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Cloud observations and modeling within the European BALTEX Cloud Liquid Water Network

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A prototype of a European cloud observation network was established as part of the EU-project CLIWA-NET during three campaigns. The first CLIWA-NET network campaign (CNN I) took place in August/September 2000 and first results are presented in this work. Cloud properties, with a focus on liquid water path (LWP), were derived at 11 stations within the BALTEX modeling area from passive microwave radiometer, lidar ceilometer and infrared radiometer measurements. In an indirect evaluation of LWP accuracy performed during cloud free scenes, clear-sky biases in LWP ranging between –15 and +6 gm^{-2} were identified, which are well within the theoretical accuracy of the retrievals. For the Lindenberg station the retrievals were compared with forecasts from four atmospheric models. After restricting the model predictions to non-precipitating cases, which are the only cases for which retrieved LWPs are accurate, reasonable agreement was found between the observations and three of the models.

Introduction

Within the EU project CLIWA-NET (BALTEX Cloud Liquid Water Network) one objective is to establish a prototype of a European Cloud Observation Network (ECON), which can provide data almost in real time to a broad community. Another objective is to use these data together with satellite measurements to evaluate and improve cloud parameterizations in weather forecast and climate models. The most important parameter linking dynamics to clouds, in both the real world and in forecast models, is the water content of clouds which is quite difficult to measure. By far the most accurate method to determine the liquid water path (LWP) is ground-based passive microwave radiometry. However, for many applications it is also crucial to know the vertical distribution of the cloud water. To determine the cloud base height several instru-

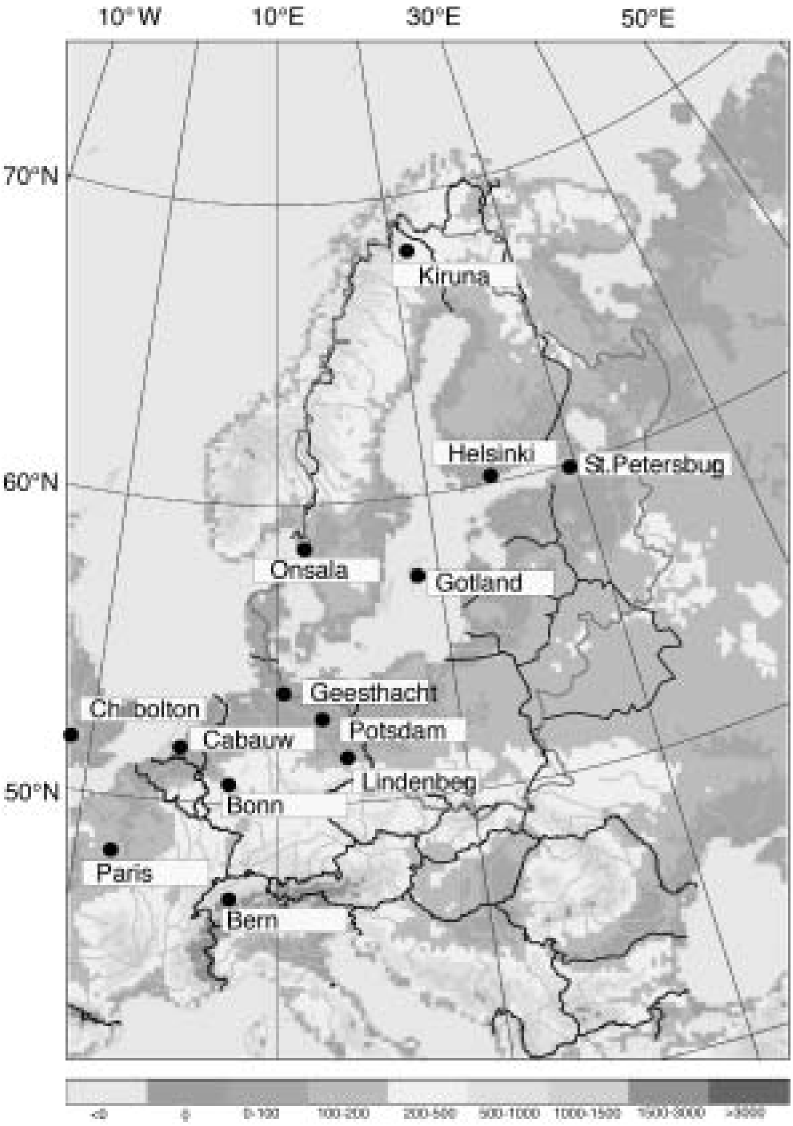

Fig. 1. Location of stations performing ground-based observations during CNN I. The station Gotland was operated during CNN II only.

ments can be used, e.g., cloud radars, lidar ceilometers and infrared (IR) radiometers, while for profiles of liquid water content (LWC) techniques using a combination of passive microwave and cloud radar measurements are promising (Löhnert *et al.* 2001, Frisch *et al.* 1998).

A prototype of ECON is implemented within CLIWA-NET by co-ordinating the use of existing, mostly operational, ground-based passive microwave radiometers and profiling instruments. This network feeds high quality cloud information, with high temporal and spatial resolution, but poor spatial coverage, into the calibration of satellite-based estimates of cloud water content with high spatial resolution. The CLIWA-NET network (CNN) was operated during the two continental-scale measurement campaigns CNN I (August–September 2000) and CNN II (April–May 2001). Both periods correspond to BALTEX/BRIDGE enhanced observation periods (EOP I and III). Measurements within a regional network were carried out during the BALTEX BRIDGE campaign (BBC) in August–September 2001 in the Netherlands. Here, we will report on the preliminary results from CNN I and present the potential use of the data for cloud process studies and atmospheric model evaluation. Furthermore, the ability of present-day atmospheric models to represent resolved-scale cloud processes and the effect of sub-grid scale cloud processes will be assessed in a consistent way. In this paper we focus on the evaluation of model predictions of cloud liquid water path, with particular emphasis on the role of precipitation in identifying the proper model quantity to compare with observed LWP. More detailed information on the CLIWA-NET objectives and project plan can be found at http://www.knmi.nl/samenw/cliwa-net.

Instrumentation

During CNN I, eleven stations (Fig. 1) within the BALTEX modeling area were operated. An overview of all stations, including the responsible operators and the deployed instrumentation, is given in Table 1. The primary instrument at each station for the observation of LWP was a passive microwave radiometer. Several types of these microwave radiometers were used during CNN I. Some of them were commercially available, while others were self built by the ECON partners. As a set, the microwave radiometer consisted of different frequencies, bandwidths, viewing geometries, beam widths and integration times. Nearly all stations were equipped with IR radiometers and lidar ceilometers. This combination of a lidar ceilometer and IR radiometer is quite useful in characterizing cloud height to an accuracy of ~30 m from the ceilometer measurements and cloud base temperature to an accuracy of 1–2 K from the IR sky temperature after subtracting the atmospheric contribution (Feijt and van Lammeren 1996). At three stations cloud radars (*see* e.g., Danne *et al*. 1999) were operated. In order to detect small cloud droplets, cloud radars usually operate at higher (for example) microwave frequencies. Because attenuation is relatively strong at these frequencies cloud radars typically point vertical and gather time-height series. Weather radars, intended for precipitation measurement, use much lower frequencies (e.g., 1–9 GHz) and continuously scan the horizon at very low elevation angles. Therefore the Baltex radar network (BALTRAD; Koistinen and Michelson 2002) covers nearly the whole BALTEX area including seven CLIWA-NET stations. For the BALTRAD pixel closest to a CLIWA-NET station time series of the radar reflectivity factor were available. For all overpasses of satellites carrying the Advanced High Resolution Radiometer (AVHRR) cloud classifications were performed (A. Dybbroe *et al*. unpubl.). The retrieval of microphysical quantities from the combination of satellite and ground-based is described in Feijt *et al*. (2002).

Table 1. Stations and instrumentation during CNN I. Crosses (x) indicate instruments already present at stations and circles (o) the instruments (and their owners), which were moved to the station.

	Station	Operator*	Lat. / Long.	Microwave Radiometer	Infrared Radiometer	Lidar Ceilometer	Cloud Radar	BALTRAD
BE	Bern	UNIBE	46.9 N / 7.7 E	x	x			
CA	Cabauw	KNMI	51.9 N / 4.9 E		x	x		
CH	Chilbolton	CLRC	51.1 N / 1.4 W	x	o KNMI	x	3, 94 GHz	
GE	Geesthacht	GKSS	53.4 N / 10.4 E	o MIUB	x	x	95 GHz	x
HE	Helsinki	HUT	60.2 N / 24.8 E	x	o KNMI	o Vaisala		x
KI	Kiruna	Chalmers	67.9 N / 21.1 E	o Chalmers	o KNMI	o MIUB		x
LI	Lindenberg	DWD	52.2 N / 14.1 E	x	xo KNMI	x		x
ON	Onsala	Chalmers	57.4 N / 11.9 E	x	o KNMI	o IFM		x
PA	Paris	CETP	48.7 N / 2.2 E	x	o KNMI			
PO	Potsdam	DWD	52.4 N / 13.1 E	x	o KNMI	x		x
SP	St. Petersburg	KNMI/IRE	59.9 N / 30.7 E	x	o KNMI		3, 9.6 GHz	x

* UNIBE (University of Bern), KNMI (Royal Netherlands Meteorological Institute), CLRC (Rutherford Appleton Laboratory), GKSS (GKSS Research Center), HUT (Helsinki University of Technology), Chalmers (Chalmers University of Technology), DWD (Deutscher Wetterdienst), CETP (Centre de Environnements Terrestre et Planetaires), IRE (Institute for Radioengineering, Moscow)

On average, the delivered data products were processed on a weekly basis including quality checks and internet visualization. To retrieve the LWP and the integrated water vapor (IWV) statistical retrieval algorithms were developed for each instrument based on a ten-year data set of European radio sondes. The LWP accuracy for the different stations ranged between 15 and 35 g m^{-2}, while the IWV accuracy ranged between 1 and 1.5 kg m^{-2} due to different instrument specifications. Note, that these accuracies were derived from instrument specifications and are purely theoretical. Within the retrieval development only LWPs lower than 500 g m^{-2} were considered. Retrieved values which are higher than this threshold should be handled with care. An overview on retrieval development for ground-based microwave measurements is given by Westwater (1993).

Preliminary results from CNN I

A major activity within the CLIWA-NET project is combining ground-based observations and satellite measurements to high quality LWP fields. This unique data set with high temporal resolution time series for the ground stations and spatial coverage for the satellite overpasses will be used to evaluate and improve numerical weather prediction models. In the following sections, first, the potential of the ground-based measurements will be presented and second, the comparison with model results for one station will be discussed (*see* below). A comparison of LWP fields derived from satellite and ground-based measurements with model results is presented by Feijt *et al*. (2002).

Ground based measurements

In order to demonstrate the potential and the problems in combining multi-sensor measurements time series at two CLIWA-NET stations, Geesthacht (GE) and Lindenberg (LI), are discussed. These stations were depicted because they comprise observations with the shortest (1 s for GE) and the longest (~10 min at LI) integration times of the instruments and therefore reveal cloud variability on different scales. Cloud radar observations during CNN I were still not as operational as the other ground-based instruments and are only available for a few case studies not shown here. Observations from the two stations from September 4 (GE) and August 10 (LI) are shown in Fig. 2. During CNN I both stations were equipped with a ceilometer, an IR radiometer and a microwave radiometer. The Lindenberg radiometer was a 12-channel profiler (Güldner and Spänkuch 2001). For the LWP and IWV retrievals the 23.055 and 30.0 GHz channels were used with data collected at about ten-minute intervals. The Microwave Radiometer for Cloud CarthographY (MICCY) that was located at Geesthacht is a 22-channel radiometer operated by Bonn University (Crewell *et al*. 2001). The LWP and IWV retrievals produced from MICCY measurements had one-second temporal resolution and were based on the 22.985, 28.235, 50.8 and 90.0 GHz channels. Since no useful LWP and IWV retrievals can be performed during rain, these conditions have to be identified. This was done with the rain shutter of the IR radiometer at Lindenberg and an upward looking visible wavelength video camera for cloud observations at Geesthacht. Additionally, rain rates were derived from the time series of radar reflectivity factor provided by the BALTRAD network.

As expected, the correlation between cloud base height and IR temperature is high. During the presence of clouds, IR temperatures are high, while in the absence of clouds the IR temperature of the atmosphere drops to –30 to –55 °C. High and thin cirrus clouds can not always be detected in IR temperature. From 1:30 to 2:00 UTC at Lindenberg the presence of high clouds results in an increase of 2 to 3 K in the observed maximum IR temperatures. The 10 minute averages remain uneffected. Since there are no corresponding changes in the LWP values, it can be assumed that the observed clouds are pure ice clouds. For low clouds characterized by high LWPs, e.g., 10:00 to 12:00 UTC at Lindenberg, IR temperatures of 10 to 20 °C were found. Ceilometer and IR radiometer measurements contain the cloud base information. Therefore, they can not be compared directly with cloud LWP, which is a vertically integrated quantity. For example, the

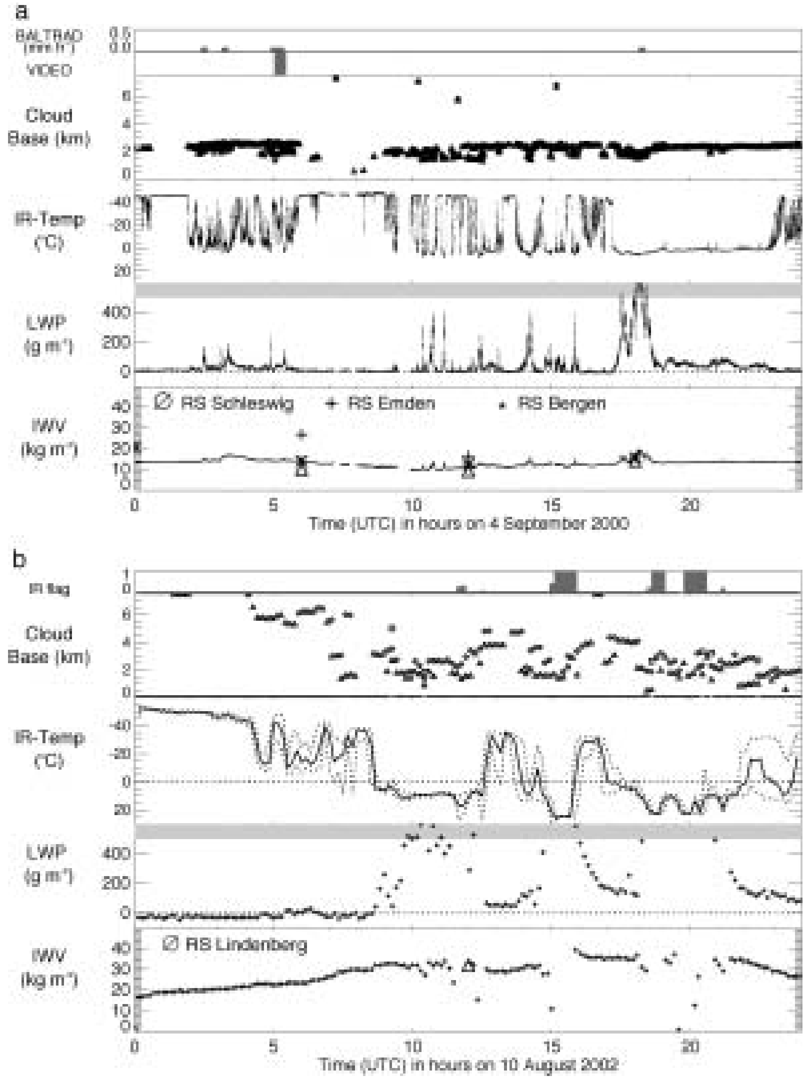

Fig. 2. — **a**: Time series of cloud base height, IR temperature, LWP, and IWV as observed from ceilometer, IR radiometer and passive microwave radiometer at Geesthacht station on 4 September 2000. The top panel shows rain indices derived from BALTRAD measurements and the station's video camera. — **b**: Atmospheric parameters as in **a** but for Lindenberg on 10 August 2000. The rain indices were derived from a rain shutter mounted with the IR radiometer. The infrared radiometer at Lindenberg measured the mean temperature within 10 minute integration time (solid line). Minimum and maximum temperature within this interval are given by the dotted line.

time periods from 13:45 to 14:30 UTC and 17:30 to 18:30 UTC in the Geesthacht time series are characterized by almost identical values for the cloud base height (1.5 to 2.5 km) and IR temperatures (0 to 10 °C). The corresponding peak LWP values for the first period varied between 310 and 420 g m^{-2}, while for the second period they varied between 500 and 820 g m^{-2}. Moreover, values larger than 500 g m^{-2} should be handled with care. Ice clouds are transparent at the microwave frequencies used for this study and, therefore, do not contribute to the microwave radiances.

Integrated water vapor (IWV) is derived as a by-product in the LWP retrieval. For the validation of the IWV time series presented in Fig. 2 we integrated water vapor profiles from radiosonde ascents. For the Lindenberg station the retrieved and sonde-derived IWV are in good agreement. At the Geesthacht station no launches were performed and the symbols in Fig. 2a are based on radiosonde ascents at the German upper-air stations of Schleswig, Emden, and Bergen. The closest station of Bergen (~75 km) produced IWV in good agreement with the microwave derived IWV. These comparisons are an indirect validation of the microwave radiometer observations.

Rainfall severely limits the retrieval of LWP and IWV from microwave radiometer measurements, since the instrument antenna or radom can become at least partly covered with water droplets or a thin water layer. Therefore, the detection of rainfall was a crucial part of the data analysis. At Geesthacht precipitation was inferred both from BALTRAD radar data, which are spatially integrated measurements, and from the video camera data. For the Lindenberg time series only data from the IR shutter were available for the selected day due to BALTRAD radar technical problems. The Geesthacht time series clearly shows the potential of the radar data for rain detection. During the day time, when radar data can be compared to video observations, the correspondence between the two measurements is good.

A preliminary overview of the cloud properties during CNN I is given in Table 2. Rain events identified from the individual point measurements at the specific sites (column 2) were excluded from the cloud analysis. The time of operation (t_{all}) is given as a percentage value of the total experiment period of 61 days. Percentages were calculated based on the different instrument sampling time intervals and only periods when valid measurements from the microwave radiometer, IR radiometer and ceilometer were available are included in t_{all} (*see* column 3). In order to discriminate between cloudy and cloud free observations, measurements from the IR radiometer and the ceilometer were used. Whenever the IR temperature was below –30 °C and the ceilometer did not detect a cloud base, the atmosphere was assumed to be cloud free. The presence of water clouds was defined by IR values exceeding 0 °C and cloud bases below 4000 m. This definition of cloudy (column 4) and clear (column 5) scenes resulted in a number of observations that did not fall into either one of these two classes, e.g., ice clouds, super cooled water clouds, mixed phase clouds or clouds with high variability within the integration time of the measurement. The difference between 100% and the sum of cloudy and clear percentages (columns 4 plus 5) gives the percentage of these mixed conditions. The higher number of unclassified scenes at Lindenberg (43.1%) compared to Geesthacht (27.9%) can be explained by the longer integration time at this station leading to averages of clear-sky and cloudy scenes. The mean values for IR temperature (T_{IR}), cloud base height (z_b), liquid water path (LWP), and integrated water vapor (IWV) are given in Table 2 for clear and cloudy

Table 2. Mean cloud base height (z_b), infrared temperature (T_{IR}), liquid water path (LWP) and integrated water vapor (IWV) for the stations within the CNN I network during cloudy and clear sky conditions (for definition *see* text). The percentages of cloudy and clear sky observations refer to the times when valid measurements of all instruments at the station are available (t_{all}).

Station	Rain (%)	t_{all} (%)	Cloudy (%)	Clear (%)	z_{bcloud} (m)	$T_{ircloud}$ (C)	LWP_{cloud} (g m^{-2})	IWV_{cloud} (kg m^{-2})	$T_{irclear}$ (C)	LWP_{clear} (g m^{-2})	IWV_{clear} (kg m^{-2})
BE	4.6	69.5	13.5	43.0	–	5.9	104.8	25.3	–36.8	0.9	18.2
GE	9.9	51.5	29.5	42.6	1411	8.8	101.3	22.0	–41.8	5.7	14.5
HE	2.7	13.1	15.6	41.9	1880	5.2	132.0	23.9	–42.9	1.5	17.2
KI	4.4	28.0	37.7	24.3	1360	6.5	108.8	16.4	–37.3	–0.8	12.1
LI	5.6	77.2	22.5	34.4	1637	7.6	107.3	25.0	–45.4	–8.5	17.3
ON	10.2	56.7	24.1	47.2	1254	7.7	124.1	22.3	–47.9	–8.7	14.9
PA	3.0	45.5	26.4	52.7	–	8.8	80.2	26.7	–42.6	–14.7	20.9
PO	3.9	88.7	46.8	45.3	1599	–	69.8	23.5	–	–11.6	18.9
SP	6.2	20.6	13.2	40.3	806	8.2	128.6	23.7	–45.9	55.0	16.8

scenes. At Paris and Bern no ceilometer data were available. Therefore, quantities from these two stations can not be compared directly with the results for other stations.

The LWP for clear-sky situations is of special interest since it can be used to assess the systematic error of the LWP retrieval for each instrument at the different locations. The biases range from 5.7 g m^{-2} at Geesthacht to –14.7 g m^{-2} for Paris. These values are within their expected range of uncertainty and demonstrate that reasonable LWPs can be retrieved at different locations within Europe covering a variety of climates. The bias of 55 g m^{-2} for St. Petersburg is due to severe instrument drifts in the morning hours, which will be dismissed in future analysis.

Note that additional measurements from IR radiometers and ceilometers might be used to correct biases in the microwave radiometer derived LWP at the individual stations. Within the framework of the BALTEX BRIDGE Cloud campaign, where all instruments were operated at the Cabauw super-site for two weeks, we will be able to investigate whether the biases in the LWP measurements are due to different calibration methods or algorithm uncertainties. One result to date is the detection of a systematic miscalibration of the Paris radiometer, leading to an underestimation of LWP and an overestimation of IWV.

Model evaluation

Four European institutes participated in the evaluation of model predicted cloud parameters: the European Center for Medium-range Weather Forecast (ECMWF), Deutscher Wetterdienst (DWD), the Swedish Rossby Center, and the Royal Netherlands Meteorological Institute (KNMI). The ECMWF participated with the global forecast model (version CY24R1) operated at an effective horizontal resolution of 40 km and with 60 layers in the vertical. It employed the prognostic cloud scheme of Tiedtke (1993) in which cloud content and cloud fraction are both treated prognostically. The DWD contributed with the recently developed Lokal Modell (LM; Doms and Schättler, 1999) operated in non-hydrostatic mode at a resolution of 7 km and with 35 layers in the vertical. At this resolution convection is still parameterized, but stratiform clouds are assumed to be resolved, implying that the cloud fraction of an entire grid box is determined by an all-or-nothing scheme. The Rossby Center has developed a climate version of the numerical weather prediction model HIRLAM, hereafter referred to as the RCA-model (Jones 2001). In this model cloud parameters are represented by the convection scheme of Kain and Fritsch (1991) and a stratiform cloud scheme proposed by Rasch and Kristjansson (1998). The group at KNMI operated a regional version of the ECHAM4 GCM, hereafter referred to as RACMO (Regional Atmospheric Climate Model; Christensen *et al*. 1996). Cumulus convection is represented by a mass-flux scheme and stratiform processes by a modified version of a scheme originated by Sundqvist *et al.* (1989) in which cloud content is prognosed. Details can be found in Roeckner *et al*. (1996).

The RCA-model and RACMO were operated in as much an identical fashion as possible. The two models shared the same domain, where the horizontal resolution was 18 km and the number of model layers was 24. Both models used the same set of ECMWF analyses to initialise the atmospheric component of the model and to drive the model from the lateral boundaries. The output from all four models refers to a 12 to 36 hour window taken from each daily forecast initiated at 12:00 UTC.

As an illustration, Fig. 3 shows the model predictions of IWV and LWP for Lindenberg on 10 August 2000. Model values were calculated for sub-domains centered around the CLIWA-NET site (here Lindenberg). The size was chosen to be in the order of 50 × 50 km. For ECMWF this leads to just one grid cell, for RCA and RACMO to 3 × 3 grid cells, and for the LM to 7 × 7 grid cells. The model LWP for the grid-box mean was derived from the profiles of cloud liquid water content containing no rain contribution. Clearly, all models succeeded in reproducing the observed rise in IWV during the course of the day that was related to the crossing of a synoptic frontal system with embedded convection. Consistent with this weather event, LWP evolved from zero in cloud free conditions or in conditions with only high clouds present

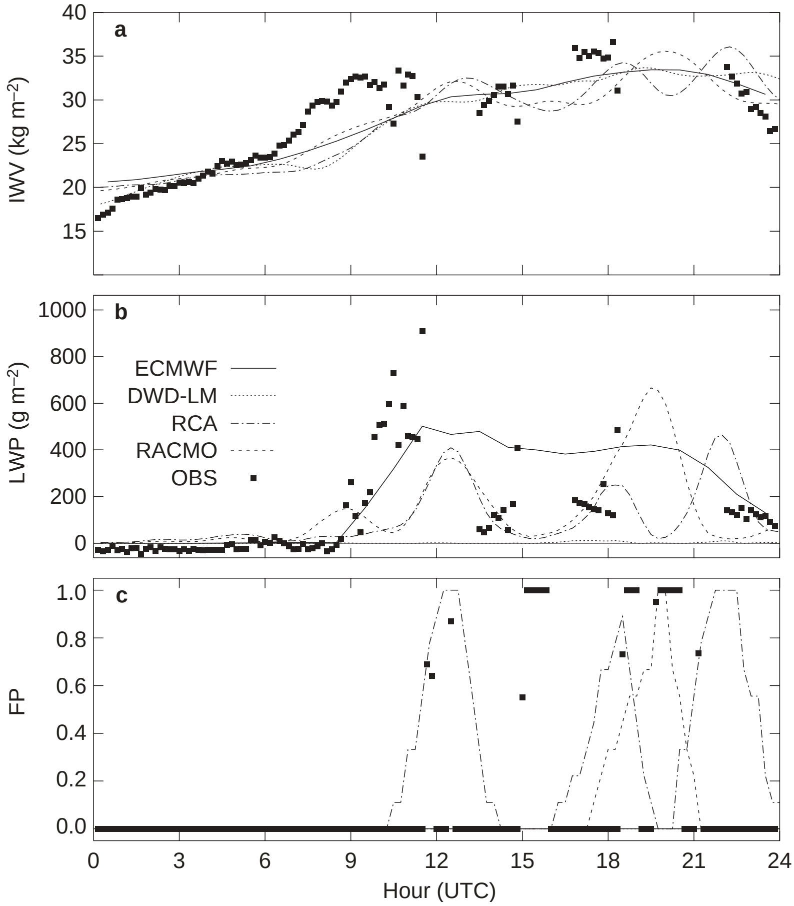

Fig. 3. Model predicted time series of (**a**) IWV, (**b**) LWP and (**c**) FP (Frequency of Precipitation) for Lindenberg on 10 August 2000. The observations are similar to those shown in Fig. 2b, but slightly differently processed.

to very substantial values in the range of 300 to 700 g m^{-2} by mid-day. The trend in the LWP observation was well captured by three of the four models, while the LM failed to produce any significant LWP for this event. The reason for the poor LM performance was an omission in adding the convective contribution to LWP to the (resolved) stratiform contribution before exporting the field from the model.

The observed LWP and IWV time series on 10 August at Lindenberg (Fig. 3) were interrupted at several times. These breaks corresponded to the occurrence of precipitation reaching the surface and wetting the instrument. During these precipitation events the measurements were no longer reliable and had to be rejected from further analysis. As is shown in Figs. 2b and 3, a number of short rain showers began to occur around noon lasting into the second half of the day. Only the RCA and RACMO models predicted precipitation with the RCA model nicely reproducing a number of convective events. Both models showed an oscillating structure in both LWP and IWV with rising amounts prior to a (model) event of rainfall and falling off afterwards.

We studied the role of precipitation in more detail by evaluating IWV, LWP (all times), frequency of precipitation (FP) and LWP (non-precipitating conditions) for the full time series for Lindenberg during CNN I (Fig. 4). The daily variations of IWV were strongly controlled by synoptic systems, which in general are quite well captured by large-scale atmospheric models (Fig. 4a). Observed and model predicted daily averaged values of LWP for Lindenberg are illustrated in Fig. 4b. As we already pointed out, a sensible retrieval of LWP can only be performed in the absence of precipitation. In the present analysis, retrieval values of LWP during

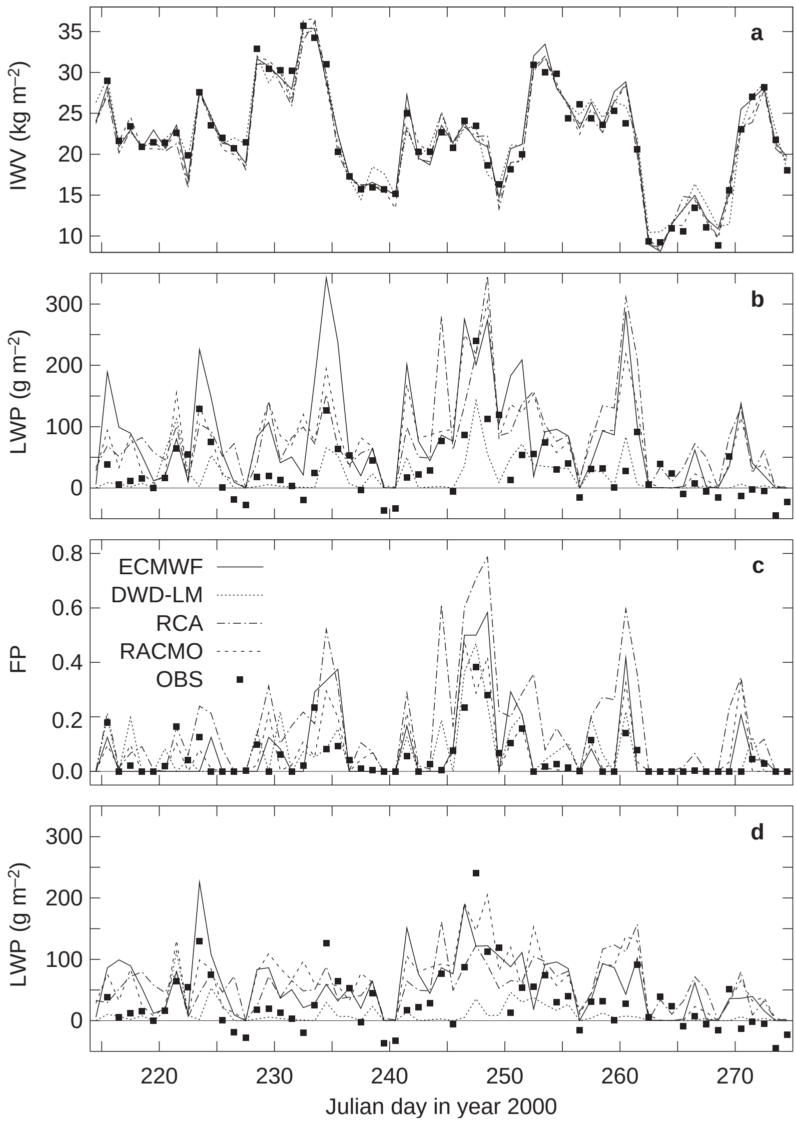

Fig. 4. Model predicted daily averaged values of (**a**) IWV, (**b**) LWP (unconditional), (**c**) FP and (**d**) LWP (only events without model precipitation), respectively, for Lindenberg during CNN I. The observations of IWV and LWP are averaged for episodes without precipitation.

rain events were labeled as missing and not included in the analysis leading to Fig. 4b, which implies that the observed LWPs in Fig. 4b likely provide a lower limit. The model-predicted LWP values in Fig. 4b are unconditioned.

Information on the occurrence of precipitation is essential to the interpretation of observed LWP. The frequency of rainfall for Lindenberg during CNN I both inferred from observations and predicted by the models is illustrated in Fig. 4c. The model curves refer to model precipitation rates of at least 0.1 mm h^{-1}. A few days with persistent precipitation occurred during the campaign, but they never exceeded 40% of the time within a single day (Fig. 4c). The models captured the rainy days reasonably well, but all four models, and especially the RCA model significantly overpredicted the duration of precipitation. In general, the events of precipitation within the models did not match the observations sufficiently well to allow use of observed occurrence of precipitation as a mask in order to condition the model-predicted LWP to non-precipitative events. To merge the model information contained in Fig. 4b and c we confined the model-predicted LWP to events with model predicted precipitation rates smaller than the above mentioned limit and arrived at the conditioned LWP (Fig. 4d). The model predicted LWP values in Fig. 4d, as compared with those in Fig. 4b, have indeed been reduced significantly. In general, LWP values predicted by the ECMWF model, the RCA model and RACMO compared reasonably well in magnitude with the observed amounts, with the ECMWF and RACMO models tending to be on the high side and the RCA model tending to be on the low side. The LM model, however, was too low in LWP, for reasons explained above.

Discussion

Cloud parameters were derived within the European cloud observation network (ECON) of 11 stations operating continuously during a two month period. Cloud liquid water path (LWP) as a key parameter was retrieved from microwave radiometer measurements at all stations. Additional observations from ceilometers and infrared radiometers gave information about the altitude of the clouds, allowing us to distinguish between ice and water clouds and to assess microwave radiometer LWP biases in cloud free conditions. The mean biases for 10 out of 11 stations were well within their corresponding theoretical accuracies. However, the magnitude of the biases puts a limit on the detection of low LWP values, which are still of relevance to atmospheric radiative transfer. Whether the analysed biases were caused by instrument calibrations or the retrieval algorithm will be investigated using data from a microwave intercomparison campaign, which took place in the first two weeks of the BALTEX BRIDGE campaign (BBC).

Reliable values for LWP can only be inferred from microwave radiometer measurements when the instrument is dry. When the instrument is wet, the moisture is mostly due to ongoing or very recent rainfall. Therefore, sophisticated rain detection schemes have to be used to screen out rainfall events from the ground-based measurements. Rain shutter or continuously monitoring rain gauges are appropriate for this task. Radar data can be used as an additional source of information, but the reliability of these data is more uncertain due to their representation of a larger area. Detection and protection against precipitation is an important issue in the design of a low-cost microwave radiometer suited for use within an operational network, which is also a CLIWA-NET objective.

A preliminary comparison of LWP and IWV observed at Lindenberg with modeled values shows very promising results for three out of the four numerical weather prediction models after the model results were restricted to non-precipitating cases. Since precipitation correlates with high values of LWP and retrieved LWPs during precipitation events are unreliable, LWPs inferred from microwave radiometer measurements during non-precipitative conditions must likely constitute a lower limit on the range of actual amounts.

When verifying model-predicted LWP one must restrict the evaluation to non-precipitative episodes in order to avoid positive biases. Since most models overpredict the number of precipitation events, as well as their duration, and often mispredict the correct timing of the event, correlating model-predicted LWP to model events of precipitation, rather than to observed events, leads to more reliable results.

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References

Christensen J.H., Christensen O.B., Lopez P., van Meijgaard E. & Botzet M. 1996. The HIRHAM4 regional atmospheric climate model. *DMI Scientific Report* 96-4, 51 pp.

Crewell S., Czekala H., Löhnert U., Simmer C., Rose Th., Zimmermann R. & Zimmermann R. 2001. Microwave Radiometer for Cloud Carthography: A 22-channel ground-based microwave radiometer for atmospheric research. *Radio Sci.* 36: 621–638.

Danne O., Quante M., Milferstädt D., Lemke H. & Raschke E. 1999. Relationships between Doppler spectral moments within large-scale cirro- and altostratus cloud fields observed by a ground-based 95 GHz cloud radar. *J. Appl. Meteor.* 38: 175–189.

Doms G. & Schättler U. 1999. The Nonhydrostatic Limited-Area Model LM (Lokal-Modell) of DWD — Part I: Scientific Documentation, Deutscher Wetterdienst, Offenbach, Germany, 155 pp.

Feijt, A. & van Lammeren A. 1996. Ground-based and satellite observations of cloud fields in the Netherlands. *Mon. Wea. Rev.* 124: 1914–1923.

Feijt, A. J., Jolivet, D. & van Meijgaard, E. 2002. Retrieval of the spatial distribution of liquid water path from combined ground-based and satellite observations for atmospheric model evaluation. *Boreal Env. Res*. 7: 265–271.

Frisch A.S., Feingold G., Fairall C.W., Uttal T. & Snider J.B. 1998. On cloud radar and microwave measurements of stratus cloud liquid water profiles. *J. Geophys. Res*. 103: 23195–23197.

Güldner J. & Spänkuch D. 2001. Remote sensing of the thermodynamic state of the atmospheric boundary layer by ground-based microwave radiometry. *J. Atmos. Oceanic Technol*. 18: 925–933.

Jones C.G. 2001. A brief description of RCA2 (Rossby Centre Atmosphere Model Version 2). *SWECLIM Newsletter* 11: 9–15. Rossby Centre SMHI, Norrköping, Sweden.

Kain J.S. & Fritsch M. 1991: A 1D entraining/detraining plume model and its application in convective parameterisation. *J. Atmos. Sci.* 47: 2784–2802.

Koistinen, J. & Michelson, D.B. 2002. BALTEX weather radar-based precipitation products and their accuracies. — *Boreal Env. Res*. 7: 253–263.

Löhnert U., Crewell S., Macke A. & Simmer C. 2001. Profiling cloud liquid water by combining active and passive microwave measurements with cloud model statistics. *J. Atmos. Oceanic Technol.* 18: 1354–1366.

Rasch P.J. & Kristjansson J.E. 1998. A comparison of the CCM3 model climate using diagnosed and predicted condensate parameterisations. *J. Climate* 11: 1587–1614.

Roeckner E., Arpe K., Bengtsson L., Christoph M., Claussen M., Dünenil L., Esch M., Giorgetta M., Schlese U. & Schulzweida U. 1996. *The atmospheric general circulation model ECHAM-4: Model description and simulation of present-day climate*. Report 218, Max Planck Institute for Meteorology, Hamburg, Germany, 90 pp.

Sundqvist H., Berge E. & Kristjansson J.E. 1989. Condensation and cloud parameterization studies with a Mesoscale numerical weather prediction model. *Mon. Wea. Rev.* 117: 1641–1657.

Tiedtke M. 1993. Representation of clouds in large-scale models. *Mon. Wea. Rev*. 121: 3040–3061.

Westwater E.R. 1993. Ground-based microwave remote sensing of meteorological variables. In: Janssen M.A. (ed.), *Atmospheric remote sensing by microwave radiometry*, John Wiley, New York, pp. 145–213.

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