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Vertical distribution of spectral solar irradiance in the cloudless sky: A case study

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[1] First airborne measurements of spectral solar down- and upwelling irradiances with a high spectral resolution (2–3 nm) are presented. The data were gathered in cloudless, hazy conditions over sea and land using a new instrument (called *albedometer*), which is equipped with a unique sensor head leveling technique. The downwelling irradiances and their spectral slope increase with altitude, illustrating the impact of Rayleigh scattering and boundary layer aerosols. The upwelling spectra reveal typical reflection features of the underlying surface (e.g., vegetation step around 700 nm). The measurements are compared with radiative transfer model results based on simultaneous airborne aerosol observations. The downwelling irradiances mostly agree to ±10% which is within the experimental and modeling uncertainties. The upwelling irradiances are highly sensitive to uncertainties in the spectral surface albedo. Reasonable agreement between measurements and simulations required us to determine the surface albedo from flights at low altitude, rather than adopting literature values. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0394 Atmospheric Composition and Structure: Instruments and techniques; 1610 Global Change: Atmosphere (0315, 0325); 1640 Global Change: Remote sensing; 3359 Meteorology and Atmospheric Dynamics: Radiative processes. **Citation:** Wendisch, M., and B. Mayer, Vertical distribution of spectral solar irradiance in the cloudless sky: A case study, *Geophys. Res. Lett.*, *30*(4), 1183, doi:10.1029/2002GL016529, 2003.

1. Introduction

[2] Solar radiation, incident at the top of atmosphere (TOA) is the driving force of weather and climate of the earth. Hence, the modification of solar radiation on its way through the atmosphere is of major importance for the global energy budget. Solar radiation is quantified by the irradiance which is the radiative energy flux through a horizontal surface. In order to characterize the atmospheric radiation field, accurate spectral irradiance measurements as well as validated calculations are required.

[3] In the past the accuracy of the airborne irradiance measurements was significantly limited by calibration problems, distortions due to horizontal sensor misalignments, uncertainties in separating diffuse and direct irradiances, non-ideal cosine response of the sensors, or re-radiative thermal effects in the instruments. Also, the spectral resolution of the airborne irradiance measurements was poor. As a consequence *Wendisch et al.* [2001] and *Pilewskie et al.* [2003] developed a new generation of airborne irradiance instruments with improved measurement accuracy and higher spectral resolution. The *albedometer* by *Wendisch et al.* [2001] is unique due to (a) its active horizontal stabilization of the up- and downward facing sensor heads (thus avoiding sensor misalignment problems), and (b) its high spectral resolution (2–3 nm). The instrument by *Pilewskie et al.* [2003] has a moderate spectral resolution (8–12 nm), and the sensor heads are fixed with the aircraft fuselage. The advantage of this instrument is the larger wavelength range (300–1700 nm) compared to the albedometer (290–1000 nm).

[4] In this paper first airborne measurements of down- and upwelling solar irradiances with high spectral resolution are presented. The data were obtained using the albedometer in cloudless, hazy conditions over sea and land. The measured spectra were compared with the output of two independent 1-D (one-dimensional) radiative transfer models. The input for the models was identical and included concurrently measured profiles of aerosol microphysical data and meteorological observations. Both models have been previously evaluated with respective benchmarks. Using state-of-the-art instrumentation and two tested radiative transfer models conclusions about correspondence between measured and calculated down- and upwelling spectral irradiances under cloudless conditions are drawn.

2. Experimental

2.1. Instrumentation

[5] The albedometer consists of two optical inlets (one upward-, the other one downward-looking) to measure down- and upwelling spectral irradiances. The optical inlets are connected with two identical multi-channel spectrometers (MCSs) using independent fiber optical cables. Each MCS consists of a fixed grating for wavelength splitting and a 1024 pixel diode array for detection and covers the wavelength range 290–1000 nm. The use of a fixed grating instead of a scanning spectrometer ensures a high time resolution of the measurements (usually 0.3 s), and guarantees robustness during airborne operation as well as temporal wavelength stability. It should be noted that for wavelengths smaller than about 310 nm and larger than 965 nm the data are uncertain due to the decreasing sensitivity of the diode array detectors towards their edges.

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The two albedometer components were consistently calibrated in absolute irradiance units using a 200 W tungsten halogen lamp, which is traceable to an absolute standard maintained at PTB (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany), the German National Calibration Authority. The deviations from the ideal cosine angular response were characterized in the laboratory as a function of incidence angle and wavelength, and were used to correct the irradiance measurements. The wavelength calibration of the two spectrometers has been checked and the FWHM (Full Width at Half Maximum) has been determined as a function of wavelength using different gas lamps (Hg, Ne, Kr, Xe, Ar) with distinct spectral peaks. FWHM values between 1.8 and 3.5 nm were obtained and the average value of 2.9 nm was used in the data analysis. The albedometer is equipped with a unique active horizontal stabilization unit, which significantly minimizes uncertainties related to horizontal misalignment of the up- and downward-looking optical inlets during the airplane movements [*Wendisch et al.*, 2002]. Altogether a measurement uncertainty for the spectral irradiance measurements with the albedometer of 4% for wavelengths between $\lambda = 400-770$ nm and of ±6% for $\lambda \leq 400$ nm and $\lambda \geq 770$ nm was estimated [*Wendisch*, 2002]. This error estimate is based on Gaussian error propagation of contributions due to absolute calibration with the PTB lamp (±3% for wavelengths between 400–700 nm, otherwise ±5%), temporal calibration drifts (±2%), determination of the effective receiving plane (±1%), coupling of optical fibers (±1%), corrected cosine error (±1%), and remaining uncertainties due to horizontal sensor head leveling (±1%).

2.2. Measurements

[6] The radiation measurements were accompanied by airborne aerosol particle microphysical (mainly particle size distribution) and meteorological (air pressure, temperature, and relative humidity) observations. The data were gathered with an instrumented airplane during an experiment at the German North Sea coast (≈54.3°N, ≈9.4°E) in September and October 2000. The aircraft payload has been described in detail by *Keil et al.* [2001] and *Wendisch* [2002]. Several profile data were collected over open sea and land (hereafter referred to as 'SEA' and 'LAND', respectively) under cloudless, hazy conditions. In particular, data of two descending flight patterns performed on 30 September 2000 (a very hazy day) are analyzed. An example of the measurements is shown in Figure 1.

[7] During the slant aircraft descent the solar zenith angle θ_s varied between the values indicated in the figure. In general the values of the downwelling irradiances are quite low, which is a result of the very high particle optical thickness on this hazy day. The average θ_s for the measurement over 'SEA' was about 5° smaller than for the 'LAND' measurements. Therefore the downwelling irradiance over 'SEA' is higher (for the same altitude and wavelength) compared to the respective measurement over 'LAND'. The most obvious feature of Figure 1 is the systematic increase of both down- and upwelling irradiances with altitude. It is also striking, that the spectral slope of the spectra increases with altitude due to Rayleigh scattering and the high amount of large particles at lower altitudes. The spectra clearly reveal the gas absorption bands of O_3, H_2O, and O_2 as well as some Fraunhofer line features, especially at the shortwave end of the spectrum. The upwelling irradiances show the typical reflection properties of the underlying surface. Over 'SEA' the spectral slope is more or less continuous, whereas over 'LAND' the typical vegetation step around 700 nm is obvious.

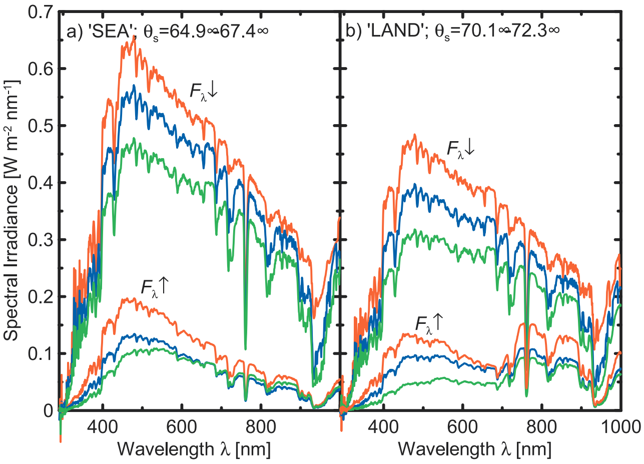

Figure 1. Down- and upwelling spectral irradiances ($F_\lambda\downarrow$ and $F_\lambda\uparrow$, respectively) measured at 3 km (red lines), 1.2 km (blue lines), and 0.4 km (green lines) altitude over 'SEA' (a) and 'LAND' (b).

3. Radiative Transfer Models

[8] Two spectral 1-D radiative transfer models were used in order to compare the measurements with respective simulations: A matrix operator model (MOM) and the discrete ordinate code DISORT implemented in the libRadtran package (LRM). The MOM is described by *Wendisch et al.* [2002]; it participated in ICRCCM-III (InterComparison of Radiation Codes in Climate Models, Phase III) [*Barker et al.*, 2003] and was tested against measurements [*Wendisch et al.*, 2002]. LRM is a comprehensive radiative transfer model package (A. Kylling and B. Mayer, http://www.libradtran.org, 2002), which also has been validated by comparison with other models [*Koepke et al.*, 1998; *van Weele et al.*, 2000] and radiation measurements [*Mayer et al.*, 1997].

[9] Both models were run with identical aerosol optical properties and meteorological input, which was based on the simultaneous aircraft measurements. The volume scattering coefficients, the single scattering albedo, and the phase functions of the particles (as functions of wavelength and altitude) have been calculated by a Mie-routine using the measured airborne particle size distributions. These measurements cover the optically most relevant accumulation particle size mode. The Aitken and coarse particle mode size distributions which were not measured during the experiments reported here were adopted from the LACE 1998 field campaign [*Ansmann et al.*, 2002]. For the spectral refractive indices of the particles an internal mixture between ammonium sulfate and black carbon was assumed for the Aitken and accumulation mode particles. The coarse mode particles were assumed to consist of pure ammonium sulfate. The sensitivity of the calculated spectral irradiance to these assumptions has been investigated in detail by

Wendisch et al. [2002] and is estimated to be less than ±15%. Using sea salt instead of ammonium sulfate for the calculations over 'SEA' does not significantly change the results of the calculations. Humidity effects on particle growth and refractive indices were considered similar to *Wendisch et al.* [2002].

[10] The calculated spectral down- and upwelling irradiances of both models were convoluted with the measured spectral slit functions for the two MCSs (Lorentz function with a FWHM of 2.9 nm).

4. Comparison of Measurements and Calculations

[11] The measured and calculated downwelling irradiances are shown in Figure 2. The calculated values mostly agree with the measurements shown in Figures 2a and 2c taking into account the experimental uncertainties (vertical bars) and the modeling problems (mostly due to uncertain microphysical input). The MOM yields a systematically lower spectral slope compared to the LRM and the measurements. Figures 2b and 2d show that the deviations between measurements and the simulations are mostly less than ±10%. Some spikes occur due to the Fraunhofer structure of the solar spectrum in the ultraviolet range and due to the gas absorption bands of water and oxygen in the visible and near-infrared. This problem is caused by the strong spectral gradient in these wavelength regions, which leads to large statistical deviations between measurement and calculation even for small uncertainties in the wavelength alignment of the instrument.

[12] In Figure 3 the corresponding results for the upwelling irradiance are shown. Differences between observation and simulation are considerable and mostly far outside the measurement and model uncertainties. This is due to the upwelling irradiance close to the surface being directly proportional to the spectral surface albedo. Hence, discrepancies between the actual surface albedo and the values assumed in the model directly translate into uncertainty of the modeled upwelling irradiances. Here the spectral surface reflectance data by *Bowker et al.* [1985] were chosen, which seem to be not representative of the actual surface albedo. These data also do not consider for the solar zenith angle dependence of the surface reflectance. The differences are larger over 'SEA' compared to the case over 'LAND'. Figure 3c shows that the actually measured vegetation edge is less pronounced than that resulting from the data by *Bowker et al.* [1985].

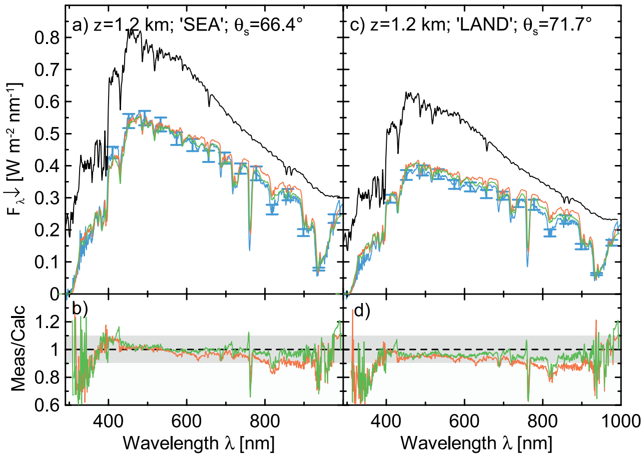

Figure 2. Measured (blue lines) and calculated (red lines: MOM; green lines: LRM) spectra of downwelling irradiances at an altitude of z = 1.2 km over 'SEA' (a) and 'LAND' (c). The black lines show TOA irradiance for the respective θ_s. In the calculations spectral surface albedo data by *Bowker et al.* [1985] are used (Type sea [no. 149] over 'SEA' and type grass [no. 73] over 'LAND'). The error bars represent the measurement uncertainties. The two lower panels show the ratio of measured to calculated values as a function of wavelength over 'SEA' (b) and 'LAND' (d), respectively. The grey area marks a deviation of ±10%.

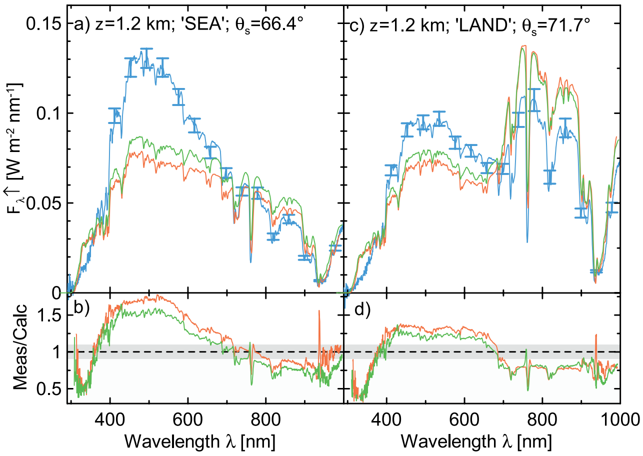

Figure 3. The same as Figure 2 but for the upwelling irradiance and different vertical scales.

[13] Similar comparisons were performed for other flight levels [*Wendisch*, 2002]. The results for z = 0.4 km are comparable to those at z = 1.2 km. At z = 3 km somewhat larger differences between measured and calculated spectral irradiances occurred, which were probably related to instrumental problems (condensation).

[14] In a second step, the observations at the lowest possible flight level (75–110 m) were used to determine the actual spectral surface albedo, which is a function of both wavelength and solar zenith angle. This was realized by varying the surface albedo systematically to minimize the difference between measured and calculated upwelling irradiances at this low altitude. The dashed red lines in Figure 4 show the resulting tuned spectral surface albedo of sea (Figure 4a) and of land (Figure 4b) in comparison with the values of *Bowker et al.* [1985] (solid blue curves). There are significant differences between the literature data and those determined from the lowest flight level. Especially over sea the differences are enormous. For this reason the data were additionally compared with the parameterization of the bidirectional reflectance distribution function of water surfaces by *Cox and Munk* [1954] and *Nakajima and Tanaka* [1983]. The dash-dotted black line in Figure 4a shows the parameterized curve. The agreement with the values determined from the low-level observations is improved, although significant quantitative differences remain, which cannot be explained by uncertainties of the parameterized reflectance and the assumed wind speed. Both findings, over 'LAND' and over 'SEA', highlight

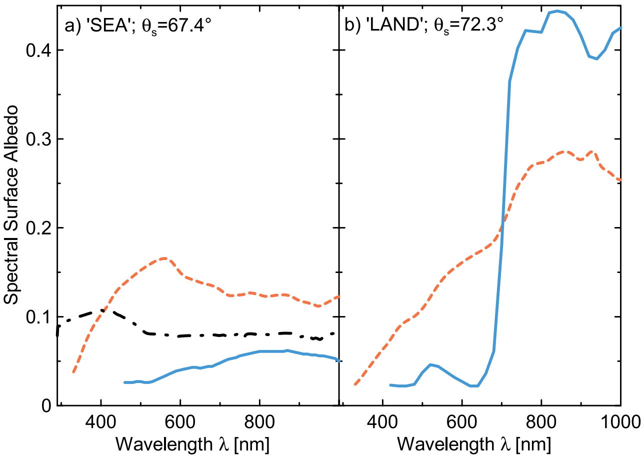

Figure 4. Spectral surface albedo tuned to the spectral upwelling irradiance at the lowest flight level (dashed red lines) and literature data by *Bowker et al.* [1985] (solid blue lines). The data over 'SEA' are shown in Figure 4a, those over 'LAND' are plotted in Figure 4b. The parameterization of the bidirectional reflectance distribution function of water surfaces by *Cox and Munk* [1954] and *Nakajima and Tanaka* [1983] for a wind velocity of 5 m s^{-1} is shown as dash-dotted black line in Figure 4a. The retrieved spectral surface albedo values only hold for the solar zenith angle indicated in the figure.

the need to use measured spectral surface albedo rather than adopting literature data if high accuracy is required in the simulation, because of the possibly large variability of the albedo within a given surface type.

[15] Using the tuned spectral surface albedo the calculations were repeated for all flight levels. Compared to Figure 3 significant improvement of the measurement-model comparison was achieved. Root mean square deviations between measured and calculated spectral upwelling irradiances around 20% were obtained when using the tuned surface albedo values, compared to up to 130% for the case when literature albedo data were used. The reason for the remaining deviations of 20% is the fact that the measurements at the different flight levels during the descent were actually performed over similar surfaces but not over one and the same area. From these calculations it also became evident that the downwelling irradiances are only slightly affected by the choice of the spectral surface albedo in the model runs. The relative differences between the calculated downwelling irradiance using the literature data and the actually determined albedo was less than 1.6% at all altitudes with largest influence at lower altitudes.

5. Conclusions

[16] First airborne measurements of spectral down- and upwelling irradiances with a spectral resolution of 2–3 nm in the wavelength range between 290–1000 nm are presented. The data are obtained in cloudless, hazy conditions over sea and land surfaces. The downwelling irradiances as well as the their slope increases with altitude, showing the influence of Rayleigh scattering and aerosol particles in the planetary boundary layer. The upwelling spectra clearly represent the reflection features of the underlying surface.

[17] The measurements are compared with the output of two radiative transfer models. The differences between measurements and calculations of spectral downwelling irradiances are mostly less than ±10%, i.e., within the uncertainties of the measurements and calculations. However, the measured upwelling irradiance significantly deviates from the respective simulations, which is due to the unrealistic representation of the spectral surface properties in the models. Therefore, it is necessary to determine the spectral surface albedo specifically for each location or campaign and as a function of solar zenith angle, rather than adopting literature values. With the albedometer a suitable experimental tool for this task is available.

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