10.7 RESULTS AND APPLICATIONS OF LONG-TERM CLOUD LIQUID WATER PROFILING BY AN INTEGRATED PROFILING TECHNIQUE

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1. INTRODUCTION

Within the EU-project CLIWA-NET a prototype of a European cloud observation network was operated. A major objective was the evaluation and improvement of cloud parameterizations in atmospheric models with focus on vertically integrated cloud liquid water and cloud vertical structure. During the BALTEX/BRIDGE campaign (BBC), the central facility Cabauw, NL was equipped with a unique combination of meteorological and advanced remote sensing instruments. This combination of instruments was used to develop an Integrated Profiling Technique (IPT) to optimally derive profiles of cloud liquid water content (LWC) during non-precipitating situations. The derived LWC time series were compared to the predicted LWC profiles of the global ECMWF model (European Centre for Medium-range Weather Forecast), the two regional climate models RACMO (Regional Atmospheric Climate Model operated at KNMI) and RCA (Rossby Centre Atmospheric Model), and the non-hydrostatic DWD-LM (Deutscher Wetterdienst Lokal-Modell).

2. AN INTEGRATED CLOUD LIQUID WATER CONTENT RETRIEVAL

The IPT applies optimal estimation theory (e.g. Rodgers et al. 2000) to simultaneously retrieve profiles of temperature (T), humidity (QV) and LWC from six different types of measurements. In contrast to common methods, which use the microwave radiometer-derived liquid water path (LWP) to scale the radar reflectivities (e.g. Frisch et al. 1998), the IPT directly combines the 19 brightness temperatures (TB) measured by the multi-channel microwave radiometer MICCY (Crewell et al. 2001) with 95 GHz cloud radar reflectivity profiles (Z), lidar-ceilometer cloud base, ground-level measurements of T, QV, and pressure, closest (in time and space) operational radiosonde profiles, and a priori data from a LWC climatology derived from a single column cloud model using explicit microphysics and initiated with local radiosonde profiles. The IPT bears the following advantages compared to common LWC profiling methods:

- All three retrieved profiles are "physically conform". This means that the retrieved profiles meet the ground-level measurements and fulfill the condition of saturation within the detected cloud boundaries. Additionally, the forward-modeled brightness temperatures of the retrieved profiles are constrained to the measured values within their specified accuracies.

- The IPT is independent on LWP retrieval errors because within the IPT, the brightness temperatures are directly inverted to the atmospheric parameters.

- The IPT explicitly includes T and QV profile information obtained from the closest operational radiosonde site. Since T and QV strongly influence the microwave radiative transfer, this a priori information is of crucial importance for the IPT because it reduces the degrees of freedom of the inverse problem. Thus, T, QV, and LWC profiles can be derived with high accuracies for every combined measurement at the site.

2.1 *Algorithm Formulation*

In order to apply an optimal estimation algorithm to an independent set of measurements ($\mathbf{y}$), the forward model $\mathbf{F}$ relating the atmospheric

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parameters ($\mathbf{x}$) to the measurements ($\mathbf{F}(\mathbf{x})=\mathbf{y}_i$), its error, and the error of the measurements themselves must be known. In case of a moderately non-linear problem a Newtonian iteration scheme can be applied, which will yield the following solution for the desired profile ($\mathbf{x}_{op}=\mathbf{x}_{i+1}$) after i iterations leading to convergence:

$$\mathbf{x}_{op} = \mathbf{x}_i + \left(\mathbf{K}_i^T \mathbf{S}_e^{-1} \mathbf{K}_i + \mathbf{S}_a^{-1}\right)^{-1} \times \left[\mathbf{K}_i^T \mathbf{S}_e^{-1}\left(\mathbf{y} - \mathbf{y}_i\right) + \mathbf{S}_a^{-1}\left(\mathbf{x}_i - \mathbf{x}_a\right)\right]. \quad (1)$$

All variables used (1) are described in Tab. 1. Principally the IPT is applicable at any location, however, the covariance matrix $\mathbf{S}_a$ must be adjusted according to the distance to the closest-by operational radiosonde site and the cloud model used to calculate the a priori LWC profile must be initiated with local radiosondes.

Theoretically calculated LWC accuracies bring forth strong improvements compared to single instrument techniques. However, in the future forward calculations in the infrared of the optical region may be included to further increase accuracies.

2.2 Algorithm Applicability

During the third extensive observation period of CLIWA-NET (BBC campaign) in the months of August and September 2001 in Cabauw, the IPT was successfully applied to simultaneous measurements as described above. In order to apply the IPT to the BBC data certain measurement conditions must be fulfilled. *First*, the measurements of microwave radiometer, cloud radar, and lidar-ceilometer must be available simultaneously. A threshold time window of 30s is chosen as this corresponds to twice the integration time of the lidar-ceilometer measurement, the longest integration time of the three remote

Tab. 1: Description of variables contained in equation (1).Note that bold face variables indicate vectors.

Variable	Description
$\mathbf{y}$	Measurement vector consisting of **Z**, **TB**, and ground-level T and QV
$\mathbf{x}_i$	Retrieved profile (after i-1 iteration steps) consisting of $\mathbf{T}_i$, $\mathbf{QV}_i$, $\mathbf{LWC}_i$.
$\mathbf{y}_i$	Simulated measurement vector after applying the forward model $\mathbf{F}$ to $\mathbf{x}_i$.
$\mathbf{K}_i$	Jacobian matrix, or $\partial\mathbf{F}(\mathbf{x}_i)/\partial\mathbf{x}_i$
$\mathbf{S}_e$	Error covariance matrix of the measurement vector $\mathbf{y}$
$\mathbf{x}_a$	A priori profile consisting of **T**, **QV** (radiosonde) and **LWC** (cloud model)
$\mathbf{S}_a$	Covariance matrix of the a priori profile

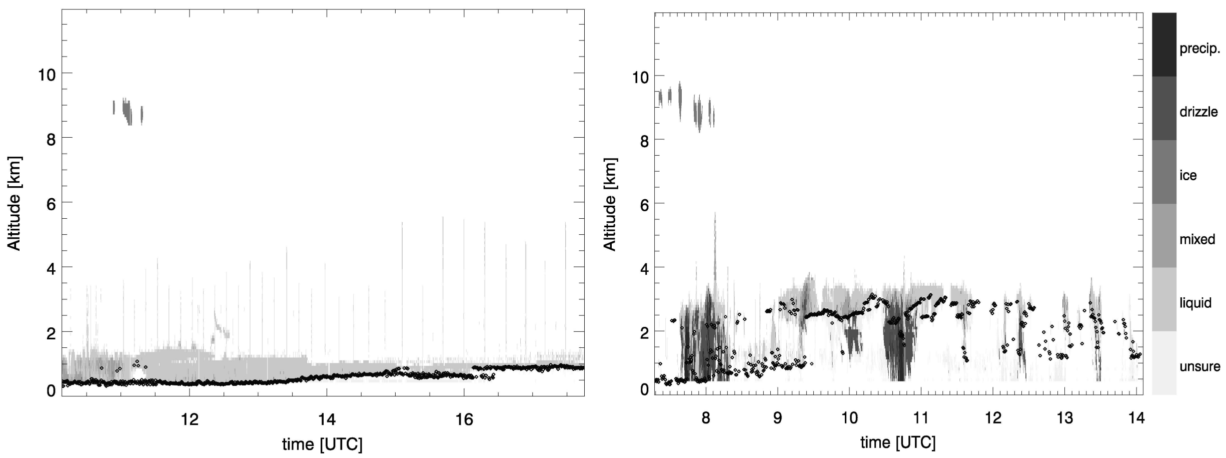

Fig. 1: *Cloud classification scheme (see grey scale on the right) applied to BBC cases on August 13 (left panel) and August 4 (right panel).The black diamonds indicate lidar-ceilometer cloud base.*

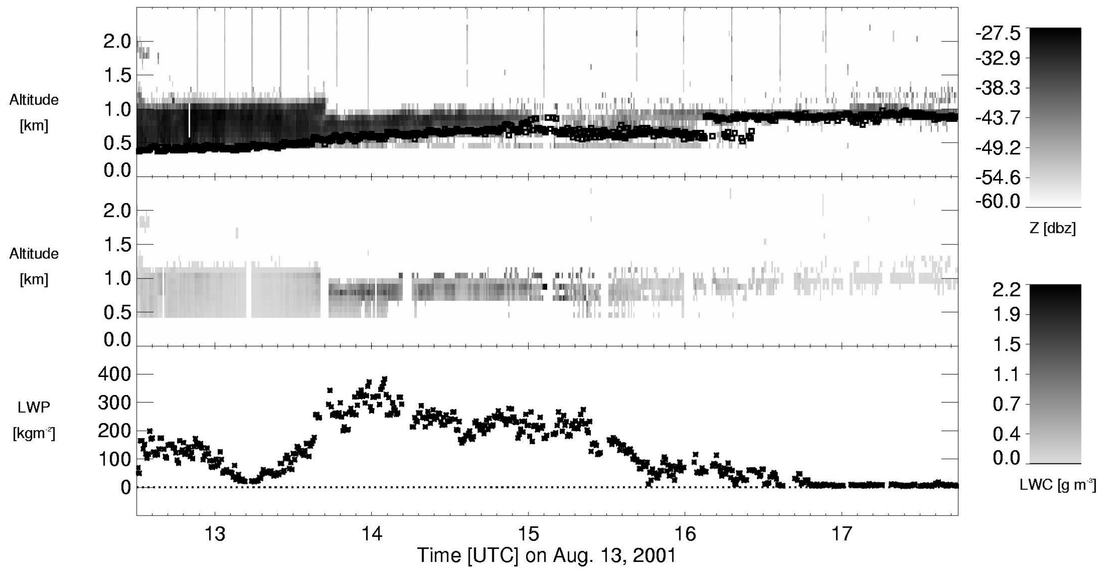

Fig. 2: *Example of a LWC-profile (IPT) time series (middle panel) on August 13, 2001 at the CLIWA-NET central facility Cabauw, NL. The top panel shows the measured radar reflectivities (vertical lines indicate a radar malfunction) and the cloud base retrieved by lidar-ceilometer (squares). The bottom panel shows the liquid water path (LWP) resulting from a vertical integration of LWC.*

measurements. The IPT is always applied at the radar measurement time. Within the time window, the closest measurement of MICCY and the lidar ceilometer are identified and combined within the IPT. *Second*, a cloud base must be detected by the lidar-ceilometer. *Third*, if a cloud base is detected a radar cloud top must exist. During BBC this was not the case in roughly 12 % of the cases, meaning that the lidar-ceilometer detects a cloud, but Z is below the radar detection threshold. The *fourth* condition to be met is that no mixed phase clouds are detected above. In the microwave region the TBs are generally insensitive to ice, however the Z signal is composed of ice and liquid contributions.

Up to now only a crude operational procedure for classifying cloud phase is available for the BBC campaign data. This procedure classifies cloudy radar pixels into significant precipitation, drizzle, ice, mixed phase, pure liquid, or unsure. Two examples of this classification scheme are shown in Fig. 1. The August 13 case is clearly classified as non-precipitating pure liquid and the IPT can be applied. On August 4 precipitating cases alternate with non-precipitating cases. The classification scheme assumes that clouds above 7 km consist totally of ice meaning that the algorithm can be applied to simultaneously existing lower liquid clouds. It was assumed that clouds can consist either of liquid and/or of ice within the height range from 3.5 to 7 km. Within this layer additional temperature checks originating from the closest operational radiosonde ascent were performed such that clouds were also considered as pure ice if ambient temperature was less than -20 °C. In roughly 17% of radar measurement time, ice was also detected in layers below 3.5 km. A sufficient condition for the presence of ice clouds is a threshold of ~-26 dB in the linear depolarization ratio of the cloud radar MIRACLE (M. Quante, personal communication). Such cases are mainly measured during (onset of) precipitation, where the rain droplet formation goes via ice-nucleation. The *fifth* condition to be met is that no significant precipitation is present during retrieval application. Significantly precipitating cases are classified by Doppler velocities larger than 3 ms^{-1} towards the radar. Drizzling cases are not principally excluded from the IPT-applicable cases because drizzle is assumed not to contribute significantly to the microwave signal. Since the lidar-ceilometer base is not very sensitive towards drizzle occurring below cloud

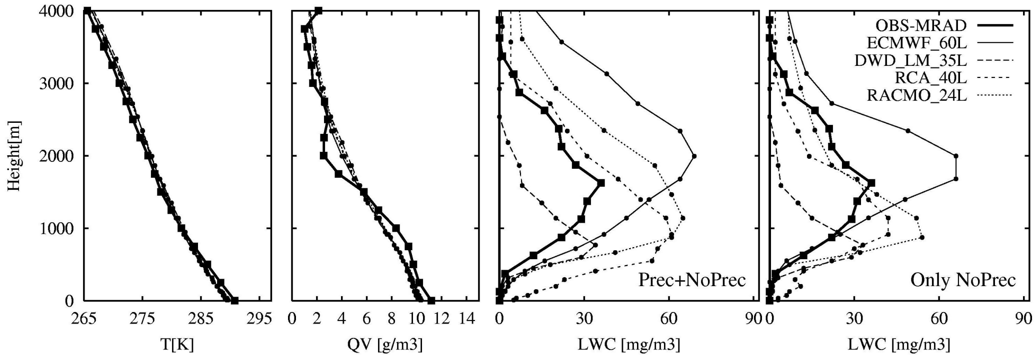

Fig. 3: *Mean retrieved and model-predicted profiles of T, QV, and LWC at Cabauw during ~7.2% of total BBC-campaign time. The LWC profiles are shown for all (Prec+NoPrec) and for only non-precipitating (Only NoPrec) model-predicted cases. The model profiles are synchronous with the IPT*

base, cloud base determination is principally not affected by drizzle. However, clouds which contain drizzle within their boundaries are excluded by using a threshold of 1 ms^{-1} in Doppler velocity.

If all of these limiting factors are considered the IPT can be applied to ~15 % of the time MIRACLE measured during BBC. Owing to the fact that MIRACLE could only be operated during working hours this corresponds to ~7 % total BBC time coverage. An example LWC time series derived with the IPT on August 13 is shown in Fig. 2.

3. EVALUATION OF MODEL CLOUD LIQUID WATER

Short-term (daily) model predicted vertical structure of cloud liquid water has been evaluated on the basis of the IPT retrievals in Cabauw during the BBC-campaign. Mean model-predicted LWC profiles are shown in Fig. 3. The model predictions are confined to the time slots for which profile information was successfully retrieved from the measurements. For T and QV all four models are comparable, but fail to reproduce the observed vertical structure in humidity, which may be related to the position of the boundary-layer height. To indicate the effect of precipitation, the LWC profiles are shown for all (precipitating and non-precipitating) model cases and for only non-precipitating model cases. When all cases are considered the models generally overestimate LWC compared to the observations. The reason becomes evident when precipitation events are removed from the model forecasts. Although no precipitation was observed at Cabauw during the considered time intervals precipitation was forecasted by the models leading to a positive LWC bias in the models. If only non-precipitating model forecasts are considered the LWC values of models and observations are much closer. Still large discrepancies between the observations and the models exist with the observations falling between the different models. While ECMWF has twice as high LWC values as the observations for altitudes higher than 1750 m, hardly any LWC is predicted by the LM above 2000 m. Significant differences can also be seen in the position of the LWC maximum. With the exception of ECMWF all models predict too low clouds. These comparisons show the obvious deficiencies of up-to-date numerical models in correctly predicting LWC. Comparable studies are planned in future and may be used to update existing cloud parameterizations.

4. REFERENCES

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