European networks observing the atmospheric boundary layer: Overview, access and impacts

Chapter: Impact of current and future networks

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Authors	Document preparation conducted by U. Löhnert Authors: Ulrich Löhnert (UC), Rolf Rüfenacht (MCH), Joelle Buxmann (MO), Simone Kotthaus (IPSL), Anca Nemuc (INOE), Jasmin Vural (DWD), Annika Schomburg (DWD), Claire Merker (MCH), Tanya Nomokonova (HErZ Cologne/Bonn), Maria Toporov (HErZ Cologne/Bonn), Pauline Martinet (MF), Constanze Seibert (UHH), Thomas August (EUMETSAT), Lukas Pfitzenmaier (UC)

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Introduction

This section shows impacts of ABL observation networks within the frame of PROBE and makes clear why such networks are of high relevance for science and society. Application areas are Environmental Monitoring and Satellite Evaluation, but also results from Observation System Experiments (OSE) and Observation System Simulation Experiments (OSSE) as potential benefits of assimilating these observations in numerical weather prediction are expected. While an OSE quantifies the impact of including or excluding ABL profiling observations to a standard measurement configuration, an OSSE can simulate these impacts with any arbitrary measurement network structure / set-up of the future.

Note, not all of the following impact discussions focus solely on the ABL, but it is shown that instruments having their highest sensitivity in the ABL, such as those considered in PROBE, but sense the atmosphere above, can additionally be used for applications in the free troposphere.

This section, by no means, claims to provide a full picture of all impacts that ABL observations can have. The idea is to depict examples, some of which have been already successfully carried out and are now part of operational procedures, others which are in an experimental status, and even others which are in the status of preparation. Thus, we provide a snapshot of a selected scientific status and with this would like to underline the importance of European (and world-wide) ABL networks.

Environmental monitoring

Automated Lidar Ceilometers (ALC)

Thanks to the continuous operation of the E-PROFILE ALC network and its high spatial density, this network can be used for monitoring of all relevant aerosol events in a 4-dimensional frame (geographical location, altitude, time). In the past, this has included Saharan dust and biomass burning events, but would work identically for volcanic ash or other large scale aerosol pollution events. The E-PROFILE ALC network is also providing *observation minus background statistics* (O-B) allowing the CAMS model to be assessed concerning the impact of model changes (e.g., a change of the Saharan dust parametrization led to large-scale O-B offsets in central and Southern Europe).

Further, special Lidar networks in Europe are used to inform the Vulcanic Ash Advisory Centers (VAAC). Météo-France has an operational network since 2017 of six mini-micro pulse lidars (mini MPL) used for such VAAC activities. The Met Office network is described in more detail in the following.

Advanced Raman-Depolarisation Lidar Network

The Met Office currently operates one of the most extensive and advanced operational lidar networks in the world with nine Raman-depolarisation lidars (Raymetrics model LR111-D300), besides eleven CHM15K (Lufft) and 32 CL31 (Vaisala) Ceilometers as part of the E-PROFILE ALC network for atmospheric profiling and cloud information. In addition, there are about 100 CL31 and CT25K (both Vaisala) for cloud base height and cloud fraction only, that could be incorporated into profiling applications in future.

Especially, the Raman-depolarisation lidars form a unique ground based operational network (LIDARNET), with the main purpose of both qualitative and quantitative monitoring of Volcanic Ash (VA) over the UK for the London VAAC (Volcanic Ash Advisory Centre) within the Met Office head quarter in Exeter (funded by the civil aviation authority and the department for transport). The instruments are evenly distributed across Great Britain, from Camborne in Cornwall to Lerwick in the Shetland Islands. All lidars are accompanied by a sun photometer (polarized model, CE-318 NE DPS9) to provide additional information such as size distributions. The lidars are research grade instruments set in an operational network. It can identify aerosol types, including VA, dust, biomass burning and pollution and furthermore providing aerosol mass concentrations; this utilizes the combination of Raman N2-channel (387 nm), lidar parallel and cross polar channel (340 nm) as well as sun photometers to obtain relevant parameters such as lidar ratio and linear particle depolarization ratio.

On 15–16 October 2017, the network was put to its first test of the quantitative capabilities (Osborne et al. 2019). Ex-hurricane Ophelia passed to the west of the British Isles, bringing dust from the Sahara and smoke from Portuguese forest fires. During that time the high aerosol loading dyed the sky in red and was reported in the UK's national press. The Raman lidars were used to estimate the atmospheric concentration of both aerosol types with peaks of 420±200 µg m^{-3} for the dust and 558±232 µg m^{-3} for the biomass burning aerosols. In comparison an ash concentration between 200-2000 µg m^{-3} would be regarded as "low" with very little concern about engine damage, while anything above 4000 µg m^{-3} would be high and engine damage becomes a danger. The fact that the network provides quantitative values with detection limits at the lower end of those safety limits is a major advantage of the network as compared to conventional ceilometers.

Atmospheric Boundary Layer Height (ABLH) Testbed

The *ABLH testbed project* is supported by ACTRIS, ICOS and E-PROFILE. The objective is to establish methods that can be implemented to derive ABL heights from ground-based remote sensing for the relevant for aerosol and cloud studies, air quality forecasts, or greenhouse gas assessment. Two advanced automatic algorithms (Kotthaus et al. 2020) for the detection of atmospheric boundary layer heights (mixed layer height, residual layer height) are currently being evaluated at eleven E-PROFILE sites. Using attenuated backscatter profile data from different ALC models, collected at site locations with contrasting geographical setting (in terms of e.g., latitude, vicinity to the coast, orography) and land cover (e.g., agricultural, forest, urban) is crucial for the performance assessment of the methods across the diverse European networks. In a first step, ABL height results will be inter-compared between ALC models and sites to evaluate their ability of capturing seasonal and diurnal variations in boundary layer dynamics in various synoptic conditions. In a second step, the aerosol-derived layer heights are compared against layer estimates from thermodynamic methods, applied to radiosonde data or observations from other ground-based remote sensing profilers such as MWR or DWL.

Satellite validation studies

IASI Temperature and Humidity Profiles

Space-borne hyperspectral infrared (HSIR) sounders provide vertically resolved information of atmospheric temperature and humidity (in approximately 1 km layers), and of surface and cloud properties. EUMETSAT is operationally exploiting the IASI (Infrared Atmospheric Sounding Interferometer) mission, with three instruments flying in Low Earth Orbit (LEO) on-board the Metop-A, -B and -C satellites. Future hyperspectral missions are in preparation, with increased sounding and coverage performances to ensure service continuity beyond 2024. This includes the geostationary infrared sounder IRS on board Meteosat Third Generation (MTG), which will deliver operational atmospheric sounding at unprecedented spatial and temporal sampling (every 30 minutes over Europe), and the Next Generation IASI-NG, with improved vertical atmospheric information content. Satellite products performances are routinely monitored, notably against world-wide coordinated radiosounding *in situ* measurements. These are usually launched only once or twice a day, at fixed synoptic times and often a few hours apart from the satellite overpasses, making direct inter-comparisons difficult. Ground-based MWR with temperature and humidity profiling capabilities can fill this gap, especially in the ABL.

Thus, through networking initiated by PROBE partners from Météo-France and the University of Cologne, EUMETSAT made an internship possible by inter-comparing, for the first time, operational IASI with MWRs sounding products in order to evaluate

- the potential of an operational MWR network for the daily monitoring of satellite HSIR products, with the goal to initiate an automatic statistical analysis and reporting;
- the co-registration (temporal and spatial) uncertainties and how they contribute to the difference budget with radiosondes in the current performance monitoring;
- the ability to detect temperature inversions close to the ground by IASI, given its limited vertical resolution in the boundary layer.

To that end, MWR products from six different sites of the SOFOG3D international fog campaign (2019/2020) led by Météo-France have been statistically analysed and compared to IASI products in order to better understand the latter performance in relation to different atmospheric conditions (cloudiness, boundary layer stability…). A first inter-comparison showed that IASI and MWR temperature profile correspond within +/- 1 K up to about ~4 km. Larger differences (~1 K) are seen near the surface and the lowest ABL. (Fig. 1) more especially when the scanning capability of MWRs is used to improve the vertical resolution of MWR products.

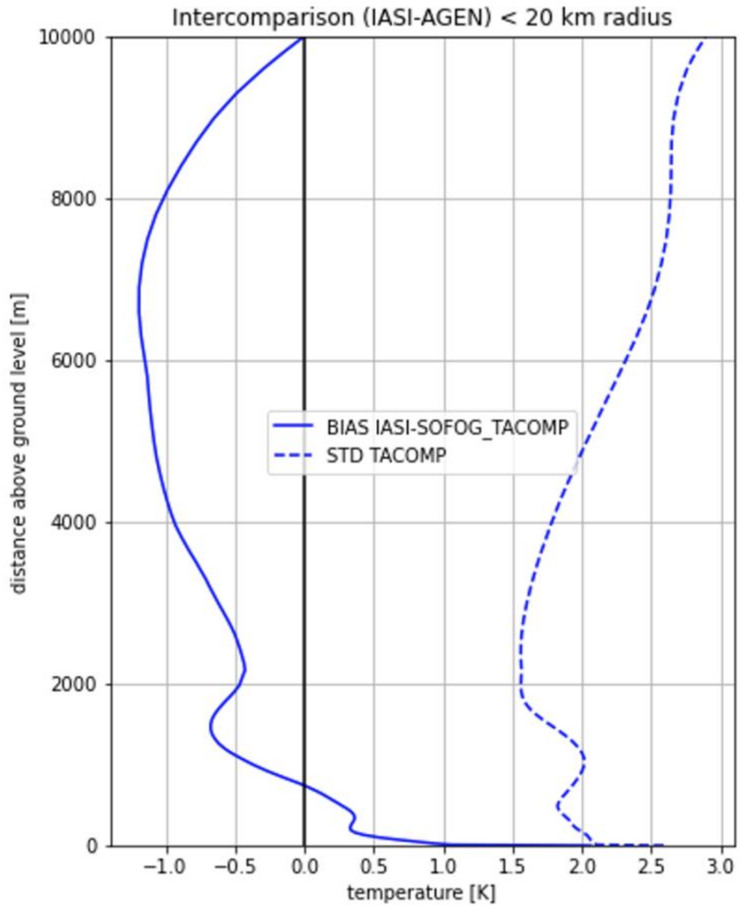


Figure 1: BIAS and STD between IASI and MWR temperature profile during the SOFOG3D campaign. Plot courtesy of Constanze Seibert, University of Hamburg and EUMETSAT

FRM4RADAR

FRM4RADAR is an ESA-funded project with goal to establish an observation network for validation, verification and calibration of EarthCARE cloud profile measurements based on ground-based, high-quality remote sensing observations. FRM4RADAR has acquired, deployed, operated and exploited cloud radars at two new sites, one in Sweden, and one in Romania, extending by this the geographical coverage of cloud observations in Europe towards North and East. The project is carried out by PROBE partners at the University of Cologne (lead) supported by INOE, FMI and SMHI. PROBE has facilitated the project realization through joint workshops and knowledge transfer, especially in WG4. The project has defined operation procedures and data handling procedures and led to the development of specific tools and products to be applied for EarthCARE Cal/Val activities after the planned launch in 2024. Within a current extension, a simulator is applied to the ground-based radars to order to make possible a 1:1 comparison of the level1 (reflectivity) data.

Sentinel 5 Validation

On 13 October 2017 the Copernicus Sentinel 5 Precursor (S5P), the first of the European Sentinel satellites dedicated to monitoring of atmospheric composition, was launched. The mission objectives of S5P are to globally monitor air quality, climate and the ozone layer in the time period between 2017 and 2023. The single payload of the S5P mission is TROPOspheric Monitoring Instrument (TROPOMI), a nadir viewing shortwave spectrometer that measures from UV to the near IR. The TROPOMI Aerosol Layer Height (ALH) product focuses on retrieval of vertically localized aerosol layers in the free troposphere (above PBL height which is usually 1 km), such as desert dust, biomass burning aerosol, or volcanic ash plumes. The height of such layers is retrieved for cloud-free conditions.

Currently, INOE is working with the E-PROFILE ALC network to validate the TROPOMI ALH product. An algorithm based on the gradient method (Nicolae et al, 2018) is applied to the attenuated backscatter profiles to retrieve all aerosol layers including those in the free troposphere. A cloud mask algorithm will also be applied to the measured profiles (e.g. Binietoglou et al 2018). Suited E-PROFILE stations will be chosen such that four European core regions are covered: Central Europe, Western Mediterranean, Central Mediterranean and eastern Mediterranean. More information is given in the Algorithm Theoretical Basis Document (ATBD).

Observation system experiments

Microwave Radiometers

Microwave radiometer data from Lindenberg (DWD), Payerne, Schaffhausen and Grenchen (MeteoSwiss) are currently used for first assimilation experiments using the KENDA data assimilation system based on an ensemble Kalman filter with the ICON or COSMO model, respectively. The aim is the direct assimilation of measured brightness temperatures using RTTOV-gb (De Angelis et al. 2016, Cimini et al. 2019) developed in the TOPROF Cost Action as observation operator.

The assignment of pressure level heights to the channels, which is needed for the localization in the EnKF, is achieved by a combination of humidity, temperature, and cloud liquid water Jacobians to compute the associated pressure level using a weighted average. The resulting pressure levels are mainly below 800hPa but are not completely constant with time. For some channels, the associated pressure levels show a strong sensibility to the state of the atmosphere (i.e., the presence of clouds). With the employed localization widths, we end up with increments in the region below 500 hPa.

Several assimilation experiments have been run so far comparing the assimilation of conventional observations only (CONV) with both CONV and MWR observations assimilated. We obtained mostly positive results in observation space; the results in model space are a bit more mixed.

A 10-day assimilation experiment performed at MeteoSwiss with the COSMO model at 1.1 km resolution shows that the run with CONV and MWR observations assimilation reproduces the observed brightness temperatures in the analysis much better than the reference run using only CONV data (Fig. 2). A remaining challenge is the transfer of those encouraging results from the analysis to forecasts, and to the prognostic model variables, such as temperature or humidity.

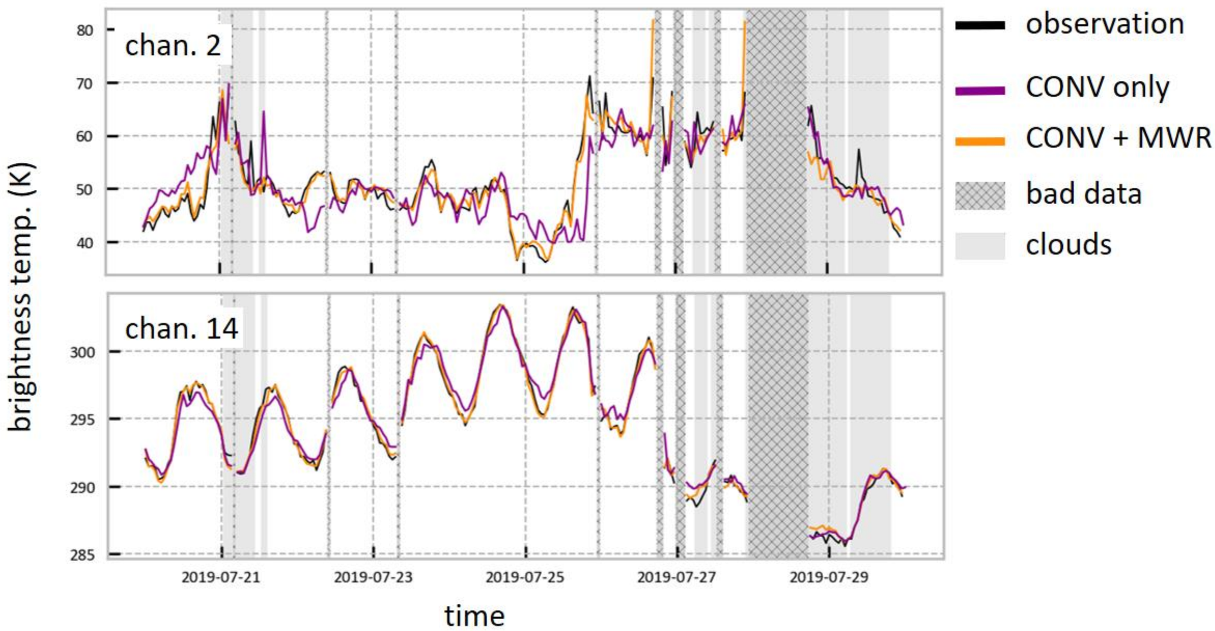


Figure 2: Time series of hourly brightness temperature data for two exemplary MWR channels in Payerne (zenith scan). The model brightness temperatures (violet and orange) are computed from the analysis mean of the hourly assimilation cycle.

Figure 3 shows the upper-air verification of the ICON-LAM forecast for the Lindenberg station (DWD) after 11 days of cycling. Here, only eleven channels were assimilated as omitting the transparent V-band channels turned out to be beneficial. The observation errors were determined using the method of Desroziers et al. 2005. As this method yielded very small error values, which were partially smaller than the instrument error, the values were inflated by a factor of 2. The bias is corrected dynamically during the assimilation, i.e., it is updated by current O-B values using a weighting factor. We obtain a positive impact for the temperature, however, the impact on the specific humidity is less clear.

Detailed evaluation is still on-going and the system is not tuned properly yet, especially with regard to potentially cross-correlated random errors and the optimal selection of channels.

For the moment, only cloud-free observations are assimilated but experiments using observations under cloudy conditions will be performed as well to check for a possible benefit.

The number of MWR OSE experiments is expected to increase with the development of a MWR network within the EUMETNET E-PROFILE program (Rüfenacht et al. 2021) to be operational in 2023.

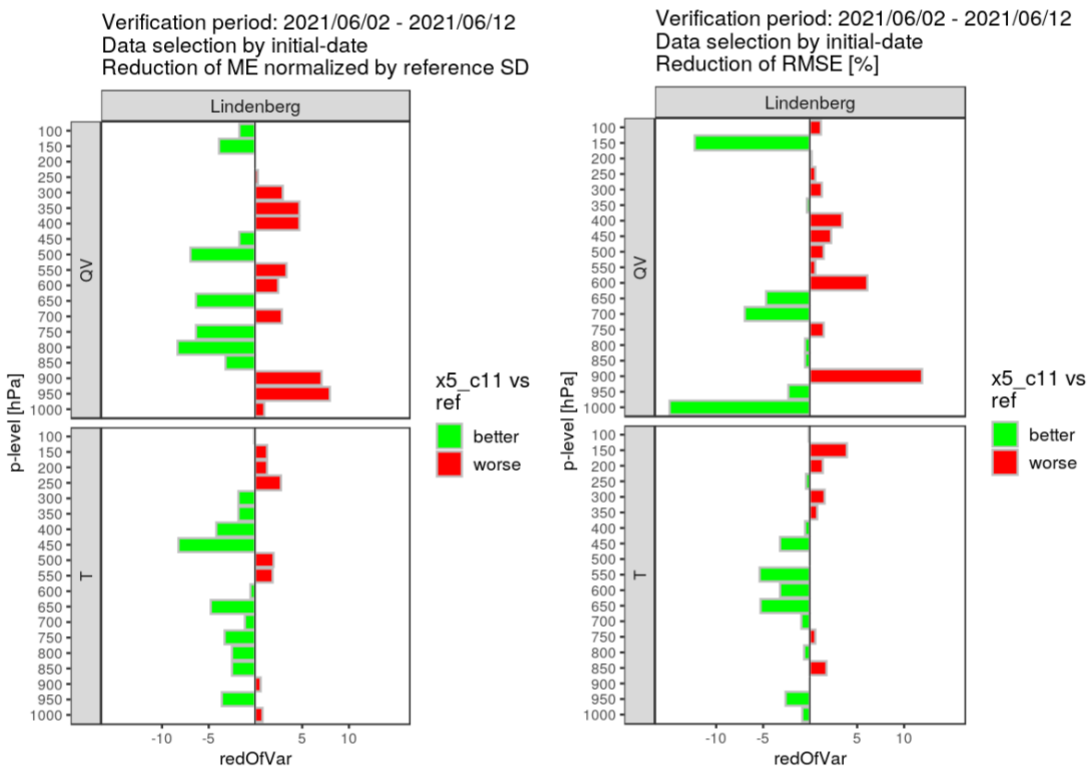


Figure 3: Verification scores. Mean error (left) and root mean square error (right) for specific humidity (top) and temperature (bottom). An assimilation experiment omitting the transparent V-band channels (x5_c11) is compared against the reference run (ref).

<u>Radar Wind Profilers</u>

The E-PROFILE wind profiler network has assessed the value of the wind observations from different types of radar wind profilers, wind from precipitation radars and airborne wind observations (AMDAR, Mode-S, …) for assimilation to global NWP (ECMWF) in two impact studies (Rüfenacht et al. 2017, Soulié et al. 2021). Both studies were based on the Forecast Sensitivity to Observations Index (FSOI). They show the highest impact is achieved by troposphere-/stratosphere wind profilers.

<u>Water Vapor and Temperature Lidar</u>

Raman lidar (RL) and differential absorption lidar (DIAL) are two emerging active remote sensing technologies for water vapor and temperature profiling (Lange et al. 2019; Newsome et al. 2020; Weckwerth et al. 2016). While commercially available DIAL systems measure water vapor only, RL combine the capability of temperature profiling and are therefore particularly interesting for assimilation experiments. With an integration time of typically 10 min, RL profiles cover the entire troposphere during nighttime and the lower troposphere (up to 4-5 km) during daytime. RL and DIAL cannot penetrate clouds and typically do not perform measurements during rain.

MeteoSwiss has performed a series of data assimilation (DA) experiments of temperature and humidity profiles (30 min availability) with its operational RL based in Payerne, Switzerland (Dinoev et al. 2013, Brocard et al. 2013, Martucci et al. 2021). The experiments were focused on convective situations where improvements of the initial conditions in terms of the atmospheric stability before convection starts (Leuenberger et al. 2020) are expected.

The operational numerical weather prediction (NWP) model of MeteoSwiss is the non-hydrostatic COSMO model and for the DA experiments, the ensemble version with 2.2 km grid spacing was used. The conventional observations assimilated by default include radiosondes, synoptic observations, air reports (AMDAR, Mode-S), wind profilers as well as surface precipitation estimates from the radar network. Each experiment consists of a control run without RL assimilation and an experimental run with RL assimilation and both runs include hourly assimilation cycles from which 24-hour forecast are made.

We assessed the forecasts based on the probability of the 24h sum of surface precipitation to exceed 1 mm. The analyses from the experimental runs showed a higher convective available potential energy during the pre-convective phase since the RL assimilation led to a cooling of the middle troposphere and warming and a moistening of the boundary layer. In both experiments, we therefore observed higher probabilities of precipitation, which were in better agreement with the observations.

Autonomous Uncrewed Aerial Vehicles (UAV)
PROBE partner FMI has operated an autonomous *UAV system* (multi-rotor copter equipped with dropsonde) for several months of a test period during summer and autumn months in consecutive years. In summary the UAV technique is developing quickly and has become suitable for operational observation in the vertical profile of atmospheric boundary layer. Due to safety reasons and further regulations, human resources will be required for monitoring the autonomous operation. Observations can be gained with good accuracy (Laitinen, 2019). Weather forecasters use profile observations of meteorological variables in near-real time to supplement traditional radiosounding observations. These datasets have not yet been assimilated but are available for such studies.

With the same model set-up as described above, MeteoSwiss also conducted DA experiments assimilating profiles of temperature, humidity, and wind from UAV (Leuenberger et al. 2020). These experiments were focused on fog events, and it could be shown that the assimilation of temperature and humidity profiles significantly improves the analysis in terms of the presence / absence and distribution of fog. It is expected that the positive impact from the observations will last only for a few hours lead time. For better forecasts over longer lead times, also the model physics need to be improved.

Observation simulation system experiments

Ensemble variance reduction for wind energy applications
An important application is an estimation of the potential of ground-based Doppler wind lidars, one of the core ABL network-capable instruments within PROBE, to improve the short-term forecasts of low-level wind essential for renewable energy applications. In this study the ensemble sensitivity analysis (ESA) approach is used. The ESA approach was applied on the convective-scale 1000-member ensemble simulations over Germany (Necker et al., 2020) which were obtained from the full-physics non-hydrostatic regional SCALE-RM model. Within this study the changes in the forecasted variance due to the added hypothetical Doppler wind lidar observations to the existing surface-based observations operationally used for data assimilation are estimated.

A case study investigates the variance reduction for the domain-averaged low-level wind speed at 80 m which is a typical hub-height of wind turbines. The forecasted low-level wind speed was averaged within the Rhein-Ruhr area (RRA, shown by gray rectangle in Fig. 4). The locations of the surface stations operationally used for assimilations by DWD are shown by blue dots in surroundings RRA and green dots inside the RRA. Hypothetical wind lidar observations inside RRA (collocated with the surface stations) are denoted by green dots. Using different combinations of the stations a relative change in the domain-averaged wind speed at 80 m was calculated.

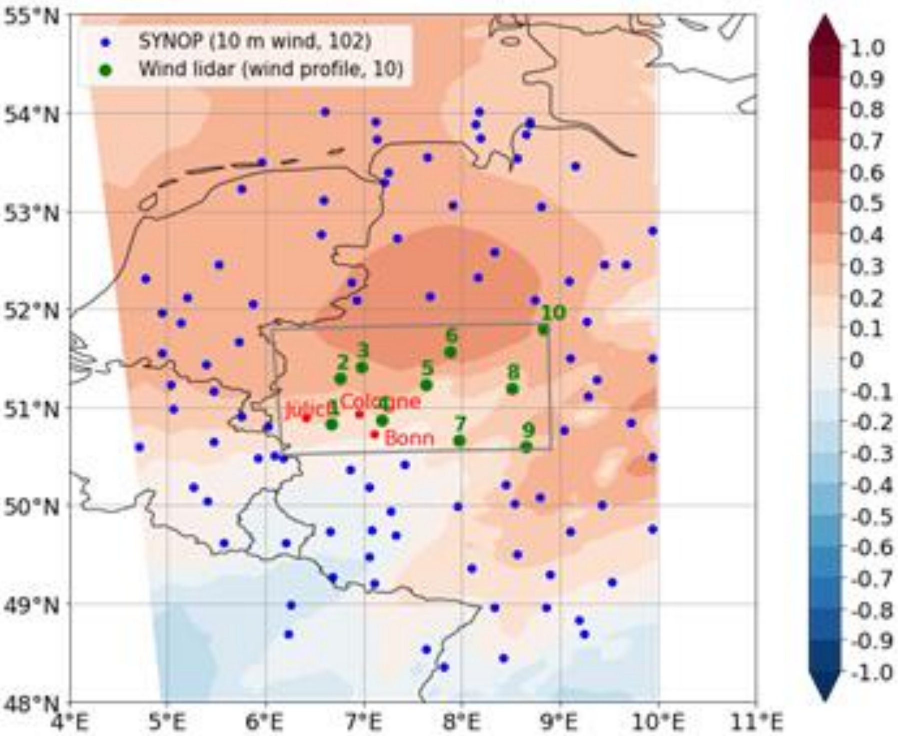


Figure 4: Distribution of the stations used for variance reduction calculations. The blue dots correspond to the surface stations. The green dots indicate location of hypothetical wind lidar observations. Green numbers denote the order of stations inclusion. Correlation between the forecast metric (domain-averaged low-level wind speed at 80 m at 17 UTC) and the state vector of initial conditions (wind speed at 2845 m at 14 UTC) is shown as shaded.

Figure 5 summarizes the changes in the variance reduction of the 3-hour forecasted wind speed on 30 May 2016. The variance reduction estimated only for the surface 10 m wind stations (102 stations denoted as SYNOP in Fig. 4) is almost 12% with respect to the state without any stations assimilated. After the inclusion of hypothetical wind lidar profiles (inside RRA shown in Fig. 4) an additional relative change in variance reduction is found from 3% to 13% depending on different wind lidar ranges, influenced by ABL conditions. The total relative change in variance reduction when both types of stations are included in the assimilation is up to 25%.

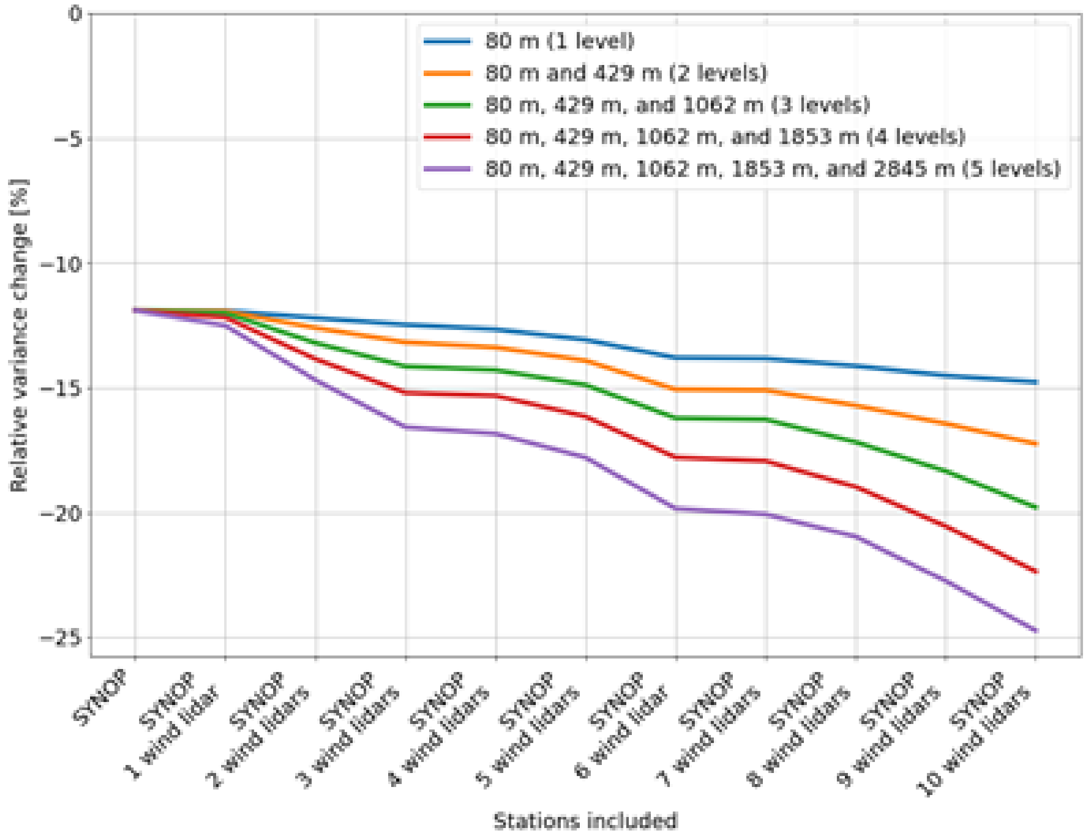


Figure 5: Relative change in variance due to assimilation of different combinations of stations and different ranges of wind lidars. SYNOP denotes surface stations (shown by blue dots in Fig. X). Number of hypothetical wind lidar locations (marked by green dots in Fig. X) which are included in the calculations is indicated in x axis. The forecast wind speed at 80 m at 17 UTC is averaged over the RRA indicated by the gray rectangle in Fig. 4. Figure courtesy of Tanya Nomokonova

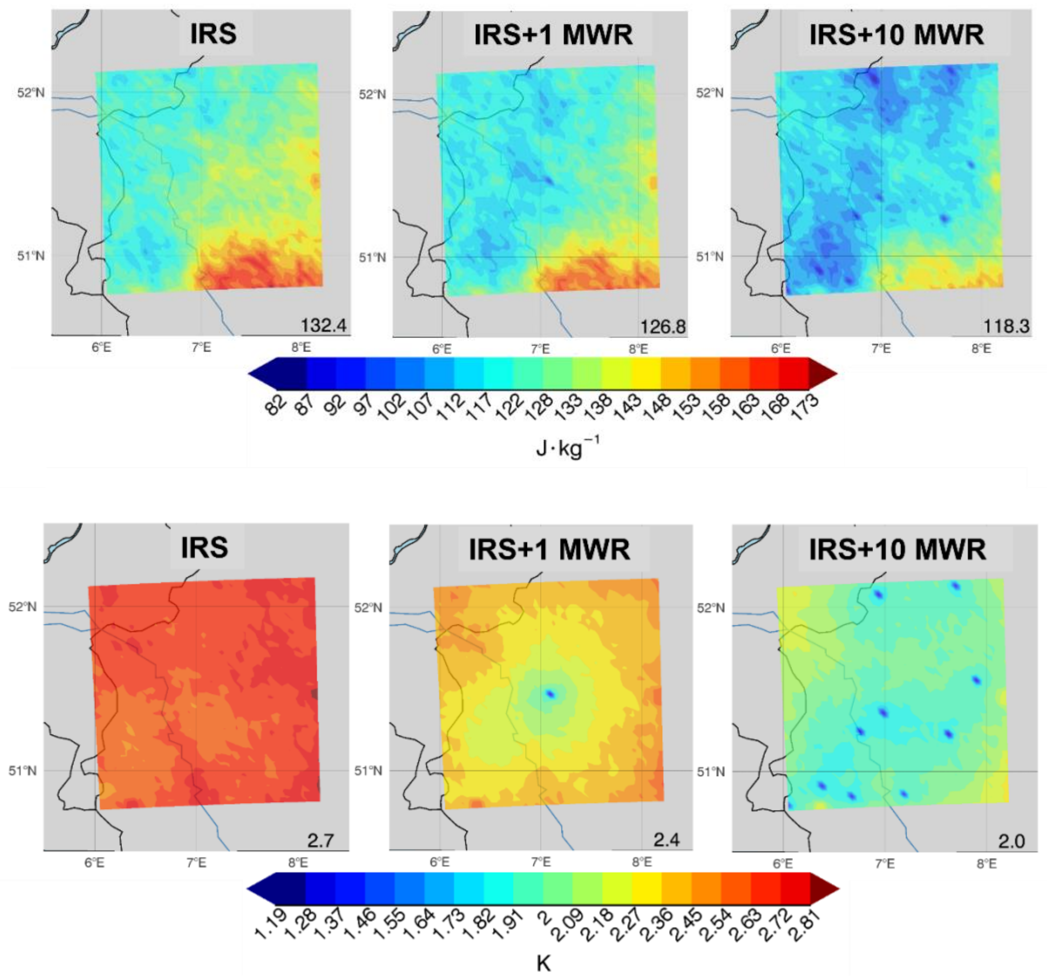
The first results show that wind lidar gives a potential to improve the low-level wind forecasts. More benefit can be gained from the network of wind lidars and the impact is influenced by the atmospheric boundary conditions. The method has been applied to only one case study. Further, the analysis will be extended to more available forecasts and will include more dates to cover different weather situations and also investigate the impact on the forecasted variables averaged over the locations of the largest wind parks.

<u>Synergy of ground-based ABL and satellite observations</u>

The potential of a network of ground-based MWR to provide information on atmospheric stability and to complement observations of future Infrared Sounder (MTG-IRS) is very relevant for future satellite applications and can be shown using simulated observations. In this experiment, atmospheric stability is described in terms of CAPE and Lifted Index (LI). Based on the COSMO-REA2 reanalysis as "truth", a neural network retrieval of CAPE and LI from simulated IRS and MWR measurements was developed (Toporov and Löhnert, 2021). Under clear sky conditions, both instruments, MWR and IRS, achieve almost similar accuracy with correlation values of 0.79 and 0.92 for CAPE and LI, respectively. Under cloudy conditions, MWR shows similar performance as under clear sky conditions, whereas the accuracy of IRS retrievals degrades leading to correlation values of 0.68 for CAPE and 0.79 for LI. The synergistic approach (i.e., using combined observations MWR+IRS as the input for neural networks) is beneficial under both, clear sky and cloudy conditions. The MWR+IRS retrieval is less sensitive to the presence of clouds and results in the correlation values of 0.88 and 0.97 for CAPE and LI, respectively.

To assess the spatial representativeness of observations of a single ground-based MWR and to investigate the impact of the MWR network in the presence of future horizontally resolved IRS observations the retrievals were applied to MWR and IRS observations simulated over a 150*150 km^2 reanalysis domain located in the Rhein-Ruhr area. Using spatial statistical interpolation, the fields of CAPE/LI retrieved from IRS observations were merged with the CAPE/LI values from a network of MWR. The number of MWR distributed in the domain varied from 1 to 200. In the grid points with MWR the synergistic retrieval (MWR+IRS) was applied to show the maximal possible impact. Within the statistical interpolation, the weight given to the CAPE/LI values in the grid points with available MWR observation is determined by the relationship between the error variance of both retrievals, IRS and MWR+IRS. The impact of MWR observations in the surrounding grid points is mostly determined by the error covariance matrix of IRS retrieval.

Figure 5: Left column: RMSE of CAPE (top) and Lifted Index (bottom) fields derived from simulated IRS observations. Middle and right column: RMSE of the analysis based on the interpolation between IRS retrieved CAPE/LI fields and CAPE/LI values from a single MWR (in the center of the domain) and from a network of 10 MWR (collocated with the DWD surface stations). The



number in the right lower corner gives the RMSE value for the entire data set.

The images in the left column of the Figure 5 show the root mean squared error of the CAPE and LI fields retrieved from IRS observations. The middle and right column show the error of the fields obtained through the interpolation between the IRS retrieved fields and CAPE/LI values from a single MWR and from a network of 10 MWR. The results are shown for all sky data set. Considering the clear sky and cloudy cases separately, the decrease of the error and thus, the impact of additional ground-based MWR observations is more pronounced under cloudy conditions. The decrease in the RMSE was shown to be significant for the first one to around 25 MWR distributed over the domain (corresponds to ~40 km distance between the instruments). As a next step an Observing System Simulation Experiment will be performed to show the possible benefit of assimilation of ground-based MWR observations into the regional high-resolution ICON model.

Final remarks

The European ABL-network developments driven and communicated by PROBE are more and more impacting science and society. Aerosol lidars with Raman channels and Doppler lidars for wind and turbulence observations are being installed to monitor air quality, air safety or green-house gas mixing. ABL networks of MWR, cloud radar and lidar are essential also for the evaluation of current and future satellite missions. Data assimilation experiments conducted with MWR, water vapor and temperature lidar and even UAVs clearly show the benefit of temperature and humidity profile observations on NWP. These are stimulating results which are leading European weather services to invest in new ABL-observation systems and networks with the goal to operationally assimilate such data in NWP. These plans are undermined by simulation results that suggest that a network (O(100)) of microwave radiometers could significantly enhance the value of satellite temperature and humidity sounders or that a network of Doppler lidars could be beneficial for short-term wind forecasts for wind energy applications.

Finally, this should also motivate the development, application and assessment of further remote sensing systems suitable for network application, such as Differential Absorption Lidar (DIAL) or spectrally highly resolving infrared spectrometers.

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