Forest albedo in the context of different cloud situations derived from irradiance measurements at the Leipzig floodplain crane - A pilot study

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Summary: The surface albedo significantly modulates the atmospheric energy budget and, thus, vertical radiation, energy, and mass fluxes. Therefore, it regulates the local and regional effects of climate warming. Over a forest canopy, the surface albedo mainly depends on the seasonal leaf state. Furthermore, for certain surface types, such as snow, it has been shown that the surface albedo changes as a function of cloudiness. A similar effect is expected over forest surfaces, leading to complex feedback loops between forest surfaces and climate. To investigate these processes, a pilot study was performed at the Leipzig floodplain crane to observe the forest canopy albedo under different atmospheric conditions in 2021. First analyses revealed a dependency of the forest albedo from the cloud state, which is slightly stronger in the near-infrared wavelength range compared to the visible wavelength range.

Zusammenfassung: Der atmosphärische Strahlungshaushalt und damit auch die vertikale Strahlungsverteilung, Energie- und Massenflüsse werden signifikant durch die Bodenalbedo gesteuert. Diese regulieren somit lokale und regionale Effekte der Klimaerwärmung. Über einem Wald hängt die Bodenalbedo hauptsächlich vom saisonalen Blattstatus ab. Zudem wurde für bestimmte Bodentypen wie Schneeoberflächen gezeigt, dass die Bodenalbedo eine Funktion der Bewölkung ist. Ähnlicher Effekte werden für Waldoberflächen erwartet, welche zu komplexen Rückkopplungseffekten zwischen Waldoberflächen und dem Klima führen. Um diese Prozesse zu untersuchen wurde im Jahr 2021 eine Vorstudie am Leipziger Auwaldkran durchgeführt, um die Waldalbedo unter verschiedenen atmosphärischen Bedingungen zu beobachten. Erste Analysen zeigen, dass auch die Albedo des Waldes von den Bewölkungsbedingungen abhängt. Der Effekt ist dabei etwas stärker im nah-infrarotem als im sichtbaren Wellenlängenbereich zu beobachten.

1 Introduction

The surface albedo strongly modulates the atmospheric energy budget and, thus, vertical radiation, energy, and mass fluxes. Therefore, it can regulate the local and regional effects of climate warming (e.g. Davin et al., 2014; Kala and Hirsch, 2020). Over a forest canopy, the surface albedo mainly depends on the leaf state, which changes with meteorological seasons. However, also extreme weather conditions such as droughts or floods influence the leaf state (leaf orientation, e.g., Yanagy and Costa, 2011), the aerosol production (e.g., BVOC emissions, Mentel et al., 2013) and, therefore, the surface albedo on a shorter time scale, which in turn feeds back to the energy budget.

Furthermore, for certain surface types, such as snow, it has been shown that the surface albedo changes as a function of cloudiness (Gardner and Sharp, 2010; Stapf et al., 2020). This is important because the modification of the spectral distribution of solar irradiance by clouds can significantly modify the broadband albedo (Gardner and Sharp, 2010). An increased liquid water path in the atmosphere leads to higher absorption of the downward irradiance in the near-infrared wavelength range, which results in an increased surface broadband albedo. Furthermore, in case of clouds, the direct and diffuse components of the downward irradiance are redistributed to a predominant diffuse component, which further increases the potential for absorption within the near-infrared wavelength range insight clouds. If a similar effect could be demonstrated over forest surfaces, potential feedback loops between forest surfaces and climate would be much more complex.

Assuming, a future climate will be characterized by an increased number of extreme events with longer periods of either cloud-free or cloudy conditions (droughts, extended winter inversion), these differences of the surface albedo are key to better understand possible feedbacks on the local energy budget and vertical exchange of energy, mass, and momentum. Such feedbacks may buffer or even amplify the stable meteorological conditions of extreme periods. However, forests may directly react on extreme weather events by a changing forest-canopy albedo, which needs to be decoupled from the cloud-albedo effect. Furthermore, forest reactions like pollen expectoration, biogenic emissions, and new particle formation are expected in such cases. Depending on the energy budget, turbulent mass fluxes will then redistribute the biogenic aerosol and lead to an exchange with the boundary layer above the canopy where aerosol particles may become relevant as cloud condensation nuclei, which opens another biogenic-atmospheric feedback mechanism.

To investigate if similar effects can be found over a forest like it is discussed by Gardner and Sharp (2010) or Stapf et al. (2020) for Arctic conditions, a pilot study has been performed at the Leipzig floodplain crane in the summer of 2021 to observe the forest albedo under different atmospheric conditions. Spectral irradiance measurements have been obtained at a fixed location at the top of the crane from which the spectral albedo was derived. The cloudiness was characterized by daily observations.

Here, we will give a brief introduction of the pilot study, including descriptions of the measurement site and instrumentation in Sect. 2. Preliminary results from the measurements are discussed in Sect. 3. Subsequently, the potential of this instrument setup to study albedo-vegetation interactions will be evaluated and used to identify gaps in the instrumentation, which have to be filled in future studies.

2 Measurement site and instrumentation

2.1 Leipzig floodplain crane

The following information within this section on the history and specifications of the Leipzig floodplain crane are taken from https://www.auwaldstation.de. The Leipzig floodplain crane (Ger. Leipziger Auwaldkran, LAK) was installed under supervision

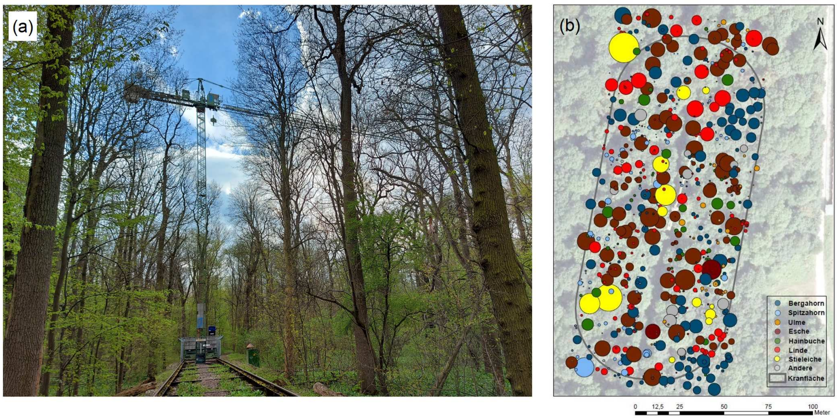

*Fig. 1: **(a)** Photo of the Leipzig floodplain crane taken on 29 April 2021. **(b)** Overview of the distribution and size of the different species in the area that can be reached by the gondola of the Leipzig floodplain crane. Graphic by Ronny Richter, iDIV, https://www.auwaldstation.de/projekte/beobachtungsplattform/der-leipziger-auwaldkran-und-aktuelle-baumkronenforschung/.*

of Prof. Wilfried Morawetz in March 2001. It is located within the Leipzig floodplain north-west of Leipzig, slightly south-west of the Leipzig Auensee at 51.36° N and 12.31° E. After a heavy damage during the century flood in the year 2013, it was reconstructed by the research center iDiv of the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) under supervision of Prof. Christian Wirth. Figure 1a shows a recent photo of the Leipzig floodplaine crane taken on 29 April 2021.

The floodplaine crane reaches 40 m in altitude with a 45 m long crane boom. A gondola is installed at the crane boom to reach the tree tops. The crane itself is installed on rails and can be moved along a horizontal distance of about 120 m. Therefore, tree tops in an oval area of 210 m length and 90 m width can be reached. This includes 800 trees of different species. Figure 1b shows an overview of the distribution and size of the different species in the area that can be reached by the gondola. These species include the common ash (Fraxinus excelsior), the pedunculate oak (Quercus robur), sycamore maple (Acer pseudoplatanus), Norway maple (Acer platanoides), small-leaved lime (Tilia cordata), and hornbeam (Carpinus betulus).

2.2 Spectral irradiance measurement system

To investigate the spectral albedo at the Leipzig floodplain crane it is planned to develop a new measurement system including measurements of the up-and downward spectral irradiance in the visible and near-infrared wavelength range and measurements of the broadband up- and downward irradiance in the solar and terrestrial wavelength range. The system shall be completed by an all-sky imager.

However, to clarify the needs for such a new measurement system with respect to, e.g., sensitivity, power consumption, or installation, the pilot study was performed with the existing COmpact RAdiation Measurement System (CORAS, Brückner et al., 2014), which initially was designed for non-autonomous field studies.

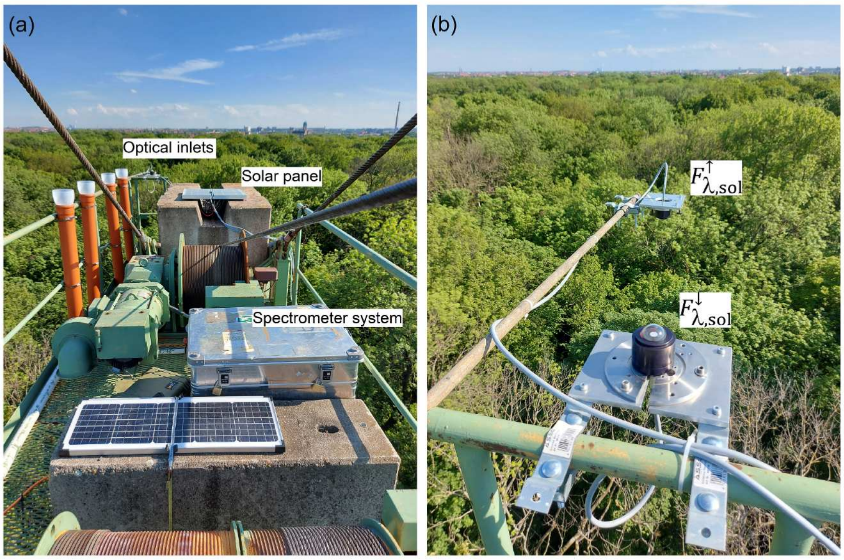

Fig. 2: Photos of the ***(a)*** *spectral irradiance measurement system on the platform of the Leipzig floodplain crane and* ***(b)*** *the up- and downward facing optical irradiance inlets.*

CORAS is a ground–based version of the albedometer introduced by Wendisch et al. (2001), which was designed as a modular system to measure spectral radiometric quantities from airborne platforms. The instrumentation setup installed on the tail platform of the Leipzig floodplain crane is illustrated in Fig. 2. The main parts are the spectrometers and data acquisition installed in a weatherproof box, the optical irradiance inlets, which are connected by optical fibres to the spectrometers, and the power supply, which is realized by a solar panel and batteries.

Two up- and downward–facing optical inlets collect down- and upward irradiance ($F^{\downarrow}_{\lambda}$, $F^{\uparrow}_{\lambda}$). The collected radiation from the inlets is transferred via two bifurcated optical fibers to the spectrometer system. The fibres are isolated with a specific synthetic material adjusted to humid conditions (Brückner et al., 2014).

CORAS consists of four grating spectrometers; per optical inlet one sensitive to the visible and near-infrared wavelength range (VNIR, $\lambda = 400 - 1000$ nm) and one sensitive to the shortwave-infrared wavelength range (SWIR, $\lambda = 1000 - 2200$ nm). The incoming radiation is spectrally dispersed by a grating and detected by a single–line photo-diode array. Data acquisition from CORAS is realized with one computer in a sequential order.

3 Measurements

The pilot study was carried out from 2 June 2021 to 15 December 2021. However, due to the high power consumption of CORAS (120 W) and no permanent power supply at the crane, it was not possible to perform measurements over a full daily cycle each day. Therefore, the daily measurement time was reduced to one hour starting at noon. The rest of the daytime was used to recharge the main battery (400 Wh) by a 200 W solar panel. However, if overcast conditions prevailed for several days, the solar panel did not provide sufficient power to recharge the main battery, which led to data loss for single days. To buffer such cases, the batteries were manually recharged and exchanged weekly. Especially at the end of the measurement period (November, December) with

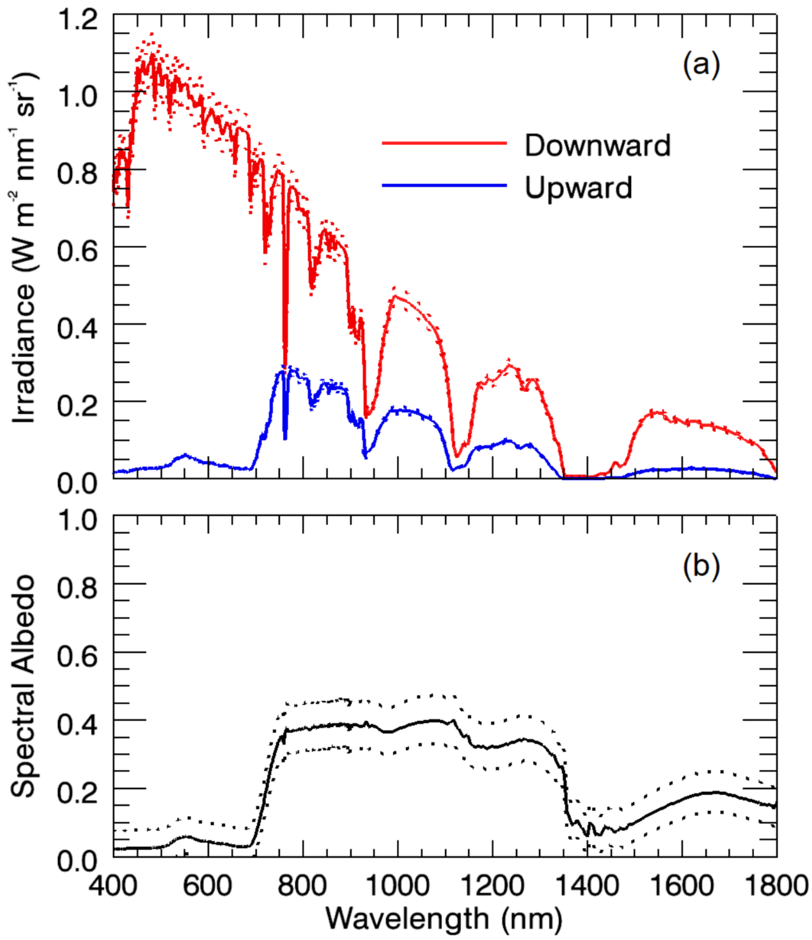

*Fig. 3: **(a)** Spectral up- (blue) and downward (red) irradiance measured at the Leipzig floodplain crane on 2 June 2021, 12:00 local time, 32° solar zenith angle. **(b)** Spectral albedo derived from spectral irradiance displayed in (a). Dotted lines represent measurement uncertainties.*

low Sun conditions the number of data gaps increased. However, for the full period of measurements, irradiance data on 51 different days were collected.

3.1 Spectral irradiance and albedo

Figure 3a shows example measurements of the spectral downward (red) and upward (blue) irradiance. While the shape of the downward measured irradiance spectrum is mainly influenced by atmospheric absorption bands, the upward irradiance is clearly shaped by the imprint of vegetation features. It shows low irradiance below 700 nm followed by the steep vegetation step.

The spectral albedo calculated from the upward and the downward irradiance is displayed in Fig. 3b. For values up to about 700 nm the albedo shows the same behaviour like the upward irradiance, starting with low values at small wavelengths followed by the steep vegetation step. However, for the wavelength range between 800 nm and 1300 nm the influence of the atmospheric absorption bands almost vanishes.

However, the main focus of the pilot study was to investigate, if a dependency of the forest albedo on the presence of clouds can be identified. For this, a first test is

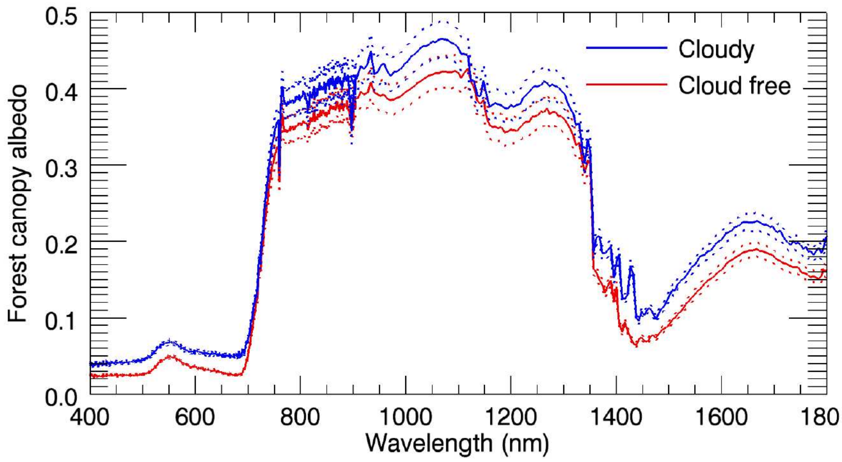

*Fig. 4: **(a)** Spectral albedo measured during cloud-free conditions on 9 September 2021 (red) and during overcast conditions on 10 September 2021 (blue) at 12:00 local time, 48° solar zenith angle. Dotted lines represent measurement uncertainties.*

performed by comparing the spectral albedo for the two extreme cases of fully cloud-free and fully cloudy conditions. The particular times were identified manually. One important requirement for the comparison was that these two cases appeared in close temporal collocation to avoid large differences of solar zenith angle, atmospheric and forest conditions. A further requirement was that the crane was located at the same position on the rail with equal horizontal orientation of its boom to observe the same part of the forest canopy in both cases. Several of these combinations were found.

Figure 4 shows a selected case with cloud-free measurements performed on 9 September 2021 and overcast conditions measured on 10 September 2021. In general, larger albedo was observed in the cloudy case compared to the cloud-free case. A more detailed spectral comparison reveals differences in the albedo spectra of 0.02 in the visible wavelength range to up to 0.05 in the near-infrared wavelength range. The broadband albedo is 0.17 for the cloud-free case and increased to 0.2 for the cloudy case. Similar differences were found for the other identified cases, while the differences were negligible for inter-comparisons of cloud-free measurements or cloudy measurements only.

Although the presented measurement case is still based on preliminary results and need further evaluation, it already implies a good potential of the measurements at the Leipzig floodplain crane.

3.2 Temporal variation of the forest canopy albedo

At the moment only data of one hour per day with an increasing number of data gaps until the end of the period exist. However, to gain statistical significance and to consider also cloud fractions in between the maxima of overcast and cloud-free conditions, a time series of the whole measurement period was analyzed.

Since the cloudiness at the site was not recorded automatically, the cloud fraction data for the following analysis were taken from satellite observations with Sentinel 5P. An advantage of this method is that the cloud fraction is then also available with high resolution in decimal values between 0 (cloud free) and 1 (cloudy).

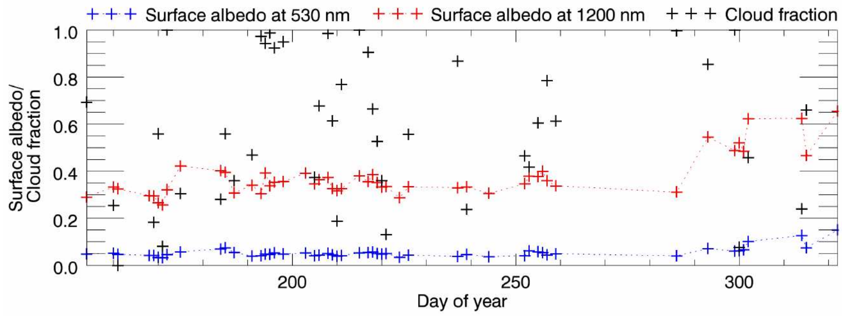

*Fig. 5: **(a)** Time series of forest canopy albedo at 530 nm (blue) and 1200 nm (red) measured with CORAS at 12:00 local time and mean cloud fraction (black) observed by Sentinel 5P in the time period from June to November 2021.*

Figure 5 shows the forest canopy albedo observed by CORAS at 530 nm (blue crosses) and at 1200 nm (red crosses) and the cloud fraction observed by Sentinel 5P (black crosses) during the whole period of the pilot study. The forest canopy albedo is fluctuating around a rather constant average value over most of the measurement period until it is rising while approaching the end of the measurement period. This increase of the forest canopy albedo at the end of the measurement period is related to the change of the vegetation structure from a state of trees with many healthy green leaves via a time when the leaves turn yellow until the trees have lost almost all their leaves.

However, besides this increase of the forest canopy albedo at the end of the measurement phase, the forest canopy albedo shows constant fluctuations around a mean value. These fluctuations are most likely related to changes in the cloudiness. Comparing the time series of the averaged broadband albedo with the time series of the mean cloud fraction indicates a slight correlation. In both time series, when the averaged broadband albedo has a peak to higher values, often also in the mean cloud fraction a peak with higher values is observed. For minima in the albedo values it behaves vice versa. This hints to a measurable dependency of the forest canopy albedo from the state of cloudiness and is worth to be analysed by a longer time series with measurements during a full daily cycle.

4 Summary and conclusions

To investigate the forest canopy albedo as a function of the cloudiness, it is planned to develop a new measurement system including measurements of the up-and downward spectral irradiance in the visible and near-infrared wavelength range and measurements of the broadband up- and downward irradiance in the solar and terrestrial wavelength range. The system shall be completed by an all-sky imager. However, to clarify the needs for such a new measurement system with respect to, e.g., sensitivity, power supply, or installation, a pilot study was performed at the Leipzig floodplain crane to observe the forest canopy albedo under different atmospheric conditions in the year 2021. For this pilot study, measurements at a fixed location at the top of the crane including irradiance observations were performed with the existing COmpact RAdiation measurement System (CORAS).

First analysis reveal a similar behaviour of the forest canopy albedo like it was described by Gardner and Sharp (2010) or Stapf et al. (2020) for Arctic surfaces; an increasing cloudiness leads to a higher surface albedo compared to the cloud-free state. For the measurements at the Leipzig floodplain crane this was demonstrated by comparing albedo spectra of both cases; cloud-free and cloudy conditions. Furthermore, it was shown that the time series of the forest canopy albedo and cloud fraction hints to such a dependency, although the variations in the forest canopy albedo need to be disentangled from seasonal variations.

However, the findings within this study are based on a preliminary analysis using a dataset with only one hour measurement time per day. A more comprehensive data set including complementary measurements to characterize cloud properties are required to quantify the interaction between clouds and vegetation. It needs to be a system, which covers a full daily cycle of irradiance measurements with high temporal resolution. Furthermore, the system must be able to automatically record the state of cloudiness in parallel and to allow the retrieval of the cloud microphysical properties from measurements of the transmitted radiation. Such a new system is currently in planning and might be operational by the end of 2022. As soon as it is established the continuously gathered data will allow to parameterize the forest canopy albedo as a function of the cloud state.

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