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Ground-Based Atmospheric Remote Sensing in the Netherlands: European Outlook

Herman RUSSCHENBERG[†a)], **Fred BOSVELD**[††], **Daan SWART**[†††], **Harry ten BRINK**[††††], **Gerrit de LEEUW**[†††††], **Remko UIJLENHOET**[††††††], **Bertram ARBESSER-RASTBURG**[*], **Hans van der MAREL**[**], **Leo LIGTHART**[†], **Reinout BOERS**[††], ***and*** **Arnoud APITULEY**[†††], ***Nonmembers***

SUMMARY This paper describes the contours of a Dutch monitoring and research site for climate change and related atmospheric processes. The station has large benefits for atmospheric science, both in The Netherlands and internationally. It provides a platform for collaboration in this important field, and will provide the routine observations needed to assess the impact of the different atmospheric parameters on the local climate. The station fits in directly in the selected group of global monitoring networks that are currently operational or being set up to address the problems of climate. In addition, the station can play a major role in supporting worldwide satellite measurements of climate related parameters. The only way to get a global picture of the essential climate change parameters can be found in the combination of satellite measurements and ground-based stations equipped with advanced remote sensing and in situ instrumentation. Furthermore, the combined expertise of European universities and research institutes, encompassing the whole field of atmospheric research, offers a unique chance for the training of young scientists. The research site is an attractive center for international young scientists to develop and deepen their skills.

key words: *remote sensing, atmosphere, climate change, observatory*

1. Introduction

Human activities are changing the climate. The intergovernmental panel on Climate Change (IPCC) states in its Third Assessment Report [1] that:
"an increasing body of observations give a collective picture of a warming world and other changes in the climate system."

There is a large scope of adverse effects associated to this change: ranging from regional changes in precipitation, increased frequency of 'extreme' weather and the shifting climate zones, to reductions in crop yield, decreased water availability, increased spread of diseases like malaria and cholera, increased risk of flooding of human settlements. Although many of the discerned uncertainties remain to some degree, scientific progress allows the more firm conclusions [1] that:
"There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities. Human influences will continue to change atmospheric composition throughout the 21st century. Anthropogenic climate change will persist for many centuries."

Finally, the IPCC concludes which actions are needed to address the remaining gaps in information and understanding. Further research is required to improve the ability to detect, attribute and understand climate change, to reduce uncertainties and to project future climate changes.

"In particular, there is an need for additional systematic and sustained observations, modeling and process studies, (...) to sustain and expand the observational foundation for climate studies by providing accurate, long-term consistent data including implementation of a strategy for integrated global observations, (...) to improve understanding of the mechanisms and factors leading to changes in radiative forcing, (...) to understand and characterize the important unresolved processes and feedbacks in the climate system."

Where should this additional effort been focused? The comparative study of the IPCC has shown that from the different contributors to the global mean radiative forcing the level of scientific understanding of the effect of greenhouse gases is by far larger than that of aerosols and clouds. It is clear that a specific scientific effort is needed for aerosols, including their indirect effect on cloud formation, lifetime and cloud radiative properties. Regionally, the effect of aerosols may be very large, as aerosol concentrations are spatially inhomogeneous and mostly concentrated in the developed countries, while greenhouse gases like CO_2 are well-mixed worldwide. Next to the large uncertainties related to aerosols and their interactions with clouds, all cloud related feedbacks are poorly understood and badly described by the climate models. Based on these considerations, the initiative was taken to develop the Cabauw Experimental Site for Atmospheric Research, hereafter referred to as CESAR, with the aim to:
To set-up and operate at the Cabauw site in The Netherlands an observational facility with a comprehensive set of remote sensing and in-situ equipment to characterize the state of the atmosphere, its radiative properties and interaction with

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[†] The authors are with Delft University of Technology-IRCTR, The Netherlands.

[††] The authors are with Royal Netherlands Meteorological Institute, KNMI, The Netherlands.

[†††] The authors are with National Institute for Public Health and the Environment, RIVM, The Netherlands.

[††††] The author is with Netherlands Energy Research Foundation, ECN, The Netherlands.

[†††††] The author is with Netherlands Organization for Applied Scientific Research, TNO, The Netherlands.

[††††††] The author is with Wageningen University and Research Centre, WUR, The Netherlands.

[*] The author is with European Space Agency, ESA-ESTEC, The Netherlands.

[**] The author is with Delft University of Technology-Aerospace Engineering DUT-AE, The Netherlands.

a) E-mail: h.w.j.russchenberg@irctr.tudelft.nl

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the land surface, for the study of physical processes, climate monitoring and validation studies.

2. Science Background

CESAR addresses challenging questions in atmospheric research- especially the questions that are related to the interaction between clouds, aerosols and radiation and the land-atmosphere interface.

2.1 Clouds-Aerosol-Radiation Interactions

Forecasts of the 21st century's average global warming range from 1 to 6 degrees, with large regional variations. Accurate predictions of climate variability over different spatial and temporal scales are of enormous economical and societal value, because the counter measures society has to take to cope with the changing climate will largely be based on them. The predictions rely on global numerical models. All such models divide the atmosphere into a series of grid boxes, typically 20–50 km in the horizontal and 500 m in the vertical. For each box, clouds are represented by prognostic variables such as fractional cloud cover, ice and liquid water content, particle size, together with some implied cloud overlap for each vertical stack of grid boxes. The overlap assumptions affect both the radiative transfer and the precipitation efficiency of the clouds. The models are currently hampered by large uncertainties, due to shortcomings in the treatment of cloud and aerosol processes and the lack of observations to validate cloud and aerosol parameterizations. In brief, the role of clouds and aerosols in the radiation balance can be described as follows:

Low-level clouds cool the earth by reflecting sunlight back into space. In contrast to that, high-level clouds tend to warm the earth by losing less infrared radiation to space. Hence, if cloud properties change or if the number of clouds changes in response to any future climate change, then the "cloud radiative feedback" can either amplify global warming or counteract it. Changes in the vertical profile of clouds lead to different heating rates and consequently to significant changes in the atmospheric dynamics. Aerosols can have a significant effect on the radiation balance. Like low-level clouds, white aerosols (sulphate, nitrate) can cool the earth by scattering back incoming sunlight into space. The black fraction of the aerosol (e.g. soot from diesel engines or biomass-burning) can absorb incoming and scattered solar radiation and heat the local atmosphere. In addition to these 'direct' aerosol effects, there are 'indirect' effects associated to the role the aerosol plays in cloud formation (aerosols acting as condensation nuclei). An increase in the aerosol concentration (for instance due to human activity) can have an 'indirect' effect by (i) increasing the cloud reflection properties, and (ii) changing the cloud lifetime. This indirect effect is estimated to be important, but the quantification of its impact is, as yet, highly uncertain.

2.2 Land-Atmosphere Interactions

The land-atmosphere interface is a major factor in atmospheric processes. The surface energy flux directly influences growth of the planetary boundary layer, as well as moisture, cloud formation and, consequently, precipitation patterns. The surface carbon dioxide flux and its relation to vegetation and soil processes is an important factor in the global carbon cycle and consequently to climate change. To date, atmospheric models are lacking a sufficient accurate representation of precipitation, energy surface fluxes, boundary layer dynamics and CO_2; the combination with soil hydrology introduces anomalies on the time scale of seasons. The terrestrial hydrological balance serves as a lower boundary condition in atmospheric models. The complications to implement the lower boundary condition follow from

- the temporal, non-linear, dynamics of the processes underlying the hydrological balance
- the variability in spatial behaviour of these processes
- the interactions between atmospheric and land surface processes.

Closing the hydrological balance for the area surrounding Cabauw implies measurement of, spatially and temporally, the following components: precipitation, soil moisture storage, evapotranspiration and discharge/seepage. Knowledge of the microstructure (e.g. the dropsize distribution) of precipitation is seen to be important information for making progress in the quantification process. Surface fluxes of greenhouse gasses escaping from the nearby peat-moor area in relation to local water management and hydrological response are an important issue in this respect. The 213 m-mast of Cabauw offers good opportunities for measuring regional scale fluxes of CO_2. The observations at CESAR concentrate on obtaining long term time series of the quantities that are indispensable for the evaluation of atmospheric models and satellite retrievals: surface energy fluxes, the hydrological parameters and CO_2 exchange. Upscaling of local information to the scale of a grid box in a global circulation model is of prime importance. Special attention is given to scale matching: linking the local observations of surface fluxes and retrieved model parameters to satellite derived quantities on a larger scale.

2.3 Scientific Approach

Several types of research can be distinguished: process studies, model evaluation, climate monitoring, and development of new observational techniques. For every objective, specific demands are put on the instrumentation, mode of operation and necessary infrastructure.
– Process and model evaluation studies
For process and evaluation studies it is crucial to observe as many as possible relevant parameters. These parameters will often be obtained during intensive observation periods:

campaigns with a typical duration of a few weeks to several months. Most often, several different research groups will be involved in these studies.

– Monitoring
The objective of monitoring is to establish the present state of the atmosphere and to detect long-term changes of the physical quantities. It requires observations over long time periods. It is planned to set up a climate-monitoring program for CESAR, involving many different instruments to measure the relevant parameters.

– Development of new observational techniques
Before reliable observation tools can be made, one has to establish the accuracy and reliability of the observation technique. This testing, evaluation and improving of the observational techniques can best be done at an experimental site were independent data are available for the validation. New retrieval algorithms, based on the synergy of sensors, can be developed. This enables the retrieval of physical parameters with greater accuracy than before, or even: the determination of parameters that could otherwise not be obtained.

– Validation of satellite products
Space-based monitoring of the atmosphere has been and will be important for the detection of global changes of climate and environment, as well as for accurate weather prediction. Quality assessment of the data coming from these observational platforms can only be achieved with proper validation and calibration techniques. The CESAR site offers excellent opportunities for this: the combination of in situ and remote sensing equipment provides a comprehensive characterization of the atmospheric state that is necessary for this validation.

3. CESAR Research Activities

In atmospheric science many open issues still need to be addressed. Many of these issues are directly related to the uncertainties in the prediction of global climate change; CESAR is optimally suited to address atmospheric process studies and monitoring issues. The following list is not meant to be fully comprehensive.

Direct aerosol effects. The long-term variability of aerosols is and will be monitored and analyzed- with special emphasis on the relation with the radiation balance. To this end a wide suite of instrumentation is used, ranging from in situ probes mounted on the measurement mast at the CESAR site, a sunphotometer measuring the extinction of incoming solar radiation, and lidar showing the vertical structure and optical properties of the aerosols. While past research projects have mainly focussed on understanding and quantifying the role of aerosol on the radiation balance on "clear days," Cabauw will now allow the acquisition of a year-round climatological dataset. From this, the total impact of aerosol on the regional climate can be assessed with much greater accuracy. It has been recognised only recently that in the Netherlands, elevated aerosol layers between the top of the boundary layer and the tropopause can represent more than 50% of the total aerosol optical depth. These elevated aerosols in general have a different origin, composition and optical properties compared to the boundary layer aerosols. At Cabauw, a new Raman lidar will provide the means to measure aerosol extinction in elevated layers without critical assumptions about the aerosol properties.

Cloud microphysics. An increase in aerosol concentration will change the cloud microstructure (and cloud lifetime: see below), which in turn changes the energy balance: it will cool the atmosphere. The equipment at the CESAR site will be used to monitor the long-term variability of cloud geometry and microstructure (droplet sizes and concentration) in relation to the spatial distribution of aerosol concentration. In combination with observations of radiation at several wavelengths, these data will be used to study the indirect aerosol effect. While this will largely be a monitoring effort over long time periods, so-called *intensive observation periods* aiming at the details of the processes involved will be necessary to enhance the understanding of the underlying physics.

Cloud lifetime. Cloud formation is closely linked to aerosol concentration and humidity. With the CESAR equipment set-up it is possible to macroscopically study the transformation of dry aerosols into cloud droplets and possible drizzle depletion. Process studies utilizing the CESAR equipment will aim at a better understanding of this transition and hence result in better definitions of cloud boundaries in the climate and weather prediction models.

Validation of satellite products. To date, many instruments on board of satellites are being used to monitor the earth. Satellite missions like ENVISAT and CloudSat/Calipso as well as proposed future missions like EarthCARE produce many valuable data concerning the physical and chemical status of the atmosphere. The retrieved satellite products, like radiative fluxes, cloud structure and concentration of greenhouse gases are based on assumptions regarding the vertical structure of the atmosphere. These satellite products will be validated with the data of the CESAR site.

The macrostructure of precipitation. Precipitation is normally measured by rain gauges. Nowadays rain gauges may have a high temporal resolution but continue to suffer from very coarse area coverage. This fact seriously hampers the use of this device for large-scale studies in hydrology and meteorology. Therefore there is renewed interest in quantification of precipitation by remote sensing using radars- ground based and space-borne. Long-term monitoring of precipitation around Cabauw can be achieved by the C-band Doppler radar in De Bilt combined with a network of tipping bucket rain gauges.

The microstructure of rain. Knowledge of the microstructure (the statistical distribution of the size, shape as well as the position of the particles) is seen to be important for making progress in the understanding of rainfall processes and quantification of rainfall amounts. This will be acquired with the advanced Doppler-polarimetric S-band radar TARA and a network of raingauges and disdrometers.

Surface energy fluxes. Surface fluxes of radiation and heat are continuously observed. The so-called non-closure of the surface energy budget is subject of further research. Additional monitoring of the sensible heat flux is possible by scintillometry at optical and microwave frequencies. From the combination of the two measurements the evaporation can be determined.

Spatial and temporal monitoring of the soil moisture balance. Soil moisture is a key parameter in the hydrological balance. Furthermore, the surface moisture condition is important in several remote sensing applications. Soil moisture storage varies over relatively small vertical and horizontal distances (~dm's). However, one is normally interested in an area-integrated value. Available techniques, like Time Domain Reflectometry (TDR) characterize the soil moisture condition very locally (~ dm3). In order to monitor soil moisture fluctuations at a parcel-scale a small network of six or seven vertical arrays of TDR-sensors is installed at CESAR.

Evapotranspiration is the common term in the surface energy budget and in the terrestrial hydrological balance. This component will be monitored by tower-measurements and, indirectly, by scintillometer measurements. To close the hydrological balance, the polder-area around Cabauw is defined conform a (human-made) catchment.

Development of new observation techniques

The existing measurement techniques do not always allow for observations with the required accuracy or temporal/space resolution. They will have to be improved or new techniques will have to be developed. CESAR offers unique possibilities for this: the suite of available instruments can be used to exploit new measurement strategies and methods for sensor synergy. Furthermore, new methods for data analysis and retrieval techniques can be developed. The CESAR site is set up for monitoring and for intensive observation periods. Clearly, the instruments that are used for monitoring should be operational for most of time and their specifications should not change during the observation time. This puts a constraint on the availability of these instruments for separate experiments for the development of new techniques. The data that the monitoring instruments routinely produce can, however, very well be used for the development of new retrieval algorithms. Below a list is given of the envisaged studies for new techniques.

– Cloud base and top altitude are basic cloud parameters, important for every cloud related research. However, reliable observation of these fundamental parameters already requires the combination of two different remote sensing techniques. Radar and lidar are sensitive to the size of cloud particles. The radar signal is dominated by the large particles, while the lidar signal originates from small particles. Furthermore, the lidar signal is severely attenuated by water droplets. This implies that for a ground-based set-up, the lidar will mainly see the cloud base, whereas the radar will, due to the small droplets at the cloud base, only see the upper part of the cloud. It is clear that neither the radar nor the lidar alone will measure the cloud geometry sufficiently accurate.

Table 1 Overview of the instruments.

	Instrument	**Responsible institute**
Remote Sensing Instruments	Wind/RASS profiler	KNMI
	3 GHz radar	IRCTR
	10 GHz surveillance rain radar	IRCTR
	35 GHz radar	KNMI
	Ceilometer	KNMI
	GPS-receiver	DUT-AE
	Ir-radiometers	KNMI
	μWave radiometer	ESA-ESTEC
	Raman lidar	RIVM
	Pyranometers	KNMI
	Sun photometer	TNO-FEL
	Dual-frequency Radiolink	WUR
In-situ instruments in 213 meter meteo tower	Aethalometer	RIVM
	CCN counter	ECN
	Nephelometer	TNO-FEL
	Particle counter	TNO-FEL
	SJAC	ECN
	Sonic anemometer	KNMI
	H2O/CO2 turbulence	KNMI
In-situ instruments (ground-based)	Video disdrometer	WUR
	Rain gauges	WUR,KNMI
	TDR	WUR
	Discharge meters	WUR
	Ground water	WUR
	Soil heat flux plates	KNMI
	Soil thermometers	KNMI
	Ground water sensors	WUR/KNMI

– Cloud liquid water is a prognostic variable in present day cloud parameterizations. For validation, reliable observations are needed. The retrieval of the cloud liquid water content with a passive instrument like a microwave radiometer needs independent input concerning the vertical structure of the atmosphere. Instruments like lidar and radar provides this data.

– Cloud microphysical properties like particle size and number density play a crucial role in the radiative transfer. These properties can only be derived from the surface by exploiting the synergy of different sensors like lidar and radar.

– The microstructure of rain (particle size and shape, velocity of the raindrops) is important in many fields of meteorology and hydrology. It can be obtained with Doppler-polarimetric radar. Other instruments like lidar and conventional radar can be used for validation.

– Improvement of the GPS retrieval technique of water vapour, especially with respect to the temporal and spatial resolution.

– Improvement of the measurement technique for the absorption by the black fraction of the aerosol. Current aethalometer techniques need to be improved and/or alternative techniques developed to get the measurement to the level of accuracy needed by radiative transfer models.

– Development and implementation of a raman lidar to measure absolute extinction by aerosol in the boundary layer and in elevated layers, combination with sunphotometer measurements and radiative transfer models to assess the role of different layers on the radiation balance.

– Support of the development of retrieval methods of aerosol properties from multispectral sensors on satellites. Lidars and sunphotometers will be used for validation. Aerosol optical density fields as obtained by satellites are a cornerstone in the assessment of the impact of aerosols on the regional and global scale.

Table 1 shows an overview of the instruments at the CESAR Observatory. With this set of instruments a large range of atmospheric phenomena can be measured: clouds, aerosols, rainfall, surface fluxes, soil moisture, radiation, greenhouse gases, and standard meteorological quantities as temperature and wind. Most instruments are operated by different institutes.

4. European Outlook

There are only a few atmospheric observatories in Europe and worldwide sufficiently equipped to fulfill the task needed for climate studies. Recognising the need for systematic observations and process studies, the initiative is now taken to set up a European network of advanced atmospheric monitoring and research observatories, thus building a network of European anchor stations for sustained observations in support of climate and weather studies and related atmospheric research. The network of observatories is called EurAt Observatory. The organizing consortium will aim at

- coordinated provision of experimental facilities to the scientific community;
- co-operation in the development of the observatories towards atmospheric anchor stations in support of climate studies and related atmospheric research;
- harmonizing the quality of the parameters retrieved at the different observatories; this will be achieved by harmonizing routine operation of the instruments, coordinated calibration procedures and common data interpretation procedures;
- setting up a European data archive of the atmospheric parameters retrieved at the observatories;
- ensuring dissemination of the data by close collaboration with end users of the data;
- setting up a long term observation program for climate and weather studies
- scientific collaboration in experimental atmospheric science.

EurAt Observatory consists of already existing observatories in Europe. Two categories are distinguished:
Core sites that employ an extensive suite of state-of-the-art remote sensing as well as in situ instruments to characterize the state of the atmosphere and the earth surface. The multi-sensor capabilities at these core sites enable detailed studies of the key atmosphere and land-atmosphere processes related to climate change; the physical phenomena can be studied in relation to the surrounding environment. Most notably these sites are: Cabauw (The Netherlands), Chilbolton (United Kingdom), Palaiseau (France) and Lindenberg (Germany).

Associate sites, which are instrumented with the aim to measure a limited selection of components of the atmospheric and land surface system.

All core sites have the capability to cover the entire range of areas mentioned above, or will develop it in the course of this project. This is of vital importance to meet the requirement of regional representation of data for climate studies. EuratObservatory is embedded in a larger network of data users, data suppliers and commercial companies:

- users of satellite observations
- model communities: climate, numerical weather prediction, hydrology
- small and medium enterprises
- technical research institutes

5. Examples of Measurements

The advanced instruments at a core site enable a multitude

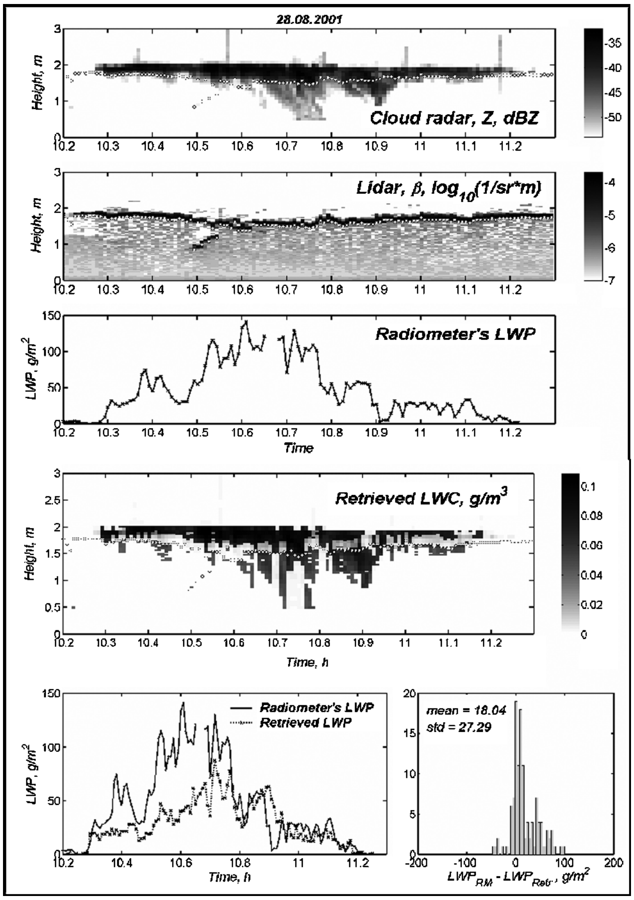

Fig. 1 Example of the observation of the liquid water content of stratocumulus clouds with radar and lidar. The top panel shows height-time profiles of the radar and lidar backscatter data as well the liquid water column observed with a microwave radiometer. From the combination of radar and lidar the liquid water profiles is derived and compared to the output of the radiometer (see lower panel).

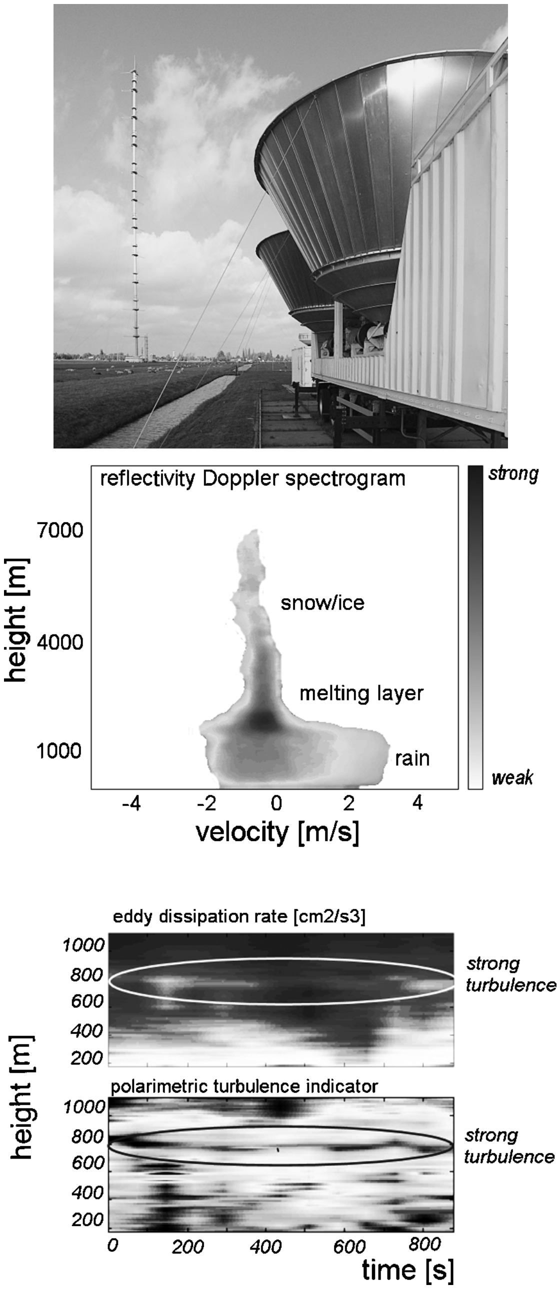

Fig. 2 Example of Doppler-polarimetric radar observations of turbulence in rain measured with the Doppler-polarimetric radar TARA, shown in the top panel. The middle panel shows a Doppler velocity spectrogram of straiform rain. The polarimetric turbulence indicator, shown in the lower panel, is derived from the combination of Doppler and polarization measaurements.

of possibilities for atmospheric profiling. In this section we will show two examples, dealing with monitoring (long term observations) and process studies.

Example of sensor synergy; Fig. 1. On the top panel a combined radar-lidar-microwave radiometer measurement of slightly drizzling stratocumulus is shown. By combining these instruments the internal distribution of liquid water inside the cloud can be obtained. This is not possible with any of the instruments individually. These observations were taken at the CESAR Observatory, but are also possible at other core sites in Europe. Long time series of such cloud parameters are very important for climate studies, as they are dominant in the atmospheric radiation balance. The data of this example was obtained by GKSS and University of Bonn in Germany, KNMI in The Netherlands. The analysis was done by IRCTR, The Netherlands.

Example of a radar process study of rain; Fig. 2. The middle figure is a spectrogram of stratiform rain, observed with the Doppler-polarimetric radar TARA- shown on the top. With the combination of Doppler and polarization measurement, information about the intensity of turbulence in rain can be obtained. An example is shown in the lower panel. Apart from monitoring, as shown in the first example, also in depth studies like these are performed at the core sites.

6. Conclusions

Driven by the need for reliable atmospheric data for climate studies, European research institutes are in the process of joining forces and capacity. This is materialized in setting up a network of atmospheric observatories spread over the continent. Many groups are involved, partially funded by the European Union in past and present framework programs. This is an important development, which has its international counter part in the US ARM Program. Intense cooperation between European and US partners is foreseen, which will lead to a global network of observatories. The first steps in this direction have already been taken: to set up a working group for advanced atmospheric profiling stations under the flag of the Global Energy and Water Cycle Experiment GEWEX.

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More information: www.cesar-observatory.nl

Herman Russchenberg is head of the Remote Sensing Sector of DUT/IRCTR. He has extensive experience in remote sensing of clouds and precipitation with ground-based radar, lidar and microwave radiometry. He is one of the initiators of this work in Europe. He is experienced in theoretical and experimental research of the scattering process and the retrieval of geo-phyiscal parameters. He plays a key role in the Cesar-consortium, and has recently taken the initiative to set up a European network of atmospheric observatories.

Fred Bosveld is working in the field of atmospheric boundary layers and their interaction with the land surface. He became specialised in forest meteorology during the 1990's. Since 1995 research activities shifted towards the KNMI meteorological site Cabauw. Here research focus is on the budgets of momentum, heat, water vapour and CO_2 and the representativeness of local flux.

Daan Swart is a senior scientist in the Laboratory for Environmental Measurements of RIVM (the Dutch National Institute for Public Health and the Environment) and project leader of the RIVM Remote Sensing research. He studied Physics at the University of Utrecht, where he graduated in 1985 on a thesis on LIDAR research.

Harry ten Brink Photograph and biography are not available.

Gerrit de Leeuw is responsible for 'Environmental Effects and Research' in the Electro-Optical Systems Group of the Observations Systems Division of TNO-FEL. His primary interest are physical processes in the atmosphere, with applications in the fields of radiative effects, pollution (air and water: effect on eco-systems and air quality) and atmospheric effects on electro-optical systems performance.

Remko Uijlenhoet holds both an MSc-degree (specialisation: hydrology and water resources) and a PhD-degree from Wageningen University, The Netherlands. He has been actively involved in research on various aspects of radar hydrometeorology since 1990 and has participated in several EU-projects on the hydrological application of weather radar.

Bertram Arbesser-Rastburg
Hans van der Marel
Leo Ligthart
Reinout Boers
Photographs and biographies are not available.

Arnoud Apituley studied physics at the Delft University of Technology, where he graduated on a thesis on waveform measurements in optical waveguides. He has fourteen years of research experience in LIDAR for applications including tropospheric ozone, clouds and aerosols.