RETRIEVAL OF SPATIAL DISTRIBUTION OF LIQUID WATER PATH FROM NOAA-AVHRR FOR ATMOSPHERIC MODEL EVALUATION

R.A. Roebeling, A.J. Feijt, D. Jolivet and E. van Meijgaard

Royal Netherlands Meteorological Institute (KNMI)
P.O. Box 201, 3730 AE De Bilt, The Netherlands

ABSTRACT

The SAF on Climate Monitoring (CM-SAF) 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 products. Furthermore, humidity and ocean wind stress vector information is retrieved. According to recent IPCC reports, clouds and cloud-radiation interactions, contribute most to uncertainties in climate model predictions. The IPCC requests for more measurements on cloud properties in order to improve the understanding of cloud processes and their representations in climate models. The CM-SAF will provide spatial distributions of measured cloud parameters. The anticipated cloud products are among others: cloud top temperature, cloud top height, cloud thermodynamic phase, cloud optical thickness and cloud liquid water path (CLWP). These parameters will be compared with model values. In this paper we will describe the retrieval method for cloud optical thickness and cloud liquid water path. For a test case NOAA-AVHRR retrieved CLWP values were compared to climate model predictions.

The cloud liquid water path may be calculated from the optical thickness and droplet particle size, retrieved from 0.6 and 1.6 micron channel radiances. Radiative transfer calculations with DAK are done to relate the cloud radiances observed in these two channels to optical thickness and the droplet radius. In this paper we used the KNMI Local Implementation of APOLLO in an Operational System (KLAROS) to estimate the visible optical thickness from the 0.6-micron channel and relate to liquid water path. The droplet particle size was assumed constant. Ground-based LWP data of the CLIWA-Net project were used to optimise the CLWP retrievals for a test run with AVHRR data of May 2002. The CLIWA-Net LWP observations were obtained from a network of ground-based microwave radiometers over Europe. The optimised CLWP fields were compared to LWP fields of the Regional Atmospheric Climate Model (RACMO).

This study has been carried out to examine the prospect of CLWP retrievals from MSG radiances, in combination with information form ground-based cloud measurement. Examples of the results of the NOAA-AVHRR retrievals are shown. The added value of satellite retrieved CLWP for evaluation of climate models is demonstrated.

INTRODUCTION

Clouds dominate the vertical transport of energy and trace gases in the free atmosphere. Despite their importance, clouds are represented in a rudimentary way in climate and weather forecast models. The low quality of the representation of clouds in climate models has been identified to be one of the largest sources of uncertainty in climate predictions based on climate model runs (IPCC 2001, Cess et al. 1989). Accurate information on cloud properties such as cloud cover, cloud thermodynamic phase, cloud optical thickness (COT) and cloud liquid water path (CLWP) are of great importance for weather prediction and climate models.

The European CLIWA-Net project aims to measure and model the atmospheric components of the hydrological cycle over the Baltic Sea catchment area. The measurements were obtained during three observational campaigns in August/September 2000, April/May 2001 and August/September 2001. The campaigns have provided a wealth of cloud parameters. The main objectives of the Cloud Liquid Water Network project (CLIWA-Net) are: to implement a prototype of a European cloud observational network, to contribute to the program of the continental–scale experiment BALTEX , to objectively evaluate cloud related output from atmospheric models for weather and climate prediction (Lammeren, 2000).

The CM-SAF of EUMETSAT aims to generate and archive high quality data sets from meteorological satellite measurements on climate relevant products. Climate data derived from satellite measurements are understood as an important component in the climate observing system that consists of conventional observations, remote sensing data and data sets, which are created by means of Numerical Weather Prediction (NWP) models. Satellite derived data provide a high spatial coverage compared to conventional surface networks and especially fill gaps in areas with sparse conventional observations such as oceans. They also provide information that cannot be measured from the ground, like the outgoing radiation at the top of the atmosphere (Science plan, 2000). The cloud physical products of the CM-SAF will be generated on continuous bases and may be utilised for studies on monitoring of the climate state and its variability and for the validation of Climate and NWP models.

The objective of this study is to demonstrate the application of satellite generated Liquid Water Path fields that are combined with ground based measurements, for the evaluation of a climate-monitoring model (the Regional Atmospheric Climate Model (RACMO)). Section 2 describes the method to retrieve COT and CLWP for semitransparent and opaque water clouds. In section 3 the Regional Atmospheric Climate Model is shortly presented. the results of a case study of 4 May 2002 are presented in section 4. For this study LWP fields were retrieved from NOAA-16 AVHRR channel radiances. Ground based microwave radiometer measurements of the CLIWANET project were used to recalibrate the retrieved LWP fields. The recalibrated LWP fields were used to evaluate the LWP fields of the RACMO model. In section 5 conclusions are drawn.

RETRIEVAL OF CLOUD PHYSICAL PROPERTIES

The properties of clouds are determined on a pixel by pixel basis. The method to retrieve cloud liquid water path (CLWP) uses satellite retrieved cloud optical thickness (COT, an equivalent abbreviation is τ) and cloud droplet effective radius (r_e) information. The underlying principle on which this method is based is the fact that the reflection function of clouds at a non absorbing channel in the visible wavelength region is primarily a function of the cloud optical thickness, whereas the reflection function at a water (or ice) absorbing channel in the near infrared is primarily a function of cloud particle size (Nakajima and King 1990, Nakajima and Nakajima 1995, Watts 1996). By combining the information of non-absorbing and water absorbing channels it becomes possible to estimate the droplet effective radius (r_e) and to retrieve the cloud optical thickness. The retrieval method applied in the CM-SAF derives the Cloud Optical Thickness (COT) from measurements of the reflectivity in the visible channel (0.6 micron). The droplet effective radius is derived from 1.6 micron near infrared radiance information (Roebeling et al., 2001).

A radiative transfer model is used to simulate the reflectivity at 0.6 micron and at 1.6 micron as a function of τ_{vis} and r_e, taking into account the atmospheric absorption and the cloud scattering and absorption properties. The calculations are done for plane parallel clouds with different optical thicknesses, as a function of surface albedo (r), satellite zenith angle (θ), solar zenith angle (θ_0), relative azimuth angle (ϕ) and cloud thermodynamic phase. In this study the Doubling Adding KNMI (DAK) radiative transfer model is used, which is based on the doubling-adding method (Van der Hulst, 1980, Stammes, 1994). DAK solves the monochromatic radiative transfer problem for solar radiation in the Earth's atmosphere. Multiple scattering and polarisation are taken fully into account. The atmosphere is assumed to be plane-parallel. The scattering phase function for a size distribution of liquid water droplets is calculated with Mie theory. Ice crystal scattering is modeled using ray-tracing, assuming imperfect hexagonal shape (Hess et al. 1998). The underlying surface is assumed Lambertian. The absorption properties of atmospheric molecules are calculated from the HITRAN database (Kneizys et al. 1996). The midlatitude summer atmosphere model is used. Figure 1 shows examples of DAK simulated reflectances as function of optical depth and droplet particle size at 0.6 (A) and 1.6 (B) micron. The figure shows that the reflection of clouds at 0.6 micron is primarily a function of the cloud optical thickness, and the reflectance at 1.6 micron more a function of particle size.

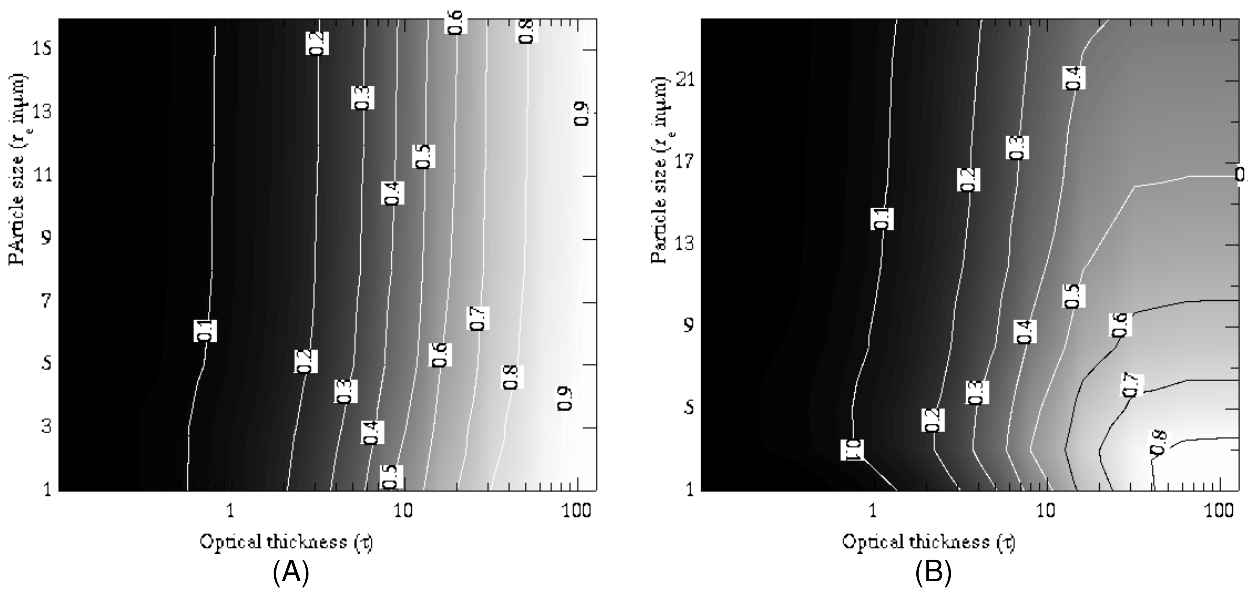


Figure 1: ***DAK simulated reflectances as a function of optical depth and droplet particle size at 0.63 micron (A) and 1.6 micron (B). With satellite zenith angle (θ=19.68), solar zenith angle (θ_0 =38.63), relative azimuth angle (ϕ=126.45)***

The cloud liquid water path is derived with the cloud optical thickness (τ_{vis}) and the droplet effective radius estimates (r_e) using the following equation (Stephens, 1978):

$$CLWP = \frac{2}{3}.\tau_{vis}.r_e.\rho_l \qquad (1)$$

Where ρ_l is the density of liquid water.

r_e is the droplet effective radius of water particles. The effective radius is a measure of the size distribution of cloud particles. It should be noted that an effective radius retrieved from the satellite data, hereinafter denoted as $r_{e(1.6\,\mu m)}$, is based on reflectivity of the cloud top. There is a correlation between $r_{e(1.6\,\mu m)}$ and r_e. It needs, however, 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. For the calculation of CLWP in this paper we assumed that $r_{e(1.6\,\mu m)}$ is equal to r_e.

THE ATMOSPHERIC MODEL

For the model evaluation the Regional Atmospheric Climate Model (RACMO) is chosen. RACMO is developed in collaboration with the Danish Meteorological Institute (Gustafsson 1993, Christensen et al. 1996) and operated at KNMI. The model is based on the weather forecast model HIRLAM and employs the package of physical parameterizations of ECHAM4 Global Climate Model. Cumulus convection is represented by a mass-flux scheme (Tiedtke 1989) and stratiform processes are represented by a modified version of the scheme of Sundqvist (1989), in which cloud content (water+ice) is predicted. Details can be found in Roeckner et al. (1996). For the results presented in this paper RACMO is operated at an 18km horizontal resolution and with a 24-layer mesh in the vertical. A 36-hour hind cast, initialized by the ECMWF-analysis valid at noon on the previous date, produces the model fields. ECMWF-analyses are also used to drive the atmospheric variables from the lateral boundaries

CASE STUDY

A case study was performed to illustrate the concept of evaluating RACMO predicted LWP fields with ground-based and satellite inferred observations. For the Netherlands, 4 May 2001 appeared to be a suitable day. The case meets the following selection criteria for at least one of the ground-base stations: i) non-precipitating clouds, else the microwave radiometer would not operate, ii) no ice-topped clouds and/or cirrus, else the satellite retrieval of LPW would not be applicable, iii) reasonably thick clouds, at least a couple of hundreds of meters, else the model vertical resolution would be too coarse to predict any clouds. LWP fields were retrieved from NOAA-16 AVHRR radiances for the 4th of May 2001 at 15:15. The KNMI Local Implementation of APOLLO in an Operational System (KLAROS) was used to estimate the visible optical thickness from 0.6-micron channel radiances. The liquid water path is calculated assuming a constant droplet particle size of 10 micron. For the selected case RACMO LWP fields were generated with time steps of 15 minutes.

Meteorological conditions

Synoptical conditions on 4 May 2001 were controlled by a high pressure system over the Azores with a ridge across Scotland towards Norway, and a belt of low pressure from northern Scandinavia across western Poland, Czechia, Austria towards southern France, generating convective cloud systems in central Europe and frontal cloud systems in the northern Baltic, and in the central and south eastern part of France. Governed by this pressure distribution, moderate winds (at most 10m/s) across the Netherlands came from directions between northwest and northeast throughout a 2km thick layer and during the entire day. Above 3 km, winds were from the southwest. In the coarse of the day, an inversion developed over the Netherlands which gradually came down to about 1200 m. Hence, during the entire day air was advected over the relatively cool North Sea, picking up enough moisture to generate and maintain boundary-layer clouds, but not enough to generate precipitation, apart from isolated patches of drizzle. Due to persistent subsidence the inversion came down, and since the flow gradually veered to the northeast the moisture supply by the North Sea was cut off. As a result the cloud deck became thinner and tended to dissolve by the end of the day.

One of the objectives of the CM-SAF is to provide satellite based cloud products for the evaluation of the output of atmospheric models for weather and climate predictions. In the framework of the CLIWANET project a comparison between time series of ground based measurements and model cloud parameters is done for the CLIWANET network (Crewell et al.2002).

CLIWANET measurements

The 4^{th} of May 2001 lies in the second measurement period of the CLIWA-NET Network (CNN2), which lasted from April the 1^{st} 2001 until May the 30^{th} 2001. During CNN2 micro-wave radiometer (DRAKAR) measurements of Liquid Water Path and Integrated Water Vapour were collected at the CLIWANET measurement site in Cabauw (latitude 51.9 N, longitude 4.9 E) and in Postdam (latitude 52.4 N, longitude 13.1 E). Figure 2 shows time series of ground-based liquid water path measurements at Cabauw and RACMO predicted liquid water path field. There is a gap in the microwave measurements between 17:00 and 18:00 hr. The graph shows that both the model predicted LWP and the predicted LWP decreases from about 280gm--2 at 12 UTC to nearly 0 at 24 UTC. However, the ground-based values drop off much faster. At 15 UTC an absence of cloud water was measured for the first time, whereas the model predicted still about 250gm--2. Between 15 and 16 UTC the observed values range from 0 to 120gm-2. The low LWP values are consistent in time and seem to indicate that there is a large cloud field with low LWP that is advected over the Cabauw site.

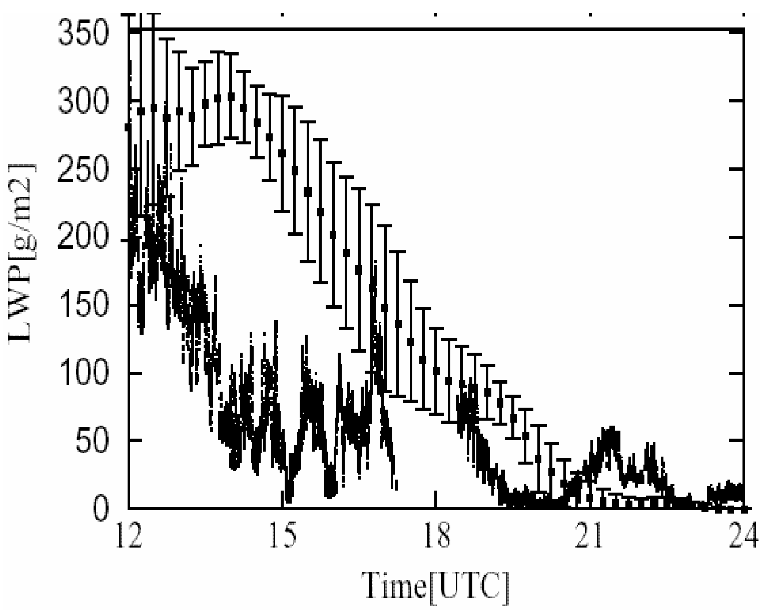
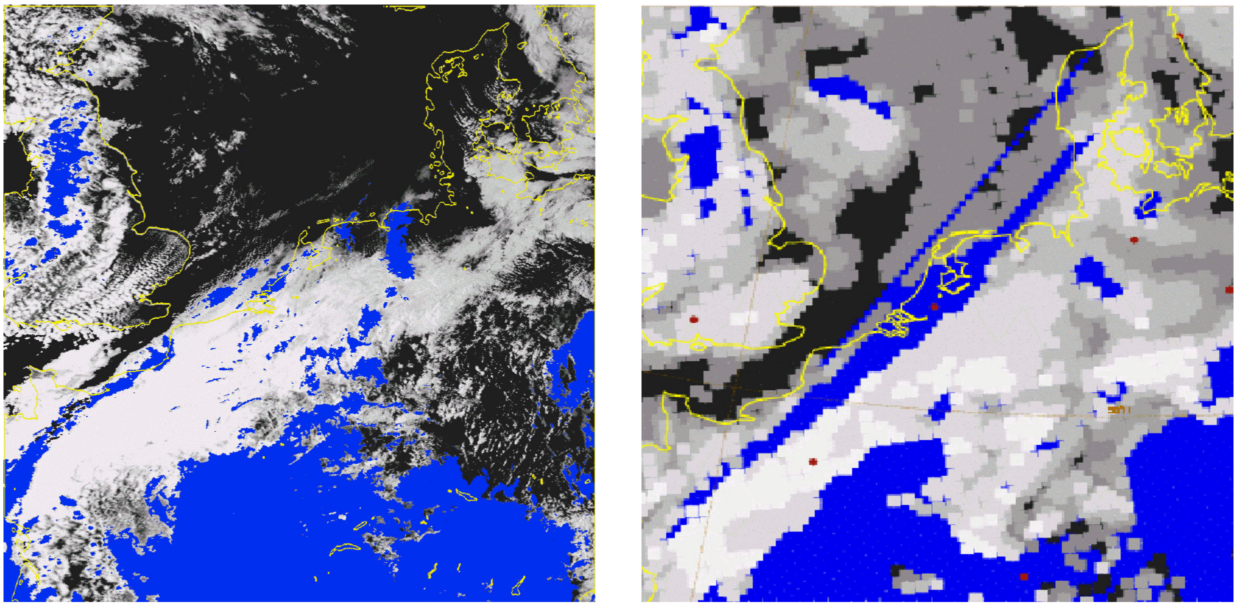


Figure 2: Time series of liquid water path at Cabauw, the Netherlands during 4 May 2001 for ground-based observations (dots) and model predictions (squares). The model averages and spatial variance are calculated for 3*3 model points.

Evaluation of the RACMO model

Figure 3 shows images AVHRR retrieved (left) and RACMO predicted (right) LWP at 15:15 UTC. Clouds with top temperatures below 260K are indicated by the blue colour. These clouds are considered ice clouds and are rejected from further analysis because the satellite retrieval is sensitive to cloud particle phase. The grayscales represent LWP values ranging from 0 to 250 $g.m^{-2}$, with and increasing liquid water path when going from dark gray to white. At the Cabauw site, the average LWP value in the one-hour interval centered around the time of satellite overpass is 58gm-2. The AVHRR retrieval was tuned slightly to improve the correlation between these measurements and satellite values.

When comparing the AVHRR analysis and the RACMO results it can be seen that the ice-topped clouds that are observed over the British Islands and the Middle of France are predicted well. A streak of Cirrus reaching from Bordeaux to Denmark is more extended in the model. Cold clouds over the middle of Germany are shifted towards the South in the model. The model produces too much liquid water over the North sea, but in general the large-scale features of the LWP-fields are reasonably well in agreement.



(A) *(B)*

Figure 3: AVHRR retrieved LWP (A) and RACMO predicted LWP (B) for 4 May 2001, 15:15. From dark grey (1 g.m-2), via light grey to white (250 g.m-2) increasing liquid water path. Ice clouds are indicated in blue.

In order to make a more quantitative comparisons, a transect was defined between Cabauw (51.9 lat, 4.9 long) and Potsdam (52.4 lat, 13.1 long). In Potsdam there are small cumuli at the time of satellite overpass. The ground-based microwave radiometer measures a maximum LWP of $100gm^{-2}$ in Potsdam, which is consistent with the values observed in the satellite analysis. In figure 4 the LWP values from observations and model are plotted for this transect. The solid line represents the AVHRR values at a pixel resolution of 1.2 km. Ice topped clouds are indicated by diamonds. The LWP values show at 4.9 degrees (where Cabauw is located) a clear dip that is only half a degree wide. According to the ground-based measurements this dip represents a cloud field with low LWP values (0 to $120gm^{-2}$) that lasted for hours. This illustrates how sensitivity the comparison of time series of ground-based measurement and spatial distribution from satellite is to local variations in cloud fields. The dotted line indicates the observed LWP averaged over a model grid box. The values do still show small dips, but less pronounced as a result of the smoothing effect of spatial averaging. The values peaks a little east of Cabauw and decrease slowly from there till about 8 degrees. The long dashed line indicates the model values. The values peaks west of Cabauw and decrease till zero at Potsdam. In general the model represents the observed large-scale feature well, as we already concluded from visual inspection of the spatial distributions in Figure 2. The discrepancy between ground-based and model predicted values can be attributed to a small-scale feature in the cloud field that was located over the Cabauw measurement site.

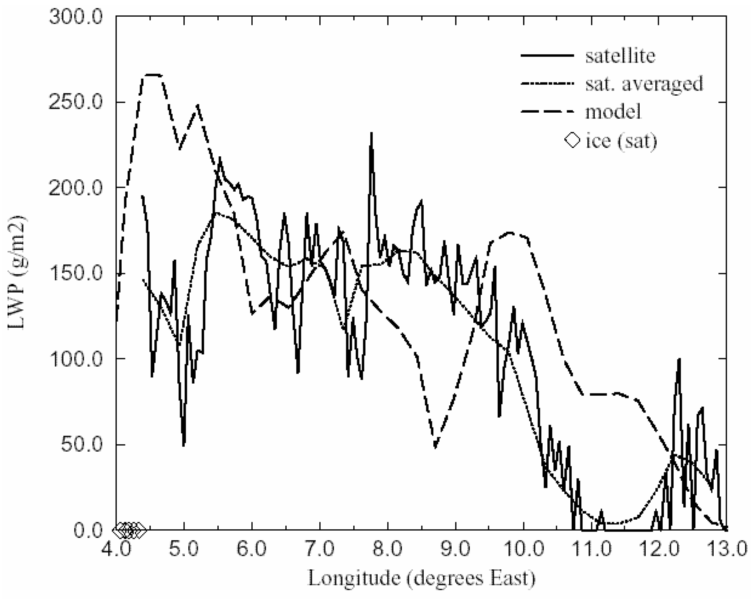


Figure 4: Instantaneous liquid water path along a line connecting Cabauw, The Netherlands (51.9 lat, 4.9 long) and Potsdam, Germany (52.4 lat, 13.1 long). DAK simulated reflectances as a function of optical depth and droplet particle size at 0.63 micron (A) and 1.6 micron (B). With satellite zenith angle (θ=19.68), solar zenith angle (θ_0 =38.63), relative azimuth angle (ϕ=126.45)

DISCUSSION AND CONCLUSIONS

A new approach to observing spatial distributions of LWP is presented. The method combines cloud analysis from ground-based microwave radiometers and satellite measurements from AVHRR. The satellite analysis is optimized such that it represents the time series from ground-based measurements. The method results in a spatial distribution of LWP of optimum accuracy.

A case study was presented, that demonstrates the added value of this type of observations for atmospheric model evaluation relative to direct comparison of ground-based and model predicted values. It is not useful to draw conclusions on the quality of the model on this single case. Model evaluation requires statistical analysis of a large set of cases. This can be monthly statistics of LWP as measured over ground stations as reported by Crewell et al. (2002). Also analysis of the spatial distribution of the frequency of occurrence of specific cloud types, modeled versus measured from satellite, can indicate shortcomings in cloud parameterization. The CLIWA-Net data set contains six months of cloud observations for model evaluation and thus statistical analysis is feasible.

In conclusion this study demonstrated the application of combining ground-based measurements with satellite retrievals of LWP for the evaluation of an atmospheric model. This approach may be applicable to the platforms of the Meteosat Second Generation, MSG, because its passive imager includes the relevant spectral channels.

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