Wiss. Mitteil. Inst. f. Meteorol. Univ. Leipzig Band 48(2011)

Airborne measurements of reflectivity and albedo of urban and rural surfaces of Megacities

B. Mey[1], C. Xingfeng[2], L. Zhengqiang[2], X. Gu[2], Y. Tao[2], and M. Wendisch[1]

Abstract

Spectral reflectivity and albedo are obtained from airborne measurements of spectral irradiance and radiance during two field campaigns in Leipzig, Germany and Zhongshan, China. The data measured above urban and rural areas have been investigated with respect to the heterogeneity and anisotropy of the surface. Furthermore the spectral albedo and reflectivity measured above the same surface but at different flight altitudes have been analyzed. These data is used to estimate the impact of multiple scattering processes by aerosol particles and gas molecules.

Abstract

Spektrale Reflektivität und Albedo wurden aus Flugzeug getragenen Messungen der aufwärtsgerichteten spektralen Strahlungsflussdichte (Irradianz) und Strahldichte (Radianz) während zweier Messkampagnen in Leipzig, Deutschland und Zhongshan, China, bestimmt. Die Daten, die über urbanen und ländlichen Flächen auf konstanter Flughöhe gemessen wurden, wurden in Hinblick auf Heterogenität und Anisotropie der Oberfläche untersucht. Desweiteren wurden die spektrale Albedo und Reflektivität, die über gleichem Untergrund aber während unterschiedlicher Flughöhen gemessen wurden, analysiert. Diese Daten werden verwendet um den Einfluss von Mehrfachstreuprozessen durch Aerosolpartikel und Gasmoleküle abzuschätzen.

1 Introduction

The yearly mean global radiant energy budget is dominated by interactions of the solar radiation with clouds, trace gases, aerosol particles, and the ground surface. The solar radiation is absorbed or scattered by these components, which can locally lead to a cooling or a warming of the atmosphere. Aerosol particles and the ground surface are the largest contributors in the reflection of solar radiation in a cloud free atmosphere Therefore they should be considered especially in the vicinity of strong aerosol sources, like Megacities (cities with more than 10 Million citizens, Molina and Molina, 2004) with high productions of anthropogenic aerosol particles. To obtain a global view on the aerosol distribution satellite measurements are required. To retrieve the Aerosol Optical Depth (AOD) from space borne measurements, the measured reflected radiation has to be separated into the fractions of radiation reflected by aerosol and the surface. This separation needs assumptions which are sources of uncertainties in the satellite aerosol retrieval. The heterogeneity of the urban surface structure enhances the uncertainty of aerosol retrievals from satellite borne measurements, e.g. the AOD retrieval from measurements with the MODerate resolution Imaging Spectroradiometer (MODIS, Justice et al., 1998, Kaufman et al., 1997, Levy et al., 2007) data onboard the NASA satellites Aqua and Terra.

Surface reflectivity and albedo properties retrieved from airborne measurements are an option to estimate the surface albedo (lower boundary condition) in the satellite retrieval algorithm. albedo α_λ describes the hemispheric reflection of radiation on a surface, whereas reflectivity ρ_λ describes the reflection of radiation into a certain solid angle. The physical formulas of albedo and reflectivity are shown in Eq. [1] and [2]:

$$\alpha_\lambda = \frac{F_\lambda^\uparrow}{F_\lambda^\downarrow} \quad [1]$$

$$\rho_\lambda = \frac{\pi \cdot I_\lambda^\uparrow}{F_\lambda^\downarrow} \quad [2].$$

$F_\lambda^\uparrow$ is the spectral upward irradiance (spectral radiant flux density in W m^{-2} nm^{-1}), $F_\lambda^\downarrow$ is the spectral downward irradiance, and $I_\lambda^\uparrow$ is the spectral upward radiance (radiant density in W m^{-2} sr^{-1} nm^{-1}).

Due to lower flight altitudes of the aircraft the spatial resolution of the data is much higher than the resolution of the MODIS data. Although most of the particle load within the atmosphere is in the boundary layer, less atmospheric corrections are necessary for the retrieval of surface albedo and reflectivity in comparison to satellite data. We present measurements conducted during the field campaigns of the Megacities-project of 2007 and 2009.

2 Field campaigns

Airborne measurements of spectral albedo and reflectivity have been conducted during the field campaigns for the framework of the priority program (SPP 1233) “Megacities Megachallenge – Informal Dynamics of Global Change” funded by the German research foundation (DFG) in the years 2007 and 2009. In 2007 the area of Leipzig has been sampled, in 2009 measurements in China (Zhongshan, Guangdong province) have been obtained. The priority program is an interdisciplinary program bringing together scientist from different research area (e.g. economy, geography, engineering, and public health) within the frame of different kind of challenges in Megacities.

The first field campaign took place in September 23-24, 2007 in Leipzig, Germany. During four scientific flights, the spectral upward irradiance and radiance were measured, as well as images of the surface in three wavelength bands, of the urban structure of Leipzig.

The second field campaign was conducted in November/December 2009 in Zhongshan, China. The research flights on December 3 and 4 covered the area over Zhongshan. The flight pattern of December 3 is shown in Fig. 1.

3 Instrumentation

Airborne measurements of upward spectral irradiances and radiances were performed with the Spectral Modular Airborne Radiation measurement system (SMART-Albedometer, Wendisch et al., 2001). The SMART-Albedometer consists of two types of spectrometers which are connected via optical fibers to two kinds of optical inlets, for measuring radiance and irradiance. The two types of spectrometers cover the spectral wavelength range of 0.35 to 2.2 µm.

Ground-based measurements of the downward irradiance in the wavelength range of 350 to 1000 nm were conducted with a ground based version of the SMART-Albedometer, the COmpact RAdiation measurement System (CORAS) during the field campaign in Zhongshan 2009.

Data of downward irradiance could not been obtained during the field campaigns due to aircraft installation limitations and is simulated with the library for Radiative transfer code (libRadtan, Mayer and Kylling, 2005). Previous work (Bierwirth et al., 2008) showed that the simulated irradiance spectra match the measured ones within the measurement uncertainties for cloud free atmosphere and the knowledge of the aerosol optical properties.

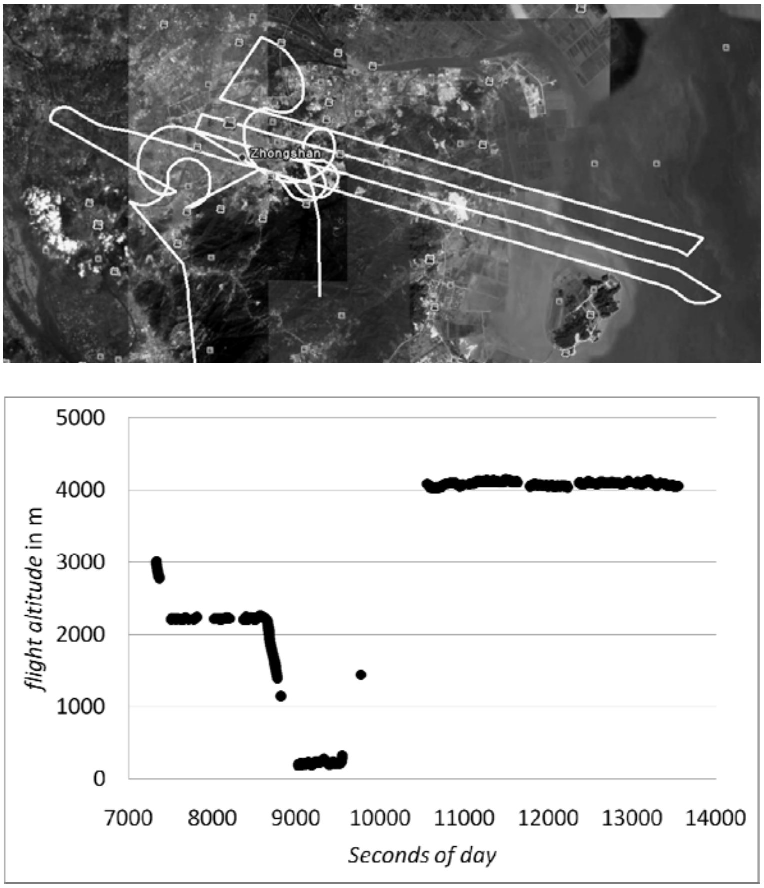

Fig. 1: Flight pattern (upper image) and flight altitude (lower image) of the flight over Zhongshan on December 3, 2009. Urban, rural, and coastal structures were surveyed by this flight pattern as it can be seen in the underlying satellite picture in the upper image.

Measurements of the AOD, the single scattering albedo (SSA), the asymmetry parameter (g) and the vertical extinction profile were retrieved from sun photometer and LIDAR measurements respectively. These measurements have been provided by the Leibniz Institute for Tropospheric research (IfT, Leipzig, Germany) and the Institute of Remote Sensing Applications, Chinese Academy of Sciences (IRSA, CAS, Beijing, China).

4 Results

We present results obtained from the data measured in 2007 in Leipzig, Germany and in 2009 in Zhongshan, China. The presented data at flight level still includes the signal of the solar radiation reflected on gas molecules and aerosol particles in the layer between aircraft and ground; therefore it is not possible to draw any conclusion about surface reflectivity and albedo. Features in the data which could already be observed at flight level without extrapolating albedo and reflectivity to surface level are discussed.

Two major differences between the data sets of Leipzig and Zhongshan can be highlighted. Both locations are characterized by a different aerosol load during measurements. The AOD at 532 nm measured on September 23, 2007 in Leipzig was much lower (AOD = 0.2) in comparison with the AOD on December 3, 2009 in Zhongshan (AOD = 0.9). Furthermore, the flight altitude during the measurements in Leipzig was about 600 m above sea level (approx. 500 m above surface), whereas the flight altitude during the measurements in Zhongshan was mostly 4000 m with two short flight tracks in 2000 m and 200 m flight altitude. This gives the opportunity to analyze the data focussing on different aspects, surface heterogeneity during the first campaign, and flight altitude dependence for the data of the second campaign in Zhongshan.

4.1 Surface heterogeneity and homogeneity

Different surface types with different grade of heterogeneity were observed during the measurements in Leipzig, Germany. The measurements were performed at low flight altitudes of 500 m above ground (600 m above sea level) and only minor corrections are necessary to obtain the surface albedo from the measurements at flight level to reduce the atmospheric masking. A time series of albedo and reflectivity, corresponding to their spatial distribution gives an idea about the heterogeneity of the surface (Fig. 2).

The time series of the albedo is obviously smoother than the time series of the reflectivity which can be explained by the definition of the quantities itself. The albedo data includes the reflection properties of the geographical measurement position and the information of the vicinity. Reflectivity that is calculated by multiplying the radiance with π, is typically locally different from the albedo for anisotropic surfaces. The reflectivity is higher than the albedo, if the surface observed in the field of view is highlighted, or lower than the albedo, if the surface is shadowed. Part (a) in Fig. 2 shows the reflectivity and the albedo of a heterogeneous surface (urban/industrial surface). Fluctuations in the reflectivity data and differences between albedo and reflectivity are clearly visible. These differences show that the surface reflects solar radiation anisotropic. The fluctuations in the reflectivity data indicate that the measured surface is heterogeneous. Exemplarily, part (b) shows both quantities for a rather homogeneous surface (agriculture). The values of the albedo and the reflectivity are almost constant and correspond within the error bars for most times, which shows that the surface is most likely an isotropic reflecting surface.

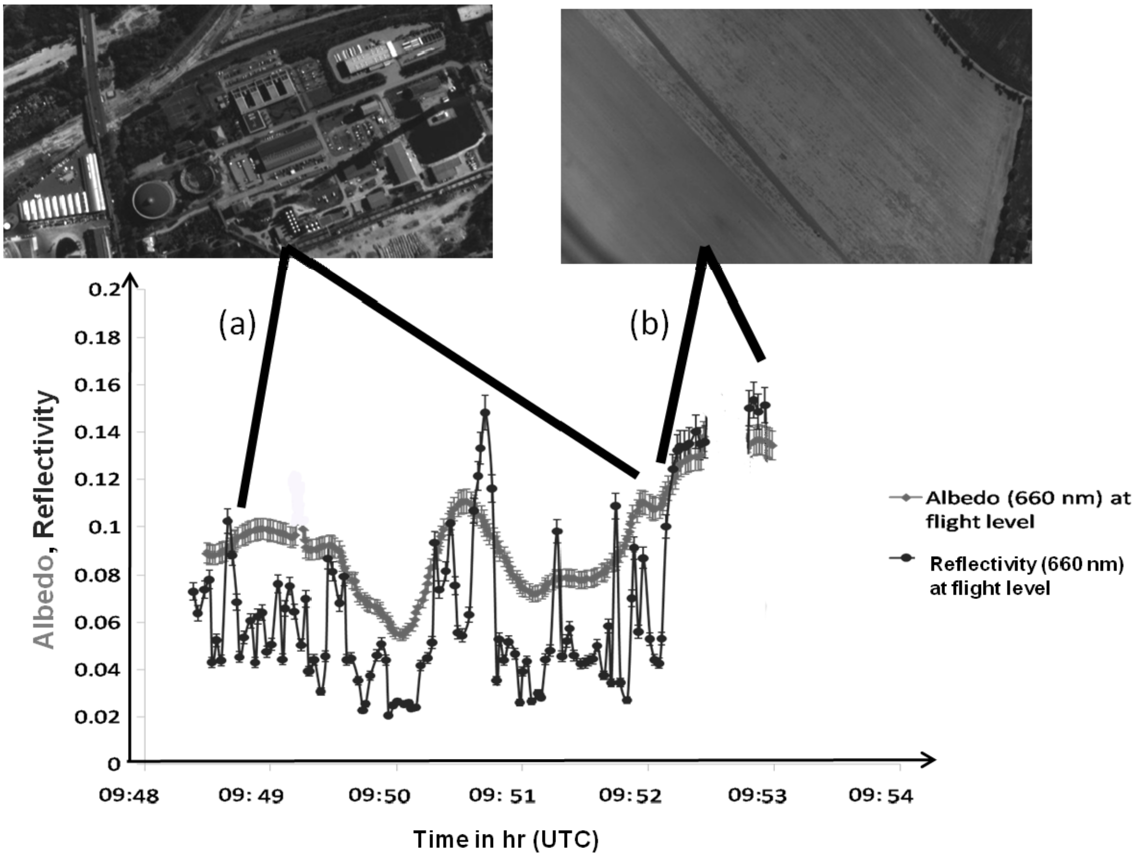

Fig. 2: Time series of albedo (light grey) and reflectivity (dark grey) of 660 nm at flight level, measured on September 23, 2007 over Leipzig, Germany. The time seires corresponds to a spatial data series as the aircraft is moving. Parts (a) and (b) representing different surfaces. (a) Heterogeneous urban surfaces, (b) homogenous agricultural surfaces. The missing data in part (b) was caused by strong aircraft movement (high roll angles) during a turn. The images above are examples for the present surface during the measurements in part (a) and (b).

4.2 Albedo and reflectivity of different surfaces at high flight altitudes

In contrast to the measurements over Leipzig the measurements conducted in Zhongshan have been obtained at a flight altitude of about 4000 m, with two short flight legs (approximately 2 minutes) at 2000 m and 200 m. Two implications on the measured data result from the high flight altitude. Due to the high atmospheric column between surface and optical inlet, the amount of solar radiation scattered by aerosol particles and molecules into the optical inlet is increased compared to the fraction of radiation reflected by the surface. This effect is enhanced by the fact that the main amount of aerosol was in the layer between the surface and the flight level.

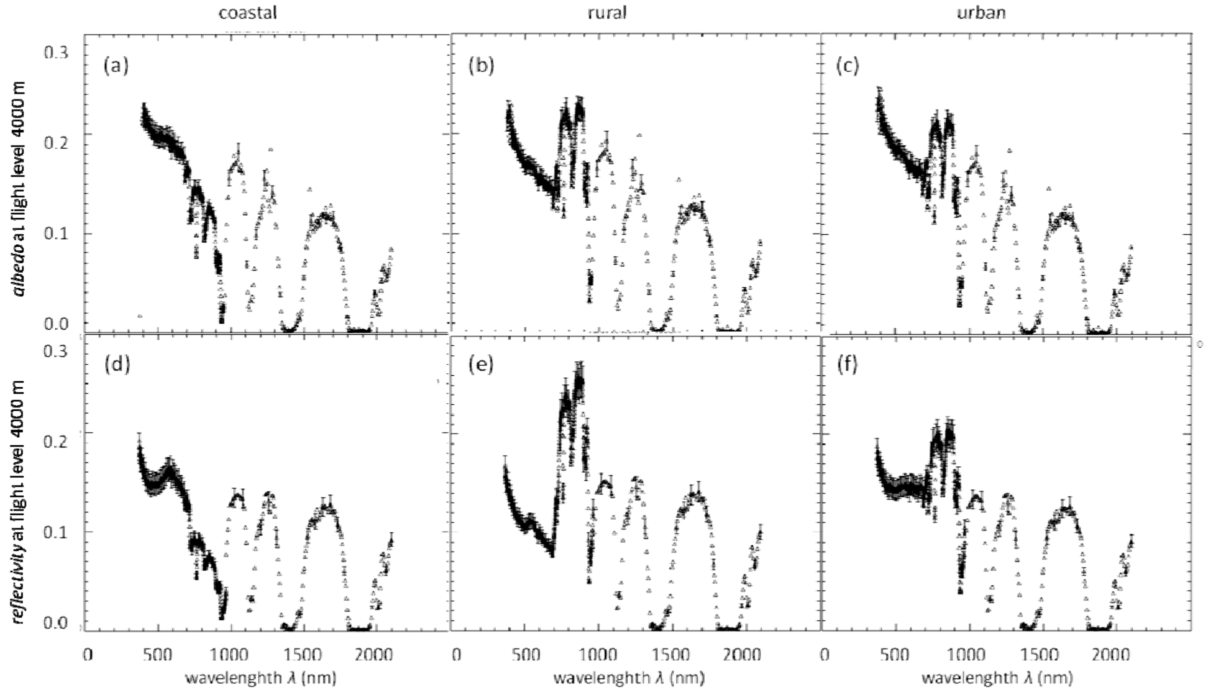

Fig. 3: Albedo (upper row) and reflectivity (lower row) measured at 4000 m flight altitude for different surfaces ((a) and (d) coastal/ocean surface, (b) and (e) rural surface, (c) and (f) urban surface).

Furthermore the surface area relevant for the irradiance measurements is larger compared to measurements obtained at low flight altitude. Therefore, different surface types may be included in one single measurement, e.g. urban surfaces are still visible in the coastal region and vice versa. Figure 3 shows three exemplarily albedo measurements (upper row) and three reflectivity measurements (lower row) of different surfaces. Coastal/ocean surface ((a), (d)) which was observed approximately 7 km away from the coastline, where the sea is relatively shallow and a small island nearby can additionally influence the measurement. Figure 3 (b) and (e) show spectra of rural surfaces in the area between the city of Zhongshan and the coastline. The albedo is therefore influenced both by urban surface and coastal/ocean surface. Spectra of urban reflectivity and albedo are shown in images (c) and (f). Especially the spectra (b) and (c) look similar what can be explained by the mutual influence of the surfaces in the measurements. The reflectivity spectrum in (d) shows a local maximum between 500 and 600 nm which could be caused by four factors: the nearby land surface of the main land, the nearby small island, contamination of the water by green algae, and the ocean surface visible through shallow water.

4.3 Influence of altitude on the observed albedo and reflectivity

The observed albedo and reflectivity at flight altitude is affected by the field of view of the optical inlet and the optical properties of the aerosol below. With increasing flight altitude the observed area is also increasing. Figure 4 shows the spatially averaged spectra of the albedo (upper row) and the reflectivity (lower row). The same surface area of Zhongshan was sampled three times in different flight altitudes (approximately 200 m, 2000 m, and 4000 m). The measured data was averaged for 2 minutes. Additionally to the mean values the standard deviations are shown in Figure 4. The standard deviations indicate the spatial variability of the surface. As expected, the standard deviation of the reflectivity spectra is higher compared to the standard deviation of the albedo spectra, illustrating that the surface heterogeneity is more pronounced in the reflectivity measurements than in the albedo. Especially the reflectivity obtained from measurements at 200 m flight altitude shows high standard deviation values. By contrast, the information of the surface reflectivity is already at 2000 and 4000 m flight altitude and has lower standard deviation values. Both measurements at 2000 and 4000 m ((b), (e) and (a), (d)) look similar and differ from the spectra measured at 200 m ((c), (f)). This can be explained again by multiple scattering processes at higher altitudes, and additionally the stronger influence of the surface in the vicinity of the measured spot in comparison to the measurement at 200 m.

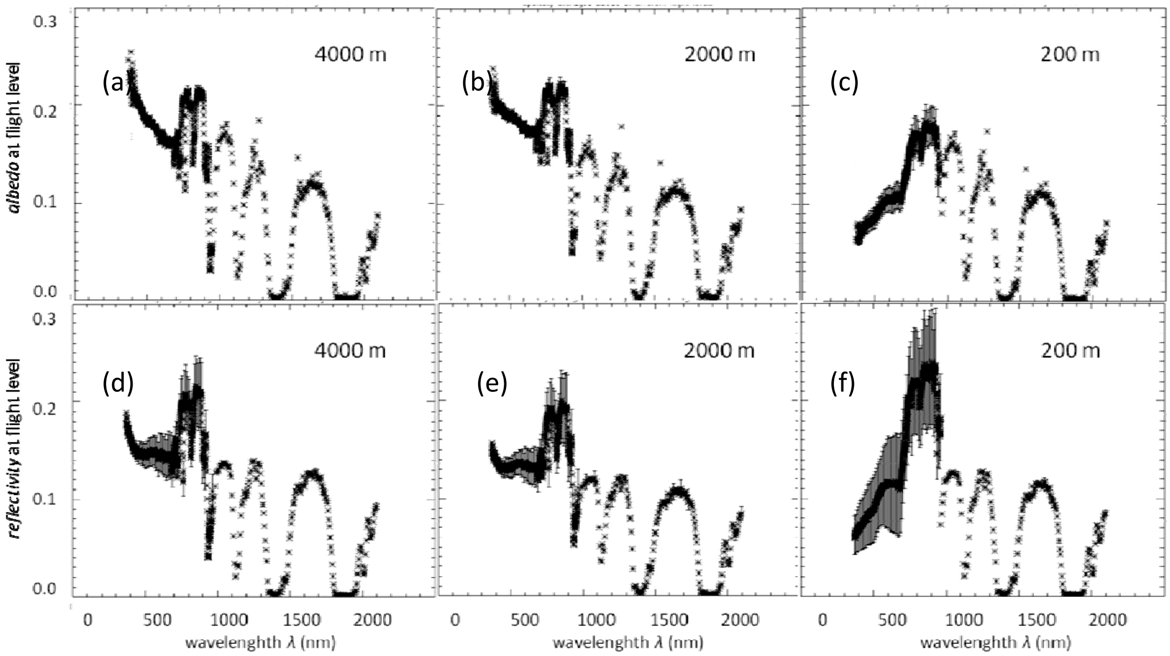

Fig. 4: Spatially averaged albedo and reflectivity at flight level measured at different flight altitudes and corresponding standard deviations as error bars. Only every tenths error bar is displayed for visibility reasons.

5 Conclusions and Outlook

A dataset of reflectivity and albedo measured at flight altitude of the cities Leipzig, Germany and Zhongshan, China was obtained within the framework of the priority program SPP 1233 of the German Research Foundation (DFG) in the years of 2007 and 2009. The simultaneous airborne measurement of albedo and reflectivity allows to draw conclusions about the heterogeneity of a surface, and if a surface is isotropic reflecting or not. It was shown that agricultural surfaces are homogeneous and rather isotropic reflecting surfaces. In contrast, urban surfaces are heterogeneous, visible in the spatial variability of the spectral reflectivity, and not isotropic which is indicated by the difference between spectral albedo and reflectivity.

The measurements of albedo at flight level are strongly influenced by the flight altitude as the area included in the albedo and reflectivity data increases with increasing flight altitude. By this the measurement of urban albedo might for example include ocean albedo information and vice versa. Additionally the effect of multiple scattering increases with increasing flight altitude, as more aerosol particles are available for scattering processes between the observed object and the optical instrument. Same is valid for scattering of radiation on gas molecules.

Atmospheric correction (Wendisch et al., 2004) to obtain surface albedo and reflectivity from the flight level albedo and reflectivity will show if the retrieved spectra are dependent on the flight altitude. Surface reflectivity data of Leipzig and Zhongshan will be used as input parameter in the MODIS AOD retrieval algorithm to check whether it improves the retrieved AOD in comparison to sunphotometer measurements of the AOD (e. g. data from the AErosol RObotic NETwork, AERONET, Holben et al., 1998).

Literature

Bierwirth, E., Wendisch, M., Ehrlich, A. et al., 2008: Spectral surface albedo over Marocco and ist impact on radiative forcing of Saharan dust. Tellus B, Volume 61 (1): 252 – 269

Holben, B.N., Eck, T.F., Slutsker, I. et al., 1998: AERONET—A Federated Instrument Network and Data Archive for Aerosol Characterization. Remote Sensing of Environment, 66 (1): 1 – 16

Justice, C.O., Vermote, E., Townshend, J.R.G, et al., 1998: The Moderate Resolution Imaging Spectroradiometer (MODIS): land remote sensing for global change research. IEEE Transactions on Geoscience and Remote Sensing. 36 (4): 1228 – 1249

Kaufman, Y.J., Wald, A.E., Remer, L.A., et al., 1997: The MODIS 2.1- µm Channel—Correlation with Visible Reflectance for Use in Remote Sensing of Aerosol. IEEE Transactions on Geoscience and Remote Sensing, 35 (5): 1286 – 1298

Levy, R. C., Remer, L. A., Mattoo, S., et al., 2007: Second-generation operational algorithm: Retrieval of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance. Journal of Geophysical Research. 112: D13211

Mayer, B., and Kylling, A., 2005: Technical note: The libRadtran software package for radiative transfer calculations – description and examples of use. Atmos. Chem. Phys. Discuss., 5, 1319–1381

Molina, M.J. and Molina, L.T., 2004: Megacities and Atmospheric Pollution. Air & Waste Manage. Assoc. 54:644 – 680

Wendisch, M., Müller, D., Schell, D. et al., 2001: An airborne spectral albedometer with active horizontal stabilization. J. Atmos. Oceanic Technology, 18, 1856-1866

Wendisch, M., Pilewskie, P., Jäkel, E. et al., 2004: Airborne measurements of areal spectral surface albedo over different sea and land surfaces. Journal of Geophysical Research, 109: D08203

Addresses of Authors

[1] Leipzig University, Institute for Meteorology, Stephanstr. 3, 04103 Leipzig, Germany, b.mey@uni-leipzig.de
[2] Institute of Remote Sensing Applications, Chinese Academy of Sciences, No. 20 Datun Road, Chaoyang District, P.O. Box 9718, Bejing 100101, P.R. China