VALIDATION OF CLOUD LIQUID WATER PATH RETRIEVALS FROM SEVIRI ON METEOSAT-8 USING CLOUDNET OBSERVATIONS

R.A. Roebeling and A.J. Feijt

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

ABSTRACT

METEOSAT-8 is the first European satellite with the potential to provide accurate spatial distributions of cloud properties that can be used to examine daily variations in cloud properties with a 15 minutes temporal resolution. Although there has been progress in quantifying the accuracy of cloud property retrievals from NOAA-AVHRR, little research has been done on the validation of these retrievals from METEOSAT-SEVIRI.

Within the Climate Monitoring Satellite Application Facility (CM-SAF) KNMI developed a cloud properties retrieval algorithm, based on narrowband visible and near-infrared radiances from NOAA-AVHRR and METEOSAT-SEVERI. This algorithm provides Cloud Optical Thickness (COT), droplet effective radius and Cloud Liquid Water Path (CLWP) over Europe. The CloudNET research project, supported by the European Commission, provides quasi continuous measurements of ground-based cloud properties for the development and implementation of cloud remote sensing algorithms. The accuracy of the ground-based measurements is superior to current satellite remote sensing techniques, which makes these observations the appropriate data source for assessing the accuracy of METEOSAT-8 cloud property retrievals.

This paper quantifies the accuracy of SEVIRI retrieved CLWP values over Europe during the summer months. A four-month dataset of about 5000 CLWP retrievals from SEVIRI is compared to microwave radiometer (MWR) LWP observations at two CloudNET stations. The bias and accuracy are determined for the instantaneous and daily SEVIRI CLWP retrievals. The magnitude of the bias differs per CloudNET station, but never exceeds 10 g m^{-2}. The difference of 60 g m^{-2} for instantaneous CLWP retrievals is acceptable, taking into account validation uncertainties such as the accuracy of the CloudNET MWRs (about 35 g m^{-2}). The comparison of daily median CLWP from SEVIRI and MWR, taking advantage of the 15 minutes sampling frequency of METEOSAT-8, led to an improvement of the accuracy to about 25 g m^{-2}.

1. INTRODUCTION

Clouds strongly modulate the energy balance of the Earth and its atmosphere through their interaction with solar and thermal radiation (King and Tsay, 1997). Cess et al. (1989) showed that clouds are the major source of uncertainty in model responses to climate forcing. Despite their importance, clouds are represented in a rudimentary way in climate and weather forecast models. The Intergovernmental Panel on Climate Change calls for more measurements on cloud properties to improve the understanding of cloud processes and their representations in climate and weather forecast models. The radiative behavior 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 et al., 2003). With the launch of Meteosat Second Generation (Meteosat-8) and later METOP, better methods can be developed to improve the retrieval of cloud physical parameters.

Various methods have been developed to retrieve Cloud Optical Thickness (COT), cloud particle size and Cloud Liquid Water Path (CLWP) from satellite radiances. The principle of these methods is that the reflection of clouds at the non-absorbing visible channel (0.6 or 0.8 μm) is primarily a function of the cloud optical thickness, while the reflection at a water (or ice) absorbing near-infrared channel (1.6, 2.1 or 3.7 μm) is primarily a function of cloud particle size. For the absorbing wavelengths, some methods use the 3.7 μm (Han et al. 1994 and Nakajima and Nakajima 1995), while others use the 2.1 μm (Platnick et al., 2002) or the 1.6 μm channel (Watts et al. 1998, Jolivet et al. 2000, Roebeling et al. 2001).

Little research has been done on the application of the 1.6 μm channel for the retrieval of cloud properties. Within the Climate Monitoring Satellite Application Facility (CM-SAF) of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Royal Netherlands Meteorological Institute (KNMI) (Feijt et al. 2004 and Roebeling et al. 2006a) developed an algorithm to retrieve COT and CLWP from visible (0.6 μm) and near-infrared (1.6 μm) reflectances of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard the Meteosat Second Generation (MSG). The purpose of this study was to assess the accuracy of SEVIRI retrieved cloud physical properties by comparing them to ground based observations of cloud properties collected during the CloudNET research project.

The outline of this paper is as follows. In section 2, the satellite and ground based measurement devices that are used to retrieve cloud properties are described. In section 3, the methods to retrieve cloud properties are presented. The results of a four-month comparison of SEVIRI and ground based CLWP retrievals is presented in Section 4. The paper concludes with remarks on the accuracy of instantaneous, daily and monthly mean cloud property retrievals from SEVIRI.

2. MEASURMENTS

Satellite observations

Meteosat Second Generation is a new series of European geostationary satellites that is operated by EUMETSAT. In 2002 the first Meteosat Second Generation satellite (METEOSAT-8) has been launched successfully. METEOSAT-8 is a spinning stabilized satellite that carries the 12-channel SEVIRI instrument with 11 channels at visible and infrared wavelengths between 0.6 and 14 μm and one high-resolution visible channel. SEVIRI operates imaging channels that are comparable to AVHRR. On-board METEOSAT-8, all SEVIRI channels are operated simultaneously. On-board NOAA-17 the AVHRR instrument operates the 1.6 μm and 3.8 μm channel in series. The 1.6 μm channel is active during daytime, while the 3.8 μm channel is active during nighttime.

Ground based observations

The ground based microwave radiometers (MWR) measurements were collected in the framework of the CloudNET project, which was an EU-funded research project that provided a data base of cloud measurements at three remote sensing observation stations. The project started on April the 1st 2001 and ended on April the 1st 2005. The three experimental research sites are located at Cabauw (The Netherlands), Chilbolton (UK) and Palaiseau (France). Each site is equipped with radar, lidar and a suite of passive instrumentation. The use of active instruments (lidar and cloud radar) resulted in detailed vertical profiles of important cloud parameters, which cannot be derived from current satellite sensing techniques. More information on the CloudNET project can be found on http://www.met.rdg.ac.uk/radar/cloudnet/.

MWRs measure incoherent radiant electromagnetic energy. From the ground, zenith-pointing radiometers measure energy radiated (emitted) by atmospheric gases and liquid water in the form of cloud droplets and rain. This energy is dependent on the measurement frequency and is proportional to the amount of material present in the atmosphere. At the CloudNET sites of Chilbolton and Palaiseau, dual-channel MWRs are operated. The radiometer at Chilbolton measures at 22.2 and 28.8-GHz, while the radiometer at Palaiseau measures at 24 and 37-GHz (DRAKKAR).

3. METHODS

Retrievals from satellite radiances

The Cloud Physical Properties algorithm (CPP) uses reflectances at visible (0.6 μm) and near-infrared (1.6 μm) wavelengths. The COT and particle size are retrieved for cloudy pixels in an iterative manner, by simultaneously comparing satellite observed reflectances at visible and near-infrared wavelengths to Look Up Tables (LUTs) of simulated reflectances for given optical thicknesses and particle sizes (Roebeling et al., 2006a). The retrieval of cloud thermodynamic phase is done simultaneously with the retrieval of COT and particle size. The phase “ice” is assigned to pixels with a Cloud Top Temperature (CTT) lower than 265 K for which the 0.6 μm and 1.6 μm reflectances correspond to simulated reflectances for ice clouds. The remaining cloudy pixels are considered to be water clouds. The CLWP is computed from the retrieved cloud optical thickness (τ_{vis}) and droplet effective radius (r_e) as follows (Stephens et al., 1978):

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

where ρ_l is the density of liquid water. For ice clouds the CLWP is retrieved for imperfect hexagonal ice crystals with an assumed effective radius of 30 μm and 40 μm.

The Doubling Adding KNMI (DAK) radiative transfer model is used to generate LUTs of simulated cloud reflectances. DAK is developed for line-by-line or monochromatic multiple scattering calculations at UV, visible and near infrared wavelengths in a horizontally homogeneous cloudy atmosphere using the doubling-adding method (De Haan et al., 1987; Stammes, 2001).

Retrievals from ground based observations

Passive microwave radiometers provide brightness temperature measurements at different frequencies that are used to make accurate retrievals of integrated water vapor path (IWV) and liquid water path (LWP). The measurements of the two-channel MWRs that are operated at the CloudNET sites are used to simultaneously retrieve LWP and IWV (Löhnert and Crewell, 2003). The microwave brightness temperatures at two frequencies have distinct atmospheric absorption characteristics. The 22 GHz brightness temperatures provide mainly information water vapor, whereas the 30 GHz brightness temperatures provide mainly information on the cloud liquid water path. The retrieval of LWP from MWR is strongly disturbed by rainfall, since the instrument antenna or radome can become covered by water droplets or a thin water layer. Moreover, none of the MWRs are sensitive to ice clouds since ice crystals do not contribute to the MWR radiances at the probed frequencies.

According to Crewell and Löhnert (2002), the accuracy of LWP retrievals varies between 15 and 35 g m^{-2}. Note that these accuracies were derived from instrumental specifications and are completely theoretical, and reflect only to a minor degree the normal distributed radiometric noise. The two-channel MWRs that are operated at Chilbolton and Palaiseau have an expected accuracy of about 35 g m^{-2}. A large increase of accuracy is possible by adding a 90-GHz channel to the standard two-channel MWRs (Crewell and Löhnert, 2003).

4. RESULTS

A statistical analysis of frequency distributions of microwave radiometer and MSG/SEVIRI cloud liquid water path is performed to determine the accuracy of SEVIRI-CLWP retrievals. The CLWP values were retrieved from 15 minutes SEVIRI data over the period May-August 2004 at Chilbolton, UK and Palaiseau, France. The MWR-LWP values were averaged over 40 minutes to represent more or less the field of view of the satellite, assuming Taylor’s hypothesis of frozen turbulence, and compared to the SEVIRI-CLWP value of the pixel over the ground station. Because microwave radiometer observations for thick clouds are known to be unreliable it was decided to exclude MWR-LWP retrievals with values above > 600 g m^{-2}. Rain gauge observations were used to identify and exclude the MWR measurements that are disturbed by rain. The SEVIRI cloud thermodynamic phase retrievals were used to identify conditions with ice clouds overhead the observation station, which were also excluded from the data set because of the insensitivity of MWR observations to ice clouds.

Figure 1 presents the frequency distributions of MWR-LWP and SEVIRI-CLWP values and their differences for June 2004 in Chilbolton and Palaiseau. The frequency distributions (left panels) show that the percentage of clouds with CLWP values below 25 g m^{-2} is about 10% higher from SEVIRI than from MWR. The higher percentage of low CLWP values from SEVIRI is most probably related to sampling area differences. Note that the variations in the MWR-LWP values do often occur at a sub-pixel level. Although the MWR-CLWP retrievals are averaged over a 40 minutes period, aiming to represent more or less the field of view of the satellite, the MWR samples a substantially different portion of the cloud (~0.1x15 km^2) than METEOSAT-8/SEVIRI (~4x6 km^2). The frequency distributions of differences (right panel) are not normally distributed. This is best observed from the strong peak frequency at differences around zero and the rapid drop of frequencies as the differences increase. The 66th quantile (Q66) is used to quantify the deviation between SEVIRI-CLWP and MWR-LWP observations. Here Q66 is the difference between the 17% and 83% quantiles of the deviations, Q95 mutatis mutandis. For a normal distribution, this would amount to twice the standard deviation. The slightly positive skew suggests higher LWP values from MWR than from SEVIRI. The Q66 values of 62 and 25 g m^{-2} are about equal to the value of the mean MWR-LWP values of about 70 and 30 g m^{-2} for Chilbolton and Palaiseau, respectively. The Q95 values of 313 g m^{-2} for Chilbolton and 195 g m^{-2} for Palaiseau are about eight times larger than the Q66 value. This indicates that for a limited number of observations the differences between SEVIRI-CLWP and MW-LWP values are very large. Possible reasons for these large Q95 values are the nature of cloud in-homogeneity, multi-layer clouds, and the decreasing accuracy of both ground based and SEVIRI LWP retrievals with increasing cloud optical thickness.

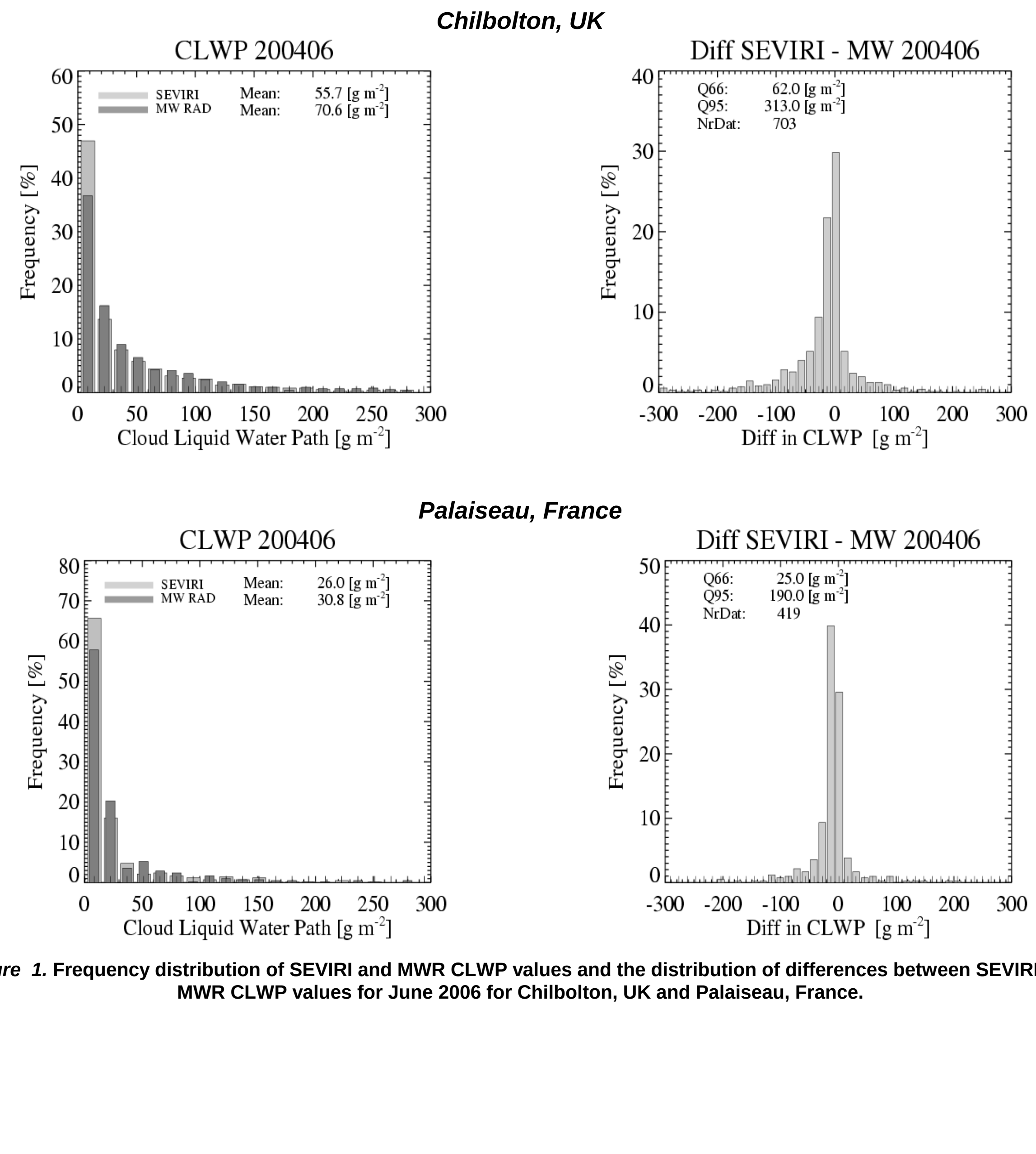
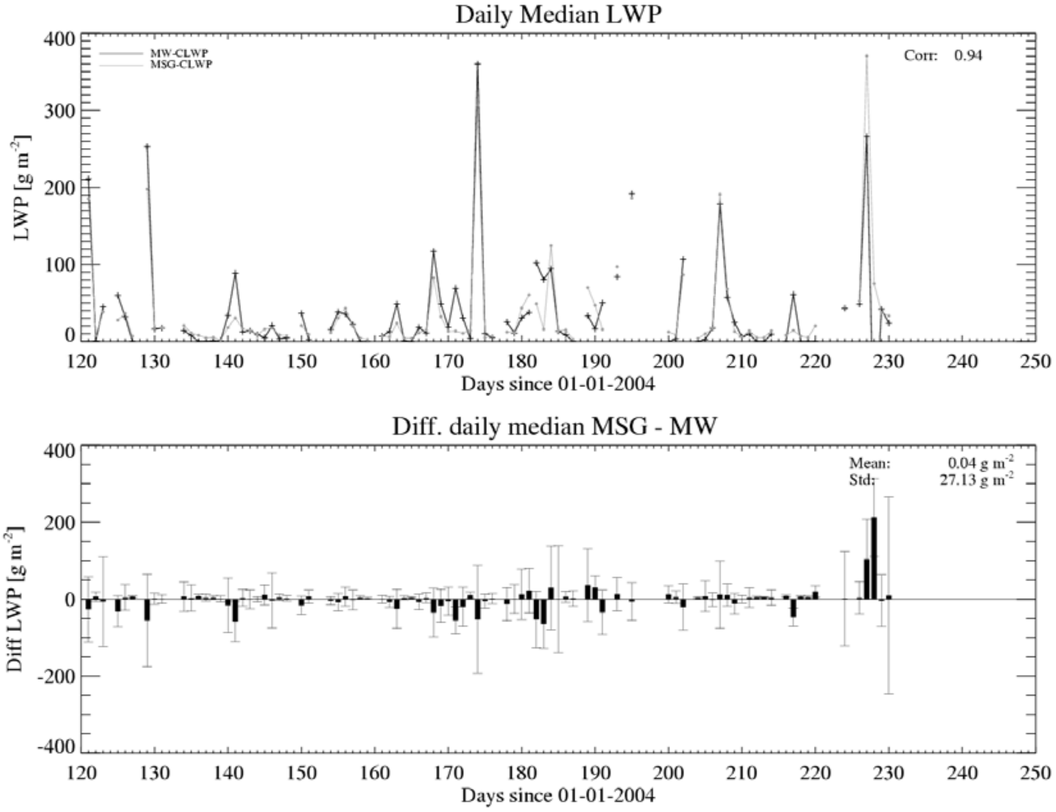


Figure 1. **Frequency distribution of SEVIRI and MWR CLWP values and the distribution of differences between SEVIRI and MWR CLWP values for June 2006 for Chilbolton, UK and Palaiseau, France.**

Chilbolton, UK



Palaiseau, France

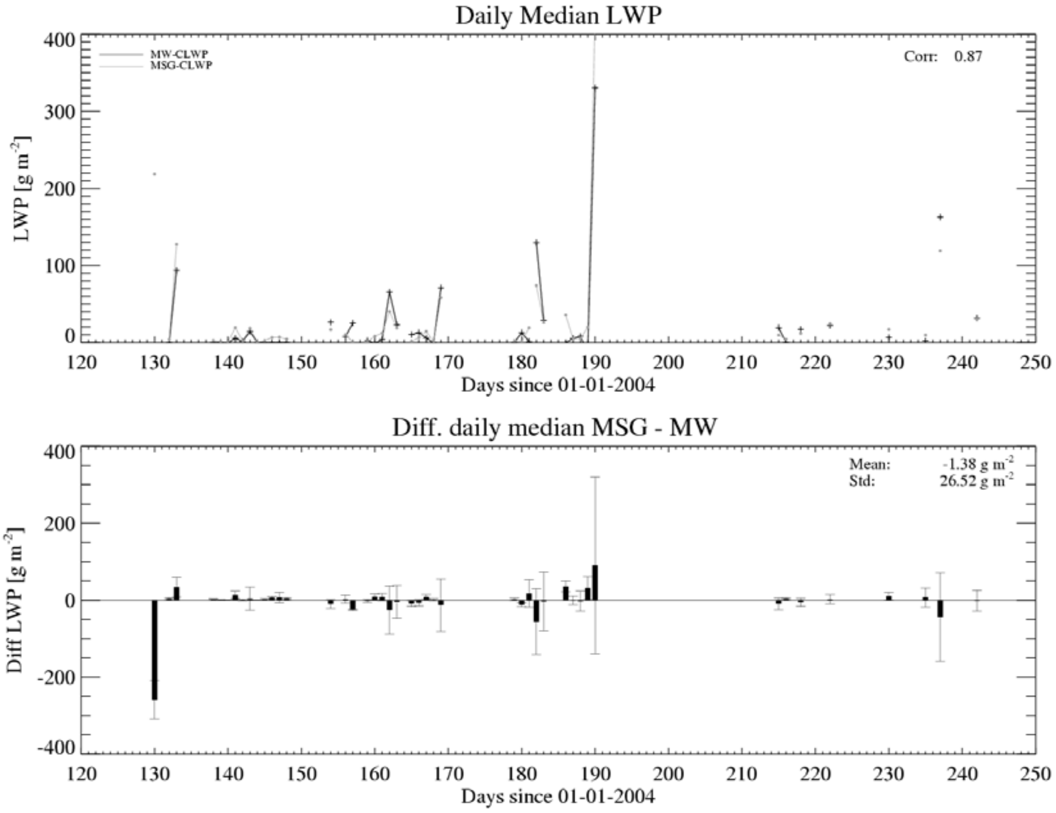


Figure 2. **Time series of daily median LWP values from SEVIRI and MWR (upper panel), and the corresponding difference in LWP (lower panel) for Chilbolton over the period May-September 2004. The error bars indicate the Q66 value of differences between the instantaneous retrievals.**

The unique characteristic of SEVIRI is that the high sampling frequency (15 minutes) combined with the spectral channels similar to AVHRR allows the calculation of daily median LWP values. To reduce the effect of spatial mismatching, daily median MWR-LWP and SEVIRI-CLWP are compared instead of instantaneous retrievals. The daily median LWP values were calculated from SEVIRI-CLWP and MWR-LWP retrievals for days with at least 6 observations. Figure 2 presents the daily median LWP values from MWR and SEVIRI during the period May – September 2004 for 91 days at Chilbolton and 45 days at Palaiseau. The figure shows at both locations large variations in daily median LWP values, ranging from 0 to 400 g m^{-2}. However, for about 90% of the days the daily median LWP values are below 100 g m^{-2}. There is good agreement between the MWR and SEVIRI daily median LWP values with correlation of 0.94 at Chilbolton and 0.87 at Palaiseau, which is surprisingly high considering the fact that the MWR and SEVIRI sample different portions of the cloud. Apart from 2 days at both sites, the differences between the daily median MWR-LWP and SEVIRI-CLWP values for Chilbolton and Palaiseau are below 50 g m^{-2}. The Q66 values (error bars) indicate that the differences between the instantaneous LWP retrievals are high on a few days, with Q66 values as high as 200 g m^{-2}. In general, the agreement between the daily median LWP retrievals from MWR and SEVIRI is very good. The median SEVIRI-CLWP values, which have a negligible bias against the daily median MWR-LWP values, are retrieved with an accuracy of about 27 g m^{-2} at both CloudNET sites.

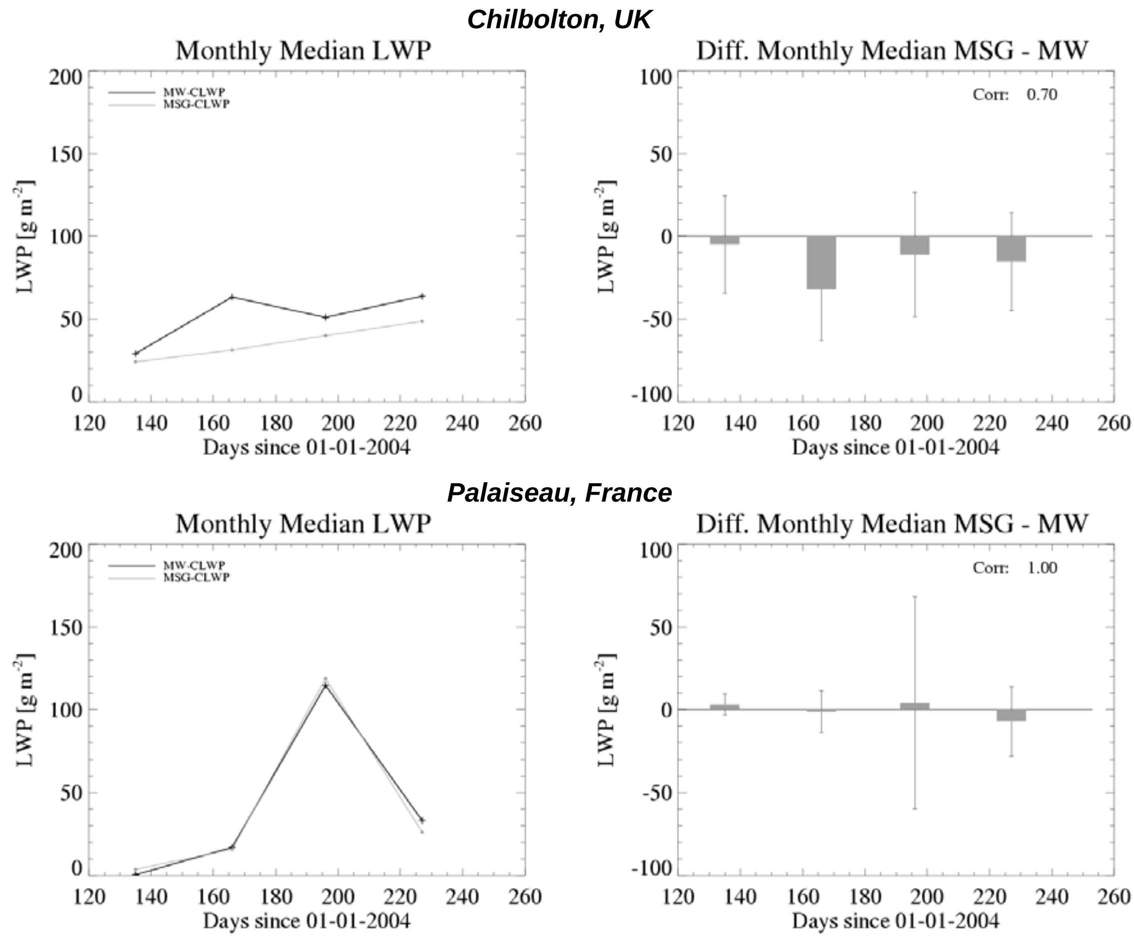


Figure 3. **Time series of monthly median CLWP from SEVIRI and MWR and their difference for Chilbolton (upper panel) and Palaiseau (lower panel). The error bars in the difference plots indicate the Q66 values of the differences on the instantaneous retrievals.**

The monthly median LWP retrievals from MWR and SEVIRI are presented in Figure 3. The values are directly calculated from the instantaneous retrievals as they are presented in Figure 1. The high number of observations per month (> 400) allows the calculation of statistically relevant values of the monthly median

LWP. Contrary to the results presented for the daily median LWP values, the results of the comparison of monthly median LWP values are different for Chilbolton and Palaiseau. At Chilbolton a small but consistent bias of -5 to -30 g m^{-2} is observed between SEVIRI and MWR LWP retrievals, while almost no bias is observed at Palaiseau. It is suggested that the differences between Chilbolton and Palaiseau are related to the differences between the MWRs and the LWP retrieval algorithms that are used. Although no microwave intercomparison study has been done for the MWRs at the CloudNET sites, Löhnert and Crewell (2003) showed that bias errors of about 5 – 10 g m^{-2} due to using different MWRs are common. Apart from the high Q66 value of July 2004 for Palaiseau, the Q66 values show that monthly deviation between SEVIRI and MWR LWP values varies between 10 and 60 g m^{-2}. Roebeling et al. (2006b) showed for stratocumulus clouds that about 50 g m^{-2} of the differences between ground-based and satellite retrievals of CLWP can be explained by uncertainties due to co-location, parallax, position of the ground station and sampling of different portions of the cloud.

5. DISCUSSION AND CONCLUSIONS

In this paper we have shown that SEVIRI has the ability to make accurate retrievals of CLWP over Northern Europe during four summer months in 2004. The comparison between ground-based microwave radiometer LWP and SEVIRI CLWP retrievals shows good agreement for the CloudNET sites of Chilbolton, UK and Palaiseau, France. The high sampling frequency of METEOSAT-8 allows the comparison of daily and monthly median CLWP from SEVIRI and MWR, using a statistically relevant number of observations.

Based on the results presented in this paper, a first estimate of the SEVIRI-CLWP retrieval accuracy can be made. The comparison of instantaneous CLWP retrievals shows that the Q66 values of the difference between MWR-LWP and SEVIRI-CLWP are below 60 g m^{-2}. About 50 g m^{-2} of these differences can be explained by uncertainties due to co-location (~40 g m^{-2}), sampling differences (~20 g m^{-2}) and MWR accuracy (~30 g m^{-2}) (Roebeling et al., 2006b). The comparison of daily median CLWP values of both retrievals, for which co-location and sampling errors are less important, leads to a higher accuracy of about 25 g m^{-2} and almost no bias. The comparison of the monthly median CLWP retrievals shows a remarkable difference between Chilbolton and Palaiseau. At Chilboton MWR-LWP values are 5 to 30 g m^{-2} higher than the SEVIRI values, while at Palaiseau almost no bias is observed. It is suggested that these differences are related to differences between the MWRs and the algorithms used to retrieve MWR-LWP.

Parts of the discussed differences are related to localization and sampling problems and may be alleviated through improving the sampling strategy. In this paper a simple sampling strategy is used, in which SEVIRI-CLWP values over the ground station were compared to 40 mean MWR-LWP values. Improvements in the validation may be obtained by determining the optimum ground track length that corresponds with the track that overlaps best with the SEVIRI pixel. Thus for an optimal correspondence, ground observations need to be averaged over different periods depending on the wind speed at cloud altitude.

The validation was only performed for summer months. In future work we want to determine if METEOSAT-8/SEVIRI is suited for climate monitoring of cloud properties. Therefore, the validation period shall be extended to at least one year. This would allow an analysis of inter-seasonal variations in cloud properties, but also an evaluation of the retrieval sensitivity at different solar and viewing geometries.

6. ACKNOWLEDGEMENT

This work was part of the EUMETSAT funded Climate Monitoring Satellite Application Facility (CM-SAF) project. Finally, we acknowledge the Cloudnet project (European Union contract EVK2-2000-00611) for providing the microwave radiometer data, which was produced by the University of Reading using measurements from the Chilbolton Facility for Atmospheric and Radio Research, part of the Rutherford Appleton Laboratory. Finally, I want the thank Erwin Wolters for giving the oral presentation on this work at the EUMETSAT Meteorological Satellite Conference in Helsinki, Finland.

7. REFERENCES

Cess, R.D., G. L. Potter, J. P. Blanchet, G. J. Boer, A. D. Del Genio, M. Deque, V. Dymnikov, V. Galin, W. L. Gates, S. J. Ghan, J. T. Kiehl, A. A. Lacis, H. Le Treut, Z. X. Li, Z. Liang, B. J. Mc Aveney, V. P. Meleshko and J. F. B. Mitchell (1990) Interpretation of climate feedback processes in 19 atmospheric general circulation models. J. Geophysic. Res., 95, 16601-16615.

Crewell S., and U. Löhnert (2003) Accuracy of cloud liquid water path from ground-based microwave radiometry 2. Sensor accuracy and synergy, Radio Sci., 38, 3, 8042, 7–10.

De Haan, J. F., P. Bosma, and J. W. Hovenier (1987), The adding method for multiple scattering calculations of polarized light, Astron. Astrophys., 183, 371-391.

Dong X., P. Minnis, T. P. Ackerman, E. E. Clothiaux, G. G. Mace, C. N. Long, and J. C. Liljegren (2000), A 25-month Database of Stratus Cloud Properties Generated from Ground-based Measurements at the ARM SGP Site. J. Geophys. Res. 105, 4529-4538.

Feijt, A.J., D. Jolivet, R. Koelemeijer and H. Deneke (2004), Recent improvements to LWP retrievals from AVHRR, Atmos. Res., 72, 3-15.

Govaerts Y. and Clerici M. (2004), MSG-1/SEVERI Solar Channels Calibration Commissioning Activity Report, EUM/MSG/TEN/04/0024

Han Q, Rossow W.B., Lasis A.A. (1994), Near-Global Survey of Effective Droplet Radii in Liquid Water Clouds Using ISCCP Data," J. of Clim. 7, 465-497

King, D., and S.-C. Tsay (1997) Cloud retrieval algorithms for MODIS: Optical thickness, effective radius, and thermodynamic phase. MODIS, Tech. Rep. ATBD-MOD-05, 83 pp.

Löhnert, U. and S. Crewell (2003), Accuracy of cloud liquid water path from ground-based microwave radiometry. Part I. Dependency on Cloud model statistics. Radio Science, 38, 3, 8041, 6–11.

Nakajima T. Y. and Nakajima T. (1995), Determination of Cloud Microphysical Properties from NOAA NOAA-17 Measurements for FIRE and ASTEX regions., J. of Atmosph. Sciences, 52, 4043-4059.

Platnick, S., M. D. King, S. A. Ackerman, W. P. Menzel, B. A. Baum, J. C. Riedi, and R. A. Frey (2002), The MODIS cloud products: Algorithms and examples from Terra. IEEE Transactions on geoscience and remote sensing, Special Aqua Issue.

Roebeling R.A., D. Jolivet, A. Feijt (2001), Cloud optical thickness and cloud liquid water path retieval from multi-spectral NOAA-AVHRR data, Proc. The 2001 EUMETSAT Meteorological Satellite Data User's Conference, Antalya, Turkey, 2001, 629-637.

Roebeling, R.A., A.J. Feijt en P. Stammes (2006a), Cloud property retrievals for climate monitoring: implications of differences between SEVIRI on METEOSAT-8 and AVHRR on NOAA-17, *J. Geophys. Res.* (accepted).

Roebeling, R.A., N.Schutgens and A.J. Feijt (2006b), Analysis of uncertainties in SEVIRI cloud property retrievals for climate monitoring, Proceedings: published, 12th Conference on Atmospheric Radiation, 2006, Madison, USA, AMS

Stammes, P. (2001), Spectral radiance modeling in the UV-Visible range. *IRS 2000: Current problems in Atmospheric Radiation*, edited by W.L. Smith and Y.M. Timofeyev, pp 385-388, A. Deepak Publ., Hampton, Va.

Stephens G. L., G. W. Paltridge, and C. M. R. Platt (1978), Radiation profiles in extended water clouds. III. Observations, J. Atmos. Sci, 35, 2133-2141.

Watts P.D., Mutlow C.T., Baran A.J., and Zavody A.M. (1998), Study on Cloud Properties derived from Meteosat Second Generation Observations,Final Report, EUMETSAT ITT no. 97/181.