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In Higher Spheres

40 years of observations at the Cabauw Site

Wim Monna and Fred Bosveld

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Cover photo
The Cabauw mast seen from the remote sensing site. On the left the Humidity and Temperature Profiler (HATPRO), a microwave radiometer from KNMI. To the right of the mast a microwave radiometer from the European Space Agency: the Atmospheric Propagation and Profiling System (ATPROP). On the foreground a CT75 Lidar Ceilometer from KNMI and behind it a Present Weather Sensor from the Wageningen University & Research centre. On the right on top of the small mast a GPS receiver from the Delft University of Technology for Integrated Water Vapour measurements.
Photo: Jacques Warmer, KNMI, 2011.

In Higher Spheres

40 years of observations at the Cabauw Site

Technological developments and scientific results

The culmination of an instrumental tradition of 150 years at KNMI

Wim Monna and Fred Bosveld

Contents

Introduction

In 1964 the need for high measuring masts for studying the dispersion of air pollution and the wind climate was discussed at KNMI and estimates were made of the funds needed. This led to the construction of an 80 m high mast in the city of Vlaardingen in the highly industrialized area near the city of Rotterdam. Using the expertise developed in Vlaardingen, the Cabauw-mast was designed and built. A continuous measurement programme with analogue data registration was started on October 26, 1972. In the following years new and better instruments were installed including advanced remote sensing systems in the last 20 years. The development of digital data registration techniques and the increasing data storage capacity allowed the operation of much larger observational programmes, so that new and challenging research themes could be tackled. Cooperation with other research institutes and with universities led to the establishment of CESAR (Cabauw Experimental Site for Atmospheric Research) in 2002. CESAR has developed into a high-tech observatory with an international reputation and plays a key-role in various international research programmes and networks on regional and global scale. The measurement programme comprises the physical and chemical aspects of the entire atmospheric column and its interaction with the earth surface.

On October 26, 2012, at the occasion of the 40th anniversary of the observatory, an international symposium was organised at Cabauw[1].

In this report we review the technological developments and the research themes that were developed at Cabauw in the past 40 years. Regarding the research during the first 24 years, we gratefully made use of an overview article about Cabauw by Van Ulden and Wieringa (1996) at the occasion of the 25th anniversary of the mast.

In the Appendix early work done at KNMI to obtain meteorological information at higher altitudes is presented. This illustrates that KNMI has a tradition of more than 150 years in the development and deployment of meteorological instruments and methods of observation, which eventually culminated in the high-tech Cabauw-observatory.

This report is an extended version of an article in Dutch in Meteorologica (Monna and Bosveld, 2013), the magazine of the "Nederlandse Vereniging ter Bevordering van de Meteorologie (NVBM)", the Dutch Society of the Promotion of Meteorology.

[1] http://www.knmi.nl/bibliotheek/knmipubDIV/40_Years_Cabauw_Observatory.pdf and http://www.knmi.nl/samenw/cesar/cabauw40/index.php

First meteorological measurements on high masts

In the 1960's KNMI initiated experimental programmes to study the interactions between weather, land surface and the atmospheric boundary layer during all seasons. Initial observations were made on existing TV and broadcasting masts (Rijkoort, 1961), but from 1965 onwards the 75 m high radio mast of Noordwijk Radio at the North Sea coast was also used. In 1967 measurements started on an 80 m high lattice mast in the city of Vlaardingen, which was built especially to study the climatology of air pollution in the highly industrialized area near the city of Rotterdam (Rijkoort et al., 1970). Using the experience of these first observational programmes, a decision was made to build a 213 m high mast at a carefully selected site for the study of the dispersion of air pollution. The building of the mast started October 21, 1969 (figure 1). In 1972 the mast in Vlaardingen had to be dismantled because of corrosion due to air pollution. In the same year the first observations started on the new 213 m mast in Cabauw. The observations at Noordwijk were terminated as well.

Figure 1
Building the mast. The mounting of a prefabricated section.

Location and construction of the Cabauw-mast

A suitable location was found in the western part of the Netherlands, just west of the village of Lopik, 20 km southwest of the city of Utrecht and 45 km from the North Sea. The coordinates are 51.971 °N and 4.927 °E. To avoid confusion with the TV mast in Lopik, we use the name Cabauw-mast, after a village west of the mast. The location is representative for the polder landscape in the western part of the Netherlands. Within a radius of 20 km the surrounding land mainly consists of pasture with numerous small ditches used for cattle grazing (figure 2). The immediate surroundings to a distance of at least 400 m from the mast are flat and homogeneous grass land. At greater distances we find windbreaks, and to the east the small houses of Lopik. Towards the west, which is the dominant wind direction, the

Figure 2
Aerial photograph of the mast, showing the typical pattern of pasture and ditches, and river Lek in the background. Picture taken during the EUCAARI-IMPACT campaign. Photo: Wouter Knap, KNMI.

landscape is open grass land up to a distance of 2 km from the mast. Because of this open and homogeneous landscape, instruments at the top of the mast sense with westerly winds the same landscape type as instruments placed on lower levels. The soil consists of a 0.6 m thick layer of river clay, on top of a thick layer of peat. Because the water level in the ditches is regulated, the water table is mostly less than 1 m below the surface, but can be close to the surface during wet periods. It is important that the topography around the mast remains unchanged throughout the years to allow for meaningful intercomparison of measurements made in different years. Therefore regular interaction with local and regional governments is necessary to keep abreast of local planning intentions and to influence planning decisions. The most important changes in the surroundings since 1972 were the removal of the row of trees along the road just east of the mast in March 1975 and the extension of the village of Lopik into the direction of the mast in the period after the year 2000.

The mast consists of a closed steel cylinder of 2 m diameter guyed at 4 levels, with an elevator inside. Every 20 m, 9.4 m long booms are mounted into 3 directions. This enables measurements that are not disturbed by the mast-cylinder for any wind direction (Wessels, 1983). The booms can be hydraulically swivelled-up to allow for maintenance and replacement of instruments from a balcony above. Zeevenhooven (1975) gives an extensive technical description of the construction of the mast (in Dutch). At the foot of the mast a streamlined laboratory of 200 m^2 for data registration and maintenance was built. Because of this building no undisturbed measurements can be made below 20 m. Therefore, in 1977 20 m high masts southeast and northwest of the main mast were constructed to avoid the impeding obstructions of this laboratory. Furthermore, a special terrain was prepared at a distance of 200 m north of the mast in order to initiate observations of the surface energy budget.

First results

The first observational programme was run in 1973 (Van Ulden et al., 1976). In order to understand the dispersion of air pollution, the transport properties of the atmosphere in relation to the weather conditions were studied. As no suitable data registration system was available on the market, a system consisting of 27 measuring channels was developed at KNMI (Van Gorp, 1976). Two-minute analogue mean values were registered on paper tape. At each measuring level wind direction and wind speed were measured on three booms, thus assuring that for any wind direction an instrument was available which was not disturbed by the mast.
As for temperature measurements it was found that the required accuracy could be realised with one instrument on one boom. The booms created also the unique opportunity to measure vertical profiles of horizontal visibility by mounting transmissometers on the boom tips (figure 3).

Wind direction and wind speed were measured at 10, 80 and 200 m, and temperature at 2, 9, 20, 40, 80, 160 and 200 m. In addition, humidity (3 levels), visibility (8 levels), global radiation (2 and 215 m), radiation balance, precipitation and SO_2 concentration (3 levels) were registered on analogue recorders. The sensors for wind (figure 4) and temperature were developed and built at KNMI. Vertical temperature differences in the profile are often very small. To achieve the desired accuracy of less than a tenth of a degree the design of the ventilated psychrometer for temperature measurements (figure 5) required special attention to limit radiation errors (Slob, 1978). The vertical temperature differences were measured directly with thermocouples (figure 5). Also, state-of-the-art low-noise and very stable amplifiers had to be built.

The first observation period was focused on the nocturnal boundary layer. An interesting result was the frequent observation of a low level jet (figure 6). By combining observed profiles of wind and temperature more insight could be gained on the decoupling of the mixing layer from

Figure 3
Transmissometer to measure visibility. Some instruments were also installed along the mast to measure the vertical profile of visibility. Photo: November 1975.

Figure 4
Wind vane and cup anemometer. Photo: J.G. Van der Vliet, KNMI, August 1973.

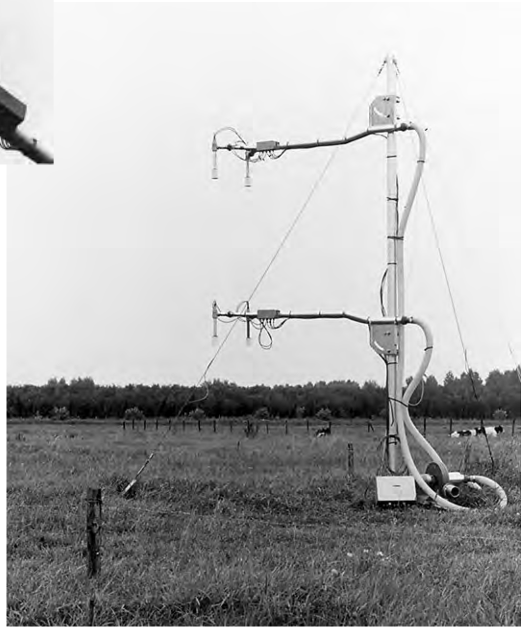


Figure 5
Ventilated and shielded psychrometers to measure vertical gradients of dry- and wetbulb temperature with Cu/Co thermocouples. These were also installed along the mast to observe vertical profiles. Photo's 1975.

the surface due to night-time radiative cooling (Van Ulden and Wieringa, 1996).

From the beginning the National Institute for Public Health and the Environment (RIVM) contributed to the measurement programme with continuous observations of trace gasses. Utrecht University also contributed with similar measurements.

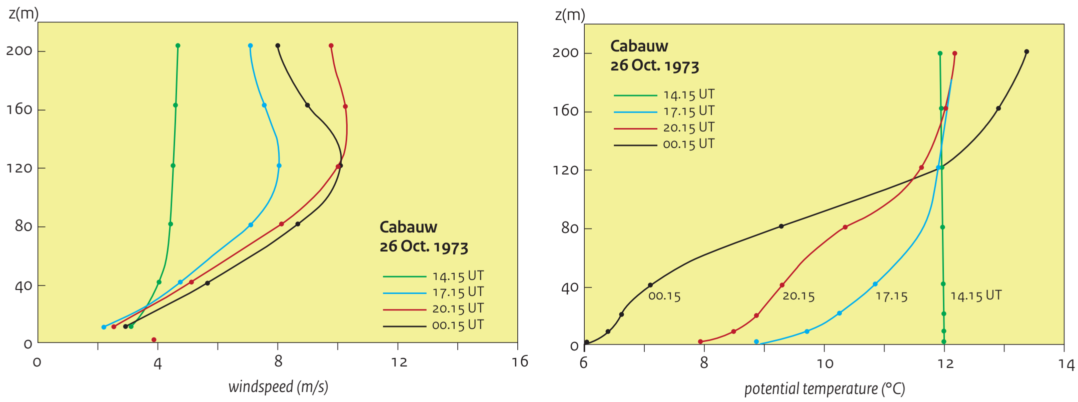


Figure 6
Example of the diurnal cycle of the vertical profiles of wind and potential temperature, showing the development of a low level jet at 120 m altitude. After Van Ulden and Wieringa, 1996.

A more extensive measurement programme

In order to understand the dispersion of air pollution a more comprehensive continuous measurement programme was run from March 1977 until March 1979. In this period a number of special experiments was carried out, during which in addition to the mean profiles also profiles of turbulent fluxes were measured. To this end a fast responding trivane measuring also the vertical component of the wind (Wieringa, 1967), and a fast responding psychrometer (Kohsiek and Monna, 1980) were developed and built at KNMI. With these instruments (figure 7) turbulent fluxes of sensible and latent heat and of momentum could be recorded. The components of the surface energy budget were measured on a carefully controlled terrain for micrometeorological measurements. Radiosondes were launched to study the coupling of the boundary layer with the atmosphere above. In cooperation with KEMA experiments were executed to study the dispersion of gasses from high sources, using SF_6 as tracer. With some interruptions for maintenance these observations continued until 1984. An overview of the continuous observations is given by Wessels (1984).

Figure 7
To measure turbulence the so-called bivane (also called trivane) was developed. It could rotate along a vertical and a horizontal axis and was equipped with a propeller. Together with a fast response dry- an wetbulb thermometer vertical fluxes of momentum, sensible heat and evaporation could be derived. These instruments were only installed for special campaigns. Photo May 1978.

Between 1984 and 1986 a major revision of the measuring infrastructure was carried out.

In this period several papers were published that received international recognition. We mention here four of them.

1) Beljaars (1982) studied the influence of obstacles in the terrain on vertical profiles and fluxes. It was found that in perturbed areas the flux-profile relationships deviate substantially from those over uniform terrain.
2) De Bruin and Holtslag (1982) compared two methods to determine the surface fluxes of sensible and latent heat during daytime. The relatively simple (modified) Priestly-Taylor evaporation model was found to have a similar skill as the Penman-Monteith approach.
3) Investigating local scaling in the stable boundary layer, Nieuwstadt (1984) showed that dimensionless combinations of turbulent variables can be expressed as a function of a single stability parameter measured at the same height.
4) Van Ulden and Holtslag (1985) used Cabauw data to develop a scheme for estimating surface layer similarity parameters from routine observations of cloud cover, mean wind, mean air temperature and estimated effective terrain roughness. With simple parameterizations net radiation, evaporation and soil heat flux were estimated. Monin-Obukhov similarity functions were used to derive profiles of wind speed and temperature. This work formed the basis of many air quality models.

The continuous measurement programme from 1986 until 1996

As detailed representation in atmospheric models of small-scale physical processes in the atmosphere evolved, validation of these aspects of models with observations became necessary. In this context, the focus of experimental research at KNMI shifted towards the evaluation of weather models. To facilitate this research a continuous observational programme was run for 11 years, creating a database with observations of mean profiles and surface parameters, radiation, surface fluxes, and soil heat flux and soil temperature. In this period the first remote sensing instrument operating on a continuous basis was introduced, namely a SODAR (Sound Detection and Ranging) to observe the height of the inversion at night. During this programme also several experiments were carried out. Sonic anemometers became available to measure turbulence. A sonic anemometer also measures temperature fluctuations, thus providing observations of the sensible heat flux. To measure the latent heat flux a fast responding Lyman-alpha hygrometer was developed which could be mounted close to the sonic probe (Kohsiek, 1987a). A sensor for measuring fast temperature fluctuations was also developed (Kohsiek, 1987b). By mounting this sensor together with a commercially available Lyman-alpha hygrometer close to a sonic probe (figure 8) the fine scales of turbulence could be measured.

Figure 8
Sonic anemometer with Lyman-alpha hygrometer and fast response temperature sensor. Photo 1988.

Figure 9
Infrared sensor mounted on a sonic anemometer.

Figure 10
The scintillometer receiver mounted on the 40-m platform of the Cabauw mast.

A new SODAR with Doppler capability was purchased to observe wind profiles up to several hundreds of meters. See Monna and Van der Vliet (1987) for a description of this programme. In the years after the start of this programme some additional instruments were installed. Kohsiek (2000) developed an infrared sensor with fiber optics that could be mounted close to a sonic anemometer (figure 9) to measure H_2O and CO_2 fluxes. Also a scintillometer was developed (Kohsiek et al., 2002) to measure the path-averaged vertical flux of sensible heat between the Cabauw-mast and the TV mast at the village of Lopik (figure 10).

The analogue data were stored on a DEC PDP11 computer. Channels were sampled every 3 seconds and 10 minute mean values and standard deviations were computed. A telephone connection was used to transmit the data to KNMI. After a thorough and partly manual quality check the surface fluxes were computed, and the data were stored on an optical disc. Because of the near real-time transport of the data to KNMI the profiles of wind and temperature could now be used for weather forecasting. Also the data proved to be valuable for wind energy research. An extensive description of the instrumentation and data processing is given by Van der Vliet (1998).

As an example of research with this database we mention the PILPS project (Project for Intercomparison of Land-Surface Parameterization Schemes). Cabauw data for 1987 were used as input for 23 land surface schemes designed for use in weather and climate models. These schemes were evaluated by comparing their outputs with long-term measurements of surface sensible heat fluxes into the atmosphere and the ground, and of upward longwave radiation and total net radiative fluxes, and also by comparing them with latent heat fluxes derived from surface energy balance observations. Analyses focused on the energy budget, the water budget, and their linkage. Significant differences were found between observations and models, facilitating further development of these schemes (Chen et al., 1997).

Wind observations at Cabauw have found their way into many disciplines like building regulation, aviation and wind energy. In the characterisation of the wind field over the Netherlands above the standard synoptical height of 10 m Cabauw has played a crucial role (Wieringa, 1988). Frequency distributions of winds at heights up to 200 m have been derived and characterized by Wieringa (1989). In 1996 a year of turbulence observations was obtained with K-vanes on the mast and analyzed in terms of roughness characteristics around the Cabauw site (Verkaik, 1998), (Verkaik and Holtslag, 2007).

The Tropospheric Energy Budget Experiment TEBEX, 1994-1996

As global warming, climate change and the influence of mankind on climate became important international issues, KNMI research focussed more and more on climate change. It became clear that an adequate representation of clouds and their interaction with radiation is essential in climate models. As part of the Tropospheric Energy Budget Experiment (TEBEX) (Stammes et al., 1994) an intensive measurement campaign was started in 1994 which lasted two years. In the following years this programme was continued in an international context, surch as the Baltex Bridge Campaign.

A cloud detection network covering 130 x 130 km was established, comprising 12 sites, each utilizing a cloud-lidar, a narrow-band infrared radiometer and a short-wave pyranometer. This network included a site near the village of Garderen in a forest and Cabauw (grassland), where all components of the balances of radiation and energy were measured. The network also included the synoptic station De Bilt (KNMI) where a radiosonde was launched four times a day. At Cabauw a wind profiler (1290 MHz) plus RASS (Radio Acoustic Sounding System) was installed to obtain detailed observations of the boundary layer. Satellite observations were added to the database. These data were used to validate cloud detection algorithms based on satellite observations (Feijt et al., 1999), and for improving the detection of clouds by combining satellite and ground-based observations (figure 11) (Crewell et al., 2004). Also the representation of clouds in climate models was evaluated by Van Meijgaard et al. (2001).

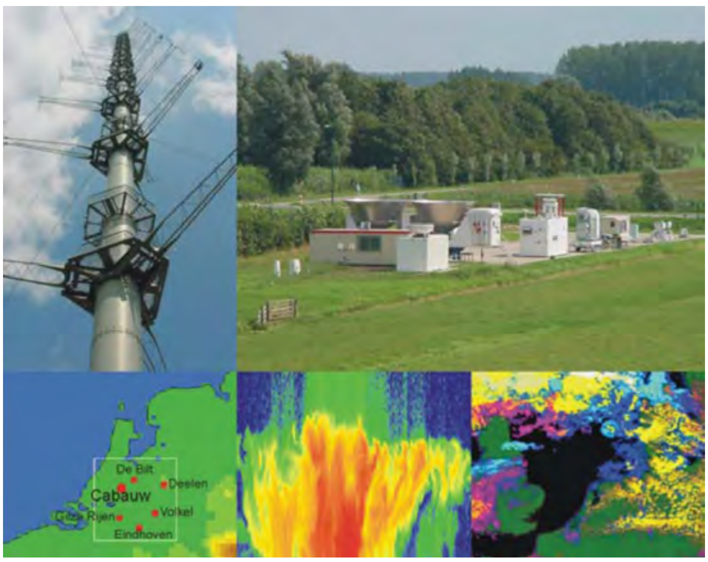


Figure 11
Schematic overview of the Baltex Bridge Campaign (Sept./Oct. 2001), an integrated approach for a better understanding of clouds. Cabauw is part of a regional network consisting of 10 remote sensing stations. Aircraft observations, satellite analyses, and atmospheric modelling were carried out with Cabauw as centre. The upper panels show the Cabauw mast and the remote sensing site. The lower panels show stations of the regional network, a radar measurement of a cumulus mediocris, and a cloud classification from satellite AVHRR measurements. From Crewell et al., 2004.

National cooperation, the CESAR Consortium; 2002 and beyond

Figure 12
The mast in January 2005. On the foreground the BSRN instruments. Photo: Wouter Knap, KNMI.

After the TEBEX experiment the measurements at Cabauw were interrupted for a renovation. The infrastructure for data transport and data acquisition of the continuous observations was no longer state-of-the-art and maintenance had become troublesome. A modernization programme was started in the course of the year 2000.

International research showed an increasing demand for more detailed information on the atmosphere for the development of weather, climate and air quality models. In addition, monitoring of essential climate variables, as defined by WMO, became necessary. The development of new measuring techniques and methods enabled the observation of an increasingly wider field of atmospheric properties. To participate in the Baseline Surface Radiation Network (BSRN) special instruments were installed to observe solar and atmospheric radiation with instruments of the highest available accuracy and with high time resolution (figure 12). It became clear that this broad range of observations needed, requiring all sorts of expertise, could neither be carried out nor interpreted by one single institute. Emerging from existing projects and based on cooperation between institutes with complementary expertise, the CESAR consortium was established in 2002. The CESAR Consortium (Cabauw Experimental Site for Atmospheric Research, http://www.cesar-observatory.nl) consists of four major research institutes {KNMI, the National Institute for Public Health and the Environment (RIVM), the Netherlands Energy Research Centre (ECN) and the Netherlands Organization for Applied Scientific Research (TNO)}, the universities of Delft, Wageningen and Utrecht, and the European Space Agency (ESA). All relevant atmospheric observations carried out by these institutes were now concentrated at the Cabauw site. Stimulated by

the national programme Climate for Space, and also building on earlier forms of international cooperation in COST[1] projects, CESAR developed into an internationally front ranking atmospheric observatory for the study of the atmospheric column and its interaction with the land surface, and became the centre for experimental atmospheric research in the Netherlands. The 213 m mast is still the eye catching feature at the site, but throughout the years observations with remote sensing instruments became key-elements in the measurement programme.
As many high-tech instruments are available on the market nowadays, the in-house development of instruments at KNMI is no longer necessary. Exceptions are the Raman lidar for aerosol, water vapour and cloud measurements, which was developed by RIVM and KNMI in the years 2006 – 2009 (Apituley, 2009) and the cloud radars TARA and IDRA, developed by the Delft University of Technology.
The CESAR web site www.cesar-observatory.nl gives detailed information on the instrumentation used at present.

Many CESAR-observations are available in the CESAR-database (www.cesar-database.nl). The CESAR partners use these data for a wide range of applications, such as:

- Monitoring of long-term trends of climate variables in the atmosphere
- Validation of satellite observations and retrieval products
- Studies of processes in the atmosphere and at the land surface for the improvement of weather, climate and air quality models
- Evaluation of weather, climate and air quality models
- The development, implementation and validation of new methods of observation
- Education of young researchers at post-doc, PhD and master level

CESAR is part of a number of international networks (table 1). CESAR-data are included in major international data bases, and are used by a great number of researchers throughout the world. This is in line with the KNMI tradition of making Cabauw data freely available for research.

Since 1995 thirteen international measurement campaigns have been carried out (table 2), where CESAR either hosted the campaign, or participated as observatory. Research topics varied widely, ranging from macro- and microphysics of clouds with remote sensing instruments and airborne in situ sensors, to the validation of satellite observations with ground based remote sensing measurements. During these campaigns special instruments were usually installed to complement the continuous measurement programme. On some occasions also measurements with aircraft were carried out. For the IMPACT campaign in 2008 an aerosol inlet was installed at

Table 1
The international networks represented at Cabauw.

Acronym	Since	Organisation	Description
CWINDE	1999	COST/EUMETNET	The Co-Ordinated Wind Profiler Network in Europe
CLOUDNET	2001	EU	Development of a European pilot network for observing cloud profiles
CEOP	2003	GEWEX	Coordinated Energy and Water Cycle Observation Project
CARBOEUROPE	2004	EU	GHG surface flux network
EARLINET	2004	EU	European Aerosol Research Lidar Network
EMEP	2005	CLTAP*	Aerosol chemistry (station nr NL11)
BSRN	2005	GEWEX	Baseline Surface Radiation Network
AERONET	2006	NASA	Aerosol retrieval through sun photometers
NITROEUROPE	2006	EU	Nitrogen concentration network
IMECC	2006	EU	Near-Real-Time CO_2 network
GEOMON	2006	EU/GEOSS	CO_2 and CH_4 surface obs. network
GRUAN	Candidate	WMO-GCOS	GCOS reference upper-air network
GAW		WMO	Monitoring of trace atmospheric constituents
ACTRIS	2011	EU	Aerosols, Clouds, and Trace gases Research InfraStructure Network

[1] *European Cooperation in Science and Technology*

Acronym	Description	Year
TEBEX	Tropospheric Energy Budget Experiment	1995
CLARA	Cloud macro- and microphysics	1996
CaPRIX	Test of VHF/UHF boundary layer windprofiler	2000
CNN-I	Cloud macro- and microphysics	2000
CNN-II	Cloud macro- and microphysics	2001
BBC	Cloud macro- and microphysics	2001
CREX-02	Small scale structure of rain	2002
BBC2	Cloud macro- and microphysics	2003
DANDELIONS	Aerosol and Nitrogen Dioxide OMI and Sciamachy	2005
SPE	Sound Propagation experiment	2005
DANDELIONS	Aerosol and Nitrogen Dioxide OMI and Sciamachy	2006
EAGLE	Land surface remote sensing	2006
SatLink	Linking Satellite Observations of Aerosol Optical Depth with Ground Level Observations of Particulate Matter (SATLINK)	2006
EMEP	Highly time resolved measurements of inorganic gases and aerosols	2006-2008
GOP	Quantitative Precipitation Forecasting	
2007		
EUCAARI-IMPACT	Cloud aerosol interaction	2008
ESA-CALIPSO	NASA/CNES Cloud Aerosol Lidar with Orthogonal Polarisation (CALIOP) correlative measurements	2009
CINDI	Cabauw Intercomparison of Nitrogen Dioxide measuring Instruments	2009
CLIC	Cabauw Lightmeter Intercomparison	2012
PEGASOS	Pan-European Gas-Aerosols-Climate interaction Study	2012

Table 2
List of national and international campaigns conducted at Cabauw.

the 60 m level and connected to equipment in the basement of the laboratory at the foot of the mast. During the PEGASOS campaign in 2012, CESAR was a key-observatory, where a Zeppelin was flown to observe chemical components in the atmosphere. Because of the continuous measurement of numerous parameters, individual researchers regularly visit the Cabauw site for the testing of new instruments.

Selection of research based on CESAR-observations

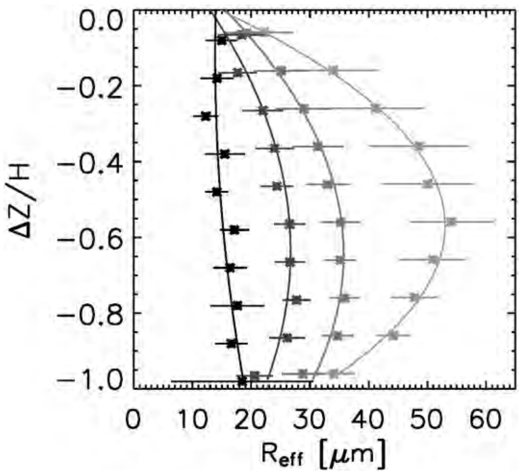


Figure 13
Mean R_{eff} versus normalized cloud depth (ΔZ/H) seen from cloud top adopting the complex polycrystals as ice habit for 4 different total cloud thickness (H [km]) regimes (H>4.5, 3.0<H<4.5, 1.5<H<3.0, and H<1.5 from light-grey to black points) at the ARM site. Note that Cloud top is at 0 and Cloud bottom at -1. The error bars show the error in the mean and the solid line shows a second order polynomial fit to the data.

In this paragraph we present a concise selection of publications of research in the fields of clouds and radiation, boundary layer and land surface, precipitation, aerosols and trace gasses, based on CESAR-data. Finally a summary of a publication on the KNMI Testbed is presented.

Clouds and radiation

Van Zadelhoff et al. (2004) developed an improved parameterization of the particle size in a cloud as a function of depth into the cloud and total cloud thickness. They compared the microphysical properties of ice clouds observed at three different sites, CESAR (Netherlands), ARM-SGP (United States), and Chilbolton (United Kingdom), using active remote sensing data. By combining lidar and radar signals, the effective radii, extinction and ice water content were derived and correlated to each other, and to temperature, radar reflectivity and depth into the cloud. They showed that it was not possible to construct a single effective radius parameterization based on temperature valid for the three sites but that this was possible when using depth into cloud (figure 13).

Wang et al. (2009) presented a clear-sky shortwave radiative closure analysis for the BSRN site at CESAR by comparing BSRN measurements and Doubling Adding KNMI (DAK) model simulations of direct, diffuse, and global irradiances for six cloud-free days. The data span a wide range of aerosol properties, water vapour columns, and solar zenith angles. The model input consisted of operational Aerosol Robotic Network (AERONET) aerosol products and radiosonde data. Excellent closure was obtained: the mean differences between model and measurements are 2 W/m^2 (+0.2%) for the direct irradiance, 1 W/m^2 (+0.8%) for the diffuse irradiance, and 2 W/m^2 (+0.3%) for the global irradiance (figure 14). It appeared that a correct description of the wavelength dependence of the aerosol optical properties is important for achieving broadband closure.

Boers et al. (2010) followed a novel approach in their investigations on which instruments and techniques would best be able to replace the ‘Human Observer’ for the determination of cloud cover. They used five different ground based remote sensing instruments operated at CESAR to observe fractional cloudiness. Three hemispheric (passive) methods observe the entire sky, while two (active) column methods only observe a small portion of the sky directly overhead. The outputs were compared against the (1971-2000) climatological records from the human observer at De Bilt and Rotterdam Airport. A reference algorithm

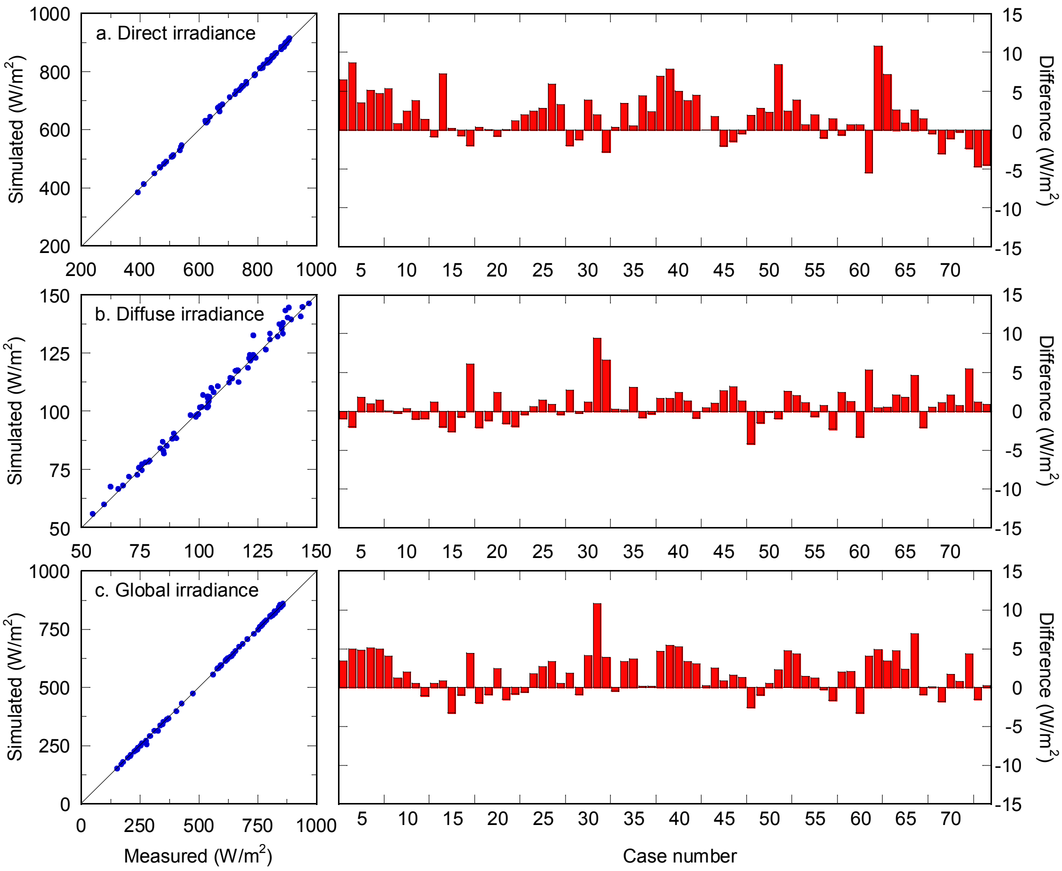


Figure 14
Scatterplot of DAK simulations versus BSRN measurements of direct irradiance for 72 cases (left panel) and differences between DAK simulations and BSRN measurements for direct irradiance (top), for diffuse irradiance (middle) and for global irradiance (below).

was used to reflect the combined performance of the five instruments (figure 15). The passive instruments, especially the NubiScope, were best able to reproduce the observations of the 'Human Observer' at least for low- and midlevel clouds. The NubiScope scans the entire sky every 6 minutes and registers the infrared radiation emanating from each point of the sky. From these observations cloud cover values can be calculated.

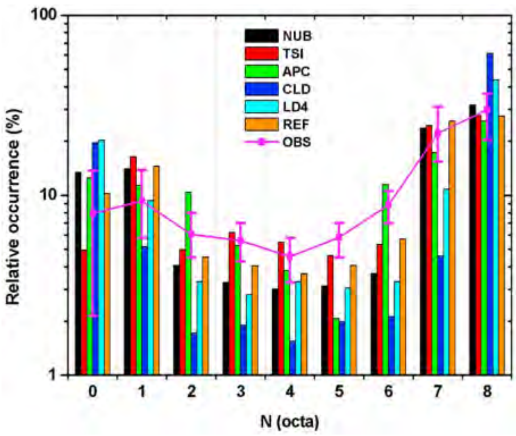


Figure 15
Cloud fraction histogram for all instruments and the reference algorithm. The Observer-data combined from Rotterdam and De Bilt are shown in the purple line with error bar. The error bar denotes the absolute maximum and absolute minimum values for the last 30 year climate record (1971–2000). NUB, NubiScope; TSI, Total Sky Imager; APC, Pyrgeometer algorithm; CLD Cloud radar – Cloud Lidar combination; LD4, Cloud Lidar; REF, reference; and OBS, Observer.

Bouniol et al. (2010) assessed the ability of four operational weather forecast models (ECMWF, ARPEGE, RACMO and UKMO LAM) to generate a cloud at the right location and time, using a two-year time series (1.10.2002 - 30.9.2004) of observations collected by profiling ground based active remote sensors (cloud radar and lidar) at CESAR, Chilbolton (UK) and Palaiseau (France). All models tend to produce too many high-level clouds, with too-high cloud fraction and ice water content (figure 16). The midlevel and low-level cloud occurrence is also generally overestimated, with too-low cloud fraction but a correct ice water content. The use of continuous ground-based radar and lidar observations is found to be a powerful tool for evaluating model cloud schemes.

Boundary layer and land surface

Baas et al. (2009) presented a climatology of low-level jets (LLJ) to facilitate the evaluation of atmospheric models (figure 17). Half-hourly observations of wind profiles measured at CESAR over a period of 7 years were analyzed. Combining measurements of the 213 m mast with data from a 1290 MHz wind

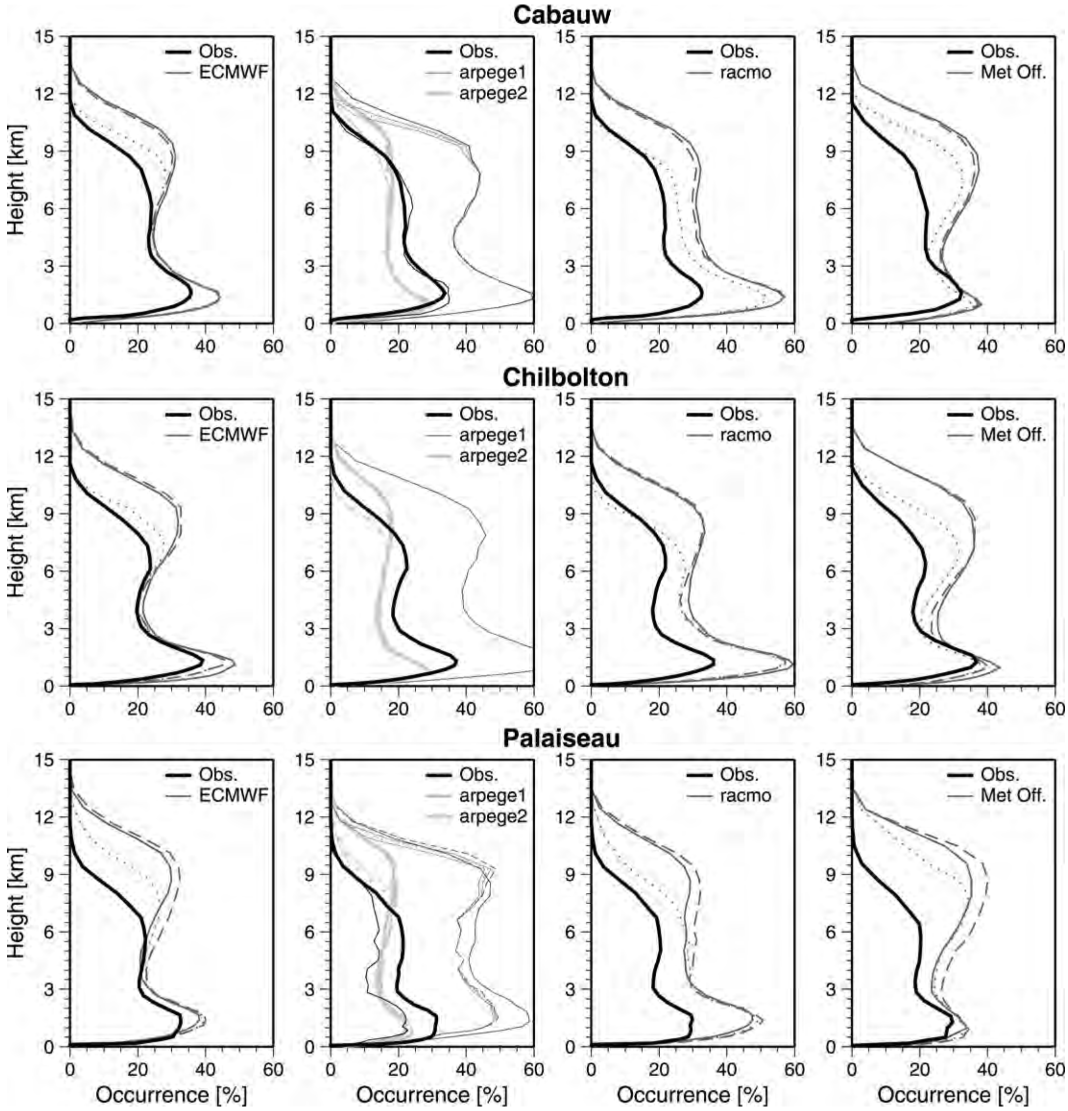
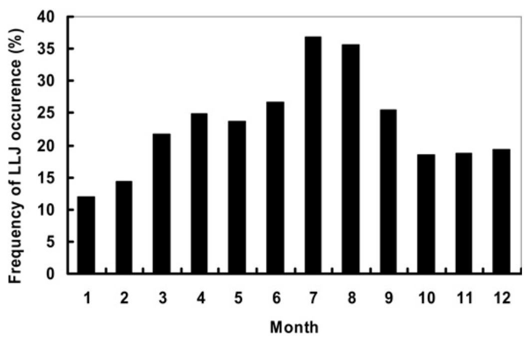


Figure 16
Frequency of cloud occurrence for models and observations at the three sites for the Cloudnet period. Black lines show observations. ARPEGE1 is the thinnest line, the thickest line represents ARPEGE2. For models, gray lines with different styles correspond to the model samples: solid line for whole model sample, dashed line for model subsample corresponding to instrument hours of operations, dotted line for model subsample corresponding to instrument hours of operations, including instrumental effects. Thinnest dotted lines show the same occurrence including sensitivity effect but accounting for a 3-dB more–less sensitive radar.

Figure 17
Frequency of occurrence of LLJ nights per month. LLJs occur most often in the summer months. This can be explained by two reasons. First, in summer the daytime boundary layer is much more convective than in winter. More vigorous turbulence is associated with larger ageostrophic wind components. As a result, nocturnal inertial oscillations will show larger amplitude than in winter. Second, in winter the frequency of unfavourable conditions, cloudy nights with strong geostrophic forcing, is much higher than in summer.

profiler, wind profiles up to 1420 m altitude were obtained. In about 20% of the nights a substantial maximum in the nocturnal wind speed profile occurs. Analyses suggest that frictional decoupling after sunset as a result of stable stratification is the main mechanism for the formation of a LLJ. Comparison with the ERA-40 archive shows that LLJs in the model are less frequent and situated at a higher level than in the observations. The turning across the boundary layer is smaller than observed. Also the speed of the LLJ is underestimated. This is attributed to a too strong mixing in the model during stably stratified conditions.

Pinsky et al. (2010) proposed a new method for retrieving air velocity fluctuations in the cloud-capped boundary layer (BL) using radar reflectivity and the Doppler velocity fields (figure 18). The method was developed on the basis of data obtained



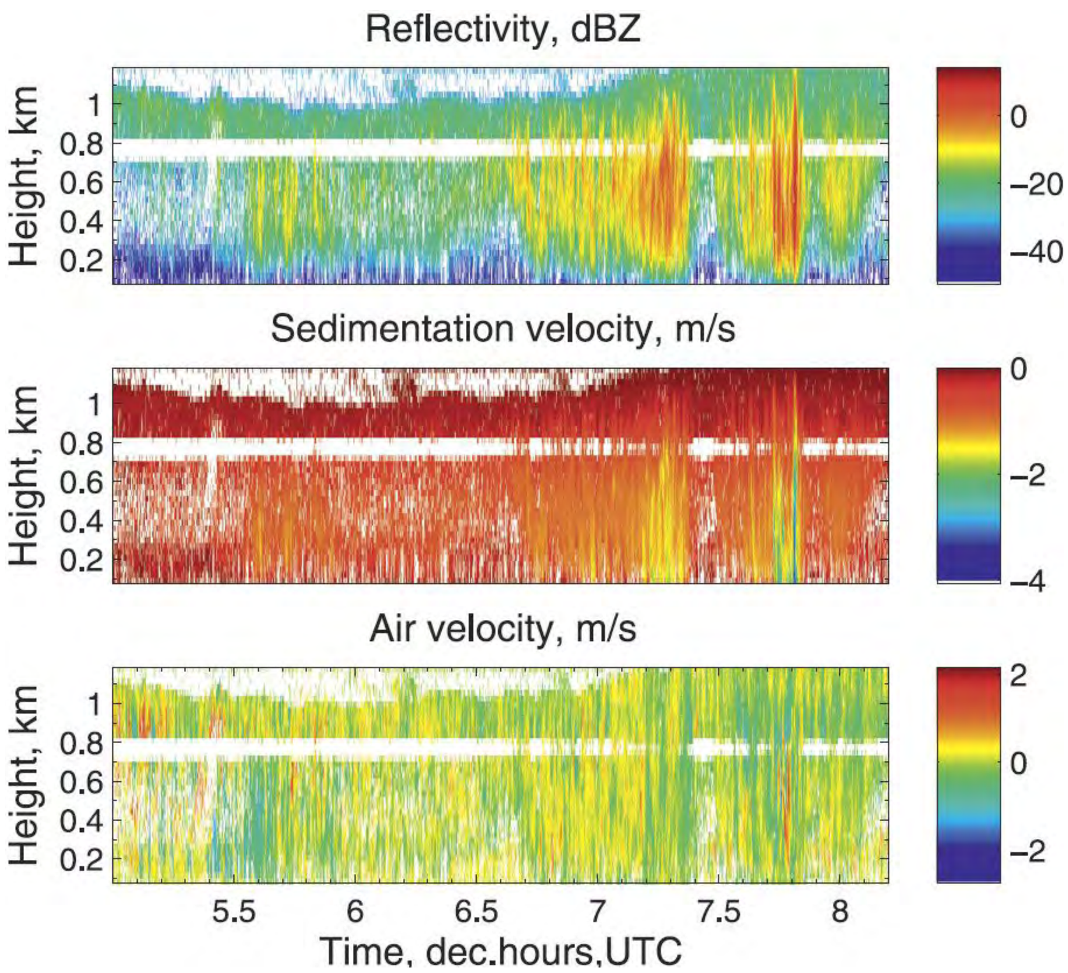


Figure 18
Fields of the (top) radar reflectivity, (middle) retrieved sedimentation velocity, and (bottom) retrieved air velocity obtained from the Cabauw observation data.

on a day in May 2004 by the TARA radar at CESAR, and was tested using a detailed trajectory ensemble model of the cloud-capped BL. No preliminary assumptions concerning the shapes of drop size distributions were made. TARA data were used to estimate vertical profiles of the vertical air velocity standard deviation, of the turbulent dissipation rate, et cetera. Analysis of the structure functions indicates that turbulence above 400 m can be considered to be isotropic. The importance of using the cloud-capped BL model as a link between different types of observed data (radar, lidar, aircraft, etc.) is discussed.

Van Heerwaarden et al. (2010) developed a method to analyse the daily cycle of surface evapotranspiration. It quantifies the influence of external forcings as radiation and advection, and of internal feedbacks induced by boundary layer, surface layer, and land surface processes on evapotranspiration. A budget equation for evapotranspiration is derived by combining a time derivative of the Penman-Monteith equation with a mixed-layer model for the convective boundary layer. Analysis of measurements at CESAR (figure 19) and Niamey (Niger, semiarid) and model results show that evapotranspiration is initiated by radiation, but is significantly regulated by the atmospheric boundary layer and the land surface throughout the day. At CESAR the variations

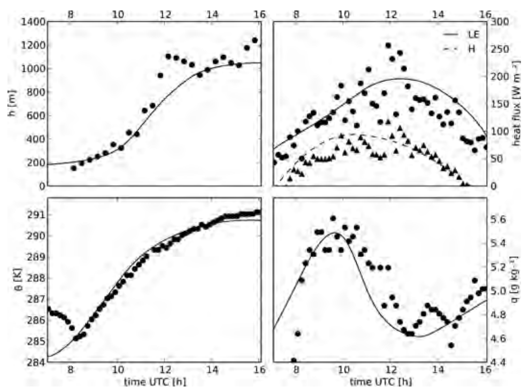


Figure 19
Time evolution of (top left) boundary layer height, (top right) surface heat fluxes, (bottom left) potential temperature of the mixed layer, and (bottom right) specific humidity of the mixed layer for the Cabauw case. The model is represented by continuous lines, observations by symbols.

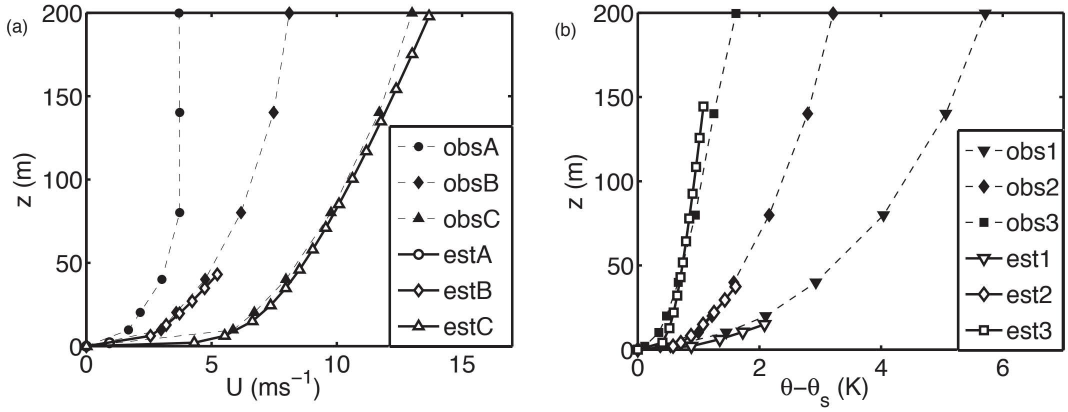


Figure 20
Left: Climatology of wind profiles (dashed lines) from Cabauw for night time cases with moderate cooling for three wind speed classes, compared with predictions by the conceptual model (solid lines). Right: Temperature profiles relative to the surface temperature at moderate wind speed for three surface cooling classes.

of moisture and temperature in the atmosphere play an equally important role, while at Niamey the effect of temperature fluctuations dominates the feedbacks and moisture fluctuations become irrelevant.

Donda et al. (2012) introduced a simple, physically consistent method to predict nocturnal wind and temperature profiles from external forcing parameters such as the geostrophic wind. As an indicator of the radiative 'forcing' the net longwave radiative cooling is used as a proxy. Surface fluxes are expressed in terms of these parameters by coupling an Ekman model to a rudimentary surface energy balance. Additionally the model assumes validity of Monin-Obukhov similarity in order to predict near-surface wind and temperature profiles up to a height equal to the Obukhov length. The predictions are validated against an independent dataset that covers 11-years of observations at Cabauw. It is shown that the characteristic profiles in response to external forcings are well-captured by the conceptual model (figure 20). For this period the observational climatology is in close agreement with ECMWF re-analysis data. As such, the conceptual model provides an alternative tool to giving a first-order estimate of the nocturnal wind and temperature profile near the surface in cases when advanced numerical or observational infrastructure is not available.

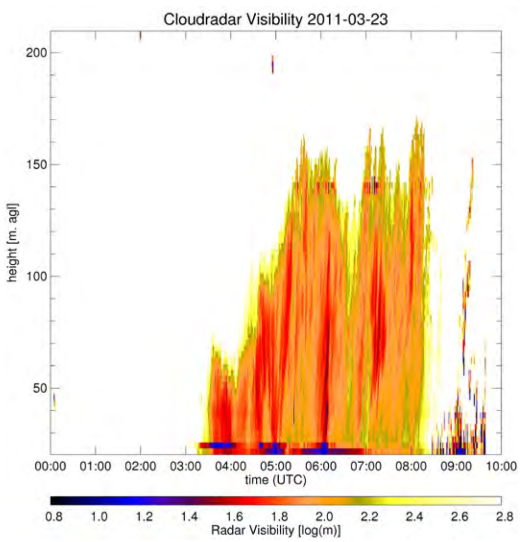


Figure 21
Colour plot of the time–height cross section of visibility as derived by radar reflectivity converted to visibility by means of the modelled relationship.

Boers et al. (2013) modelled the evolution of a radiation fog layer which was observed with in-situ instruments and radar at CESAR on March 23, 2011 (figure 21). The onset and evaporation of fog produce different radar reflectivity-visibility relationships. A droplet activation model used the aerosol size distribution observed at the 60-m altitude mast level as input. Radar reflectivity and visibility were calculated from model drop size spectra using Mie scattering theory. Since radiative cooling rates are small compared to cooling rates due to adiabatic lift of aerosol-laden air, the modelled super saturation remains low so that few aerosol particles are activated to cloud droplets. The results suggest that the different radar reflectivity-visibility relationships are the result of differences in the interplay between water vapour and cloud droplets during formation and evaporation of the fog. During droplet activation, only a few large cloud droplets remain after successfully competing for water vapour with the smaller activated droplets. These small droplets eventually evaporate (deactivate) again. In the fog dissolution/evaporation stage, only these large droplets need to be evaporated. Therefore, to convert radar reflectivity to visibility for traffic safety products, knowledge of the state of local fog evolution is necessary.

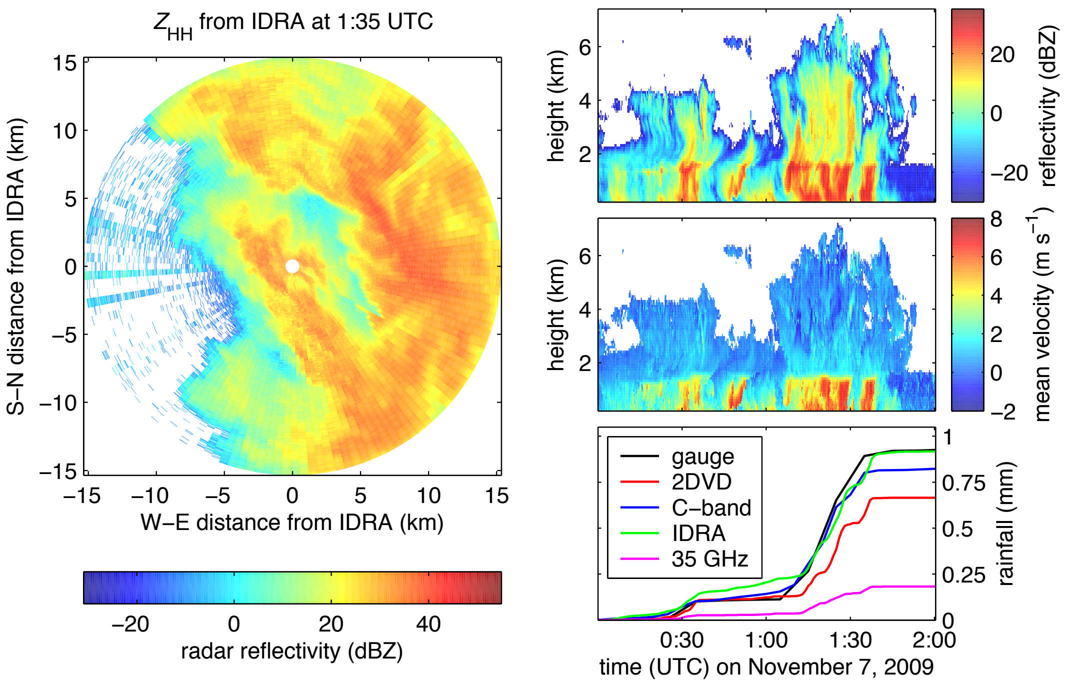


Figure 22
Several aspects of the rainfall event on 7 Nov 2009: (left) radar reflectivities measured by IDRA at 01:35 UTC and (right) time series of (top) reflectivity and (middle) mean Doppler velocity as a function of height as measured by the 35-GHz cloud radar for the event (bottom right). Also shown is the time evolution of rainfall accumulation for this event measured by a rain gauge, the 2D video distrometer (2DVD), the operational C-band radar located in De Bilt, IDRA, and the lowest range cell (250 m) of the 35-GHz cloud radar.

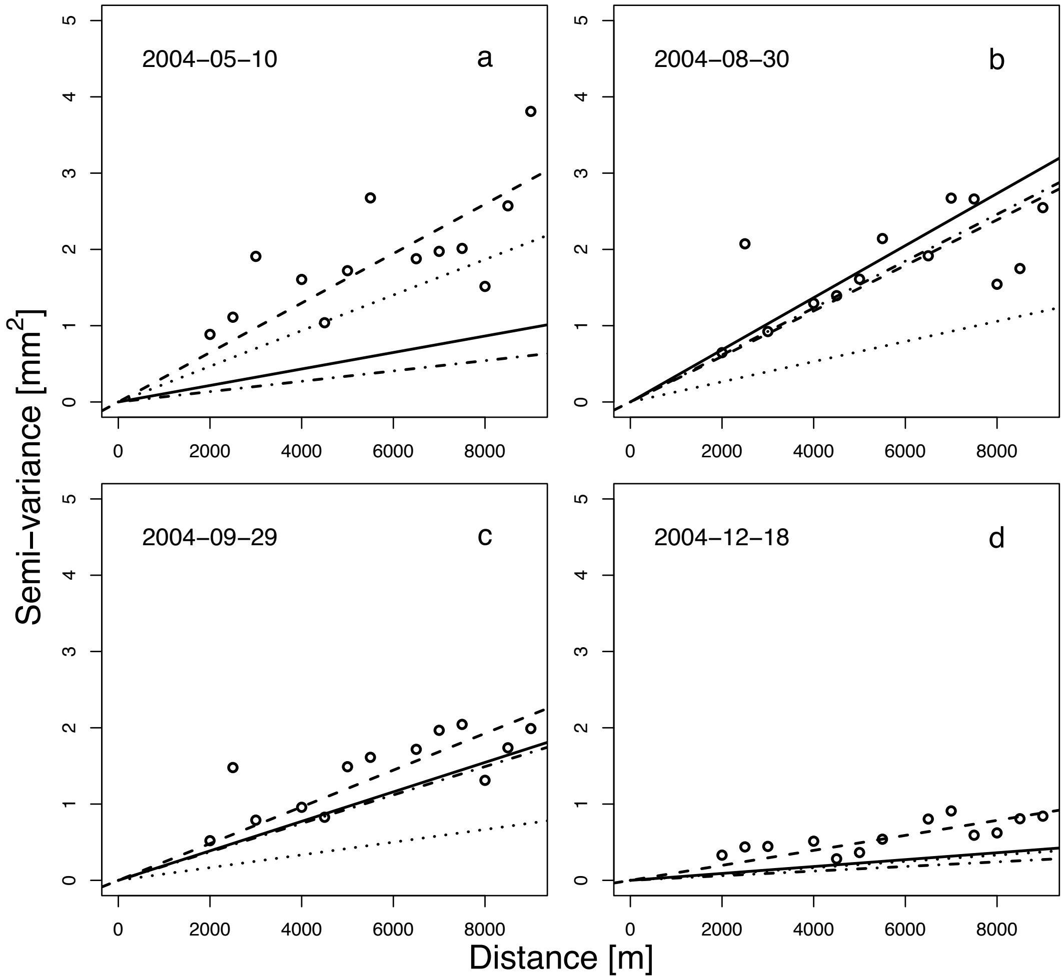


Figure 23
Four examples of fitted variograms using only 10 gauges of the dense rain gauge network between March 2004 and March 2005. The dashed lines are the actual fits (UU-WUR), the dash dotted lines are the fits through the KNMI data (KNMI), the solid lines are the fits found from the combined KNMI and UU-WUR rain gauge data (KNMI-UU-WUR), and the dotted lines are the climatological fits.

Precipitation

Leijnse et al. (2010) illustrated the potential for precipitation research at the CESAR observatory. The unique combination of in situ and remote sensing instruments provides data to quantitatively study many processes related to precipitation on different spatial and temporal scales. The synergetic use of these instruments provides great potential for improving our understanding of atmospheric and hydrologic processes related to precipitation (figure 22). One important aspect is related to the space-time variation of the microstructure of precipitation. The polarimetric variables measured by the IDRA drizzle radar, vertically pointing Doppler radar and a combination thereof can be used to obtain information on the microphysics of precipitation with unprecedented extent and resolution, contributing greatly to our understanding of precipitation-related atmospheric and hydrologic processes.

Van de Beek et al. (2011) showed that networks of rain gauges can offer insight into the space-time variability of rainfall, but they tend to be too widely spaced for accurate estimates between points. While remote sensing systems, such as radars and networks of microwave links, can offer good insight in the spatial variability of rainfall they tend to have more problems in identifying the correct rain amounts at the ground. The variability of rainfall between gauge points can be estimated by interpolating between them using fitted variograms. If a dense rain gauge network is lacking, it is difficult to estimate variograms accurately. A 30-year dataset of daily rain accumulations gathered at 29 KNMI automatic weather stations and a one-year dataset of 10 gauges in a network with a radius of 5 km around the CESAR observatory are employed to estimate variograms (figure 23). Fitted variogram parameters vary according to season, following simple cosine functions. Semi-variances at short ranges during winter and spring tend to be underestimated by these cosine models, but semi-variances during summer and autumn are well predicted.

Otto and Russchenberg (2011) introduced a novel method to estimate the specific differential phase and the differential backscatter phase from polarimetric weather radar measurements of rain. This estimation does pay off particularly at the X-band where the scattering regime is non-Rayleigh already in moderate rain. In this case, the differential backscatter phase is useful as an additional weather radar observable with manifold applications such as rain rate estimation, microphysical retrieval, and operational radar calibration (figure 24). The novel method also provides an improved range resolution of the specific differential phase compared to conventional estimators. They illustrate the estimation of the differential phases with data from the Doppler-polarimetric X-band drizzle radar (IDRA) of the Delft University of Technology, installed at CESAR.

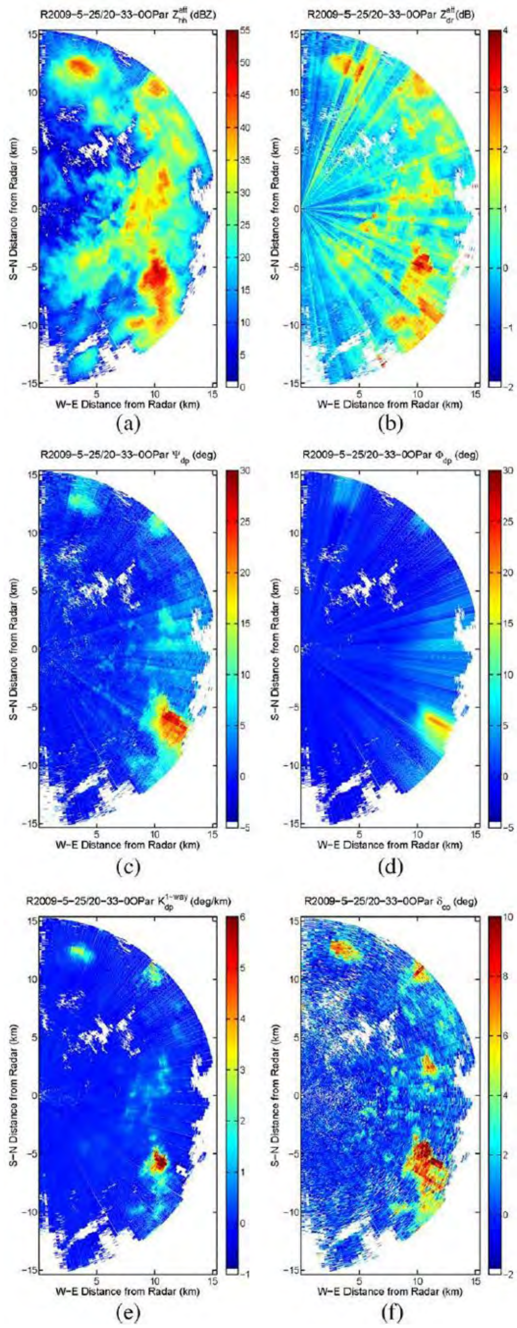


Figure 24
Application of the method to an IDRA data set from May 25, 2009, 20:33 UTC. Radar images of the same rain event but with different postprocessing. Shown is a horizontal half circle with a radius of 15 km.

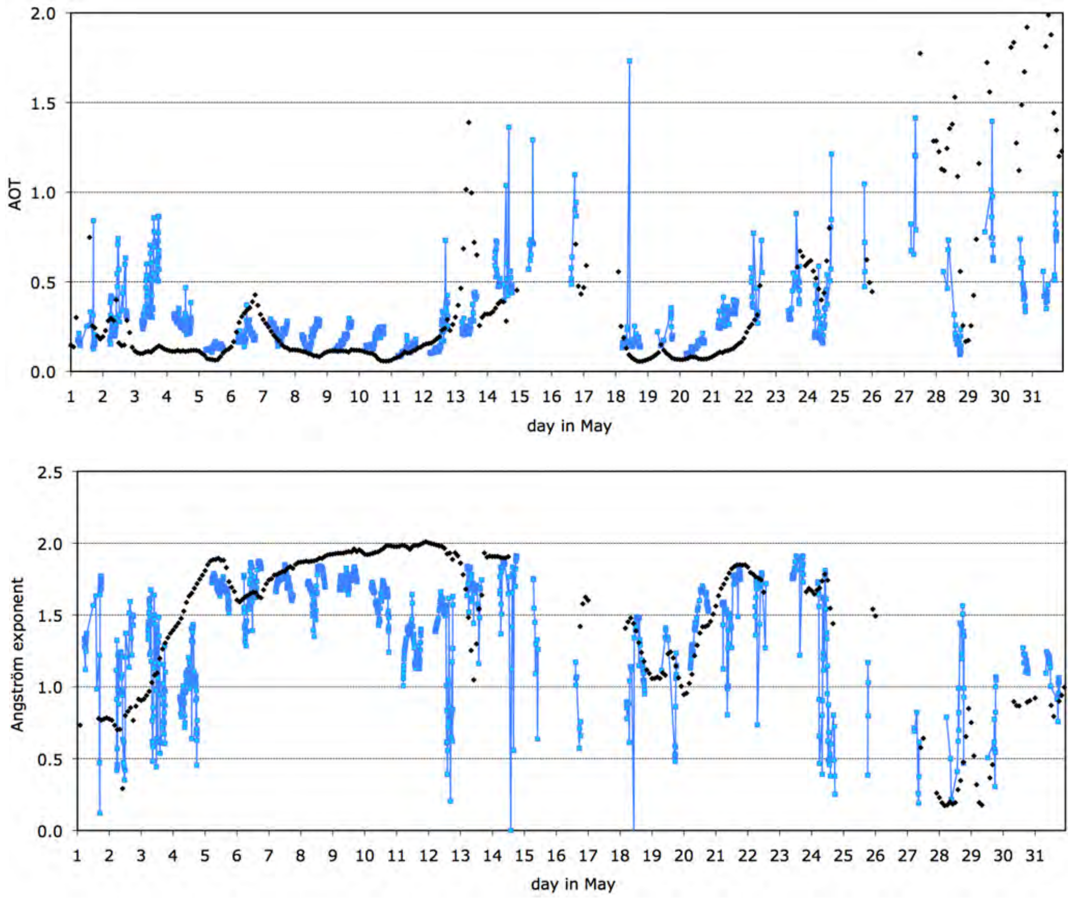


Figure 25
Above: Observed (blue) and simulated (black) AOT. Below: Observed and simulated Angström exponent.

Aerosols

Roelofs et al. (2010) conducted a model simulation of the atmosphere above CESAR in May 2008, the period of the IMPACT campaign for observation of atmospheric aerosol and cloud properties. A nudged version of the coupled aerosol-climate model ECHAM5-HAM simulated the size distribution and chemical composition of the aerosol and the aerosol optical thickness (AOT) (figure 25). Synoptic scale meteorology is represented realistically through nudging of vorticity, divergence, temperature and surface pressure. The monthly averaged AOT from the model is 0.33, 20% larger than observed. For selected periods with relatively dry and moist conditions the simulated AOT is 30% smaller, respectively 15% larger than the observations. Discrepancies during the dry period are partly caused by inaccurate representation of boundary layer (BL) dynamics by the model. The model simulates too strong exchange between the BL and the free troposphere, resulting in weaker concentration gradients at the BL top than observed for aerosol and humidity, while upward mixing from the surface layers into the BL is underestimated. The results indicate that beside aerosol sulphate and organics also aerosol ammonium and nitrate significantly contribute to aerosol water uptake.

Weijers et al. (2011) carried out measurements at five locations in the Netherlands (among them CESAR) from August 2007 to August 2008 to determine the composition of PM_{10} and $PM_{2.5}$, aiming at reducing the uncertainties on the origin of Particulate Matter (figure 26). This is necessary for the development of mitigation strategies to reduce PM concentrations. Generally, a considerable conformity in the chemical composition is observed. The secondary inorganic aerosol is the most dominant (42–48%) in $PM_{2.5}$, followed by the total carbonaceous matter (22–37%). Contributions from sea salt (maximum 8%), mineral dust and metals (maximum 5%) are relatively low. In the coarse fraction (PM 10-2.5) contributions of sea salt, mineral dust and metals are relatively larger, resulting in a more balanced distribution between the various constituents. Through mass closure a considerable part of the PM mass could be defined

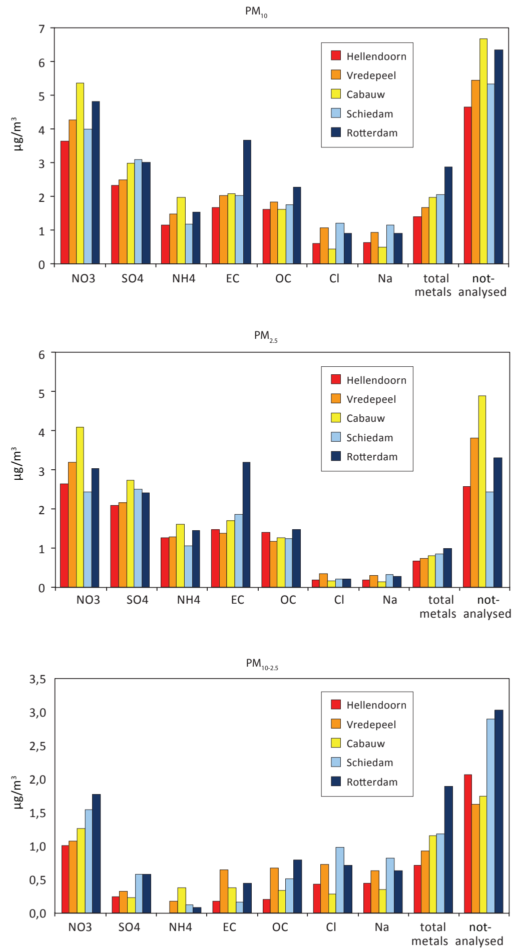


Figure 26
Absolute concentrations at the five sites.

($PM_{2.5}$: 80–94%). Days with high PM levels show a distinct increase in nitrate and in the unaccounted mass. The contribution from natural sources in the Netherlands (at a rural station) was estimated to be 19 to 24% for PM_{10} and 13 to 17% for $PM_{2.5}$.

Aan de Brugh et al. (2012) carried out an explanatory model study to investigate the partitioning of ammonium nitrate aerosols in the convective boundary layer on clear days in May 2008 at CESAR during the IMPACT campaign. A single column model in combination with the equilibrium aerosol model ISORROPIA was used to calculate the gas-aerosol partitioning of ammonium nitrate, with surface observations from IMPACT as input (figure 27). ISORROPIA showed a clear diurnal cycle in the equilibrium of ammonium nitrate, with a maximum gas phase fraction during daytime and a maximum aerosol phase fraction during night-time. The diurnal cycle in the calculated equilibrium, however, is stronger than the diurnal cycle in the partitioning observed with the MARGA-instrument at CESAR. Mixing of air from higher altitudes is shown to have a significant influence on the calculated partitioning at the surface. Coarser-resolution models may treat the gas-aerosol equilibrium of ammonium nitrate by calculating the equilibrium with a temperature and humidity sampled at a different altitude. It was found that the equilibrium at an altitude of 200 m (night) up to 600 m (day) is representative for the partitioning of ammonium nitrate at the surface in the beginning of May 2008.

Mensah et al. (2012) performed extensive aerosol chemical composition measurements at CESAR for two intensive measurement periods in May 2008 and March 2009. Submicron aerosol chemical composition was measured by an Aerodyne Aerosol Mass Spectrometer (AMS) and is compared to observations from aerosol size distribution measurements as well as composition measurements with a Monitor for AeRosol and GAses (MARGA) based instrument and a Thermal-Desorption Proton-Transfer-Reaction Mass-Spectrometer (TD-PTR-MS). In May 2008 enhanced pollution was observed with organics contributing 40% to the PM1 mass. In contrast the observed average mass loading was lower in March

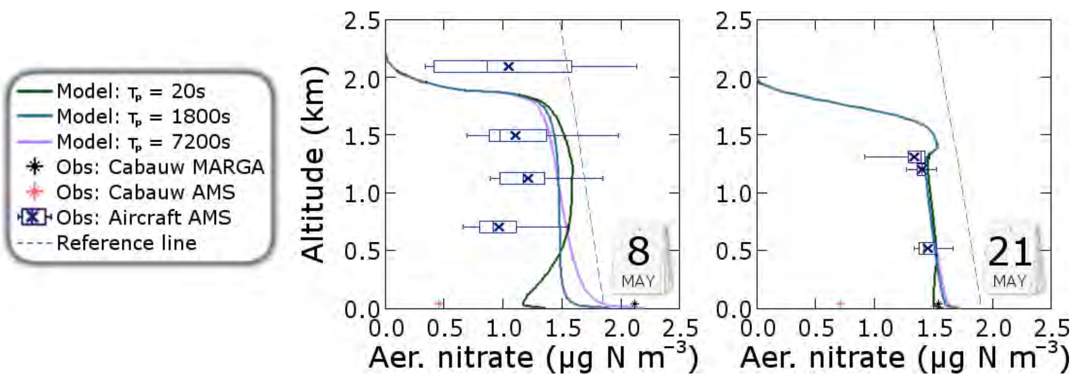


Figure 27
Modelled aerosol nitrate profiles with partitioning timescales of 20 s, 1800 s and 7200 s, at 15:30 UTC for 8 May and at 11:30 UTC for 21 May. Airborne aerosol nitrate concentrations measured with the aerosol mass spectrometer, surface aerosol nitrate concentration measured with the aerosol mass spectrometer at Cabauw, and PM10 observations by the MARGA instrument at Cabauw. The reference line shows a scaled concentration of 2.0 µgNsm⁻³ (scaled to standard temperature and pressure).

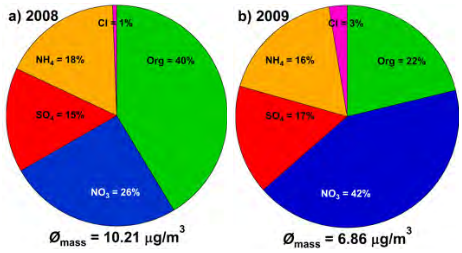


Figure 28
Mean aerosol composition in May 2008 (left) and March 2009 (right). While the aerosol chemical composition is dominated by organics (40 %) in May 2008, the main fraction is composed of nitrate (42 %) in March 2009. The average mass loading was 10.21 µgm^{-3} in May 2008 and 6.86 µgm^{-3} in March 2009.

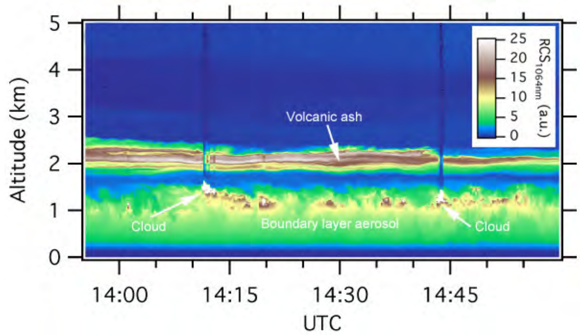


Figure 29
Backscatter signals derived from the Raman lidar system (CAELI) in Cabauw on 16 April 2010. The brown band indicates the presence of ash particles originating from the Eyjafjallajökull volcano. Below the volcanic ash, regular boundary layer aerosol is present, together with occasional clouds. Picture: Arnoud Apituley, KNMI.

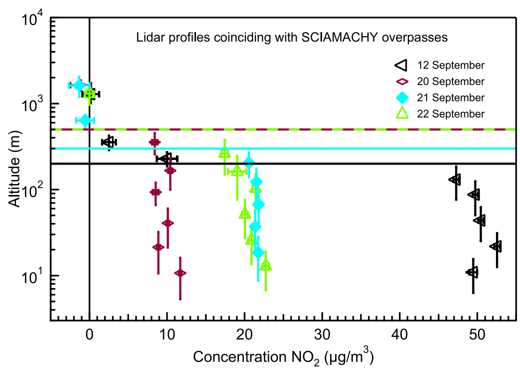


Figure 30
Lidar NO$_2$ profiles on a log scale coinciding with SCIAMACHY overpasses between 09:00 and 11:00 UTC. Vertical bars: height intervals over which concentrations have been determined. Horizontal bars: ±1s values for the concentrations. Where no error bars are visible, they are smaller than the symbols plotted. The boundary layer heights between 09:00 and 10:00 UTC (for 12, 21, and 22 September) or 10:00 and 11:00 UTC (for 20 September) are indicated by lines in the corresponding colour for each profile.

2009 and a dominance of ammonium nitrate (42 %) was observed (figure 28). The semi-volatile nature of ammonium nitrate is evident in the diurnal cycles with maximum concentrations observed in the morning hours in May 2008 and little diurnal variation observed in March 2009. Size dependent composition data from AMS measurements show a dominance of organics in the size range below 200 nm.

Pappalardo et al. (2013) presented the four-dimensional (4-D) distribution of the Eyjafjallajökull volcanic cloud over Europe during the entire volcanic event (15 April–26 May 2010), as observed by the European Aerosol Research Lidar NETwork (EARLINET), in which CESAR participates. Based on multi-wavelength Raman lidar systems, EARLINET is the only lidar network worldwide that is able to provide dense time series of high-quality optical data to be used for aerosol typing and for the retrieval of particle microphysical properties as a function of altitude. All optical properties directly measured (backscatter, extinction, and particle linear depolarization ratio) were stored in the EARLINET database available at http://www.earlinet.org. For the first time, quantitative data about the presence, altitude, and layering of the volcanic cloud were available for most parts of Europe. This eruption not only allowed interesting research, but also showed that these measurements can contribute significantly to the safety of air traffic. Many CESAR instruments are in operation continuously, and by putting the Raman lidar into operation on very short notice, the specific data needed at this occasion could be provided (figure 29), illustrating the capabilities of this high-tech observatory.

Trace gasses

Volten et al. (2009) described a novel instrument, the RIVM NO_2 mobile DIAL lidar, to measure tropospheric NO_2 profiles for the interpretation and validation of satellite data. During the DANDELIONS campaign (Dutch Aerosol and Nitrogen Dioxide Experiments for vaLIdation of OMI and SCIAMACHY) in 2006 at CESAR they obtained an extensive collection of lidar NO_2 profiles, coinciding with OMI and SCIAMACHY overpasses (figure 30). On clear days and early mornings lidar and in situ measurements at the surface and the top of the mast showed excellent agreement. At other times the in situ monitors with molybdenum converters suffered from NO_y interference. The lidar NO_2 profiles indicated a well-mixed boundary layer, with high NO_2 concentrations in the boundary layer and concentrations above not differing significantly from zero. The boundary layer concentrations spanned a wide range, which likely depends on the wind directions and on the intensity of local traffic. Large diurnal differences were mainly driven by the height of the boundary layer, although direct photolysis or photochemical processes also contribute. A preliminary comparison with lidar data showed that the satellite data tend to overestimate the amount of NO_2 in the troposphere.

Peters et al. (2010) presented an estimate of net ecosystem exchange (NEE) of CO_2 in Europe for 2001-2007. It is derived by data assimilation of 70,000 atmospheric CO_2 mole fraction observations, among them CESAR-data, to guide relatively simple descriptions of terrestrial and oceanic net exchange, while fossil fuel and fire emissions are prescribed. Weekly terrestrial sources and sinks were optimized (i.e. a flux inversion) for 18 large ecosystems across Europe, in which prescribed climate, weather, and surface characteristics introduce finer scale gradients. They found that the terrestrial biosphere in Europe absorbed a net average of −165 Tg C yr^{-1}. This uptake is predominantly in non-EU countries, and is found in the northern coniferous (−94 Tg C yr^{-1}) and mixed forests (−30 Tg C yr^{-1}) as well as in the forest/field complexes of Eastern Europe (−85 Tg C yr^{-1}) (figure 31). An optimistic uncertainty estimate derived using three biosphere models suggests the uptake to be in a range of −122 to −258 Tg C yr^{-1}. Uncertainties are hard to estimate given the nature of the system and are probably significantly larger. The largest anomaly of NEE occurred in 2005, possibly because of the strong negative phase of the North Atlantic Oscillation in that year. For all results see http://www.carbontracker.eu.

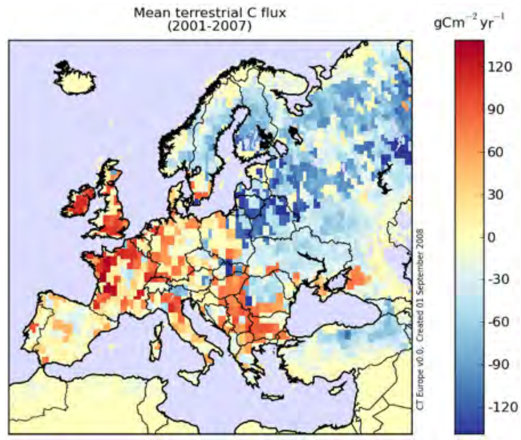


Figure 31
2001 – 2007 mean terrestrial biosphere carbon flux over Europe. The 1° x 1° pattern is constructed with a detailed a priori biosphere model and a set of 18 weekly linear scaling factors. Blue colours denote net carbon uptake, while red colours denote carbon release to the atmosphere.

Popa et al. (2011) performed for the first time in situ, quasi-continuous long term measurements of vertical profiles of atmospheric hydrogen (H_2) in the lower continental boundary layer. In October 2007 the measurements started at the CESAR-mast. Mole fractions of H_2, CO and several greenhouse gasses are determined simultaneously in air sampled at four heights between 20 and 200 m. 222_{Rn} measurements are performed at 20 and 200 m. Seasonal cycles are present at all heights in both H_2 and CO, and their amplitude varies with the sampling height (figure 32).

The seasonality is evident in both the ‘baseline’ values and in the short term (diurnal to synoptic time scales) variability, the latter being significantly larger during winter. The H_2 short term signals and vertical gradients are in many cases well correlated to other species, especially to CO. On the other hand, H_2 has at times a unique behaviour, due to its particular distribution of sources and sinks. Using the radon tracer method, the regional H_2 soil uptake flux appears to be significantly smaller

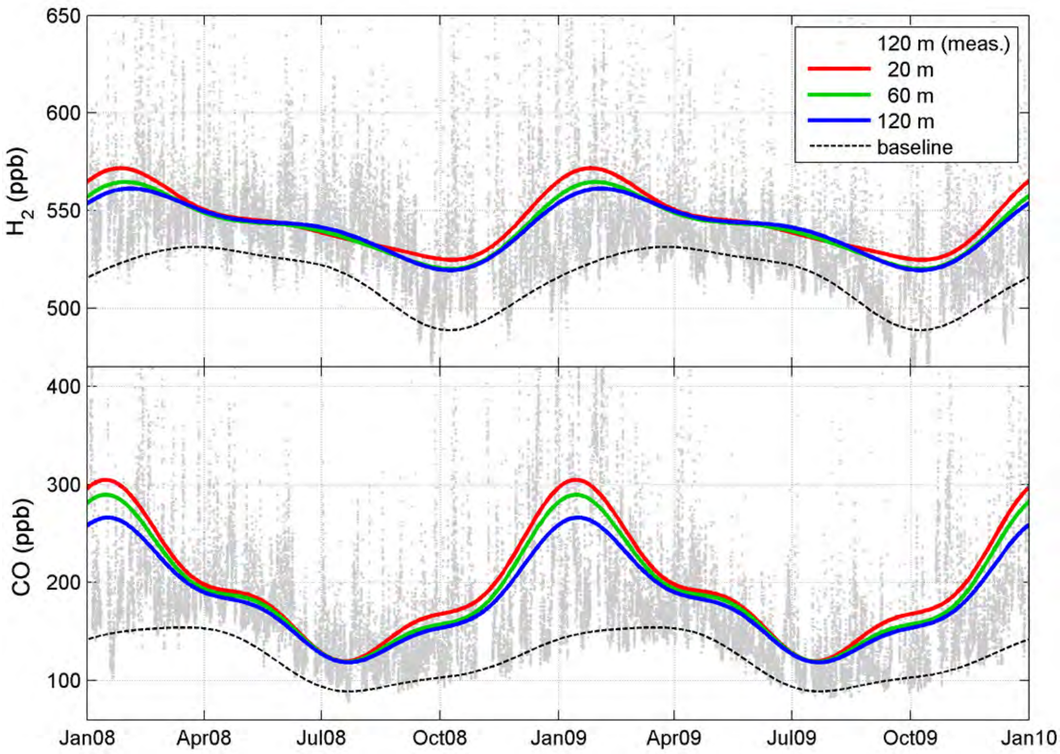


Figure 32
Seasonal cycles of H_2 and CO at three sampling heights (colour lines) and the baseline at 120 m (black dashed line). Grey dots are the measurement series from 120 m sampling level.

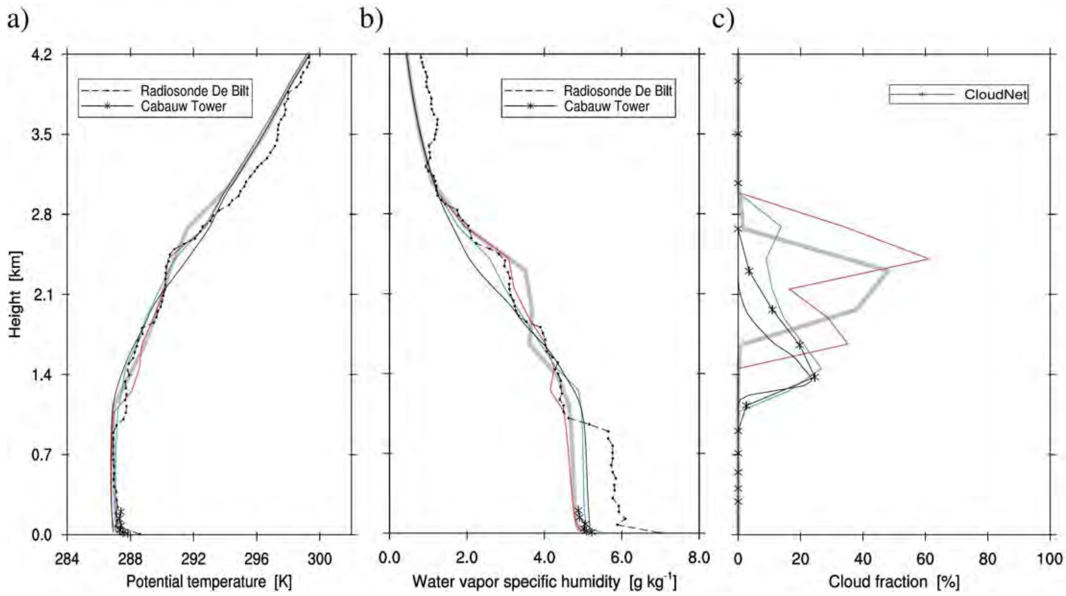


Figure 33
The vertical structure of thermodynamic and cloudy state of the shallow cumulus-capped boundary layer as observed and simulated at 12:00 UTC 16 June 2008 at Cabauw. (a) Potential temperature, (b) water vapour specific humidity, and (c) cloud fraction (area averaged). The solid coloured lines refer to two research versions of the Single Colum Model (SCM) of a present-day weather forecasting model. The solid black line represents LES, while the marked black lines represent observational data streams as annotated in the legend.

than other recent results from Europe. H_2/CO ratios of the traffic emissions are larger and more variable than in other studies in Europe, probably due to a different traffic regime.

The KNMI Testbed

It was already mentioned above that many CESAR-observations are available on the CESAR-database (www.cesar-database.nl). However, the need was felt to stimulate the use of the CESAR-data for the development and verification of models. To this end, Neggers et al. (2012) developed the Royal Netherlands Meteorological Institute (KNMI) Parameterization Testbed (KPT). This KPT is part of a general move toward a more statistically significant process-level evaluation, with the purpose of optimizing the identification of problems in general circulation models that are related to parameterization schemes. They applied continuous long-term Single-column models and LES simulations in combination with comprehensive evaluation against observations at multiple time scales (figure 33). They illustrated that by using this method it becomes possible to reproduce typical long-term mean behaviour of fast physics in larger-scale models, while still preserving the benefits (e.g., model transparency) of single-case studies. It was argued that this strategy facilitates the tracing and understanding of errors in parameterization schemes, which should eventually lead to a reduction of related uncertainties in numerical predictions of weather and climate. KPT is operational on a permanent basis as a KNMI internal project. Work is in progress to make KPT accessible to external participants by means of a dedicated server. Detailed information is provided on the KPT website (www.knmi.nl/~neggers/KPT). The KPT project takes part in the ongoing European Union Cloud Intercomparison, Process Study and Evaluation project (EUCLIPSE; www.euclipse.eu/), as well as in the Fast-Physics System Testbed and Research project (FASTER; www.bnl.gov/esm/).

Summary and conclusion

In the 1960's KNMI initiated experimental programmes to study the interactions between the weather, land surface and the atmospheric boundary-layer. This led to the building of the 213 m high Cabauw-mast for the study of the dispersion of air pollution. The Cabauw-mast stands in a long tradition at KNMI of performing observations at elevated levels in the atmosphere. A short historic overview is presented in the Appendix.

On October 26, 1972, continuous observations of the profiles of several atmospheric parameters with focus on the nocturnal boundary layer started. A more comprehensive continuous measurement programme was run from March 1977 until March 1979, in which also the components of the surface energy budget were monitored. Special experiments were carried out to measure profiles of turbulent fluxes. This led to several publications on the behaviour of the boundary layer that received international recognition.

As atmospheric models became more complex, validation of small-scale processes with observations became necessary, and experimental research shifted towards the evaluation of weather models. A programme was run from 1986 until 1996, creating a database with observations of mean profiles, fluxes and surface parameters. These data were for instance used for the comparison of land surface schemes designed for use in weather and climate models.

As global warming became an important issue KNMI research focussed on climate change. As it became clear that adequate representation of clouds and their interaction with radiation is essential in climate models, a cloud detection network around Cabauw was established. Remote sensing instruments were installed, and satellite observations were added to validate cloud detection algorithms. Also the representation of clouds in climate models was evaluated.

In the beginning of the twenty-first century international research showed an increasing demand for more detailed information on the atmosphere for the development of weather, climate and air quality models. The development of new measurement techniques enabled the observation of an increasingly wider field of atmospheric properties. A major revision of the measurement programme became necessary. It became clear that this broad range of observations needed, requiring all sorts of expertise, could neither be carried out nor interpreted by one single institute. Based on existing cooperation between institutes with complementary expertise, the CESAR consortium, consisting of four research institutes, three universities and the European Space Agency, was established in 2002.

CESAR is part of a number of international networks and participated so far in thirteen international measuring campaigns. Research topics varied

[1] *Cabauw Experimental Site for Atmospheric Research*

widely, ranging from macro- and microphysics of clouds with remote sensing instruments and airborne in situ sensors, to the validation of satellite observations with ground based remote sensing measurements. CESAR data are included in major international data bases. In the final chapter a concise selection is given of publications of research in the fields of clouds and radiation, boundary layer and land surface, precipitation, aerosols and trace gasses, based on CESAR data.

One may wonder whether nowadays a facility as CESAR could be built from scratch. The decision made by the government over 40 years ago to invest in a large scale atmospheric research facility was daring at that time and can in hindsight be considered as visionary. The start of the measurements at Cabauw marked the beginning of an era of vigorous atmospheric research in the Netherlands, and at present CESAR is one of the leading atmospheric observatories in the world. In a recent report, where the Royal Netherlands Academy of Arts and Sciences (KNAW) (2011) presents a vision on the future of earth sciences until 2020, CESAR is mentioned as an outstanding example of the organisation of collaborative national research.

Figure 34
The remote sensing site as seen from the mast in September 2011.

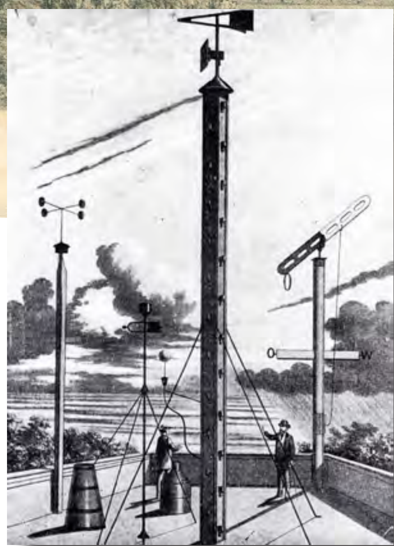
Appendix

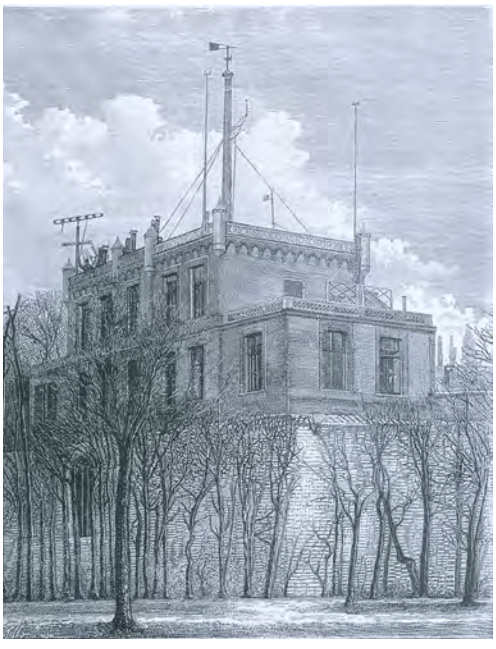
In this Appendix some early work done at KNMI to obtain meteorological measurements at higher altitudes is presented. This illustrates that KNMI has a tradition of more than 150 years in the development and deployment of meteorological instruments and methods of observation, which eventually culminated in the establishment of the Cabauw-mast in 1972, which developed into the high-tech Cabauw Experimental Site for Atmospheric Research CESAR.

The first part of the Appendix shows measurements for weather forecasting and climatology on the roof of the first KNMI building in Utrecht and on the successive three towers at KNMI in De Bilt. The second part highlights masts that allowed for research measurements. They were built as slender as possible to avoid disturbance of the measurements by the mast itself, and they were usually guyed. The last part illustrates that upper air measurement methods were developed many years before the introduction of remote sensing techniques.

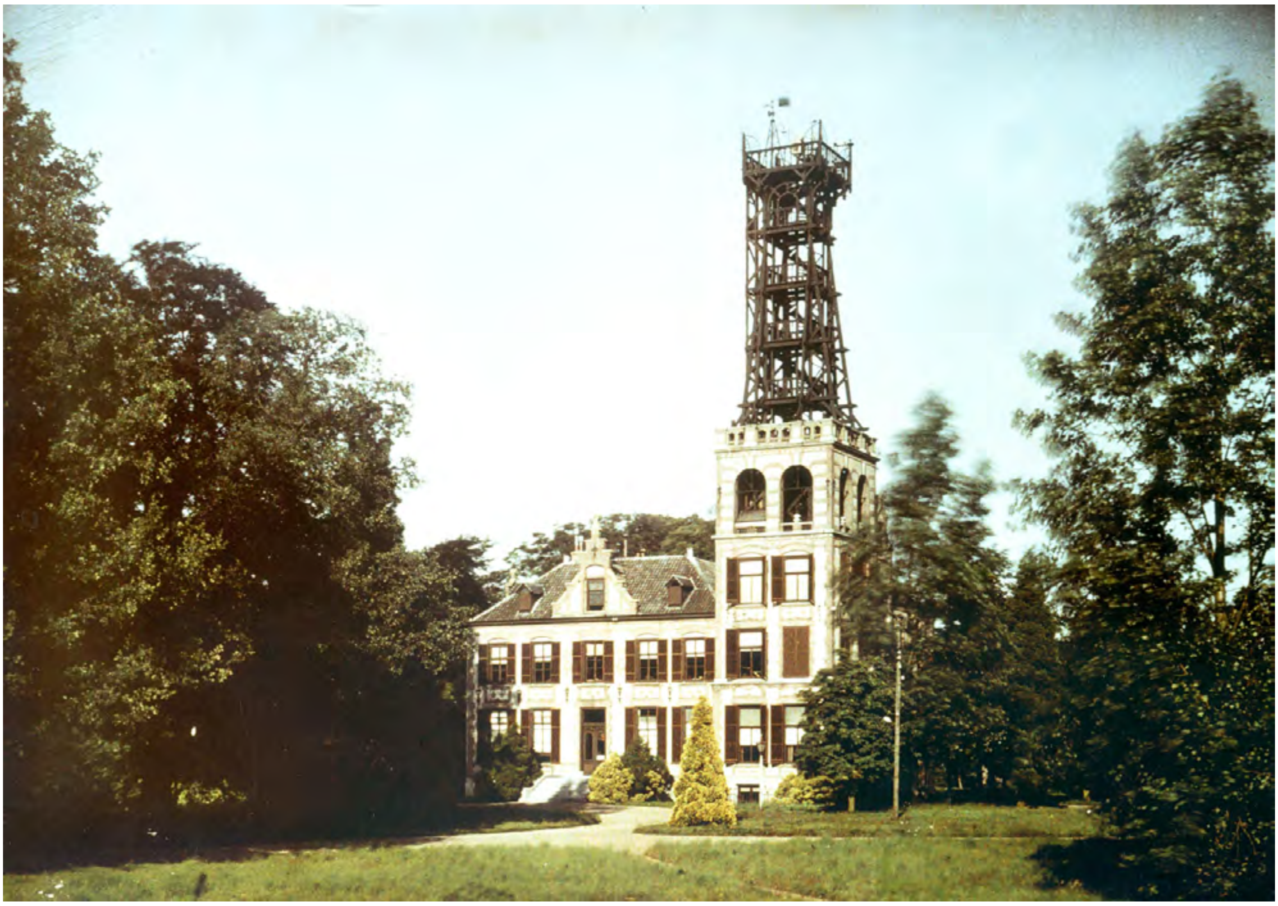
The text that accompanies the illustrations is largely based on information found in old archives. Because only a quick scan could be made of numerous minutes of meetings, informal reports, et cetera, there may be some uncertainties in the dates and the information on instruments. The available time series of measurements were helpful to uncover when some measurements were started.

Measurements for weather forecasting and climate at KNMI on towers

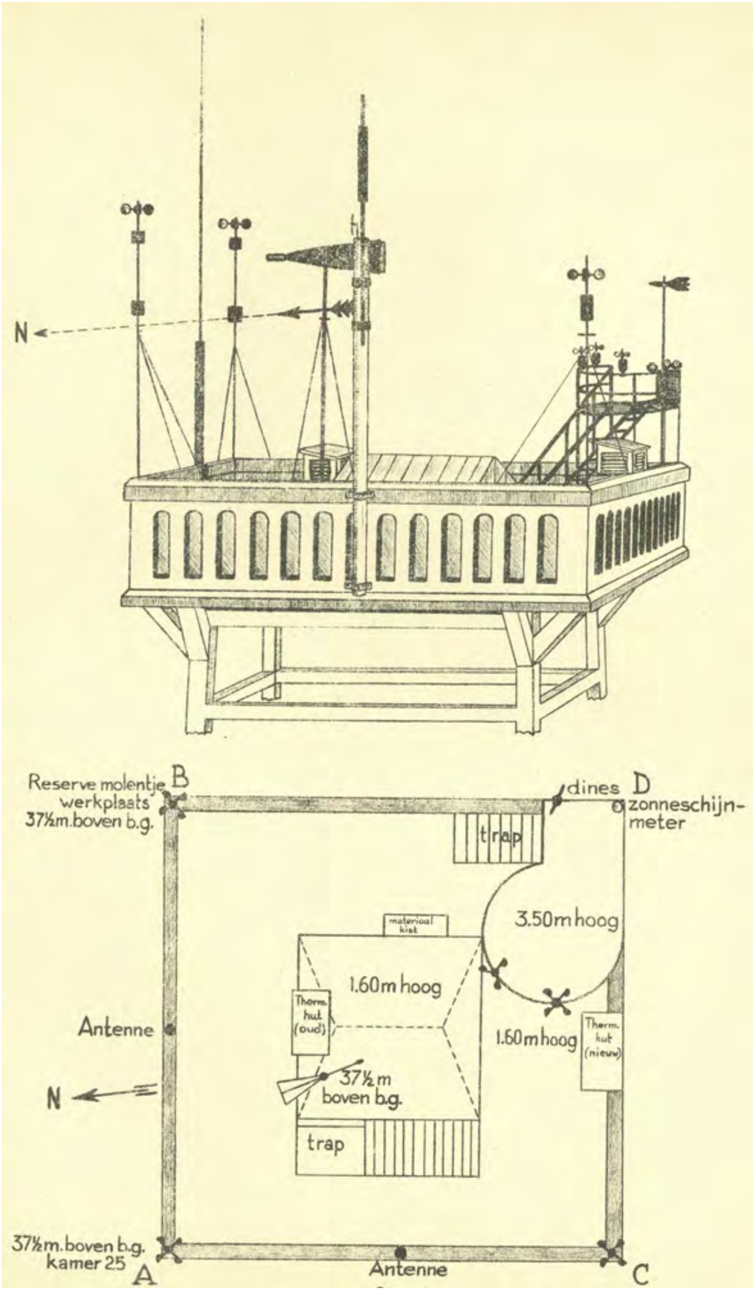




KNMI was founded in 1854. The astronomical observatory at the rampart "Sonnenborgh" in Utrecht hosted the institute until it was moved to its present location in De Bilt. Observations were made on the roof of the observatory. According to Krecke (1849) the following instruments were installed: a mercury barometer, a mercury barograph, a psychrometer, a thermograph, a maximum and minimum thermometer, a registrating wind vane and anemometer, a Whewel anemometer, a rain gauge with reservoirs for several wind directions, two types of evaporation meters and an instrument to detect the height and distance of clouds. In addition there was an instrument to measure the magnetic declination, a pyrheliometer to measure the radiation from the sun, a clock, a theodolite and a sextant. Some of these instruments are described by B.J.G. Volck with illustrations drawn by A.J.M. Monné (manuscript II.r.1a. in the KNMI library). The T-shaped structure on the pictures is a so-called aëroklinoscope, a device developed by KNMI's founder Buys Ballot, which was used to visualise the magnitude and the direction of the air pressure gradient.



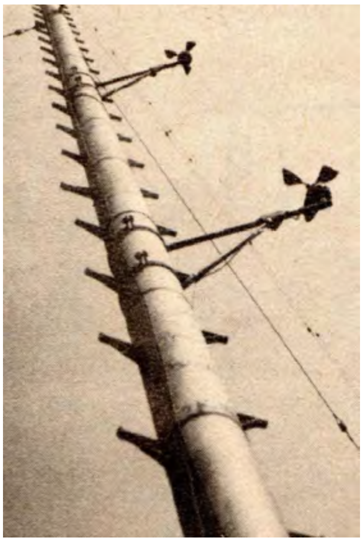
The first wooden tower on top of the old KNMI building. The tower was built in 1895, when KNMI moved from Utrecht to De Bilt. The measurements started in December 1896. Measurements in Utrecht continued until November 1898 to allow for comparisons between the old en the new location. The tower was dismantled in 1915. The 33.5 m high tower was used for observations of wind speed and direction. Sunshine duration was monitored with a Campbell-Stokes sunshine recorder. Also a Stevenson screen was mounted, suggesting that temperature and perhaps also humidity were measured. It is not clear why this was done, because the 'official' temperature and humidity measurements were made in screens at ground level. This picture was taken around 1900.



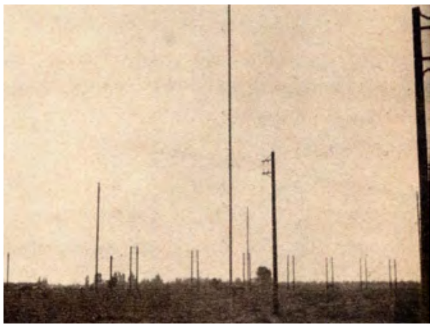
The second tower, a concrete structure, on top of the old KNMI building. It was built in 1916 and dismantled in 1953. The tower was 33 m high. Several Robinson cup-anemometers and wind vanes were installed on the top. A Stevenson screen was also mounted on this new tower, so it seems that the registration of temperature and humidity were continued in parallel with the observations on ground level. Sunshine duration measurements with a Campbell-Stokes sunshine recorder were also continued. On the lower-left picture we see the launch of a pilot balloon. To investigate the accuracy of the wind speed measurements the recordings of the various anemometers were compared. Also the influence of the tower and the devices on the platform, such as the Stevenson screen, on the wind measurements was investigated (Rijkoort, 1952). The roof on the ground in front (upper-left picture) is a so-called Pagoda radiation screen to shield e.g. the temperature measuring instruments.

The 35.5 m high brick tower was built in 1952. On top again several cup anemometers and wind vanes were installed. The Campbell-Stokes measurements were continued. Temperature and humidity were monitored in two Stevenson screens. Rijkoort (1954) investigated the disturbance on the wind measurements caused by the structures on the platform also on this new tower. Until 1960 wind observations were only made on the roof of Sonnenborgh and on top of the three successive KNMI towers. Since 1960 wind measurements for weather forecasting and climatology are made on small masts at a special site at some distance from the KNMI buildings. Parallel registration of tower and field measurements was carried out in 1958/59. No report could be found.
It is not clear for what reason the wind measurements on the tower were continued after 1960.
A precipitation radar was installed on the top of the tower around 1978, and a bigger one around 1985. This implied that wind measurements there could not be continued. This radar is still operational.

Measurements on masts for research



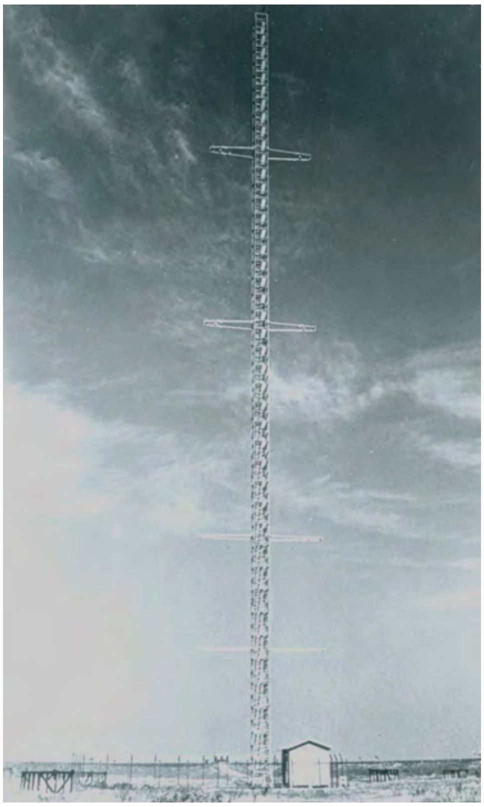
The first regular tower measurements of wind and temperature for research were made in 1954 on broadcast masts between Lopik and IJsselstein, SW of Utrecht, up to a height of 182 m (Rijkoort, 1961 and 1969). In spite of the disturbance of the temperature measurements by the strong electric fields and the influence of the tower on the wind measurements some of these measurements have led to acceptable and useful results. Wind speed was measured on the TV mast at 12, 15, 54, 101 and 182 m, and temperature at 2, 54, 101 and 182 m height. On the broadcast mast wind was measured at 5, 10 and 30 m height. Rijkoort (1961) compared these observations with four different formulas that describe the wind profile.



In 1955 and 1956 wind speed was measured at 15 and 54 m height. Also wind speed and lapse-rate measurements at 10 and 30 m height were carried out. Rijkoort (1969) used these observations to study the dependence of low-level wind shear on averaging period and lapse-rate.
In 1959 wind speed was measured at 10 and 30 m, and temperature at 1.5 and 54 m height. These data were used to check the validity of the description of the increase of wind speed with height for a dozen published formulas (Rijkoort, 1968).

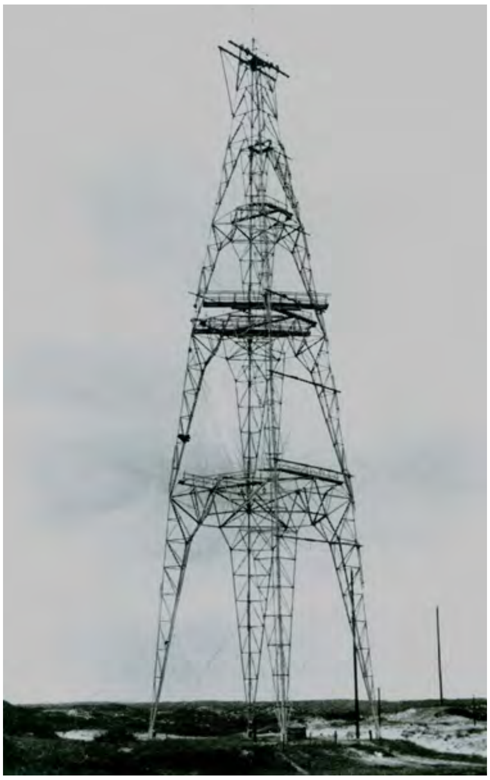
In 1964 a 20 m high lattice mast was erected on a field near to the KNMI building for investigating the accuracy of various observation methods for profiles of wind and temperature and to develop instrumentation in view of the plan to build an 80 m high mast in Vlaardingen.
Temperature measurements were carried out to determine what accuracy could be achieved. In 1965 wind speed was measured at 5, 10 and 20 m, wind direction at 10 and 20 m, and temperature at 2, 5, 10 and 20 m height.
Various wind measuring instruments, including one for turbulence measurements, were tested (Wieringa and van Lindert, 1971). In 1968 a second mast was erected to develop transmissometry for monitoring a visibility profile. The 'old' mast was dismantled in 1974.
The other mast was used until 1980. The picture was taken around 1965.

Within the framework of a reclamation programme of a part of Lake IJssel in the centre of the Netherlands a 20 km wide lake, Lake Flevo, was temporarely formed and had a well controlled water budget. In 1967 an 8 m high mast and a data registration facility were put in the middle of this huge evaporation pan. Instruments were installed to monitor wind, dry- and wet-bulb temperature and radiation, as well as turbulent fluctuations of wind and temperature. Part of the data was used for a comparison of methods of estimating the evaporation of the lake (Keijman and Koopman, 1973) and Hicks (1975) used the turbulence data for air-sea interaction modelling. Wieringa (1973) used the data for modelling of wind gust factors over open water compared with land roughness.



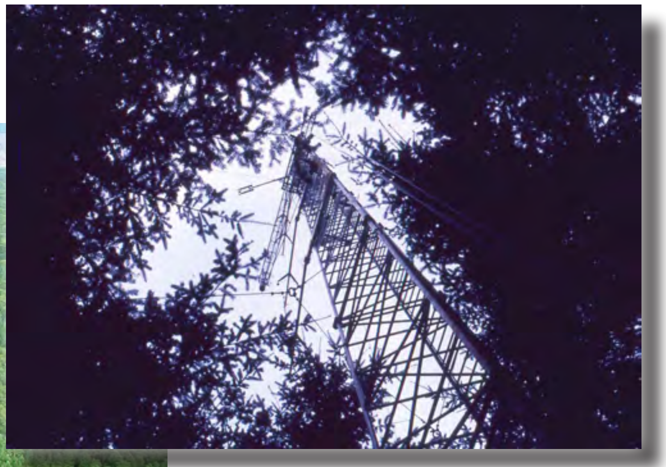
An 80 m high lattice mast was built in 1967 in the city of Vlaardingen to study the climatology and diffusion of air pollution in the highly industrialized area near the city of Rotterdam. To avoid disturbance by the registration shed, the measurements close to the ground were carried out on small masts of 10 and 5 m at some distance from the main mast. Observations started in December 1967. Wind speed and direction were measured with cup anemometers and wind vanes at 5, 10, 20, 40, 60 and 80 m height. Vertical temperature differences were measured with Cu/Co thermocouples mounted in psychrometers at 0.2, 2, 10, 20, 40, 60 and 80 m. A novelty was that instruments were placed on booms which were much longer than one mast width, swivelling upwards for upkeep or replacement. The absolute reference temperature was measured at 2 m. Also short-wave radiation was measured at 77 m. Precipitation was monitored with a pluviograph. Paper recorders were used for data registration. See Rijkoort et al. (1970) for a detailed description. A second shed was built to accommodate measurements of concentrations of SO_2 *at 2, 50 and 80 m and* O_3 *at 2 m, for which some technical problems had to be solved. Wisse and Velds (1970) reported on* O_3 *and* SO_2 *measurements at ground level in the summer of 1968 that were analysed in relation with the atmospheric stability and radiation in view of the production of oxidants. No other report on a database or analysis of these measurements could be found. Wind speed and direction distributions for the period April 1967 – April 1968, listed by Wieringa (1989), were analysed by Rijkoort (1972) and Raaff (1975). Wieringa (1973) derived gust factors up to 80 m height. In the fall of 1971 and in the spring of 1972 occasional turbulence measurements were carried out with trivanes and temperature fluctuation sensors. These instruments were installed at 10, 50 (1971 only) and 80 m height. These turbulence data were recorded on paper tape (Engeldal, 1973) but proved not to be good research material (Wieringa, personal communication). The mast was used until the end of 1973, when it had to be dismantled because of corrosion due to air pollution.*

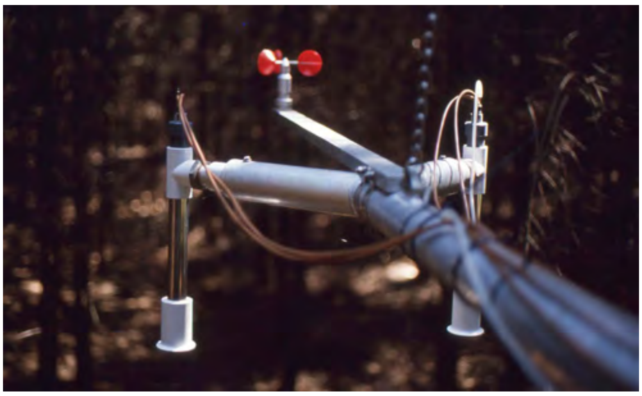
A 45 m high mast was temporarily erected at Schiphol Airport near Amsterdam to study slant visibility during fog in support of air traffic control. From January 1968 till February 1969 six lights along the mast were used to observe slant visual range. From September 1971 till February 1973 horizontal as well as slant visibility were measured with transmissometers. Two transmitters were installed on the ground. The detectors were mounted on the mast at a height of 2 and 40 m. Wind speed was measured at a height of 10 m, and the vertical temperature profile was recorded. It was found that slant visibility can be derived from measurements of horizontal visibility in combination with standard wind speed and temperature gradient measurements (Stalenhoef, 1974).



From 1965 to 1971 meteorological observations were made on a 75 m high radio mast near the village of Noordwijk at the west coast of the Netherlands. This mast was originally built for long-distance radio traffic. Wind speed, wind direction and temperature were measured at 25, 45 and 75 m height. The mast was dismantled around 1980. A new mast of 70 m height was built in 1982. During the COAST field experiment (Cooperative Operations with Acoustic Sounding Techniques)in 1983 (Durand et al., 1989) some instruments were installed on this new mast.

In 1988 a 36 m high meteorological tower was constructed at the Speulderbos research location close to the village of Garderen in the forested area of the north-west Veluwe. The work was done in the context of the Dutch Priority Programme on Acidification. At that time the site coordination was done by Wageningen University & Research centre (WUR). Additionally to the air quality observations, which were measured on separate masts, the meteorological mast was designed to derive the site specific turbulent exchange coefficients (upper-left figure, the slim tower in the front). These coefficients were then used to derive vertical fluxes of chemical components from vertical concentration gradients (Bosveld, 1997). Long booms were used to avoid interference with the tower (upper-right figure). The lower-left figure shows a cup anemometer (WUR-type) and a ventilated and shielded psychrometer (KNMI-type). This set of instruments was installed at four levels above the forest (18, 24, 30 and 36 m) and at one level (2 m) in the forest interior. At the 30 m level turbulence instruments for wind, temperature and humidity were installed for vertical flux measurements (lower-right figure). During the period 1995-1996 the site participated in the KNMI TEBEX project (Stammes et al., 1994). The meteorological tower was dismantled in 1997. The Speulderbos research site still exists, and the site coordination is currently done by RIVM. Research results on the interaction between the forest and the atmosphere can be found in Bosveld (1999).



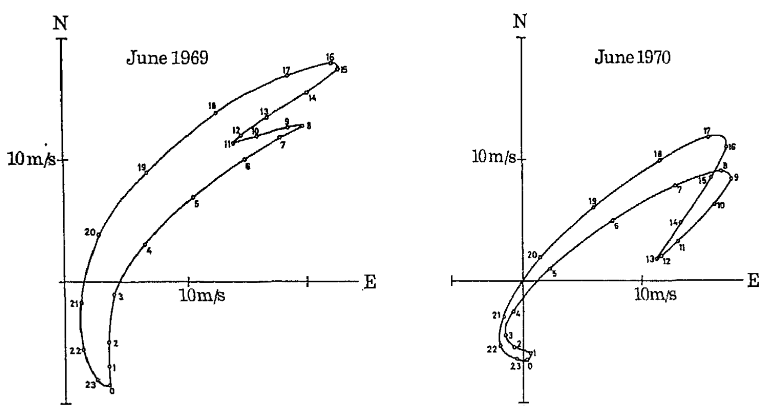


Upper air observations

Military aviation started in 1913 at the airfield Soesterberg, eight kilometres north-east of KNMI. Cooperation between KNMI and the military aviation organisation was established. From 1911-1920 KNMI flew big kites with selfregistrating instruments at the airfield, where a small wooden building was constructed for this purpose (upper-right picture). Clearly this was only possible when there was sufficient wind. Also manned balloon flights were carried out. The future director of KNMI, Dr. Cannegieter, was actively involved in these new upper air observations (KNMI, 1954). It is the gentleman in the grey suit on the picture of the balloon. With the development in 1919 of a construction that enabled the vibration-free mounting on an aircraft of a meteograph (lower-left picture), a devise that registered pressure, temperature and humidity, regular upper air measurements became possible up to a height of around five kilometres. Until 1919 about 300 flights per year were carried out by specialised pilots. These flights lasted about one hour. The data was not only used at KNMI, but also transmitted to Berlin where they were combined with observations from similar flights elsewhere to map the meteorological situation over Europe (Bartels, 2013). Log-books indicate that these flights continued until the end of the nineteen thirties.

A relatively simple way to obtain upper air wind information was to track the flight of a pilot balloon with a theodolite. KNMI started the use of this technique in 1908. From 1957 onward radar was used to track a reflector suspended below the balloon. From then on wind observations were also possible in cloudy weather. Pilot balloons were used until 1970. In 1927 Molchanov invented the radiosonde. Before the Second World War experiments with this new devise were carried out at KNMI, and regular observations with radiosondes started in 1945. Radar replaced the theodolite in 1957 to track the flights until 1984, when radio positioning systems became available (Lablans and Rothe, 2002).

Research of the ionosphere at KNMI started in 1949. The characteristics of the ionosphere were measured with a so-called ionosonde. This is a radio transmitter with a slowly varying frequency between 1 and 15 MHz with pulse modulation. The echoes that are detected by a receiver contain information on the ionosphere. A technique was developed to derive the drift of the ionosphere at heights between 100 and 130 km, the so-called E-layer, by correlating the echoes of signals received by three closely spaced (90 m) receivers, using a frequency between 2.1 and 2.6 MHz. These observations, an early example of remote sensing, started in 1969.
The figure shows the mean daily drift ('wind') of the E-layer for June 1969 and June 1970 (Vesseur, 1972).
Ionosphere research at KNMI continued until the mid nineteen eighties.



Polar diagram of hourly values of E-region drift for June 1969 and June 1970

Acknowledgements

We acknowledge Reinout Boers for contributing to the content and the editing of this report.
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We acknowledge KNMI librarian Wouter Jansen and Jan Huizinga for providing us with photographs and related information on meteorological towers and masts, methods of observation and instrumentation dating back to 1854.
Discussion with Gerard van der Vliet uncovered nearly forgotten details.
Theo Brandsma and Gerard van der Schrier provided information on early time-series of observations.
We thank Arie Kattenberg for suggesting to include some remarks on ionospheric research.
Gé Verver reminded us of the Speulderbos research location.
We finally thank Wouter Knap for his suggestion to write this report and for commenting on the final draft.

Acronyms

AERONET	Aerosol Robotic Network
AMS	Aerodyne Aerosol Mass Spectrometer
AOT	Aerosol Optical Thickness
ARM	Atmospheric Radiation Measurement (Programme)
ARPEGE	Action de Recherche Petite Echelle Grande Echelle (Research Project on Small and Large Scales)
ATPROP	Atmospheric Propagation and Profiling System
AVHRR	Advanced Very High Resolution Radiometer
BL	Boundary layer
BSRN	Baseline Surface Radiation Network
CAELI	CESAR Water Vapour, Aerosol and Cloud Lidar
CESAR	Cabauw Experimental Site for Atmospheric Research
COAST	Cooperatieve Operations with Acoustic Sounding Techniques
COST	European Cooperation in Science and Technology
DAK	Doubling Adding KNMI (model)
DANDELIONS	Dutch Aerosol and Nitrogen Dioxide Experiments for validation of OMI and SCIAMACHY
DIAL	Differential Absorption Lidar
EARLINET	European Aerosol Research Lidar Network
ECHAM5	European Centre Hamburg Model, version 5 (a general circulation model)
ECMWF	European Centre for Medium-Range Weather Forecasts
ECN	the Netherlands Energy Research Centre
ERA-40	ECMWF 40 Year Re-analysis
ESA	European Space Agency
EUCAARI	European Integrated project on Aerosol, Cloud, Climate, and Air Quality Interactions
EUCLIPSE	European Union Cloud Intercomparison, Process Study and Evaluation
FASTER	Fast-Physics System Testbed and Research project
GPS	Global Positioning System
HATPRO	Humidity and Temperature Profiler
IDRA	IRCTR Drizzle Radar
IMPACT	Improved Meteorological Predictions for Airport Capacity Tuning
IRCTR	International Research Centre for Telecommunications and Radar (of the Delft University of Technology)
ISORROPIA	A thermodynamic equilibrium model for multiphase multicomponent inorganic aerosols
KEMA	NV Keuring van Elektrotechnische Materialen; at present Det Norske Veritas (DNV) KEMA Energy & Sustainability
KNAW	Royal Netherlands Academy of Arts and Sciences

KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
KPT	KNMI Parameterization Testbed
LAM	Limited Area Model
LES	Large Eddy Simulation
LLJ	Low-level jet
MARGA	Monitor for Aerosol and Gases
NEE	Net Ecosystem Exchange
OMI	Ozone Monitoring Instrument
PEGASOS	Pan-European Gas-Aerosols-climate interaction Study
PILPS	Project for Intercomparison of Land-Surface Parameterization Schemes
PM	Particulate Matter
RACMO	Regional Atmospheric Climate Model
RASS	Radio Acoustic Sounding System
RIVM	Rijksinstituut voor Volksgezondheid en Milieu; the National Institute for Public Health and the Environment
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SGP	Southern Great Plains
TARA	Transportable Atmospheric Radar
TD-PTR-MS	Thermal-Desorption Proton-Transfer-Reaction Mass-Spectrometer
TEBEX	Tropospheric Energy Budget Experiment
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek; the Netherlands Organization for Applied Scientific Research
UKMO	United Kingdom Meteorological Office
UU	Utrecht University

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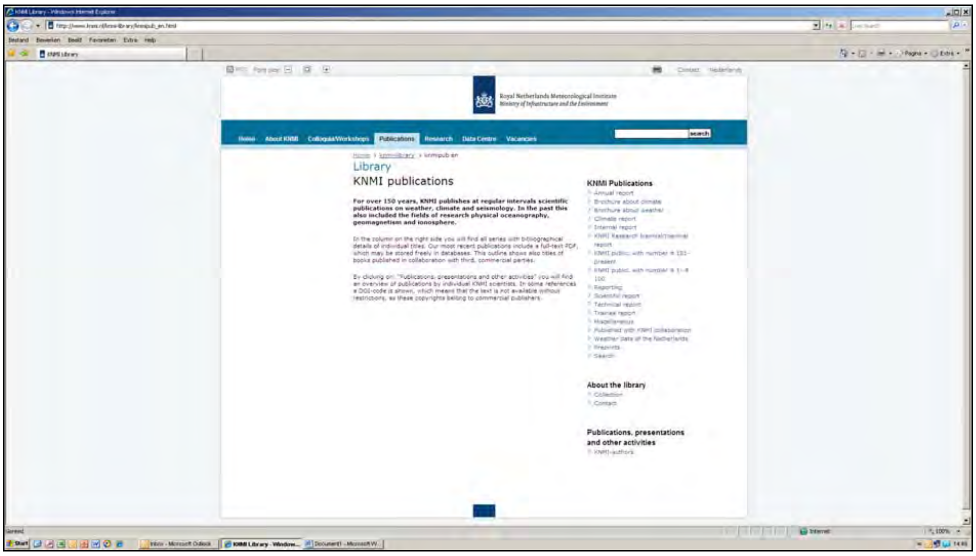

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