RETRIEVAL AND VALIDATION OF MSG AND AVHRR BASED CLOUD PHYSICAL PROPERTIES IN THE CM-SAF

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ABSTRACT

According to recent IPCC reports, clouds and cloud-radiation interactions, contribute most to the uncertainty in climate predictions based on climate model runs. The IPCC calls for more measurements on cloud properties in order to improve the understanding of cloud processes and the representations in models. The SAF of Climate Monitoring will provide the climate research community with products derived from geo-stationary and polar orbiting meteorological satellites. The focus will be on cloud and radiation components.

The KNMI developed for the CM-SAF the algorithms to retrieve cloud physical products from both AVHRR and MSG satellites. The anticipated cloud physical products are cloud thermodynamic phase, cloud optical thickness and cloud liquid water path. The method to retrieve cloud physical parameters utilizes observed reflectivities in the visible 0.6 and near infrared 1.6 micron range, which provide information on cloud optical thickness and cloud particle size, respectively. By combining both types of information the cloud liquid water path can be calculated. A radiative transfer model is used to simulate channel reflectances for water and ice clouds with different a thickness and particle distribution. The comparison of AVHRR derived liquid water path retrievals with Cloud Water Network project (CLIWANET) ground measurements showed a good correlation between the retrieved and ground-based microwave radiometer liquid water path. The Baltex Bridge Cloud campaign – 2 will provide data to validate the first set of MSG retrieved cloud physical products. The ground based set-up includes among others ground based lidars, radars, microwave radiometers. Furthermore aircraft flights are foreseen to measure cloud microphysical properties.

This article focuses on showing the CM-SAF cloud physical products retrieved from NOAA-AVHRR (and MSG). As an assessment of the quality of the NOAA (and MSG) cloud physical products we present the results of a comparison between CLIWANET ground measurements and AVHRR (and MSG) retrieved cloud physical properties. In addition an inter-comparison NOAA retrievals and NWP model LWP fields was done to assess applicability of AVHRR based products for climate studies.

1. INTRODUCTION

Accurate information on cloud properties and their spatial and temporal variation is crucial for climate studies. Clouds strongly modulate the energy balance of the Earth and its atmosphere through their interaction with solar and thermal radiation (King and Tsay, 1997). Despite their importance, clouds are represented in a rudimentary way in climate and weather forecast models. Cess et al. (1989) showed that clouds are the major source of uncertainty in model responses to climate forcing. The radiative behaviour of clouds depends predominantly on cloud properties such as thermodynamic phase, optical thickness and droplet effective radius. Satellites provide useful information on global cloud statistics and radiation budget (Feijt, 2000). With the launch of Meteosat Second Generation (MSG) and later METOP, the methods to retrieve cloud physical parameters can be improved further.

Several researchers have developed methods to retrieve cloud optical thickness and cloud particle size from cloud radiances at a non-absorbing visible and a moderately absorbing solar infrared wavelength (Han et al. 1994, Nakajima and Nakajima 1995, Watts et al. 1998 and Jolivet et al. 2000). The principle of these methods is that the reflection of clouds at the non-absorbing wavelength is primarily a function of the cloud optical thickness, while the reflection at the absorbing wavelength is primarily a function of cloud particle size (Nakajima and King 1990). For the non-absorbing wavelength all methods use the 0.6 micron channel. For the absorbing channel some methods use the 3.7 micron channel (Han et al. 1994 and Nakajima and Nakajima 1995), while others use the 1.6 micron channel (Watts et al. 1998, Jolivet et al. 2000, Roebeling et al. 2001). The 0.6 and 1.6 micron channel can also be used to retrieve the cloud thermodynamic phase (King and Tsay, 1997). Radiative transfer models (RTMs) are used to relate the observed radiance to cloud physical properties, by simulating cloud reflections at given viewing geometries and predefined physical properties. In the RTM simulations of this study clouds are assumed homogeneous and plane parallel. Not taking into account 3D cloud effects, multilayer cloud effects and the presence of aerosols may lead to errors in the retrievals.

Little research has been done on the application of the 1.6-micron channel for the retrieval of cloud properties. No research has been done so far on the application of these methods on MSG data. The purpose of this study was to assess the accuracy of NOAA retrieved cloud physical properties from 0.6 and 1.6-micron narrow band radiances in preparation of the retrieval of these parameters from MSG data. This topic was identified as important to the Climate Monitoring SAF (CM-SAF) of EUMETSAT where these retrieval methods will be applied on MSG data . The CM-SAF will generate and archive high quality data sets on climate relevant products from MSG and NOAA/AVHRR and METOP satellites for a region covering Europe and Africa (Science plan, 2000).

The outline of this paper is as follows. Section 2 describes the method to retrieve Cloud Thermodynamic Phase (CPH), Cloud Optical Thickness (COT) and Cloud Liquid Water Path (CLWP) for semitransparent and opaque clouds. The procedure followed in conducting this study is described in Section 3. The results are presented in Section 4. The paper concludes with remarks on our experiences with the retrieval of cloud physical properties from meteorological satellites using 0.6 and 1.6 micron radiances .

2. METHODS

Radiative transfer calculations

The Doubling Adding KNMI (DAK) algorithm is used for RTM simulations. DAK is based on the doubling-adding method (Van der Hulst, 1980, Stammes, 1994) and solves the radiative transfer problem for solar radiation in the Earth's atmosphere monochromatically. The reflection and transmission is calculated for two thin layers. In each layer no more than one scatter event may occur. Due to this restriction the radiative transfer equation can be solved. The reflection and transmission from the two layers can be obtained by computing successive reflections back and forth between the layers. The number of layers is doubled until the actual thickness of the cloud is reached. DAK takes into account multiple scattering and polarisation, but thermal emission is not considered. The atmosphere is assumed to be plane-parallel.

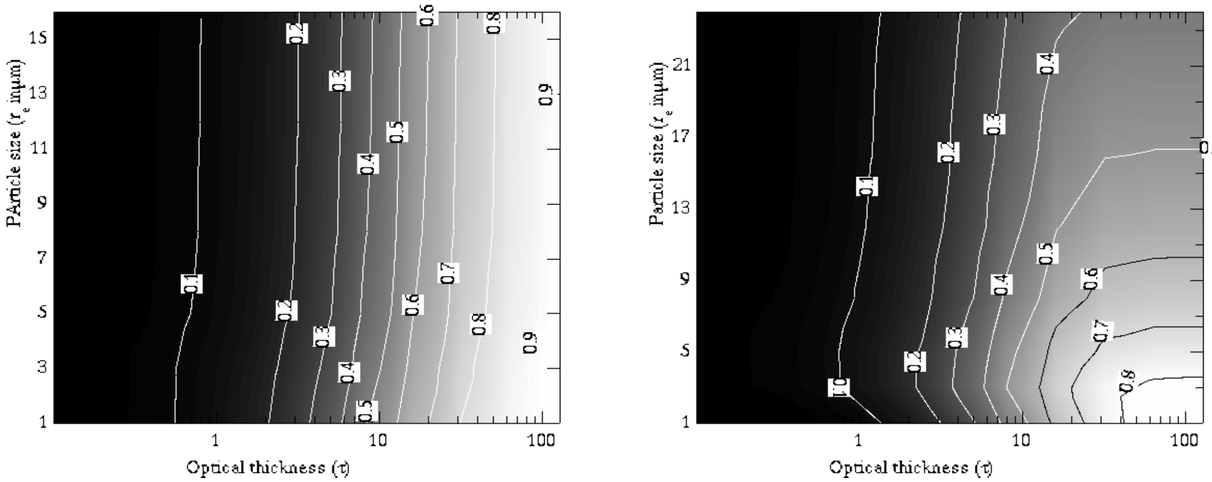
Narrow band reflectances in relation to cloud physical parameters

Figure 1 shows examples of DAK simulated reflectances as function of optical depth and droplet particle size at 0.63 (A) and 1.6 (B) micron. Figure 1A demonstrates that the reflection of clouds at a non-absorbing wavelength in the visible region is almost fully explained by differences in the optical thickness, and there is very little dependence on the effective radius. Figure 1B shows that the reflectance at 1.6 micron is mainly a function of optical thickness at low optical thicknesses (τ_{vis} <10) , and mainly a function of particle size for optically thick clouds (τ_{vis} >10).

Retrieval of cloud physical properties

The method described by described Watts et al. 1998 and Jolivet et al. 2000 is implemented to retrieve the Cloud Optical Thickness and Cloud Liquid Water Path in the CM-SAF.

To determine the thermodynamic phase of cloud particles the ratio of the reflectivity at 0.6 micron over the reflectivity at 1.6 micron is used in combination with the 10.8 micron brightness temperature (King and Tsay, 1997; Jolivet and Feijt, 2003). Liquid water clouds typically have a low 0.6 over 1.6 micron ratio and a high brightness temperature at 10.8 micron. The opposite holds for ice clouds, which have a high 0.6 over 1.6 micron ratio and a low brightness temperature. Jolivet and Feijt, 2003 mention that for optically dense clouds the 10.8-micron brightness temperature represents the thermodynamic temperature of the cloud top. However, for optically thin clouds a correction procedure is required, since the brightness temperature is a mixture of radiation from the surface and the cloud.



(A) (B)

Fig. 1. DAK simulated reflectances as a function of optical depth and droplet particle size at 0.63 micron (A) and 1.6 micron (B). With satellite zenith angle (θ=19.68), solar zenith angle (θ_0 =38.63), relative azimuth angle (ϕ=126.45)

The cloud optical thickness (τ) and the droplet effective radius (r_e) are retrieved by combining the reflected radiances at 0.6 and 1.6 micron. The cloud particle size, expressed as the droplet effective radius, is an adequate parameter to represent the size distribution of water particles and their radiative properties (Hansen and Hovenier, 1974). The optical thickness and corresponding particle size are retrieved from the Look Up Tables of cloud reflectivity by using an iteration procedure. The cloud liquid water path (CLWP) is calculated form the cloud optical thickness and the droplet effective radius (Stephens, 1978):

$$CLWP = \frac{2}{3}.\tau_{vis}.r_e.\rho_l \tag{1}$$

Where ρ_l is the density of liquid water. The droplet effective radius of water particles is a function droplet size distribution. Note that the effective radius retrieved from the satellite data is based on reflectivity of the cloud top layer, hereinafter referred to as the radiative equivalent effective radius $r_{e(1.6\ \mu m)}$. There is a correlation between $r_{e(1.6\ \mu m)}$ and r_e . But it needs further study to define the relationship and variance between r_e and the retrieved $r_{e(1.6\ \mu m)}$, and its validity for CLWP calculations.

Cloud measurement campaigns

CLIWANET was a EU funded project that focused on ground observations of cloud physical parameters i.e.: cloud droplet profiles of water clouds, cloud particle profiles, particle velocity for ice clouds measured with lidar and radar (Donevan, 2000), the cloud liquid water path and water vapour content (microwave radiometer), the sky or cloud base temperature (infrared radiometer) and vertical profiles of air temperature and pressure (radiosonde data) (Lammeren, 2000). The CLIWANET ground-based stations were equipped with a microwave radiometer, a ceilometer, and an infrared radiometer. For the CLIWANET Network Campaigns in April-May 2000 (CNN1) and August-September 2001 (CNN2), the stations were distributed over 11 sites in the Baltex modelling area. During the Baltex Bridge Intensive Experimental Campaign in August-September 2001 (BBC) a large number of instruments was shipped to the meteorological tower at Cabauw, the Netherlands (51.9N, 4.9E). The total measurement set-up included: several radar, lidar and microwave radiometer systems; an extended set of radiation instruments; three aircraft and two tethered balloons.

As a follow up of CLIWANET the KNMI and the University of Bonn organised in May 2003 the second intensive (cloud) measurement campaign "BBC2" that was held at Cabauw, the Netherlands. Beside these two organizing research groups, more than 100 scientists from 20 institutes participated. Most of the objectives and many of the participants are the same as those of the first BBC campaign. The focus of BBC2 was on clouds and radiation, but other subjects of research were also included, such as turbulence in the atmospheric boundary layer and small-scale structures of rainfall. The BBC2 provided the first set of ground measurements that can be applied for validation of MSG retrieved cloud physical products.

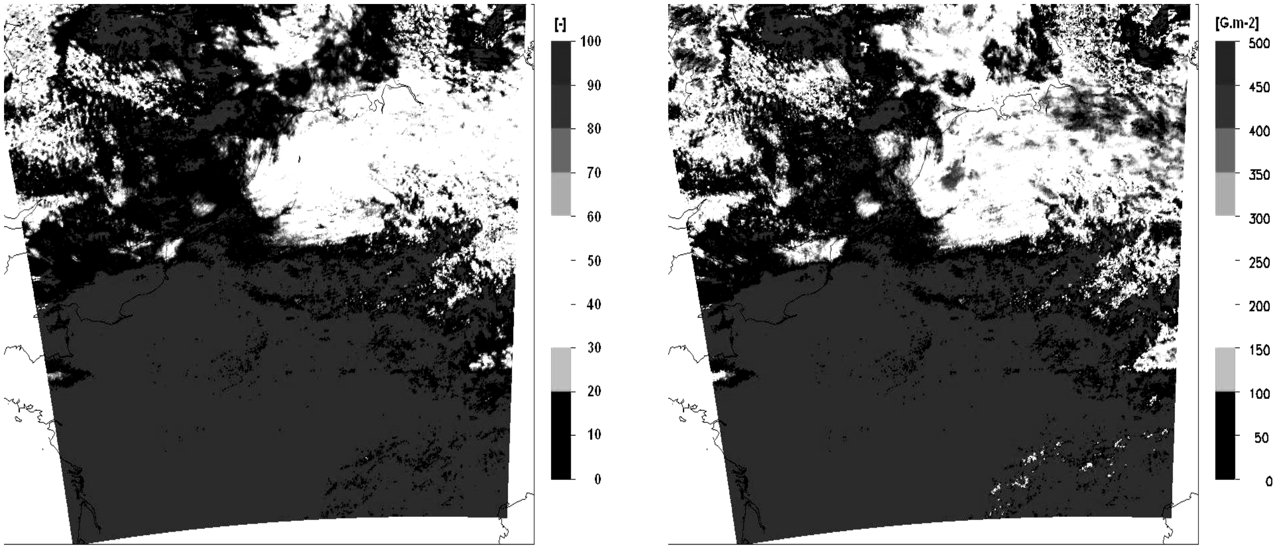
3. STUDY PROCEDURE

The CM-SAF cloud physical products were generated for two periods of two month, corresponding with the CNN2 campaign in April and May 2001 and the BBC campaign in August and September 2001. Look Up Tables (LUT) of the top of atmosphere reflectivities were generated with DAK, for different optical thicknesses, as a function of surface albedo (r), satellite zenith angle (θ), solar zenith angle ($\tilde{\theta}$), relative azimuth angle (ϕ) and cloud thermodynamic phase. For the atmospheric profiles the midlatitude summer profiles of Anderson et al., 1986 were used. The underlying surface was assumed Lambertian. The absorption properties of atmospheric molecules are obtained from the HITRAN database (Kneizys et al. 1996, Rothman et al., 1996).The clouds were treated as plane parallel and homogeneous layers. The cloud properties were assumed vertically and horizontally constant in the model layer. The liquid cloud particles were assumed to be spherical. The optical properties of the droplets were parameterised in terms of the effective radius (r_e), the effective variance (v_e) and the droplet size distribution n(r). The scattering phase functions for spherical droplets were calculated with Mie theory. For ice clouds randomly oriented imperfect hexagonal ice crystals were used (Hess et al. 1998, Knap et al 1999). This crystal is known to fits well to satellite measurements. For ice crystals the single scattering properties were calculated with ray tracing (Hess et al., 1998).

A comparison was made between ground based microwave radiometer LWP observations and satellite retrieved LWP for CNN2 and BBC, using data of Cabauw, Chibolton, Potsdam, Paris and Lindenberg. For the comparison only observations with homogeneous and non precipitating water clouds were included (20% of the data). To minimize the collocation errors we averaged the microwave data over 40 minutes and the liquid water path retrievals over 5*5 pixels. In addition, horizontal distributions of LWP from satellite were compared to the Regional Atmospheric Climate Model (RACMO) predicted LWP fields for 60 days of BBC. Probability density functions were studied to analyse the differences between RACMO and satellite retrieved LWP fields.

4. RESULTS

Examples of the NOAA-16 based cloud physical products are shown in Figure 2. The products were generated for 13 August 2001, 12:25 UTC, when The Netherlands were covered by a uniform layer of stratocumulus clouds, which extended towards Germany. Figure 2A indicates that the optical thickness for the stratocumulus field varies between 30 and 60, which are realistic values for water clouds with a thickness between 500 and 1000 meter. The cloud liquid water path for the stratocumulus field varied between 200 and 300 g.m-2. For MSG a preliminary version of the COT and CLWP algorithm has been developed. This version is not yet ready to retrieve quantitative cloud physical products, because the procedure to calibrate the radiances needs to be improved. An example of MSG derived CLWP and the related frequency distribution for 25 August 2003 is shown in Figure 3. This preliminary result indicates that the MSG retrieved CLWP are in the right order of magnitude. The majority of the clouds have a CLWP of approximately 100 g.m^{-2}. In the active cloud systems the values go up much higher values (app. 500 g.m^{-2}). Bearing in mind the high sensitivity of optical thickness to 0.6-micron radiances of optically thick clouds, the CLWP of the first retrievals cannot be considered representative.



(A) (B)

Fig. 2. NOAA-16 derived cloud optical thickness (A) and cloud liquid water path (B) for 13 August 2001, 12:25 UTC.

For CNN2 and BBC ground based microwave radiometer and NOAA-AVHRR derived liquid water path were compared for the stations of Cabauw, Chibolton, Potsdam, Paris and Lindenberg. The observations included in the scatter plot represent cases of non-precipitating water clouds on days with sufficient overcast. From a database of approximately 120 observation days only 17 representative cases were found. This is a limited number for a statistically significant validation of the CLWP product. Considering the number of rejected observations it is clear that there is a strong need for more ground based microwave observations. The graphs are plotted in Figure 4 on a linear (A) and a logarithmic scale (B). The ground based and AVHRR retrieved LWP are in agreement, with a correlation coefficient of 0.81. The standard deviations (STD), of both satellite and ground based LWP, are about 20 g.m^{-2}. For cases with a heterogeneous cloud cover the STD is about 100 g.m^{-2}. The graphs also indicate that the STD of satellite retrieved CLWP increases with increasing CLWP.

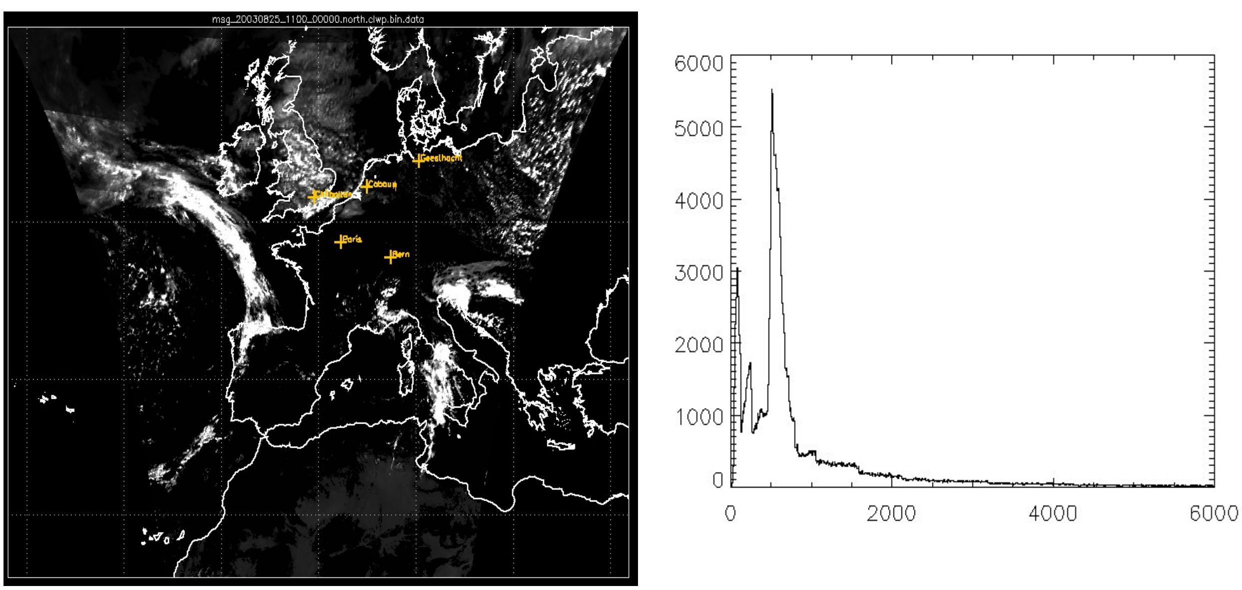
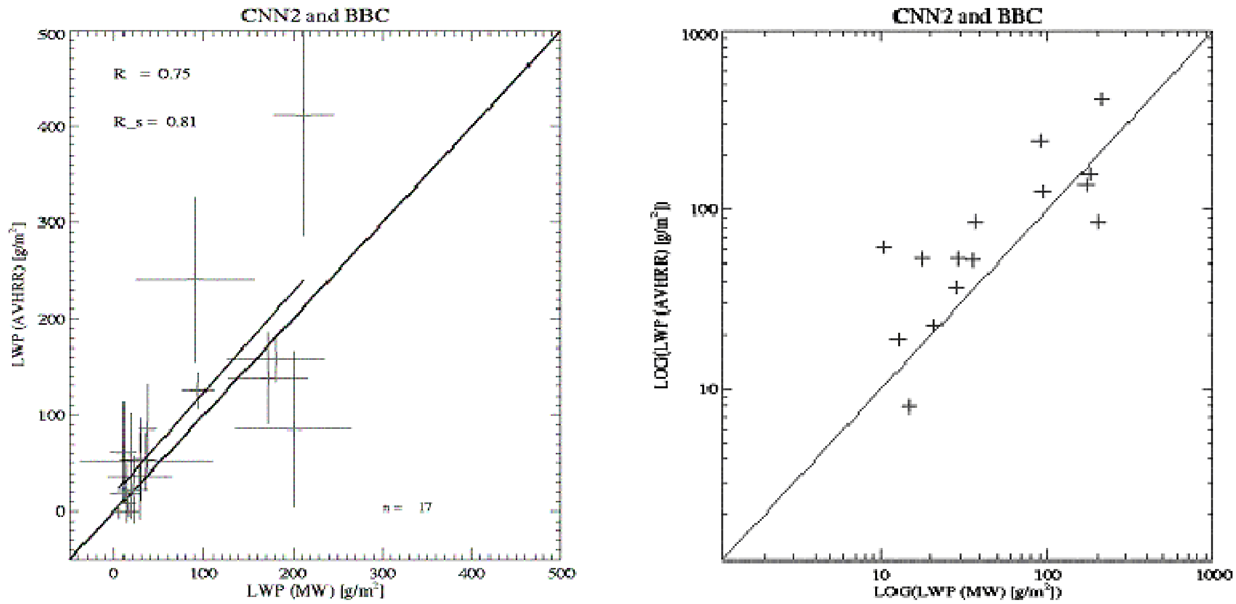


Fig. 3. Example of MSG derived cloud liquid water path and related frequency distribution [clwp*10], for 25 August 2003, 11:00 UTC.



(A) (B)

Fig. 4. Relationship between microwave radiometer liquid water path and NOAA-AVHRR derived liquid water path for CNN2 and BBC observation days at Cabauw, Chibolton, Potsdam, Paris and Lindenberg. The graphs are plotted on a linear (A) and a logarithmic scale (B).

For 60 days of the BBC campaign RACMO and satellite derived LWP were compared. In figure 5 the probability density functions of RACMO and satellite derived LWP are presented. The figures shows that, compared to RACMO, the not resampled ("raw") satellite frequencies are high for the low LWP values (<50 g.m-2) and low for the high LWP values (> 300 g.m^{-2}). These differences become smaller when the satellite LWP is brought to the resolution of the model, but the phenomenon does not disappear. An explanation for the high frequency of satellite based clouds with a low LWP (< 50 g.m^{-2}) could be that the particle size retrievals are less reliable for optically thin clouds, when 1.6-micron radiances have a low sensitivity to particle size. This explanation, however, does not explain the bias towards a low frequency of satellite based clouds with a high LWP.

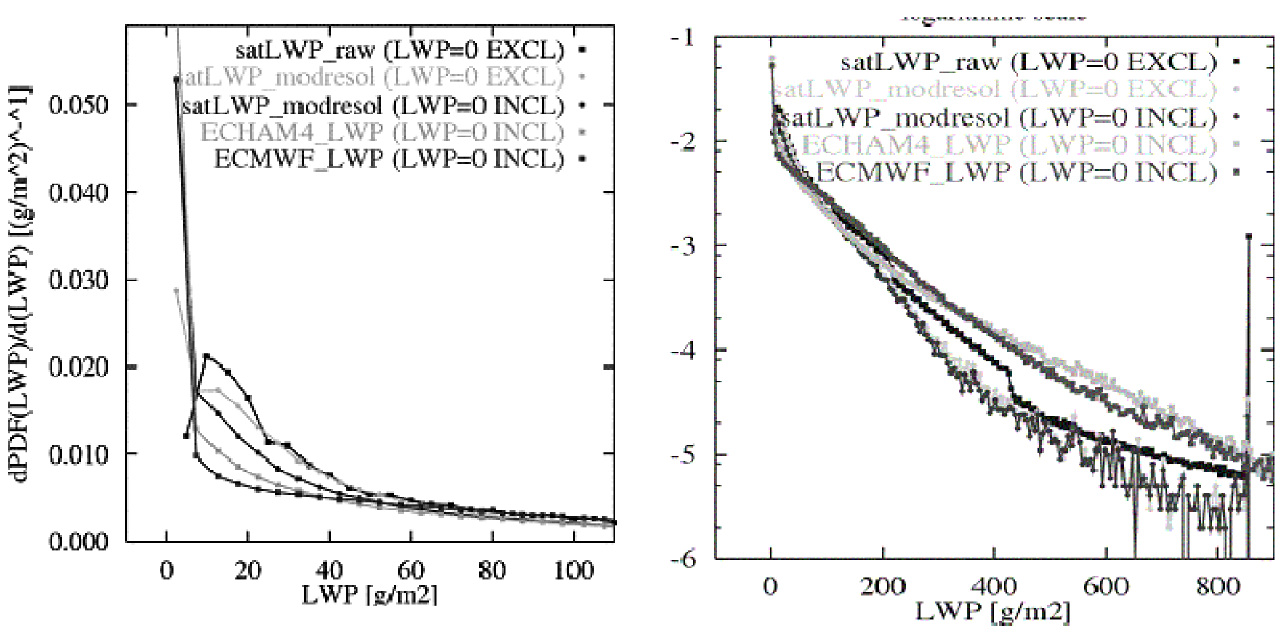


Fig. 5. Probability Density Functions of model and satellite inferred LWP plotted on a linear (A) and a logarithmic scale (B)

5. DISCUSSION AND CONCLUSIONS

The results presented in this paper demonstrate the applicability of narrow band reflectivities observed at 0.6 and 1.6 micron for the retrieval of cloud physical properties over Northern Europe. It was demonstrated that both compared to ground observations and to climate model data the satellite derived liquid water path values are quantitatively and statistically plausible. Note that the retrievals of cloud physical products concentrated on water clouds. It was premature to concentrate on ice clouds in this paper. For practical applications we assumed hexagonal columnar shapes to represent the optical properties of particles inside an ice cloud (mainly cirrus cloud) in a reasonable manner. Ice crystals have a large variety of different shapes, depending on the conditions in the cloud. Although the possible shapes may be sorted into a limited number of classes, the individual crystal shapes may deviate considerably from the idealized shapes. Comparison to flight observations and radar and lidar measurements on ice clouds is needed to asses the quality of COT and CLWP for ice clouds.

For optically thin clouds, the retrieval is sensitive to errors because the reflectivities at 0.6 and 1.6 micron are strongly related to the optical thickness and less strong to the particle size. Theoretically the 3.7-micron channel is more suited for the retrieval of cloud particle size for thin clouds (Rosenfield, 2003). It needs consideration that the 3.7 micron channel has a number of disadvantages that may lead to significant errors. Firstly, radiance observed at 3.7 micron consists of reflected solar radiance and thermal radiance. The procedures developed to remove the thermal radiance at 3.7 micron introduce errors that will be largest for thin clouds. Secondly, the reflectance of solar light at 3.7 micron is approximately 4 times lower than at 1.6 micron, which lowers the signal to noise ratio. Above described sources of error make the quantitative retrieval of cloud properties from 3.7 micron radiances less accurate, and may compensate for the theoretical advantages of the 3.7 micron channel. A thorough sensitivity study is needed to really assess the advantages and disadvantage of both the 1.6 and 3.7-micron channel for specific applications.

For the CLIWANET ground stations AVHRR derived CLWP is in good agreement with microwave LWP. The slope of linear regression closed to 1 and the points scattered around the linear regression. Errors due to comparing in-situ ground measurements to instantaneous satellite retrievals. Due to the tight selection criteria the number of observations that were part of the validation was limited with 19 suitable observations.

First results of MSG retrievals look realistic. Quantitative analysis of MSG products is not yet possible due inaccurate calibration data and lack of ground based cloud measurements. BBC2 is the only measurement campaign that provides data for validation of MSG cloud physical products.

6. ACKNOWLEDGEMENT

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