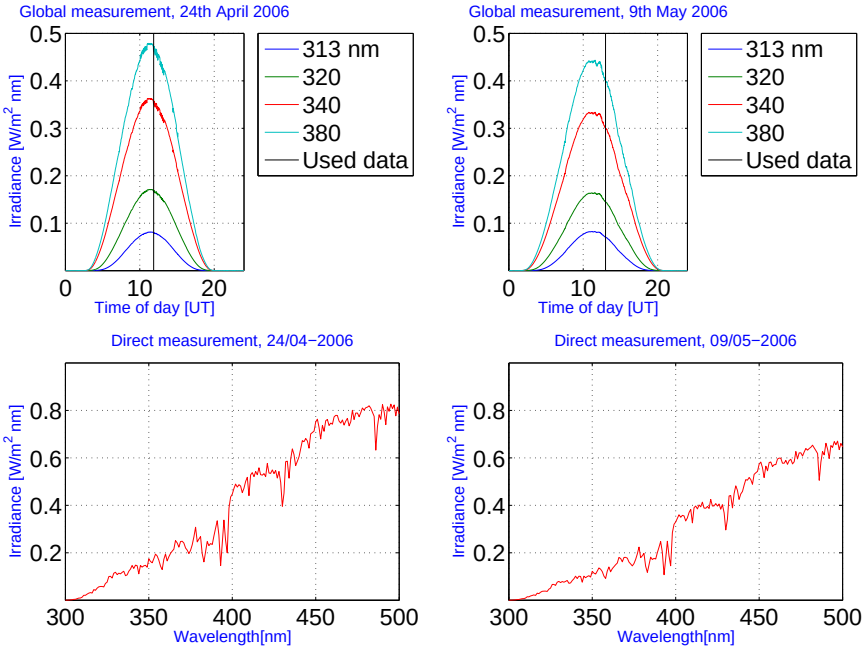

Fig. 1. Upper pannel; Global irradiance as function of time of day for 313, 320, 340, and 380 nm measured by GUV. The data are from 24th of April (upper left) and 9th of May (upper right). Also shown is the exact time of the used data for each day (vertical lines) which corresponds to SZA=50°±0.5°.
Lower pannel; Direct irradiane as function of wavelength measured by spectroradiometer. The data are from 24th of April (lower left) and 9th of May (lower right), SZA=50°±0.5°

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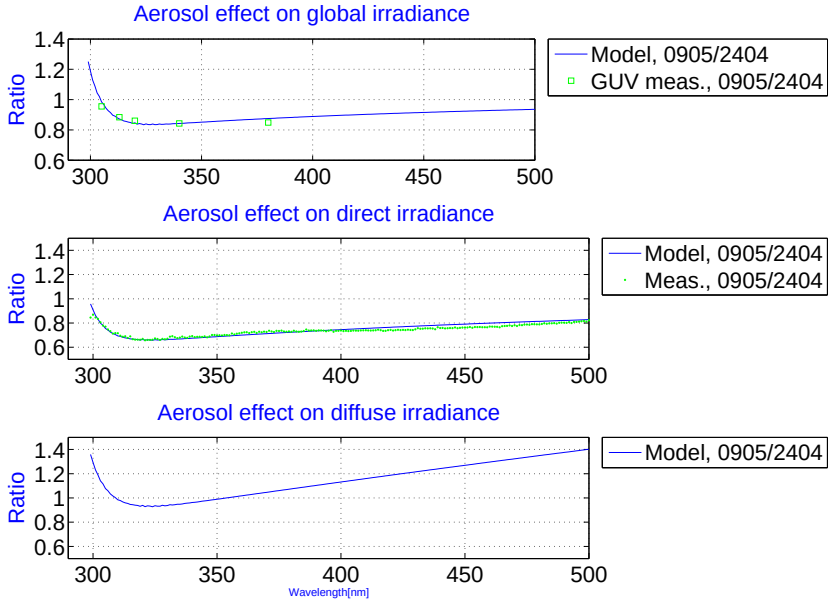

Fig. 2. Ratio of modeled and measured irradiance between 9th of May to 24th of April as function of wavelength, the solar zenith angle is 50°±0.5°. Total ozone column for 24th of April and 9th of May were 338 DU and 324 DU, respectively.

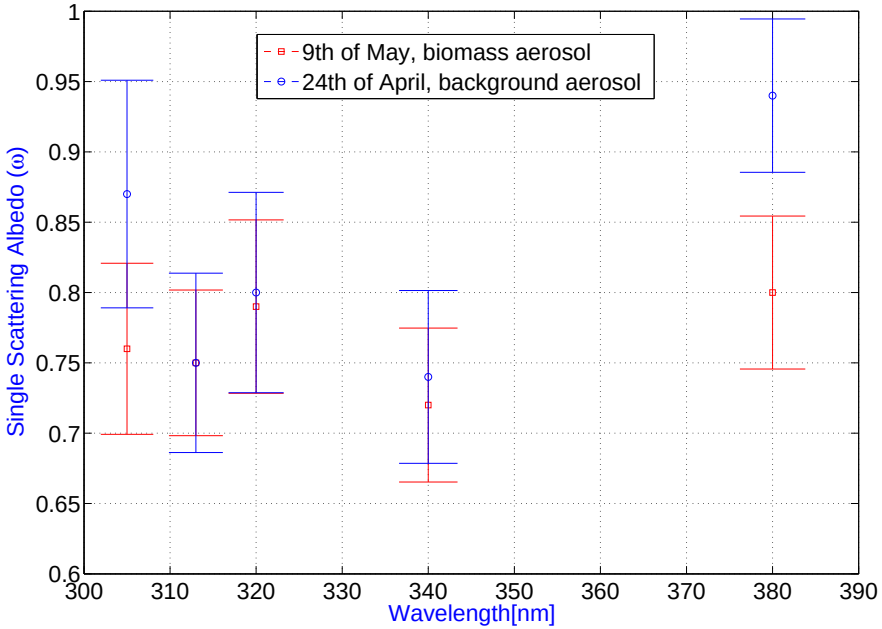

Fig. 3. Retrieved aerosol single scattering albedo (ω) at the 305, 313, 320, 340, and 380 nm channels for 24th of April and 9th of May with relative errors.

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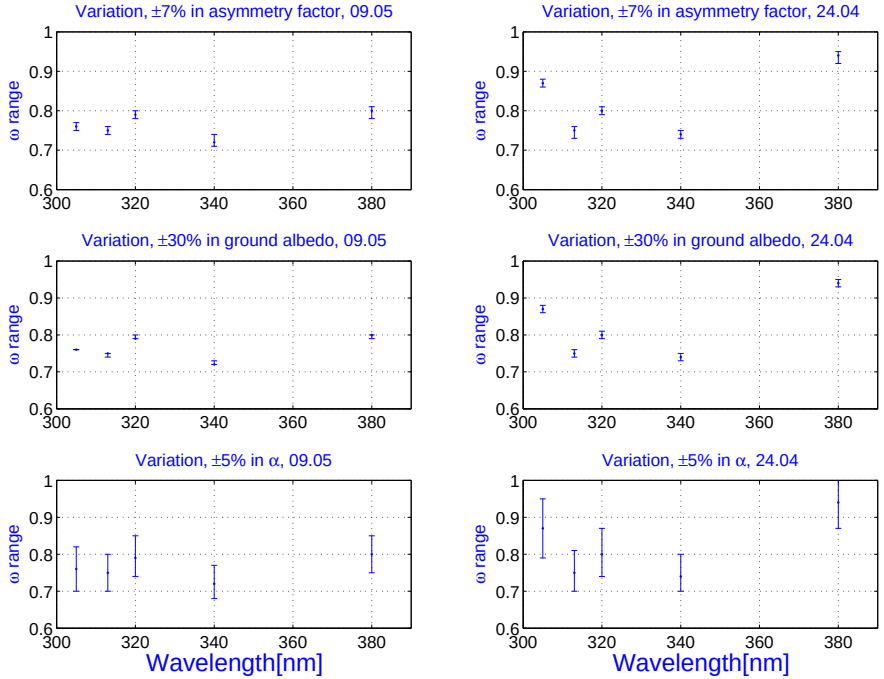

Fig. 4. Variation of ω due to change in asymmetry factor, ground albedo, and α for 24th of April (right panel) and 5th of May (left panel).

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