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Angular Variability of the Liquid Water Cloud Optical Thickness Retrieved from ADEOS-POLDER

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► **To cite this version:**

Jean-Claude Buriez, Marie Doutriaux-Boucher, Frédéric Parol. Angular Variability of the Liquid Water Cloud Optical Thickness Retrieved from ADEOS-POLDER. Bulletin of the American Meteorological Society, 2001, 58 (20), pp.3007-3018. 10.1175/1520-0469(2001)0582.0.CO;2 . hal-00811820

HAL Id: hal-00811820

<https://hal.science/hal-00811820v1>

Submitted on 16 Dec 2020

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a given target, constraining such a model to adequately match a set of bidirectional observations is much more demanding. Consequently, POLDER not only allows retrieval of cloud optical thickness for some assumed model (e.g., plane-parallel assumption with an assumed droplet size distribution), but it also provides a means of examining the self-consistency in the retrieved optical thicknesses, and thus the validity of the assumed model.

This ability to test cloud models was first demonstrated from measurements acquired by the POLDER airborne simulator during the Atlantic Stratocumulus Transition Experiment (Descloîtres et al. 1995) and the European Cloud and Radiation Experiment (Descloîtres et al. 1998). The validity of the plane-parallel cloud model was investigated. The standard water droplet cloud model (with an effective radius of $10 \mu\text{m}$) used in the ISCCP analysis was found to be suitable for stratocumulus clouds. For cirrus clouds, the ice polycrystal model chosen for the reanalysis of ISCCP (Rossow et al. 1996) appeared highly preferable.

The standard cloud water droplet model is also used in the operational algorithm of the POLDER “Earth Radiation Budget (ERB) and clouds” line that derives cloud optical thickness from Advanced Earth Orbiting Satellite (ADEOS)–POLDER data. As expected, first results based on the 10 November 1996 observations over ocean have confirmed that the water droplet model is suitable for liquid water clouds and inadequate for ice clouds (Parol et al. 1999). Since then, several ice cloud particle models were investigated (Doutriaux-Boucher et al. 2000).

This paper focuses on liquid water clouds. Despite a general agreement observed for such clouds from a limited dataset, Parol et al. (1999) outlined a possible weakness of the $10\text{-}\mu\text{m}$ plane-parallel cloud model for values of scattering angle around 80° . That corresponds to large solar zenith angles in the forward direction, which may induce a serious weakness of the plane-parallel approximation as already noted from Advanced Very High Resolution Radiometer (AVHRR) observations (Loeb and Coakley 1998). The aim of this paper is to investigate further the validity of this model for liquid water clouds. Observations sampled throughout the eight months of available ADEOS–POLDER are examined.

Section 2 presents the criteria of selection and the corresponding selected POLDER data. The departure of the observations from the standard plane-parallel model used in the ERB and clouds line is analyzed with respect to different geophysical parameters. The results are reported in section 3. The influence of cloud droplet size and of cloud heterogeneity is considered in sections 4 and 5, respectively. Some conclusions about the plane-parallel approximation are drawn in section 6.

2. Selected POLDER ERB and clouds data

The POLDER instrument functioned nominally aboard ADEOS during 8 months (between November

1996 and June 1997). POLDER is a camera composed of a wide field-of-view ($\sim 2200 \text{ km}$) telecentric optics, a rotating wheel carrying spectral filters and polarizers, and a charged coupled device (CCD) array of 242×274 detectors that induces a moderate spatial resolution of 6.2 km . POLDER was in a sun-synchronous orbit with an equatorial crossing time of 1030 LT. As the ADEOS satellite passed over a scene, up to 14 successive measurements were acquired in eight narrow spectral bands located between 443 and 910 nm. The POLDER level 1 products routinely processed by CNES (the French Space Center) consist of calibrated radiances and Stokes parameters at full spatial resolution. The level-2 ERB and clouds product provides cloud properties (cloud amount, cloud optical thickness, cloud thermodynamic phase, cloud pressure, etc.) over $\approx 56 \text{ km} \times 56 \text{ km}$ “superpixel” regions ($\approx 9 \times 9$ full-resolution $6.2 \text{ km} \times 6.2 \text{ km}$ POLDER pixels).

A detailed description of the ERB and clouds algorithm is given in Buriez et al. (1997) and Parol et al. (1999). The cloud detection scheme consists of a sequence of threshold tests based on reflectance R_λ ($\lambda = 865 \text{ nm}$ over ocean, 443 nm over land), 443 and 865 nm polarized radiance, and R_{763}/R_{765} and R_{443}/R_{865} ratio. Cloud optical thickness is estimated from 670 nm reflectance using a lookup table approach based on plane-parallel theory; a small modification was added to improve this estimation (see appendix). Cloud phase is derived from polarized reflectance at 865 nm . Cloud level pressure is derived using two different methods: the “oxygen” pressure is derived from absorption measurements in the oxygen-A band and the “Rayleigh” pressure is derived from spectral polarization measured at scattering angles ranging between 80° and 120° . Note that the algorithms are applied to each full-resolution POLDER pixel and direction but the whole results are averaged at the superpixel scale.

The analysis of the different “directional” values of cloud optical thickness is not very meaningful since a change in optical thickness by 1 can correspond to a change in cloud reflectance by 0.1 or 0.001, depending on whether the optical thickness is small or large. Instead, a logarithmic scale is often preferred (e.g., Pawlowska et al. 2000). Here we choose to make use of a representation, introduced in the ISCCP scheme, that is equivalent in radiative energy amount. Practically, the calculated parameter is the cloud visible spherical albedo. The spherical (or diffuse) albedo is obtained by integrating the reflectance over all viewing zenith, solar zenith, and relative azimuth angles, and is defined for a plane-parallel cloud layer over a black surface with no atmosphere. In other words, it represents the cloud reflectance independent of directional, surface, and atmospheric effects. Therefore it is a one-to-one function of the cloud optical thickness for a given microphysical model. In the POLDER processing scheme, this function (hereafter referred to as S_{10}) is calculated for a homogeneous cloud layer composed of liquid water droplets

it clearly appears that any realistic value of droplet size cannot explain the observations for the smallest values of scattering angle under the assumption of the homogeneous plane-parallel model.

In the foregoing, the plane-parallel cloud layer is assumed vertically homogeneous. As the effective radius of cloud droplets generally increases with height (e.g., Gerber 1996), one can question whether this vertical variability can significantly affect the retrieval of cloud optical thickness as a function of scattering angle. Following Nakajima and King (1990), for typical distributions of droplet size the effect of this vertical stratification induces an overestimation of the cloud optical thickness by no more than 3% and moreover this error is not very dependent on the observational angles. To be sure, we computed the reflectance of an adiabatic cloud model with a typical optical thickness of 10, for a solar zenith angle of 60° : the liquid water content w increases linearly with height and the effective radius of droplets increases as $w^{1/3}$ up to $10 \mu\text{m}$ at the cloud top. We inverted the reflectance values by assuming an effective radius of $10 \mu\text{m}$ constant throughout the whole cloud. The retrieved cloud optical thickness is then 10.32 at nadir ($\Theta = 120^\circ$) and decreases only down to 10.25 in the forward direction ($\Theta = 60^\circ$). That corresponds to a $S_{10}(60^\circ) - S_{10}(120^\circ)$ difference weaker than 0.002, which is quite negligible. Consequently, any realistic microphysics of liquid water cloud appears to be definitely insufficient to explain the decrease of the retrieved optical thickness in the forward direction.

5. Influence of cloud heterogeneities

Heterogeneities in cloud properties can have a large impact on cloud bidirectional reflectances. They can occur because of horizontal variations in cloud liquid water path or because of the variations in cloud shape (finite clouds or simply nonflat cloud tops). Using the independent pixel approximation (IPA) (Cahalan et al. 1994), which is the simplest extension of plane-parallel radiative transfer, we only consider horizontal variations in liquid water path and neglect net horizontal photon transport.

From high spatial resolution Landsat imagery of marine boundary layer clouds, Barker et al. (1996) showed that the distributions of optical thickness can often be approximated by the gamma distribution function,

$$p(\tau) = \frac{1}{\Gamma(\nu)} \left(\frac{\nu}{\langle \tau \rangle} \right)^\nu \tau^{\nu-1} e^{-\nu\tau/\langle \tau \rangle}, \quad (1)$$

where $p(\tau)$ is the normalized distribution function of cloud optical thickness, $\Gamma(\nu)$ is the gamma function, and $\nu = (\langle \tau \rangle / \sigma)^2$ in which $\langle \tau \rangle$ and σ are mean and standard deviation of τ , respectively. In order to investigate the effect of horizontal variations of cloud optical thickness on cloud property retrievals, we make use of this approximation for all the POLDER pixels identified as

liquid water clouds and choose $\nu = 1$. This value is representative of heterogeneous cloudy scenes such as broken clouds rather than overcast stratocumulus clouds and therefore that would correspond to a high degree of heterogeneity at the global scale.

The reflectance of a POLDER full-resolution pixel is then assumed to be

$$\langle R \rangle = \int_0^\infty p(\tau) R_{\text{pp}}(\tau) d\tau, \quad (2)$$

where $R_{\text{pp}}(\tau)$ is the reflectance of a plane-parallel layer of optical thickness τ . Practically $\langle R \rangle$ is approximated with $\nu = 1$ by

$$\begin{aligned} \langle R \rangle &= \sum_i R_{\text{pp}}(\tau_i) \int_{(\tau_{i-1} + \tau_i)/2}^{(\tau_i + \tau_{i+1})/2} p(\tau) d\tau \\ &= \sum_i R_{\text{pp}}(\tau_i) \left[\exp\left(-\frac{\tau_{i-1} + \tau_i}{2\langle \tau \rangle}\right) - \exp\left(-\frac{\tau_i + \tau_{i+1}}{2\langle \tau \rangle}\right) \right], \end{aligned} \quad (3)$$

where two successive values of optical thickness τ_i correspond to a 0.004 increment in spherical albedo.

The POLDER data of the 16 selected days were again processed by replacing the lookup table of R versus τ by a new lookup table of $\langle R \rangle$ versus $\langle \tau \rangle$, by considering cloud droplets with an effective radius of $10 \mu\text{m}$ as in the standard model. Now, the relation between the mean cloud spherical albedo $\langle S_{10} \rangle$ and the mean optical thickness $\langle \tau \rangle$ significantly differs from that of the homogeneous case, as shown in Fig. 1. For example, a cloud spherical albedo of 0.3 corresponds to a mean optical thickness $\langle \tau \rangle = 4.9$ in the inhomogeneous case instead of $\tau = 3.6$ in the homogeneous case. This difference increases with the albedo: a cloud spherical albedo of 0.7 corresponds to $\langle \tau \rangle = 48$ instead of $\tau = 23$. The angular variation of the difference $S_{10,\text{INH}}(\Theta) - S_{10}(\Theta)$ between the directional spherical albedo retrieved with the inhomogeneous cloud model and with the homogeneous one, respectively, is shown in Fig. 13. For a fixed value of scattering angle, the variability of the $S_{10,\text{INH}}(\Theta) - S_{10}(\Theta)$ around the mean difference is typically ± 0.01 . The difference $S_{10,\text{INH}}(\Theta) - S_{10}(\Theta)$ remains always small for large scattering angles but becomes quite significant when Θ decreases down to 60° .

The difference between the directional values of cloud spherical albedo $S_{10,\text{INH}}(\Theta)$ and the reference value $S_{10,\text{INH}}(120^\circ)$ is reported in Figs. 14a and 14b. The inhomogeneous cloud model provides results that are more self-consistent than the homogeneous one. That is obvious from Fig. 14a for maritime situations. This improvement chiefly concerns the observations corresponding to low solar elevations and/or to high spatial variations over the 9×9 pixels composing a super-pixel. For continental situations, the better agreement would be obtained for the inhomogeneous model with

