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Areal-Averaged Surface Albedo (ArealAveAlb) Value-Added Product

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Executive Summary

The surface albedo plays an important role in the Earth's radiation balance. This report provides information on how to estimate areal-averaged surface albedo from ground-based measurements of solar radiation at five wavelengths (415,500,615,675, and 870 nm). The report first explains why this estimation is important and challenging. Then the report defines both the required and complimentary inputs for the corresponding Areal-Averaged Surface Albedo (ArealAveAlb) Value-Added Product (VAP) and highlights the major outputs of this VAP. The following section explains how estimation of the areal-averaged surface albedo at four wavelengths (500,615,675, and 870 nm) can be performed for different surface types, including those partly covered by snow. The final section provides three examples that illustrate the VAP's performance and emphasizes the benefits of complementary inputs, such as distinct cloud types and precipitation.

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Acronyms and Abbreviations

AMF	ARM Mobile Facility
ArealAveAlb	Areal-Averaged Surface Albedo Value-Added Product
ARM	Atmospheric Radiation Measurement
CBH	cloud base height
cldtype	Cloud Type Classification Value-Added Product
COD	cloud optical depth
ENA	Eastern North Atlantic
MFR	multifilter radiometer
MFRSR	multifilter rotating shadowband radiometer
MFRSRCLDOD	Cloud Optical Properties from the Multifilter Shadowband Radiometer Value-Added Product
NetCDF	Network Common Data Form
PNNL	Pacific Northwest National Laboratory
SGP	Southern Great Plains
SURFSPECALB	Spectral Surface Albedo Value-Added Product
TSI	total sky imager
VAP	value-added product

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1.0 Introduction

Surface albedo, the ratio of irradiance reflected from a surface to the downwelling irradiance reaching that surface, is essential for understanding the Earth's radiation balance. To estimate both broadband and spectral surface albedo over large areas, researchers often rely on reflected solar radiation measured by aircraft and satellites (e.g., Jäkel et al. 2024). However, these methods have well-documented uncertainties, primarily due to the lack of direct measurements of solar radiation incident on and reflected from the surface. Conversely, towers measure both incident and reflected radiation and provide "local" surface albedo data for a small area. Typically, tower-based measurements of surface albedo are limited to a few well-established sites, largely due to the high cost of these measurements.

Unlike the few well-established sites, the ARM Mobile Facilities (AMFs) have been deployed to many locations around the world. The AMFs are equipped with a range of instruments for measuring surface downwelling solar radiation, including the multifilter rotating shadowband radiometer (MFRSR). Spectrally resolved measurements of solar radiation offered by the MFRSR have been widely used to retrieve cloud optical and microphysical properties, such as cloud optical depth (e.g., Turner at al. 2021). Barnard et al. (2008) introduced a simple expression that analytically links the cloud optical depth (τ), surface albedo (A), and asymmetry factor (g) with measured atmospheric transmission under overcast conditions. This transmission can be obtained from widely available ground-based measurements of downwelling irradiances at both the well-established sites and AMFs. The atmospheric transmission provided by MFRSR at five wavelengths (415, 500, 615, 675, 870 nm) together with the simple expression (Barnard et al. 2008) were used to retrieve spectrally resolved areal-averaged albedo at four wavelengths (500 ,615, 675, 870 nm). The feasibility of this retrieval has been demonstrated for different snow-free landscapes using multiyear data collected at the ARM Southern Great Plains (SGP; Kassianov et al. 2014) and Eastern North Atlantic (ENA; Kassianov et al. 2017) sites.

The ARM value-added product (VAP) known as Areal-Averaged surface Albedo (ArealAveAlb) has extended this retrieval (Kassianov et al. 2014). The extension includes two major new components. The first component incorporates additional information, such as cloud base height (CBH) and cloud type. The CBH information is beneficial to estimate an area represented by the retrieved areal-averaged surface albedo, while cloud type information (e.g., liquid clouds versus ice clouds) helps in specifying the asymmetry factor properly. The second component involves merging available tower-based surface albedo measured at 415-nm wavelength with the spectrally resolved MFRSR transmittance. This merging enables the retrieval of areal-averaged surface albedo at four wavelengths (500, 615, 675, 870 nm) for both snow-free landscapes and areas partly covered by show. However, if tower-based measurements of surface albedo at 415-nm wavelength are unavailable, the VAP assumes a surface albedo of 0.04 at 415 nm wavelength, representing snow-free landscapes. Consequently, without these tower-based measurements, the VAP can only be applied for snow-free environments.

2.0 Input Data

The ArealAveAlb VAP requires the following input files with standard ARM NetCDF format. These files are provided by three ARM-supported VAPs.

2.1 Cloud Optical Properties from the MFRSR (MFRSRCLDOD) VAP

mfrsrcldod1min.c1

This VAP provides both the primary and complementary inputs (Turner at al. 2021). These inputs represent "horizontally homogeneous" stratiform clouds with optical depths greater than 7 for snow-free locations.

Primary inputs:

1. atmospheric **transmittance** measured at five wavelengths (415, 500, 615, 673, and 870 nm)
2. **cosine of solar zenith angle**
3. **fractional sky cover** obtained from broadband measurement.

Complementary input: **cloud optical depth** at 415-nm wavelength.

2.2 Spectral Surface Albedo (SURFSPECALB)

surfspecalb1mlawer.c1

This VAP provides complementary **surface albedo at 415-nm wavelength** using data offered by downward-looking multifilter radiometers (MFRs) installed at designated tower levels (McFarlane et al., 2023). The exact levels vary by site location. For instance, at the SGP Central Facility, surface albedo is measured at both the 10-m and 25-m tower levels.

2.3 Cloud Type Classification (cldtype) VAP

cloudtype.c1

This VAP provides complementary **cloud types** (Table 1) using macrophysical data offered by vertically pointing lidar and radar (Flynn et al. 2017).

Table 1. Seven cloud types classified by the cldtype VAP and their abbreviations.

Cloud Type	Abbreviation
1. Low clouds	LC
2.Congestus	Cong
3. Deep convection	DC
4. Altocumulus	ACum
5. Altostratus	AStr
6. Cirrostratus	CiStr
7. Cirrus	Ci

Moreover, this VAP provides complementary information regarding precipitation (mm/min) offered by the surface meteorological system.

2.4 Total Sky Imager (TSI) Primary Variables

tsiskycover.c1

Two primary variables are obtained from hemispheric sky images during daylight hours (Morris 2005): (1) the **percentage of opaque clouds** and (2) the **percentage of thin clouds**. The ArealAveAlb VAP uses these two variables as complementary input to confirm the presence of optically thick stratiform clouds.

3.0 Output Data

The ArealAveAlb VAP generates both primary and complementary outputs. The primary output is **areal-averaged surface albedo** estimated at four wavelengths (500, 615, 673, and 870 nm). The complementary output is **cloud optical depth** estimated at 415-nm wavelength.

One file is created each day named with the following convention:

SSSarealavealbXX.c1.YYYYMMDD.hhmmss.nc where: SSS = the location of the instrument (sgp, ena, etc.) arealavealb = the name of this VAP XX = facility (e.g., C1, E13, …) YYYYMMDD = year, month, day hhmmss = hour, minute, second.

4.0 Method

The solution for cloud optical depth is expressed by a one-line equation (Barnard et al. 2008):

$$\tau_\lambda \ = \ \frac{4}{3}\left(\frac{1.25}{r_\lambda} - 1\right) \ / \ [(1 - A_\lambda)(1 - g_\lambda)], \tag{1}$$

where r_λ, A_λ and g_λ are a "normalized" atmospheric transmission, area-averaged surface albedo, and asymmetry factor for a given wavelength (λ), respectively. The normalized atmospheric transmission is defined as $r_\lambda = T_\lambda/\mu^{1.5}$, where T_λ and μ are the measured atmospheric transmission and cosine of solar zenith angle.

Equation (1) can be re-written for the surface albedo estimation as:

$$A_\lambda \ = \ 1 \ - \ \frac{4}{3}\left(\frac{1.25}{r_\lambda} - 1\right) \ / \ [\ \tau_\lambda(1 - g_\lambda)] \tag{2}$$

Equations (1) and (2) form the basis of the ArealAveAlb VAP. Here is an outline of two major steps:

1. The estimation of cloud optical depth at the 415-nm wavelength using Equation (1). This equation includes the measured normalized transmission (r_{415}) and two input parameters (A_{415}, g_{415}). These two parameters can be assumed or obtained from independent measurements. If measurements of A_{415} are unavailable, the VAP assumes that A_{415} is small (0.04). This assumption is generally accurate for most surfaces, with the exception for snow, ice, and sand. If measurements of A_{415} are available at a given level, the VAP uses the measured surface albedo. For the SGP Central Facility, where surface albedo is measured at two levels (both 10-m and 25-m), the VAP takes the average of these two measurements as A_{415}. The VAP assumes that g_{415} is equal to 0.87 for liquid water clouds (e.g., Hu and Stamnes 1993). For ice clouds, the typical value of g_{415} is lower, around 0.80 (e.g., Hu and Stamnes 1993).

2. The estimation of spectral surface albedo at other wavelengths using Equation (2). This equation includes the measured normalized transmission (r_λ) and two cloud parameters (τ_λ and g_λ) for a given wavelength. The VAP assumes that cloud optical depth depends only slightly on wavelength within the spectral range considered here (415-870 nm): $\tau_\lambda = \tau_{415} c_\lambda$. Values of spectrally variable coefficient c_λ (Table 2) are obtained from conventional reports (e.g., Hu and Stamnes 1993) and generally remains close to one. Also, the VAP assumes that asymmetry factor is wavelength-independent ($g_\lambda = g_{415}$) across all wavelengths (415-870 nm). The nearly spectrally neutral behavior of these two major cloud parameters (τ_λ and g_λ) within this spectral range (415-870 nm) has been repeatedly confirmed by numerous observational and theoretical studies (e.g., Hu and Stamnes 1993, Kokhanovsky 2004).

Table 2. Coefficient c_λ as a function of wavelength.

Wavelength, nm	415	500	615	675	870
c_λ	1.0	0.99	1.005	0.96	0.96

5.0 Examples

The ArealAveAlb VAP generates daily quicklooks. To illustrate, three quicklooks generated for the SGP Central Facility are shown in Figures 1-3. Also, a quicklook generated for the ENA observatory is shown in Figure 4. These quicklooks represent four days with predominately overcast and optically thick multi-level clouds, where total τ_415 frequently exceeds 10. Its temporal changes are likely driven by cloud layers mainly composed of water droplets. Examples of these layers include low clouds and water-dominated layers of deep convection clouds at lower altitudes. Thus, the assumed value of 0.87 value for g_415, typical for water clouds, (Section 4) appears appropriate for these days. The latter are characterized by distinct surface types at the SGP and ENA sites and surrounding areas.

On the first day, the surface was partially covered by snow throughout the day. The areal-averaged surface albedo was relatively high (around 0.7), with small spectral variations as illustrated in Figure 1. These variations are likely associated with the opposite spectral changes of snow-covered surfaces and those covered by vegetation and soil. Typically, snow albedo decreases with increasing wavelength moderately (about 10-20%) in the 415-870-nm range (e.g., Miller et al. 2016), whereas albedo for vegetation and soil tends to increase with wavelength substantially (up to several times) in this spectral range (e.g., Michalsky et al. 2003, McFarlane et al. 2011).

On the second day, the surface remained snow-free and dry throughout, with small-to-moderate diurnal and spectral changes in the areal-averaged surface albedo (Figure 2). The diurnal changes were likely influenced by small-to-moderate variations in the CBH. Note that the areal-averaged surface albedo represents a large area, with a radius more than three times greater than the CBH (Kassianov et al. 2015).

On the third day, the surface was also snow-free but wet due to precipitation throughout the day. Like the previous dry day (Figure 2), the diurnal changes in the areal-averaged surface albedo were small to moderate (Figure 3). However, unlike the dry day (Figure 2), the albedo values across all wavelengths showed a noticeable reduction (Figure 3), likely due to enhanced soil moisture making the surface darker (e.g., Twomey et al. 1986, Yang et al. 2020).

On the fourth day, the surface was partially covered by ocean. In contrast to the snow albedo, ocean albedo is relatively low, approximately 0.06 at a 500-nm wavelength (Kassianov et al. 2017). Similar to the snow albedo, the ocean albedo decreases slightly (about 10-20%) with increasing wavelength (Kassianov et al. 2017). These characteristics of the ocean albedo regarding its magnitude and spectral dependence contribute to the differences observed in the areal-averaged surface albedo estimated for the SGP site (Figures 1-3) and the ENA site (Figure 4). Specifically, the areal-averaged surface albedo at the ENA site was moderate, around 0.25 at 870 nm, with relatively minor spectral variations (see Figure 4 compared to Figure 2).

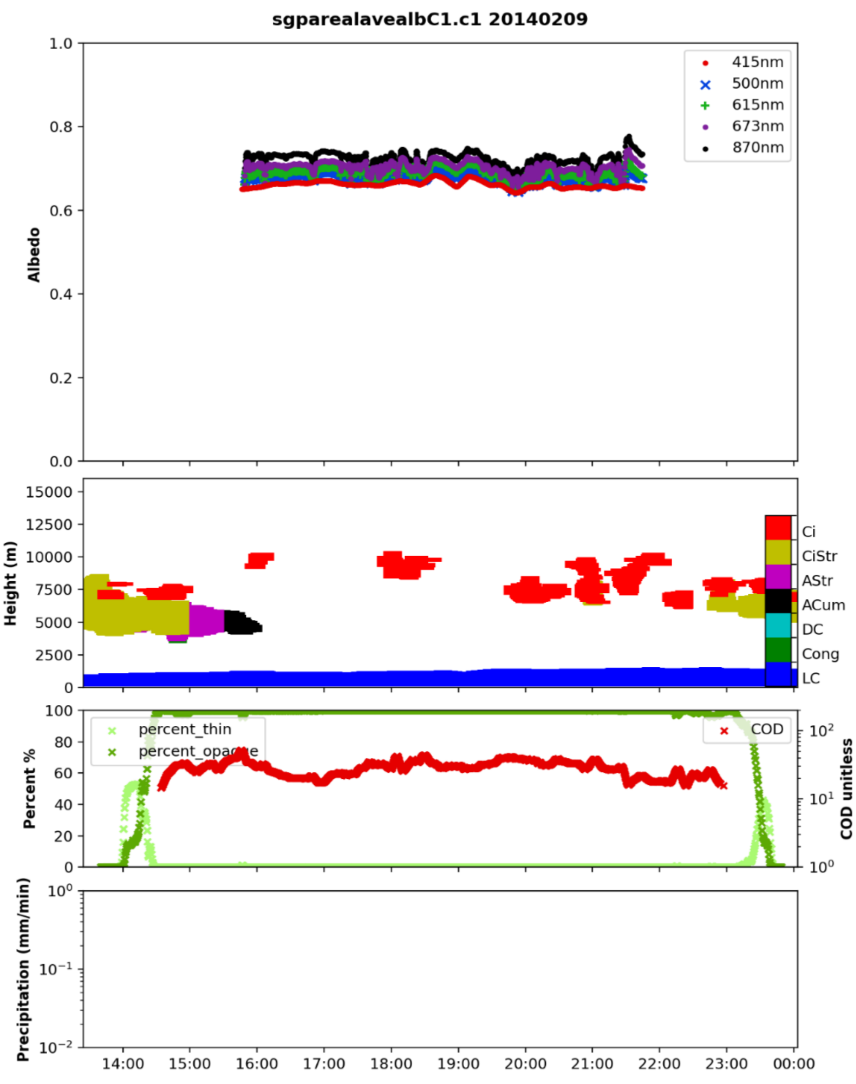

Figure 1. Example of quickplot generated for a given day (February 9, 2014) at the ARM SGP C1 site. First panel from the top: average of 10-m and 25-m tower-based surface albedos measured at 415-nm wavelength (red) and areal-averaged surface albedo retrieved at four wavelengths (500, 615, 673, and 870 nm). Second panel: distinct cloud types. Third panel: cloud optical depth (COD) retrieved at 415-nm wavelength (red) and the percentage of opaque clouds (dark green) and the percentage of thin clouds (light green). Fourth panel: precipitation.

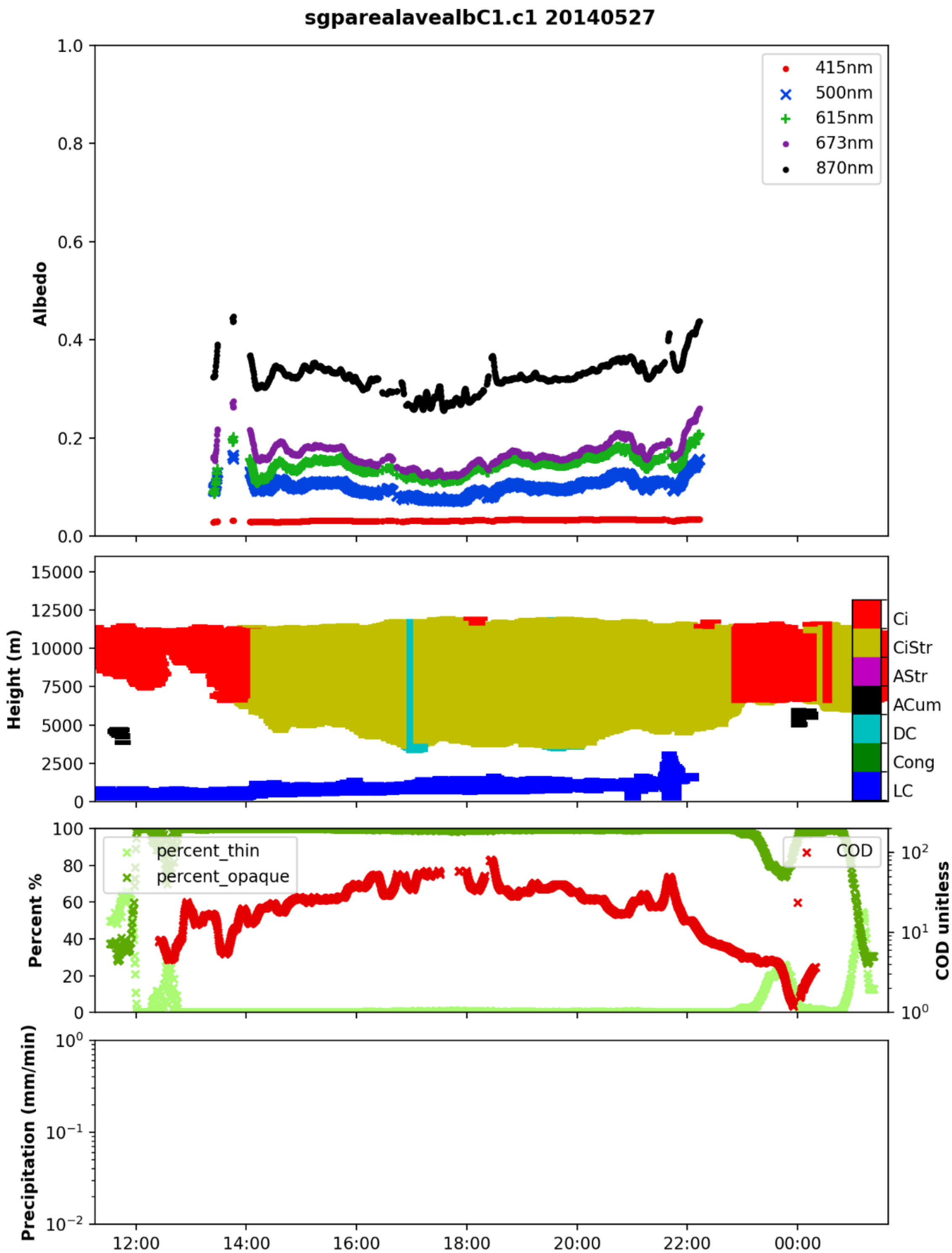

Figure 2. The same as Figure 1 except for another day (May 27, 2014).

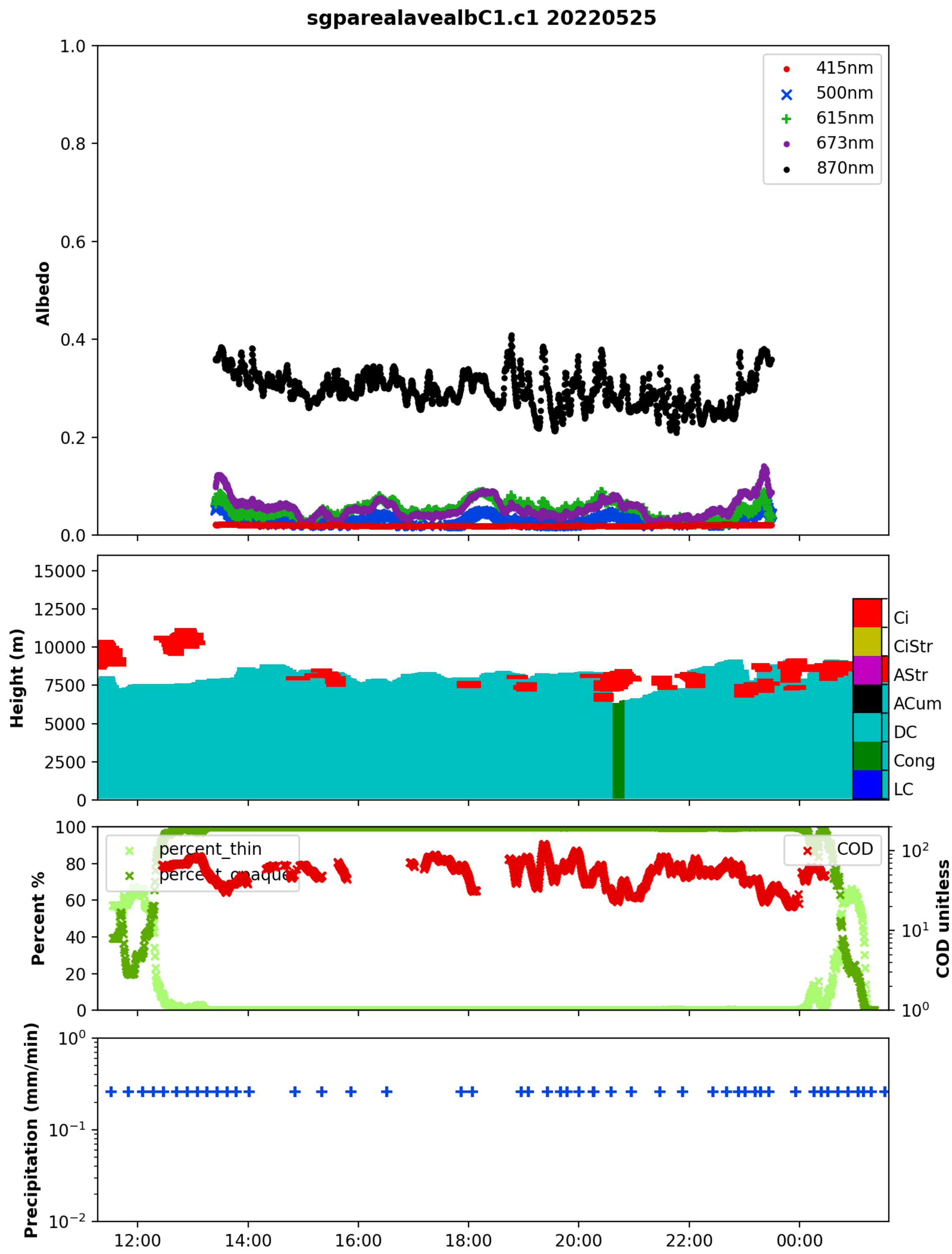

Figure 3. The same as Figure 1 except for another day (May 25, 2022).

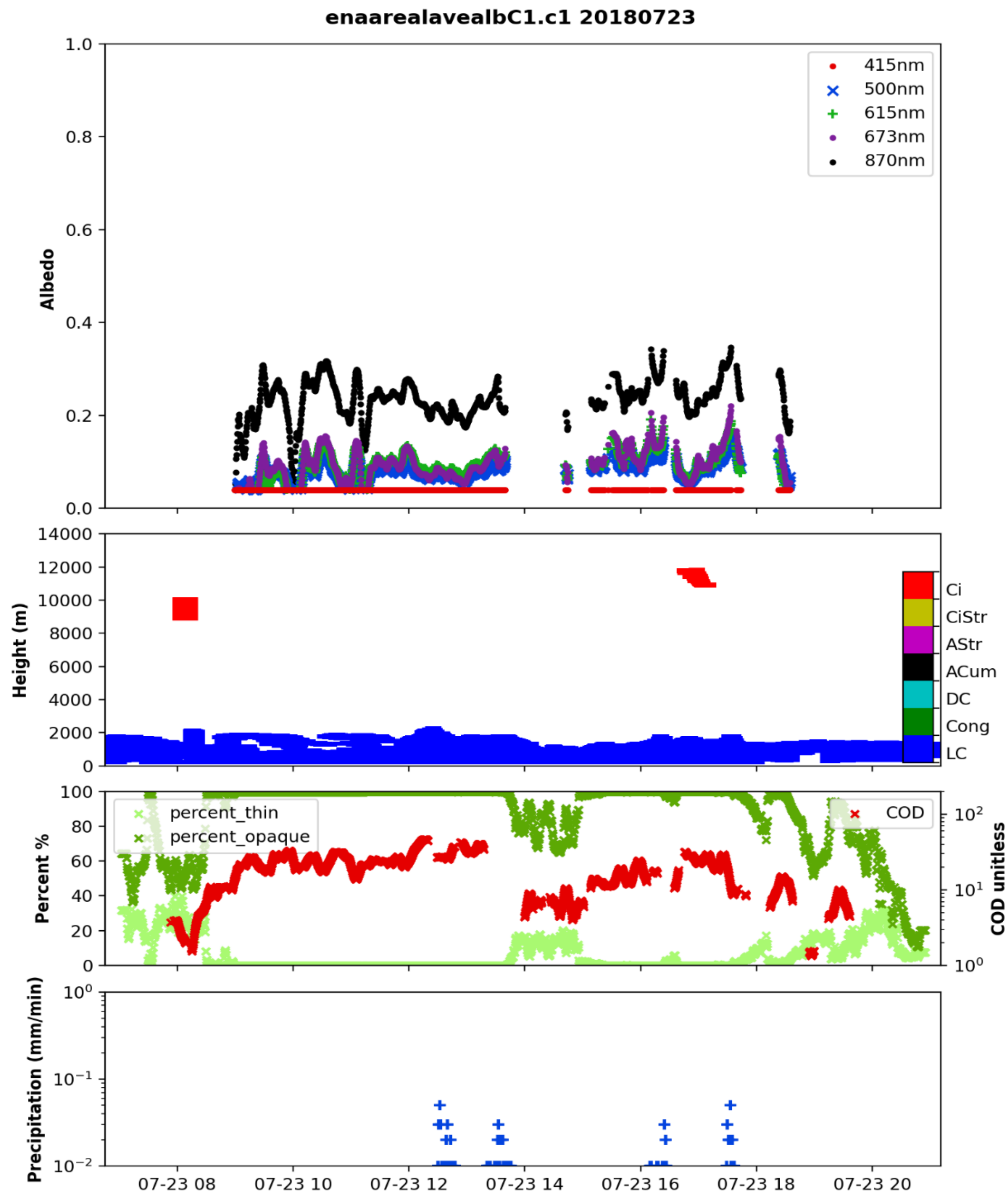

Figure 4. The same as Figure 1 except for another site (ENA) and day (July 23, 2022).

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