BOREAL ENVIRONMENT RESEARCH 7: 265–271 ISSN 1239-6095
Helsinki 2 October 2002

Retrieval of the spatial distribution of liquid water path from combined ground-based and satellite observations for atmospheric model evaluation

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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. ISSN 1239-6095

In the framework of CLIWA-Net, observations and model values of cloud properties are compared. The observations are obtained from a network of ground-based radiometers and polar orbiting meteorological satellites. The project includes a number of novel aspects among which the retrieval of the horizontal distribution of cloud liquid water from a combination of AVHRR and ground-based measurements. This new approach results in a spatial distribution of LWP of optimum accuracy. A case study is presented, that demonstrates the added value of this approach for atmospheric model evaluation.

Introduction

The low quality of the representation of clouds in climate models has been identified to be one of the largest sources of uncertainty in climate predictions based on climate model runs (IPCC 2001). As a result, clouds are a main topic in climate modeling efforts. In order to provide the atmospheric modeling community with appropriate reference data for the improvement of cloud parameterizations, new measurement techniques of cloud properties are developed.

The European CLIWA-Net project aims to measure and model the atmospheric components of the hydrological cycle over the Baltic Sea catchment area. The measurements were obtained during three observational campaigns in August–September 2000, April–May 2001 and August–September 2001. The campaigns have provided a wealth of cloud parameters. The main objectives of the Cloud Liquid Water Network project (CLIWA-Net) are:

— to implement a prototype of a European cloud observational network
— to contribute to the program of the continental-scale experiment BALTEX
— to objectively evaluate cloud related output from atmospheric models for weather and climate prediction.

The concept of the observations is to combine ground-based and satellite measurements. Cloud parameters are inferred from high accuracy remote sensing measurements from the ground. The ground stations are organized in a network. A spatial distribution at one moment in time is obtained from measurements from the polar orbiting meteorological satellite. The latter measurements are less direct and thus are expected to be of lower quality than the ground-based measurements. According to the observational concept, the combination of ground-based and satellite measurements provide spatial distributions of cloud parameters with an optimum accuracy.

Ground-based observations

Continuous cloud remote sensing measurements with microwave radiometers and various other instruments were conducted in a ground-based network of twelve stations in the Baltic Sea catchment area. The network was operated in August–September 2000 (CNNI) and April–May 2001 (CNNII). Measurements are collected and organized per day and per site. Liquid water path (LWP) and integrated water vapor (IWV) are retrieved with statistical algorithms based on a 10-year data set of European radiosondes. A more detailed description of the ground network is given by Crewell *et al.* (2002).

AVHRR Analysis

The instrument

The Advanced Very High Resolution Radiometer, AVHRR, is a passive imager onboard the polar orbiting meteorological satellites. The radiometer measures in six spectral bands centered at 0.6, 0.9, 1.6, 3.7, 10.8 and 11.9 μm. The instrument scans across-track and has a sub-satellite spatial resolution of 1.2 km. Several qualitative and quantitative cloud parameters are retrieved from AVHRR radiances. Cloud analysis using the SCANDIA algorithm (Karlsson 1996) produces a meteorological cloud type classification in 21 scene types. KNMI's Local implementation of APOLLO Retrievals in an Operational System, KLAROS, is used for quantitative cloud analysis. KLAROS yields the following cloud properties: cloud fraction, optical thickness, infrared emissivity, thermodynamic top temperature and liquid water path.

In KLAROS the APOLLO scheme threshold tests were adopted to discriminate cloudy from cloud free areas (Saunders 1986, Saunders and Kriebel 1988, Kriebel *et al.* 1989). APOLLO only requires satellite information. The thresholds are fixed values obtained from statistical analysis of long time series. KLAROS employs dynamic thresholding using information from atmospheric profiles of temperature and humidity and the surface temperature fields from the High Resolution Limited Area Model, HIRLAM (Gustaffson 1993). KLAROS can be run both in automatic and supervised mode using an interactive shell (Dlhopolsky and Feijt 2001).

Physical cloud parameter retrievals

The properties of clouds are determined on a pixel by pixel basis. The measured 0.6 μm reflectivity is compared to values from radiative transfer calculations using Doubling Adding KNMI, DAK (Stammes 1993) to obtain an estimate of the visible optical thickness at 0.6 μm, $\tau_{0.6}$. Radiative transfer calculations were done for various water droplet size distributions using Mie-scattering theory. Ice crystal scattering is modeled using ray-tracing, assuming imperfect hexagonal shape (Hess *et al.* 1998).

The optical thickness is a measure for the number of cloud particles and relates to infrared emissivity, cloud top temperature and liquid water path (Minnis *et al.* 1998, Feijt *et al.* 1999). The retrieval of Liquid Water Path (LWP) from the optical thickness includes several assumptions on surface reflectivity, cloud microphysics, atmospheric profiles and horizontal and vertical variability. The assumptions limit the accuracy of this method. Within CLIWA-Net, time series of ground-based microwave radiometer measurements are available that enable to estimate the quality of the KLAROS derived LWP. In order to optimize the accuracy of the spatial distribution of LWP values, the AVHRR values are compared and brought into accordance with measurements from the network of ground-based microwave radiometers. This provides spatial distributions of cloud parameters with an optimum accuracy.

A comparison between time series of ground-based measurements and an instantaneous spatial distribution of cloud parameters from satellite is limited by the high spatial and temporal variability of cloud parameters that is fundamental to cloud processes. A part of the time-series is compared to an area in the satellite image. For a one-to-one comparison the only data available is the ground-based measurement at the time of satellite overpass compared to the one pixel in the satellite image that collocates the ground station. Even this single direct comparison is not unambiguous, because the integration area of the satellite instrument is much larger than the sampling volume of the ground-based instrument. Therefore, the comparison is of a statistical nature. The choice of the period in the time-series and area in the satellite image that are compared is made on qualitative reasoning (Feijt and Jonker 2000).

Atmospheric model

Model evaluation using CLIWA-Net

One of the objectives of CLIWA-Net is to objectively evaluate cloud-related output of atmospheric models for weather and climate prediction. A comparison between time series of ground-based measurements and model cloud parameters is done for the stations in the CLIWA-Net network (Crewell *et al.* 2002).

The comparison between time series of ground-based measurements and model cloud parameters is liable to the effects of cloud variability. The model may resolve atmospheric features of the order of 2 to 3 times the size of the horizontal mesh. If the cloud field over the ground-based station is dominated by local phenomena, the comparison is not useful. In CLIWA-Net the AVHRR is used to resolve small-scale features (1 km) within the model grid box and make the link between local measurements and large-scale cloud parameter fields. In CLIWA-Net several atmospheric models are evaluated. This paper aims to demonstrate the observational concept, and is limited to only one model, which is described below.

Model description

The model evaluation is carried out with the regional model RACMO (Regional Atmospheric Climate Model) operated at KNMI and developed in collaboration with the Danish Meteorological Institute (Gustafsson 1993, Christensen *et al.* 1996). The model is based on the weather forecast model HIRLAM and employs the package of physical parameterizations of ECHAM4 Global Climate Model. Cumulus convection is represented by a mass-flux scheme (Tiedtke 1989) and stratiform processes by a modified version of a scheme originated by Sundqvist (1989) in which cloud content (water + ice) is prognosed. Details can be found in Roeckner *et al.* (1996). For the results presented in this paper RACMO is operated at an 18-km horizontal resolution and with a 24-layer mesh in the vertical. The model predicted fields are produced by a 36-hour hindcast, initialized by the ECMWF-analysis valid at noon on the previous date. ECMWF-analyses are also used to drive the atmospheric variables from the lateral boundaries

Case study: 4 May 2001

To illustrate the concept we have performed a case study in which we evaluated the temporal and spatial structure of model predicted LWP with ground-based and satellite inferred observations. The case had to meet the following criteria valid for an area covering at least one ground-base station: (i) non-precipitating clouds, else the microwave radiometer would not operate, (ii) no ice-topped clouds and/or cirrus, else the satellite retrieval of LPW would not be applicable, and (iii) reasonably thick clouds, at least a couple of hundreds of meters, else the model vertical resolution would be too coarse to predict any clouds. For the Netherlands, 4 May 2001 appeared to be a suitable day.

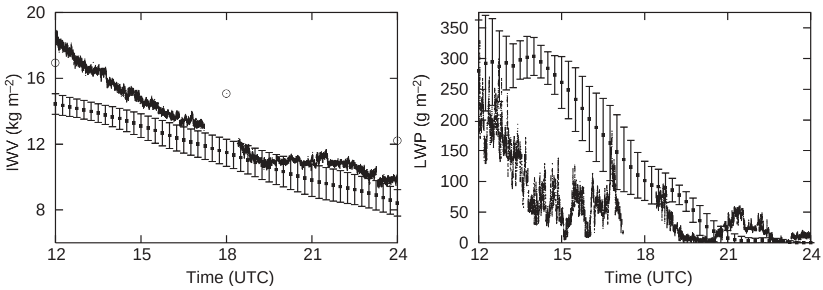

Fig. 1. Time series of IWV (left) and LWP (right) at Cabauw during 4 May 2001 from ground-based observations (dots), radiosondes (circles) and model prediction (squares). The model values are average and spatial variance over 3 × 3 model points.

Meteorological conditions

Synoptical conditions on 4 May 2001 were controlled by a high pressure system over the Azores with a ridge across Scotland towards Norway, and a belt of low pressure from northern Scandinavia across western Poland, Czech Republic and Austria towards southern France, generating convective cloud systems in central Europe and frontal cloud systems in the northern Baltic, and in the central and south eastern part of France. Governed by this pressure distribution, moderate winds (at most 10 m s^{-1}) across the Netherlands came from directions between northwest and northeast throughout a 2-km-thick layer and during the entire day. Above 3 km, winds were from the southwest. In the coarse of the day, an inversion developed over the Netherlands which gradually came down to about 1200 m. Hence, during the entire day air was advected over the relatively cool North Sea, picking up enough moisture to generate and maintain boundary-layer clouds, but not enough to generate precipitation, apart from isolated patches of drizzle. Due to persistent subsidence the inversion came down, and since the flow gradually veered to the northeast the moisture supply by the North Sea was cut off. As a result the cloud deck became thinner and tended to dissolve by the end of the day.

Measurements

Time series of vertically integrated water vapor (IWV) and liquid water path (LWP) were measured at the Cabauw site (Fig. 1), which is in the center of the Netherlands at 4.9°E and 51.9°N. The black line indicates the ground-based measurements. There is a gap between 17:00 and 18:20, which is the time, required to transmit one day of data to the central computer facility. The IWP decreases in time for both the model and the measured values. The model predicted LWP also decreases from about 280 g m^{-2} at 12:00 UTC to nearly 0 at 24:00 UTC. The measured values however, drop off much faster. At 15:00 UTC an absence of cloud water was measured for the first time, whereas the model predicted still about 250 g m^{-2}. Between 15:00 and 16:00 UTC the observed values range from 0 to 120 g m^{-2}. The low LWP values are consistent in time and seem to indicate that there is a large cloud field with low LWP that is advected over the Cabauw site.

The left panel in Fig. 2 shows the AVHRR analysis of the satellite overpass at 15:15 UTC. The grayscales represent LWP values ranging from 0 to 250 g m^{-2}. Higher values are indicated with a light gray tone. Clouds with top temperatures below 260 K are indicated in white. These areas are rejected from further analysis, because the satellite retrieval is sensitive to cloud particle phase. At the Cabauw site, the average LWP value in the one hour interval centered around the time of satellite overpass is 58 g m^{-2}. The AVHRR retrieval was tuned slightly to improve the correlation between these measurements and satellite values. The right panel in Fig. 2 shows the model results. Ice-topped clouds that are observed over the British Islands and the Middle of France are predicted well. A streak of Cirrus

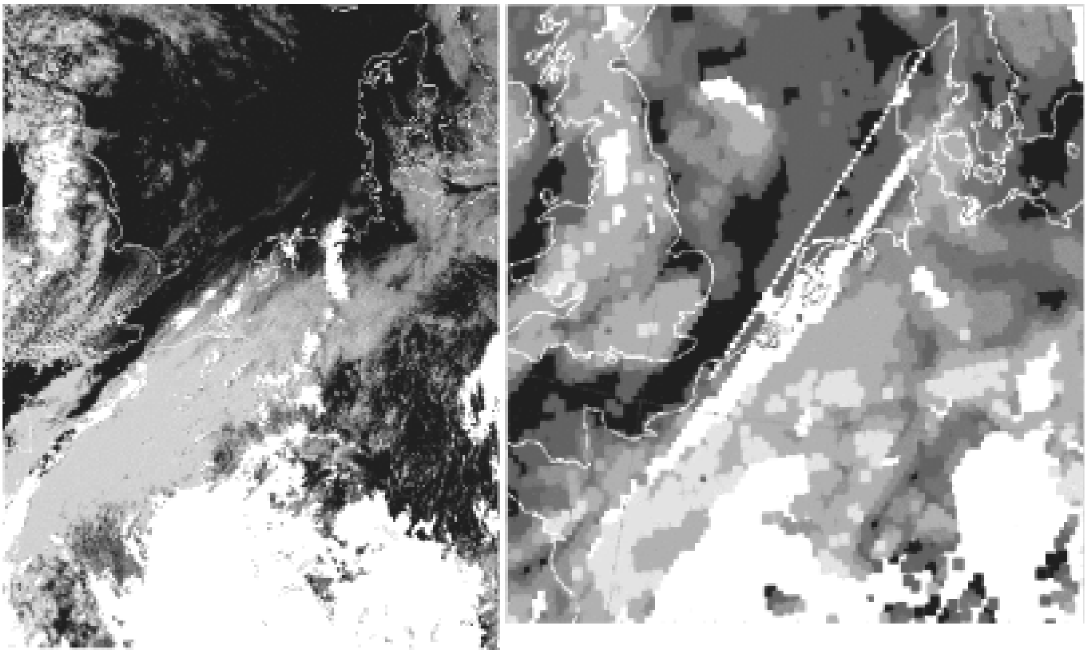

Fig. 2. Left panel shows satellite inferred LWP. The right panel shows the corresponding model prediction. The black dot near the center of the right panel indicates ground station Cabauw. Ice is flagged at a cloud top temperature of –13 °C. Ice clouds are indicated in white. Scaling: 1 g m^{-2}, dark gray < gray tone < light gray, 250 g m^{-2}. Black, cloud free.

reaching from Bordeaux to Denmark is more extended in the model. Cold clouds over the middle of Germany are shifted towards the South in the model. The model produces too much liquid water over the North Sea, but in general the large-scale features of the LWP-fields are reasonably well in agreement. This illustrates that a LWP field from satellite observations and model can be compared qualitatively. It is remarkable, that the model predicted values do not agree well with the ground-based measurements, whereas the cloud field structure of the model prediction and satellite observations are similar. In the following a more quantitative analysis is made.

Quantitative analysis

In order to make quantitative comparisons, a transect was defined that connects two ground stations: Cabauw (4.9°E and 52.4°N) and Potsdam (13.1°E and 52.4°N). The KLAROS values of LWP are also compared to the values at Potsdam to assure that the retrieval does well over the whole transect. In Potsdam there are small cumuli at the time of satellite overpass with maximum LWP of 100 g m^{-2}. The time series and satellite analysis are consistent. The LWP values from observations and model are plotted for this transect (Fig. 3). The solid line represents the AVHRR values at a pixel (1.2 km) resolution. Ice topped clouds are indicated by diamonds. The LWP values show a clear dip at 4.9 degrees where Cabauw is located. The dip is only half a degree wide. According to the ground-based measurements, this cloud field with low LWP values (0 to 120 g m^{-2}) lasted for hours. This illustrates the sensitivity to cloud variability of the comparison of time series of ground-based measurement to a spatial distribution from satellite. The dotted line indicates the observed LWP averaged over a model grid box. The values do still show small dips, but less pronounced as a result of the smoothing effect of spatial averaging. The values peek a little east of Cabauw and decrease slowly from there till about 8 degrees. From there on a rapid decrease of cloud water is observed. The long dashed line indicates the

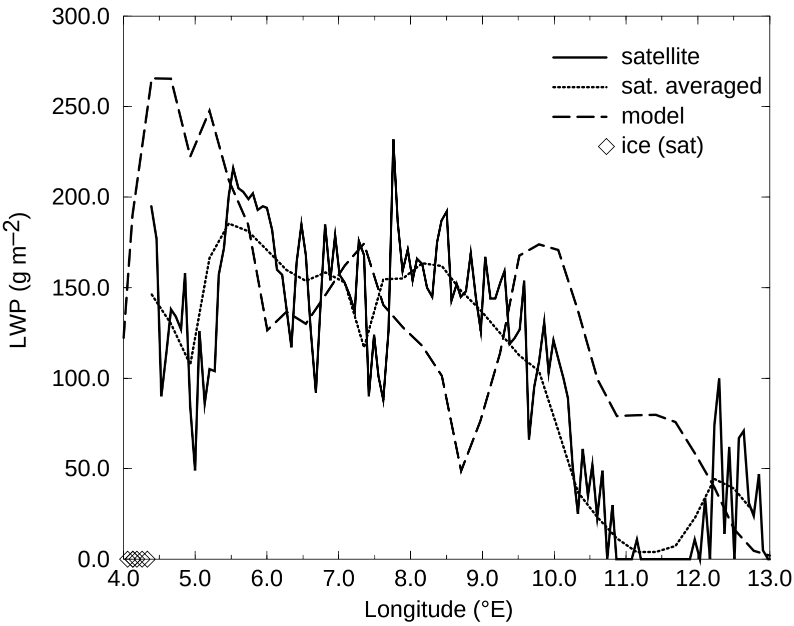

Fig. 3. LWP values between Cabauw (4.9°E) and Potsdam (13.1°E) as predicted by the model (dashed line) and as observed from satellite at measurement resolution (solid line) and at model grid resolution (dotted line). Ice clouds are indicated by diamonds.

model values. The values peek west of Cabauw and decrease till they are zero at Potsdam. So, in general the model represents the observed large-scale feature well, as was concluded from visual inspection of the spatial distributions in Fig. 3. The discrepancy between ground-based and model predicted values can be attributed to a small-scale feature in the cloud field that was located over the Cabauw measurement site. This demonstrates the strength of the combined analysis of ground-based and satellite measurements of LWP.

It is not useful to draw conclusions on the quality of the model on this single case. Model evaluation requires statistical analysis of a large set of cases. This can be monthly statistics of LWP as measured over ground stations as reported by Crewell *et al.* (2002). Also analysis of the spatial distribution of the frequency of occurrence of specific cloud types, modeled versus measured from satellite, can indicate shortcomings in cloud parameterization. The CLIWA-Net data set contains six months of cloud observations for model evaluation and thus statistical analysis is feasible.

Conclusions

A new approach to observing spatial distributions of LWP is presented. The method combines cloud analysis from ground-based microwave radiometers and satellite measurements from AVHRR. The satellite analysis is optimized such that it represents the time series from ground-based measurements. The method results in a spatial distribution of LWP of optimum accuracy. A case study was presented that demonstrates the added value of this type of observations for atmospheric model evaluation relative to direct comparison of ground-based and model predicted values. The approach to retrieval of the spatial distribution of cloud liquid water may be applicable to the platforms of the Meteosat Second Generation, MSG, because its passive imager includes the relevant spectral channels.

Acknowledgements: Members of the CLIWA-Net team are thanked for their considerable efforts in making available measurements and model results. Part of this work is sponsored by the EU under contract number EVK2CT-1999-00007.

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Received 23 January 2002, accepted 1 August 2002