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Analysis of direct comparison of cloud top temperature and infrared split window signature against independant retrievals of cloud thermodynamic phase.

V. Giraud, O. Thouaron, J. Riedi and P. Goloub

Laboratoire d'Optique Atmosphérique, Université des Sciences et Technologies de Lille, France

Abstract. An accurate determination of cloud particle phase is required for retrieval of other cloud properties. The main purpose of this letter is to demonstrate that the cloud phase assumption made in previous cirrus clouds retrievals using infrared split window signatures is not relevant. Coincident observations of the Earth surface from ERS-2 and ADEOS-1 satellites give us the opportunity to compare clouds infrared signatures, as observed by ATSR-2 onboard ERS-2, with cloud thermodynamic phase derived from POLDER onboard ADEOS-1. We find out, firstly, that large Brightness Temperature Differences (BTD), estimated between 11 and 12 μm , may occur for cold liquid water clouds consisting of small supercooled droplets (i.e. altostratus). These BTDs have no longer been attributed to cirrus clouds as previous studies have been. Secondly, the probability to observe ice or water clouds with respect to their cloud top temperature is quantified for our data set. A sharp transition between the ice and water phase is shown for cloud top temperatures ranging between 240 and 260 K. The probability for a cloud to be composed of super-cooled liquid droplets is shown to be higher over land than over ocean. This points out that ice activation susceptibility is more efficient in maritime air mass than in continental one.

Introduction

The retrieval of global cloud properties depends on accurate interpretation of satellite radiometric data. During the last 15 years, intensive research for determining cirrus clouds effective microphysical properties from multispectral satellite imagery has been performed [Inoue, T., 1985], [Minnis et al, 1993], [Giraud et al, 1997], [Chung et al, 2000]. These retrievals are commonly based on the significant wavelength dependency of cloud absorption in the infrared window (10-12 μm). Nevertheless, the main weakness of actual methods is the assumption made upon cloud phase. For satellite retrievals, cloud particles phase discrimination is quite determinant since the optical properties of liquid particle and solid ones are distinct. This is mainly due to the impact of particle's shape as well as differences in ice and liquid water refractive indices which both strongly influence radiation absorption and scattering.

The purpose of this paper is to discuss cloud top temperatures and infrared signatures, as observed with ATSR-2,

with respect to their thermodynamic phase as unambiguously derived from POLDER. The validity of cloud phase assumption made by considering cloud top temperatures is evaluated, and impact on split window retrievals is inferred.

Data processing

On June 12, 1997, POLDER and ATSR-2 observed the same Earth area within a 10 minute range. This dataset gives a first opportunity to analyze several cloudy scenes with independent and complementary satellite measurements. The overlap of the swath of the two sensors gives access to about 120 10^6 km^2 of the Earth.

POLDER has been working for 8 months from November 1996 to June 1997. Using the polarization and directionality capabilities, of this pioneer space-borne polarimeter, thermodynamic cloud phase (liquid or ice) can be inferred [Goloub et al, 2000], [Riedi et al, 2000]. Operational POLDER phase product is delivered at a spatial resolution of 60 km x 60 km [Buriez et al, 1997]. However, the Cloud Top Phase (CTP) retrieval algorithm can be applied directly to full resolution data. In the present study, the cloud thermodynamic phase has been derived at full resolution (6.2 km x 6.2 km), which is much more appropriate for a joint analysis, considering the ATSR spatial resolution at nadir (i.e. 1.1 km x 1.1 km). Also, previous studies have shown the scale of natural variability of the CTP to be much closer to full POLDER resolution than the operational product actually delivered. This gain in resolution is somehow counterbalanced by the fact that thin clouds (visible optical depth less than 2.0) or cloud edges tend to be declared as ice clouds (regardless of the actual cloud phase). This problem is more sensitive at full resolution and appears mainly on the pixels forming edges of broken liquid clouds. In the following, ice/liquid clouds refer to POLDER full resolution pixels declared as ice/liquid by the POLDER CTP algorithm. Figure 1 illustrates the global daily distribution of CTP derived from POLDER on June 12, 1997.

ATSR-2 has two thermal infrared channels centered at 10.8 and 12 μm matching those of AVHRR. Details of the instrument may be found in [Mutlow et al, 1998].

The measurements taken by POLDER are relocated on a standard reference grid. This grid is obtained from a sinusoidal projection, whose constant step is 1/18 degrees in longitude (i.e. 6, 2 km). ATSR-2 data are projected on this reference grid. ATSR-2 resolution being 6 times better, ATSR-2 pixel pertaining to the same POLDER pixel are averaged.

In this note, only pixels observed from both POLDER and ATSR-2 within ± 10 minutes are considered. The cloud

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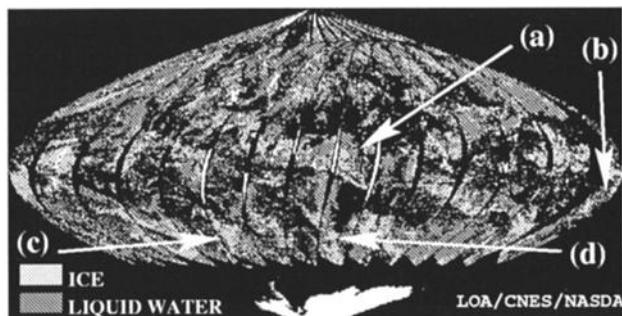


Figure 1. POLDER thermodynamic phase index on June 12.

mask, extensively discussed in [Buriez et al, 1997] and [Parol et al, 1999], is produced at full resolution by POLDER. Regions poleward 60° were rejected in our studies to avoid possible problems in cloud detection above sea ice and snow covered lands.

Analysis

BTD signatures for ice and liquid clouds

Since the imaginary part of the refractive index represents the absorptive properties of a material, it is clear from Fig. 2 that both ice and liquid water absorb more infrared radiation at $12 \mu\text{m}$ than at $11 \mu\text{m}$. These differences imply that semi-transparent clouds are more opaque to telluric radiation at $12 \mu\text{m}$, and then explain that BTD could be observed between 11 and $12 \mu\text{m}$. Figures 3a, 3b, 3c and 3d show the bispectral radiance scatter plots for the regions denoted by the boxes A, B, C and D in the image (Fig. 1), where infrared signatures are complete and well defined. The coldest temperatures corresponding to very low BTDs are representative of the opaque parts of the clouds. According to POLDER cloud detection, warmer temperatures correspond to clear sky pixels. Intermediate temperatures are associated to more or less semi-transparent clouds. Signatures in Fig. 3a and 3b exhibit very pronounced arches typical of liquid water clouds. The high BTD values can only be explained by the occurrence of small liquid droplets with effective radius less than $5 \mu\text{m}$. Ice cloud signatures shown in Fig. 3c and 3d are more scattered and smaller BTDs are reached. Figure 4 presents BTD statistical distribution values for liquid water and ice clouds. This highlights that the strongest BTDs, beyond 6 K, are predominantly associated to semi-transparent water clouds. Cloudy pixels having their BTD between 1 and 5 K are equally associated to the liquid or ice phase. These pictures clearly demonstrate the difficulties in correctly interpreting BTD signatures without phase information. Notice that in clear sky conditions, BTDs are due to water vapor absorption and are limited to 1 or 2 K. However, Figure 4 shows high BTD even where no cloud is detected from POLDER. This makes doubt about the ability to detect very thin clouds from POLDER, but has no impact on our analyses.

T. Inoue[1985], has suggested that semi-transparent cirrus clouds could be detected from large BTDs. This is clearly in contradiction with our observations which suggest that semi-transparent liquid water clouds present large BTDs, too. Assuming spherical particles, Giraud et al [1997] show that, for overcast pixels, and a fixed optical depth,

BTD decreases with the size of the particles and increases with the contrast between the cloud-free and the opaque cloud brightness temperatures. Complementary simulations demonstrate that BTDs are larger for ice spheres than for liquid water spheres for identical cloudy conditions (i.e. if only refractive index is changed). Thus, assuming that cirrus microphysics could be described by spherical particles, we may expect a retrieved effective radius for cirrus clouds greater than for liquid water clouds.

Considering the above results, some retrievals of cirrus cloud's effective microphysical properties developed by several authors should probably be attributed to liquid clouds. In particular, [Giraud et al, 1997] and [Lin and Coakley, 1993] found high values of the microphysical parameter, which correspond to small spheres, for cloud warmer than 240 K. Our results tend to demonstrate that clouds analyzed in these studies were actually liquid clouds (i.e. altostratus clouds). The surprising decrease of effective radius at temperature larger than 235 K (Fig. 8 in [Giraud et al, 1997]) may probably be explained by a change in CTP. The lack of small size particles found by these authors, for temperature below 235 K, is in agreement with our observations and consolidates our assumption that cirrus clouds generally don't exhibit as high BTDs as expected. Small BTDs observed for ice clouds may be attributed to the effects of particle sizes as well as particle shapes.

Phase versus Cloud Temperature

In this part, we analyse relation between cloud top phase derived from POLDER and the cloud top temperature from ATSR-2 IR channel. Brightness temperature, as derived from infrared channels, is representative of the cloud top thermodynamic temperature when the two following conditions are satisfied. First, the influence of the clear atmosphere located above the cloud is negligible. In the infrared window, water vapor is the principal atmospheric gas absorber. It is concentrated at low altitude, thus very low atmospheric absorption occurs above high or middle level clouds. Second, clouds are assumed to be opaque and radiate like blackbody. As mentioned previously, cloudy pixels are selected according to POLDER algorithm whereas

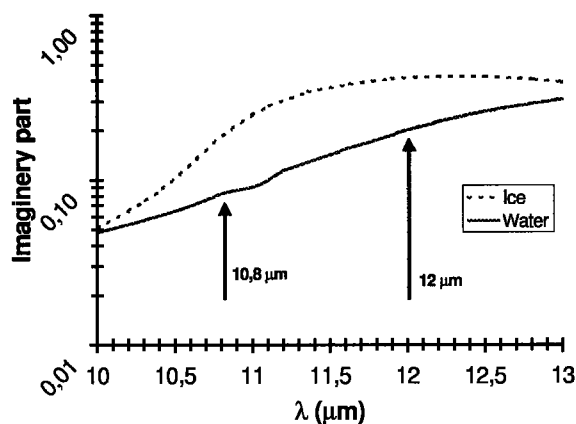


Figure 2. Imaginary part of refractive index for water and ice from 10 to $13 \mu\text{m}$. The two arrows correspond to the two ATSR-2 thermal channels used in the study.

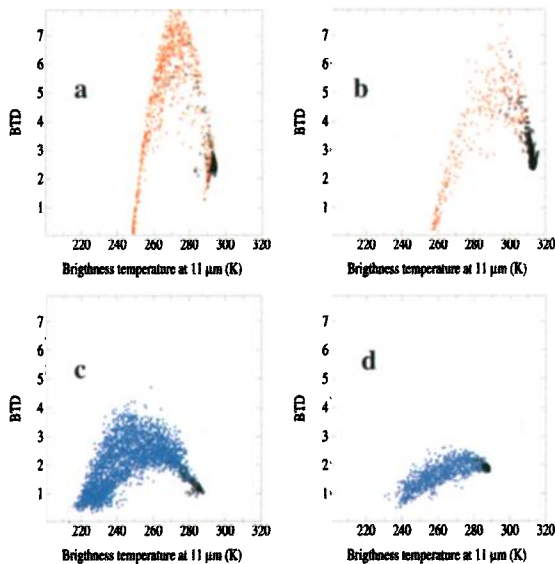


Figure 3. Examples of bidimensional scatter diagrams as observed with ATSR-2 data from the regions A, B, C and D, respectively (see Fig. 1). CTP information is represented in black for clear sky, red for liquid clouds and blue for ice clouds.

opaque clouds are selected when BT D is lower than 1 K, (i.e. emissivity is quite similar to 1 in the two channels).

The presence of ice particles, within clouds, increases as temperature decreases below 273 K, as illustrated in Fig. 5, showing the combined results of POLDER phase and ATSR-2 cloud top temperature retrievals. Distinction between clouds over land and those over ocean exhibits several differences in the probabilities for a cloud to be liquid or ice. Considering a temperature within the range of 220 to 270 K, the probability for a cloud to be composed of ice particles is always smaller over land. In other words, liquid clouds persist at lower temperature over land than over ocean. Over land, clouds having their top temperature greater than 260 K consist, in great majority (95%), of super-cooled droplets. Over ocean, at the same temperature, about 30% are ice clouds. Ice and water cloud equal distributions are reached around 250 K over land, 255 K over ocean.

In pure cloud droplets or highly diluted deliquescent condensation nuclei, the spontaneous ice formation is expected to occur over a narrow range of temperatures from about 238 to 235 K [Pruppacher, H.R., 1995]. Our results show that below about 240 K there is more than 95% probability that clouds over the ocean are glaciated. Over land, the same probability is only reached below 230 K. At 240 K, 12% of the cloud over land remain liquid. Based on numerous theoretical studies which explain homogeneous freezing of haze particles (e.g., [Sassen and Dodd, 1988,1989]; [Heymsfield and Sabin, 1989]; [Heymsfield and Miloshevich, 1993]; [Heymsfield et al, 1995]; [DeMott et al, 1994]; [Jensen et al, 1994a,b]), we speculate that freezing temperatures may be lower in continental environments than in maritime ones, as a result of different aerosol mass concentrations. Indeed, more cloud condensation nuclei lead to smaller supercooled droplets and elevation of solute concentrations. The transition temperatures, at which homogeneous nucleation rapidly ensues, are depressed for elevated solute concentration or for small haze particles.

For temperatures larger than 240 K, the freezing temperature differences between continental and maritime air masses range from 3 K at 245 K to 10 K at 270 K. These differences cannot be explained by a homogeneous freezing processes. For this temperature range, ice appears from heterogeneous processes like deposition, condensation freezing, immersion freezing and contact freezing, which all require ice nuclei (IN) [Masson, B.J., 1957]. Surface physical and chemical property requirements, for an aerosol to act as IN, are complex and poorly understood. While the potential impact of heterogeneous ice nuclei in ice formation has been clearly stated ([Sassen and Dodd, 1988]; [Detwiler, A., 1989]; [Heymsfield and Sabin, 1989]; [Heymsfield and Miloshevich, 1993]; [Heymsfield et al, 1995]; [Jensen et al, 1994a,b]), effects on cirrus cloud formation have not been yet clearly understood. Difficulties in studying heterogeneous nucleation processes are probably due to the fact that these processes have not shown themselves to be readily tractable through the application of classical theory [Pruppacher and Klett, 1978]. Several sources of IN can be found both over ocean and over land. For example, sea water rich in plankton and decayed plant leaves contain copious ice nuclei. Our results seem to point out that maritime IN are more efficient than continental ones, probably due to their differences in chemical and physical properties, as suggested before by [Heymsfield et al, 1998] during SUCCESS experiments.

Result interpretations will remain speculative until appropriate new measurements of CN and IN concentration and efficiency to nucleate ice are obtained in the upper troposphere.

Conclusions

Two main results have been obtained from the direct analysis of cloud infrared signatures against their thermodynamic phase. Firstly, the higher BT Ds were observed for semi-transparent liquid clouds. Cirrus clouds don't exhibit as high BT D values as expected by previous results. Results of many cloud retrievals have to be revised considering that cloud phase assumption is not relevant. Secondly, in continental air mass, the probability that liquid clouds form and maintain at lower temperatures is higher than in maritime air mass. We speculate that in maritime air mass, aerosols could be activated in warmer conditions than in continental ones. Of course, this study is limited to a unique day and has to be confirmed and completed with a larger data set. Nev-

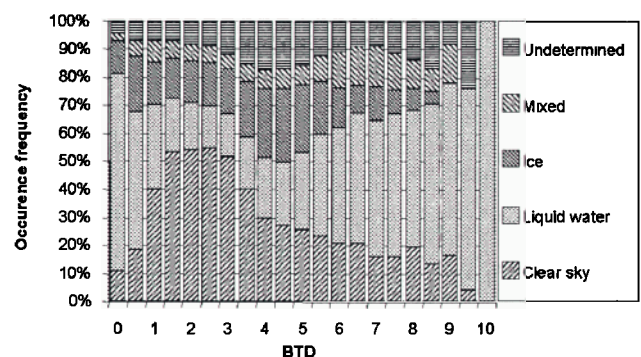


Figure 4. Two-dimensional histograms of the frequency of POLDER CTP index versus ATSR-2 BT D.

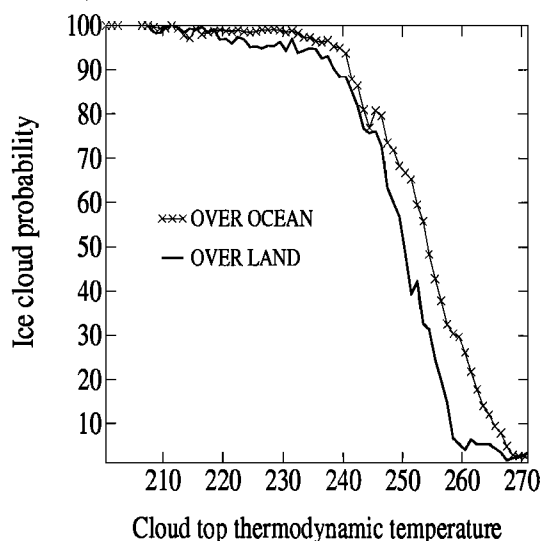


Figure 5. Probability of ice being detected in clouds as a function of the cloud top temperature, over ocean and land.

ertheless, the analysis presented in this paper clearly shows the potentialities of mixing observations from very complementary satellite measurements. This kind of analysis will be more attractive again from future satellite missions such as EOS-PM, PICASSO-CENA, PARASOL and CloudSat which will be in orbit at a coincident time and location in 2003.

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- V. Giraud, P. Goloub, J. Riedi and O. Thouron Laboratoire d'Optique Atmosphérique, Université des Sciences et Technologies de Lille, 59655 Villeneuve d'Ascq Cedex. France, Phone: (33) 03 20 43 47 66, Fax: (33) 03 20 43 43 42, (e-mail: giraud@loaser.univ-lille1.fr; goloub@loaser.univ-lille1.fr; riedi@loaser.univ-lille1.fr; thourown@loaser.univ-lille1.fr)

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