Cloud statistics and NWP-model validation based on long term measurements of a 35 GHz radar

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1 Introduction

Clouds have an important impact on the earth radiation budget and are strongly linked to the hydrological cycle. The simulation of their spatial and temporal distribution is still one of the big challenges for numerical weather prediction (NWP) and climate models (e.g. Stephens, 2005). Studies to improve the parametrization of clouds in models require more information about the real cloud distribution as well as about their microphysical properties. In general these cannot be provided by classical observation methods. During the last two decades millimeter-wave radars (often named as cloud radars) have been established as valuable systems for remote sensing of cloud structures and processes (Kropfli and Kelly, 1996; Kollias et al., 2007a). The main advantage compared to optical systems is the property of microwaves to penetrate clouds in their complete vertical extension and thus to provide information from inside the clouds even if they are optically very thick.

That means also the cloud top can be derived from radar measurements. By continuous operation of a radar, a new type of cloud statistics can be provided and used for improving our understanding about cloud behaviour in particular with the purpose to validate NWP and climate models (e.g. Mace et al., 1998; Hogan et al., 2009; Bouniol et al., 2010; Illingworth et al., 2007; Henderson and Pincus, 2009).

Since November 2003 the Lindenberg observatory is continuously operating a 35.5 GHz coherent and polarimetric Doppler radar to measure vertical profiles of reflectivity, velocity, spectral width and the Linear Depolarization Ratio (LDR) between 250 m and 15 km height. By combination with a co-located laser ceilometer a homogeneous data set of macroscopical cloud parameters has been created and used for model validations.

Section 2 starts with a short description of the radar hardware, parameter settings and data processing. In the next section time series of cloud cover are compared to human expert observations and to NWP model simulations of the German Meteorological Service (DWD), both for the global and limited area scale. Section 4 goes more into the detail of radar - model comparison to find out the reasons for differences.

2 System and data base

2.1 Radar Hardware

The radar MIRA36 is designed for long term measurements and is equipped with a magnetron transmitter to provide RF pulses with a maximum power of 30 kW. The radar has a vertically pointed cassegrain antenna with a polarization filter, two receivers for simultaneously receiving of co- and cross-polarized signals and a computer including a

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DSP board for data acquisition and processing. For diagnostic and control purposes the most important system parameters are measured and stored by the radar PC. In February 2010 the radar was equipped with a higher gain antenna and a digital receiver which lead to an increase of sensitivity by about 4 dB to -55 dBz in 5 km for 10 s averaging time. Due to the high transmitting power it is unnecessary to use pulse compression to achieve a sufficient high sensitifity. Some technical details and parameter settings are given in Table 1.

	MIRA36
Frequency	35.5 GHz
Peak Power	30 kW
Noise figure	3.5 dB (6.3 dB)
Antenna type	Cassegrain with polarization filter
Antenna diameter	1.9 m (1.0 m)
Antenna gain	53 dBi (49 dBi)
Beam width	0.4 ° (0.55°)
Pulse width	200 ns
Vertical resolution	30 m
Pulse repetition frequency	5 kHz
FFT-Length	256
Min. measuring height	240 m
Max. measuring height	15 km (12 km)
Averaging time	10 sec
Sensitivity at 5 km (10 sec)	-55 dBz (-50.3 dBz)

Table 1: Technical characteristics of MIRA36. The values in the parentheses are parameters before the system upgrade in February 2010.

To estimate changes in the radar calibration, transmit power and receiver noise figure are continuously monitored, the latter by means of a noise diode. Gains and losses of individual RF components are taken into account for the estimation of reflectivity. Comparisons against reflectivities of a similar cloud radar (see Görsdorf and Handwerker, 2006) or versus a micro rain radar yield mean differences between the system of less than 2 dB, which was confirmed by a comparison against the cloudsat radar (Protat et al., 2009).

The reliability of the system is high, with a mean annual data availability varying between 88 % and 99 % during the last seven years.

2.2 Data base

The main data used in this study are the 10 s vertical profiles of radar Doppler moments and the Linear De-polarization Ratio (LDR) from April 2004 until December 2010. Caused by the dependency of the reflectivity from the sixth power of droplet (particle) diameter, the radar is not only detecting cloud particles (high number concentration) but also rain as well as insects and aerosol (particularly occurring in the boundary layer and named sometime as atmospheric plankton). A target separation has been achieved by combining radar and ceilometer (Vaisala LD40) measurements.

The detection rate of clouds depends essentially on the radar sensitivity, which decreases by $1/r^2$. At lower levels (approx. $r < 1000$ m) the near field characteristic of the antenna causes a loss of sensitivity. That means that especially low level clouds with small droplets (e.g. Cumulus humilis, Stratus) and high level ice clouds may not be detected by the radar. All cases where the radar did not detect a cloud below 3 km while the ceilometer has clearly indicated a cloud were excluded from the analysis.

The horizontal distribution of clouds can not be obtained from an individual radar measurement as it is the case for human expert observations or the forecasts of numerical models. Assuming the Taylor hypotheses of frozen turbulence, the horizontal cloud distribution can be derived from the temporal development. An integration time of 1 hour has been chosen in accordance with the time steps of observations and model predictions. An adaptation of integration time to the horizontal wind speed would of course be more precise, but will lead to very similar results as found by Hogan et al. (2009) and was therefore not applied.

For comparison and validation purposes human expert observations (referred as synoptic observation in the following) and predicted values from the three numerical models of the German Weather Service have been used. The synoptic observations are available as hourly estimates of the cloud cover at the Lindenberg weather station for the entire period. The values are given in octa for the total cloudiness and for the low, middle and high level.

The models are the GME for the global scale (grid spacing Δs= 40 km, 40 layers, time step Δt= 1 hour (Martin/Axel: ist das korrekt?)), the COSMO-EU (Δs= 7 km, 40 layers, Δt= 1 hour)

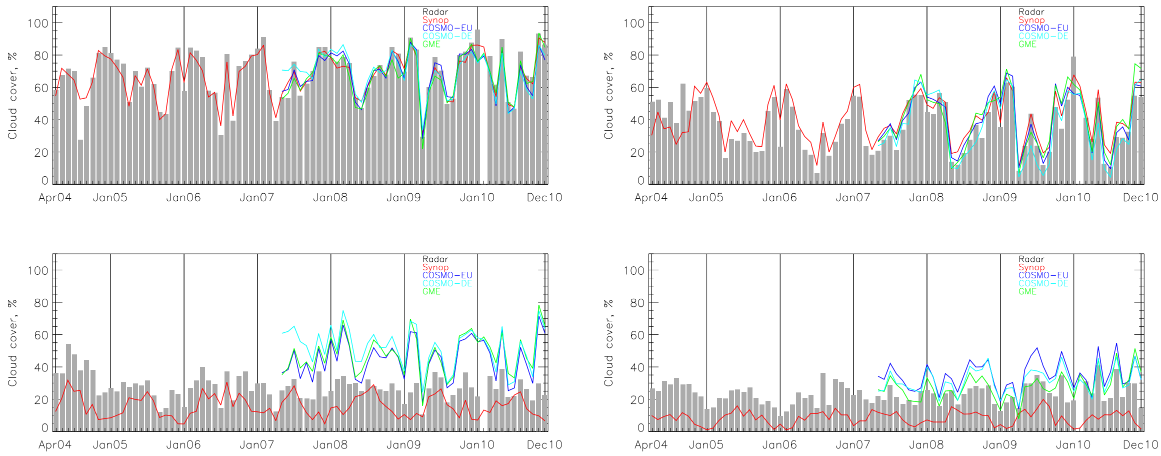

Figure 1: Time series of cloud cover derived from radar/ceilometer measurements, provided by the local observer (synop), and predicted by the three NWP-models of the DWD. Upper left: total cloud cover, Upper right: loud cover for low level clouds, bottom left: middle level clouds, bottom right: high level clouds

and COSMO-DE (Δs = 2.8, 50 layers, Δt= 0.25 hour) for a limited area. The cloud cover is given as total value and for the three levels low (<800 hPa), middle (800 - 700 hPa) and high (> 700 hPa). The 12 - 24 hour forecasts at the both runs 00 and 12 UTC period were used for the GME and the COSMO-EU, the 6 - 12 hour forecasts at the 6 hourly runs for the COSMO-DE. More details about the models can be found in (Reference?). Model values are available from May 2007 (Martin: Du nanntest mir diese Zahlen, gibt's dafür eine Begründung? spin up time?).

3 Time series of cloud cover

Corresponding to the cloud classification scheme applied by Kollias et al. (2007b) monthly averages of the cloud cover cc have been calculated for low (cloud base $h_b < 2$ km) , middle ($2km \leq h_b < 6km$ and high level clouds ($h_b \geq 6km$) as well as for all clouds (total cloud coverage).

As can be seen in Figure 1, the total cloud cover at Lindenberg shows a significant annual cycle with a maximum in winter and a minimum in summer, which is mainly caused by the cycle of low clouds. In February 2010 the radar was not in operation for a system upgrade and therefore no cloud coverage could be derived. The amount of high and middle level clouds is significantly lower than for low level clouds and also the variability over the year is much smaller. High level clouds have a weak minimum in winter and a maximum in summer, whereas for middle level clouds no clear annual cycle can be recognized. The red line shows the monthly mean of cloud cover hourly estimated by the local observer at the Lindenberg weather station (synoptic). The rather good agreement ($\Delta cc < 1.5\%$) for the total and low level clouds - at least in the monthly means - is surprising, when the total different observing strategies are recognized. It is also an indication that the Taylor hypothesis is apparently a valid assumption for deriving cloud cover from pointlike radar measurements. High and middle level clouds are strongly underestimated by synoptic observations, which is a logical consequence, since higher clouds are often hidden by the low clouds. Therefore, the observer estimated annual cycle of middle and high clouds is opposite to them of low clouds.

A similar good agreement can be found between radar observations and model predicted cloud cover for the total cloud cover and them for low clouds. The mean differences are smaller than 3%. Only COSMO-DE underestimates low level clouds by about 6% compared to the radar measurements. At middle and higher levels the models overesti-

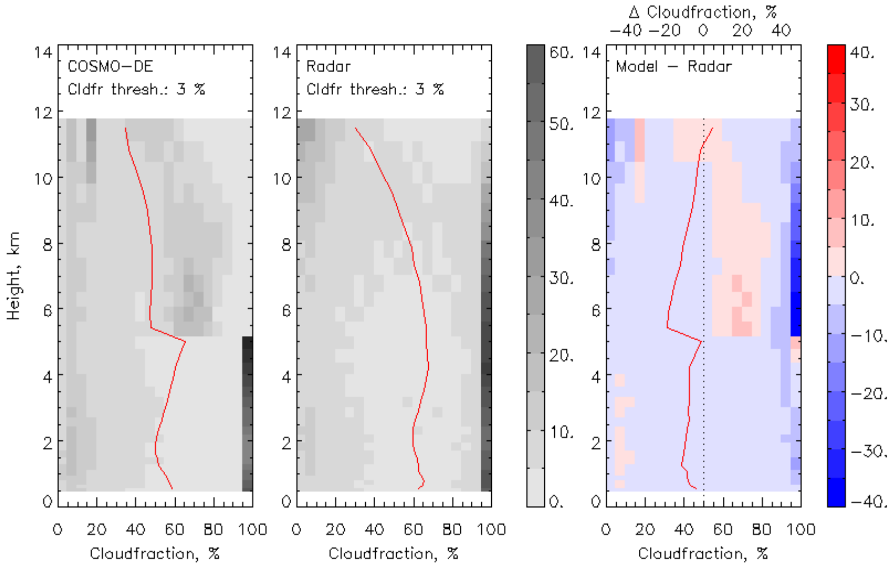

Figure 2: Mean cloud fraction (red lines) and their probability density for radar observations (left) and COSMO-DE forecast (middle). The cloud fraction differences (in %) are shown on the right.

mate the cloud cover clearly. In the middle level the mean differences varies between 20 and 26%, in the high level between 4% (GME) and 9% (COSMO-EU). The reasons can be: a) deficiencies in the cloud parameterisation of the models, b) wrong overlap assumptions, wrong initial data and/or c) measurement errors of the radar. Possible reasons will be analyzed on the example of the COSMO-DE in the next section.

4 Analysis of differences model - radar

For a more detailed analysis the mean cloud fraction has been calculated as main parameter to describe the differences between radar observations and models. The mean cloud fraction is a diagnostic parameter of the models and available for each model level and each time step. The radar cloud fraction is the ratio between the "pixels" that are cloudy and the total number of "pixels" in the two-dimensional grid box, which is given by the number of radar levels lying within the model layer times the number of measurements in one hour.

Figure 2 shows the mean cloud fraction and the pdf's for classes of 5% for the COSMO-DE - radar comparison. Only cases were considered where the cloud fraction was larger than 3%, that means all cloud free situations were neglected. The radar observed mean cloud fraction varies between 45 and 65 % below 10 km with a maximum at lowest heights and between 4 and 6 km. Above 6 km the mean cloud fraction decreases down to 30 % at 11 km. The mean values of model predicted cloud fraction are smaller than the radar derived cloud fraction by about 10 to 20 % except for the highest levels. Remarkable is a discontinuity at 5 km which corresponds with an abrupt change of the vertical pdf behaviour. Up to a height of 5 km, the maximum probability occurs in the highest class of cloud fraction in both the radar observations and the model forecasts. Above this heights the model is not predicting clouds in the highest class in the right frequency. The greatest values can be observed between 40 and 60 %. The other models (GME, COSMO-EU, not shown here) yield similar results.

An explanation for this behavior can be obtained by the parametrization scheme of stratiform clouds. The cloud fraction is corrected for thin upper level ice clouds ($p < 500hPa$) with a ice water content $q_i < 50$ mg/kg depending on the estimated ice wa-

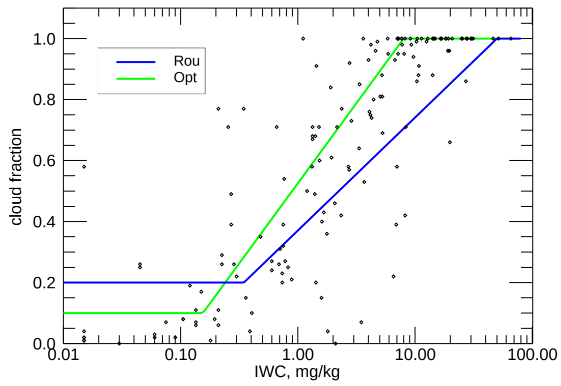

Figure 3: Scatter plot of cloud fraction versus ice water content derived from radar measurements at 6330 m for January 2011. The blue line is the cloud fraction correction applied in routine operation corresponding to equation 1. The green line as optimum fit results when use modified parameters.

ter content corresponding as

$$C = min\left[1, max\left(a, \frac{log(q_i) - log(10^{-7})}{log(b) - log(10^{-7})}\right)\right] \quad (1)$$

with the empirical parameters a=0.2 and b=5×10^{-5}. This correction is applied in order to remove ice clouds which are not visible for human eyes. Obviously this correction is too large and shifts the pdf-maximum of cloud fraction to lower values. To find more realistic parameters for a and b in eq. 1 the relationship between cloud fraction and ice water content has been investigated based on radar measurements. The ice water content q_i is derived using the Cloudnet retrieval package (Illingworth et al., 2007) and a formular given by Hogan et al. (2006) as function of radar reflectivity Z and temperature T corresponding to

$$log(q_i) = (0.000242)ZT + 0.0699Z - 0.0186T - 1.63 \quad (2)$$

Mean values of q_i were calculated for one-hour intervals. Cloudless samples did contribute with zero.

Figure 3 shows the scatter plot: cloud fraction - ice water content for January 2011 and the 6330 m height level. A rather strong correlation can be recognized between observed cloud fraction and ice water content. But, there is no optimal fit by the routine parametrization (blue line). A variation of the parameters a to 0.1 and b to 8×10^{-6} seems to be a better approximation (green line). To study the impact of this modification an experimental simulation by COSMO-DE has been carried out for January 2011.

The cloud fraction was compared again versus radar derived cloud fraction (Figure 4). It can be seen that the artifacts in the model simulated cloud fraction above 5 km are almost completely eliminated. This promising results need to be verified for a longer period. Furthermore, the relationship between cloud fraction and q_i will be investigated for other seasons and for the complete vertical range.

5 Conclusions

The Ka-band radar MIRA36 has been operated for more than 7 years at the Lindenberg observatory with high reliability and provided valuable data for cloud statistics and model validation. Long term time series of cloud cover give an insight to the cloud variability of different levels. A comparison of cloud cover versus traditional human expert observations shows a surprisingly good agreement for the total cloud cover and low clouds. Comparisons between radar and the NWP models of the DWD yield different results, while the total cloud cover is in good agreement between radar and models, there have been found significant differences regarding the vertical distribution and the PDF. Deficiencies in the parametrization of upper level ice clouds could be analyzed as one reason for radar-model differences. A modification of parametrization parameters on the base of radar measurements lead to an significant improvement A significant improvement has been achieved by a modification of parametrization parameters, which were derived from radar measurements. For a final introduction of the new parametrization the study will be extended to a larger data set.

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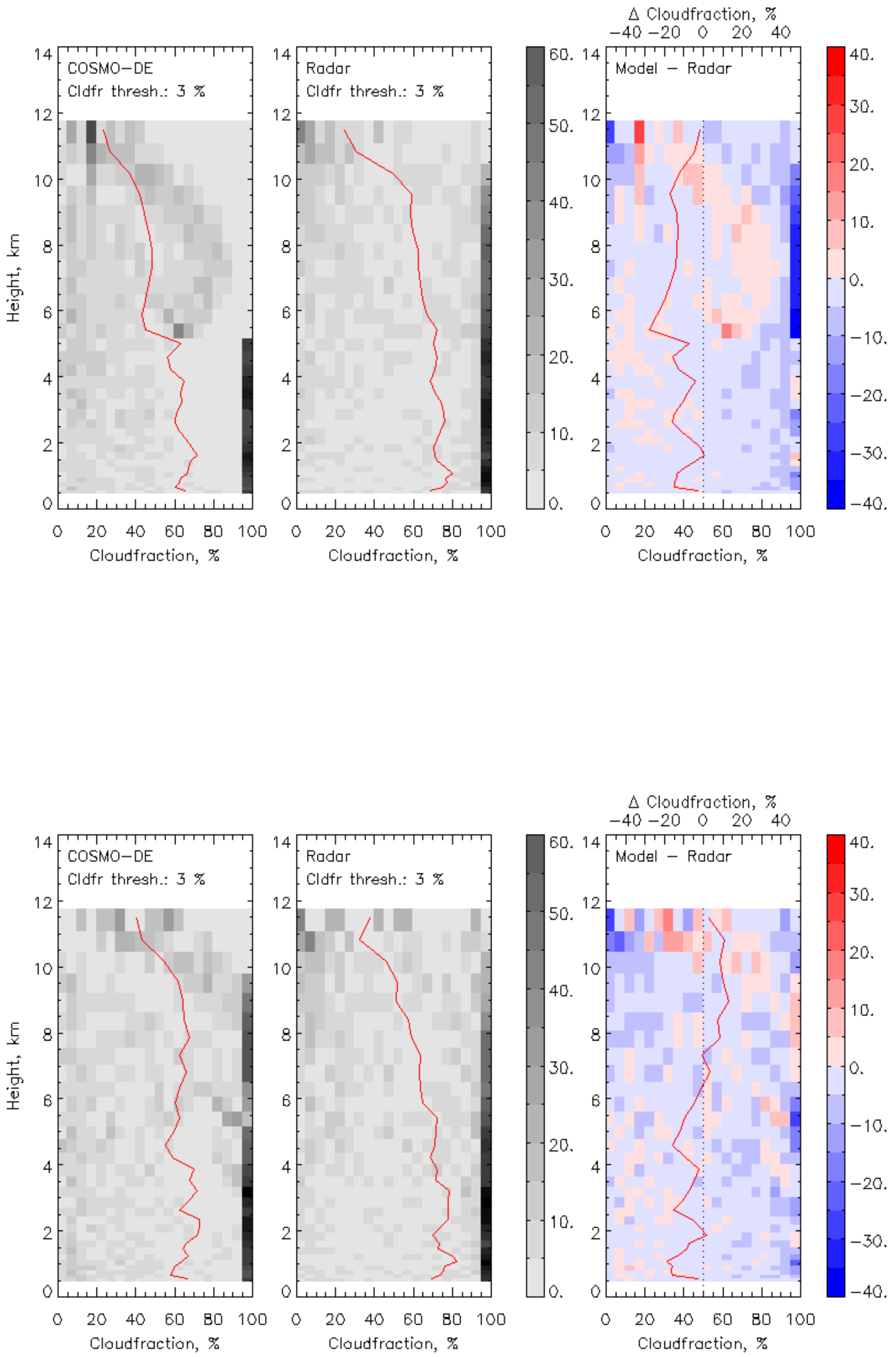

Figure 4: Same as in Figure 2, but for January 2011 with parameters used in routine operation (top) and modified parameters a and b in equation 1 (bottom).

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