DO WE NEED A CLOUD PROFILING RADAR IN SPACE?

Ehrhard Raschke and Markus Quante
GKSS Research Centre
Geesthacht, Germany

1. INTRODUCTION

The world-wide observation of cloud and aerosol field characteristics, also from satellites, is still quite imperfect and calls for more advanced technology. In particular the vertical placement of cloud layers and the vertical distribution of cloud water and ice are needed. It is feasible to obtain such information from active sounders.

Radar and lidar technology has provided spectacular views into cloud interiors since many years. Rain radar became operational and also research tools in many countries to observe precipitation events over distances as far as 150 to 200 km or to study cloud dynamics. There exist extended radar networks in Europe and North America.

A well-functioning rain radar operating in the centimetre wavelength range, is now in orbit onboard the satellite TRMM (Tropical Rainfall Monitoring Mission) and is excellently performing over a period of more than a year (Meneghini et al., 1999; Simpson et al., 1999). Higher frequency cloud profiling radar operating in the millimetre wavelength range has now been proven to reliably identify internal structures and the boundaries of most non-precipitating clouds even of those with a thickness of several kilometres (Danne et al., 1999; Clothiaux et al., 2000).

Lidar technology is also now in use in research and many applications related to clouds with lower optical depth (e.g. Sassen et al., 1990; Ansmann et al., 1992; Platt et al., 1994). A first lidar in space, the mission LITE onboard a space shuttle (Winker et al., 1996), provided spectacular views on thin cloud and aerosol layers in the troposphere and lower stratosphere (e.g. Flentje et al., 2000). It therefore is natural to apply this advanced technology of active sounders in space also to the well documented needs of observing our atmosphere on a regular basis.

2. THE PROBLEM

Clouds in the troposphere and lower stratosphere play a dominant role in the tropospheric dynamics and related heat and water exchanges (e.g. Chahine, 1992), in the chemistry of our climate system and in the maintenance of the electric field in the atmosphere. Clouds are source of almost all precipitation to the Earth's surface, which is essential for its biochemistry and water supply determining our life. Therefore their location, structure and substance (ice and/or water) must be known accurately and reproduced in all global atmospheric circulation models.

Despite of the many enhanced efforts made in improving the observation of macro- and microphysical cloud field characteristics and in modelling them in numerical weather and climate prediction models, there are still many deficiencies in the results of the latter. These uncertainties decrease the reliability of those forecasts. Numerous examples are known from the daily weather forecasts and also from intercomparisons of climate models (e.g. in the project AMIP I, Gates et al., 1999) and also in the search for an anthropogenic fingerprint in the presently observed global warming patterns (Barnett et al., 1999).

Fig. 1, shows global maps of the total radiative heating/cooling of the atmosphere as computed with many global circulation models with controlled unique boundary conditions (Potter, priv. comm. 1999) and their deviations from values of the same quantity but derived from data of the Earth

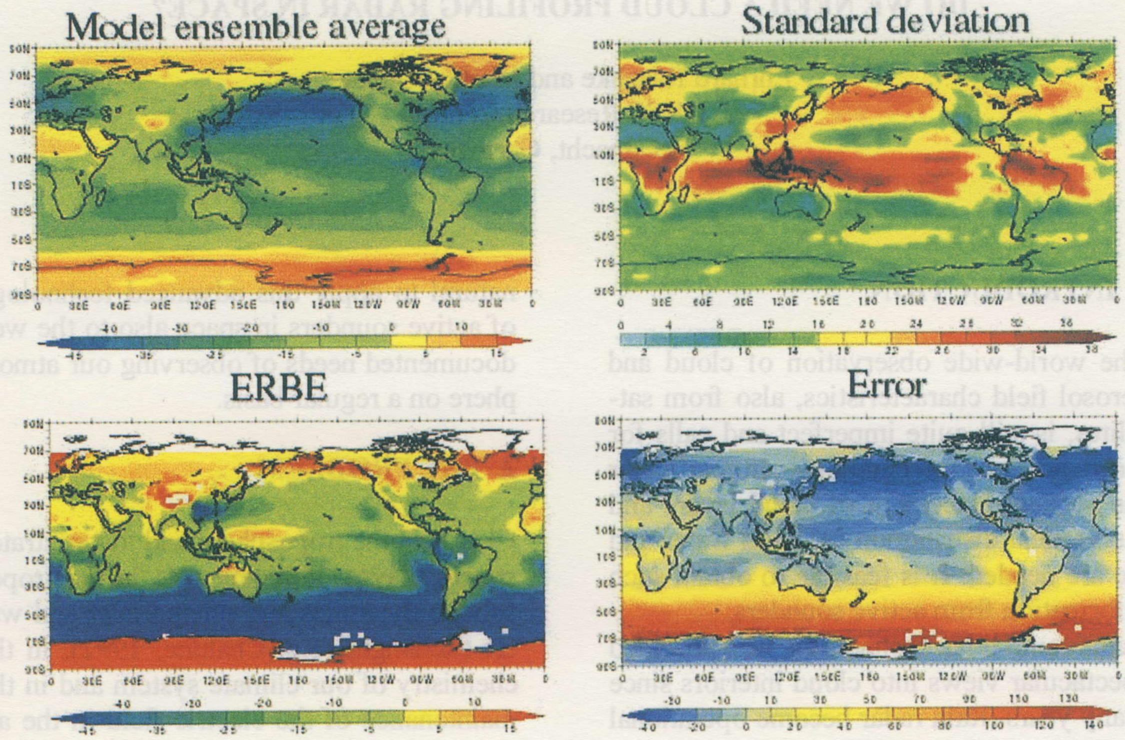

Figure1: Ensemble average and standard deviation of net cloud radiative forcing in Wm^{-2} from about 32 models contributing to the AMIP project (upper graphs). ERBE cloud radiative forcing for the model time period and its deviation from the model results, model-ERBE, (lower graphs). The figure has been provided by J. Potter (1999, pers. communication).

Radiation Budget Experiment (Barkstrom et al., 1989; Ramanathan et al., 1989). Note the large deviations over most regions of the earth, indicating that the model results contain still large uncertainties in the computation of cloud radiative heating and cooling of the atmosphere.

Therefore, the present intensive efforts made within the frame of the World Climate Research Program and its various subprograms, such as the Global Water and Energy Cycle Experiment (GEWEX) need to be continued over the next decade. One of the major deficiencies in our knowledge on cloud field characteristics is related to the vertical distribution of water and ice in cloud fields and of other microphysical properties (e.g. the particle size) determining the exchange of radiative energy. Further the vertical overlap of cloud field elements (Liang and Wang, 1997; Stubenrauch et al. 1997) and the spatial inhomogeneity of clouds is responsible for triggering the precipitation and also air-chemical processes (Jakob and Klein, 1999).

The diabatic heating/cooling of the atmosphere by absorption/emission of radiative energy and the release/consumption of latent heat depends strongly on the three-dimensional distribution of water vapour and cloud water. This fact and the various interactions with the atmospheric dynamics have been demonstrated in various studies. The sketch in Fig. 2 (taken from Webster and Stephens, 1984) illustrates clearly these considerations.

So far satellites observe cloud fields only passively in the visible, infrared and microwave spectral ranges. Their data provide only information on cloud tops and on the total liquid water content. The operational algorithms of the International Satellite Cloud Climatology Project ISCCP provide only statistical information on up to three cloud layers. No information is available on cloud bottom altitudes although this quantity is required to compute

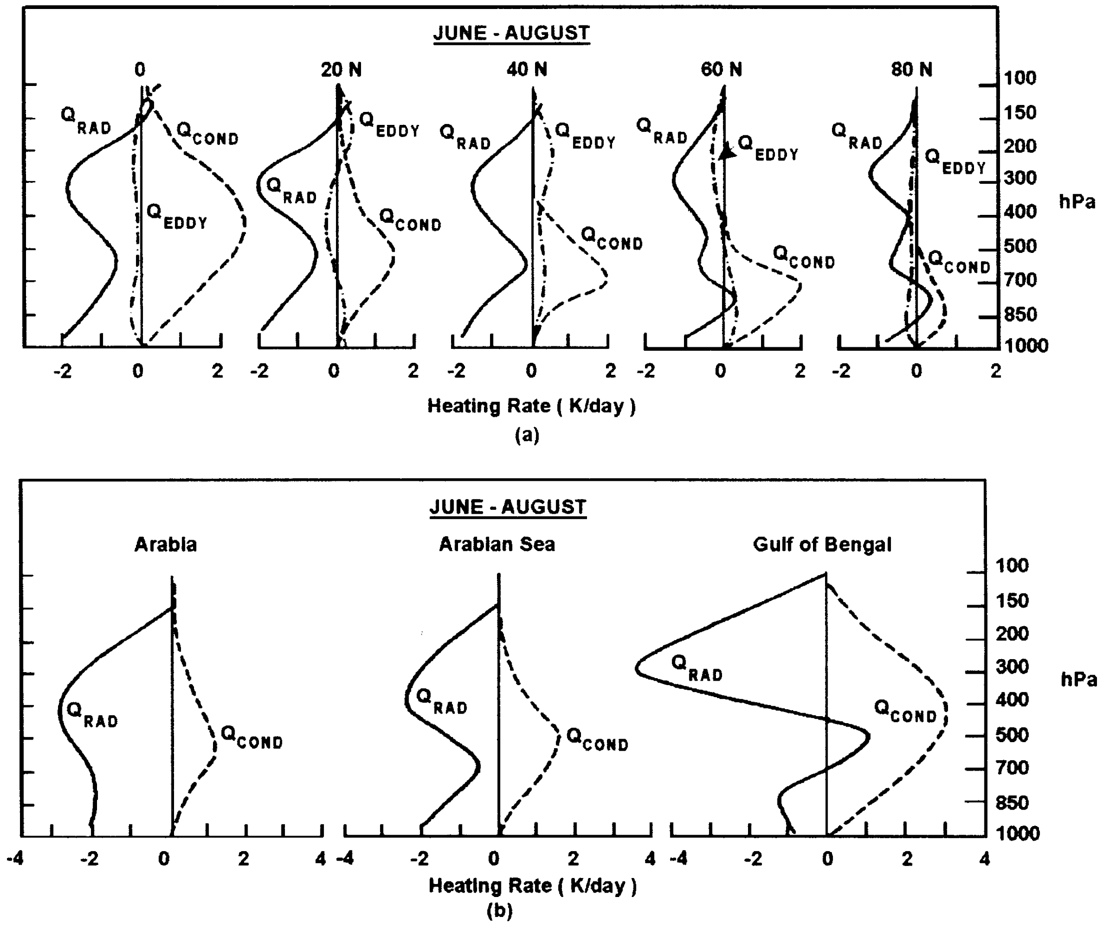

Figure 2: Heating rates due to radiation (RAD), latent heat release (COND), macro-scale transport (EDDY) for zonal means (a) and specific regions (b). These diagrams demonstrate the height dependence of radiative and latent heating, which in turn interacts with the atmospheric dynamics (from Webster and Stephens, 1984; modified by Baptista, 1999).

the downward longwave radiation reaching the ground. Only the rain radar on board the satellite TRMM provides vertical profiles of reflecting echoes in tropical rain clouds. Numerous examples of such precipitation measurements can be seen on the TRMM web sites and are discussed now also in the scientific literature. (http://trmm.gsfc.nasa.gov).

The location of lower cloud boundaries is not only of importance for climate studies and other immediate application. Its knowledge is essential for computations of the downward atmospheric heat radiation, which in turn effects various processes at ground, e.g. the evapotranspiration, recycling water back into the atmosphere.

Aerosols increase the backscattering of solar radiation and interact intensively with atmospheric water vapour during the formation of clouds. Their amount and vertical distribution can also often be related to sources (e.g.: volcanoes and biomass burning) and the atmospheric circulation patterns.

3. CLOUD PROFILING RADAR AND LIDAR ON GROUND AND IN SPACE

To measure the vertical distribution of water and ice particles, and also of aerosols in the atmosphere, already many years ago various studies have been made to demonstrate the potential value of active sounders in satellites to improve our knowledge on cloud field properties and the many processes which are involved in their formation. Their results encouraged further studies and field programmes in the US [e.g. Atlas et al., 1995; within the ARM project (Stokes and Schwartz, 1994) several cloud profiling radars (Moran et al., 1998) were deployed for long-term studies], in Europe [e.g. Fox and Illingworth, 1997; Illingworth et al., 1997; Lemke et al., 1997; Pelon et al., 1998; Park et al 1999; CLARE, 2000] and in Japan and culminated in plans for satellite projects.

In the US, with co-operation from other countries two satellites, CLOUDSAT (Stephens et al. 1998) and PICASSO/CENA (Pelon et al., 1999; Winker and Wielicki, 2000), will be built and launched in the year 2003. The European Space Agency in co-operation with Japanese institutions is planning a satellite project [at present called "Earth Radiation Mission ERM" (ESA/ESTEC, 1999)], to measure cloud characteristics with a CPR, a lidar and other passive sensors in one single satellite. These still experimental projects will be followed by operational systems, once their results have demonstrated to improve the performance and results of operational weather analyses and forecasts.

As it is shown in several other papers of this workshop, the scientific community expects from a synergetic use of simultaneous and co-located radar and lidar data, concurrently measured also with those of multispectral imagers, to derive profiles of quantities (e.g. mean particle size) which allow accurate estimates of liquid and ice water profiles and of the vertical radiative flux divergence. In addition also cloud field element overlap and spatial inhomogeneity.

4. SOME CAUTION TO EXPECTED RESULTS

We indeed expect also uncertainties in the characteristics to be derived from such data. A simulation of expected radar data is shown in Fig. 3, where an original ground-based radar sounding (a) with a vertical resolution of about 82.5 m, and a horizontal resolution of about 100 m (assuming a mean speed of the observed cloud field of 20 m/sec) has been further "degraded" to a vertical resolution of 500 m and horizontal resolution of 1 km (b), as expected from satellite-borne instruments. These latter values correspond to the margins in the above-mentioned satellite projects. A minimum sensitivity threshold of –37 dBZ (as planned for the ERM) has been applied to the degraded data. The visual inspection of this figure already shows, that various details seen in the original will be lost. A reduction from an upper sensitivity of –37 dBZ (as planned for the European Earth Radiation Mission ERM) to the lower value of –28 dBZ (as planned for CLOUDSAT radar) leads already to the loss of most thinner cloud elements (Fig. 4).

These losses, however may be compensated in part – at least for thinner clouds not covered by optically thicker clouds – when also a lidar is measuring the same cloud elements. Powerful lidar has been demonstrate in the experiment LITE (Winker et al., 1996) and also in various airborne experiments to penetrate through optically thinner clouds, like most cirrus fields an example is shown in figure 5 (see also Flentje et al., 2000).Other uncertainties will occur in the anticipated retrievals of microphysical properties of clouds from the back-scattered lidar and cloud profiling radar signals, since most cloud particles are not entirely spherical and also their refractive index may change due to the chemical composition. Further there are considerable spatial inhomogeneities in the microphysical parameters even inside of cloud decks appearing to the outside observer as quite homogeneous. Such inhomogeneities may have sizes from a few hundreds of meters to a few kilometres.

Finally, both active instruments will in the near future only provide information along the sub-satellite track. Thus new innovative methods have to be developed to incorporate information from other globally imaging satellites to extend the major two-dimensional information of cloud fields structure, as derived from the active sensors in the orbital plane, into 3-dimensional space over the areas between adjacent sub-satellite tracks. Here also the time evolution of cloud fields has to be taken into account, where the new generation of geostationary satellites will provide most helpful information.

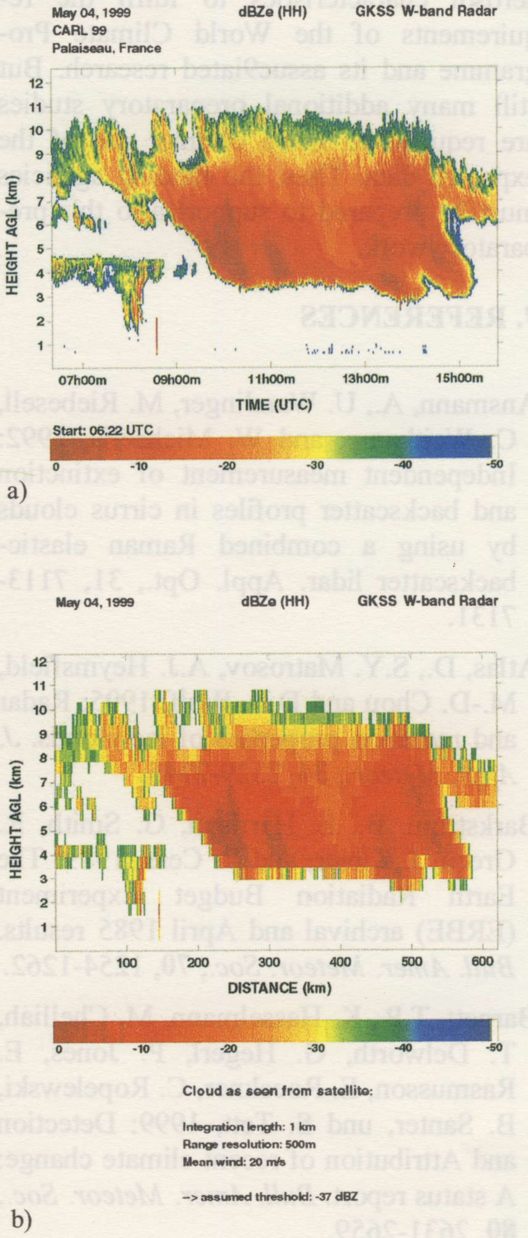

Figure 3: *(a) Cloud field as measured by the the GKSS 95-GHz cloud radar during the CARL 1999 field observation phase at Palaiseau, France. The displayed original data has a vertical resolution of 82.5 m and a temporal resolution of 5s, the minimum sensitivity is about –45 dBZ at this resolution. (b): same as a) but the data has been degraded to 500 m vertical resolution and 1 km horizontal resolution assuming a mean wind speed of 20 ms*$^{-1}$*. Additionally a sensitivity cut-off of –37dBZ (as planned for the Earth Radiation Mission) has been applied.*

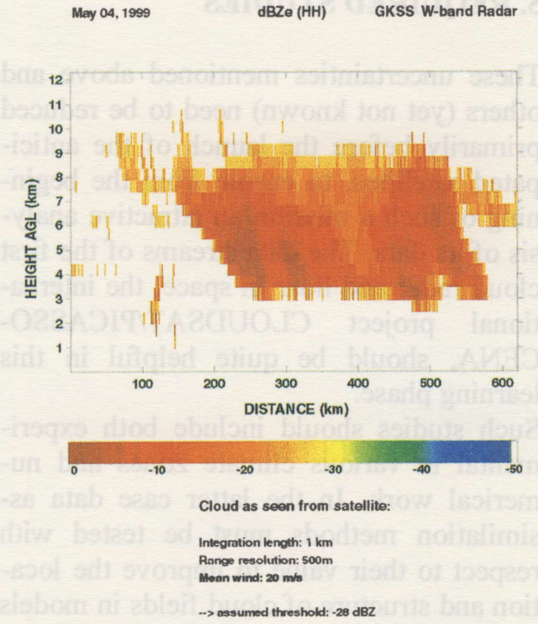

Figure 4: *Same as figure 3 b) but using a sensitivity threshold of –28 dBZ as proposed for the CloudSat radar. Note, that most thinner cloud elements on the left are lost.*

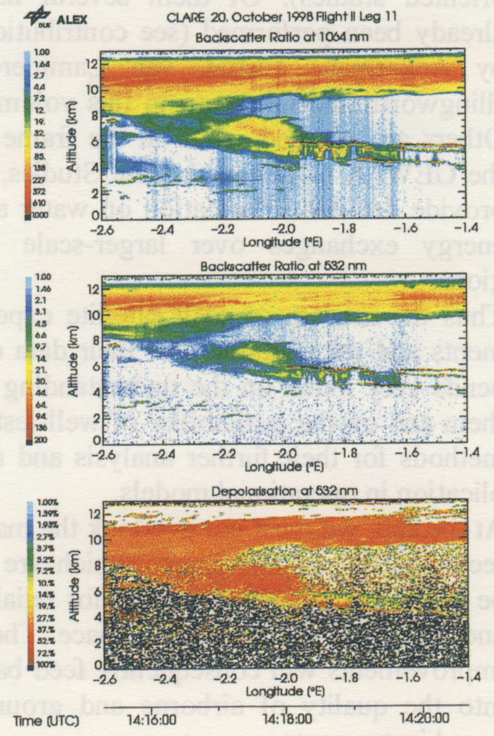

Figure 5: *Lidar backscatter ratio at 1064 nm, 532 nm and the depolarisation ratio at 532 nm for high and mid-level clouds during the CLARE 1998 campaign as measured by the DLR-ALEX onboard the Falcon aircraft (figure from Quante et al., 2000).*

5. REQUIRED STUDIES

These uncertainties mentioned above and others (yet not known) need to be reduced primarily before the launch of the anticipated satellites, to enable from the beginning of such a mission an attractive analysis of its data. The data streams of the first cloud radar and lidar in space, the international project CLOUDSAT/PICASSO-CENA, should be quite helpful in this learning phase.

Such studies should include both experimental in various climate zones and numerical work. In the latter case data assimilation methods must be tested with respect to their value to improve the location and structure of cloud fields in models when data of active sounders may become available. Such tests can be done with airborne and ground-based measurements. Studies of various retrieval techniques require data from field campaigns (process-oriented studies). Of them several have already been performed (see contributions by Ackerman, Testud, van Lammeren, Illingworth and Okamoto in this volume). Others are planned, often in the frame of the GEWEX Continental-Scale Studies, to provide detailed information on water and energy exchanges over larger-scale regions.

Thus the success of such satellite experiments and the usefulness of their data depends very much on the understanding of them and on the availability of well-tested methods for their further analysis and application in operational models.

At the end, we must not overlook the many technological improvements which are to be applied to the active sensors for reliable and multiyear functioning in space. These improvements will consequently feed back into the quality of airborne and ground-based instruments.

6. CONCLUSIONS

In concluding these considerations we state, that there is an urgent need for worldwide active soundings of cloud and aerosol characteristics to fulfil the requirements of the World Climate Programme and its assuc9iated research. But still many additional preparatory studies are required to make optimal use of the expected data. Thus, the funding agencies must be prepared to support also this preparatory work.

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