Impact of aerosol particles on measured and simulated polarized solar radiation

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Abstract

Solar radiation scattered within the atmosphere by atmospheric particles and aerosol particles has been investigated with regard to their state of polarization. Therefore measurements are performed with the COmpact RAdiation measurement System CORAS to analyze the individual components of the Stokes vector describing the measured radiation. For this purpose new optical inlets including a polarization filter have been developed. In parallel, radiative transfer simulations are conducted to interpret the measurements. For this purpose, two different radiative transfer solvers (SCIATRAN and polRadtran) were used. The simulations have been compared with the measurements to characterize the aerosol optical thickness and the predominant aerosol type.

Introduction

The electromagnetic radiation emitted by the Sun (solar radiation) is unpolarized. That means the oscillation of the electromagnetic waves has no preferred orientation. In the atmosphere scattering of solar radiation by air molecules and atmospheric particles (aerosol and/or clouds) may change the state of polarization. The intensity of the polarized radiation depends on several parameters like scattering angle, wavelength of radiation, particle size and shape. Thus, measurements of the polarization state of the scattered solar radiation enable a variety of analysis to retrieve detailed information on the scattering particles. (Emde et al, 2009)

Aerosol particles are one key element in the current debate on the Earth's climate change. The effect of aerosols on the radiation budget and cloud formation is still not sufficient understood (IPCC, 2007). Therefore, new measurement methods to characterize aerosol by polarized radiation have been developed. While active methods obtain information on the polarization state already exist (i.e. using lidar for example, (Weitkamp, 2005)), there is also an interest to apply passive techniques utilizing solar radiation as it is more applicable to retrieve information without the need of a simulated input. In this work ground-based radiance measurements were performed to characterize the state of polarization of sky light for clear sky conditions.

The state of polarization of an electromagnetic wave is described by the Stokes-vector which is defined by

$$\vec{S} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

The components I, Q, U and V of the Stokes vector are defined as time averages of linear combinations of the electromagnetic field vector,

$$I = \langle E_l E_l^* + E_r E_r^* \rangle \tag{1}$$

$$Q = \langle E_l E_l^* - E_r E_r^* \rangle \tag{2}$$

$$U = \langle E_l E_r^* + E_r E_l^* \rangle \tag{3}$$

$$V = \langle E_l E_r^* - E_r E_l^* \rangle \tag{4}$$

where E_l and E_r and the corresponding complex conjugated values (*) are the components of the electromagnetic field vector $\vec{E}$. E_l describes the fraction parallel to the reference plane, and E_r the fraction perpendicular to the reference plane. There are three different kinds of polarization, all described by the direction and the value of the field vector in fixed coordinates. The linear, circular and elliptic polarization.

Due to the use of linear polarization filters only the measurements did not cover circular and elliptic polarization (Stokes parameter V). Therefore investigations on circular and elliptic polarization are excluded in this work.

With knowledge of the Stokes parameters the degree of linear polarization is given by:

$$P_I = \frac{\sqrt{Q^2+U^2}}{I} \tag{5}$$

A value of P_I=0 corresponds to unpolarized radiation; P_I=1 indicates total linear polarized radiation. Here, P describes the polarized part measured within the total radiance.

Polarization measurement and simulations

The measurements were done with the Compact Radiation measurement System (CORAS).

CORAS was configured to measure spectral radiances in the wavelengths range between 300nm and 700nm, where aerosol affects are expected to be high. To retrieve the influence of aerosols only, “clear-sky” measurements were made. In this way the influence of water-droplets and/or ice-crystals could be excluded.

It receives radiances using a multi channel spectrometer (grating spectrometer, manufactured by Zeiss) with spectral resolution (full mean of half width) between 2-3nm wavelength. The optical inlet includes a polarization filter with an effective spectral range of 400-700nm. Radiances are measured in zenith direction.

To measure the full Stokes vector radiances have to been measured using a polarization filter. Four different orientations of a polarization filter ($I_{0°}$, $I_{45°}$, $I_{90°}$, $I_{135°}$) have to be realized during one measurement as illustrated in *Fig. 1*. The parameters *I*, *Q*, *U* and (and *V*) are then calculated by:

$$I = I_{0°} + I_{90°} \tag{6}$$

$$Q = I_{0°} - I_{90°} \tag{7}$$

$$U = I_{45°} - I_{135°} \tag{8}$$

$$(V = I_{RZ°} - I_{LZ°}) \tag{9}$$

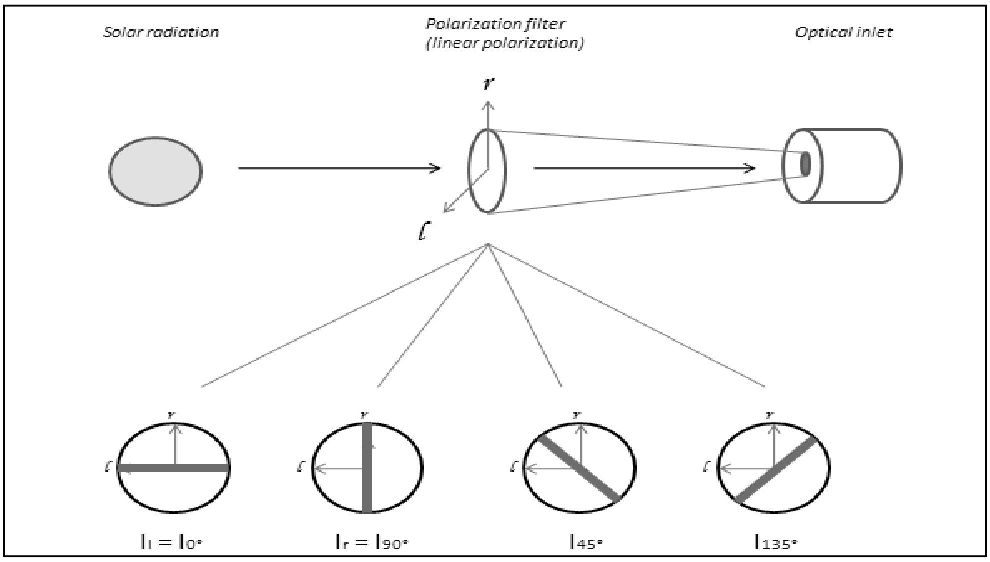

Fig. 1: Principle of measurement: The axis of the polarization filter is illustrated by a thick gray line. The parameters $I_{0°}$, $I_{90°}$, $I_{45°}$ and $I_{135°}$ are obtained by turning the polarization filter in intervals of 45°.

To analyze the ground-based measurements it is necessary to compare the measured data with radiances simulated by radiative transfer models (in the following RTM). To simulate polarized radiation the applied RTMs have consider all components of the Stokes vector. As a basic element, the RTMs include the interaction of the solar radiation with atmospheric molecules (Rayleigh scattering). Aerosol is implemented using the scattering properties of aerosol particles calculated from Mie-Theory. For investigations presented here two different RTM were applied; the polradtran solver (Evans et al. 1991,1995) as part of the „library for radiative transfer calculations“ (libRadtran, Mayer 2005)) and a new vector radiative transfer model included in the SCIATRAN 3.0 package (Rozanov et al. 2006). The aerosol optical properties accord to the standard WMO-model (Kokhanovsky, 1986) for SCIATRAN and to the OPAC database (Hess et al., 1998) for the polRadtran solver. In line with the presented radiation measurements, validation and tests of SCIATRAN will be discussed.

Results

Polarization measurements have been obtained with CORAS on August, 7th and August, 20th 2009 during clear sky conditions. The total radiances for the two measurements in zenith direction are displayed in *Fig. 2a*.

At first, the radiances of two measurements are displayed on the left, done on August, 7th and August, 20th 2009 *(Fig.2).* The corresponding degrees of linear polarization (P_l) are shown in *Fig.2b*

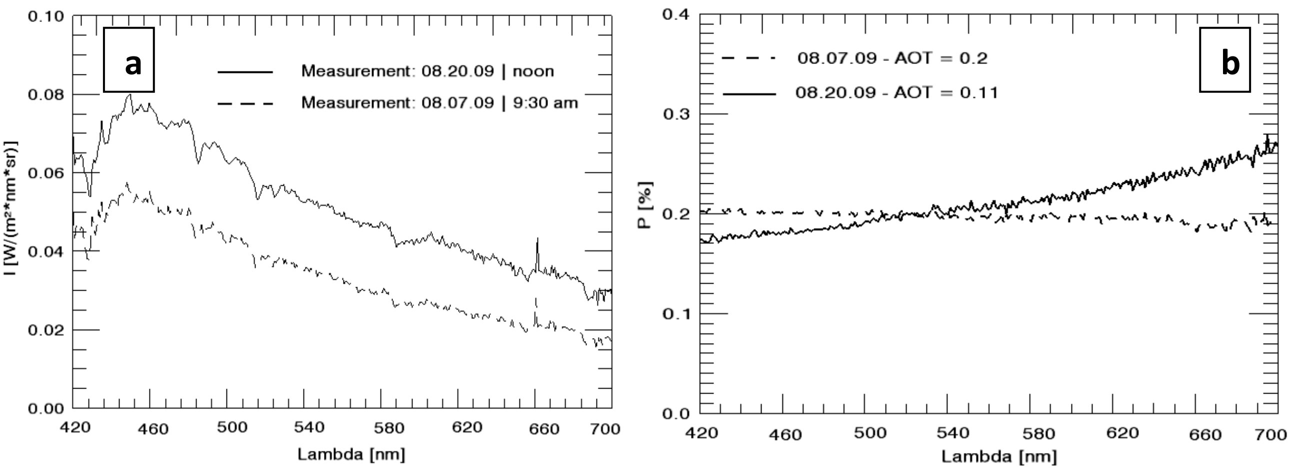

Fig.2: Measured radiances obtainedon August, 20th (solid line, θ = 41,68°) and August, 7th (dashed line θ = 56,75°) are shown in panel a. The corresponding degree of polarization is displayed in panel b.

The direct comparison of both cases shows that the radiance was higher for August, 20th than for August, 7th. The difference results mainly from the different solar zenith angle θ (42° for August, 20th and. 57° for August 7th), which alters the available amount of solar radiation. Potential effects caused by different aerosol optical thicknesses (AOT) are weaker than changes of θ and thus not observable in the radiances shown here. Nevertheless, the differing aerosol optical thickness has beside of the solar zenith angle a significant impact on the degree of the linear polarization. As shown in *Fig.2b*, for lower case of low AOT (0.2) measured on August, 20th, P_I increases with increasing wavelengths. The change of the spectral characterization of the polarization goes with the different AOT of both measurements. Regarding to theory, the lower SZA on August, 20th compared to August, 7th supports the increase of P with wavelength (Coulson, 1960: Tables related to radiation emerging from a planetary atmosphere with Rayleigh scattering)

To analyze and evaluate the impact of each factor simulations of spectral radiance and degree of polarization by RTMs are employed. Next to the point, that as cause of restrictions of the polarization filter, data acquisition is limited to the visible spectral range between 350nm-700nm the RTM's force this spectral window as well. They only calculate the aerosol optical properties within these wavelengths.

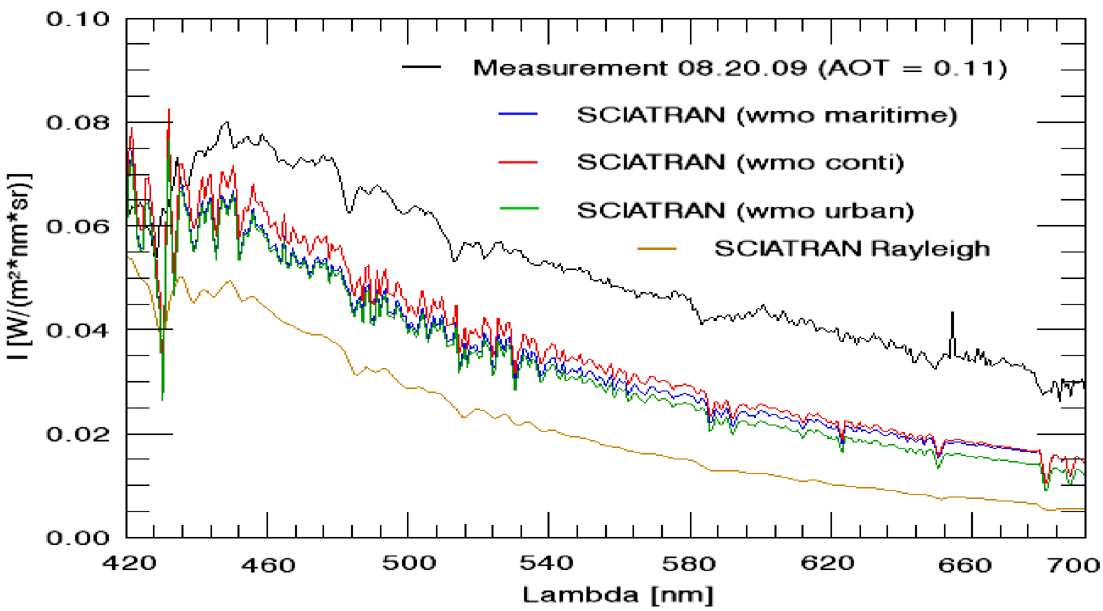

Fig. 3: SCIATRAN simulations for Rayleigh atmosphere and different aerosol situations. For all simulations with aerosol AOT was set to 0.2. The Rayleigh case is convoluted. As comparison, the measured radiance from August, 20th (Fig. 2) is added.

Fig.3 displays a comparison of simulated and measured radiances for August, 20th . Four calculated radiances simulated for different aerosol properties are shown. The ocher-colored line refers to the radiance simulated for a pure Rayleigh-atmosphere (AOT=0). With no aerosol particles included this is the reference case. The three colored lines show radiances simulated with aerosol particles included. The data bases use pre-defined mixtures of different aerosol types. For the simulations an urban (green line in Figure 4), continental (red line) and maritime aerosol composite (blue line) was used. The continental and maritime aerosol type contains 90% water-soluble aerosol, while the maritime one adds sea salt-accumulated aerosol. The urban composite contains 50% soot. While the simulations for the Rayleigh atmosphere have been convoluted with the according spectral resolution of the measurements, the simulations including aerosol are displayed in full spectral resolution of one nm.

In comparison to the measurements of August, 20th the modeled radiances show similar results. However, higher AOT's are necessary to obtain equal results. The simulations were performed with an AOT of 0.2 while AOT measurements from August, 20th showed an average of AOT=0.11 which was given by the AErosol RObotic NETwork (AERONET) station of the Institute for Tropospheric Research (IfT), Leipzig.

One possible reason for this difference may result from the data-averaging due to AERONET. An uncertainty resulting from the RTM is the impact of the surface albedo, which was set to 0.15 for the simulations. A higher albedo may result in increasing upwelling and consequently downwelling radiances and reduce the degree of linear polarization. Further simulations are scheduled to analyze the explicit impact and weight of the albedo.

A further aspect that is present in *Fig. 3* is the difference between the three simulated aerosol calculations. Using urban aerosol the radiance has lower values than for the other composites. This is caused by the soot particles included in the urban composite. The soot absorbs radiation, which results in a greater attenuation of the incoming radiation and in lower sky radiances.

Furthermore, a difference between the spectral characteristic of the radiances for the different aerosol cases can be observed. Simulations with maritime aerosol-case show a weaker decrease of the radiance with wavelength compared to the other compositions. This is caused by spectral differences of the according scattering phase function of sea salt in the marine composition. However, these differences are small and difficult to observe in measurements. To derive more assured information on the aerosol properties, the degrees of linear polarization was calculated from the results of the simulations.

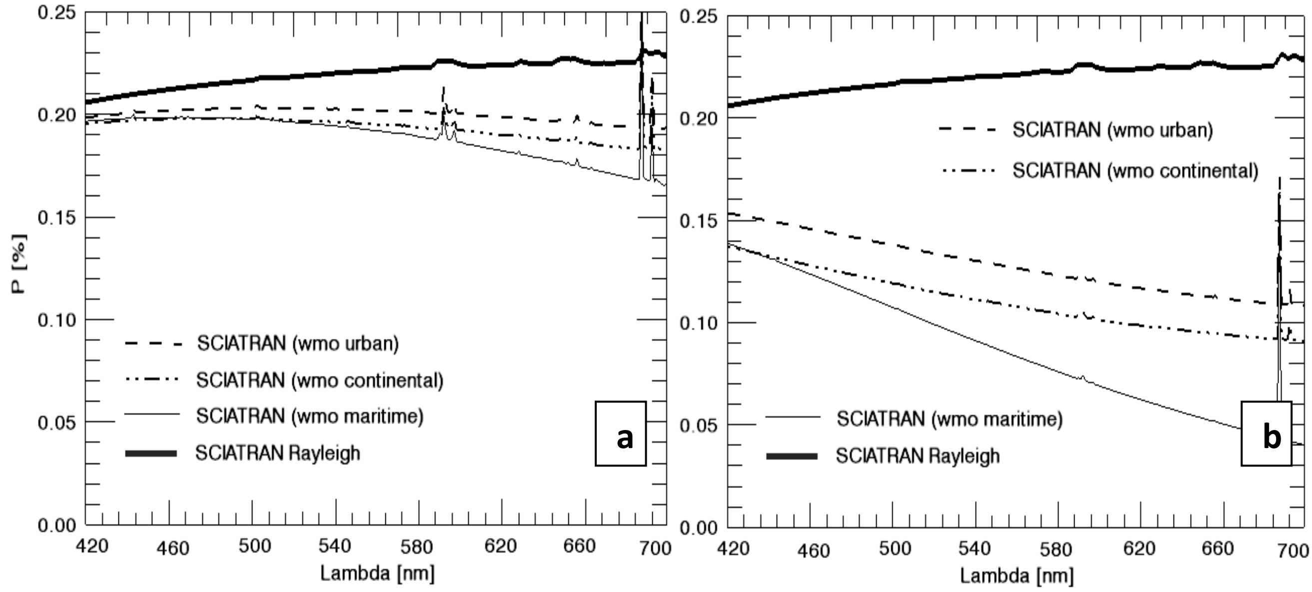

Fig.4: Degree of polarization for an AOT of 0.02 simulated with SCIATRAN based on the measurement from August, 20th is presented in panel a, while the degree of polarization for panel b was calculated for an AOT of 0.2

Fig.4 display simulations of SCIATRAN using the different aerosol composites and the Rayleigh-case as introduced above. The simulations shown in *Fig.4a* are performed with an AOT of 0.02 while the results displayed in *Fig.4b* are obtained for an AOT of 0.2. In general, the degree of linear polarization decreases with increasing AOT, while the maximum values are given by the Rayleigh case. Without aerosol P_I increases slightly with the wavelength. In comparison, the spectral pattern of P_I obtained for AOT=0.02 shows a slight increase of P_I up to 500 nm. For wavelengths above there is a decrease. For AOT=0.2 P_I decreases over the entire wavelength range. In comparison to the measurement from August, 20^{th} the spectral pattern of the measured P_I is not fully reproduced yet. Further investigations to determine the reasons are scheduled.

The comparison of these simulations has shown that P_I is highly sensitive to even smallest aerosol optical thicknesses. For AOT=0.02 P_I deviates from the Rayleigh-case up to 25% at a wavelength of 700 nm. Contrarily, the simulated radiances for AOT=0.02 (not shown here) differ only up to 3%. Thus the measurements of P_I are more suited to detect low aerosol concentration below AOT<0.05 than measurements of spectral radiances.

However, P_I is also strongly affected by the relative position of optical inlet and the Sun. To analyze the effect of the changing solar zenith angle in comparison to AOT changes simulations with different θ are shown in *Fig.6.*

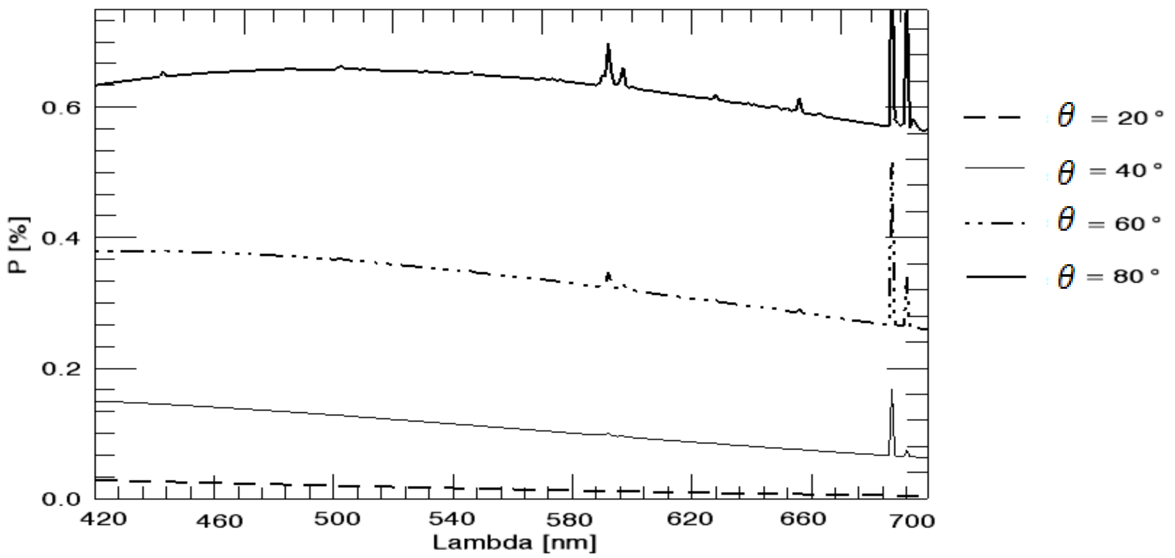

Fig.5: Impact of θ on linear polarization simulated with SCIATRAN. A maritime aerosol setting is used (AOT=0.1). The viewing direction is zenithal.

Presented are simulations for a continental aerosol setting with AOT=0.1. In general, for the chosen zenithal viewing direction the simulations reveal that an increase of θ increases the degree of polarization. While for small scattering angles ($\theta = 20°$) P_I almost diminishes, simulation with $\theta = 80°$ result in the highest P_I of up to 70%. This is due to the fact that the Rayleigh-scattered radiation has a maximum of polarization for 90° scattering angle. Compared to the simulation using a fixed θ but different AOT shown in *Fig. 5* the impact of θ exceeds the impact of aerosol. Thus the geometrical configuration of the measurement setup (inlet viewing angle and θ) have to be considered correctly to retrieve precise information on aerosol properties. In relation to the measurements shown in *Fig.2b* where both AOT and θ have changed, these simulations have shown that both attributes explain the different spectral characteristic of P_I obtained for August, 20 and August, 7.

Conclusions

The influence of aerosol on the linear polarized radiation has been analyzed by radiation measurements and simulation by the RTM SCIATRAN. The measurements and the simulated radiances were obtained for different θ and AOT. The impact of both parameters on the spectral radiance and P_I was analyzed. It has been shown that both measured quantities I and P_I are influenced by changing AOT and θ . However, P_I was found to be affected much stronger than the radiance.

Furthermore, differences in the impact of AOT and θ on the measured and simulated radiation were analyzed. While the absolute effects are higher for a changing θ, AOT was found to have a higher impact on the spectral characteristics of P_I. In contrary the spectral characteristic of the radiance is only slightly affected by different θ and AOT. This reveals that P_I is suited better then measurements of the radiance to retrieve information about aerosol properties from solar sky radiation measurements. The higher absolute and spectral sensitivity of P_I with respect to changes in the aerosol properties enables to identify even small amount of aerosol AOT<0.01 which are not detectable by measurements of the radiance. Additionally, P_I is a relative measure and therefore independent on the accuracy of the radiometric calibration of the instrument.

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