Proc. Symposium Remote Sensing of Cloud Parameters: Retrieval and Validation, pp. 5-10, 21-22 October 1999, Delft, The Netherlands.

CLOUDS AND RADIATION: INTENSIVE EXPERIMENTAL STUDY OF CLOUDS AND RADIATION IN THE NETHERLANDS (CLARA)

André van Lammeren, Arnout Feijt, Dave Donovan and Hannelore Bloemink,
Royal Netherlands Meteorological Institute (KNMI), The Netherlands

Herman Russchenberg, Victor Venema and Jan Erkelens,
Delft University of Technology, International Research Centre for Telecommunication-transmission and Radar (IRCTR), The Netherlands

Arnoud Apituley,
National Institute of Public Health and the Environment (RIVM), The Netherlands

Harry ten Brink and Andrey Khlystov,
National Energy Research Foundation (ECN), The Netherlands

Suzanne Jongen, Gert Brussaard and Matti Herben,
Eindhoven University of Technology (EUT), Faculty of Electrical Engineering, The Netherlands

Abstract

To understand and model the radiative transport in a cloudy atmosphere, information on the cloud structure, optical properties and microphysics is indispensable. In order to obtain a complete data set, four national institutes joined their efforts in the CLARA project. After the start of the preparations for the first campaign, the total number of participating national and international institutes increased to ten. In total three experimental campaigns took place in the Netherlands in 1996. An extensive set of instrumentation was employed during the experimental campaigns including lidars, radar, infrared radiometers, microwave radiometer and radiosondes. Furthermore, in-situ aircraft measurements were carried out. With an FSSP the cloud droplet size distribution and the liquid water content was measured.

The CLARA project has several sub-projects and related projects. It is not the scope of this paper to cover all the aspects. In this paper a short description of the CLARA-project is given.

Introduction

Climate model output plays an important role in present policy making discussions. The representation of clouds and of their impact on radiative transfer remains one of the greatest sources of uncertainty in present day climate models. The IPCC'95 report states: ".. the most urgent problem requiring attention to determine the rate and magnitude of climate change and sea level rise are the factors controlling the distribution of clouds and their radiative characteristics …" [IPCC, 95]. To improve the representation, of clouds in models, better parameterizations of clouds are needed, both of the macrophysics and dynamics (cloud cover, cloud structure and turbulence) and of the microphysics (droplet spectra, distinction between ice and water, role of condensation nuclei and precipitation formation). In addition, the relation between the micro- and macro properties of clouds and radiative transfer has to be clarified.

For model improvements, dedicated measurements are needed. In the Netherlands, KNMI has established a cloud detection system, which focuses on the observation of macro properties of clouds and radiation, but which also provides some information on microphysics. This network was operated continuously for a period of more than two years [Van Lammeren et al., 1999].
To test the detection and retrieval methods used in this system, more detailed field projects were needed. The CLARA campaigns focused on microphysics, their relation with the macro properties of clouds and their importance for routine observations of clouds by satellite and ground based remote sensing.

Anthropogenic aerosol particles serve as extra cloud condensation nuclei. This results in clouds with a larger number of smaller droplets for a given liquid water content. Clouds with a higher number of cloud droplets have a higher albedo. This "indirect" effect of aerosol on global albedo [Twomey, 1991] is very difficult to quantify. The characteristics of cloud droplets that are formed in different air-types (clear versus polluted air masses), are measured in the ECN cloud chamber.
It was found that the number of cloud droplets in "polluted" air is higher by a factor of four compared to that in clean air. These findings provide an upper limit for the influence of anthropogenic aerosols. However, it had to be verified by real cloud measurements, that the cloud chamber results can indeed be extrapolated to the actual atmosphere. One of the CLARA objectives was to clarify this point.

Advanced ground based remote sensing techniques like radar and lidar, as well as satellites play a crucial role in monitoring of clouds. The algorithms which are used to

Institute/University	Main Research Objectives
Royal Netherlands Meteorological Institute, KNMI	Improvement of algorithms for deriving clouds properties; Sensor Synergy; Validation of cloud representation in weather forecast and climate models.
Energy Research Centre Netherlands, ECN	Research on influence of anthropogenic aerosol on clouds
International Research Centre for Telecommunications Transmission and Radar, Delft Technical University, IRCTR	Derivation of cloud properties such as water content and droplet size from radar measurements; Sensor synergy.
National Institute for Public Health and Environment, RIVM	Determination of geometrical and optical properties from Lidar observations
Department of Telecommunication, Faculty of Electrical Engineering, Eindhoven Technical University, TUE	Determination of water vapour and liquid water content of the atmosphere from microwave radiometer measurements
Atmospheric Science Division, Rutherford Appleton Laboratory, RAL (UK)	Validation of satellite measurements made by the ATSR instrument
Netherlands Space Research Foundation, SRON	Validation of satellite measurements made by the GOME instrument
Faculty of Civil Engineering and Geosciences, Delft University of Technology, TUD	Determination of column integrated water vapour of the atmosphere from GPS measurements
Netherlands Organisation for Applied Scientific Research, Physical and Electronic Laboratory, TNO/FEL	Study of infrared properties of clouds
ESA Technology Centre, ESTEC	Sensor synergy

Table 1: CLARA participants and their main research objectives.

derive physical parameters from these measurements (e.g. liquid water path, extinction profiles, total optical depth, albedo) are based on several crude assumptions about the micro-physical properties of the cloud and the relation between these properties and the measured (macro-physical) properties. The CLARA project offers the opportunity for validation of the different remote sensing techniques with in situ measurements. Furthermore, the excellent collocation of the remote sensing instruments made it possible to develop sensor synergy algorithms. Major progress has been made in this area.

CLARA started as collaboration between KNMI, IRCTR/TUD, ECN and RIVM and has expanded into a project involving a large group of scientists from ten institutes (see table 1).

CLARA Objectives

The first objective of this project was to produce a validated data set on clouds and cloud-radiation interaction. This campaign-data set is composed of many cloud parameters derived from the different instruments (see Table 2). A platform independent JAVA interface has been developed which makes it possible to visualise the major part of the data.

The second objective of CLARA was to validate and calibrate the retrieval algorithms of various ground based and satellite remote sensing instruments.

The third objective is to validate cloud- and radiative transfer models and parameterizations of clouds and radiation.

Furthermore, the results of this project will be used to improve the quantification of the "indirect effect" of anthropogenic aerosols on radiative forcing.

Finally, the radar measurements are also used to analyse and model the propagation of radiowaves in clouds. This is closely linked to the study of the scattering of electromagnetic waves by random media as applied to retrieval algorithms in remote sensing.

CLARA Campaigns

In 1996 three experimental campaigns took place. A schematic overview of the experimental sites at which the CLARA observations took place is given in Fig. 1. At the University of Technology in Delft a wide variety of instruments were installed (see table 2). During the campaigns the ground based remote sensing instruments were operated continuously. Three radiosondes were launched from the experimental site every day. During a flight additional radiosondes were launched. In close co-operation with the weather service, detailed forecasts for water clouds were generated to enable the planning of the aircraft flights. From the aircraft the cloud droplet size distribution was measured in-situ with an FSSP-instrument. The flight patterns were planned to yield representative samples of the cloud field. The aircraft tracks were 50 km long. The tracks were perpendicular and parallel to the wind at different heights in the clouds. The crossing points of the tracks were over the experimental site were the ground based instruments were located. Due to the presence of Schiphol airport, 50 km North-East of the experimental site, air traffic control did not always allow us to fly the desired patterns. In order to study the representativeness of the cloud chamber measurements at ECN, about five flights passed over the ECN-site in Petten.

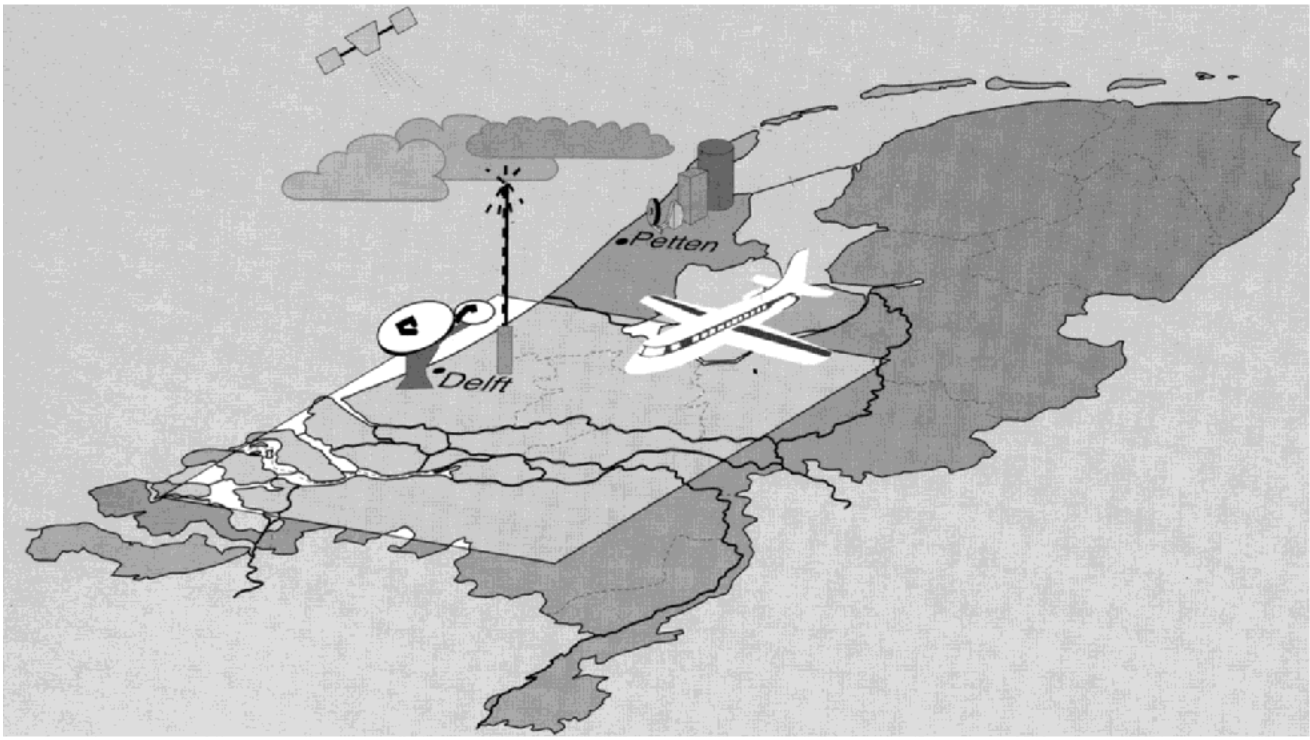

Figure 1: Overview of the experimental sites at which the CLARA observations took place. The light grey shaded area in the centre of the Netherlands indicates the Cloud Detection System-area. In Delft most Remote sensing instruments were installed (lidar, radar, radi0meters etc.). In Petten the cloud chamber was located. Aircraft observations were taken over Delft, the CDS area and Petten.

Ground-based instruments	**Observed/Derived Parameters**
Lidars: 1064, 532, 906 nm	Cloud base height, optical depth, cloud top height (for thin clouds)
Radar: 3 GHz	Cloud base/top height, vertical velocity within the cloud
Microwave Radiometer: 20, 30, 50GHz	Column integrated water vapour and liquid water
IR-radiometer: 9.6 - 11.5 micro m	Cloud base temperature
Radiosondes	Temperature, water vapour and wind profiles
GPS-receiver	Column integrated water vapour
Visual and IR-video	Visual archive of the sky
Cloud Detection System	Cloud base height and –temperature, surface radiation over an area of 120x120 km^2
Aircraft	
FSSP	Droplet size spectra for water clouds
Satellite	
AVHRR	Cloud cover, cloud top temperatures, LWP/IWP
Meteosat	Cloud cover, cloud top temperatures
ATSR	Cloud cover, cloud top temperatures, LWP/IWP
GOME	Spectra of reflected light

Table 2: Overview of the instruments which were involved during the CLARA-campaigns

The campaigns took place in April, August and November 1996. In total more than 7 weeks of continuous, collocated lidar/radar observations were taken. The aircraft measurements were taken during 15 flights, with over 40 flight hours.

Main Research topics

In this section the major research topics are briefly described. References are given in which the research is described in more detail.

- *Satellite Retrieval Algorithms Validation*

A wide range of satellite instruments are available to measure cloud properties. However, the retrieval techniques suffer from a major drawback. The microscale cloud processes introduce variability of cloud parameters at centimetres scale, which is much smaller than the instruments' instantaneous field of view. Furthermore, the microphysical properties which determine the radiative transfer are not known (e.g. droplet size, crystal geometry). As a result assumptions about the variability and microphysics have to be made in the retrieval algorithms. Some of these assumptions for the AVHRR retrieval algorithms have been tested with CLARA observations. It was shown that the results of AVHRR retrieved cloud liquid water path values for stratocumulus clouds agreed very well with the observed values from the microwave radiometer in the case that the actually observed cloud particle sizes were used. If the standard particle sizes were used, an error of 40% was introduced [Feijt et al., 1999]

- *Lidar observations of cloud geometry and cloud optical parameters*

Lidars have been used in the past for cloud studies and have proven adequate in obtaining geometrical cloud parameters [Pal et al., 92] and also to retrieve optical parameters [Ansmann et al., 92]. During CLARA a two-wavelength system was constructed and employed that stores single-shot lidar returns (High Temporal Resolution Lidar, HTRL). The high temporal resolution of the systems made it possible to study the effect of temporal averaging on the observed cloud geometry and cloud optical properties. It is shown that unless information on the variability is retained, biased estimates of the retrieved cloud parameters are made [Apituley et al., 1999**].** A theoretical study of the siginifance of multiple scattering for the lidars in the CLARA-campaigns has been perfomed [De Wolf et al, 1999].

- *Micro-physical properties of Sc clouds*

Clouds formed in polluted regions could contain more droplets and simple radiative transfer calculations show that this leads to an increase in reflection of clouds [Twomey, 1991]. In contrast to the effect on the short-wave albedo (reflectivity), an increase in droplet number concentration does not lead to higher absorption of infrared terrestrial radiation and thus does not increase the greenhouse action of clouds. Anthropogenic aerosols, thus, act (in an indirect way) as a radiative cooling factor in the atmospheric radiation balance.

In order to address this effect the relationship between the droplet number and the aerosol number was studied in a cloud chamber during a previous project. Comparison of the droplet number in clean and polluted air masses revealed that the droplet number concentration in polluted air was increased on average by a factor of 4 relatively to clean air. It was not clear, however, whether the results obtained in the cloud chamber were representative to the real clouds in the Netherlands.

During the CLARA campaigns microphysical observations were taken simultaneously in the cloud chamber and in the stratiform clouds above the chamber. From the comparison of the cloud chamber results with the airborne measurements it was concluded that the results from the cloud chamber is representative for the stratiform clouds in the Netherlands. Based on these findings the annual mean indirect aerosol forcing in the Netherlands is estimated to be -6.5 ±2.5 W/m^2 [Khlystov, 1998].

- *Cloud radar research*

The radar that is used is the Delft Atmospheric Research Radar, which differs from other cloud radars in its frequency: it operates at a frequency of 3.315 GHz instead of 35 or 94 GHz. In most cases the measurements with this radar however are similar to those of high frequency systems. Some differences may occur in the case of boundary layer clouds, where different scattering mechanisms come into play. The impact on the radar observations of incoherent particle scatter, coherent particle scatter and coherent air scatter has been investigated [Erkelens et al., 1999].
The radar is used in the retrieval of cloud properties. DARR is an FM-CW system, which makes it more flexible than the widely used pulse radars. Studies have been made to retrieve cloud boundaries [Venema et al., 1999] and cloud microphysical properties from the radar data alone and in synergy with other remote sensing data. For the cloud microphysical properties it was concluded that, due to the occasional presence of a large particle, input from other remote sensing instruments is needed in order to obtain reliable results (see also section on sensor synergy).

- *Sensor Synergy*

The CLARA data set is used as a test bed for the development of new sensor synergy algorithms that yield cloud parameters unavailable from each of the instruments alone. Because of the excellent collocation of the sensors, it is possible to derive microphysical properties.

A new method was developed and tested to retrieve cloud droplet concentration from combining microwave radiometer, lidar and radar observations. It relies on the observation of cloud size (radar), liquid water path (microwave radiometer) and optical extinction near the cloud base (lidar). Aircraft observations were used to validate the result. The agreement between in situ and remote sensing observations was reasonable [Boers et al., 1999].

Combined lidar and radar cloud measurements are capable of providing detailed height resolved information of the effective sizes of cloud particles [Intrieri et al., 1993]. However, one of the obstacles to successfully using this method is the fact that it is difficult to account for the effects of attenuation for the lidar. A novel method was developed for simultaneously determining cloud particle effective size profiles together with the lidar attenuation profile [Donovan et al., 1999]. The method has proven to be robust and has been successfully applied to several cases, mainly ice clouds.

An existing method for deriving cloud emissivity from infrared radiometer and lidar measurements has been applied to the CLARA data. The relation between the derived emissivity and the cloud liquid water path (from the microwave radiometer) has been studied. It was concluded that, for water clouds the emissivity in the infrared is independent from the particle size [Bloemink et al., 1999]. It solely depends on the water path. This opens the possibility to estimate the LWP from the derived emissivity.

Conventional linear algorithms for retrieval of water vapor path and liquid water path by microwave radiometry have the disadvantage that they are site and season dependent. More advanced algorithms use radiative transfer calculations (see e.g. [Jongen et al. 1999]). The modelled atmospheric profiles, which are used in these algorithms, can be improved by using input from other remote sensing instruments. For example, lidar and radar may improve the modelling of clouds because they can provide cloud height and thickness, and therefore also the estimate of cloud temperature will be better. This will improve the retrieval of liquid water path because liquid water absorption depends strongly on temperature in the microwave region.

It is expected that more synergy studies will take place in the near future. The results of the present and future studies is very relevant for data analysis of future satellite platforms. Plans are being developed or already approved to launch lidar and radar on separate or combined platforms (e.g. Picasso/CENA, Cloudsat, ERM, MDS II).

Concluding remarks

The CLARA project has developed from a small scale project into a major undertaking. The original number of four organising institutes increased to ten. This increase in the number of participating institutes of course also increased the number of research topics. In this paper a short overview was given. The main focus was on the research performed by the four organising institutes. However, it has to be stressed that much more work has been done with the data set then can be reported here.

The data set is a valuable data set for the development and validation of sensor synergy algorithms. Collocated lidar, radar and infrared radiometer data is available for a total period of over seven weeks. The presence of in-situ aircraft measurements and other remote sensing instruments allows for a detailed analysis of sensor synergy algorithms. Interested research groups are invited to work with the data.

For more information on the CLARA project, e.g. copy of the final report, copy of the CLARA data-set or reprints of published papers, please contact the first author of this paper or visit the CLARA web-site (http://www.knmi.nl/CLARA).

References

Ansmann, A., U. Wandinger, M. Riebesell, C. Weitkamp and W. Michaelis: Independent measurement of extinction and backscatter profiles in cirrus clouds by using a combined Raman elastic-backscatter lidar. Appl. Opt., **31**, 7113-7131, 1992.

Apituley, A., A. van Lammeren and H. Russchenberg, 1999: High time resolution cloud measurements with lidar during CLARA. Accepted for publication in Phys. Chem. Earth.

Boers, R., H. Russchenberg, J. Erkelens, V. Venema, A. van Lammeren, A. Apituley and S. Jongen, 1999: Ground-based remote sensing of stratocumulus cloud droplet concentration during CLARA-1996. Accepted for publication in J. Appl. Meteor.

Bloemink, H., A. van Lammeren, A. Feijt and S. Jongen: Active-passive sensor synergy for cloud observations; IR cloud properties and cloud liquid water. Proceedings of the symposium on “Remote sensing of cloud parameters: retrieval and validation”, Delft, The Netherlands, 21-22 October 1999.

De Wolf, D.A., H.W.J. Russchenberg, L.P. Ligthart, Estimate of the incoherent-scattering contribution to lidar backscatter from clouds, Applied Optics, Vol 38, No3, 1999, pp 585-593

Donovan, D, A. van Lammeren: Combined lidar and radar cloud particle effective size retrievals made during CLARA. Submitted for publication in Phys. Chem. Earth.

Erkelens, J, V. Venema and H. Russchenberg, 1999: Coherent particle scatter in developing Cumulus clouds. Proceedings International Conference on Radar Meteorology, Montreal, 12 – 16 July, 1999, pp 904 - 906.

Intrieri J.M., G.L. Stephens, W.L. Eberhard, and T. Uttal, 1993: A method for determining cirrus cloud particle size using lidar and radar backscatter technique. J. Appl. Meteor., **32**, 1074-1082.

Feijt, A.J., H.M. ten Brink, S.C.H.M. Jongen and A.C.A.P. van Lammeren, 1997: Validation of cloud parameter retrieval methods with objective measurements, Presented at the 1997 EUMETSAT Meteorological Satellite Data Users’ Conference, Brussels, 29 September - 3 October 1997.

IPCC’95, Intergovernmental Panel on Climate Change, 1995: IPCC Second Assessment Report – Climate Change 1995, UNEP/WMO.

Jongen, S., G. Brussaard and M. Herben, 1999: Atmospheric water vapour, liquid water and temperature profile retrieval using 20/30/50 GHz radiometer data. Workshop on Remote sensing of cloud parameters: retrieval and validation, 21-22 October 1999, Delft, The Netherlands.

Khlystov, A., 1998: Cloud forming properties of ambient aerosol in the Netherlands and resultant shortwave radiative forcing of climate. PhD Thesis Wageningen University.

Pal, S., A. Carswell, I. Gordon, and A. Fong, 1992: Lidar-derived cloud optical properties obtained during the ECLIPS program, J. Appl. Meteor., **34**, 2388-2399.

Twomey S., 1991: Aerosol, Clouds and radiation. Atmos. Environ. V25A, 2435-2422.

Van Lammeren, A., A. Feijt, J. Konings, E. van Meijgaard and A. van Ulden, 1999: Combination of ground based and satellite cloud observations on a routine

basis. Accepted for publication in Contr. Atmos. Phys.
Venema, V, H. Russchenberg, A. Apituley, A. van Lammeren and L. Ligthart, 1999: Lidar-radar synergy to study cloud geometry: measurements and new measurement techniques. Accepted for publication in Phys. Chem. Earth.

Acknowledgement

The authors would like to thank all CLARA-partners for their contributions to the CLARA-project. The CLARA project is partly funded by the National Research Program on climate change and environmental protection in the Netherlands.
More information on the CLARA project can be found on internet: http://www.knmi.nl/CLARA/