Use of integrated profiling techniques (IPT) for studying cloud-radiation interactions

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1. Introduction

The accurate knowledge of the atmospheric state, i.e. temperature, humidity, cloud liquid water and cloud ice profiles is needed for a number of applications - the calculation of radiative flux profiles being a particularly demanding one. In order to study cloud-radiation interactions the atmospheric state has been derived for a nine month period of the Atmospheric Radiation Measurement (ARM) programs mobile facility (AMF) in the Black Forest, Germany (Fig.1), using the Integrated Profiling Technique (IPT) and the Cloudnet retrieval algorithms. The derived profiles are subsequently used as input data for radiative transfer calculations to estimate the cloud radiative effect and forcing.

Measurements

The AMF was deployed in the Black Forest, Germany (N48°32', E08°24'), from April 1 to December 31, 2007. Together with data from the multispectral microwave radiometers of the University of Cologne, a set of long-term continuous measurements is available to apply the

Fig. 1:ARM Mobile Facility in the Black Forest.

Baseline Instruments and Data for IPT:

- **Cloud Radar**: AMF W-Band (95 GHz) Cloud Radar → **Z**
- **Microwave Radiometer**:
  - HATPRO (Humidity And Temperature PROfiler): 2 bands (22.335-31.4 GHz, 51-58 GHz), 7 channels in each, availability of elevation and azimuth scans
  - DPR (Dual Polarization Radiometer): 3 channels (90 GHz, two orthogonal polarisations at 150 GHz)

  → **TBs**
- **Radiosondes** → a priori profiles of temperature **T, q** and **LWC**

3. Retrieval of atmospheric profiles

(A) Integrated Profiling Technique

- MWR **TB**s
- Radar reflectivity **Z**
- a priori information of **T**, **q**, **LWC**

→ **optimal estimation** with forward model $F(T,q,LWC) = \begin{Bmatrix} RTO(T,q,LWC) \\ a \cdot LWC^b \end{Bmatrix} = \begin{Bmatrix} TB \\ Z \end{Bmatrix}$ →

continuous atmospheric profiles of **T**, **q** and **LWC** and error estimates

Fig. 2: Schematic overview of the IPT

The IPT [1] is used to derive physically consistent atmospheric profiles of T, q, and LWC (see Fig. 2). Physically consistent means that measurements are reproduced within the measurement accuracy, if a forward model F is applied to the retrieved atmospheric state.

(B) Cloudnet Target Classification

Information on the occurrence and vertical location of clouds is included in the IPT by means of the Cloudnet target categorization product [2] developed at the University of Reading, UK. The target classification is a synergy product of cloud radar, ceilometer, microwave radiometer and model data.

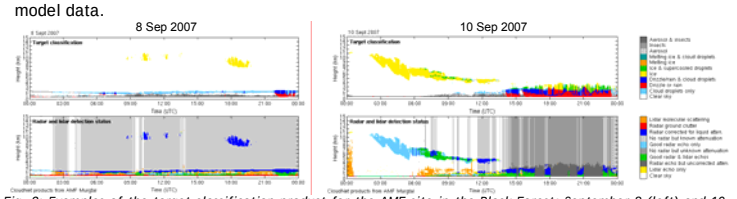

Fig. 3: Examples of the target classification product for the AMF site in the Black Forest: September 8 (left) and 10 (right), 2007. Cloudnet Target Classification (top) and radar/lidar detection status (bottom).

4. Cloud statistics for AMF site April-Dec 2007

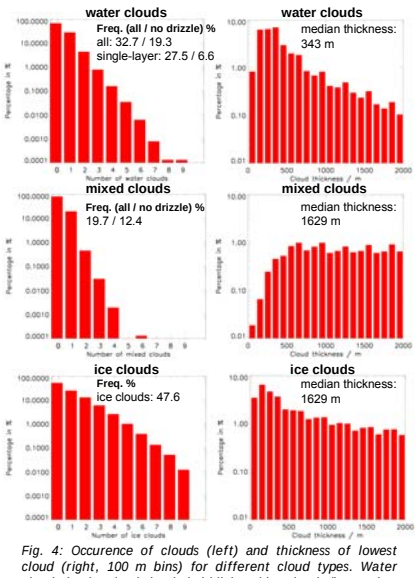

Fig. 4: Occurence of clouds (left) and thickness of lowest cloud (right, 100 m bins) for different cloud types. Water clouds (top), mixed clouds (middle) and ice clouds (bottom).

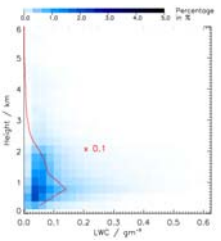

Fig. 5: Frequency distribution of IPT-LWC with height. The red line indicates the mean LWC profile of all cloudy profiles. Note that the values of the mean profile have been multiplied by 10 to fit the x-axis.

Tab. 1: Water cloud statistics for all profiles and for times only when MWR information is available.

	all profiles	match. MWR obs.
# profiles	768,838	609,668
Cloud cases (all/water) / %	71.6 / 32.7	77.8 / 39.4
Only water clouds in column (all/ single-layer) / %	13.7 / 11.3	17.0 / 14.1
Median cloud base height of lowest water cl. / m	664	664
Single-layer water cl. with thickn. > 500m (all/no drizzle) / %	7.8 / 4.0	9.7 / 5.0
Single-layer water cl. with thickn. > 1000m (all/no drizzle) / %	2.7 / 1.1	3.3 / 1.4
Median LWP of single-layer water cl. / gm^{-2}	-	54
Single-layer water cl. with LWP > 500 gm^{-2} / %	-	4.3

5. Radiative transfer simulations

The broadband radiative transfer simulations are performed with the Rapid Radiative Transfer Model for GCM applications (RRTMG) of the Atmospheric Environmental Research, Inc. [3].

- 14 solar and 16 thermal broadband spectral intervals
- two-stream algorithm for scattering
- water clouds: optical thickness τ, single-scattering albedo ω, and asymmetry parameter g are parameterized as a function of $r_{e,liq}$ and LWP [4]
- ice clouds: τ, ω, and g are parameterized as a function of $r_{e,ice}$ and IWP [5]

For the RRTMG input parameters $r_{e,ice}$ and $r_{e,liq}$ following parameterizations are used:

$r_{e,ice} = (75.3 + 0.5895 \cdot T)/2$ from [6]

$r_{e,liq} = r_m \exp\left(\frac{5}{2}\sigma^2\right)$ from [7] with $r_m = \left(\frac{3}{4\pi\rho_w} \frac{LWC}{N_d \exp\left(\frac{9}{2}\sigma^2\right)}\right)^{1/3}$

with N_d=288 cm^{-1} and σ=0.38 from [8]. For IWC, the Cloudnet IWC product [9] is applied.

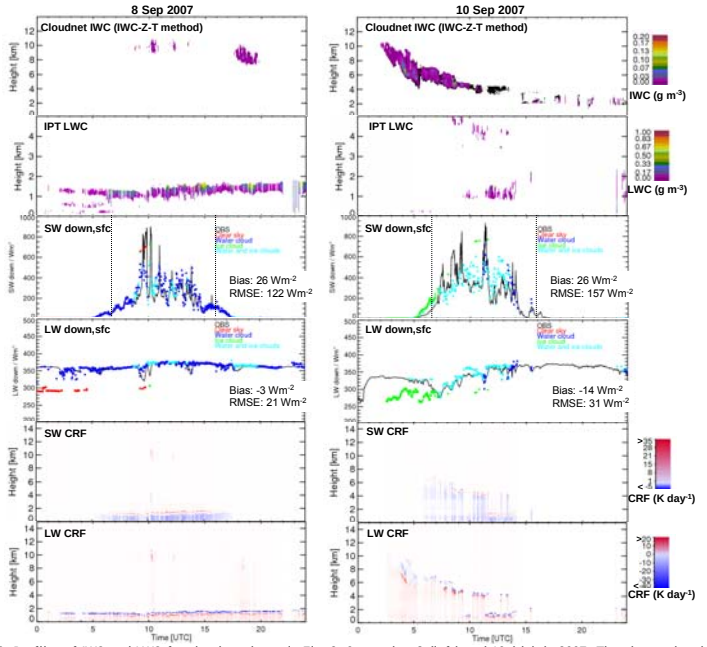

Fig. 6: Profiles of IWC and LWC for the days shown in Fig. 2: September 8 (left) and 10 (right), 2007. The observed and modelled downwelling surface fluxes and the calculated shortwave (SW) and longwave (LW) cloud radiative forcing ($CRF=HR_{cloudy}-HR_{clear}$) are also shown.

6. Sensitivity tests

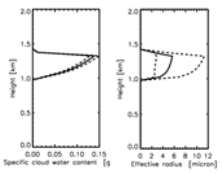

Fig. 7: Specific cloud water content (left) and effective radius (right) on September 9, 2007, 11:04 UTC. The dashed lines indicate the uncertainties. For the LWC, the IPT derived uncertainty is used; for r_e an error of -50% /+100% is applied.

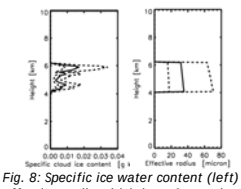

Fig. 8: Specific ice water content (left) and effective radius (right) on September 10, 2007, 8:11 UTC. The dashed lines indicate the -50% /+100% uncertainties.

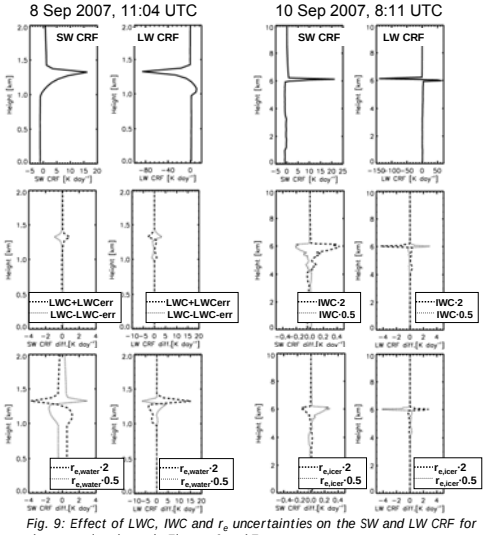

Fig. 9: Effect of LWC, IWC and r_e uncertainties on the SW and LW CRF for the examples shown in Figures 6 and 7.

7. Summary and outlook

- **Integrated Profiling Technique** has been applied to AMF data set resulting in **88,110 profiles of temperature, humidity and liquid water content**, including 33,168 cloudy scenes
- Cloudnet data reveal a cloud freq. of 71.6% with 11.3% single-layer water clouds (no cloud above)
- Median thickness of lowest water cloud is 343 m and median MWR-LWP 54 gm^{-2}
- Calculated SW fluxes overestimate downwelling radiation and exhibit a considerable scatter compared to observations → possible reasons: assumption of horizontal homogeneous conditions, misclassification of profile bins, uncertainties in derived cloud properties
- Next step: Profiles need to be thoroughly checked and uncertainties in fluxes and heating rates due to uncertainties in the cloud properties need to be characterized for the whole period
- Assessment of the cloud radiative forcing and effect with respect to different cloud types

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