EG-CLIMET: OVERVIEW OF THE ACHIEVEMENTS OF THE ACTION

INTRODUCTION

This document provides a summary of the major findings and conclusions of the COST EG-CLIMET action. It highlights four profiling instruments, their synergy, and NWP applications. The instruments provide profiles of aerosol and cloud backscatter, winds, temperature and humidity:

1) Ceilometers,
2) Doppler lidars,
3) Wind profilers,
4) Microwave Radiometers,
5) Synergy and NWP applications.

For each instrument we provide:
i) Background discussion,
ii) The scope of the instrument,
iii) Calibration, accuracy, sensitivity, and maintenance issues,
iv) Original contributions made by the EG-CLIMET action.

The full wiki-based report can be found at http://wiki.eg-climet.org/.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

Ceilometers: EG-CLIMET has

- Compiled a list of hundreds of ceilometers deployed in Europe.
- Demonstrated they could supply real time backscatter profiles from clouds and aerosols.
- Demonstrated simple accurate calibration techniques using atmospheric targets.
- Demonstrated they can measure the boundary layer height in unstable boundary layers.
- Compared the backscatter profiles of clouds and aerosols with NWP models predictions.
- Recommended to EUCOS that these instruments be networked to provide real time data.

Doppler Lidars: EG-CLIMET has

- Examined the performance of new Doppler lidars; 25 are now deployed in Europe.
- Demonstrated that they can provide accurate winds in the boundary layer.
- Demonstrated they can measure turbulence and vertical exchange in the boundary layer.
- Recommended to EUCOS that these instruments be networked to provide real time data.

Wind Profilers: EG-CLIMET has

- Developed algorithms, now implemented operationally, to reject spurious bird echoes.
- Improved algorithms, now implemented operationally, for rejecting spurious ground clutter.
- Demonstrated the positive impact of well-maintained wind profilers on NWP forecasts.

Microwave Radiometers (MWR): EG-CLIMET has

- Compiled a list of MWRs in Europe and developed an international network: MWRnet.
- Demonstrated the accuracy of temperature and water vapour in retrieved profiles.
- Demonstrated the value of MWR in estimating boundary layer depth.
- Provided the first comparison of MWR retrievals with NWP model predictions.

Synergy and NWP: EG-CLIMET has shown that

- Ceilometer data may be used for evaluation of NWP models and subsequent assimilation.
- Doppler lidars, together with wind profilers, can provide winds throughout the troposphere.
- Strategically placed wind profilers have a positive impact on NWP forecasts.
- Wind profilers assimilated into operational NWP can provide warnings of nuclear hazards.

Following EG-CLIMET presentations to EUCOS, the body responsible for the European observing system, E-PROFILE has been launched which will run from 2013-2017 and will be responsible for Wind Profiler data quality and for coordinating real time exchange of backscatter profiles from ceilometers and lidars. A new COST action, ES1303, TOPROF, 'Towards Operational ground based PROFiling with ceilometers, Doppler lidars and microwave radiometers for improving weather forecasts', will address common calibration, retrieval algorithms and data quality issues.

1. CEILOMETERS

1.1 BACKGROUND

The CloudNet project (Illingworth et al., 2007) demonstrated that ceilometers and low-power automatic lidars are reliable instruments that can be used to quantify the properties of liquid clouds for long-term comparisons of observations of clouds with their representation in forecast models. Barret et al. (2009) used ceilometer and radar observations to evaluate forecasts of clouds within the boundary layer. Morille et al. (2007) proposed a portable method to retrieve and classify atmospheric layers (i.e. cloud and aerosol layers, the boundary layer). Monitoring of the atmospheric boundary layer diurnal evolution using ceilometers and low power automatic lidars is a topic of active research (e.g. Haeffelin et al., 2012; Emeis et al., 2008; Muenkel et al., 2007). Following the Iceland volcanic eruption of April 2010, several groups started investigating the possibility of monitoring long-range aerosol transport using networks of ceilometers (e.g. Flentje et al., 2010). Hence it has been demonstrated that the rather simple and widely available ceilometers are suitable for monitoring key atmospheric parameters, provided that their measurements are calibrated, analyzed and interpreted in a careful and consistent manner.

1.2 SCOPE OF THE INSTRUMENT

Ceilometers and low-power automatic lidars transmit a short pulse of laser radiation, with wavelengths ranging from 355 to 1064 nm, and receive a backscattered signal with a delay that provides range information. The name 'ceilometer' suggests they were originally conceived to measure cloud base altitude; the sensitivity of current ceilometers and low-power automatic lidars is sufficient to provide profiles of aerosol within the boundary layer, and potentially into the free troposphere. For simplicity we now refer to these systems collectively as ceilometers.

The vertical range of a ceilometer typically extends to between 7.5 km and 15 km from the surface, but it should be noted that the lidar signal is severely attenuated by liquid water clouds so that profiles can only be obtained up to cloud base (and about 200 m into such clouds). Low-level liquid water clouds are most frequent in winter and in Northern Europe. The native vertical resolution can be as low as 1.5 m, with 5 seconds temporal resolution, but, to increase sensitivity, the raw data is usually integrated up to 15-30 m in the vertical and 15-60 seconds in time. The minimum range can be lower than 100 m or as high as 1 km, depending on the optical arrangement and the overlap resulting from the physical separation of the receiver and transmitter. Correction of the signal is possible for part of the overlap region. Stray background light (solar radiation) entering the detector chain leads to a drop in sensitivity during the day.

The instrument records attenuated backscatter coefficient in units of m-1 sr-1. This can be converted to extinction through the 'lidar ratio', S, which is the extinction to backscatter ratio (in units of sr). The value of S in water clouds is well known, but is variable in both ice clouds and for aerosols. This introduces an error in the derived extinction of about a factor of two.

The ceilometer can also be used to measure the solar background light; with knowledge of the solar zenith angle this can be converted into a cloud optical depth.

Ceilometers should be soon available which will emit polarised pulses and detect the return in both the co-polar (same polarisation as emitted) and the cross polar channel. The ratio of the cross polar return to the co-polar return is reported as the depolarisation ratio, and gives an indication of the shape of the particles responsible for the backscatter. Spherical particles (such as cloud droplets and hydroscopic aerosol at high relative humidities) have a very low depolarisation ratio, whereas dry desert dust, volcanic ash, and ice particles have a much higher depolarisation ratio. Ceilometers are generally pointed 3-5 ° off zenith to avoid specular reflection from aligned pristine ice crystals.

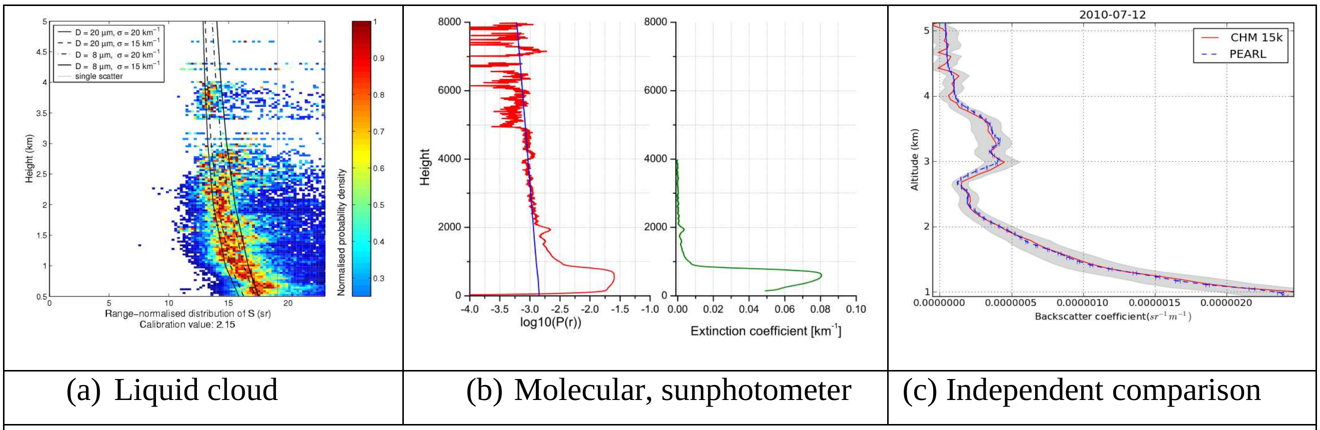
1.3 CALIBRATION, ACCURACY, SENSITIVITY AND MAINTENANCE

Calibration. Manufacturers supply a calibration but it should be checked periodically using a standard naturally occurring atmospheric target with a known backscatter. Such targets may be: molecular backscatter, aerosols observed simultaneously with a sun photometer instrument (Wiegner and Geiß, 2012), and liquid clouds which extinguish the signal (O'Connor et al., 2004). . At ultraviolet and visible wavelengths, the instruments can be calibrated using the known molecular backscatter in aerosol-free regions above the boundary-layer. At near-infrared ceilometer wavelengths (850-1064 nm), the molecular backscatter is very low and requires a long dwell period of 2-8 hours at heights of 3-7 km (location dependent) where there is no aerosol. The sun photometer technique requires a long comparison of the column-integrated aerosol optical depth with the total backscatter from the ceilometer profile and an assumed climatological value of the aerosol lidar ratio. The liquid cloud method involves integrating the attenuated backscatter within the liquid layer; which is inversely proportional to the known lidar ratio (in sr) of liquid water clouds; the calibration is adjusted until the two values agree. Figure 1 displays (a) the calibration technique for the water cloud extinction method, (b) using the known near-infrared molecular backscatter at 3-4 km height integrated for 2 hours, together with extinction values scaled to match the integrated value derived from the sunphotometer, and (c) independent evaluation of the molecular technique at near-infrared by comparison with a collocated lidar system having a much more powerful laser. A comprehensive inter-comparison of all ceilometer calibration methods at ultraviolet, visible and near-infrared wavelengths is necessary to make final recommendations for operational requirements.

Accuracy. The uncertainty in the climatological value of the lidar ratio limits the accuracy of the sunphotometer calibration technique to about 25%. The integrated backscatter from the water cloud yields a calibration accurate to about 8-10%.

Sensitivity. Sensitivity is dependent on the signal-to-noise ratio, SNR, which is a function of the emitted power, telescope design, averaging time, background light, and the strength of the backscattered return from atmospheric targets. To ascertain the comparative sensitivity achieved by various ceilometers during the day, the minimum detectable backscatter as a function of height is calculated for an integration of 30 seconds. Daytime conditions are a much a harsher test than nighttime, due to the influence of the solar background as a noise source. The minimum detectable backscatter can be expressed in terms of extinction in units of m^{-1} assuming a lidar ratio of 16, chosen as the median value for the range (2-50 sr) observed in ice clouds and aerosol.

Maintenance. Minimal maintenance required. The external optics need to be cleaned weekly or monthly.



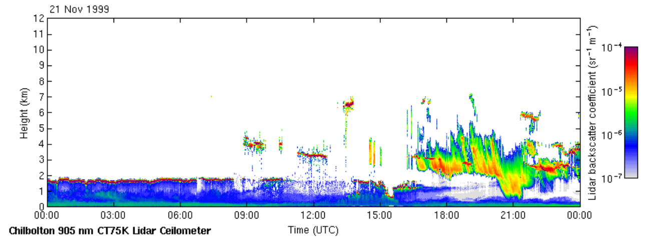
(a) Liquid cloud | (b) Molecular, sunphotometer | (c) Independent comparison

Figure 1. Calibration methods and comparison with independently calibrated lidar system.

1.4 ORIGINAL CONTRIBUTIONS MADE BY EG-CLIMET ACTION

Backscatter profiles

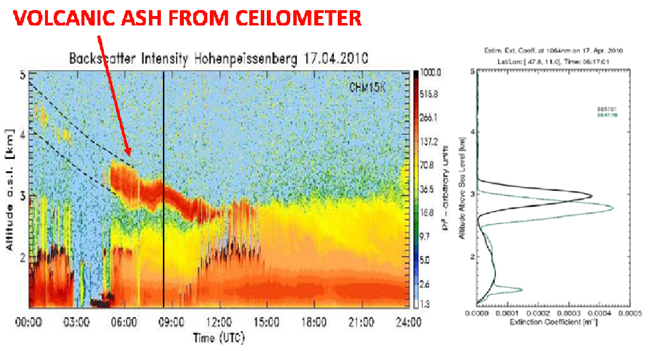
Attenuated backscatter profile for a 24-hour period over Chilbolton, UK. Liquid water clouds, ice clouds, and aerosol in the boundary layer are all detected by the ceilometer.



Detection of volcanic ash by ceilometer.

Left panel: attenuated backscatter coefficient from Hohenpeißenberg, Germany, over a 24-period. Right panel: Using co-located sunphotometer and nephelometer, the volcanic ash particle massc concentration was estimated to be: 600 (+/- 400) µg m^{-3}(Flentje et al., 2010)

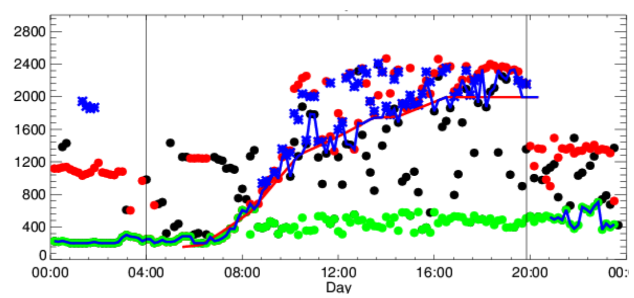
Courtesy, H. Flentje (DWD).



Mixing layer depth

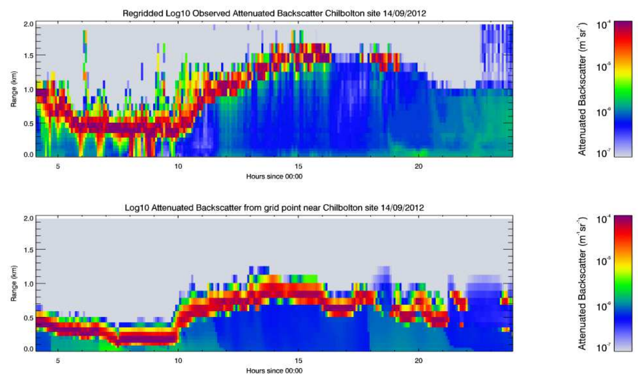
Multiple layers identified from gradients in aerosol backscatter (green/black/red points), and cloud base (blue points). Mixing layer identified as black line, provided auxiliary observations are available to confirm the presence of an unstable boundary layer.

Courtesy, M. Haeffelin (IPSL).



Model evaluation

Top panel: attenuated backscatter coefficient from Chilbolton, UK for a 24-hour period, averaged to the model vertical grid. Lower panel: predicted output from numerical weather prediction model The next step is to build up 'O-B' (Observations versus Background model) statistics leading ultimately to data assimilation.



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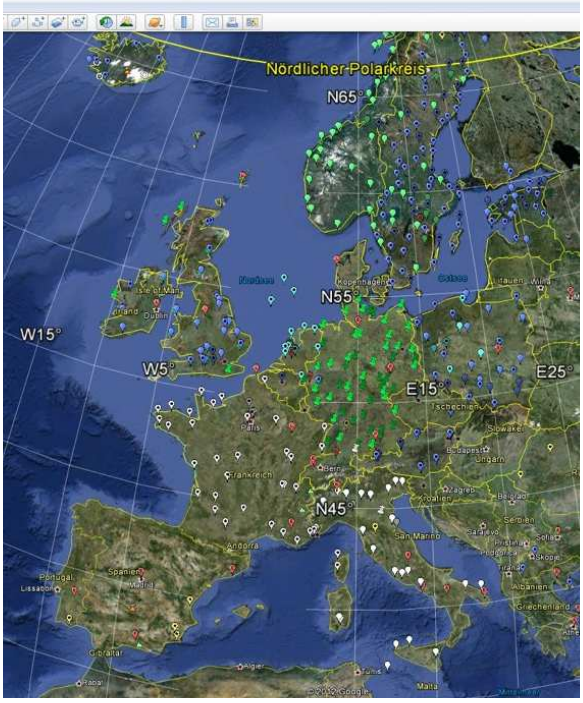
Ceilometer map

EUCOS is responsible for developing an observing system for Europe (www.eucos.net). EUCOS has launched E-PROFILE which will run from 2013-2017 with 17 member states participating and a budget of 200 kEURO in year one. E-PROFILE will be responsible for the coordination and implementation of hardware for real time exchange of backscatter profiles from ceilometers and automatic lidars.

Distribution of current ceilometers over Europe reporting backscatter profiles. These may provide data in near-real-time, but are not yet fully networked.

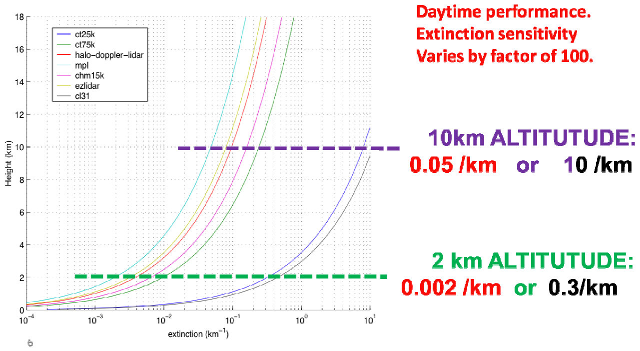
Courtesy, W. Thomas (DWD).



Ceilometer sensitivity

Daytime sensitivity to ice clouds for various ceilometer systems. Extinction derived from backscatter sensitivity, assuming a lidar ratio of 16 chosen as the median value for the range (2-50 sr) observed in ice clouds.

Courtesy, E. J. O'Connor (FMI/U. Reading).



2. DOPPLER LIDARS

2.1 BACKGROUND

Recent work has demonstrated that small autonomous Doppler lidars have the ability to continuously monitor the wind vector throughout the boundary layer, to estimate levels of turbulence and provide additional information on the cloud and aerosol particles. Hogan et al. (2009) showed how velocity variance and skewness from a Doppler lidar can be used to classify different boundary layers. Barlow et al. (2011) discuss the use of a Doppler lidar to study boundary layer dynamics over London. Dacre et al. (2010) report on the use of Doppler lidar to study the ash plume of the Icelandic volcano. The use of the Doppler lidar to estimate turbulent dissipation energy rates is to be found in O'Connor et al. (2010). Westbrook et al. (2010) describe how the properties of ice crystals falling from supercooled clouds can be inferred from Doppler lidar observations. Westbrook and Illingworth (2009) use Doppler lidar to infer the size spectrum of ice crystals in clouds.

2.2 SCOPE OF DOPPLER LIDARS

Portable autonomous Doppler lidar systems have been developed using new solid-state fibre-optic technology using coherent heterodyne detection to derive the Doppler shift of atmospheric tracers (aerosol). Two implementations are available for these robust and low-powered systems: pulsed, and continuous-wave (CW). Pulsed systems are similar to ceilometers and other pulsed lidar systems, using the time of delay to provide the range information. Minimum range is typically 50-90 m, with maximum range varying from 0.2-10 km. CW systems adjust the focus of the telescope to provide the range information; hence these are most suitable for close range operation, typically from 10-300 m. Both implementations operate at very high pulse rates and average many pulses to achieve the required sensitivity. Due to the instrument design, there is no telescope overlap issue.

The fibre optic design allows a high degree of flexibility, and these instruments are available in a number of guises: vertical stare only, full all-sky scanning capability, scan within a conical zone, or optimised for winds only. Doppler lidar systems which specialise in vertical profiles of horizontal wind obtain this by means of 'Doppler Beam Swinging', as is done for Wind Profilers, or use a conical VAD (Vertical-Azimuth-Display) scan. Wind profiles are restricted to regions where there is sufficient aerosol to provide a good signal, and in practice, this limits observations to within the boundary layer.

When operated at vertical incidence, Doppler lidars exploit the return from aerosol particles to detect convective motions and the evolution of the mixing height. Turbulence characteristics can be derived from the rate of fluctuations of the vertical velocity. Note that the signal is attenuated by liquid clouds in the same manner as for other lidars.

2.3 CALIBRATION, ACCURACY, SENSITIVITY AND MAINTENANCE

The backscatter coefficient can be calibrated in the same way as ceilometers (Westbrook et al., 2010). Doppler velocity is self-calibrating in the 'noise' region and biases can be diagnosed with tests using hard targets.

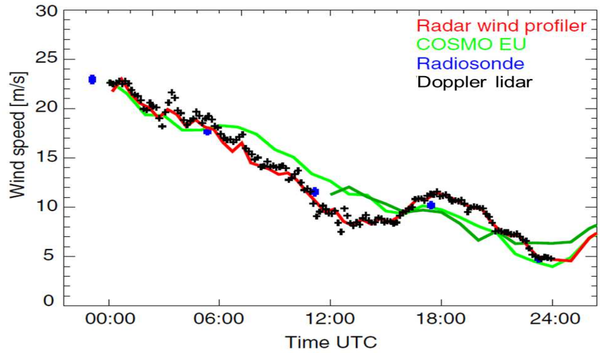
The accuracy of the radial velocity measurements depends on the signal to noise ratio and is typically much better than 0.5 m s^{-1}; less than the representativity error of radio sondes. A combination of the wavelength used, and the heterodyne nature of the system, means that Doppler lidars are insensitive to daylight. Doppler lidars need minimal maintenance and experience is that they are very reliable.

2.4 ORIGINAL CONTRIBUTIONS MADE BY EG-CLIMET ACTION

Evaluation

Comparison over several weeks of co-located wind profilers, sondes and Doppler lidars at Lindenberg (Germany) demonstrated that lidar horizontal winds were accurate to 0.2 m s^{-1} and 2 deg in direction.

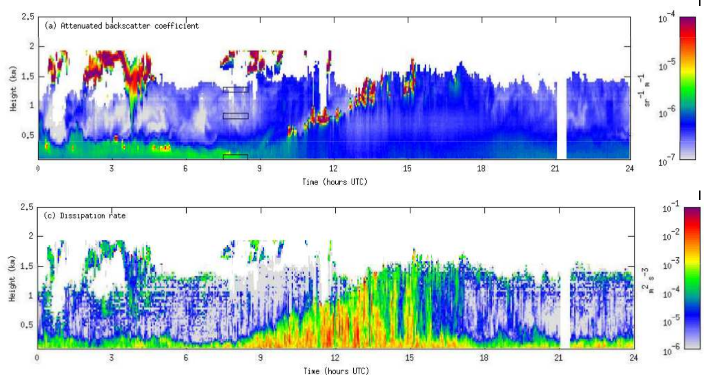
Courtesy, V. Lehmann (DWD).



Dissipation rate

The dissipation rate of turbulent kinetic energy within the boundary layer can be derived at high temporal and spatial resolution. Top panel displays attenuated backscatter coefficient from an urban site in London, UK, over a 24-hr period. Lower panel displays dissipation rate for the same period.

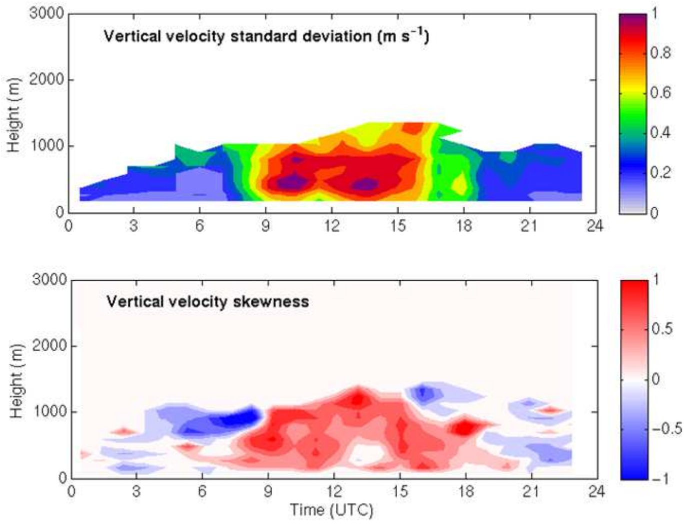
Courtesy, E. J. O'Connor (FMI/U. Reading)



Boundary layer characteristics

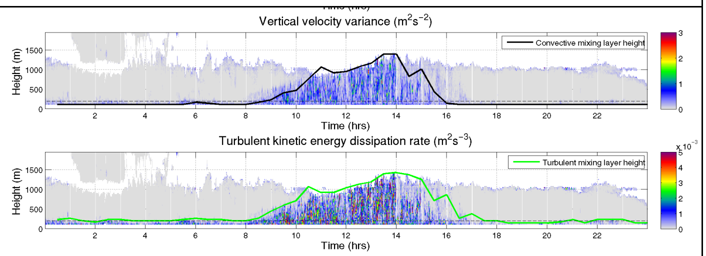
The skewness and standard deviation of the vertical velocity measurements are excellent indicators of dynamical processes in the boundary layer. Standard deviation (top panel) indicates the intensity in the turbulent regions, while the skewness (lower panel) can be used to diagnose the source of turbulence; positive skewness arises from surface-driven convection, whereas negative skewness can indicate cloud-top driven turbulent processes.

Courtesy, E. J. O'Connor (FMI/U. Reading)



Boundary layer height

Velocity variance, and dissipation rate can be used to identify the mixing-level height, which is the top of the region of the boundary layer in constant contact with the surface.



Promotion of ISO wind lidar initiative.

Discussions within EG-CLIMET working groups have lead to the on-going ISO (International Standards Organisation) wind lidar initiative, promoting the transition from remote sensing methods to fully traceable observations.

3 RADAR WIND PROFILERS

3.1 BACKGROUND

Remote sensing of the horizontal wind vector in the atmosphere by radar wind profiler (RWP) has been significantly developed since the first demonstration in the early 1970s (Woodman and Guillen, 1974). Currently, there exist several operational networks worldwide which provide continuous wind measurements in real-time and most of the data is assimilated in numerical weather prediction models, see Bouttier (2001), Benjamin et al. (2004), Ishihara et al. (2006) and Calpini et al. (2011).

Reviews of the technical and scientific aspects of RWP have been provided by Gage (1990), Roettger and Larsen (1990), Doviak and Zrnić (1993), Muschinski (2004), and Fukao (2007).

In Europe, a first demonstration of wind profiler networking was organized during the COST-76 action in early 1997 as the CWINDE-97 project (Nash and Oakley, 2001). Most radars are L-band or higher UHF boundary layer profilers (915, 1280 or 1290 MHz), but there are also four lower UHF (482 MHz) systems in Germany, and five VHF systems (45 - 64 MHz) in France, the UK and Sweden.

3.2 SCOPE OF THE INSTRUMENT

The main advantage of RWP's is their ability to provide vertical profiles of the horizontal wind at high temporal resolution under almost all weather conditions, in both cloudy and clear atmospheres. No other remote sensing method has this property. The particular advantages of RWPs are a high temporal resolution and the capability to provide unambiguous profiles independently of the assimilation system used (no a-priori information required).

Most operationally used RWPs are monostatic pulse radars with a single carrier frequency (in contrast to multi-frequency imaging radars), with the hardware architecture resembling that of a typical Doppler radar system (Muschinski et al., 2005). The wavelengths extend from about 20 cm (L-Band) to about 6 m (VHF). Electromagnetic waves in this spectral range are scattered by fluctuations of the refractive index of particle-free 'clear air' which are omnipresent due to the turbulent state of the atmosphere. This is called clear-air scattering and is classically described by the theory of radio-wave propagation through the turbulent atmosphere (e.g. Tatarskii, 1971). The second major scattering process for RWP is scattering from small particles, such as liquid droplets and ice crystals. Here, the Rayleigh approximation can be used for simplification, because the particle diameter is always much smaller than the wavelength (e.g. Gossard and Strauch, 1983). All remaining echoing mechanisms are considered as clutter. To avoid measurement errors due to misinterpretation of such echoes as atmospheric returns, the corresponding signal components need to be identified and filtered in the signal processing. Of particular practical relevance are echoes from migrating birds (Wilczak et.al., 1995). A novel filtering method based on a Gabor frame based time-frequency decomposition of the raw data and signal statistics has been developed (Lehmann and Teschke, 2008; Lehmann, 2012), and implemented in operational systems.

The increasing interest in renewable energy has led to a rapid deployment of large wind turbine farms (WT) in some countries. For profilers, the WT clutter echoes are caused by the side-lobes of the antennas and it is difficult to estimate their potential impact because the actual antenna radiation pattern at angles close to 90 degrees from boresight is not precisely known. No signal processing algorithm is currently able to suppress or filter out the WT clutter, which shows an intricate time-frequency structure, and post-processing data quality control remains the only option to suppress erroneous data.

The majority of RWPs use the method of Doppler beam swinging (DBS) to determine the wind vector. At least three linear independent beam directions and some assumptions concerning the wind field are required to transform the measured 'line-of-sight' radial velocities into the wind vector. Comparisons of RWP winds with data from a meteorological tower (Adachi et al., 2005) and balloon soundings (Rao et al., 2008) have shown that a four-beam based DBS sampling configuration is superior over a three-beam configuration in terms of data quality. In general, the RMS error of RWP measurements can be significantly reduced by increasing the number of off-vertical beams in DBS.

Wind retrievals from Doppler-Beam-Swinging can be degraded during non-homogeneous conditions, for example in a convective boundary layer (CBL), during strong gravity wave activity (Weber et al., 1992), in patchy precipitation (Adachi et al., 2005) or in complex terrain (Bingöl et al., 2009). RWP wind vector measurements are therefore typically averaged over 10-60 minutes. Problems with 3-beam DBS wind profiler data obtained during convection have even been noticed in NWP data assimilation (Cardinali, 2009). While the DBS assumptions are usually deemed to be correct for mean winds averaged over a longer time interval, it is not clear how long this time interval must be under different meteorological conditions.

3.3 ACCURACY AND MAINTENANCE

Calibration. The precise estimation of Doppler frequencies is performed through heterodyning followed by standard digital spectral estimation methods and is therefore essentially self-calibrating. As the main interest is in wind measurements, a power calibration of these radars is usually not attempted although it should be possible in principle. However, precise ranging requires an accurate determination of the group delay of the signal in the radar hardware; this can be obtained using a calibrated SAW[1] delay line. This procedure is called range calibration.

Accuracy. The accuracy of the wind measurement depends both on the correct interpretation of the estimated first Doppler moment as the average value of true radial velocity in the radar resolution volume and on the correct retrieval of the wind vector from the radial measurements in the different beam directions. A statistical intercomparison of more than 1000 independent profiles obtained with a 482 MHz RWP against a collocated radiosonde showed that the wind speed bias was less than 0.5 m s^{-1}, except for the tropopause region where it was about 0.7 m s^{-1}. Wind speed standard deviation was less than 1.5 m s^{-1} below 8 km and less than 2.2 m s^{-1} for all heights. With the exception of the lowest levels, the wind direction bias was determined to be about 1 degree, with a standard deviation of less than 20 degrees in general and below 10 degrees above 4.5 km in altitude (Dibbern et al., 2001).

Sensitivity. RWP use sensitive low noise amplifiers and can detect monochromatic signals as small as -155 dBm[2]. The availability of data in under clear air scattering conditions essentially depends on the variance spectrum of the refractive index and is further a function of mean transmit power, antenna gain, receiver sensitivity and radar wavelength.The high sensitivity of RWPs makes them vulnerable to any external radio-frequency interference (RFI) of sufficient strength that is in-band. Frequency management is therefore an essential requirement for operational networks.

Maintenance. RWP are complex technical instruments and both regular data monitoring and hardware maintenance is necessary to guarantee a constant high level of data quality. While the systems are typically specified to operate over a time period of 10-20 years without major technical upgrades, the MTBF of several system components is less and both preventive and corrective maintenance are a necessity. A comprehensive discussion of various aspects of RWP maintenance can be found in Dibbern et al. (2001).

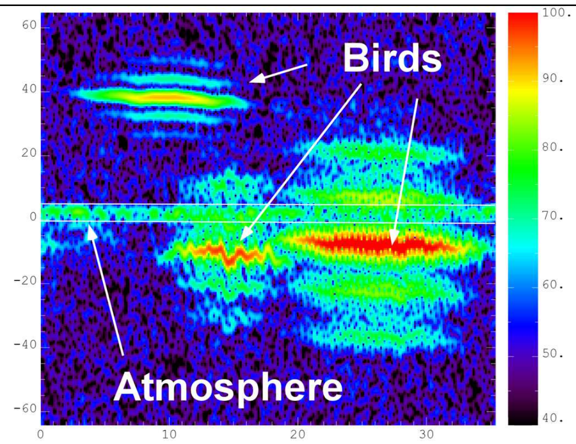
[1] Surface acoustic wave
[2] power referenced to one milliwatt in dB

3.4 ORIGINAL CONTRIBUTIONS MADE BY EG-CLIMET ACTION

Bird echo filtering

A Gabor filter has been incorporated in the standard wind profiler software to remove the intermittent echoes due to bird migration. The example shows a time-frequency decomposed RWP raw signal containing bird clutter. The abscissa shows time in seconds, the ordinate gives frequency (s^{-1}) and the colour scale denotes signal power (dB).

Courtesy, V. Lehmann (DWD).

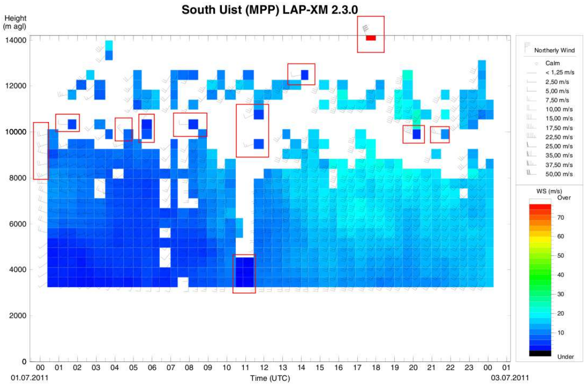


Spectral filtering

Correction of false wind retrievals due to clutter, radio frequency interference and rain events using improved spectral processing which has now been incorporated in the standard wind profiler software.

Spurious wind retrievals from the profiler at South Uist on 2 June 2011 are identified by the red boxes.

Courtesy, R. Leinweber (DWD) / C. Gaffard (MetOffice).



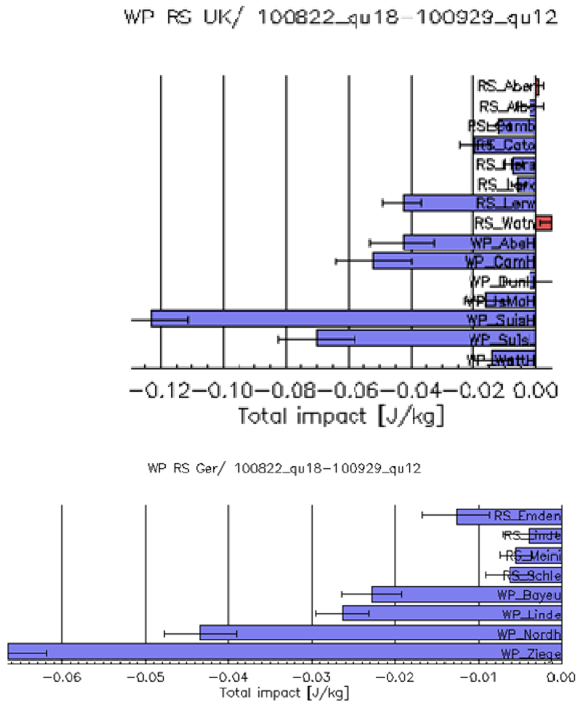
Impact of RWP on NWP

It has been demonstrated that strategically placed wind profilers (WP) have a greater impact than radiosondes (RS) in reducing errors in the forecast of the UK MetOffice global NWP model. The errors are expressed in terms of the change in a global energy norm.

The analysis used the FSO (Forecast Sensitivity to Observations) technique (Cardinali, 2009) which can identify the contribution to the reduction in the forecast error of specific observations when assimilated into the model.

The upper panel shows the impact of individual measurement systems (radiosondes and profilers) in the UK, the lower panels similar systems in Germany.

Courtesy, R. Leinweber (DWD) / C. Gaffard (MetOffice).



4. MICROWAVE RADIOMETERS

4.1 BACKGROUND

The operational performance of microwave radiometers (MWR) for estimating temperature and humidity profiles and column-integrated water vapor (IWV) and liquid water path (LWP) have been demonstrated (Güldner and Spänkuch, 2001; Crewell and Löhnert, 2003; Cimini et al., 2006). More recently the benefits of MWR measurements during dynamic weather conditions (Knupp et al., 2009) and in support of weather nowcasting and forecasting (Löhnert et al., 2007; Cimini et al., 2011) have been demonstrated. Nowadays, off-the-shelf commercial MWR are robust instruments providing continuous unattended operations and real time accurate atmospheric observations at ~1 min temporal resolution under nearly all-weather conditions.

MWR data are used for a variety of applications, including operational meteorology and weather forecasting, climate monitoring, atmospheric microphysics, air quality prediction, satellite validation, radio-astronomy, geodesy, air-sea interaction, and radio-propagation.

Concerning weather and climate, recently the focus has been on demonstrating the measurement quality and the retrieval uncertainties in the light of suitability for operational network application (Löhnert and Maier, 2012; Güldner, 2013) and on the coordination of networks for the production of quality controlled and harmonized data for the assimilation into NWP models (Cimini et al., 2012).

4.2 SCOPE OF THE INSTRUMENT

Radiometry is a passive technique. Ground-based MWR are receivers calibrated to measure the down-welling natural thermal emission from the Earth atmosphere; these measurements are then processed to estimate some atmospheric thermodynamic properties. The quantity measured by MWR is atmospheric radiance [W m^{-2} sr^{-1} Hz^{-1}], which is usually converted into brightness temperature (Tb) to adopt the intuitive units of Kelvin.

The most common commercial units operate in the 20-60 GHz range. The 22-35 GHz band provides information on vapour and cloud liquid water, because of the presence of the 22.235 GHz water vapour absorption line and the relative transparent atmospheric window at ~30 GHz. Two channels (usually 23.8 and 30-31 GHz) are required to retrieve IWV and LWP simultaneously. More channels provide information on the vertical distribution of water vapour content, WV(z). The 50-60 GHz band is characterized by the oxygen absorption complex; considering that the oxygen concentration is uniformly distributed, and observations at 50-60 GHz band provide information on atmospheric temperature. Temperature profiles, T(z), are estimated from observations corresponding to different absorption; this can be obtained either by single-channel observations at several elevation angles or by multi-channel observations at one or more elevation angles. Systems with channels in both the 22-30 and the 50-60 GHz bands are often called MWR profilers.

With careful design, MWR can make continuous observations (time scales of seconds to minutes) in a long-term unattended mode under nearly all weather conditions.

4.3 CALIBRATION, ACCURACY, SENSITIVITY AND MAINTENANCE

Calibration. To ensure proper calibration, commercial MWR use square-law detectors and a combination of external targets, internal noise diode sources, and tipping curve. Typically, MWR are calibrated every few seconds using a high-emissivity (black body) target at ambient temperature and the noise power injected by one or more diode sources. In addition, other unknowns entering the calibration equation (such as diode noise temperature and antenna/radome absorption loss) are considered together in one calibration parameter which is calibrated at regular intervals by using either the tipping curve method or a cryogenic external target. The uncertainties of these two methods are mostly related to uncertainties at the calibration points. The overall absolute accuracy is assessed to be in the order of 0.3 K for ambient target calibration, 0.5 K for tipping curve calibration, and 1 K for the cryogenic calibration (Maschwitz et al., 2013).

Accuracy. When properly calibrated, a MWR provides Tb with an absolute accuracy of ~0.3-0.5 K. Typical rms accuracy for derived products are:

- IWV ~ 1.0 kg/m2
- LWP ~ 0.02 kg/m2
- T(z) ~ 0.5 - 2.0 K (decreasing from surface up)
- WV(z) ~ 0.2 - 1.5 g/m3

The accuracy above excludes water accumulation over the radome, which represents the major limitation under precipitation. Mitigation solutions are used in current MWR instruments, including rain sensor, hydrophobic coating, tangent blower, shutter, and side-view. These effectively mitigate water accumulation impacts on the retrieved products in most of the cases, unless intense rainfall or snowfall. Quality flags are usually adopted to indicate data during precipitation and/or with wet radome.

Sensitivity. Due to high redundancy in the passive observations, MWR are sensitive to a few pieces of independent information about the temperature and humidity profiles. Lönhert et al. (2009) showed that for a generic MWR operating in the 20-60 GHz range the degrees of freedom for the signal, which range from 1 to 4 for both temperature and humidity profiles, depending upon moisture burden and the used number of elevation angles. In particular, elevation scans are important for increasing the sensitivity to temperature inversion. With elevation scans, MWR are able to identify sharp surface inversions, and even elevated inversions (up to 1-2 km) though usually with smoothed inversion strength.

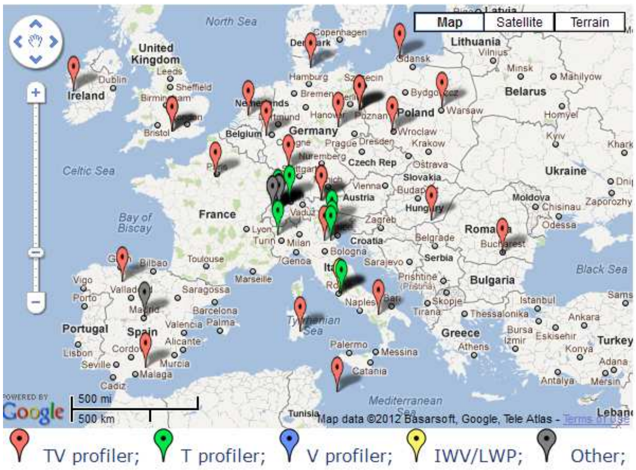
Maintenance. Accurate MWR observations are subject to instrument integrity and proper signal calibration. Commercial MWR consists of robust hardware exhibiting long life-time (years) even in extreme conditions. However, the radome protecting the antenna aperture must be kept clean, requiring services every once in a while and replacement every few months depending upon environment conditions (presence of dirt, sand, dust). The current technology is such that receivers are stable over long periods (months), thus cryogenic calibrations are recommended only few times a year.

4.4 ORIGINAL CONTRIBUTIONS MADE BY EG-CLIMET ACTION

- Setting the path for the development of a fast MWR forward operator suitable for variational assimilation into NWP models.
- Assessing the best practises for performing MWR observations and retrievals (reports available through the EG-CLIMET website, http://wiki.eg-climet.org/)
- Assessing calibration accuracy and demonstrating calibration monitoring methods for operational MWR deployment (Löhnert and Maier, 2012)

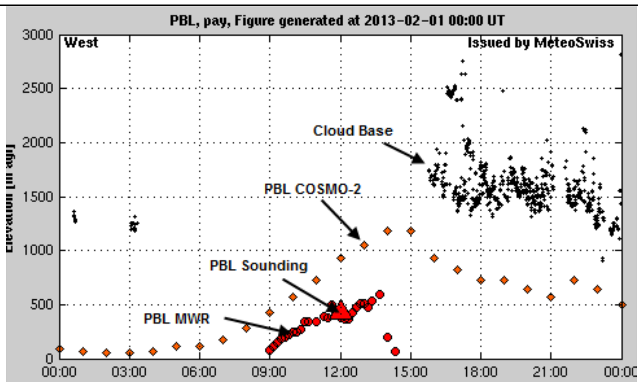
MWRnet

Spinning up MWRnet, an International Network of Microwave Radiometers (http://cetemps.aquila.infn.it/mwrnet/). MWRnet, initiated within EG-CLIMET, coordinated the participation of a network of MWR at the European level for the contribution to large scale experiments (e.g. HyMeX, http://www.hymex.org/) with observed radiances and retrieved temperature and humidity profiles. Results from these experiments should help in quantifying the significance of MWR observations for further NWP forecast improvements. The figure shows the distribution of MWR in Europe, from MWRnet member list. Different pin colors indicate different types of instruments. Temperature and humidity profilers (red) are the most widespread.



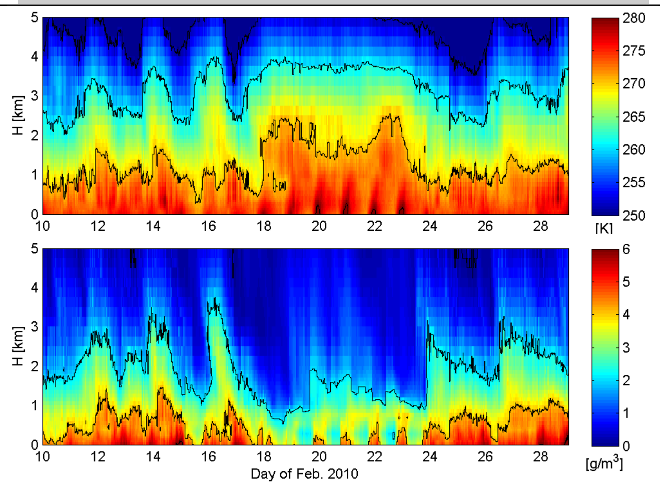
Boundary-layer height

Demonstration of boundary-layer height derived from MWR (Cimini et al., 2012a). Evaluation of radiosoundings, COSMO NWP model, and MWR over a 24-hour period at Payerne, Switzerland (Pratz et al., 2013).



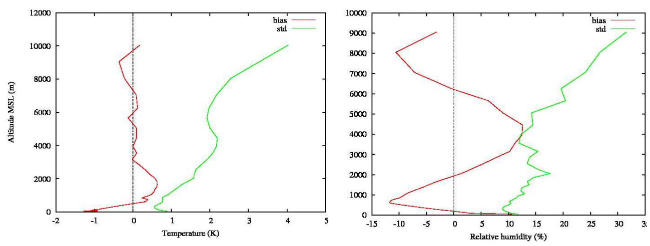
1D-var retrieval of T and q

Demonstration of NWP-aided variational (1D-var) retrievals from multi-channel MWR in all-weather conditions. Multi-day retrievals of temperature (top) and water vapor density (bottom) profiles are shown, providing temperature and water vapour density profiles within 1 K and 0.5 g m^{-3} from the surface up to 10 km (Cimini et al., 2011).



O-B statistics for assimilation

Observation-minus-background (O-B) mean (red) and standard deviation (green) differences for temperature (left) and relative humidity (right) profiles by a MWR in Lampedusa, Italy (Cimini et al., 2012b).



5. SYNERGY AND NWP

5.1 SUMMARY OF ACHIEVEMENTS

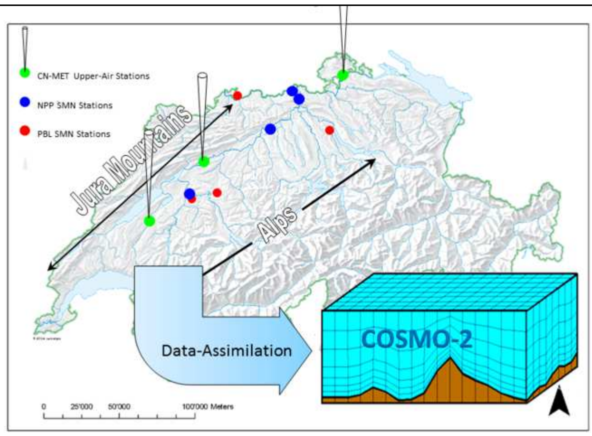
In earlier sections we have drawn attention to the following NWP applications of individual instruments and instruments in synergy:

- Ceilometers can be used for evaluation of NWP models representation of clouds, aerosols and mixing layer heights and potentially for data assimilation,
- Doppler lidars together with wind profilers can provide accurate winds throughout the troposphere,
- Strategically placed wind profilers have a positive impact on NWP forecasts,
- Comparison of planetary boundary layer height from radio sounding, microwave radiometers, and as predicted by NWP models,
- Observations versus NWP model (O-B) statistics for temperature and relative humidity derived from a microwave radiometer,
- The continuous efforts of the NWP community in improving the model horizontal and vertical spatial resolution call for an increase in high temporal resolution observations for assimilation and verification purposes. These are ideally delivered by high temporal ground-based remote sensing systems.

5.2 METEOROLOGICAL SURVEILLANCE FOR NUCLEAR POWER PLANTS

CN-MET System

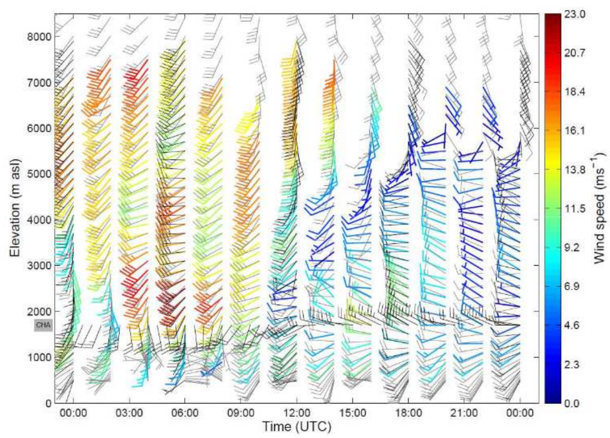
Regional-scale operational system in Switzerland whose main purpose is to deliver weather information necessary for providing security for the population in case of a nuclear hazard. It couples a specifically adapted measurement network (mainly ground-based remote sensing) to a predictive tool (COSMO-2, NWP model operated at MeteoSwiss).



Integrated wind profiles

Example of integrated on-line real-time information from COSMO-2 NWP model (grey barbs), wind profiler (coloured barbs), and nearby in-situ mountain top (dark-grey barbs) for a 24-hour period at Payerne, Switzerland (Calpini et al., 2011).

Positive impact of the three wind profilers on the quality of the forecast over the Swiss Plateau was demonstrated during the project phase. This system has been operational since 2009.



5.3 BLIND TEST RESULTS FOR SYNERGETIC RETRIEVAL OF LIQUID CLOUD PROPERTIES

Significant progress was made during EG-CLIMET in deriving profiles of liquid cloud properties and in particular liquid water content and cloud droplet concentration using from the synergetic use of instruments. Radar and lidar together can provide profiles of ice water content and ice particle concentrations, but obtaining the equivalent information for liquid water clouds has proved very difficult; the main difficulty arising from the fact that occasional liquid drizzle droplets dominate the radar reflectivity but make a negligible contribution to the liquid water content as reported below.

Low-level liquid clouds are prevalent during all seasons and on the global scale. They can be described through cloud cover, vertical distribution, total path integrated liquid water (LWP) as well as droplet size distribution (DSD), which can be expressed in terms of liquid water content (LWC), cloud droplet number concentration (N) and an effective droplet size (Reff).

The combination of passive microwave radiometer (MWR) and active cloud radar together with a backscatter lidar are currently the most robust way to profile liquid cloud microphysical properties, concerning both 24/7 instrument performance as well as algorithm applicability. Within the scope of EG-CLIMET four different cloud microphysics retrieval methods have been thoroughly assessed.

Liquid water content. A new retrieval method designed by C. Brandau (Delft Technical University, NL) shows an improvement in LWC retrieval skill over the standard scheme (Cloudnet) during non-precipitating conditions. The Brandau method includes constraints derived from cloud radar reflectivity profiles, and results from aircraft measurements according to Brenguier et al., 2011. The most crucial factor for retrieving both LWC and Reff was shown to be accurate LWP. When LWP is accurately known, random and systematic errors are on the order of ~10% for the Brandau method. The variational method IPT (Ebell/Löhnert) was shown to be very sensitive to a priori assumptions about LWC, but is, however, independent of LWP, whereas the SYRSOC method (Martucci) is very sensitive to the accuracy of the lidar measurements. All retrieval methods were shown to be very sensitive to a correct description of cloud base and cloud top and the corresponding distinction between cloud droplets and precipitation.

Effective radius and number concentration. The Brandau retrieval method delivers the most satisfactory results for cloud droplet size Reff in non-precipitating cases. Within the cloud boundaries, Reff can be derived with overall accuracies of ~15%. The Brandau method, as does IPT, assumes a constant value of N throughout the cloud profile. Although this is actually true for the simulated case analysed, systematic errors of more than 50% occur.

Precipitation. Frequently, liquid clouds contain larger precipitation drops (drizzle), which can dominate radar reflectivity signals without significantly contributing to the water content. Assumptions about the relationship between reflectivity and droplet size distribution are no longer valid, leading to large overestimation of Reff, and underestimation of N. However, both IPT and Brandau methods still deliver fairly robust results for LWC with overall errors in the range of 20-50%.

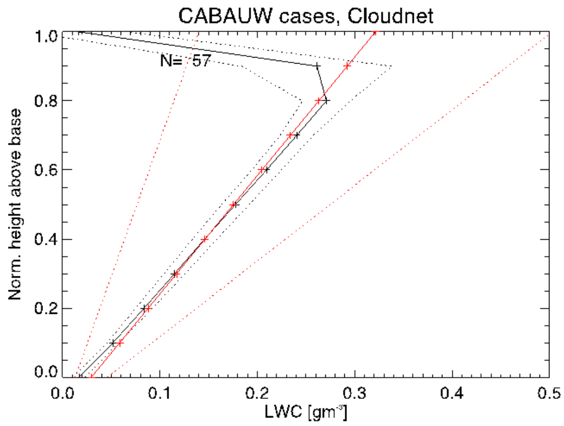
Next steps. Currently, the research focus is on methods that allow the discrimination of microphysical properties of the non-precipitating and precipitating part of the droplet size distribution. Furthermore, physically consistent a priori data (i.e. long-term statistics) of cloud profiles from in-situ measurements is required to be able to better constrain the retrieval methods. These methods should be ideally developed within a variational framework, which is flexible concerning the measurements and retrieval assumption and, additionally, inherently provides error estimates.

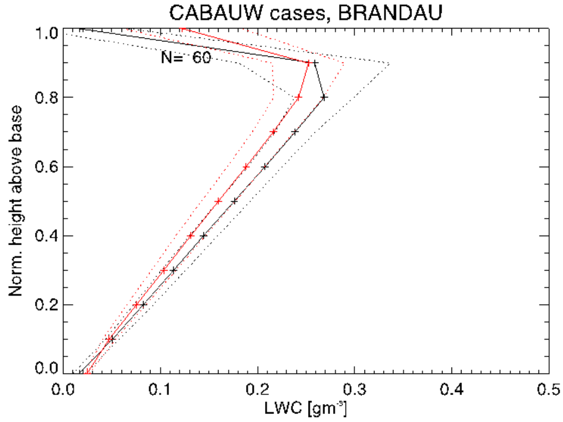
Liquid water content

Profiles of liquid water content for a cloud-resolving model same simulation initialized over Cabauw, NL.

Upper panel: mean values (bold) and corresponding 1-sigma range (dotted) are shown for the cloud-resolving model output (black) and standard Cloudnet retrieval (red).

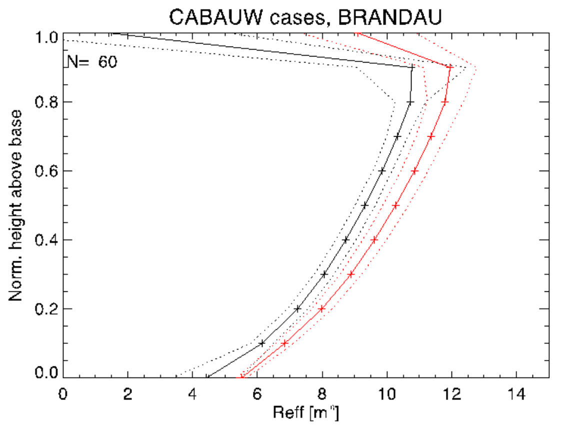
Lower panel: mean values (bold) and corresponding 1-sigma range (dotted) are shown for the cloud-resolving model output (black) and retrieval from C. Brandau, Delft University, NL (red).





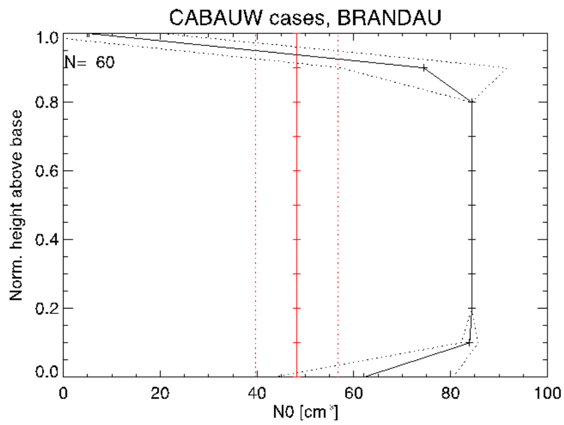
Droplet size

Profiles of cloud droplet effective radius for the same simulation initialized over Cabauw, NL. Mean values (bold) and corresponding 1-sigma range (dotted) are shown for the cloud-resolving model output (black) and retrieval from C. Brandau, Delft University, NL (red).



Number Concentration

Profiles of cloud droplet number concentration for the same simulation initialized over Cabauw, NL. Mean values (bold) and corresponding 1-sigma range (dotted) are shown for the cloud-resolving model output (black) and retrieval from C. Brandau, Delft University, NL (red).



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