# Validation of Cloud Liquid Water Path Retrievals from SEVIRI Using One Year of CloudNET Observations

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ABSTRACT

The accuracy and precision are determined of cloud liquid water path (LWP) retrievals from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board *Meteosat-8* using 1 yr of LWP retrievals from microwave radiometer (MWR) measurements of two CloudNET stations in northern Europe. The MWR retrievals of LWP have a precision that is superior to current satellite remote sensing techniques, which justifies their use as validation data. The Cloud Physical Properties (CPP) algorithm of the Satellite Application Facility on Climate Monitoring (CM-SAF) is used to retrieve LWP from SEVIRI reflectances at 0.6 and 1.6 $\mu$m. The results show large differences in the accuracy and precision of LWP retrievals from SEVIRI between summer and winter. During summer, the instantaneous LWP retrievals from SEVIRI agree well with those from the MWRs. The accuracy is better than 5 g m$^{-2}$ and the precision is better than 30 g m$^{-2}$, which is similar to the precision of LWP retrievals from MWR. The added value of the 15-min sampling frequency of *Meteosat-8* becomes evident in the validation of the daily median and diurnal variations in LWP retrievals from SEVIRI. The daily median LWP values from SEVIRI and MWR are highly correlated (correlation $>$ 0.95) and have a precision better than 15 g m$^{-2}$. In addition, SEVIRI and MWR reveal similar diurnal variations in retrieved LWP values. The peak LWP values occur around noon. During winter, SEVIRI generally overestimates the instantaneous LWP values from MWR, the accuracy drops to about 10 g m$^{2}$, and the precision to about 30 g m$^{-2}$. The most likely reason for these lower accuracies is the shortcoming of CPP, and similar one-dimensional retrieval algorithms, to model inhomogeneous clouds. It is suggested that neglecting cloud inhomogeneities leads to a significant overestimation of LWP retrievals from SEVIRI over northern Europe during winter.

## 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. (1990) 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 because of lack of knowledge on the variability of cloud properties. The Intergovernmental Panel on Climate Change calls for more measurements on cloud properties to improve the understanding of cloud processes and their representation in climate and weather forecast models (Houghton et al. 2001). The radiative behavior of clouds depends predominantly on cloud properties such as thermodynamic phase, optical thickness, and particle size. Satellites provide useful information on global cloud statistics and radiation budget (Feijt et al. 2004). With the launch of Meteorological Satellite (Meteosat) Second Generation (*Meteosat-8*), methods can be developed to monitor the evolution of cloud properties. The temporal resolution of *Meteosat-8*, coupled with the multispectral radiance observation of the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) allows more accurate estimates of daily mean cloud properties and, for the first time, permits the investigation of the diurnal cycle of these properties.

Various methods have been developed to retrieve cloud optical thickness (COT), cloud particle size, and cloud liquid water path (LWP) from radiances of passive imagers. The principle of these methods is that the reflection of clouds at the nonabsorbing visible channels (0.6 or 0.8 $\mu$m) is primarily a function of the cloud optical thickness, while the reflection at the water (or

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ice) absorbing near-infrared channels (1.6, 2.1, or 3.8 $\mu$m) is primarily a function of cloud particle size. For the absorbing wavelengths, some methods use the 3.8 $\mu$m (Han et al. 1994; Nakajima and Nakajima 1995), while others use the 2.1 $\mu$m (Platnick et al. 2003), the 1.6 $\mu$m (Roebeling et al. 2006a), or both the 1.6 and 3.8 $\mu$m channels (Watts et al. 1998)

Ground-based microwave radiometry provides well established and by far the most accurate methods for retrieving LWP and simultaneously integrated water vapor (IWV) values, which are well suited for the validation of long time series of satellite-retrieved LWP values. Microwave radiometers (MWRs) measure the energy emitted by atmospheric gases, and liquid cloud droplets and rain at various frequencies. The intensity of the microwave emissions depends on the measurement frequency and is proportional to the amount of material present in the atmosphere. Westwater (1978) showed that two-channel MWRs could be used to retrieve LWP and IWV with high accuracy. These two-channel methods typically use a frequency at the water vapor line at 22.2 GHz and a second frequency at 28.8 GHz where the signal is dominated by LWP. The precision of the LWP retrievals from MWR depends on the errors in brightness temperatures at the emitting frequencies and on the errors in the cloud model that is used to simulate vertical variations of cloud droplets and liquid water content. In general, these cloud models are used to determine the statistical relationship between brightness temperatures and LWP values, which are determined from radiative transfer simulations. Bobak and Ruf (2000) suggested that the precision of LWP retrievals can be improved by including a 85-GHz channel. Crewell and Löhnert (2003) showed that the theoretical precision of LWP retrievals from the standard two-channel approach is about 30 g $m^{-2}$. They found that including an additional microwave channel at 90 GHz reduced the retrieval error to about 20 g $m^{-2}$.

There have been several efforts to validate LWP retrievals from the Advanced Very High Resolution Radiometer (AVHRR) on board the National Oceanic and Atmospheric Administration (NOAA) satellite with ground-based LWP retrievals from MWRs (Han et al. 1995; Jolivet and Feijt 2005). Although Han et al. (1995) used different spectral wavelengths (0.6, 3.8, and 10.5 $\mu$m) than Jolivet and Feijt (2005) (0.6 and 1.6 $\mu$m), they both found that their LWP retrievals from AVHRR agreed well with those from ground-based MWR measurements. In general, the accuracies (biases) of the satellite-retrieved LWP values were better than 15 g $m^{-2}$. The precisions (variances) of these retrievals were better than 30 g $m^{-2}$ for thin clouds, whereas lower precisions were found for thick clouds (up to 100 g $m^{-2}$). The above given accuracies suggest that LWP retrievals from AVHRR could be an appropriate source of information for the evaluation of climate model predicted LWP values. For nonprecipitating water clouds van Meijgaard and Crewell (2005) found differences up to 50 g $m^{-2}$ between climate model predicted and MWR-inferred LWP values. During the First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment-Arctic Cloud Experiment (FIRE-ACE) Curry et al. (2000) compared large-scale model LWP values with MWR-inferred LWP values. They found that all models underestimate the mean LWP by 20–30 g $m^{-2}$, which corresponded to a relative accuracy worse than 60%. Although the accuracy of AVHRR-retrieved LWP values is significantly higher, it needs to be mentioned that previous validations could only be done with very limited coincident sets of satellite- and ground-based observations of LWP. This is because of the specific overpass times of NOAA satellites and the restricted availability of ground-based MWR measurements. So far, few validation studies have been done on statistically significant sets of coincident satellite- and MWR-retrieved LWP values.

Within the Climate Monitoring Satellite Application Facility (CM-SAF) of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), the Royal Netherlands Meteorological Institute (KNMI) developed a Cloud Physical Properties algorithm (CPP) to retrieve COT and LWP from visible (0.6 $\mu$m) and near-infrared (1.6 $\mu$m) reflectances from SEVIRI onboard *Meteosat-8* (Feijt et al. 2004; Roebeling et al. 2006a). The high sampling frequency of SEVIRI (15 min) provides, for the first time, the opportunity to generate a dataset of satellite-retrieved LWP values that is large enough for a statistically significant validation. The purpose of this study is to assess the accuracy (bias) and precision (variance) of LWP values retrieved from SEVIRI by comparing them with a large set of LWP values retrieved from MWR observations. The precision of SEVIRI-inferred LWP is assessed for instantaneous, daily, and monthly median values, taking advantage of the 15-min sampling frequency of SEVIRI. Moreover, a preliminary validation of diurnal variations in LWP values from SEVIRI is presented for daylight observations. This study requires accurate information on LWP at high temporal resolution from a network of ground-based MWRs. This information has been collected within the CloudNET project during which MWRs were operated at two ground-based stations from April 2001 until April 2005 (more information is available online at www.cloud-net.org).

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. The methods to retrieve cloud properties are presented in section 3. In section 4, the LWP retrievals from SEVIRI are compared with the LWP retrievals from the MWRs at Chilbolton in the United Kingdom and at Palaiseau in France for a summer period. This comparison is used to assess the differences between the MWRs at Chilbolton and Palaiseau and to evaluate the diurnal variations in LWP values from MWR and SEVIRI. The result of a 1-yr comparison of LWP data is presented in section 5. The influence of validation uncertainties and three-dimensional cloud effects is discussed in section 6. A summary is given and conclusions are drawn in section 7.

## 2. Measurements

### *a. Satellite observations*

Meteosat Second Generation (MSG) is a new series of European geostationary satellites that is operated by EUMETSAT. In 2002, the first MSG satellite (*Meteosat-8*) was launched successfully. *Meteosat-8* is a spinning stabilized satellite that carries the 12-channel SEVIRI instrument with three channels at visible and near-infrared wavelengths between 0.6 and 1.6 $\mu$m, eight channels at infrared wavelengths between 3.8 and 14 $\mu$m, and one high-resolution visible channel. Among others, SEVIRI provides the imaging channels that are comparable to AVHRR. On board *Meteosat-8*, all SEVIRI channels are operated simultaneously. This is different from the AVHRR instrument that operates on some of their satellites the 1.6 and 3.8 $\mu$m channels alternating.

### *b. Ground-based observations*

The ground-based microwave radiometer measurements were collected in the framework of the CloudNET project, which was a European Union (EU)–funded research project that provided a database of cloud measurements at three remote sensing observation stations. The project started on 1 April 2001 and ended on 1 April 2005. The three experimental research sites are located at Cabauw in the Netherlands (51.97°N, 4.93°E), Chilbolton in the United Kingdom (51.14°N, 1.44°W), and Palaiseau in France (48.71°N, 2.21°E). During CloudNET each site was equipped with radar, lidar, and a suite of passive instrumentation. The active instruments (lidar and cloud radar) provided detailed information on vertical profiles of the relevant cloud parameters, which is very well suited for validation purposes. At the CloudNET sites of Chilbolton and Palaiseau, dual-channel MWRs were operated. The radiometer at Chilbolton measured at 22.2 and 28.8 GHz, while the "DRAKKAR" radiometer at Palaiseau measured at 24 and 37 GHz. More information on the CloudNET project can be found online at www.cloud-net.org.

## 3. Methods

### *a. Cloud detection from satellite*

The algorithm to separate cloud-free from cloud-contaminated and cloud-filled pixels is based on the Moderate Resolution Imaging Spectroradiometer (MODIS) cloud-detection algorithm (Ackerman et al. 1998; Platnick et al. 2003). This algorithm has been the baseline to develop a cloud-detection algorithm for SEVIRI, which is independent from ancillary information on surface temperature or atmospheric profiles (Jolivet et al. 2006). Jerome Riédi of the University of Lille developed the cloud-detection algorithm for SEVIRI and provides the code through his personal Web site (available online at http://www-loa.univ-lille1.fr/~riedi/index.php?content = logiciels). The modifications that have been made to the MODIS algorithm are (i) some tests have been adapted and modified to account for the differences in spectral channels, calibration, and/or spatial resolution and make them applicable to SEVIRI; (ii) the number of tests used is much smaller than in the operational MODIS algorithm; and (iii) the decision logic differs significantly from the one used for MODIS. The input to the SEVIRI algorithm consists of normalized reflectances from the visible (0.6 and 0.8 $\mu$m) and near-infrared (1.6 $\mu$m) channels, whereas brightness temperatures are used from the thermal infrared channels (3.8, 8.7, 10.8, and 12.0 $\mu$m). There are spectral threshold and spatial coherence cloud-detection tests that are different for land and ocean surfaces. The cloud-detection tests are grouped together in such a way that specific cloudy- or clear-sky conditions are identified unambiguously, and the independence between the tests is maximized. Additionally, groups of tests have been implemented to specifically detect clear-sky conditions. A different weight is given to each group of cloud detection and clear-sky tests. Last, based on the results of all the tests, and the sum of the weights, a cloud mask is generated that includes four confident levels: clear certain, clear uncertain, cloud uncertain, and cloudy certain.

### b. Cloud property retrievals from satellite

The CPP uses reflectances at visible (0.6 $\mu$m) and near-infrared (1.6 $\mu$m) 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 with lookup tables (LUTs) of simulated reflectances for given optical thicknesses, particle sizes, and surface albedos for water and ice clouds (Roebeling et al. 2006a). One year of MODIS white-sky albedo data is used to generate the map of surface albedos. The white-sky albedo represents the bihemispherical reflectance in the absence of a direct component, which is a good estimate of the surface albedo below optically thick clouds. The retrieval of cloud thermodynamic phase is done simultaneously with the retrieval of COT and particle size. The cloud thermodynamic phase retrieval is based on the difference between 0.6- and 1.6-$\mu$m reflectances. At 1.6 $\mu$m ice clouds appear darker than water clouds because ice particles absorb relatively more light than spherical droplets at this wavelength, whereas the reflectance at 0.6 $\mu$m is relatively unaffected by thermodynamic phase. The phase "ice" is assigned to pixels for which the 0.6- and 1.6-$\mu$m reflectances correspond to simulated reflectances of ice clouds, and the cloud-top temperature is smaller than 265 K. The remaining cloudy pixels are considered to represent water clouds. The cloud liquid water path (CLWP) is computed from the retrieved COT at 0.6 $\mu$m ($\tau_{vis}$) and droplet effective radius ($r_e$) as follows (Stephens et al. 1978):

$$\text{CLWP} = (2/3)\tau_{vis} r_e \rho_l, \qquad (1)$$

where $\rho_l$ is the density of liquid water. This equation is also used to compute the LWP for ice clouds, but then by using the effective radius that is retrieved for imperfect hexagonal ice crystals. The scattering properties of imperfect hexagonal ice crystals are taken from the COP data library of optical properties of hexagonal ice crystals (Hess et al. 1998).

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). Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) spectra are used to calculate the conversion coefficients between the simulated line reflectances of DAK and the channel reflectances of SEVIRI at 0.6 and 1.6 $\mu$m. These spectra are convoluted with the SEVIRI spectral response functions to obtain SEVIRI channel reflectances, which are divided by the DAK reflectances to obtain the line-to-band conversion coefficients.

### c. LWP retrieval from ground-based observations

Passive microwave radiometers provide brightness temperature measurements at different frequencies that have distinct atmospheric absorption characteristics. The MWRs that are operated at the CloudNET sites measure brightness temperatures at frequencies near 22 and 30 GHz, which are used to simultaneously retrieve LWP and IWV (Löhnert and Crewell 2003). The 22-GHz brightness temperatures provide information mainly on water vapor, whereas the 30-GHz brightness temperatures provide information mainly on the cloud liquid water. The algorithm to retrieve LWP is based on the statistical relationship between the observed brightness temperatures and LWP. This relationship is derived from radiative transfer model simulated brightness temperatures for different LWP values for a given profile of atmospheric temperature and humidity. Because of uncertainties in the instruments' calibration and variations in the atmospheric profiles, the LWP retrievals during cloud-free conditions can differ significantly from zero and become both positive and negative. Marchand et al. (2003) have shown that using profile information from actual radio soundings can significantly reduce the uncertainties due to natural variability in atmospheric profiles. However, the instrument calibration and atmospheric profile coefficients at the CloudNET stations are determined from the MWR brightness temperatures that are observed during clear-sky periods. During these periods, which are identified from independent ceilometer observations, the LWP values must be zero, and hence the instrument calibration and atmospheric profile coefficients can be derived. Coefficient values during periods of cloud cover are then obtained by interpolation between consecutive clear-sky observations (Gaussiat et al. 2007). The retrieval of LWP from MWR is strongly disturbed by rainfall, since the instrument antenna or radiometer 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 (2003), the precision of LWP retrievals varies between 15 and 30 g m$^{-2}$. Note that these precisions were derived from instrumental specifications and are completely theoretical, assuming normal distributed radiometric noise to describe the errors in the brightness temperature observations. The two-channel MWRs that are operated at

Chilbolton and Palaiseau have an estimated precision of 30 g $m^{-2}$ (Crewell and Löhnert 2003).

## 4. Validation of LWP of retrievals from SEVIRI at two CloudNET sites

The differences between the LWP retrievals from SEVIRI and MWR for the CloudNET sites of Chilbolton and Palaiseau are assessed for a summer period, covering May–August 2004. The LWP retrievals from MWR were averaged over 20 min. When Taylor's frozen turbulence hypothesis (Taylor 1938) is assumed and the wind speed is about 10 m $s^{-1}$ this corresponds to a track length of about 12 km, which is considered representative for the field of view of SEVIRI ($4 \times 7$ $km^2$). The LWP values from SEVIRI were retrieved at a temporal resolution of 15 min for the pixel that coincided with the ground station. The retrievals were done between 0600 and 1800 UTC at solar zenith angles smaller than 72°. During summer, most observations had solar zenith angles smaller than 60° and scattering angles between 120° and 150°. The SEVIRI cloud-masking algorithm was used to detect pixels that were identified as "clear certain," which were excluded from the comparison. Because of the insensitivity of MWR observations to ice clouds, the comparison is restricted to water clouds. The cloud thermodynamic phase retrievals from SEVIRI were used to select observations with water clouds above the CloudNET stations. The analysis of the MWR-retrieved LWP values was restricted to nonprecipitating clouds with LWP values smaller than 800 g $m^{-2}$. The MWR measurements that were disturbed by rain were identified with rain gauge observations.

### *a. Validation method*

The statistics examined in this paper include the mean and median of the LWP retrievals and the 50th (Q50), 66th (Q66), and 95th (Q95) interquantile range of the deviation between the LWP retrievals from SEVIRI and MWR. Here, Q50 is the difference between the 25% and 75% quantiles of the deviations, Q66 and Q95 mutatis mutandis. The Q50 is an alternative measure of one standard deviation. The fact that the upper and lower 25% of the dataset are ignored makes Q50 a more robust estimator of variance than the standard deviation, and the preferred one for non-Gaussian distributions. The Q66 value is used to indicate twice the standard deviation, which would exactly be the case for a Gaussian distribution. In this study, the Q50, Q66, and Q95 values are calculated from the instantaneous or daily median values, but for different sampling periods, that is, day (Q66-D), month (Q66-M), and season (Q66-S). The accuracy is defined as the bias between the median SEVIRI- and MWR-retrieved LWP values over the observation period, whereas the precision is given by the Q50 value of the deviations between SEVIRI- and MWR-retrieved LWP values.

### *b. Frequency distribution of LWP*

A statistical analysis of frequency distributions of LWP retrievals from MWR and SEVIRI is performed to evaluate the differences between Chilbolton and Palaiseau. Figure 1 presents the distributions of LWP retrieved from SEVIRI and MWR over the period May–August 2004 for both CloudNET sites. The LWP distributions from SEVIRI and MWR are lognormally distributed and have similar shapes. The lower tails of the distributions reveal differences that are mainly related to differences between the LWP retrieval algorithms. As mentioned before, the LWP retrievals from MWR can become slightly negative because of small calibration drifts, whereas the LWP retrievals from SEVIRI are always positive. During summer, the climate of Palaiseau is continental, which is characterized by few clouds during the morning and the development of shallow convective clouds during the day. The LWP distribution of Palaiseau is dominated by clouds with low values, while thicker clouds that could be associated with deep convection (LWP $>$ 100 g $m^{-2}$) rarely occur. The maritime climate of Chilbolton is governed by stratiform and frontal clouds and to a lesser extent by convective clouds. The distribution of Chilbolton exhibits a much wider range of LWP values. Although the majority of the clouds at Chilbolton have LWP values smaller than 30 g $m^{-2}$, a considerable fraction of clouds (about 10%) have LWP values larger than 100 g $m^{-2}$. At Chilbolton, SEVIRI overestimates the frequency of clouds with LWP values between 0 and 30 g $m^{-2}$ relative to the MWR with about 20%. This overestimation reduces to about 5%, when the negative LWP values of the MWR are clipped to LWP values between 0 and 15 g $m^{-2}$. The MWR retrieves negative LWP values for about 15% of the observations. Figure 1b shows that the 5% overestimation is compensated by an underestimation of the frequency of thick clouds (LWP $>$ 50 g $m^{-2}$). Note that sampling differences partly explain why SEVIRI observes higher frequencies of clouds with low LWP values than the MWR. The variations in the LWP values from MWR do often occur at subpixel level. Although the LWP values from MWR are averaged over a 20-min period, aiming to represent more or less the field of view of the SEVIRI, the MWR samples a substantially different portion of the cloud ($\sim 0.1 \times 15$ $km^2$) than SEVIRI ($\sim 4 \times 7$ $km^2$). For example, cloud fields that contain cloud-free and

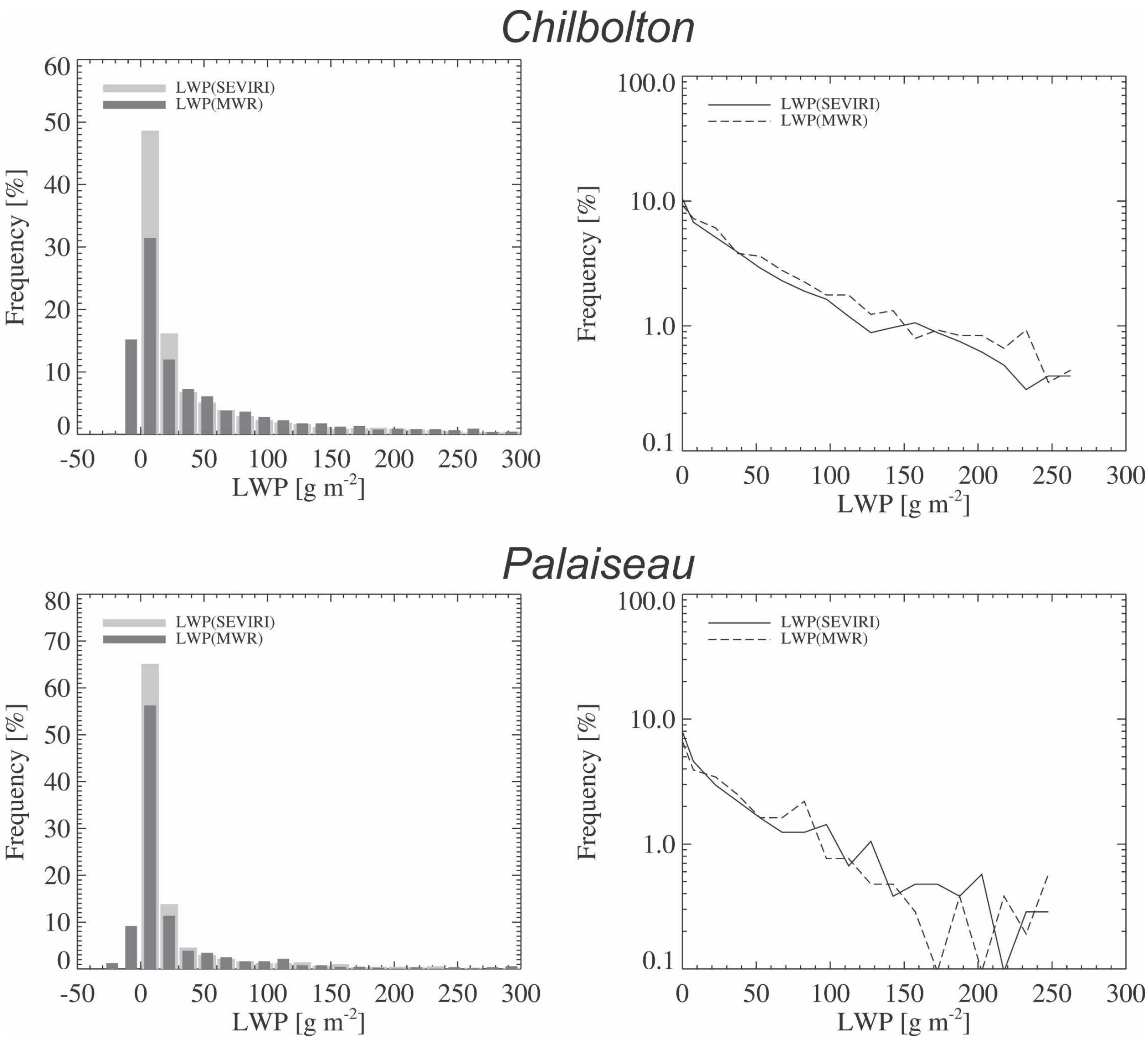


FIG. 1. Frequency distributions of SEVIRI- and MWR-retrieved LWP and their corresponding distributions plotted on a logarithmic scale for Chilbolton and Palaiseau over the period May–August 2004.

cloud-filled sections along the 0.1 × 15 $km^2$ sample track of the MWR may appear as homogeneous thin clouds at the 4 × 7 $km^2$ resolution of SEVIRI. Roebeling et al. (2006b) quantified the resulting uncertainties due sampling differences and cloud inhomogeneities between ground-based and satellite-observed LWP retrievals. They used LWP retrievals from MODIS to simulate LWP fields at the resolution of the MWR (0.1 × 0.1 km) and at the resolution of SEVIRI (4 × 7 km) by extrapolating the power spectrum. The simulated LWP fields were used to determine the optimum track length for comparison of ground-based and satellite-retrieved LWP values and to quantify the uncertainties due to sampling differences and cloud inhomogeneities. The optimum track length was found to be equal or a bit larger than the SEVIRI spatial resolution (~7 km), which corresponds to 20-min sampling for an assumed wind speed of about 10 m $s^{-1}$. The uncertainty due to sampling differences and cloud inhomogeneities was found to be at least 20 g $m^{-2}$.

Figure 2 shows that the frequency distributions of differences are non-Gaussian. This is best seen from the strongly peaked frequency at differences around zero and the rapid drop in the frequency of occurrence as the differences increase. The slightly negative skew suggests larger LWP values from MWR than from SEVIRI. At Chilbolton and Palaiseau, the Q66-S values of about 55 and 26 g $m^{-2}$ are in the same order of

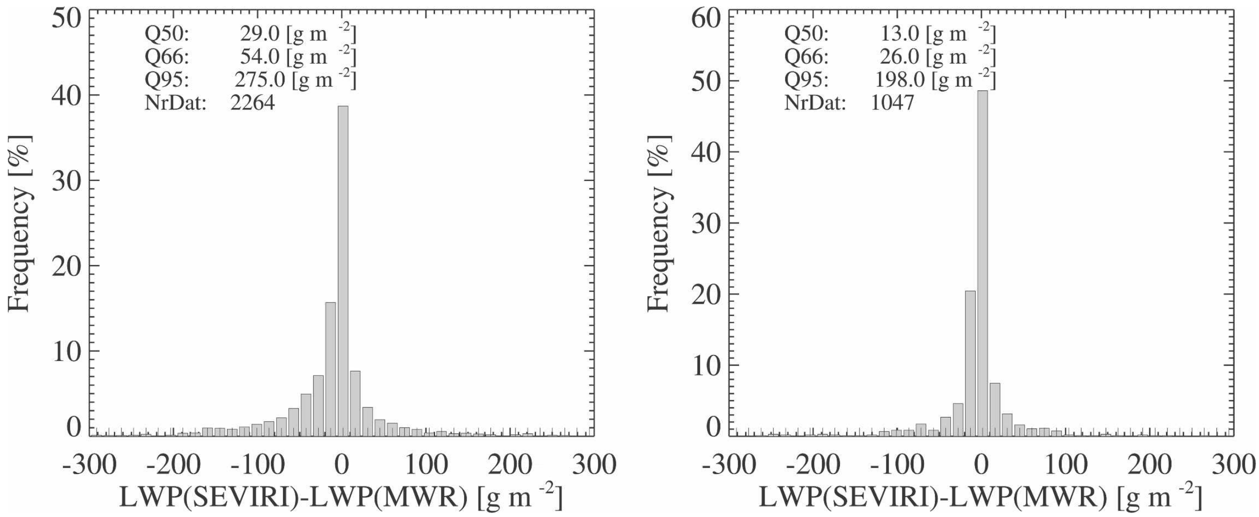


FIG. 2. Frequency distributions of differences between SEVIRI- and MWR-retrieved LWP and for (left) Chilbolton and (right) Palaiseau over the period May–August 2004.

magnitude as the mean LWP values from MWR of about 58 and 33 g $m^{-2}$, respectively. The Q95-S values are about 6 times larger than the Q66-S value, with 289 g $m^{-2}$ for Chilbolton and 206 g $m^{-2}$ for Palaiseau. This indicates that for a limited number of observations the differences between the LWP retrievals from SEVIRI and MWR are very large. Possible reasons for these large Q95-S values are the nature of cloud inhomogeneity, multilayer clouds, and the decreasing accuracy of both ground-based and SEVIRI retrievals of LWP with increasing cloud optical thickness. Figure 3 presents the accuracies of SEVIRI-retrieved LWP values as a function of the LWP values retrieved from MWR. These values are calculated for bins of 20 g $m^{-2}$ in MWR-retrieved LWP values. The number of coincident observations and the Q66-S values are also given. The figure shows a substantial reduction in accuracy with increasing LWP values from MWR, with an underestimation of about 30 g $m^{-2}$ at MWR-retrieved LWP values of about 100 g $m^{-2}$. However, the majority of the observations are made at MWR-retrieved LWP values smaller than 40 g $m^{-2}$, where the accuracies are better than 5 g $m^{-2}$. In general, the Q66-S values (error bars) are about equal to the MWR-retrieved LWP values, both at Chilbolton and Palaiseau. If the Q66-S value represents twice the standard deviation, the relative precision of the instantaneous LWP retrievals from SEVIRI is about 50%. An overview of the validation results of the instantaneous LWP retrievals from SEVIRI is given in Table 1.

### *c. Time series of daily and monthly LWP values*

Comparing daily median LWP retrievals instead of instantaneous retrievals can reduce the effect of spatial mismatching. The unique characteristic of SEVIRI is that the high sampling frequency (15 min) combined with the spectral channels similar to AVHRR allows for the calculation of daily median LWP values. The daily median LWP values were calculated from SEVIRI and MWR retrievals for days with at least six observations. Figure 4 presents the daily median LWP values from MWR and SEVIRI for 83 days at Chilbolton and 44 days at Palaiseau during the summer period. At both locations large variations in daily median LWP values are observed, ranging from 0 to 400 g $m^{-2}$. However, for about 90% of the days the daily median LWP values are below 100 g $m^{-2}$. In general, the agreement between the daily median LWP values from MWR and SEVIRI is very good, with a correlation of 0.94 at Chilbolton and 0.95 at Palaiseau. This is surprisingly high, considering the fact that the MWR and SEVIRI sample different portions of the cloud. With the exception of a few days at both sites, the differences between the daily median LWP retrievals from SEVIRI and MWR are smaller than 30 g $m^{-2}$. The Q66-D values (error bars), which indicate the variance of the differences between the instantaneous retrievals during the observation days, are for most days smaller than 100 g $m^{-2}$ but larger than the median LWP values. Both at Palaiseau and Chilbolton, the daily median LWP values from SEVIRI are retrieved with an almost perfect accuracy and a precision of about 15 g $m^{-2}$. Figure 5 is similar to Fig. 3, but then presents the accuracies and Q66-S values of the daily median LWP retrievals from SEVIRI. It can be seen that the accuracies are better than 12 g $m^{-2}$ for the entire range of daily median LWP values from MWR. The relative precisions of the daily median LWP values from SEVIRI are generally better than

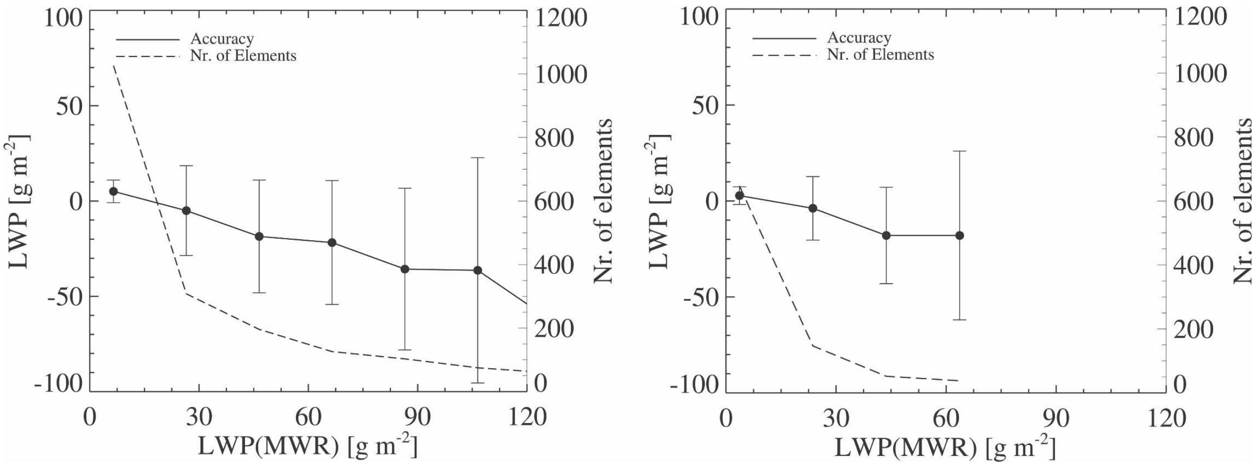


FIG. 3. The accuracies and number of observations of the instantaneous LWP retrievals from SEVIRI as function of the instantaneous LWP values from MWR for (left) Chilbolton and (right) Palaiseau. The accuracies are calculated for bins of 20 g $m^{-2}$ in LWP values from MWR over the period May–August 2004. The error bars give the Q66-S values for each bin.

30%, which is significantly better than the relative precisions of the instantaneous retrievals. Table 2 gives an overview of the validation results of the daily median LWP retrievals from SEVIRI for Chilbolton and Palaiseau.

The high number of observations per month (>400) allows for the calculation of statistically significant values of the monthly median LWP. Figure 6 presents the monthly median LWP retrievals from MWR and SEVIRI over the four summer months. The values are directly calculated from the instantaneous retrievals that have been presented in Fig. 1. The dominance of thin clouds during the summer months at Palaiseau is reflected in the magnitude of monthly median LWP values from MWR, which vary between 1 and 20 g $m^{-2}$. This is about half the magnitude of the LWP values at Chilbolton, where the clouds tend to be thicker. Contrary to the results presented for the daily median LWP values, the results of the comparison of monthly median LWP values are somewhat different for Chilbolton and Palaiseau. The difference between the LWP retrievals from SEVIRI and MWR is slightly negative for Chilbolton, while it is slightly positive for Palaiseau. These differences could be related to the differences between the MWRs at the CloudNET sites. Löhnert and Crewell (2003) showed that differences of 5–10 g $m^{-2}$ between different MWRs are common. However, the meteorological conditions at Palaiseau and Chilbolton differ too much to attribute the observed differences to instrumental differences. To quantify the accuracies of the MWRs at the CloudNET sites would require either a longer dataset, or even better, a microwave intercomparison study at one of the measurement sites. The Q66-M values (error bars) vary between 10 and 60 g $m^{-2}$, with the large Q66-M value for July 2004 at Palaiseau as an exception.

TABLE 1. Summary of the validation of instantaneous results over the period May–August 2004 for Chilbolton and Palaiseau.

| | Chilbolton | Palaiseau |
|---|---|---|
| No. obs | 2486 | 1070 |
| Mean LWP | | |
| MWR (g $m^{-2}$) | 58.1 | 32.7 |
| SEVIRI (g $m^{-2}$) | 52.1 | 33.1 |
| Median LWP | | |
| MWR (g $m^{-2}$) | 18.5 | 5.1 |
| SEVIRI (g $m^{-2}$) | 15.6 | 7.2 |
| Q50-S (g $m^{-2}$) | 29.0 | 13.0 |
| Q66-S (g $m^{-2}$) | 55.0 | 26.0 |
| Q95-S (g $m^{-2}$) | 289.0 | 206.0 |

### d. *Diurnal variations of LWP*

Figure 7 shows the diurnal variations in median LWP values from SEVIRI and MWR as function of the fraction of the day for the CloudNET sites over the summer period. The fraction of the day is the normalized period between sunrise (fraction = 0) and sunset (fraction = 1). The median LWP values from MWR exhibit a clear diurnal trend. At both CloudNET sites, the LWP values of either early morning (fraction < 0.2) or late afternoon (fraction > 0.8) observations are about 6 times smaller than the values at local solar noon (fraction = 0.5). The LWP values from MWR exhibit a sharp increase till the fraction is about 0.4, which corresponds during summer to 10 h local solar time. Note that the thickest clouds are observed around local solar noon, when the continental boundary layer is thickest and convective activity highest. There is a slight asymmetry

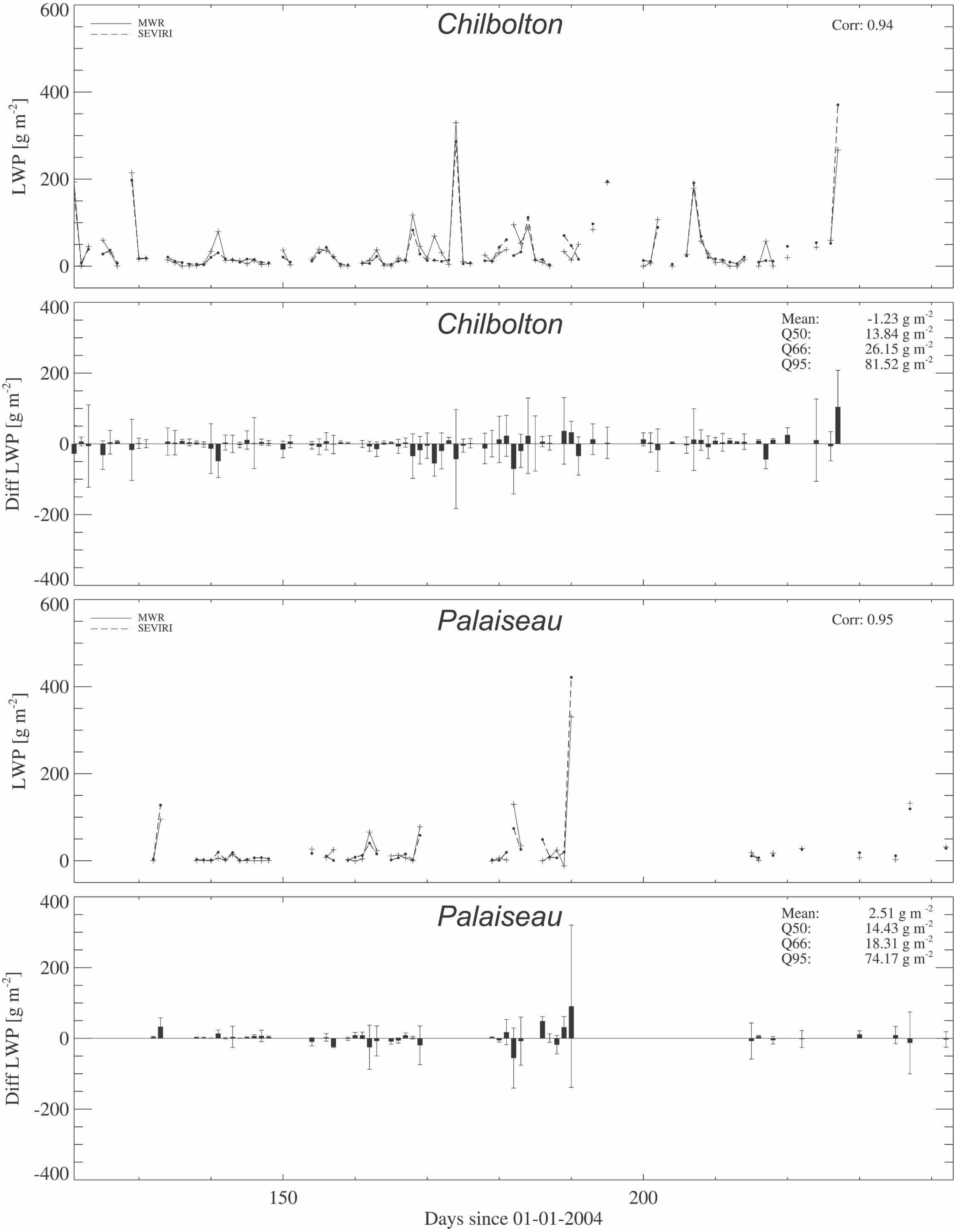


FIG. 4. Time series of daily median LWP values from SEVIRI and MWR, and their corresponding difference in LWP for Chilbolton and Palaiseau over the period May–August 2004. The error bars indicate the Q66-D values.

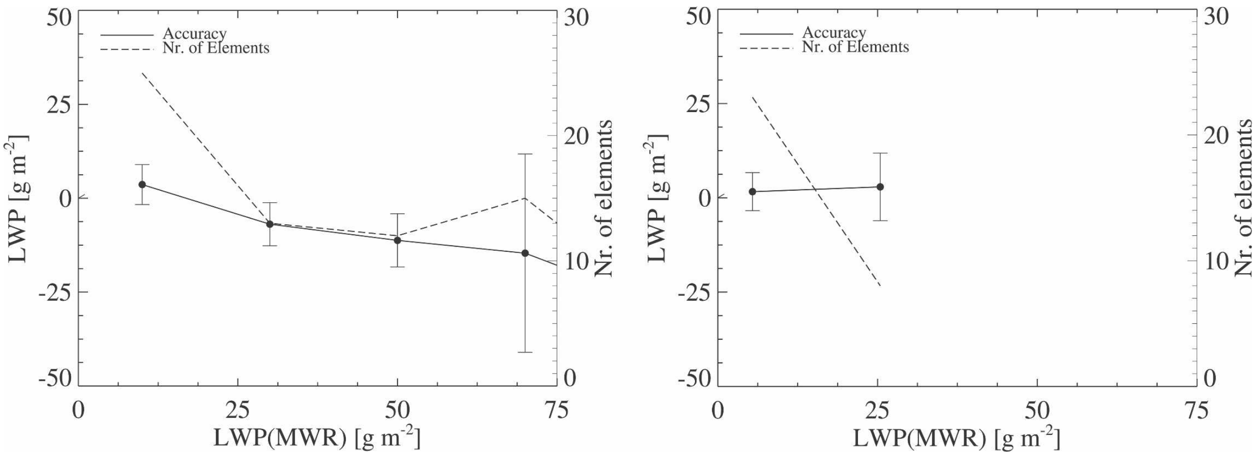


FIG. 5. The accuracies and number of observations of the daily median LWP retrievals from SEVIRI as function of the daily median LWP values from MWR for (left) Chilbolton and (right) Palaiseau. The accuracies are calculated for bins of 20 g $m^{-2}$ in LWP values from MWR over the period May–August 2004. The error bars give the Q66-S values of the deviations between the daily median LWP from MWR and SEVIRI for each bin.

between the LWP values before and after local solar noon. The afternoon LWP values are somewhat higher than the morning values, which is probably the result of increased convection from morning to afternoon. Throughout the day there are significantly thinner clouds at Palaiseau than at Chilbolton, which can be seen from the median LWP values from MWR that are about 2 times lower at Palaiseau than at Chilbolton.

In general, the median LWP values from SEVIRI exhibit similar diurnal variations as the MWR values. However, the amplitude of the diurnal variations in LWP is smaller from SEVIRI than from MWR. During early morning or late afternoon, SEVIRI always observes higher median LWP values than the MWR. It is suggested that cloud inhomogeneities may be responsible for the observed differences at these observation times. This is consistent with the results of Loeb and Coakley (1998) who found that the cloud property values, retrieved from one-dimensional schemes such as CPP, systematically increase at the solar zenith angles ($\theta_0$) that are observed during early morning or late afternoon ($\theta_0 > 60°$). For most observations at Palaiseau, the median LWP values from SEVIRI are higher than the corresponding MWR values, with a maximum difference of 5 g $m^{-2}$. This does not agree with the results of Chilbolton, where SEVIRI overestimates LWP during early morning and late afternoon, while LWP is underestimated around local solar noon.

TABLE 2. Summary of the validation of daily results over the period May–August 2004 for Chilbolton and Palaiseau.

| | Chilbolton | Palaiseau |
|---|---|---|
| No. days | 83 | 44 |
| Daily mean | | |
| Accuracy (g $m^{-2}$) | −4.4 | 2.4 |
| Q50 (g $m^{-2}$) | 20.9 | 12.1 |
| Q66 (g $m^{-2}$) | 35.7 | 20.9 |
| Q95 (g $m^{-2}$) | 86.6 | 75.0 |
| Correlation | 0.92 | 0.97 |
| Daily median | | |
| Accuracy (g $m^{-2}$) | −1.2 | 2.5 |
| Q50 (g $m^{-2}$) | 13.8 | 14.4 |
| Q66 (g $m^{-2}$) | 26.2 | 18.3 |
| Q95 (g $m^{-2}$) | 81.5 | 74.2 |
| Correlation | 0.94 | 0.95 |

## 5. Validation of one year of LWP retrievals from SEVIRI

One year of MWR- and SEVIRI-retrieved LWP values were compared to evaluate the annual cycle of the accuracy and precision of the SEVIRI retrievals. This comparison was limited to Chilbolton, where MWR-retrieved LWP and rain gauge observations were available for the period May 2004 until April 2005. For this period more than 3800 observations could be used. The comparison was restricted to the daily and monthly median LWP retrievals. The daily median LWP values were calculated for all days with more than six coincident sets of SEVIRI and MWR observations of LWP. The monthly median values were calculated from the instantaneous LWP retrievals from SEVIRI and MWR, which varied between 70 and 700 observations per month. There were no LWP retrievals from SEVIRI during the entire month of December 2004 and part of January because LWP was only retrieved at solar zenith angles smaller than 72°.

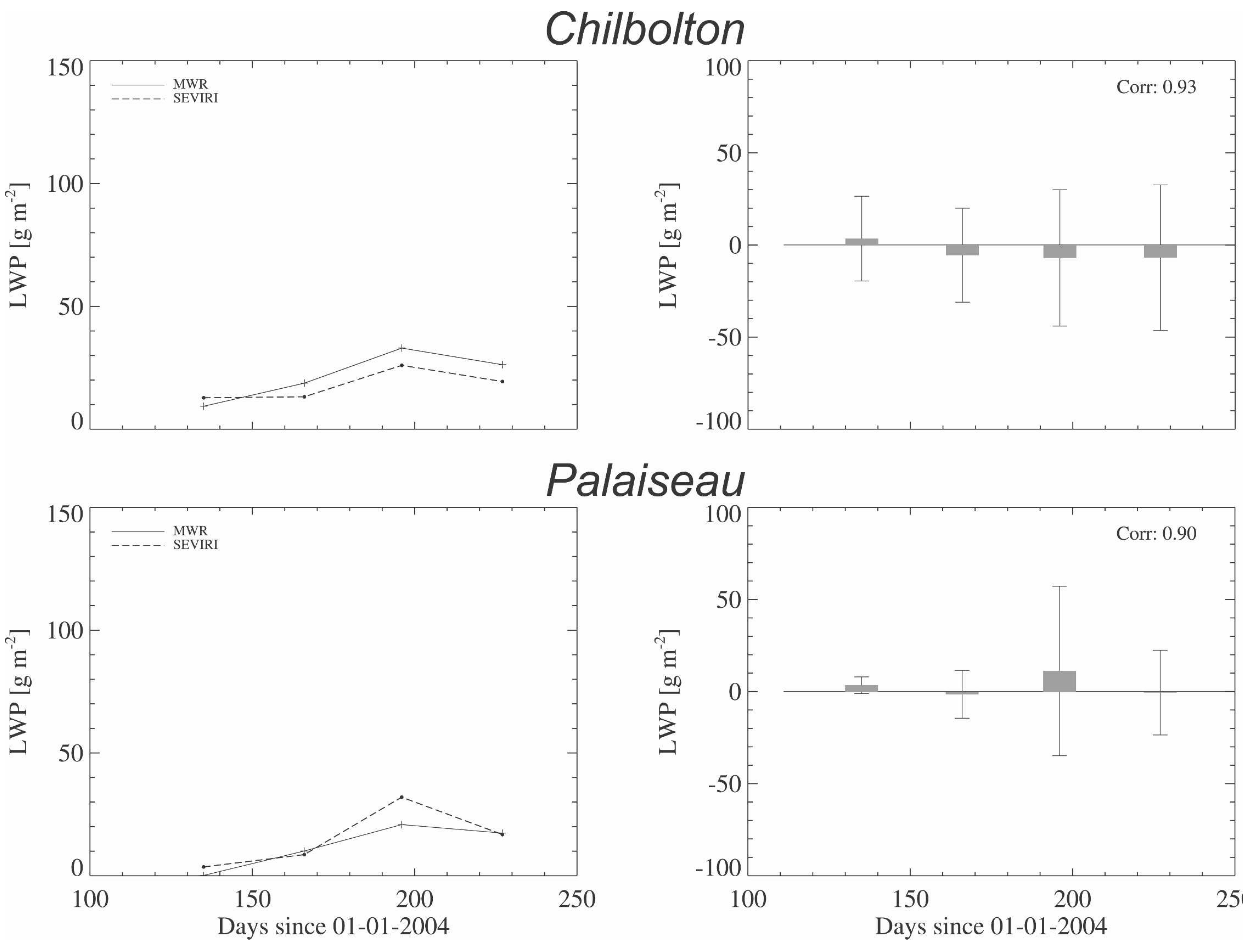


FIG. 6. Time series of monthly median LWP from SEVIRI and MWR and their difference for (top) Chilbolton and (bottom) Palaiseau. The error bars indicate the Q66-M values.

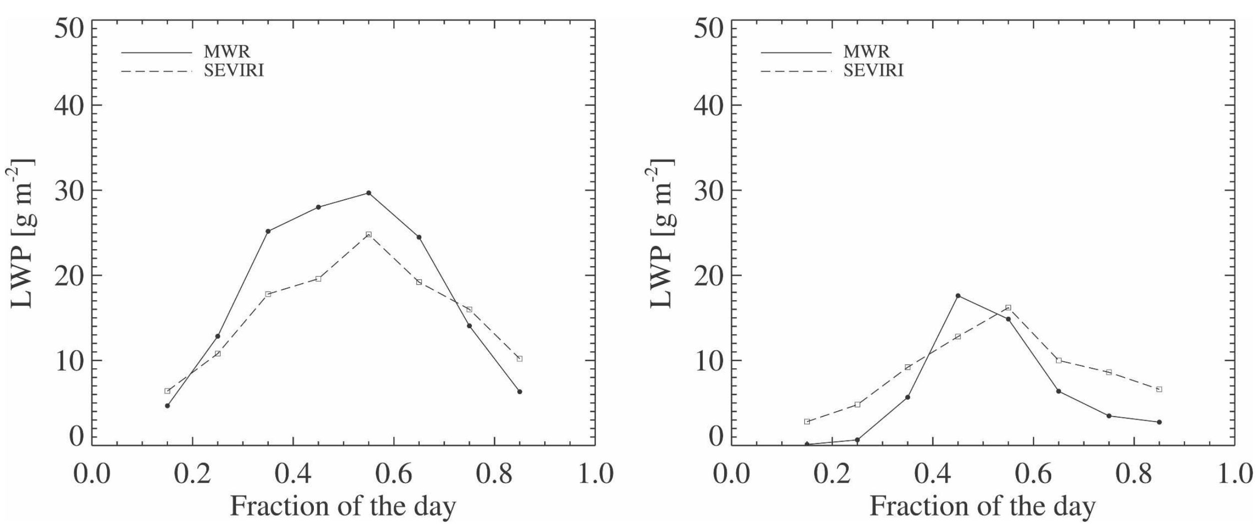


FIG. 7. The median LWP retrieved from MWR and SEVIRI as function of the fraction of the day for (left) Chilbolton and (right) Palaiseau during the period May–August 2004, where the fraction of the day is normalized period between sunrise (fraction = 0) and sunset (fraction = 1).

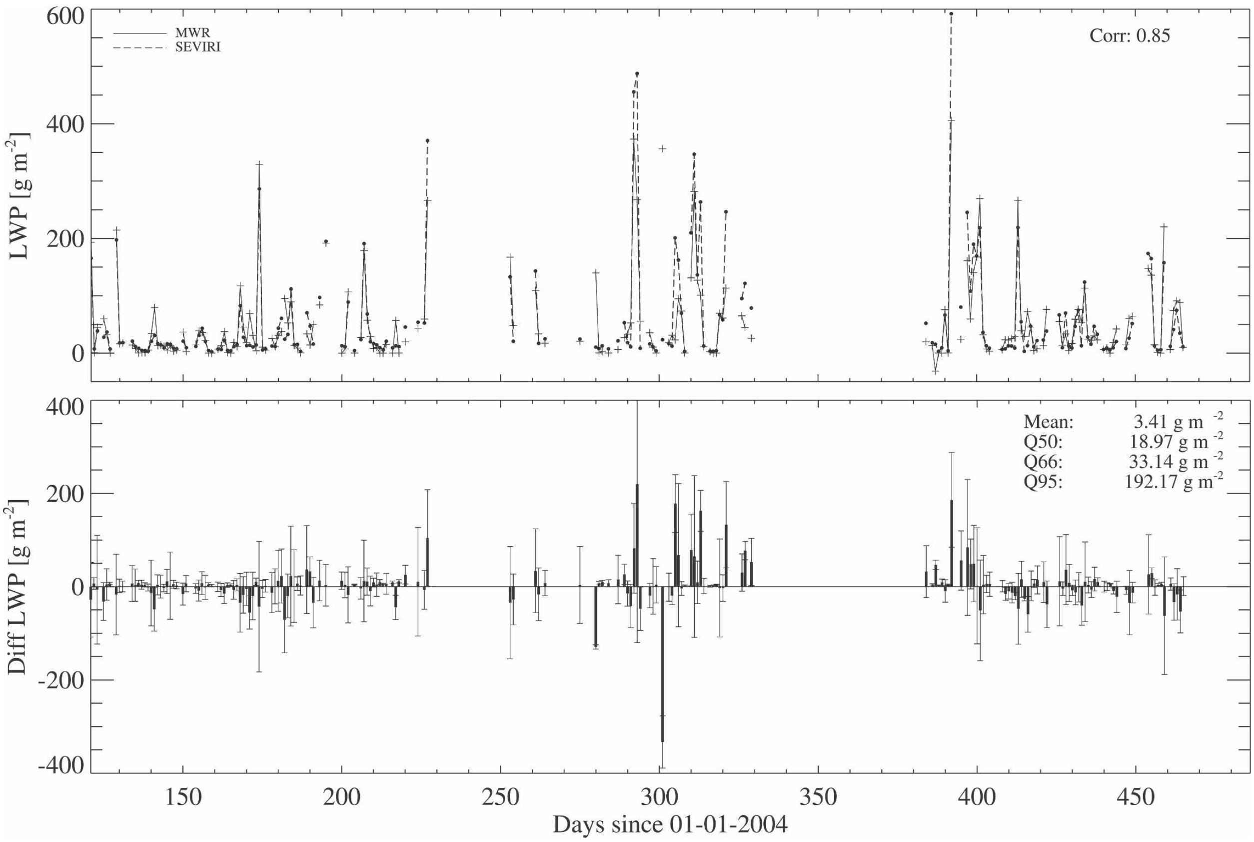


FIG. 8. Time series of (top) daily median LWP values from SEVIRI and MWR and (bottom) the corresponding difference in LWP for Chilbolton over the period May 2004–April 2005. The error bars indicate the Q66-D values.

Figure 8 presents time series of the daily median LWP retrievals from SEVIRI and MWR and their corresponding differences over one year. Figure 8 shows that the daily median LWP values from both MWR and SEVIRI vary between 0 and 600 g $m^{-2}$. Most days with high daily median LWP values occur during the winter months (October–February). For the entire year the agreement is good, with a correlation of 0.85, an accuracy of about 4 g $m^{-2}$, and a precision of about 20 g $m^{-2}$. However, there is a strong annual cycle of both the accuracy and precision of the daily median LWP values from SEVIRI. During the summer months (May–August 2004) the accuracy is almost perfect and the precision better than 15 g $m^{-2}$, whereas during the winter months (September 2004–March 2005) the accuracy is about 10 g $m^{-2}$ and the precision is as large as about 30 g $m^{-2}$.

Figure 9 is similar to Fig. 8, but then presents the results for the monthly median LWP values over the observation year. The monthly median LWP values from SEVIRI are in the same order of magnitude as the MWR values, and vary between 10 and 60 g $m^{-2}$. In general SEVIRI slightly underestimates the LWP values from MWR, with as exceptions November 2004 and January 2005. The accuracies during the summer months (~5 g $m^{-2}$) are significantly better than the during the winter months (~25 g $m^{-2}$). Besides the lower accuracies during winter, the precision, as indicated by the error bars, also reveals a strong annual cycle. During the summer months the precisions are better than 20 g $m^{-2}$, whereas during the winter months (September–March) these values are larger than 50 g $m^{-2}$.

## 6. Discussion

The instantaneous validation results presented in this paper correspond well to the results found by Han et al. (1995) and Jolivet and Feijt (2005). The Q50-S values are well within the range of expected precisions, and similar to the precisions of the LWP values retrieved from MWR of about 30 g $m^{-2}$. The fact that the precisions significantly improve when, instead of instantaneous values, the daily median LWP values are compared suggests that part of the observed differences is related to validation uncertainties. Roebeling et al. (2006b) quantified the differences in validation studies

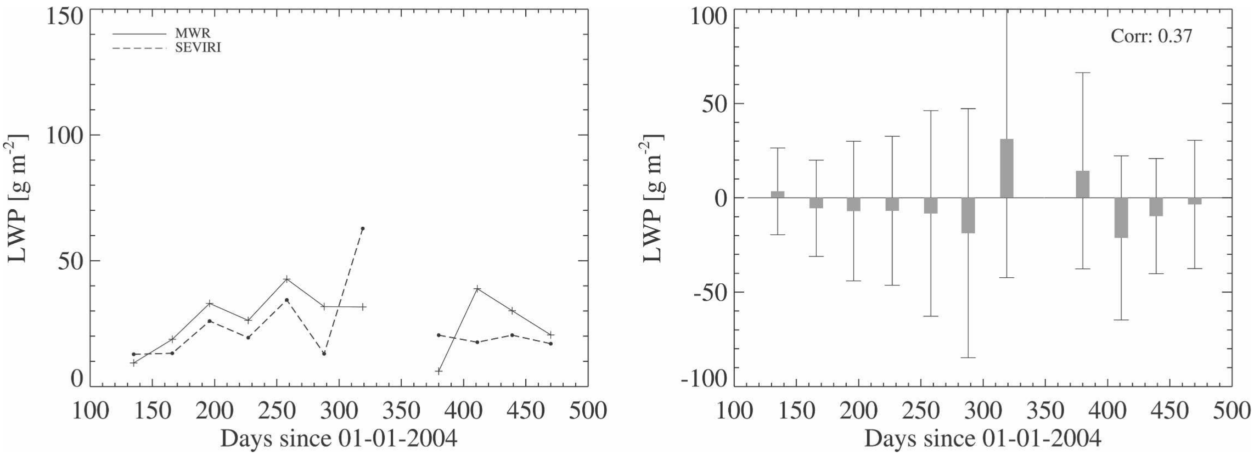


FIG. 9. Time series of (left) monthly median LWP from SEVIRI and MWR and (right) their difference for Chilbolton over the period May 2004–April 2005. The error bars in the difference plots indicate the Q66-M values.

due to uncertainties in collocation, parallax, and position of the ground station and differences due to sampling of different portions of the cloud. For marine stratocumulus clouds they found that the validation causes uncertainties similar or larger than those of the SEVIRI retrieval process, with uncertainties due to collocation and parallax of about 50 g $m^{-2}$ and uncertainties due to sampling different portions of the clouds of about 20 g $m^{-2}$. Part of these differences may be alleviated through improving the sampling strategy. In this paper, a simple sampling strategy is used, in which the LWP retrievals from SEVIRI over the ground station are compared with 20-min mean LWP values from MWR. Therefore a substantial part of the Q66 values could be due to collocation mismatch. 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-based observations need to be averaged over different periods depending on the wind speed and direction at cloud altitude.

The validation of one year of LWP retrievals from SEVIRI exhibited large differences in accuracy between summer and winter. It is suggested that these large differences are related to unfavorable viewing conditions. Beside the fact that the solar zenith angles are high ($\theta_0 > 60°$), the scattering angles are also often in backward scattering directions. Figure 10 shows the bidirectional reflectances for a water cloud with COT = 30 and effective radius ($r_e$) = 12 $\mu$m. The red lines in the plot indicate the viewing geometries over Chilbolton at the observation hours of SEVIRI for an example day in July and October. In October, the solar zenith angles hardly fall below 60° and the scattering angles are close to the backward peak at 180°. In July, the solar zenith angles are low during the early morning or late afternoon observations, but these observations do not coincide with scattering angles close to the backward scattering peak. Loeb and Coakley (1998) have shown that COT values from one-dimensional retrieval algorithms, such as CPP, show a systematic drift in the peak cloud optical thickness as the solar zenith angle increases. This shift is especially large at solar zenith angles >60°, but is observed at smaller solar zenith angles if only thick clouds are considered. Because the CLWP is approximated from the retrieved COT and droplet effective radius [Eq. (1)], the differences in COT will directly affect the retrieval of LWP. Loeb and Coakley (1998) did not find a significant shift in the peak cloud optical thickness with viewing zenith angles in backward scattering directions. However, their study was done for overcast marine stratus cloud layers that satisfy, best of all cloud types, the plane-parallel cloud assumption of one-dimensional cloud property retrieval algorithms. Loeb et al. (1998) found that the relative difference between three-dimensional and plane-parallel cloud reflectances can be large because of subpixel variations in cloud-top height (i.e., cloud bumps). Depending on the structure of the cloud field and its optical thickness, the three-dimensional models simulate up to 10% higher reflectances than one-dimensional models in backward scattering directions. The differences are largest at viewing zenith angles >60°, where it may lead to a significant overestimation of optical thickness. Figure 11 shows, for different viewing geometries, the relationship between simulated cloud reflectances at 0.6 and 1.6 $\mu$m and COT and effective radius, respectively. This figure demonstrates the high sensitivity of COT retrievals for thick cloud (COT > 30) at low solar zenith angles, because of the

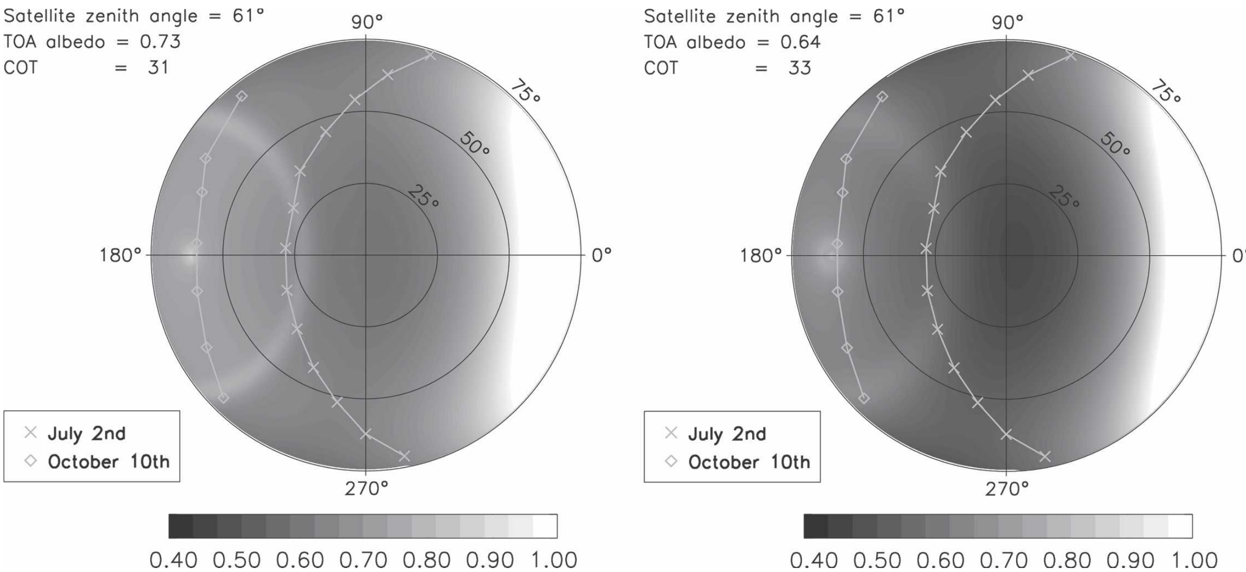


FIG. 10. Bidirectional reflectances from DAK at (left) 0.6 and (right) 1.6 $\mu$m for a water cloud with COT = 31 and $r_e$ = 12 $\mu$m. The satellite zenith angle $\theta = 61°$, the solar zenith angle $\theta_0$ increases with the radial distance from the center from 0° to 75°, and the relative azimuth angle $\phi$ increases anticlockwise from 0° to 360°. The gray lines indicate the observation geometries of SEVIRI for two example days over Chilbolton: 2 Jul and 10 Oct.

nonlinear relationship between the simulated reflectances and COT. Figure 12 presents the errors in retrieved COT and effective radius due to ±3% relative errors in simulated reflectances at 0.6 and 1.6 $\mu$m, respectively. The errors are calculated at relative azimuth angle $\phi = 160°$, viewing zenith angle $\theta = 60°$ and solar zenith angles $\theta_0$ of 40°, 50°, and 70°. The left graph Fig. 12 clearly illustrates that an error of ±3% in 0.6 $\mu$m reflectances results, for a cloud with COT = 80 at $\theta_0$ = 70°, in errors in retrieved COT of about 60 (about 75%) This sensitivity is much lower at low solar zenith angles, where the reflectances saturate at larger COT values. In addition, the one-dimensional to three-dimensional differences are smaller at low solar zenith angles. The right graphs in Figs. 11 and 12 show that the effective radius retrieval is relatively insensitive to solar zenith angle variations. From Fig. 12 it can be seen that the errors in retrieved effective radius are always smaller than 2 $\mu$m. With respect to one-dimensional retrievals, three-dimensional retrievals tend to increase the effective radius. However, for nonbroken cloud fields the effective radius retrievals are less effected by 1D–3D

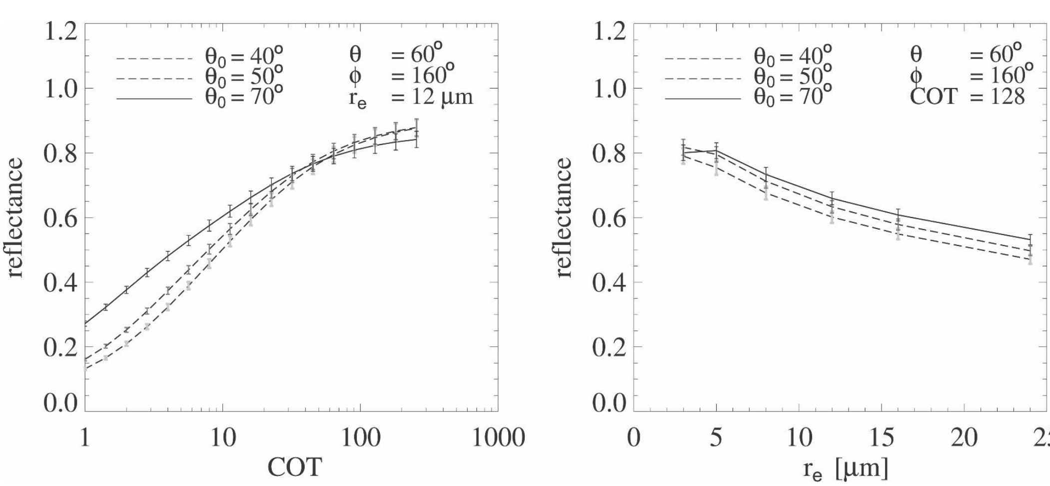


FIG. 11. Dependence of DAK-simulated cloud reflectances at (left) 0.6 $\mu$m on COT and (right) 1.6 $\mu$m on $r_e$ for $\theta = 60°$, $\phi = 160°$, and $\theta_0$ = 40°, 50°, and 70°. The reflectances are simulated for $r_e$ = 12 $\mu$m at 0.6 $\mu$m, and for COT = 128 at 1.6 $\mu$m. The error bars represent ±3% variations in reflectance.

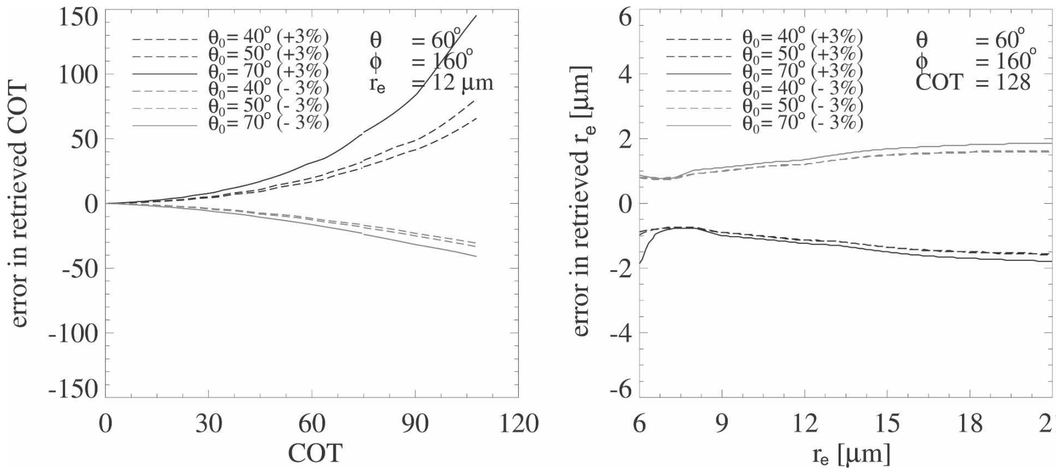


FIG. 12. Error in retrieved (left) COT assuming errors of ±3% in the reflectances at 0.6 $\mu$m and (right) $r_e$ assuming errors of ±3% in the reflectances at 1.6 $\mu$m. The errors are calculated for $\theta_0$ = 40°, 50°, and 70° at $\theta$ = 60°, $\phi$ = 160°, and $r_e$ = 12 $\mu$m at 0.6 $\mu$m and COT = 128 at 1.6 $\mu$m.

differences that than COT retrievals. Thus, it is likely that 1D–3D differences at high solar zenith angles in the backward scattering direction, the viewing geometries that correspond to SEVIRI observations during the winter season, leads to higher LWP values from SEVIRI that have lower accuracy. Várnai and Marshak (2007) analyzed one year of COT retrievals from MODIS to examine the viewing angle dependence of one-dimensional retrieval algorithms. They found that the COT retrievals for inhomogeneous clouds give more than 30% higher COT values for oblique views than for nadir view. Beside the direct effect of viewing angle dependence on COT and effective radius retrievals, the separation of water from ice clouds is expected to be affected by this dependence. This is confirmed by the findings of Wolters et al. (2008), who found an increased difference between the percentage of water clouds observed from SEVIRI and ground-based observations toward the winter season. Thus, a significant percentage of LWP retrievals from SEVIRI might be ice contaminated during the winter season, which has a degrading effect on the accuracy of LWP retrievals.

## 7. Summary and conclusions

This paper presents the validation of SEVIRI-retrieved LWP values using MWR-retrieved LWP values from the CloudNET sites in Palaiseau and Chilbolton. The ability of SEVIRI to make accurate retrievals of LWP over northern Europe has been examined. A high agreement is found during the summer months between instantaneous LWP retrievals from MWR and SEVIRI for both Palaiseau and Chilbolton. The added value of the 15-min sampling frequency of *Meteosat-8* is especially evident in the validation of the daily and monthly median LWP retrievals from SEVIRI. These retrievals agree significantly better with the MWP-retrieved LWP values than the instantaneous ones. For the first time, it is demonstrated that the diurnal variations in LWP are well reproduced by SEVIRI. The analysis of one year of daily median LWP retrievals for Chilbolton reveals a clear annual cycle of accuracy, with much lower accuracies during winter than during summer. The sensitivity of one-dimension retrieval algorithms, such as CPP, to viewing geometry and cloud inhomogeneities is evaluated to explain the observed trend in the accuracy of LWP retrievals from SEVIRI.

During the summer months, the large number of coinciding SEVIRI and MWR observations allowed a statistically significant assessment of the accuracy and precision of the instantaneous, daily and monthly median retrievals of LWP from SEVIRI, which was done for Palaiseau and Chilbolton, respectively. The mean LWP values from MWR are retrieved from SEVIRI with an accuracy better than 5 g m$^{-2}$, which corresponds to relative accuracy better than 10%. These results point out that the accuracy of SEVIRI- and MWR-retrieved LWP values are close to each other, and much better than LWP values predicted by climate models. This justifies the SEVIRI-retrieved LWP fields a meaningful source of information for the evaluation of climate model predicted LWP fields. The precision of the instantaneous LWP retrievals from SEVIRI is reflected in the Q50-S values better than 30 g m$^{-2}$. Although these Q50-S values are acceptable, their magnitude is about one-half of the mean LWP values retrieved from MWR. A significant part of these differences may be explained by uncertainties due to collocation, sampling of different cloud portions and the retrieval error of LWP values from MWR. For the marine stratocumulus clouds, Roebeling et al. (2006b) showed that these uncertainties could also add up to 60 g $m^{-2}$. Although the magnitude of the uncertainties due to sampling differences depends on the cloud conditions, it is remarkable that the uncertainties found by Roebeling et al. (2006b) are similar to the differences between SEVIRI- and MWR-retrieved LWP values. For a limited number of observations, the differences between SEVIRI- and MWR-retrieved LWP values are very large, which is indicated by Q95-S values larger than 200 g $m^{-2}$. Possible reasons for these large values are the nature of cloud inhomogeneity, multilayer clouds, and the decreasing accuracy of both ground-based and SEVIRI retrievals of LWP with increasing cloud optical thickness.

It is confirmed that collocation and sampling errors attribute less to the comparison of daily median LWP values from MWR and SEVIRI, which is reflected in precisions better than 15 g $m^2$ and the almost perfect accuracy. For the monthly median LWP values and the diurnal variations in LWP small differences are observed between Chilbolton and Palaiseau, with a negative difference of about 5 g $m^{-2}$ at Chilbolton and a positive difference of about 5 g $m^{-2}$ at Palaiseau. It is suggested that these differences are partly related to the accuracy of the LWP retrievals from MWR and to differences among the MWRs. However, the meteorological conditions at Palaiseau and Chilbolton differ too much to attribute the observed differences entirely to instrumental differences. To quantify the accuracies of the MWRs at the CloudNET sites would require either a longer dataset, or even better, a microwave intercomparison study at one of the measurement sites. The prospects for retrieving diurnal variations in LWP from SEVIRI are very promising. The diurnal variations in LWP values are very similar from SEVIRI and MWR, with increasing LWP values toward local solar noon. The diurnal variations in LWP from SEVIRI show less pronounced amplitudes than from MWR. However, the maximum difference between both observations does not exceed 5 g $m^{-2}$.

The analysis of one year of daily median LWP retrievals from SEVIRI exhibits a strong annual cycle of the accuracy and precision of LWP retrievals from SEVIRI. During the summer, the daily median LWP values from SEVIRI and MWR are highly correlated (correlation $>$ 0.95) and have a precision better than 15 g $m^{-2}$. However, SEVIRI overestimates the MWR-retrieved daily median LWP values during the winter with about 10 g $m^{-2}$, and the precision drops to 30 g $m^{-2}$. The paper discussed three possible reasons for the decreased accuracy of LWP retrievals from SEVIRI during the winter months. First, the number of daytime observations is much lower during winter. Second, the LWP retrievals from SEVIRI are much more sensitive to errors at the low solar zenith angles and backward scattering geometries that prevail during the winter months over northern Europe. Last, cloud inhomogeneities influence the reflectances most at these viewing geometries and may cause large errors in one-dimensional retrievals of LWP.

In conclusion, the presented results showed that daily median LWP values could be retrieved with a high accuracy from 15-min SEVIRI data over northern Europe during summer. The large sensitivity of one-dimensional cloud property retrievals combined with the uncertainties due to cloud inhomogeneities leads to a significant overestimation of LWP retrievals from SEVIRI during winter. In future work we intend to quantify the sensitivity of one-dimensional cloud property retrievals to viewing geometry and cloud inhomogeneities by comparing simulated reflectances of plane-parallel and inhomogeneous clouds. This information may help to better understand the quality of one-dimensional cloud property retrievals and decide which retrievals are suited for building a climate dataset. Last, information on spatial variability in cloud properties may be used to define an approach to correct for cloud inhomogeneities.

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