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Validation of liquid cloud property retrievals from SEVIRI using ground-based observations

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[1] Partly due to aerosol effects stratocumulus clouds vary considerably in liquid water path (*LWP*), geometrical thickness (*h*) and droplet number concentration (*Nc*). Cloud models have been developed to simulate *h* and *Nc* using satellite retrieved cloud optical thickness (τ) and effective radius (r_e) values. In this paper we examine the consistency between *LWP* and *h* values inferred from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard METEOSAT-8. The use of METEOSAT-8 data means that time series of *LWP* and *h* can be validated at a 15-minute resolution, and used for examining the first indirect aerosol effect. For single-layered stratocumulus clouds the *LWP* and *h* retrievals from SEVIRI are compared to corresponding ground-based observations at two Cloudnet sites. A study on the sensitivity of the cloud model to the uncertainties in SEVIRI retrievals of τ and r_e reveals that *h* and *Nc* simulations are only accurate for clouds with effective radii larger than 5 μm. The SEVIRI and ground-based retrievals of *LWP* and *h* show very good agreement, with accuracies of about 15 g m^{-2} and 20 m, respectively. This agreement could only be achieved by assuming sub-adiabatic profiles of droplet concentration and liquid water path in the cloud model. The degree of adiabaticity for single-layered stratocumulus clouds could be quantified by simultaneous analysis of SEVIRI and ground-based *LWP* and *h* values, which suggests that stratocumulus clouds over North Western Europe deviate, on average, from adiabatic clouds. **Citation:** Roebeling, R. A., S. Placidi, D. P. Donovan, H. W. J. Russchenberg, and A. J. Feijt (2008), Validation of liquid cloud property retrievals from SEVIRI using ground-based observations, *Geophys. Res. Lett.*, *35*, L05814, doi:10.1029/2007GL032115.

1. Introduction

[2] Aerosols play an important role in modulating the cloud macro and microphysical properties, and consequently the radiative behavior of these clouds. *Twomey* [1977] found that aerosols increase the droplet concentration and decrease the droplet size of clouds with a given Liquid Water Path (*LWP*), which is referred to as the first indirect aerosol effect. To improve our understanding of the representation of aerosols in models and of the first indirect aerosol effect, accurate information on cloud *LWP*, geometrical thickness (*h*) and droplet number concentration (*Nc*) is mandatory.

[3] Several methods have been developed to retrieve *LWP* from passive imager satellite radiances [*Nakajima and King*, 1990; *King et al.*, 2004; and *Roebeling et al.*, 2006]. These methods retrieve cloud optical thickness (τ) and cloud droplet effective radius (r_e) using cloud reflectances in the visible and the near infrared wavelengths, while the *LWP* is computed from the retrieved τ and r_e values. In general, models of vertical distribution of cloud microphysical and optical properties are used to simulate *h* and *Nc*, using satellite retrievals of τ and r_e. Some authors assume clouds to be simple adiabatic [*Brenguier et al.*, 2000; *Szczodrak et al.*, 2001], while others take into account the effect of mixing and the sub-adiabatic character of water clouds [*Boers et al.*, 2006]. Alternatively, *Schüller et al.* [2003] retrieve *h* and *Nc* directly from satellite radiances, by performing the radiative transfer calculations for clouds with prescribed droplet and liquid water content profiles.

[4] Several validations studies confirmed that both *LWP* and *Nc* can be retrieved with good accuracy. Very good agreement was found between *LWP* values retrieved from ground-based microwave radiometer (MWRs) and satellite measurements, with accuracies (biases) better than 15 g m^{-2} for retrievals from both the Advanced Very High Resolution Radiometer (AVHRR) onboard NOAA [*Han et al.*, 1995; *Jolivet and Feijt*, 2005] and the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard METEOSAT-8 [*Roebeling et al.*, 2008]. Although *Nc* retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) were found to correlate very well (corr. ~ 0.9) with Cloud Condensation Nuclei (CNN) numbers for marine stratocumulus clouds [*Twohy et al.*, 2005; and *Boers et al.*, 2006], the accuracy of the *h* retrievals is still questionable. *Schüller et al.* [2005] suggest that simultaneous validation of *LWP*, *h* and *Nc* retrievals would be the way forward to quantify the validity of (sub)-adiabatic cloud models.

[5] This paper aims to strengthen the consistency of *LWP* and *h* retrievals from satellite for single-layered stratocumulus clouds in support of studying the first indirect aerosol effect. The validity of a sub-adiabatic cloud model is verified by validating *LWP* and *h* retrievals from SEVIRI simultaneously. The Cloud Physical Properties (CPP) algorithm of *Roebeling et al.* [2006] is used to retrieve *LWP*, while the sub-adiabatic cloud model of *Boers et al.* [2006] is used to calculate *h* and *Nc*. Taking advantage of the 15-minutes sampling frequency of METEOSAT−8, the *LWP* and *h* from SEVIRI retrievals are compared to a statistically significant set of collocated and synchronized ground-based measurements at two Cloudnet sites [*Illingworth et al.*, 2007].

[6] To determine the uncertainties of the *h* and *Nc* simulations, the sensitivity of the sub-adiabatic cloud model to errors in τ and r_e are studied. Finally, the degree of adiabaticity is quantified for single-layered stratocumulus

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clouds by optimizing the *LWP* and *h* values from SEVIRI to the corresponding ground-based observations.

2. Data and Methodology

2.1. Ground-Based Observations

[7] The ground-based measurements of the Cloudnet project were collected for Chilbolton in the United Kingdom (51.14°N, 1.44°W) and Palaiseau in France (48.71°N, 2.21°E). These sites were equipped with a suite of active and passive instrumentation. The active instruments (lidar and cloud radar) were used for the observation of *h*. The *h* was calculated from the difference between the cloud top measured from radar and the cloud base measured from lidar, with a vertical resolution of about 60 meters [*Illingworth et al.*, 2007]. The dual-channel passive MWRs of Chilbolton (22.2 and 28.8-GHz) and Palaiseau (24 and 37-GHz) were used for the ground-based observation of *LWP*. The MWR observed brightness temperatures at two frequencies were used to simultaneously retrieve *LWP* and integrated water vapor. These *LWP* retrievals have an estimated accuracy (bias) better than 10 g m^{-2}, while the precision (variance) is better than 30 g m^{-2} [*Gaussiat et al.*, 2007]. Following the findings of *Roebeling et al.* [2008] the ground-based observations were averaged over a 30 minutes period, aiming to represent more or less the field of view of SEVIRI (4 × 7 km^2) over the Cloudnet sites.

2.2. Retrieval of Cloud Physical Properties

[8] The Cloud Physical Properties (CPP) algorithm of *Roebeling et al.* [2006] retrieves τ and r_e in an iterative manner, by comparing satellite observed reflectances at 0.6 and 1.6 μm to radiative transfer model simulated reflectances. When a fixed vertical profile of liquid water content is assumed, the *LWP* can be computed using τ and r_e.

[9] In this study the Doubling Adding KNMI (DAK) radiative transfer model [*De Haan et al.*, 1987; *Stammes*, 2001] was used to simulate reflectances for plane-parallel clouds embedded in a midlatitude summer atmosphere. The underlying surface was assumed to be Lambertian, for which the reflectances were obtained from MODIS white-sky albedo data. The vertical distribution of the assumed spherical cloud droplets was parameterized in terms of the r_e, using a modified gamma distribution with an effective variance of 0.15 [*Hansen and Travis*, 1974]. The Mie theory was used to calculate the scattering phase functions of these droplets. The cloud reflectances were simulated at 0.6 and 1.6 μm, for optical thicknesses between 0 and 256 and droplet effective radii between 1 and 24 μm. The retrievals were limited to satellite-viewing and solar zenith angles smaller than 72°.

2.3. Sub-Adiabatic Cloud Model

[10] The sub-adiabatic cloud model of *Boers et al.* [2006] parameterizes the vertical variation of cloud microphysical and optical properties. The essential point of the cloud model is that τ and r_e at the cloud top are explicit functions of *h* and *Nc*, which are computed with the following equations:

$$Nc = A_1 \tau^{\frac{1}{2}} r_e^{-\frac{5}{2}} \tag{1}$$

$$h = A_2 \tau^{\frac{1}{2}} r_e^{\frac{1}{2}} \tag{2}$$

where, the factors A_1 and A_2 are derived from implicit assumptions about the nature of four thermodynamic and microphysical conditions, i.e. (1) the sub-adiabatic behavior of the cloud, (2) the shape of the vertical liquid water content profile, (3) the relationship between r_e and volume radius, and finally (4) the mixing model that describes the vertical variations in liquid water content as function of the vertical profiles of *Nc* and volume radius. Note that the satellite retrieved r_e values are linked to r_e values at the cloud top with the correction procedure suggested by *Boers et al.* [2006]. The sub-adiabatic behavior of the cloud, denoted as the sub-adiabatic fraction (*Fr*), is the major source of uncertainty in the retrieval. The *Fr* values typically vary between 0.3 and 0.9, due to turbulent entrainment and vertical mixing in cloud. Deviations from adiabatic clouds ($Fr = 1$) lead to an increase of *h* and a decrease of *Nc* for a given τ and r_e. The shape of the liquid water content profile varies between a linear and a C-shaped profile, and is prescribed by α in the cloud profile parameterization suggested by *Boers et al.* [2006]. In this study the cloud model was run with a sub-adiabatic fraction of 0.75 and an almost linear liquid water content profile ($\alpha = 0.3$).

3. Sensitivity of the Sub-Adiabatic Cloud Model

[11] To evaluate the validity of the sub-adiabatic cloud model the sensitivity of *h* and *Nc* retrievals to errors in τ and r_e is determined. The errors of τ and r_e values are assumed ±10% and random and normally distributed, which is comparable to the errors that we found in earlier validation studies [*Roebeling et al.*, 2008]. The cloud model is run with a fixed sub-adiabatic fraction of 0.7. Figure 1 shows that the errors in *h* retrievals increase with increasing τ and r_e. However, even for large τ and r_e values these errors do not exceed 75 meters, which is close to the accuracy of the ground-based *h* retrievals. We also examined the effect of the prescribed sub-adiabatic fraction, and found that *h* values do rapidly increase for sub-adiabatic fractions smaller than 0.5. However, such small fractions are not common for single-layer stratocumulus clouds. The errors in *Nc* increase with increasing τ, and become as large as 150 cm^{-3} for optically thick clouds ($\tau > 20$). Notable is the rapid increase of the *Nc* sensitivity for effective radii smaller than 8 μm, while the sensitivities become unacceptably large for effective radii smaller than 5 μm. However, *Han et al.* [1994] found that effective radii smaller than 5 μm are rare and deviate more than one-standard deviation from the mean r_e of water clouds, which is about 10 μm. Since the τ and r_e retrievals have an accuracy of 5 – 10%, we concluded that droplets concentration retrievals for effective radii smaller than 5 μm are of no value and should be omitted. This occurred for less than 10% of the selected single-layer stratocumulus cases.

4. Comparison With Cloudnet Observations

[12] Figure 2 presents time series of *LWP*, *h* and *Nc* values from SEVIRI, and *LWP* and *h* values from ground-based observations at Chilbolton for 5 days during the period May – August 2004. The selected days represent isolated cases of single-layered stratocumulus clouds with at least

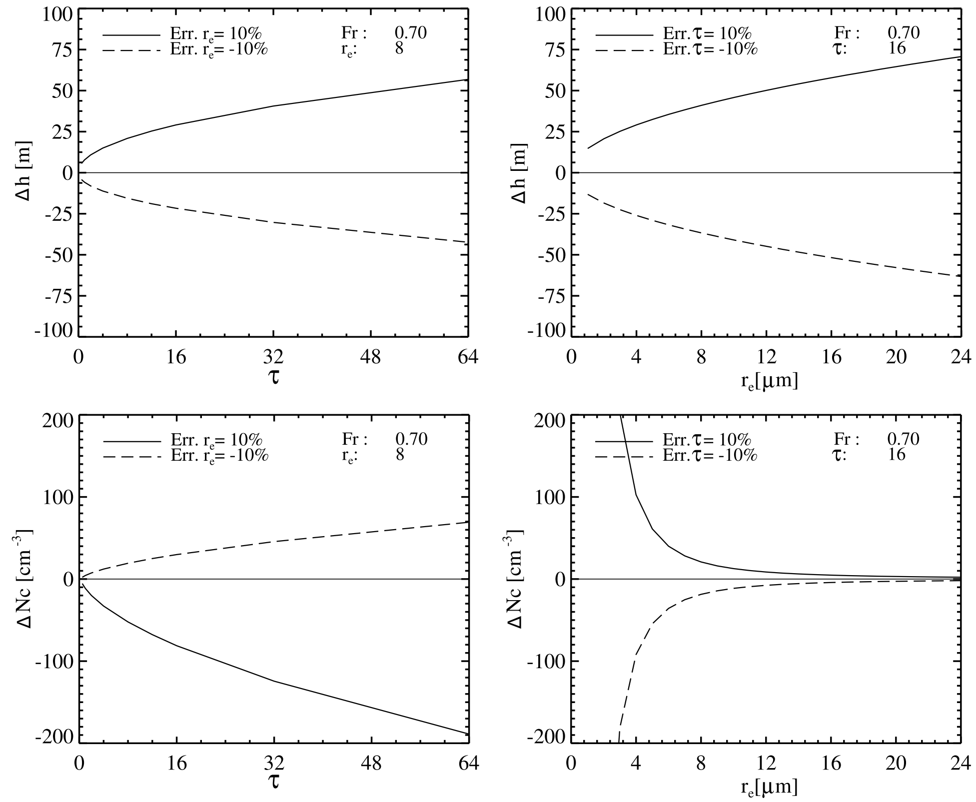

Figure 1. Sensitivity of h and Nc retrievals to r_e (8 μm ± 10%) as function of τ (left panel) and to τ (16 ± 10%) as function of r_e (right panel) for Fr = 0.7. The sensitivities are presented as deviations from the non-perturbed retrievals of h and Nc.

20 collocated and synchronized observations per day. The presence of these clouds was diagnosed from the Cloudnet target categorization data, which include information on the vertical distribution of water and ice clouds [*Illingworth et al.*, 2007]. The error bars on the *LWP*, *h* and *Nc* retrievals were calculated by setting random and normally distributed errors of ±10% on the τ and r_e values. Following the results of the sensitivity study, SEVIRI retrievals with effective radii smaller than 5 μm are rejected. Simultaneous comparison reveals that the *LWP* and *h* values exhibit similar variations, which vary between 20 and 500 g m^{-2} for *LWP* and between 200 and 800 m for *h* values. The gray shading in the Figure 2 indicates that the *LWP* and *h* retrievals from SEVIRI have relatively high precision, and fall for the majority of the observations within the uncertainty margins of the ground-based retrievals (error bars). The *Nc* values, which vary between 50 and 250 cm^{-3}, are similar to the *Nc* values measured during the ACE-2 campaign [*Pawlowska and Brenguier*, 2003]. Also notable in Figure 2 is the independence of changes in *Nc* values with respect to changes *LWP* and *h* values. This is indicted by the low correlations (<0.4) between the *Nc* and *LWP* or *h* values, while the correlation between *LWP* and *h* is very high (∼0.95). This independence suggests that the changes in *Nc* values result from external variables, such as the aerosol loading affecting the *Nc* values through the first indirect aerosol effect. The fact that the *Nc* values of 17 June 2004 are high when compared to 16 June 2004 suggests higher aerosol loadings on 17 than on 16 June. Part of the variations in SEVIRI retrieved *h* values is not explained, and may result from variations in the adiabatic fraction (*Fr*). The effect of *Fr* variations on the *h* retrievals is analyzed by determining the *Fr* value that gives the smallest difference between the *h* retrievals from SEVIRI and radar and lidar. From this analysis an optimum *Fr* of 0.72 ± 0.28 is found.

[13] Figure 3 presents the scatterplots of instantaneous and daily mean *LWP* retrievals from SEVIRI and MWR, and *h* retrievals from SEVIRI and radar and lidar. The dataset comprises 21 days during the period May – August 2004, with a total number of 462 collocated and synchronized observations at Chilbolton and Palaiseau. Only days with at least 6 observations of single-layered stratocumulus clouds with effective radii larger than 5 μm are considered. Table 1 lists the observed and retrieved cloud geometrical and microphysical properties of the instantaneous and daily datasets. The instantaneous retrievals from SEVIRI agree fairly well with the ground-based observations, with correlations of 0.78 for *LWP* and 0.63 for *h*. The agreement between ground-based and satellite retrievals improves significantly when daily mean values are considered instead of instantaneous values, with correlations of 0.91 for *LWP* and 0.90 for *h*. These results suggest that *h* and *Nc* retrievals from SEVIRI are suitable for future identification of polluted areas. Note, the retrieval is only valid for single-layered stratocumulus clouds. It requires accurate identification of these cloud types, to constrain the retrievals to adequate cloud cases. The latter has proven not to be easy from satellite.

5. Summary and Conclusions

[14] This paper has demonstrated, for the first time, the consistency between *LWP* and *h* retrievals from SEVIRI.

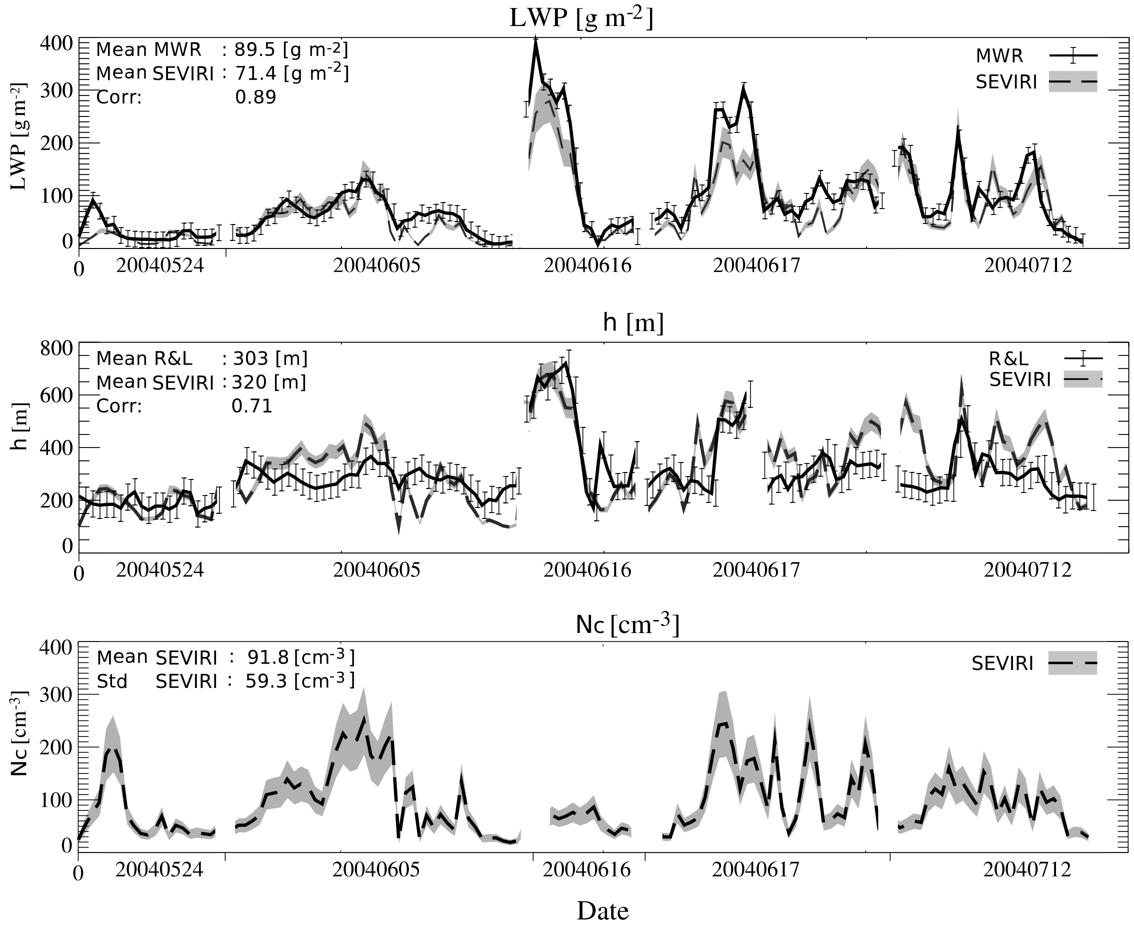

Figure 2. Time series of ground-based and SEVIRI retrieved *LWP* and *h* values and SEVIRI retrieved *Nc* values during five days with single-layer stratocumulus clouds over Chilbolton. The gray shading indicates the estimated range of uncertainty due to ±10% errors in τ and r_e presented in section 3, while the error bars indicate the retrieval errors of the ground-based *LWP* and *h* values.

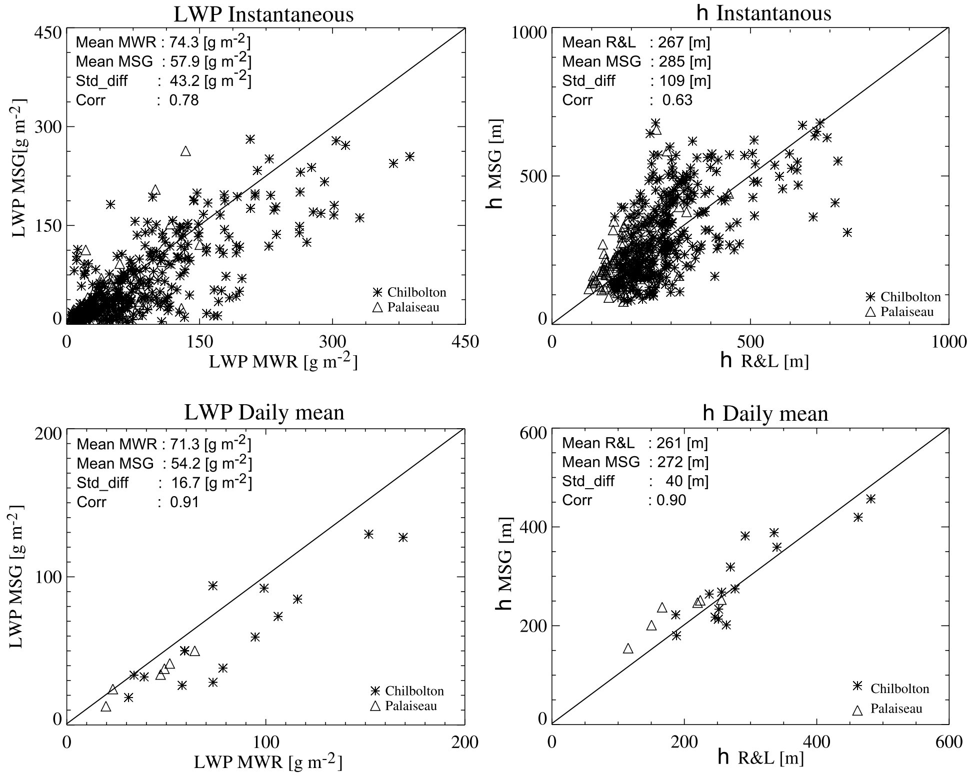

Figure 3. Scatterplot of instantaneous and daily mean *LWP* and *h* retrievals from SEVIRI and ground-based observations. The data points correspond to collocated and synchronized *LWP* and *h* retrievals at Chilbolton (squares) and Palaiseau (asterisk).

The simultaneous validation of satellite retrievals and ground-based observations provided a rigorous test which gave confidence in the *LWP*, *h* and *Nc* retrievals from SEVIRI.

[15] The sensitivity analysis of the sub-adiabatic cloud model suggests that reliable *h* simulations are feasible for τ values smaller than about 50, and reliable *Nc* simulations for effective radii larger than about 5 μm. For days with consistent single-layer stratocumulus clouds, very good agreement is found between ground-based and SEVIRI retrieved values of *LWP* and *h*, with correlations of 0.89 and 0.71, respectively. A notable finding is that the *Nc* values vary independently from the *LWP* and *h* values, which may indicate variations in sub-adiabatic fraction or aerosol loading during these days. It is shown that the sub-adiabatic cloud model can be used to estimate the degree of adiabaticity (Fr = 0.72), using simultaneously observed *LWP* and *h* values from the Cloudnet observations. For a large data set of single-layer stratocumulus clouds, *LWP* and *h* from SEVIRI are retrieved with high accuracies of about 15 g m^{-2} and about 20 m, respectively. Taking advantage of the high sampling resolution of SEVIRI, high precisions are found for the daily mean *LWP* (~20 g m^{-2}) and *h* (~40 m) values.

[16] To further improve our understanding of the first indirect aerosol effect requires simultaneous comparison of *LWP*, *h* and *Nc* values. This will be possible in the near-future when ground stations, such as Cabauw in the Netherlands, take measurements of these three cloud properties. The high consistency of *LWP* and *h* retrievals with ground-based observations suggests that SEVIRI may be used to study the first indirect aerosol effect from space.

Table 1. Statistics of the Ground-Based and SEVIRI Retrieved *LWP* and *h* Values and SEVIRI Retrieved *Nc* Values for the Instantaneous and Daily Results[a]

	Instantaneous Values					Daily Values				
	LWP MWR	LWP SEVIRI	h R&L	h SEVIRI	Nc SEVIRI	LWP MWR	LWP SEVIRI	h R&L	h SEVIRI	Nc SEVIRI
Unit	g m^{-2}	g m^{-2}	m	m	cm^{-3}	g m^{-2}	g m^{-2}	m	m	cm^{-3}
Nr. obs.	462	462	462	462	462	21	21	21	21	21
Mean	74.3	57.9	266.7	284.6	97.6	71.3	54.2	260.6	252.0	93.4
Median	56.2	35.0	247.0	251.3	71.2	59.3	41.5	273.5	251.5	78.9
Std_diff	42.4	42.4	109.6	109.6		16.7	16.7	39.9	39.9	
Corr	0.78	0.78	0.63	0.63		0.91	0.91	0.90	0.90	

[a] Statistics given are number of observations, mean and median. The standard deviation of the differences (Std_diff) and correlation (Corr.) represent the relationship between ground-based and SEVIRI values.

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