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Article

Characterization of low clouds with satellite and ground-based remote sensing systems

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Abstract

Satellite and ground-based retrievals of a number of (low) cloud characteristics are compared in this paper in order to assess the performance of the techniques and identify potential synergies. Centred on the COST720 International Comparison Campaign for Temperature, hUmidity and Cloud profiling (TUC), four cases with different meteorological situations are analysed in detail. Parameter agreement (for cloud presence, liquid water path, cloud geometrical thickness and cloud top temperature) is good in general. It is shown that satellite retrievals of liquid water path and cloud thickness could be improved using liquid water content derived from ground-based measurements, while ground-based retrievals can profit from the spatial component in satellite data. Taken together, the combination of instruments and techniques presented in this paper allows for a detailed assessment of complex cloudy atmospheres.

Zusammenfassung

Dieser Artikel vergleicht satellitengestützt und auf Basis von Bodenmessungen ermittelte Eigenschaften von niedrigen Wolken mit den Zielen, die Methoden auszuwerten und potenzielle Synergien zu indentifizieren. Rund um die TUC-Vergleichskampagne (International Comparison Campaign for Temperature, hUmidity and Cloud profiling) der COST-Aktion 720 werden vier Fallstudien mit verschiedenen meteorologischen Lagen detailliert untersucht. Wie gezeigt werden kann, stimmen die erfassten Parameter (Wolkenbedeckung, Flüssigwasserpfad, Wolkendicke, Wolkentemperatur) generell gut überein. Es zeigt sich allerdings, dass Satellitenretrievals des Flüssigwasserpfades und der Wolkendicke durch Heranziehung von Flüssigwassergehaltsinformationen aus Bodenmessungen verbessert werden könnten. Bodenbasierte Methoden wiederum finden in der räumlichen Komponente der Satellitendaten eine sinnvolle Ergänzung. Zusammengenommen ist auf Basis der hier präsentierten Kombination von Instrumenten und Techniken eine detaillierte Erfassung komplexer atmosphärischer Wolkensituationen möglich.

1 Introduction

Clouds and their interactions with radiation have been identified in the Third Assessment Report of the Intergovernmental Panel on Climate Change as “probably [the source of] the greatest uncertainty in future projections of climate” (IPCC, 2001). The physics of cloud and radiation interaction is known to be incompletely described in models. For instance, significant discrepancies have been reported between observations of short-wave radiation absorption in clouds and matching 3D model simulations (O’HIROK and GAUTIER, 2003). In addition, changes especially in low cloud coverage and type are expected due to temperature change and aerosol indirect effect, but these changes are also not understood well enough for precise predictions to be made. A comprehensive review of known uncertainties is given by STEPHENS (2005).

Improving the knowledge of cloud and radiation interaction requires the analysis of simultaneously observed radiation and cloud characteristics. While observation of radiation by both satellite and ground-based systems is relatively satisfactory, determination of cloud properties is incomplete, and still suffers from large uncertainties. Intercomparison campaigns where many systems are used in parallel for determining cloud properties offer the opportunity to identify shortcomings in cloud observing systems, determine synergies between such systems and propose solutions for improving cloud characterization. The present paper intends to accomplish such objectives by comparing satellite and ground-based remote sensing systems. The paper lays no claim to completeness, but rather aims at considering a set of

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cases, focusing on selected cloud properties. It lays a particular focus on low clouds, including fog, as these present a particular challenge, especially for satellite observations (BENDIX et al., 2005).

The intercomparison presented in this paper is based on data collected during the COST720 International Comparison Campaign for Temperature, hUmidity and Cloud profiling (TUC). This campaign took place in Payerne, Switzerland from November 2003 to February 2004. A wide range of well-established and new instruments for measuring the state of the lower atmosphere were operated in parallel during this period. In addition to ground-based measurements, satellite retrievals of cloud parameters were run for the campaign location. A more detailed description of the TUC campaign can be found in RUFFIEUX et al. (2006).

A brief outline of the instruments and algorithms is given in section 2 of the article. Section 3 explores a selection of case studies in more detail and compares some cloud parameters retrieved by the different techniques. Finally, the results are discussed in the light of individual instrument performance and potentials for instrument combinations.

2 Instruments and algorithms

2.1 Ground-based techniques

2.1.1 Routine observations

A wide range of measurements are undertaken routinely at the Payerne aerological station (RUFFIEUX et al., 2006). With respect to the objectives of this paper, synoptic observations and ceilometer measurements are of special interest.

Human eye observations of cloud layers, cover, type, base height and ground visibility are made eight times a day. One disadvantage is that in case of presence of a low cloud cover, only one cloud layer can be seen. These observations are sometimes subjective and may vary from one observer to another. Nevertheless, the synoptic observations give regular and important information about the state of the sky, the meteorological conditions (fog, snow, rain etc.) and the visibility (MÜLLER, 1982).

A Vaisala ceilometer CT25K measures cloud base height at a resolution of 15 m. It uses the reflection of light (backscatter) caused by haze, fog, mist, virga, precipitation and clouds from 905 nm laser pulses aimed vertically at the sky. Base height estimates for up to three cloud layers are computed from the backscatter profile (VAISALA GROUP, 2001). Measurements can be erroneous in the presence of fog or other very low clouds. Cirrus clouds are rarely detected, because the instrument can detect clouds only up to 7620 m above ground. In this study, only base height estimates for the lowest cloud layer are considered. The temporal resolution of the measurements is 30 s, averaged on a 15 minute time grid.

2.1.2 ASMUWARA microwave radiometer

The Microwave Radiometer ASMUWARA (All Sky MUlti WAvelength RAdiometer) (MARTIN et al., 2006a) is used to measure the Liquid Water Path (LWP) as well as humidity and temperature profiles. These profiles are needed for radiative transfer calculations of outgoing infrared radiation (see section 2.1.4). In addition, an infrared transducer measures the infrared brightness temperature integrated over the wavelength range of 8–14 μm. If the cloud is sufficiently thick (LWP >0.03 kg m^{-2} (BLOEMINK et al., 1999)), this instrument provides an estimate of the cloud base temperature.

Measurements in zenith direction were available approx. every 100 s. For the satellite comparisons, they were averaged on a quarter hour time grid.

A linear algorithm invoking the measured opacities at 23.6 GHz and 31.5 GHz is applied for the retrieval of the LWP. Temperature and water vapour profiles are also retrieved (MARTIN et al., 2006b).

2.1.3 Cloud radar

A 78.2 GHz frequency-modulated continuous wave (FMCW) radar designed at the Rutherford Appleton Laboratory (cf. RUFFIEUX et al., 2006) is used for the measurement of cloud top. For the purpose of this study, we define cloud top as the height where radar signal intensity drops significantly (VENEMA, 2000). As a first step, high frequency spatial signal variations are eliminated to smooth the radar reflectivity height profile. The gradient of the smoothed signal indicates signal changes; the most negative gradient is taken as the cloud top. This algorithm can only be applied when the ceilometer has already detected a cloud; otherwise, empirically determined thresholds must be applied.

Liquid Water Content (LWC) profiles are retrieved using the Frisch Algorithm (FRISCH et al., 1998), which weighs the LWP with the reflected radar intensity profile.

Reflectivity profiles are produced with a temporal resolution of one second and are averaged like the measurements of the instruments described above.

2.1.4 MODTRAN calculations of the outgoing infrared radiation

The MODTRAN 4 (ABREU and ANDERSON, 1996) radiative transfer model is used to calculate the infrared brightness temperature as received by the satellite when clouds are present. We used a frequency range of 862–1000 cm^{-1} with a spectral resolution of 1 cm^{-1}. A virtual blackbody at the height and the temperature of

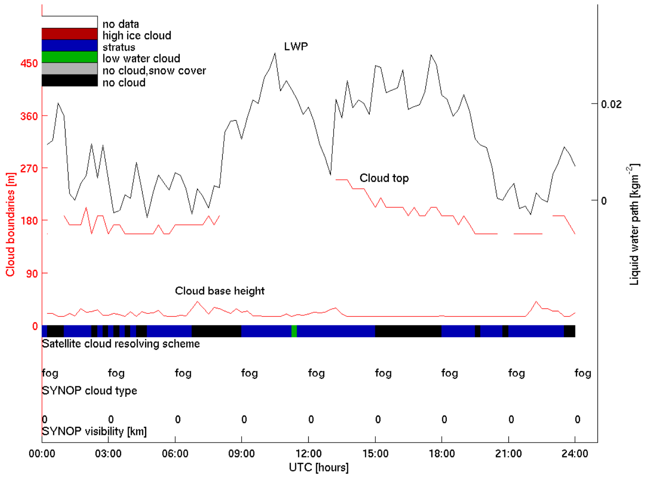

Figure 1: Various cloud parameters for 20 November 2003. Description see text.

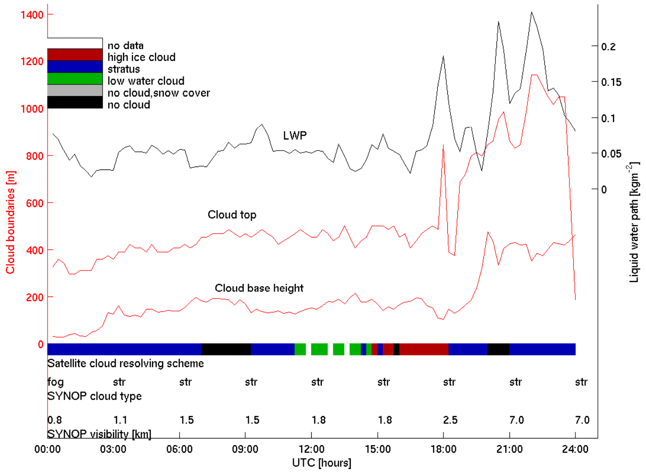

Figure 2: Various cloud parameters for 6 December 2003. Description see text.

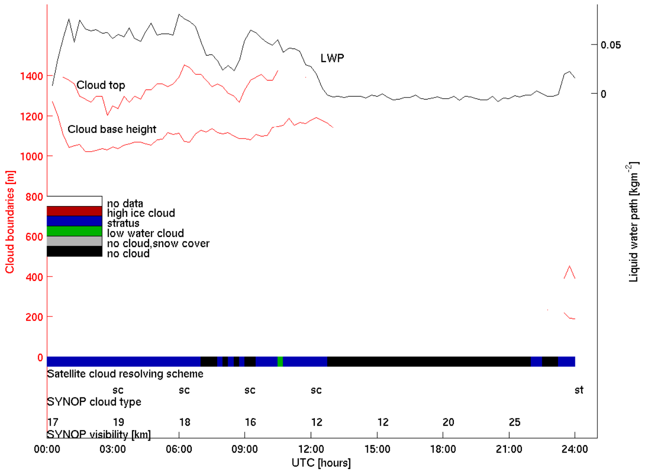

Figure 3: Various cloud parameters for 8 December 2003. Description see text.

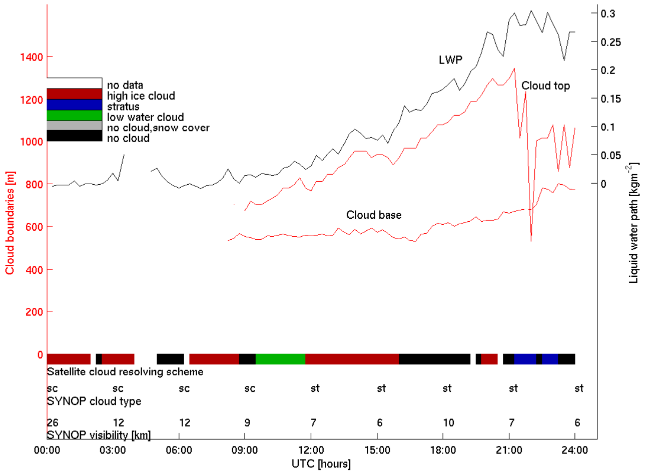

Figure 4: Various cloud parameters for 30 December 2003. Description see text.

the cloud top serves as a background. The model atmosphere needed for the radiative transfer is a combination of the temperature and humidity profiles measured with ASMUWARA at low altitudes and time-interpolated radiosonde profiles at higher altitude levels. In the stratosphere, MODTRAN's standard stratospheric background model is used. The pressure profile is determined from ground measurements as described in MARTIN et al. (2006b). Since the wavelength range of the satellite receiver does not interfere with the ozone band, standard ozone values of the stratospheric extinction model can be used. The zenith angle for the propagation path is set to 50°.

2.2 Cloud retrieval from satellite data

In parallel to the ground-based measurements, cloud properties over the campaign site were monitored on the basis of multi-spectral satellite data. The algorithms implemented at the Laboratory for Climatology and Remote Sensing (LCRS) make use of data collected by the Spinning Enhanced Visible and Infrared Imager (SEVIRI) aboard Meteosat Second Generation (MSG) 1, now known as Meteosat 8. At 15 minutes, the imager's repeat cycle is very well suited to nowcasting applications, and a nominal spatial resolution of 3 km provides useful regional detail (for MSG cf. SCHMETZ et al., 2002). All algorithms used in this intercomparison are either new developments or have been newly ported to MSG.

The satellite cloud retrieval scheme implemented on MSG SEVIRI consists of two major components: a cloud classification algorithm and a retrieval of cloud optical and microphysical properties. These algorithms are applied consecutively in operational processing of satellite data at LCRS.

Originally developed for fog detection, the main purpose of the cloud classification is to obtain information on cloud phase, altitude and type. The scheme consists of a series of picture-element (pixel)-based and object-oriented components. Initially, cloudy pixels are separated from clear pixels. Based on this initial mask, cloud phase and altitude are assessed using spectral information. For a cloud type decision, spatial information, such as cloud entity height and homogeneity is used in addition. For a description of the classification approach see CERMAK et al. (2004).

Based on the cloud contamination and phase determined in the preceding step, cloud optical depth and droplet effective radius are retrieved. The scheme applied to this end makes use of the strong dependence of near infrared radiances on droplet size and visible channel radiances on optical depth. The scheme developed by KAWAMOTO et al. (2001) (based on NAKAJIMA and NAKAJIMA, 1995) makes use of lookup tables derived from radiative transfer calculations. The algorithm has recently been ported to MSG SEVIRI (NAUSS et al., 2004). Cloud thickness and liquid water path are retrieved based on parameterizations using cloud optical depth at 0.6 μm. Based on empirically derived relations, MINNIS et al. (1992) and later, HEIDINGER and STEPHENS (2000) parameterized the thickness of a cloud:

$$\Delta z = 45\tau^{2/3} \tag{2.1}$$

with Δz the cloud thickness [m] and τ the optical depth (HEIDINGER and STEPHENS, 2000, for water clouds with $4 \leq \tau \leq 40$). In a similar fashion, cloud liquid water path can be determined from τ (KRIEBEL, 1989, STEPHENS, 1978):

$$W = \frac{10^{(0.5454\tau)^{0.254}}}{1000} \tag{2.2}$$

where W is the cloud liquid water path [kg m^{-2}]. Both parameterizations have been successfully applied to satellite data (BENDIX, 1995; BENDIX et al., 2005). As both techniques rely on 0.6 μm data, they can only be applied at daytime (solar zenith angle <80°).

3 Intercomparison and results

3.1 Approach

While one of the most important advantages of satellite measurements is the spatial component of the information, comparison of results with ground-based point measurements can be difficult. Most importantly, the following potential issues need to be considered:

- Co-location. While the geocorrection of MSG is stable on the whole, slight deviations may be encountered in individual scenes. This effects that the point sought for comparison may be in a pixel other than the one expected. Moreover, the angle of observation plays a crucial role: For Payerne, the satellite zenith (observation) angle is about 55 degrees. At this slope, the vertical profile of the atmosphere above the campaign station does not necessarily correspond to the tilted atmospheric column observed from the satellite over the same location.

- Subpixel effects. The nominal size of an MSG pixel is 3 by 3 km, with a somewhat larger actual extent over Europe. A pixel of this size may contain more than one set of cloud features. The radiance values observed from the satellite are mean values in these cases.

In order to compensate for these issues, it is customary to not only compare the precise pixel determined to be located at the point of interest. Instead, one also considers the surrounding pixels, taking their mode or mean observations into account. We have taken this approach in the present paper, using a 3 by 3 pixel matrix around Payerne for intercomparison. In comparison charts, the standard deviation from the 3 by 3 pixel mean is indicated using error bars.

3.2 Data selection

From the TUC campaign data, a set of four days were selected for detailed analysis: 20 November, 6, 8 and 30 December 2003. These days were chosen because they a) represent different meteorological situations of interest, and b) good quality data were available from the instruments. A detailed description of these days is given in section 3.3.1. Due to the short duration of the campaign and the limited number of suitable low cloud situations available, a large-scale numerical intercomparison did not seem appropriate. Also, as the greater part of the TUC campaign fell into the commissioning phase of MSG, much of the data collected during this period could not be used due to quality constraints. Therefore, a careful selection of days was necessary.

3.3 Intercomparison results

3.3.1 Cloud presence and type

For the assessment of cloud presence, space in both horizontal and vertical directions becomes of great importance to the intercomparison. On the whole, cloud cover and type are detected reliably by the satellite technique during daytime. At night and especially in twilight conditions only selected cloud types are implemented in the satellite algorithm, so that not all clouds are detected by design.

Figures 1 to 4 juxtapose selected atmospheric and cloud properties for the case study days. 20 November 2003 is an example of a consistent fog situation throughout the day. Cloud base heights retrieved from ceilometer measurements are misleading as visibility is impaired

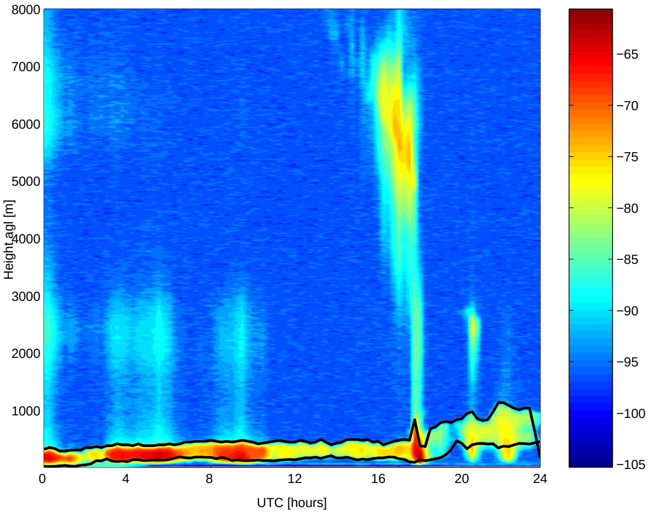

Figure 5: Radar reflectivity [dB] for 6 December 2003. Cloud base retrieved from ceilometer measurements and cloud top extracted from radar data are indicated by the black lines.

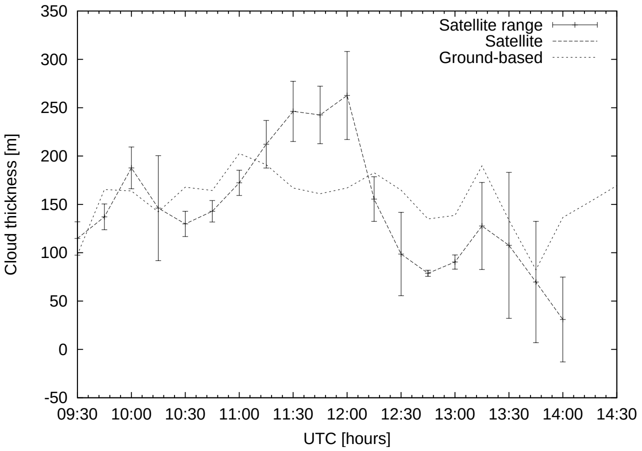

Figure 6: Cloud thickness values retrieved from satellite and ground-based instrumentation for 6 December 2003.

at all times. Liquid water path is higher during the day, cloud top is constant. On 6 December, fog is observed very early in the morning, followed by low cloud persisting over the day, with higher clouds above in the afternoon. In the evening there is some rain, with increased LWP and cloud height. On 8 December, the dissipation of a low stratus cloud can be observed. LWP drops to zero, cloud top and cloud base can no longer be identified. Only late at night another low stratus cloud forms. On 30 December, a stratus cloud increases in thickness and there is rain later in the day. Higher clouds are present above this stratus over the second half of the day.

3.3.2 Cloud thickness

Information on cloud thickness was obtained by subtracting ceilometer cloud base height from cloud radar cloud top height. This principle is presented schematically in Figure 5.

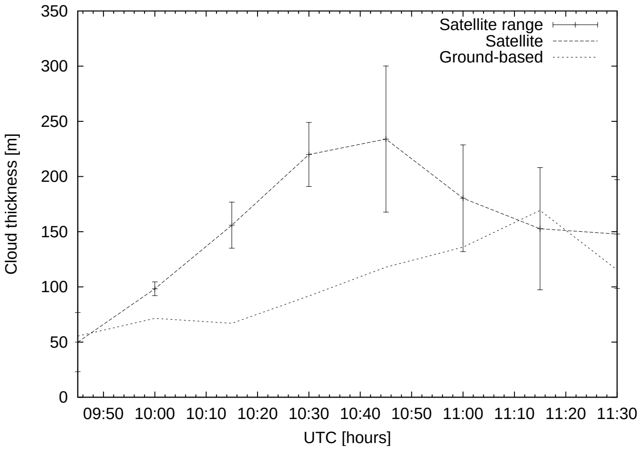

Figure 7: Cloud thickness values retrieved from satellite and ground-based instrumentation for 30 December 2003.

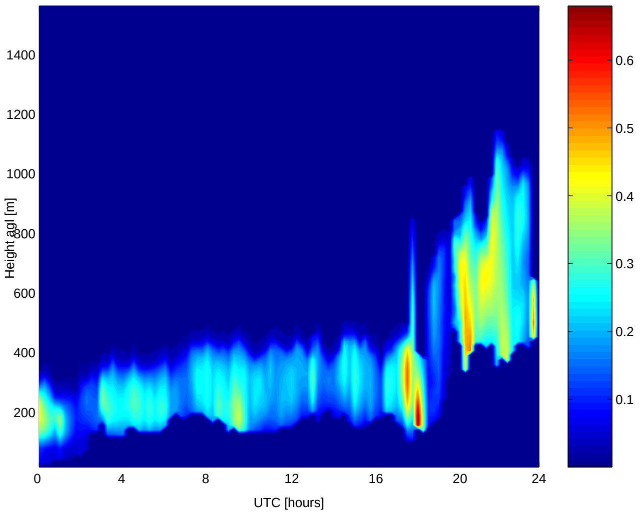

Figure 8: Cloud liquid water content [g m^{-3}] profiles retrieved using the Frisch algorithm for 6 December 2003.

On two of the test days cloud thickness retrieval in this way failed: On 20 November, cloud radar data were incomplete. On 8 December, no distinct cloud top was obtained from radar data in a cloud dissipation situation. LWC was too low, and no clear threshold could be found in the weak gradient. This highlights difficulties of cloud top height retrieval from radar measurements for dissipating clouds.

Comparisons with satellite data for the other two days show reasonable agreement. Figure 6 exemplarily shows cloud thickness values retrieved from satellite and ground-based instrumentation for 6 December 2003, Figure 7 for 30 December. The satellite data is presented as a 3 by 3 pixel mean.

It can be observed that while overall both curves show reasonable agreement, they diverge after 1330 UTC. On 30 December, divergences are a bit larger, with good agreement before 1015 and after 1100 UTC. Maximum divergences occur in two situations: when liquid water content is especially low throughout the cloud profile (see Figures 8 and 9) and just before higher cloud layers move in. This insight points to two possible sources of error: In ground-based thickness retrievals, cloud boundaries and especially cloud tops may be more difficult to identify in low water content situations (LWP $< 0.03\,\mathrm{kg\ m^{-2}}$). This explanation holds for 30 December. Secondly, the large standard deviation in satellite-derived cloud thickness from around 1330 UTC on 6 December is an indication of spatial inhomogeneities. While the low stratus layer is still observed at the campaign site, high ice clouds are moving in from the northwest (see Figure 10). For ice clouds, no thickness is computed so that mean values in a 3 by 3 pixel environment drop. Later, the entire area is covered by cirrus: thickness values are no longer available.

3.3.3 Cloud liquid water path

Liquid water path figures derived from satellite and ground data are similar over significant stretches. While at some times the values retrieved are remarkably close to each other (e.g. 1100 to 1215 UTC, 8 December, Figure 11), they diverge markedly at other times. Similar patterns can be seen on the other case days (not shown). The key to understanding this behaviour may be found in the way these values are computed: For the satellite, the LWP model represents a standardised water cloud, which results in some inaccuracies. ASMUWARA retrievals of LWP however make use of two wavelengths and therefore include some implicit information on the actual profile. Indeed, when taking a closer look at the patterns behind LWP disagreement, it appears that satellite LWP remains below ASMUWARA LWP whenever LWC profiles reveal a pronounced imhomogeneity in water distribution, i.e. large increases in LWC below the cloud top. This effect is especially strong in situations with rainfall, with larger LWC in the lower part of the cloud (e.g. drizzle around 0900 UTC in Figure 8). For this reason, there is a great potential for using cloud LWC profiles derived from ground measurements in refining satellite retrievals of cloud LWP.

3.3.4 Cloud top brightness temperature

A comparison between cloud top brightness temperatures measured at the satellite (10.8 μm channel) and those modelled with MODTRAN based on atmospheric profiles retrieved from ASMUWARA and soundings was done. Two situations occur: for a large number of cases, the agreement between the satellite-measured and the modelled temperature is satisfactory, but for satellite-measured temperature in the range between 230 and 260 K the modelled temperature is much higher (left-side of Figure 12). This observation can easily be attributed to the fact that the model approach considers the lowermost cloud top (cf. Figure 5), while the brightness temperature measured by the satellite may originate from a higher cloud storey. In these cases satellite-measured brightness temperature will naturally be lower.

This disagreement illustrates the difficulties involved in observing multiple cloud layers from one individual instrument. While ground-based retrievals will often not accurately represent clouds above the lowest layer, these lower clouds hidden under a higher layer are invisible from the satellite point of view. At the same time this highlights the potential inherent to the combined analysis of both types of data.

Divergences between modelled and measured cloud top brightness temperatures are also closely linked to the definition of a cloud top. Depending on cloud opacity, the signal received by the satellite may represent varying depths of a cloud. As cloud radar cloud top is identified along a reflectivity gradient, with a certain degree of uncertainty inherent, cloud top temperature retrieval can easily be inaccurate as well (see RUFFIEUX et al., 2006 for temperature profile discussion).

4 Conclusions and outlook

The intercomparisons presented in the previous section have shown agreement and divergences in cloud parameters retrieved from a range of instrumentation. A qualitative assessment of these results allows for conclusions regarding useful instrument combinations and directions to be pursued in future research and development.

Due to different views on the atmosphere, meteorological situations with multiple cloud layers can be described very adequately with a combination of ground-based and satellite instrumentation. In these situations, higher level clouds are registered by the satellite, while an underlying cloud layer can be observed from the ground.

When looking at single-layer low cloud situations however, the most prominent synergy potential between satellite and ground measurements is a combination of high vertical (ground-based) and high horizontal (satellite) coverage in space. As opposed to point measurements, cloud characteristics can be derived for large areas from satellite measurements. The intercomparisons have shown that cloud parameters retrieved from satellite data on the whole compare well to ground-based retrievals. So, in general, a spatially oriented assessment of these properties is possible on the basis of satellite data. However, the inclusion of some liquid water profile information would very likely improve satellite-based

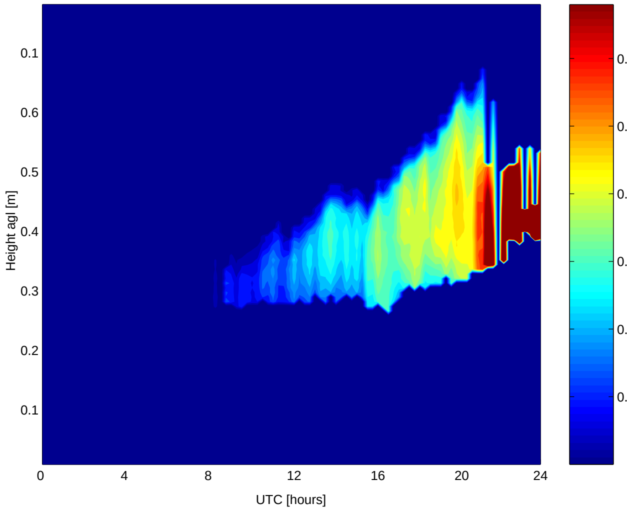

Figure 9: Cloud liquid water content [g m^{-3}] profiles retrieved using the Frisch algorithm for 30 December 2003

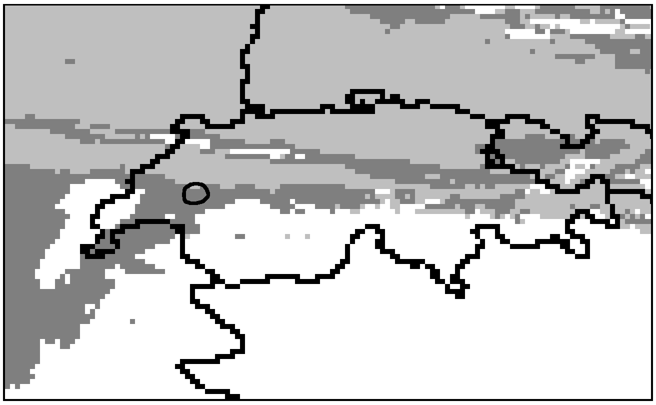

Figure 10: Cloud distribution over Switzerland derived from satellite data, 6 December 2003, 1415 UTC. White: no clouds, light grey: high ice clouds, dark grey: low water clouds. Country borders are given in black, the black circle indicates the approximate location of the campaign site.

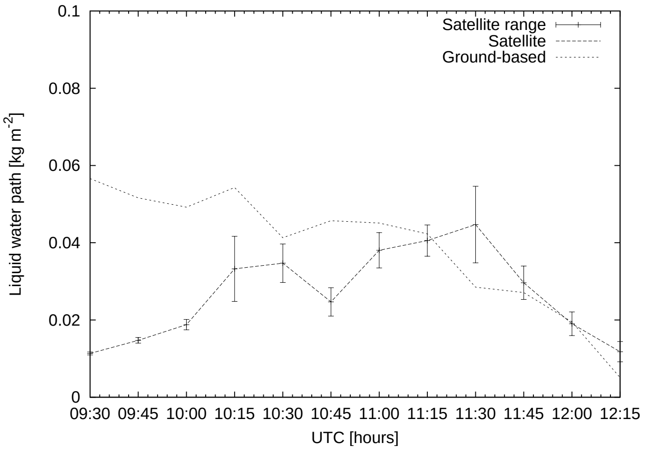

Figure 11: Cloud liquid water path retrieved from satellite and ground-based instrumentation for 8 December 2003.

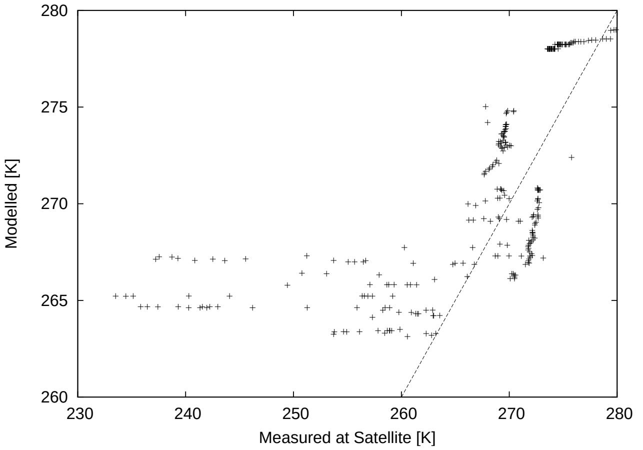

Figure 12: 10.8 μm brightness temperature registered at the satellite and modelled for four days with identity line.

retrievals of liquid water path (see above). One possible source for profile information of this sort is LWC derived from ASMUWARA and cloud radar data. The inclusion, and possibly extrapolation, of this parameter would benefit the quality of the satellite products and might allow for a more precise assessment of cloud LWP in space. On the other hand, satellite-derived cloud thickness may be used to determine cloud top height where cloud radar reflectivity gradients are too weak.

The inclusion of microphysical information retrieved from ground measurements in the satellite algorithms presented is a matter for further research. But even at the present state the paper has shown that a combination of ground-based and satellite retrievals of cloud characteristics may be of great benefit for operational forecasting. A combined view of this sort allows for a much more precise assessment of complex cloudy atmospheric situations than any unidirectional view would. The applicability of the individual techniques and the potential for combination with application to low clouds has been demonstrated in this paper.

This study has highlighted that ground-based retrievals and satellite products can be combined in various fashions. Hence, ground-based retrievals of cloud properties can contribute significantly to the training of satellite algorithms, especially concerning low cloud geometry (cf. BENDIX et al., 2005). For these purposes it would hence be very useful to have instrumental combinations similar to the one used in this paper available operationally at a number of stations.

Acknowledgements

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