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Comparison of POLDER cloud phase retrievals to active remote sensors measurements at the ARM SGP site.

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Abstract. In our present study, cloud boundaries derived from a combination of active remote sensors at the ARM SGP site are compared to POLDER cloud top phase index which is derived from polarimetric measurements using an innovative method. This approach shows the viability of the POLDER phase retrieval algorithm, and also leads to interesting results. In particular, the analysis demonstrates the sensitivity of polarization measurements to ice crystal shape and indicates that occurrence of polycrystalline ice clouds has to be taken into account in order to improve the POLDER phase retrieval algorithm accuracy. Secondly, the results show that a temperature threshold of 240 K could serve for cloud top particle phase classification. Considering the limitations of the analysis, the temperature threshold could be biased high, but not by more than about 5 degrees.

Introduction

The POLDER (POLarization and Directionality of the Earth Reflectances) instrument proved capable of deriving key information needed to improve our knowledge of clouds, radiation and climate interactions. In particular, the potential of polarization measurements of the upward shortwave radiation to derive cloud information has been clearly demonstrated by POLDER data analysis [*Bréon and Goloub*, 1998],[*Chepfer et al*, 1998],[*Goloub et al*, 2000]. From November 1996 to the end of June 1997, the satellite version of POLDER provided polarization measurements on a global scale. Because of the large POLDER field of view, the same target on the Earth can be viewed from up to 14 directions during a single ADEOS over-pass. Cloud observations over a large range of scattering angles make possible the distinction between liquid and ice phase [*Parol et al*, 1999],[*Goloub et al*, 2000]. The eight months of POLDER operational data have now been processed and are fully available to the scientific community and a first analysis of the POLDER phase product, as well as comparison to ISCCP data [*Riedi et al*, 2000], have proven the quality of POLDER retrievals of cloud phase.

Our present approach consists of analyzing a combination of data from active remote sensors located at the ARM Southern Great Plains (SGP) site. For each ADEOS pass over the ARM SGP site (approximately every day), POLDER-derived cloud phase information is compared to cloud top pressure and temperature which are derived from active remote sensor measurements combined with rawinsonde data available at the ARM SGP site.

The POLDER method of cloud phase determination is based on the polarization signature of cloud particles in the near infrared [*Goloub et al*, 2000]. Note that this signature is directly linked to cloud particle shape. This method does not require any assumption about the relationship between cloud temperature, pressure and phase.

Data

Clothiaux et al have produced an extensive dataset of cloud heights from a combination of active remote sensors at the ARM SGP site (36°37′ N, 97°30′ W) (further referred as the ARSCL dataset). The temporal capabilities of instruments such as the Millimeter-wave Cloud Radar (MMCR) or the Micropulse Lidar (MPL) together with the type of information that they can provide, make this dataset particularly well adapted for a precise study of the POLDER-derived cloud phase product. We refer here to [*Clothiaux et al*, 2000] for a complete description of instruments used to retrieve cloud heights. However, it is worth noting that this dataset is the most robust available during the POLDER operational period to conduct an analysis over a broad range of cloudiness situation. The operational POLDER phase product is delivered at a spatial resolution of about 60 km×60 km. For this study, the level 1 data set has been processed in order to get the phase index and cloud top pressure at full resolution (6.2 km×6.2 km) to enable precise comparisons to

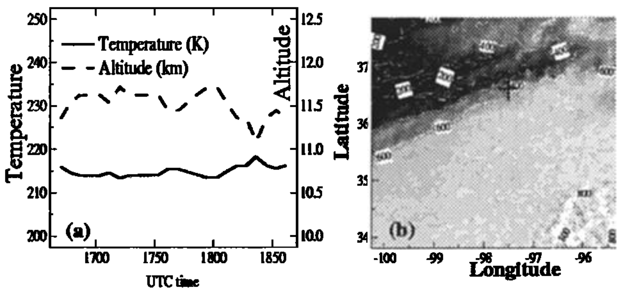

Figure 1. (a) Cloud top altitude and temperature profiles derived from ARM-SGP ground measurements. (b) Cloud top Rayleigh pressure (hPa) derived from POLDER data on same day - SGP-ARM site location is marked by the cross.

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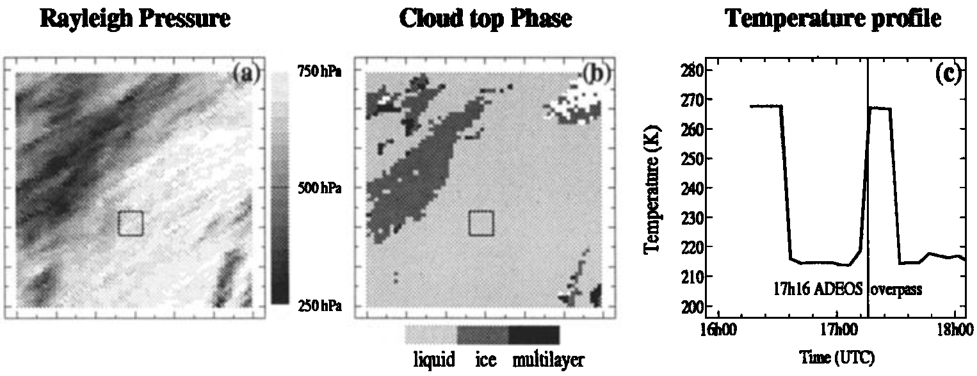

Figure 2. Cloud top Rayleigh pressure (a) and phase (b) derived from POLDER data for a case of cirrus overlaying low liquid clouds (1997-02-13). Associated cloud top temperature profile (c) derived from ARM-SGP ground measurements. Spatial extent of presented area is ~370km×370km and the box centered on the ARM-SGP site is ~31km×31km large.

ARSCL data. The cloud boundaries used in this paper are determined from a combination of radar, lidar and ceilometer data as described by Clothiaux et al. [2000]. The cloud top (especially of the highest cloud layer) is usually obtained from the radar data alone. Despite the very sensitive nature of the ARM cloud radar [1], the radar is not sensitive to very small cirrus cloud particles. Hence the radar derived cloud boundary may be less than the actual cloud top. However, Clothiaux et al. [2000] show that most of the time the underestimate of the radar cloud top to the lidar cloud top (when the two can be compared) is less than 1 km. So while it is true that our estimate of the cloud top height is likely to be biased low (i.e., temperature to be biased high), we believe this bias will be less than 1 km, or equivalently, less than about 5 degrees.

Temporal resolution of the ARSCL dataset (10s), enables one to match the time of the POLDER observations very precisely. The cloud boundary profiles have been used to derive continuous cloud top temperature and pressure time series. Cloud top temperature/pressure is derived from rawinsonde measurements at the same altitude as radar/lidar detected cloud top. Temporal variability of the cloud cover is evaluated by considering data acquired half an hour before and after each ADEOS over-pass. We have analyzed in detail the subset of 7 months of observations (from December 1996 to June 1997) when both ARSCL and POLDER data are available. A total of 201 days of matching observations were identified for the SGP site for this period. An example of data available for one particular day is presented in figure 1. The spatial area presented in figure 1b is much larger than what is useful for comparison to radar measurements, but it illustrates how the Rayleigh pressure [2] [*Parol et al*, 1999] information can be used in our analysis. The darker region in figure 1b corresponds to high thick clouds associated with low pressure of about 200 hPa. The increase of cloud top pressure from 400hPa up to 700hPa corresponds to a zone covered by thin cirrus (optical depth smaller than 2) for which Rayleigh pressure is known to overestimate cloud top pressure. Finally, the zone located in the south-east is covered by a mixture of cirrus clouds and clear sky, which explains the large Rayleigh pressure variability in that region. Although Rayleigh pressure can give useful information on the spatial variability of cloud cover, the pressure and altitude of cloud top derived from radar data are thought to be more reliable. Cloud top altitude and temperature for 16:30-18:30 UTC December 27, 1996 are presented in figure 1a. Note that these are consistent with the ice phase retrieved by POLDER over the ARM SGP site (cross on figure 1b).

Analysis

Cloud top phase retrieval accuracy

In order to assess the accuracy of the cloud top phase retrieval algorithm, we compared retrievals of cloud phase derived from POLDER data with cloud top temperature inferred from ground-based measurements. In most cases, liquid and ice clouds were well separated by a temperature threshold of about 240 K. However, there were three exceptions to this general result and we now describe them in more detail.

- case 1 - Some ice phase cases were associated with temperatures greater than 260 K. They have been identified as low cloud edges. Polarization is not saturated for small cloud optical thickness [*Goloub et al*, 2000] so that polarization features, on which the phase retrieval relies, are not always well defined for cloud edges and very thin clouds. This is not really a problem when polarization signatures are integrated over groups of 3x3, or 9x9, pixels, but liquid water cloud edges tend to be classified as ice clouds when data are processed at full resolution. This is one reason why future POLDER phase products should not be delivered at full resolution.

- case 2 - The second case concerns occurrences of retrieved liquid phase clouds below temperatures of 240 K. A detailed analysis of each case showed that they correspond to multilayered clouds. A typical situation is shown in figure 2 for a case of thin cirrus overlaying low liquid clouds that occurred on February 13, 1997. On that day, the radar reported two cloud layers and the temperature associated with the top layer is illustrated in figure 2c. The variation

[1]The MMCR is a zenith-pointing radar that operates at a frequency of 35 GHz and its main purpose is to determine cloud particle locations and the first three Doppler moments of detected cloud particles [*Moran et al*, 1998], [*Clothiaux et al*, 2000].

[2]The so-called Rayleigh pressure is derived from a differential technic using polarized information in the 443 nm and 865 nm channels.

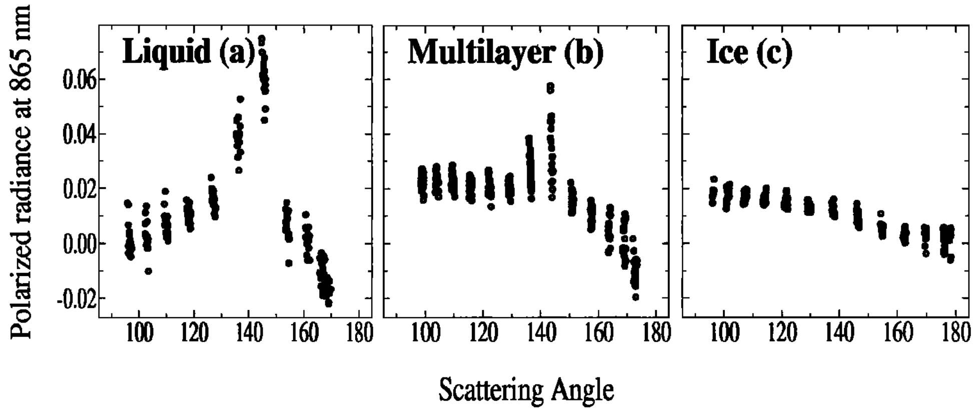

Figure 3. Observed polarized radiance as a function of scattering angle for liquid clouds (a) , thin cirrus overlaying low liquid clouds (b), and thick cirrus (c).

of Rayleigh pressure, illustrated by figure 2a, is characteristic of a cirrus with varying optical depth (as mentioned in section 2). As figure 3 illustrates, three typical polarization signatures can be observed when a cirrus overlays lower liquid clouds. If cirrus optical depth is greater than 2, polarization is saturated and Rayleigh pressure is correctly retrieved (250 hPa region in figure 2a). In this case, the polarization signature presents characteristic features of ice clouds (figure 3c). As cirrus optical depth decreases, the Rayleigh pressure increases (500 hPa region in figure 2a) and POLDER underestimates the cloud top altitude. At the same time the rainbow at 140°, characteristic of spherical liquid phase particles, begins to appear due to underlying liquid clouds (Figure 3b). Finally, as the cirrus optical depth decreases further, the polarization signature tends to present only the characteristic features of liquid clouds (Figure 3a). Clearly, POLDER sees the liquid clouds through the thin cirrus, but the radar still reports a high and cold cloud layer, leading to the apparently surprising result of liquid phase clouds below 240 K.

- case 3 - The last and most surprising case was the occurrence of liquid phase around 210 K. These cases were not actually associated with liquid clouds, but with cirrus clouds composed of particles with particular microphysics. Models of ice clouds composed of monocrystalline hexagonal particles (plates, columns) have a positive polarization that decreases with scattering angle (figure 4b). Note that our initial phase retrieval algorithm is partly based on this hypothesis. Thus, if a cirrus cloud exhibits a signature with an increasing polarization with scattering angle (Figure 4a), it could be declared as liquid cloud when no other information is available. Typically, models of cirrus composed of polycrystals could produce such a behavior. This problem can be solved using a simple threshold test, but the fact is that this has not been investigated to date during the validation process of the POLDER phase retrieval algorithm. This is a clear demonstration of the usefulness of the ARSCL dataset to conduct such studies and outlines the fact that these data should be used extensively for the purpose of validation during future POLDER missions.

Temperature dependency of cloud top phase

The mean hourly cloud top altitude derived from the ARSCL dataset is now used to assess the POLDER phase index at the ARM SGP site. We focus on days with a rather stable and homogeneous cloud cover so that problems due to cloud edges can be discarded. Also, we reprocessed the POLDER data in order to account for the microphysical findings previously mentioned.

We have selected cases with a cloud cover greater than 90% (according to the radar data) during a time interval of one hour around the POLDER over-pass. Cloud top temperature and pressure from the ground-based measurements were averaged during the one hour interval and the POLDER cloud phase index was evaluated on a 3×3 level 1 pixel zone centered on the ARM SGP site. All together, 98 cases were analyzed and each case resulted in a POLDER phase index that was a result of either a pure liquid or ice cloud. The results are presented in figure 5 as cloud top pressure versus cloud top temperature plots.

A temperature threshold of 240 K separates most retrieved ice clouds from retrieved liquid water clouds. Only 3 ambiguous cases remain, with one ice phase case occurring

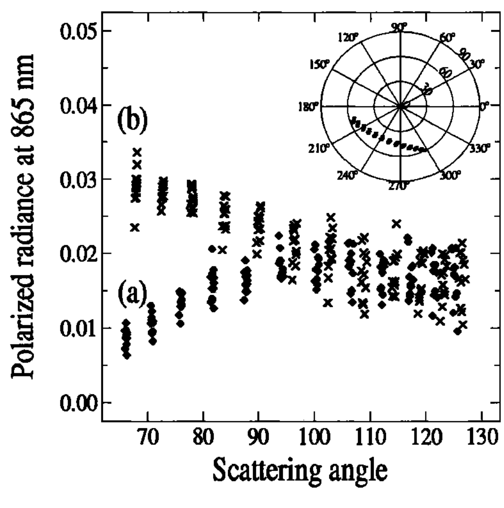

Figure 4. Polarized radiance (corrected from Rayleigh contribution) at 865nm observed by POLDER over two different high thick and cold clouds. One of them (a) present a positive polarization increasing with scattering angle whereas it does usually decrease for most ice clouds models (b). Viewing geometries associated to each case are very similar and presented on top polar diagram.

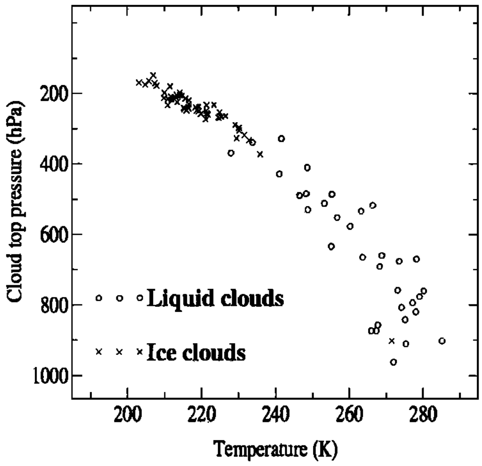

Figure 5. Temperature dependency of cloud top phase for clouds located above the SGP-ARM site (36° 37′N, 97° 30′W).

at 270 K (cloud edge) and two liquid cloud cases below 240 K (multilayered cases). These results, limited to the ARM SGP site, should not be considered representative for all locations. However, the threshold of 240 K already mentioned in the literature [*Hutchison et al*, 1997] seems to be justified by these results and comparisons of the POLDER phase product with ISCCP data [*Riedi et al*, 2000] tend to confirm these findings. Also, it should be noted that low and middle clouds associated with a temperature lower than 260 K are declared as ice clouds in the present ISCCP dataset [*Rossow et al*, 1996]. Our present results tend to demonstrate that this threshold should be revised.

Conclusion

Comparisons of the POLDER phase index to cloud top pressure and temperature data derived from completely independent ground based measurements were performed to validate POLDER phase products.

This analysis allowed us to improve the POLDER phase retrieval algorithm by taking into account particular microphysical properties of some cirrus clouds. Also, it shows the relevance of POLDER phase products to parameters useful in GCMs. In particular, the temperature threshold at 240 K is remarkable. While the limitation inherent to the use of radar/lidar measurements could bias high this value, we believe this bias will be less than about 5 degrees. Considering this range of error, our analysis is consistent with many results reporting in-situ observation of highly-supercooled liquid water drops at temperatures around 240 K [*Sassen and Dodd*, 1988], [*Heymsfield and Miloshevich*, 1993]. The question of wether or not supercooled liquid water can occur below 240 K can not be addressed here due to the possible bias of 5 degree and the lack of measurements in the range 235-240 K. However, the use of the ARSCL dataset allow us to evaluate a wide variety of cloud conditions and this is a clear advantage of the ARSCL dataset. This analysis complements very well studies where only lidar measurements were used and thin clouds sampled (see [*Chepfer et al*, 2000] for example).

In the future, a great opportunity to pursue these studies will be provided by the launch of two new POLDER instruments. The first one, on ADEOS II, will be launched mid 2002, and the second one on PARASOL (end of 2003) will be launched in conjunction with EOS-PM and Picasso/Cena. At that time, data provided by instruments operating at the ARM sites (SGP, North Slope of Alaska and the Tropical Western Pacific) will be of great interest.

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