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Comparison of POLDER apparent and corrected oxygen pressure to ARM/MMCR cloud boundary pressures

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[1] POLDER (POLarization and Directionality of the Earth's Reflectances) cloud oxygen pressures are compared to cloud boundary pressures obtained from the combination of Lidar and Millimeter Wave Cloud Radar ground measurements located at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site. Without ground reflection correction, the apparent pressures are found to be closer to the mean cloud pressure than to the cloud top pressure. Nevertheless, for almost a quarter of our comparison cases the apparent pressure level is found to be below the cloud base level. This problem practically disappears applying a simple correction for the surface reflection effect. The corrected oxygen pressures are then found to be very close (12 hPa on average) to the mean cloud pressure.

INDEX TERMS: 1610 Global Change: Atmosphere (0315, 0325); 1640 Global Change: Remote sensing; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3360 Meteorology and Atmospheric Dynamics: Remote sensing.
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1. Introduction

[2] The first suggestion of using oxygen A-band absorption to infer cloud pressure was made by Yamamoto and Wark [1961]. Together with theoretical efforts [Wu, 1985; Fischer and Grassl, 1991; O'Brien and Mitchell, 1992; Kuze and Chance, 1994], airborne measurements [Fischer et al., 1991; Parol et al., 1994] have been carried out. Recently, satellite measurements of radiances in oxygen A-band have been used to determined cloud pressure. All these studies have shown that oxygen A-band can give information about cloud pressure. They have also shown that the photon penetration problem, enhanced by the influence of ground reflectivity, leads the apparent pressure deduced from oxygen A-band to be greater than the cloud top pressure. For example, Vanbauce et al. [1998] show that apparent pressure deduced from POLDER (POLarization and Directionality of the Earth's Reflectances) measurements is in average 124 hPa larger than pressure calculated from METEOSAT

brightness temperatures and temperature profiles. In the same way, Parol et al. [1999] found an overall shift of 139 hPa between POLDER apparent pressure and ISCCP (International Satellite Cloud Climatology Project) cloud top pressure. Koelemeijer et al. [2001] also found a 65-hPa bias between the oxygen pressure obtained from GOME (Global Ozone Monitoring Experiment) and cloud top pressure deduced from ATSR-2 (Along Track Scanning Radiometer-2) brightness temperatures. Thus it appears that the retrieved oxygen pressure level is not the cloud top level but rather below it. Nevertheless until now, we don't know precisely where this retrieved pressure level is located.

[3] This paper presents a comparison of POLDER apparent oxygen pressure and ground reflectivity-corrected oxygen pressure with cloud boundary pressures obtained from a combination of Lidar and Millimeter Wave Cloud Radar ground measurements. Lidar measurements allow us to determine accurately the cloud base pressure but generally not the cloud top pressure, except for optically very thin clouds. Millimeter wavelength Radars can penetrate through the entire cloud and can obtain the cloud top pressure.

[4] POLDER data are presented in section 2.1 with a short presentation of the operational corrected oxygen pressure algorithm. Lidar and Radar data acquired at the Atmospheric Radiation Measurements (ARM) Southern Great Plains (SGP) site [Clothiaux et al., 2000] are presented in section 2.2. Finally section 3 presents the comparison between POLDER oxygen pressures and ARM cloud boundaries pressures.

2. Data

2.1. POLDER Data

[5] POLDER is a CNES (The French Space Agency) instrument, which was on board the ADvanced Earth Observing Satellite (ADEOS) polar orbiting platform. POLDER consisted of a CCD matrix detector, a rotating wheel carrying spectral filters and polarizers, and a wide field of view lens [Deschamps et al., 1994]. When the satellite passed over a target, up to 14 observations were realized in eight spectral bands of the visible and near infrared spectrum. ADEOS had a heliosynchronous orbit which allowed POLDER to overpass mid-latitude locations nearly once each day. POLDER acquired data from November 1996 to June 1997.

[6] POLDER has two spectral bands centered on the oxygen A-band. The apparent pressure P_{app} is inferred from differential absorption between the radiances measured in the narrowband and the wideband channels centered at 763 and 765 nm respectively. The algorithm of P_{app} derivation is extensively described in *Buriez et al.* [1997]. In this algorithm all scattering effects are neglected and the atmosphere is assumed to behave as a pure absorbing medium overlying a perfect reflector located at pressure P_{app} . Because in reality multiple scattering and O_2 absorption occur inside the cloud, the perfect reflector is not located at the top of the cloud but below it. The retrieved apparent pressure is then always higher than the cloud top pressure. In the case of optically thick clouds, P_{app} is generally situated between the cloud top level and the cloud base. However, in the case of an optically thin cloud layer, a lot of photons can reach the surface before being reflected back to space. In this case, the apparent pressure can be outside the cloud layer limits (apparent pressure greater than the cloud base pressure).

[7] To remove this surface contribution a method has been proposed by *Buriez et al.* [1997]. Let the corrected cloud pressure P_{cloud} be defined as the apparent pressure that would be observed if the surface reflectivity was equal to zero. Because the oxygen A-band corresponds to strong absorption lines, the oxygen transmission T_{O_2} between the top of atmosphere and the pressure level P_{app} can be treated in first approximation by means of a random band model [*Goody*, 1964]:

$$T_{O_2} = \exp(-C\sqrt{m}P_{app}) \quad (1)$$

where m is the air mass and C a constant depending on spectroscopic data. The derivation of T_{O_2} from the measured radiances at 763 and 765 nm is described in *Buriez et al.* [1997]. Schematically, this transmission can be decomposed in a term corresponding to the light directly reflected by the cloud and a term corresponding to the light reflected after reaching the surface:

$$\exp(-C\sqrt{m}P_{app}) = r \cdot \exp(-C\sqrt{m}P_{cloud}) + (1-r) \cdot \exp\left(-C\sqrt{mP_{cloud}^2 + M[P_{surface}^2 - P_{cloud}^2]}\right) \quad (2)$$

where r is the fraction of photons directly reflected by the cloud, M is the effective air mass corresponding to the mean photon path between the cloud and the surface, and $P_{surface}$ is the surface pressure. The surface contribution is obviously all the more important as the surface albedo is large and the cloud optical thickness is weak.

[8] Because P_{cloud} is not directly deducible from equation (2) we use here a simplified method, which is the one retained for the POLDER operational algorithm. Considering that the transmission between the cloud and the surface is a small corrective term and assuming that the effective air mass M is equal to the air mass m , equation (2) can be approximated as:

$$r \cdot P_{cloud} = [P_{app} - (1-r)P_{surface}]. \quad (3)$$

[9] The fraction of photons directly reflected by the cloud r is calculated using $r = R_o/R$ where R is the reflectance measured by POLDER at 765 nm after correction for

gaseous absorption [*Buriez et al.*, 1997] and R_o is the reflectance that would be measured if in addition the surface was black. So the fraction r depends on the surface albedo and the cloud optical thickness. In practice, R_o is computed by using the cloud optical thickness determined from POLDER measurements at 670 nm [*Buriez et al.*, 1997]. $P_{surface}$ is obtained from the ECMWF (European Center for Medium range Weather Forecasts) analysis. In the operational algorithm, P_{cloud} is calculated only for cloudy pixels which optical thickness is larger than 3.5. The standard POLDER products are delivered at about 60 * 60 km spatial resolution. To have the advantage of a better spatial precision, POLDER products have been reprocessed here at full resolution (6 * 6 km). In this paper, we have worked on a 3 * 3 pixels area around the ground measurements located in Oklahoma (see below). Only the cases for which the cloud cover, as determined with POLDER operational algorithm [*Buriez et al.*, 1997], was 100% for all nine pixels over this zone were selected. For the period December 1996–June 1997 we have a total of 56 cases.

2.2. ARM Data

[10] This paper presents the comparison of POLDER oxygen pressures with independent ground-based measurements. Specifically, we have used data from a Millimeter Wave Cloud Radar (MMCR) [*Clothiaux et al.*, 2000]. This radar is located at the Southern Great Plains (SGP) Central Facility (36°37'N, 97°30'W) in Oklahoma which is one of the Atmospheric Radiation Measurement (ARM) Program sites [*Xiquan Dong et al.*, 2000]. The MMCR is a vertically pointing radar that operates at a frequency of 35 GHz. Its main purpose is to determine cloud bottom and top with a 90-meter (or higher) height resolution. For this study, the radar data have been combined with data from the ARM Belfort ceilometer, micropulse lidars and radiosounding measurements to generate a time-pressure cloud series. These data are time averaged on a five-minute time-grid. This database of quasi-continuous records begins in December 1996 and we used it up to June 1997 (end of ADEOS/POLDER operational period). During this period the SGP Central Facility was the only one of the ARM sites equipped with MMCR radar.

[11] The time-pressure cloud series were analyzed 30 minutes before and after each POLDER overpass. During this hour, only clouds continuously present over the SGP and with temporally stable top and base pressure were selected. Our final database was then reduced to 37 suitable cases including 22 mono-layered and 15 multi-layered clouds. We present in Figure 1, for the 37 selected cases, the distribution of cloud optical thickness determined by POLDER as a function of their geometric thickness deduced from ARM measurements. Thermodynamical phase of clouds derived from POLDER polarized radiances at 865 nm [*Goloub et al.*, 1994] is also reported. Note that even while this database is a relatively small sample of clouds, it is rather diverse since the cloud geometric thickness extends from 25 to 735 hPa and the cloud optical thickness from 4 to 130.

3. Comparisons

[12] In this section, we present comparisons between POLDER oxygen pressures and ARM/MMCR cloud boundary pressures for the 37 selected cases. Figure 2a shows the

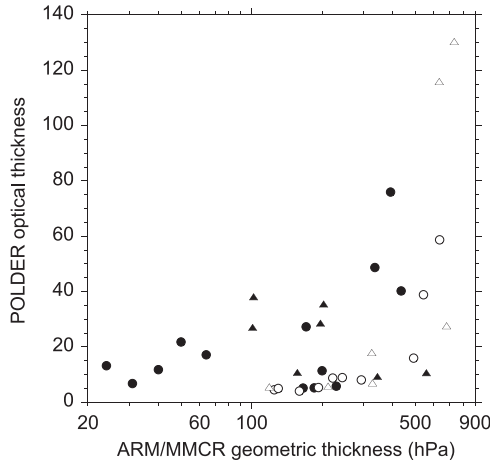


Figure 1. Distribution of POLDER cloud optical thickness versus ARMM/MMCR cloud geometric thickness for the 37 selected cases. Circles represent mono-layered clouds and triangles multi-layered clouds. White symbols are for ice clouds while liquid clouds appear in black. POLDER data are means over 3×3 pixels around the SGP Central Facility and over all viewing directions. ARM data are time averaged on a five-minute time-grid.

apparent (i.e. uncorrected) pressure levels in relation to the pressure levels of the cloud boundaries as a function of cloud geometric thickness. In this figure, the y-axis pressures have been linearly rescaled as follows: cloud tops are fixed to 0 and cloud bases are fixed to 1. POLDER data are means and standard deviations over 3×3 pixels around the SGP Central Facility and over all viewing directions. In case of multi-layered clouds, only extreme boundaries are used (upper cloud top and lower cloud base). This figure shows that apparent pressure is very rarely close to the cloud top pressure. The mean difference between P_{app} and P_{top} is 175

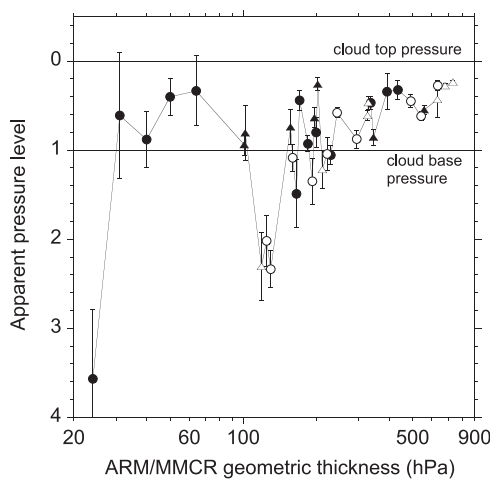


Figure 2a. Location of POLDER apparent pressure P_{app} in relation with ARM/MMCR cloud boundaries pressures, as a function of cloud geometric thickness for the 37 selected cases. POLDER data are means and standard deviations over 3×3 pixels around the SGP Central Facility and over all viewing directions. Symbols are identical to that of Figure 1.

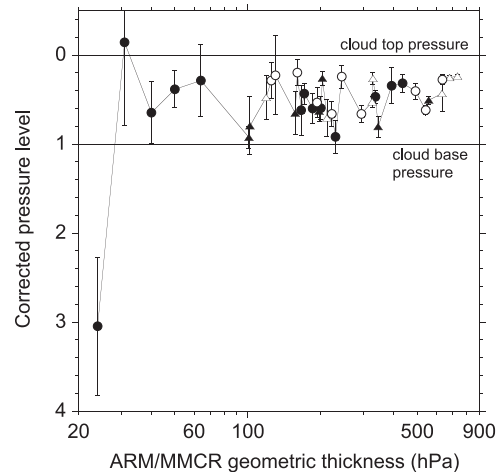


Figure 2b. Same as Figure 2a but for the corrected oxygen pressure P_{cloud} . Symbols are identical to that of Figure 1.

hPa (with a 89 hPa standard deviation) and can reach 336 hPa. We also observed that 10 of our 37 cases present an apparent pressure level below the cloud base pressure level. Such results can be explained (i) by the photon penetration effect since all scattering effects are neglected here and (ii) by the surface reflection effect (surface albedo at 765 nm varies from 0.25 to 0.37 over the ARM/SGP site during the period of our comparisons). Most of $P_{app} - P_{top}$ differences greater than 150 hPa are observed for cloud optical thickness less than 20. Nevertheless, the biggest difference (336 hPa) appears for a cloud with an optical thickness of 39 and even for the biggest optical thickness ($\delta = 130$) we observe that the difference $P_{app} - P_{top}$ reaches 175 hPa. If we define the mean cloud pressure P_{mean} as $(\text{top pressure} + \text{base pressure})/2$, we observe that the difference between P_{app} and P_{mean} is only 39 hPa on average (with a 99 hPa standard deviation). That means that even without any correction, the apparent pressure determined from POLDER measurements appears closer to the mean pressure of clouds than to their top pressure. Apparent pressures observed in case of mono-layered liquid clouds are much closer to this mean pressure than for mono-layered ice clouds. Multi-layered clouds do poorly, but these clouds often present a great pressure dispersion.

[13] The locations of corrected oxygen pressures P_{cloud} are reported in Figure 2b as a function of cloud geometric thickness. Please bear in mind that the corrected oxygen pressure P_{cloud} is only corrected for a surface reflection effect but not for the photon penetration effect. Here again this corrected pressure is far away from the top pressure (124 hPa on average with a 82 hPa standard deviation). Nevertheless, cloud oxygen pressures are now almost always located between the bottom and the top of the clouds. Only one of our 37 cases still presents a corrected oxygen pressure level below the cloud base pressure level, but this appears for our thinnest cloud which geometric thickness is only 24 hPa. More precisely, for this case the retrieved oxygen pressure is equal to 829 hPa (with a 20 hPa standard deviation) when the ARM cloud base pressure is equal to 780 hPa. For one of our cases, the oxygen pressure level is now situated very slightly over the cloud top (4 hPa). Nevertheless this also appears for a very thin cloud

(31 hPa); for this case the standard deviation of POLDER oxygen pressure is 30 hPa. Cloud oxygen pressures are often very close to the ARM/MMCR mean cloud pressure: the average difference between P_{cloud} and P_{mean} is only -12 hPa (with a 65 hPa standard deviation). The correlation coefficient between P_{cloud} and P_{mean} is equal to 0.953. Liquid and even ice mono-layered clouds now compare very well with the mean cloud pressures. Some discrepancies remain for ice multi-layered clouds.

4. Conclusion

[14] POLDER oxygen pressure have been compared to ARM cloud boundary pressures measured at the Southern Great Plains Central Facility. Only 37 suitable cases were exploitable. For these cases the apparent pressure (not corrected for the surface reflection effect) appears much closer to the mean pressure of clouds than to their top pressure. Moreover, the apparent pressure level is often retrieved below the cloud base level. This problem practically disappears using a simple surface correction. The corrected oxygen pressure is found to be even closer to the mean pressure of clouds and moreover, it seems to improve the retrieval whatever the cloud type (liquid or ice, mono or multi-layered), the cloud altitude and the cloud geometric thickness. These results and previous studies [Vanbauce et al., 1998; Parol et al., 1999; Koелеmeijer et al., 2001] show that the photon-penetration effect could be larger than initially realized. While this makes it problematic to obtain cloud top pressure, it means A-band data contains useful information on cloud thickness and cloud base. Indeed, if it can be confirmed that the corrected oxygen pressure is a good estimator of mean cloud pressure it could be used to determine the cloud base pressure when combined with one of the multiple existing methods (brightness temperature [Rossow and Garder, 1993], CO₂ slicing [Smith and Platt, 1978], stereoscopy [Prata and Turner, 1997], Raman scattering [Joiner and Bhartia, 1995], and Rayleigh scattering [Goloub et al., 1994; Knibbe et al., 2000]) to independently retrieve the cloud top pressure. This could be of great value in assessing general circulation models and in improving satellite based surface fluxes estimates.

[15] Our database is unfortunately too small for us to generalize these results. A lot of work has to be done to confirm these results. Similar comparisons are planned between cloud oxygen pressures that will be delivered by POLDER-2 (launched in December 2002) and cloud boundaries pressures provided by Lidar and Radar at ARM sites and CloudNET sites [Donovan, 2002].

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