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Global distribution of Cloud Droplet Effective Radius from POLDER polarization measurements

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Abstract. Polarization measurements from the spaceborne POLDER instrument are used to estimate the droplet effective radius of liquid-phase clouds. Eight months of measurements have been processed. Seasonal averages have been generated and are discussed here. The measurements confirm that, on average, droplets are 2 to 3 μm smaller over land than over the oceans. The smaller droplets are found over highly polluted regions and in areas affected by smoke from biomass burning activity. The influence of land masses is apparent downwind of the continents. Largest droplets are found in remote tropical oceans, away from major aerosol sources. A large zonal gradient is also apparent in the southern oceans, with very small droplets close to the Antarctic continent.

Introduction

Cloud Droplet effective Radius (CDR) is an important parameter for climate. It drives the relationship between the cloud liquid water content and its albedo. For a given liquid water content, smaller droplets lead to larger cloud albedo. This fact is a component of the "Twomey Effect", also referred to as the indirect radiative effect of aerosols, where aerosol particles can act as Cloud Condensation Nuclei (CCN), increasing the number of droplets in clouds whereby decreasing their mean radius, and in turn increasing the cloud albedo (Twomey, 1977; 1991).

Satellite estimate of the droplet effective radius is possible from the spectral signature of the cloud solar reflectance (Nakajima and King, 1991). This signature has been used for deriving a near global climatology of the effective droplet radii of liquid clouds using AVHRR (Advanced Very High Resolution Radiometer) measurements (Han et al. 1994). The main limitations of the method result from the cloud field heterogeneity and the reflectance of the underlying surface that may bias the estimates. Another uncertainty is the effective level of the radius estimate since the reflectance is sensitive to a deep cloud layer with some vertical gradient of the droplet radius.

The POLDER (Polarization and Directionality of the Earth Reflectances, Deschamps et al, 1994) was launched onboard the ADEOS (Advanced Earth Observing Satellite) in August 1996. Data acquisition was continuous on the Sun lit part of the orbits from October 30th, 1996 to June 30th, 1997 when the satellite failed from the rupture of the solar paddle. This instrument provides a new opportunity for the estimate of CDR from space, based on the directional signature of the polarized solar light reflected by clouds (Bréon and Goloub, 1998).

In this paper, we describe the global distributions of CDR as retrieved from the POLDER measurements. In the next section, we rapidly summarize the method for CDR estimate with its limitations. Seasonal averages are presented in section 3 and zonal means are discussed in section 4.

Method

The retrieval of cloud droplet effective radius from POLDER measurements makes use of the directional signature of the polarized reflectance of liquid clouds. The polarized scattering phase function $Q(\gamma)$ of droplet size distributions can be computed using Mie theory. In the scattering angle range of 145°-170°, $Q(\gamma)$ shows oscillations between positive and negative extremums. Mie computations show that the angular position of these maximums and minimums is very sensitive to the radius of the particles. On the other hand, when the size distribution is relatively broad, the oscillations are smoothed out and the sensitivity to the effective radius vanishes.

The inversion procedure compares the directional signature of the measured polarized radiance to the result of Mie radiative transfer simulations. We assume that the droplet size distribution follows :

$$n(r) = \left(\frac{r}{r_{eff}} \right)^{-3} \exp \left[\frac{1}{\sigma_{eff}} \left(1 - \frac{r}{r_{eff}} + Ln \frac{r}{r_{eff}} \right) \right] \quad (1)$$

where r_{eff} is the effective radius and σ_{eff} defines the widths of the distribution. The polarized phase functions have been computed for thirty-three size distributions defined by eleven effective radii (from 5 to 15 μm) and three widths (0.01, 0.02 and 0.05). The size distribution model that reproduces the best the observed angular signature, both at 865 nm and 670 nm is selected. A number of quality tests are applied, based on the model-measurement agreement, the coherence between the two channel results, and the range of scattering angles that is sampled (145°-165° is required). Unreliable inversions are rejected.

The main advantage of using the polarized reflectance rather than the total reflectance is that the former gives a direct access to $Q(\gamma)$ through single scattering. Radiance generated by multiple scattering within the cloud is virtually unpolarized and does not blur the features generated by single scattering. On the other hand, the radiance generated by multiple scattering dominates the signal in total radiance, which makes it impossible to extract the single scattering contribution. Because the technique makes use of the radiance generated by single scattering, it is sensitive to the cloud top, i.e. the first unit of optical thickness.

Global Fields

The inversion of CDR from POLDER measurements is possible in very specific conditions only: The viewing geometry

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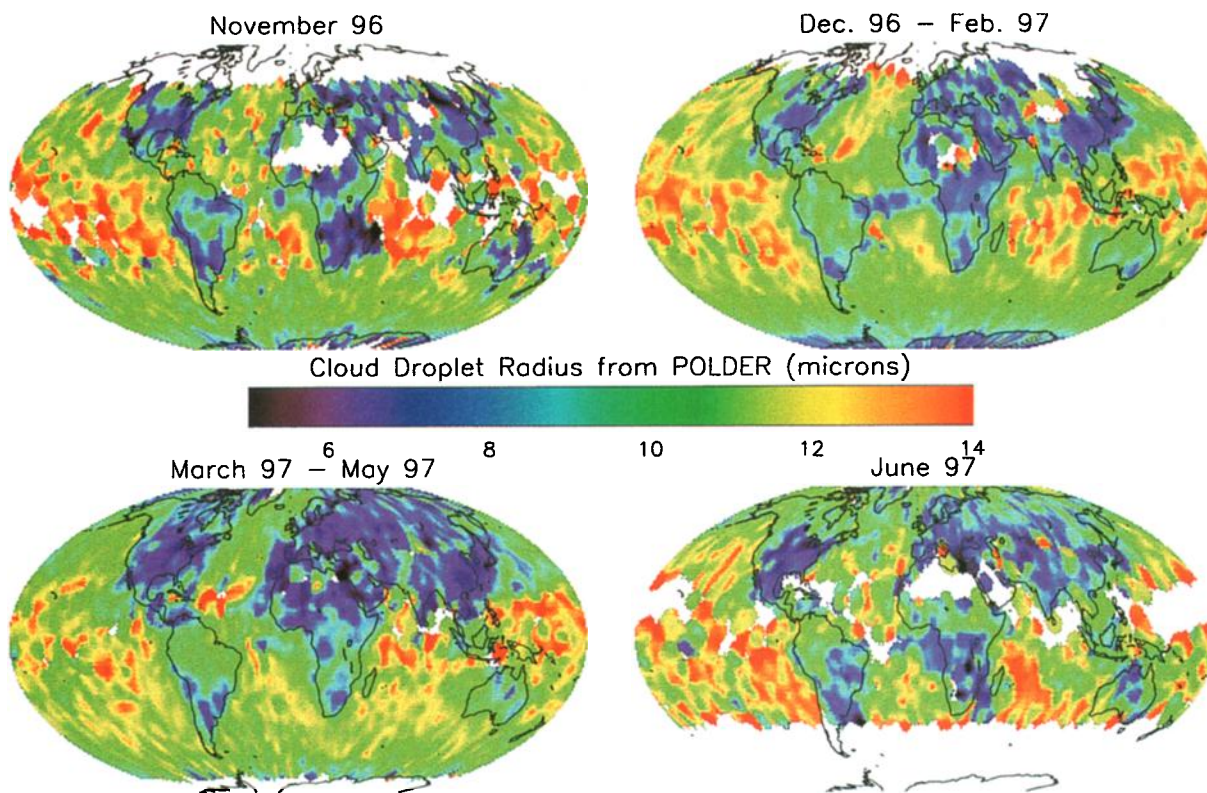


Figure 1: Seasonal distributions of cloud droplet effective radius as estimated from polarization measurements of the POLDER spaceborne instrument.

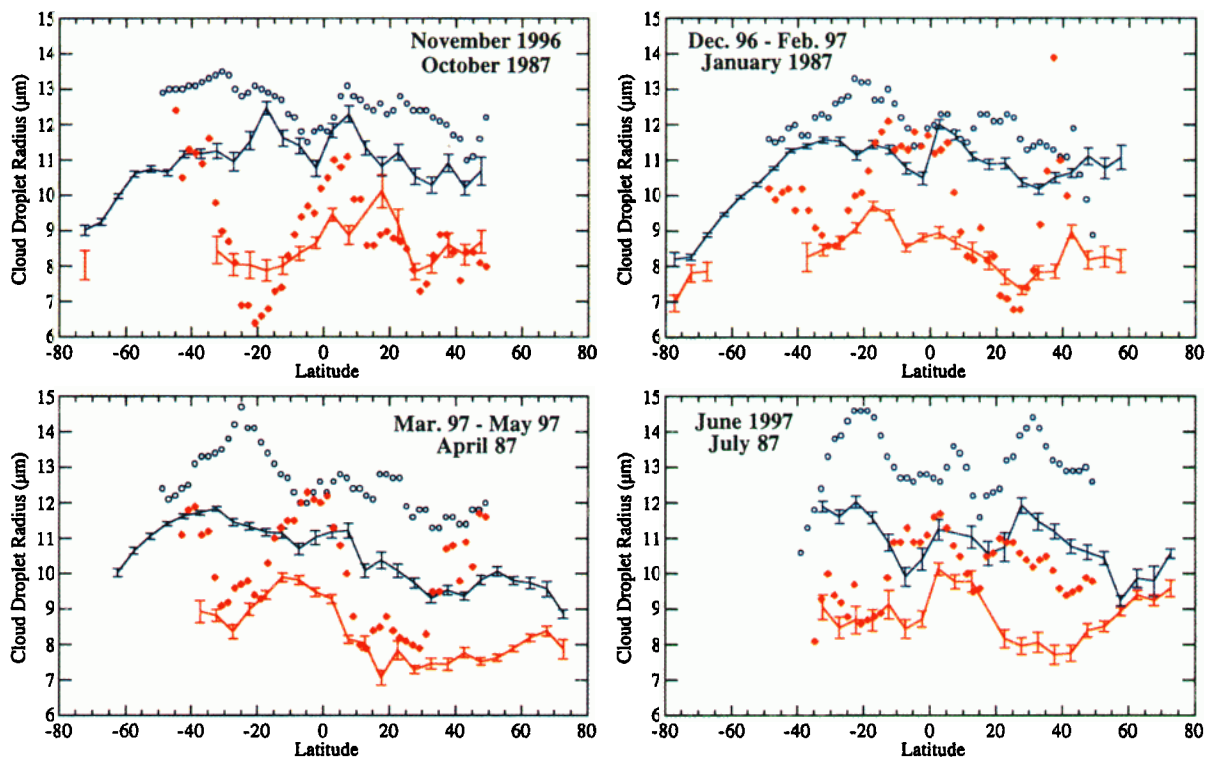


Figure 2: Zonal averages of the retrieved CDR. Land and Ocean estimates have been distinguished (land correspond to the lower curves). The error bars indicate the confidence interval on the mean value (see text). The symbols indicate the results of Han et al. (1994), Fig. 8, which are based on AVHRR measurements acquired in 1987.

must be such that the 145°-170° scattering angle range is sampled, the cloud field must have homogeneous micro-physical properties over a surface of about 150x150 km², and the size distribution must be narrow. These requirements may bias the results to specific meteorological conditions and reduce the statistical significance of our averages. From POLDER measurements, such conditions have been met 50,000 times during the 8 months life of the satellite. From these successful inversions, monthly and seasonal composites have been generated at a resolution of 2.5 degrees. Figure 1 shows the seasonal results where the autumn season is defined from November measurements, and the summer season is limited to June.

The main feature apparent on these global maps is the land/ocean contrast. On average, cloud droplets are smaller over the continents than over land surfaces. This observation confirms that of other studies, both in situ or from spaceborne remote sensing (Rosenfeld and Lensky, 1998; Han et al., 1994). Note also that the smaller droplets observed over the continents extend over the oceans downwind of land masses (wind is mostly from the East in the tropical areas, and from the West at mid-latitudes). The largest droplets are found in the middle of the oceanic basins, in areas that are far from any land influence. The largest droplets are not found at high latitudes, even in areas where the land influence is expected to be negligible (southern ocean). Note in particular the large North-South gradient during December-February over the Antarctic Ocean.

The smaller droplets are found over regions which are known to be highly polluted (China, Ganges valley, Europe, east coast of the United States), or affected by biomass burning smoke (Madagascar and Mozambique in November, central Africa in December-February, Angola in June, central America in March-May). This is consistent with the findings of Han et al. (1998). The correlation between high aerosol emission and CDR is the subject of another forthcoming paper.

Significant temporal variations are also apparent in Fig. 1. Major variations over land surfaces are in regions affected by biomass burning. Note that most of the Amazonian region shows relatively large droplets, in comparison to other land masses. In this region, biomass burning occurs during July and August, when no POLDER data is available. Over the oceans, significant variation is also observed in the North Atlantic and Pacific, the droplets being larger during the first half of the sampled period. This may result from the difference in meteorological conditions between the winter and summer periods.

Zonal Means

Figure 1 clearly shows that the CDR spatial distribution is not purely zonal, except in specific areas such as the southern ocean. Therefore, caution is necessary when interpreting the zonal means shown in Fig. 2. We have averaged the successful retrievals of CDR over 5° latitude bands, with a distinction of measurements made over land and over the oceans. We did not account for the relative number of estimates along the longitude, i.e. the results are not area-weighted. The error bars indicate the range of confidence on the mean, which is given by $\sigma_{obs} / \sqrt{N_{obs} - 1}$ where N_{obs} is the number of estimates, and σ_{obs} is their standard deviation. Note that the error bars are very small in the southern

latitudes. The meteorological conditions in the southern ocean are such that many successful inversions are made there.

In Fig. 2, we also reproduce the results from Han et al. (1994, Fig. 8). The periods of measurement are different, so extra caution is required when interpreting the differences between the two method results.

Both methods show a land-ocean contrast on the order of 2-3 microns. This contrast is apparent at most latitude bands. On the other hand, there is a clear bias between the two method results: mean CDR estimated from the spectral signature of clouds are larger by roughly 2 microns than those estimated from POLDER polarization measurements. A more detailed analysis of Fig. 2 shows some similarities between the zonal patterns retrieved by the two methods, but also significant differences. As said above, some differences may be explained by the different period of measurement. However, we believe that the main contributor to the discrepancies is the sampling of the two methods, which may select preferentially different cloud types. Note that a better agreement between the two method results is observed over land than over oceanic surfaces. A possible explanation is that more variability along the longitude is observed over the oceans; the zonal average with different area weighting would then generate larger differences than over land.

The zonal mean also quantifies the gradient observed over the southern oceans in Fig. 1. The averaged effective radius drops by about 3 μm over 30° of latitude. This gradient cannot be attributed to an aerosol effect, contrarily to most spatial structures observed at lower latitudes. This pattern is not apparent in the Han et al. (1994) results because of their requirements on the solar zenith angle. To our knowledge, such gradient has not been documented previously, possibly because of the difficulty of making measurements in this remote region. Our statistic is based on a large number of individual estimates and is therefore highly significant. On the other hand, the clouds that are sampled in these regions may be composed of a mixed phase of liquid and ice droplets. Our method is sensitive to the radiance scattered by the liquid droplets, and the retrieved effective radius is representative of those only. Ice particles may reduce the intensity of the signal and make the retrieval impossible, but they do not bias the estimate. Toward the pole, the temperature is colder. The observed gradient may be the result of a process where, as the temperature gets colder, large droplets freeze and only the smaller ones are kept liquid.

Conclusions

A new technique for cloud droplet radius estimate was presented in Bréon and Goloub (1998). The technique has been applied to the eight months of measurements acquired from POLDER onboard ADEOS. Seasonal averages have been generated. The analysis of the global maps confirms the land/sea contrast that had been observed previously, in particular using the spectral signature of cloud solar reflectance in the near infrared. Our results also show the influence of land masses over the nearby oceans, in particular downwind of the major aerosol sources. The relationship between aerosol load and CDR is further discussed in a forthcoming paper. Our results also show a large reduction in CDR towards the polar areas, an observation that was not accessible from the spectral signature method because of its limitations on the solar zenith angle.

Our results are representative of the mean droplet size at cloud top. The retrieval is possible in specific conditions only, with requirements on the cloud field spatial homogeneity, and a rather narrow cloud droplet size distribution. The processing of the POLDER data archive shows that such conditions are frequent, in particular in the southern oceans where it appears to be the rule. On the other hand, these conditions may be specific to some cloud types, and the global distributions shown here may not be representative of all liquid clouds. This may explain the significant differences with a similar climatology based on the spectral signature of clouds.

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