Impact of atmospheric boundary layer profiling

Chapter: Environmental agencies and air quality

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1 Introduction

Environmental agencies and Air quality institutions cover a large spectrum of operational activities connected with environment, land, water and air. This includes monitoring of the state of the environment and implementation of regulations. Monitoring networks provide data on which decisions are made and on which our understanding of the complicated processes involved in the natural cycles of the biosphere is based. Environmental Agencies often also provide meteorological services for public and private sector and air quality monitoring and forecasting.

Environmental data are sampled with different instruments. State of the atmosphere is monitored by surface stations, radiosondes and remote sensing platforms on the ground (e.g. weather radars, lidars, sodars), in the air (e.g. airplanes) or in space (satellites), respectively. The ground-based remote sensing networks are becoming an increasingly important segment of observations. They provide high temporal resolution vertical profiles of dynamic variables (wind, turbulence), thermodynamic variables (temperature, atmospheric water vapour, water content, etc.) and composition (aerosols). Vertical profile observations of meteorological parameters in the ABL (Atmospheric boundary layer) used to represent an observation gap, but now information-rich measurements can be obtained from ground based profiling instrument networks.

The state-of-the-art profiler instruments that are available on the market, such as automatic low-power lidars and ceilometers (ALC), radar wind profilers (RWP), doppler wind lidars (DWL), microwave radiometers (MWR) and SODARs can provide high quality data and higher level products for the operational work of Environmental agencies or Air quality institutions, like analysing, monitoring, forecasting and issuing warnings related to air quality or meteorology influenced societal sectors.

In the last two decades, many profiler networks have been established around Europe and around the world. Some are international and some are operating at the national level. A lot of work has been involved in building a common European framework for instrument networks, processing and dissemination of the ground based remote sensing data for different end user groups.

The field of ground-based remote sensing has become widely present, with international coordination and research programs providing support for standardisation, processing and common data flow of raw data and advanced products for aerosols, winds, clouds, temperature and humidity.

The following document provides information on ground based remote sensing data and products by summarising different case studies and operational user stories that show the valuable impact of the ground based remote sensing data in different application domains of Environmental and Air quality institutions. Online visualisation tools are also mentioned for the reader to get an insight on the type of information that is available.

2 Instruments

Ground-based profile remote sensing is an active area in domains of research, manufacturers and end users. Many of the measuring techniques have been implemented in the instruments that have now matured in the sense of operational 24/7 applications capabilities and have reached cost-benefit threshold for different operational end users, such as Environmental agencies and Air quality institutions.

There are several ground based profiling instruments on the market that can measure vertically resolved atmospheric data (profiles) at high temporal resolution from (near) ground-level to several kilometres altitude. Those measurements fill the observational gap in the atmospheric boundary layer (ABL).

Some of the most commonly used ground based profiling instruments are:

- Automatic lidars and ceilometers (ALC)
- Polarisation automatic lidars and ceilometers (PALC)
- Doppler wind lidars (DWL)
- Microwave radiometers (MWR)
- Doppler Cloud Radars (DCR)
- Sodar and RASS systems
- Raman lidars (RL)

Ground based profiling instruments can provide (Foken, 2021):

- vertical profiles of aerosol layers and cloud base height
- vertical profiles of wind and turbulence
- vertical profiles of temperature
- vertical profiles of humidity
- cloud water content and column integrated water vapour

Advanced quantitative products can also be derived, like:

- mixing layer height
- turbulence
- aerosol classification
- aerosol extinction coefficient profiles and AOD (aerosol optical depth)
- mass concentration profiles
- aerosol layer classification

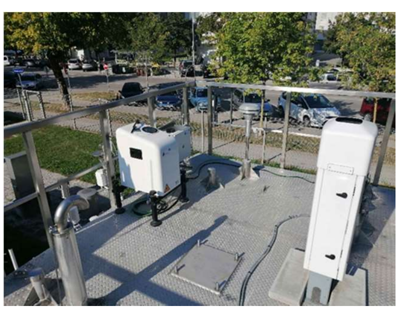

Figure1: LEFT: short-range wind profiler (METEK). RIGHT: ALC CL31 (Vaisala).

Figure 2: Sodar-rass system (METEK).

3 Networks

In the last two decades large efforts have been made to integrate the national gradually evolving ground based remote sensing profiler networks into international standardised measuring and dataflow frameworks that provide high quality near real time data or long term climatological data. Many of them are operating under the umbrella of European commission projects, EUMETNET programs or at national level, but many are also world wide programs.

Some of existing networks and services that provide near real time atmospheric ground based remote sensing data are listed here below.

- E-PROFILE is a EUMETNET program that incorporates a network of more than 400 ALCs, but also DWLs and RWPs from different national networks around Europe. Recently, MWRs have been recognized as operationally valuable instruments and incorporated into the EPROFILE data framework. Data is collected in near real-time and first level data control and calibration is implemented for some of the instrument types. Historical data are available, but also near real-time visualisation is possible through an online web page (https://e-profile.eu/; accessed 30.04.2024).
- ALICENET is an Italian network of Automated Lidar Ceilometers (ALCs) that is operated in the framework of cooperation between scientific and operational institutions involved in atmospheric science and environmental monitoring. In recent years the network has expanded and extensive work has been done to set up processing routines to provide near-real time products for different end users in the field of environmental science, monitoring and public service. Products that are available are qualitative, such as vertical profiles of aerosol return signal, but also quantitative, such as vertical profile of particle extinction coefficient and particle mass concentration. Both types of products cover the whole range from the surface to the upper troposphere. Products that classify the detected aerosol layers have also been developed. The data from ALICENET network has been extensively used in the analysis of different air pollution events, elucidating on the nature of meteorological processes (regional transport of aerosols inside PBL or aloft, vertical entrainment and coupling of the PBL and free troposphere aerosols) and aerosol sources involved. Online visualisation of some of the products is accessible on the web page (https://www.alice-net.eu/).
- CEILONET is a network of ALCs from DWD, Germany (https://www.dwd.de/EN/research/projects/ceilomap/img/plots/default_ceilonet_geoplot_de.html)
- UK Met Office LIDARNET is a network of ALCs used to measure aerosol profiles
- ACTRIS CloudNet (https://cloudnet.fmi.fi/) network of ground based profiling instruments provides visualisation products of many different parameters related to clouds and water in the atmosphere, such as cloud water content, water vapour, temperature profiles, aerosol profiles, wind profiles, hydrometeor classifications, etc.
- VAAC centre in London (Volcanic ash advisory centre), that integrates data from satellites, ground based remote sensing lidars and radars, lightning location network and dispersion models. (https://www.metoffice.gov.uk/services/transport/aviation/regulated/vaac/process#Observing)
- VAAC centre in Toulouse surveys large part of the Europe, Africa and Asia (https://vaac.meteo.fr/).
- GALION is a WMO coordination of international aerosol lidar networks (https://galion.world/).
- There are other large programs in the field of aerosol profiling are EARLINET (European aerosol research lidar network), AERONET (Aerosol robotic network), SKYNET (https://www.skynet-isdc.org/), MPLNET, PollyNET and others.

4 Applications in Meteorology

4.1 Operational weather forecaster user experience

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Keywords: weather forecaster experience with profiling instruments for operational use

Slovenian Environment Agency (SEA) has implemented its first profilers in 2021, installing sodar-rass (METEK), lidar-ceilometer CL51 (Vaisala) and a doppler wind lidar WindRagner200 (METEK).

The instruments provide high temporal resolution (10 min) vertical profiles of wind, temperature and aerosols. The data are visualised for the weather forecaster to use them at daily operational inspection of the current weather and state of the atmosphere. The profiling instruments provide information on the diurnal development of the atmospheric boundary layer (ABL) and give indications on the surface inversion strength and its lifecycle, the wind dynamics, occurrence of fog and low stratus, aerosol distribution, stratification of the ABL, mixing layer height (MLH) and height of the ABL. We have also an operational radiosounding station that makes one launch per day but this is a “one time” snapshot of the state of the atmosphere. The profilers provide important insight of mesoscale time evolution of dynamics within the ABL and also coupling of the synoptic weather patterns with the ABL. Weather processes, like surface inversion decay with winds aloft or daily convection, shallow convection and nocturnal jet, residual layers, convective boundary layer, presence of fog, estimate of mixing layer height, can be monitored.

Numerical weather models use mostly climatological values for aerosol distribution in the atmosphere. Information about the actual state of the aerosols in the atmosphere can influence the forecast of surface inversion decay and maximum daily temperatures.

In the winter season, monitoring the warm front winds aloft ABL, descending slowly into the cold inversion pool, can be very informative on the actual timing and probability of the inversion decay which influences temperatures and air-quality.

SEA has a sodar-rass system installed in the suburbs of Ljubljana and a Doppler wind lidar in the central part of the city. This gives the operational forecaster the possibility to compare urban diurnal ABL dynamics in the winter, and insight into the differences between ABL evolution in the city and on the outskirts during stable anticyclonic situations. The difference in timing during the decay of a strong winter inversions in the basin of central Slovenia where capital Ljubljana is situated are also observed.

The optical instruments like automatic lidar-ceilometer (ALC) do not see in low visibility conditions, like fog or clouds, but they show the precipitation below cloud bases and also give an indication of melting layer (snow transitioning to rain) in the precipitation signal when there is a cold air advection into the region or even lowering of the snow level due to local valley effects. Discriminating between ice/snow and water is even enhanced with newer ALC instrumentation with depolarisation capabilities.

In summer, monitoring development and transition of night and morning shallow surface layer with winds aloft is important for providing forecasts for hot air balloons.

Monitoring temporal changes of the wind, temperature and aerosol stratification in the ABL enables one to comprehend the atmospheric processes that are not yet well described in the local area models. This enables a forecaster to gain insight on the evolution of certain weather events and to monitor in “near-real time (10 min period)” the dynamic and thermodynamic evolution of a weather phaenomena, such as frontal passage, decay of surface winter inversion, diurnal mixing, advection of cold air with low aerosol loads, snow level, virga, strong outflow from mesoscale convection systems, etc.

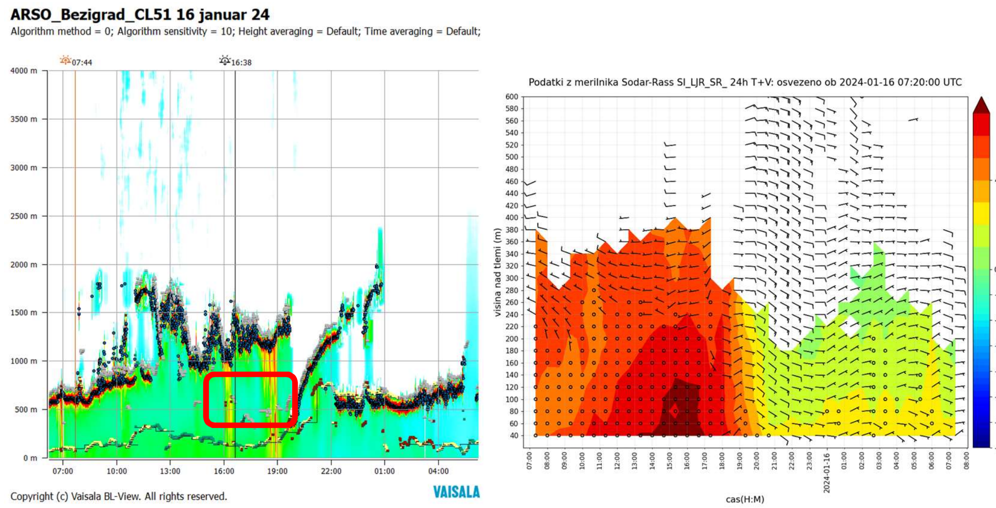

Figure 3: LEFT: ALC CL51 profile (BLView). RIGHT: Sodar-Rass profile. Cold front passage with E winds after a warmer period of SW winds. Melting layer (bright band in yellow reddish precipitation stripes) can be seen in the ALC profile. (Period: 15.-16.1.2024)

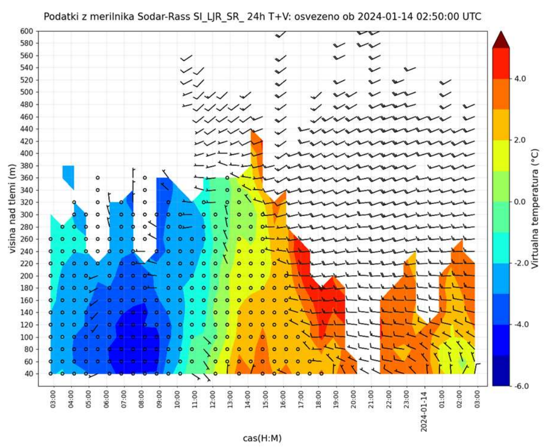

Figure 4: Sodar-rass profile: Warmer SW winds descending into the winter surface inversion. (Period: 13.-14.1.2024)

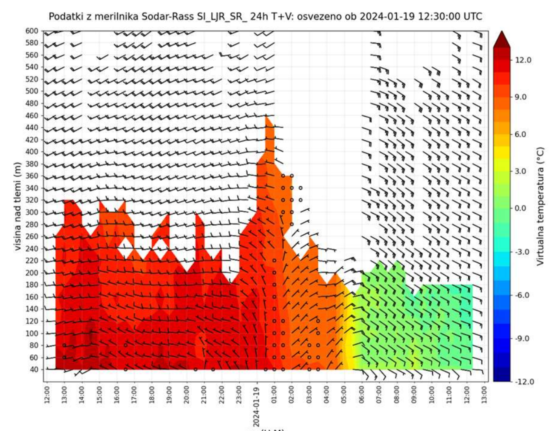

Figure 5:Sodar-rass profile: Cold front passage bringing snow and later strong surface inversion into lowlands. (Period:18.-19.1.2024)

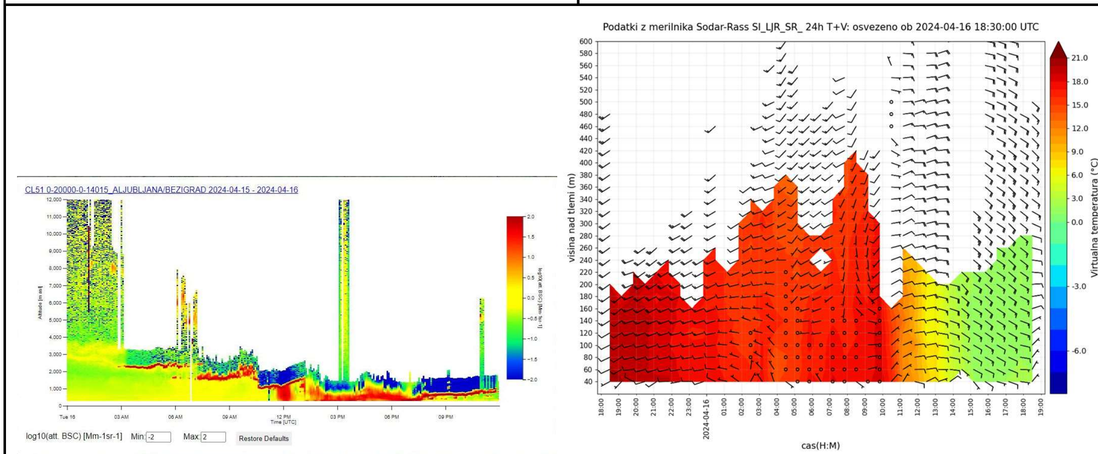

Figure 6: LEFT: ALC CL51 profile (E-PROFILE). RIGHT: Sodar-Rass profile. Cold front passage that brought record breaking temperature changes (dT/24h) of -26 °C, bringing snow into the lowlands.(Period: 15.-16.4.2024)

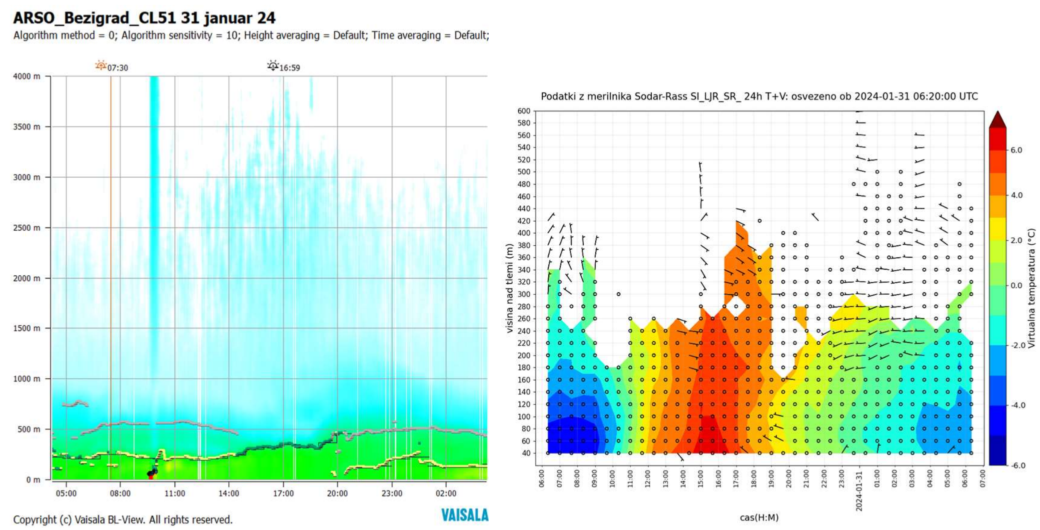

Figure 7: LEFT: ALC CL51 profile (BLView). RIGHT: Sodar-Rass profile. Diurnal weakening of winter surface inversion due to solar radiation induced mixing.(Period: 30.-31.1.2024)

4.2 Nowcasting of radiation fog events

Keywords: radiation fog, low stratus, pre warning of fog onset

Fog events are still a major issue from a forecasting perspective. Onset and life cycle of the fog influence many societal sectors, like maritime, land and air traffic.

An operational algorithm PARAFOG 2.0 has been developed (Ribaud et al, 2021) based on the PARAFOG 1.0 that provides improved fog pre-onset warnings. It captures the process of radiation fog and stratus lowering fog formation. The algorithm has been evaluated and tested at different sites around Europe, mostly airports (Munich, Zurich, Vienna, Paris-Roissy) and SIRTA observatory (https://sirta.ipsl.fr/; accessed 05-04-2024), but also in some cities (Ljubljana, Slovenia). It is based on backscatter profiles from ceilometers, visibility data from scatterometers and surface measurements of temperature and relative humidity. The concept of the Parafog algorithm is to use relatively standard instruments that are commonly found at meteorological automated stations. The new algorithm PARAFOG 2.0 improves the detection of shallow surface fog events and discrimination of different fog onset processes, like deep radiation fog formation, stratus lowering fog formation and shallow fog layer formation. The high probability signals for fog alert from PARAFOG 2.0 can range from -120 minutes to beginning of the fog formation. Evaluation showed that hit rates are close to 100 %, with false alarm rates up to 30 %. Some of the locations are provided online on the SIRTA web page.

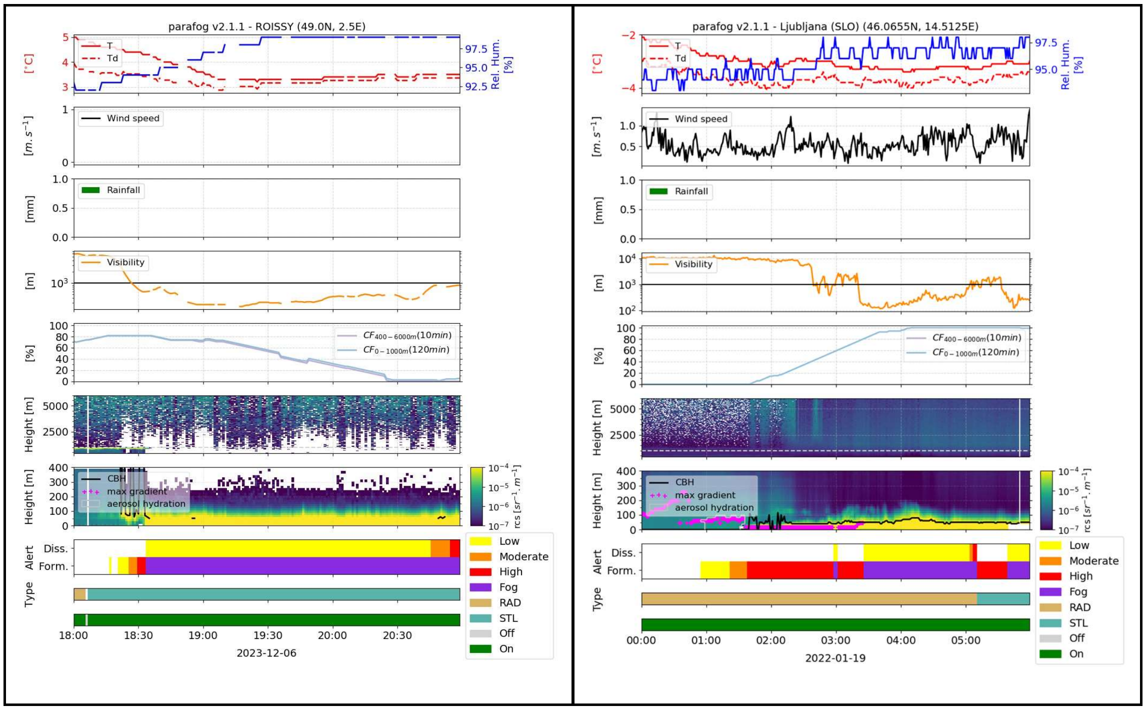

Figure 8: https://www.lmd.polytechnique.fr/sirta/parafog; accessed 25-04-2024; Example of nowcast products for fog onset for the site ROISSY (France) and Ljubljana (Slovenia).

4.3 Thermodynamic profiling, weather forecasting, NWP

Keywords: atmospheric profiling, temperature and humidity, atmospheric stability, weather forecasting

High temporal resolution vertical profiles of temperature, humidity and wind, have been investigated for operational use in meteorology (Illingworth et al, 2019). Several ground based profiling instruments, that have been used in research institutions for many years, have now reached operational maturity. Instruments like MWR, IRS and DIAL have been considered as candidates for operational tropospheric profiling including synergies between different instruments that enable derivation of thermodynamic profiles with lower uncertainty (Turner and Löhnert, 2021). Comparison campaigns between ground based profiling instruments and radiosonde profiles have shown that profiling instruments can serve as a high temporal resolution source of information on atmospheric thermodynamic stability. Studies have shown the added value of ground based profiling instruments for high-resolution numerical weather forecast models through validation and assimilation (Martinet et al, 2017; Martinet et al, 2020).

Vertically resolved temperature and humidity profiles from ground based remote sensing instruments have been evaluated for the derivation of forecast indices like CAPE, Showalter, etc. (Cimini et al, 2015) for supporting weather forecasting.

4.4 Aviation hazards - aerosols and icing

Keywords: aviation, elevated aerosol layers, icing hazard

The potential usability of lidar aerosol data in case of volcanic eruption events was noted in the 2010 Eyjafjallajokull eruption (Papagiannopoulos et al, 2020). At that time EARLINET network was providing height, time and location of the volcanic plumes to the WMO, supporting the aviation sector in managing the crisis connected with the threat of volcanic ash presence to air traffic.

In the following years the observation capabilities and the stakeholders needs were identified through several projects. Volcanic ash and Saharan dust outbreaks were identified as important hazardous events for aviation.

Different attempts have been made to implement operational tropospheric aerosol detection and early warning systems for aviation. Combination of depolarisation Raman lidars that are part of EARLINET network have been used in case study showing near real time application for detection and early warning in case of high load aerosol layers consisting of desert dust or volcanic ash particles (Papagiannopoulos et al, 2020).

High power lidars are mostly part of research networks around Europe. They are expensive and not operating 24/7. A different approach was taken in a study (Adam et al, 2022) that evaluated the use of low cost ceilometers, such as CHM15k from Lufft, and photometers to provide an effective framework for early detection and warning for presence of high aerosol load layers in the troposphere. The use of ceilometers and photometers makes use of dense profiler networks, such as E-PROFILE and MPNET. Threshold values for aerosol loads were derived from climatological values.

Software tools are being developed for data processing from newly available polarisation lidar-ceilometers providing aerosol classification products (Bellini et al, 2024).

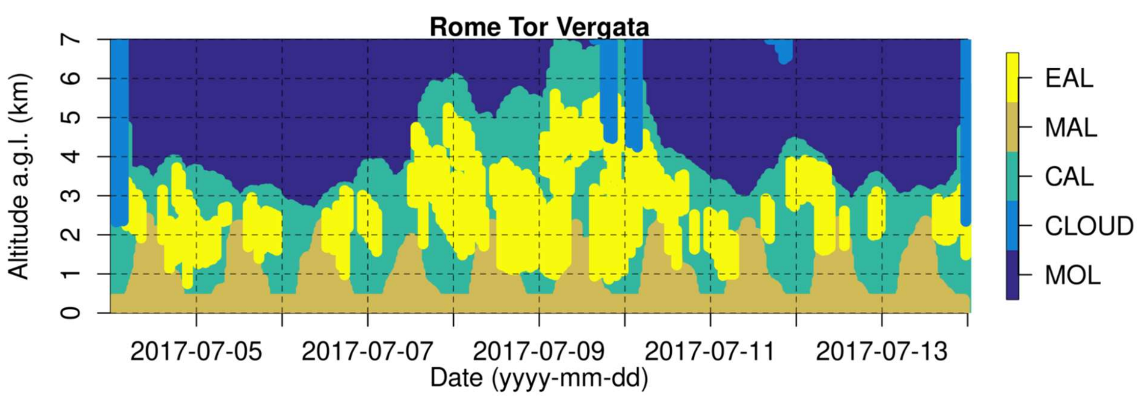

Figure 9: Example of aerosol classification product derived from ALICENET processing algorithm based on ALC instruments (CAL - continuous aerosol layer, MAL - mixing aerosol layer, EAL - mixing aerosol layer, MOL - molecules only region, CLOUD - cloud affected regions). (Bellini et al, 2024) https://egusphere.copernicus.org/preprints/2024/egusphere-2024-730/egusphere-2024-730.pdf

Icing conditions in the atmosphere and clouds have also been the subject of research with operational applications in mind (Hämäläinen et al, 2020), testing different environments and conditions. Combination of low cost ALC instruments, like CL31 or CL51 (Vaisala), with numerical weather forecast models showed added value for model verification and icing potential forecasting.

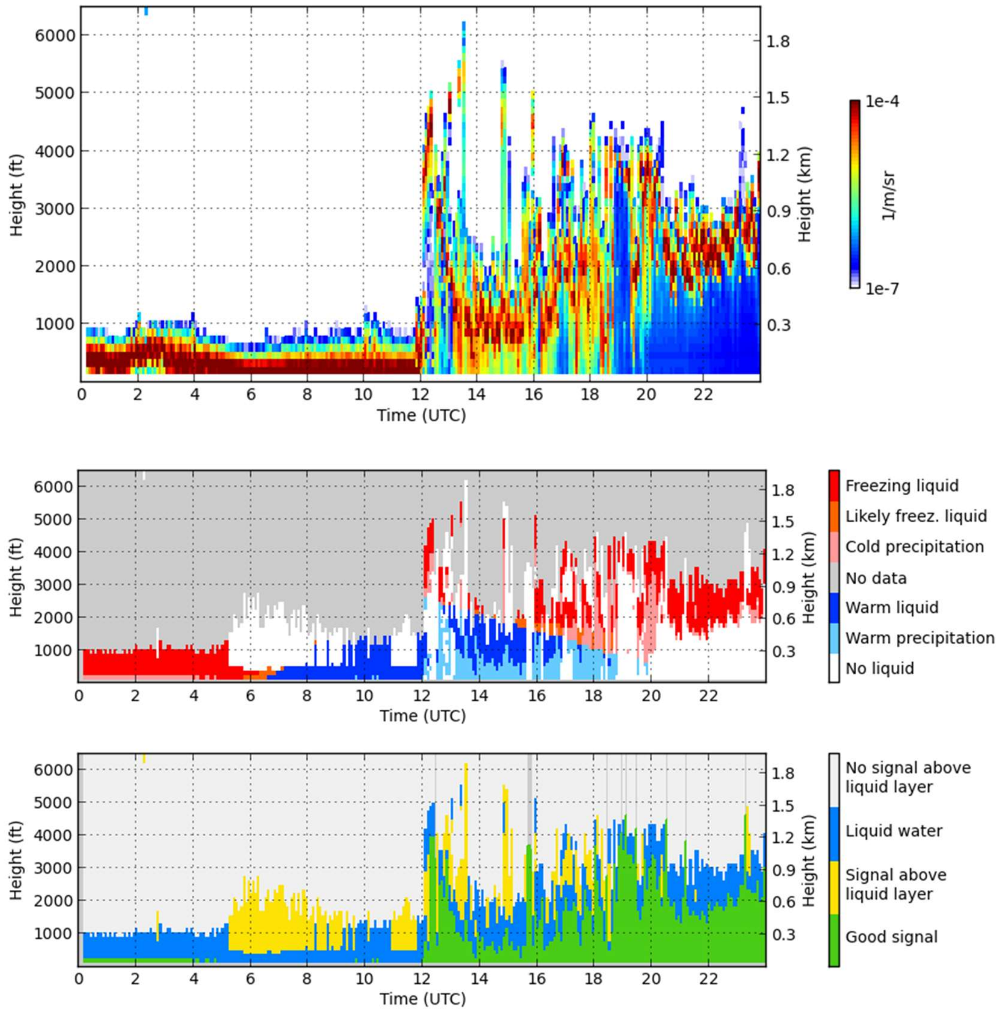

Figure 10: Example of icing classification product (middle and lower picture) from FMI (Finnish meteorological institute) based on backscatter profiles (upper picture) from ALC network (http://ceilometer.fmi.fi/). https://public.lidar.fmi.fi/icing/info.html, accessed 9.5.2024.

5 Applications in Air quality

5.1 Monitoring dynamics and stratification of ABL

Keywords: ABL, mixing layer height, elevated layers, surface and capping inversions, wind, turbulence

Advancements in ground based remote sensing instruments and rich research activities in the last two decades have enabled the ground based remote sensing field to develop advanced products (Kotthaus et al, 2023), such as information about stratification and classification of atmospheric boundary layer (ABL) characteristics and determination of ABL height (ABLH). Many remote sensing profiling instruments exist that measure profiles of different atmospheric variables (temperature, humidity, wind, aerosols) related to atmospheric processes and stratification of ABL in direct or indirect way. Ground base remote sensing networks are emerging around Europe and are becoming more dense, providing coverage of the spatial heterogeneity of the dynamical and structural layout of the ABL in space in time.

Instruments that already show operational capabilities (relatively lower costs compared to more sophisticated research instruments and manageable maintenance routines) are microwave radiometers

(MWR), doppler wind lidars (DWL), sodars and automatic lidars and ceilometes (ALC). Each of them is providing different types of variables and information about the state of the atmospheric boundary layer (Kotthaus et al, 2023): thermodynamic view about stability, dynamic view about wind and turbulence, indirect view about aerosol stratification and clouds. Those are different information sources that give a complete picture about the 4D dynamics of the ABL when combined.

Additionally, instrument synergies have been investigated that can improve temperature and humidity vertical profile derivation and reduce uncertainty (Turner and Löhnert, 2021). Synergies between instruments like MWR, IRS (infrared spectrometers) and DIAL (differential absorption lidar) have already shown to be effective, DIAL instrument now being also available commercially for operational use.

Methods for determining ABL height are available that can be used as a support tool for high temporal resolution monitoring of the night time and diurnal evolution of ALB and its height, including growth and decay of sub layers, present in the ABL due to surface or synoptic forcing (Kotthaus et al, 2023).

The methods for determining ABL height and its structure with sub-layers differ according to type of instruments and variables involved (Kotthaus et al, 2023; Kotthaus et al, 2020). One should take care when comparing derived advanced characteristics about ABL (height, residual layer, entrainment zone, etc.) at different times of day and in different surface and synoptic conditions. Each of the variables vertical profiles (temperature, humidity, wind, turbulence, aerosols) reflect different levels of information, such as environmental conditions, dynamic meteorological processes and resulting distribution of aerosols. Classification of the ABL is also possible based on turbulent sources that induce mixing processes in the ABL.

5.2 Air quality forecasting - pollution events during winter surface inversions

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Keywords: local air quality, complex topography, surface inversions

The Slovenian Environmental Agency (SEA) is responsible also for air quality monitoring, modelling, forecasting and analysis. The new ground based remote sensing instrumentation that we installed in 2021 has turned out to be an important contribution to the operational processes of the Air quality department.

The added value of the new profilers in air quality applications at SEA is complementing the outputs of numerical models by elucidating mesoscale meteorological processes and micrometeorological processes that are not well represented in numerical meteorological models and have important role in air quality of the ABL (atmospheric boundary layer), especially in the surface layer.

Monitoring of the elevated aerosol layers and visualising the entrainment into ABL enables new conceptual understanding of how the transport of aerosols in free atmosphere interacts with local ABL scale.

Period from fall to spring is the time of the year when inversions and high pollution episodes are most common in the complex terrain of Slovenia. That is when ground based remote sensing instruments are the most valuable accessory tool for interpreting and forecasting the evolution of air quality episodes.

The possibility of monitoring the onset and strength of the inversion, and evaluating diurnal mixing volume changes for air pollution dilution, gives the air quality forecaster the tools to predict and understand the evolution of local air-quality.

Slovenia has a highly heterogeneous topography with most of the population living in the valleys or basins with very frequently occurring surface inversions, especially from late fall to early spring. There are also short lasting mostly morning shallow inversions in summer time. Winter inversions in turn affect local air-quality and with synoptic situations that favour stability and low dynamics lead to high pollution events in closed rural valleys or shallow basins with cities. The main emitters are mostly local biomass heating sources from households, and partially also transport and industry. Long lasting stable synoptic situations lead to very high pollution episodes (PM10 over 100 ug/m3) that are exacerbated in cases of snow on the ground. The breakout of the shallow inversion situations in winter (inversion height from below 100 m to around 300 m above ground) is preceded by warm air advection that is normally accompanied with strong southwesterly winds and followed by cold frontal passage. The situation with strong southwesterly winds and warm advection at first even worsens the situation before the breakout of the inversion since the inversion layer is squeezed down even further and strengthened due to warm advection aloft. In the next step the onset of mixing brings a secondary peak of high PM loads. Finally the inversion breaks down and the polluted air is replaced by new air from aloft.

To elucidate the conditions for the onset and decay of surface shallow inversions and to evaluate their strength, ground based profilers, like sodar-rass and automatic lidar-ceilometer have proved to be of great value. Local area numerical weather prediction models and chemical transport models give an indication of the processes. However the local micrometeorology and terrain properties are not well captured in the models, seeing the actual process and stratification of the aerosols in real time represents a big leap in understanding different parameters that drive the local air quality dynamics.

The figures below present how ABL dynamics and thermodynamics can be operationally monitored through ground based profiling instruments (ALC and Sodar-Rass) in different weather situations that require additional information or conceptual clarification complementary to the numerical models outputs.

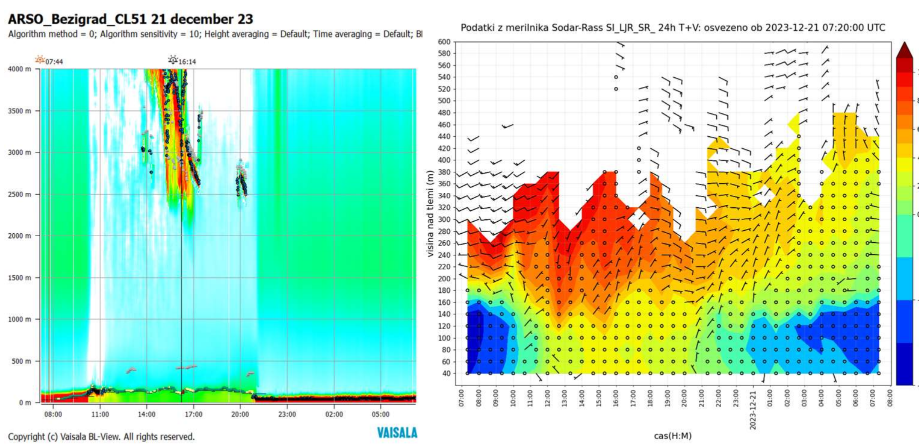


Figure 11: LEFT: ALC CL51 profile (BLView). RIGHT: Sodar-rass profile. A period of winter surface inversion in Ljubljana basin with weak upper level frontal passage and daily mixing making the dispersion volume a bit larger. (Period: 20.-21.12.2023)

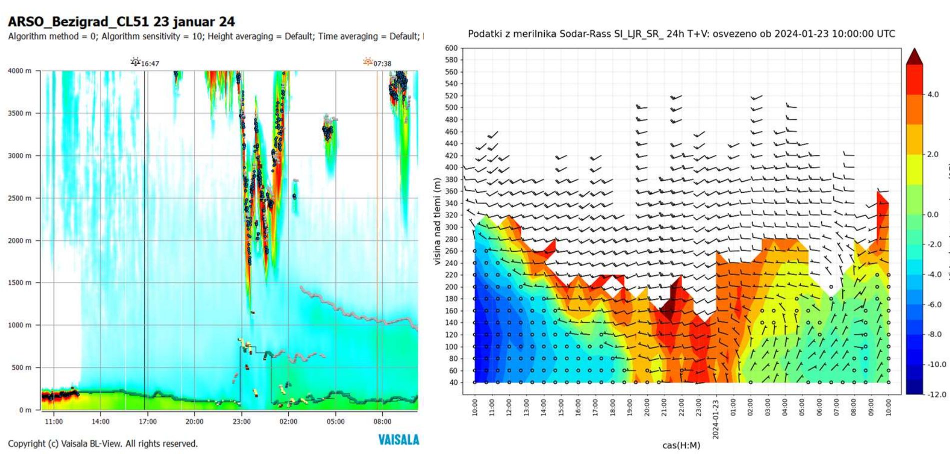


Figure 12: LEFT: ALC CL51 profile (BLView). RIGHT: Sodar-rass profile. Weak frontal passage during winter surface inversion in Ljubljana basin opening the surface inversion lid for a short time. (Period: 22.-23.1.2024)

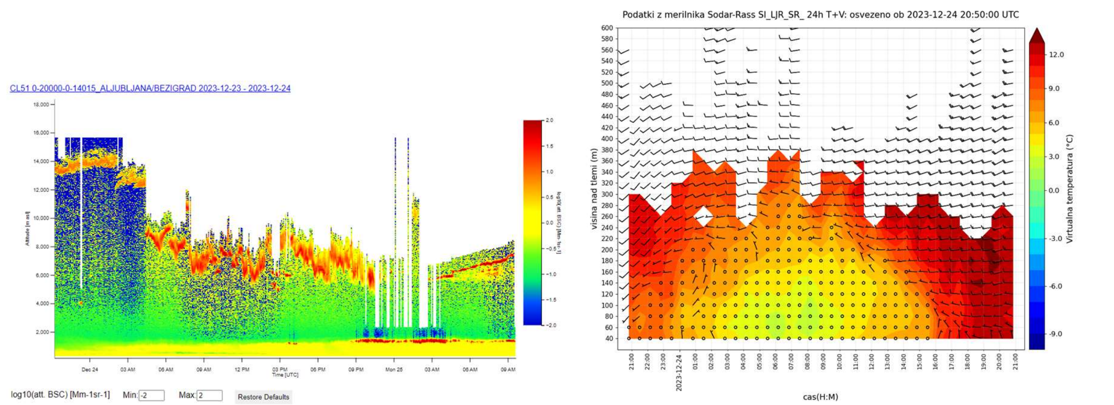


Figure 13: LEFT: ALC CL51 profile (E-PROFILE). RIGHT: Sodar-rass profile. SW winds descending and expanding the dispersion volume for particulate matter, gradually improving air quality conditions. (23.-24.12.2023)

Air quality department expressed the need for more profiling instruments that would provide vertical profiles of aerosols, wind and temperature around the country's heterogeneous terrain. That would enable air quality experts to understand the influence of mesoscale and micrometeorological features on the air quality in relation to different non-meteorological factors (topography, local emitters, land usage, etc).

5.3 The role of virga in aerosol PBL entrainment

dr. Quenting Laffineur, Royal Meteorological institute of Belgium

Keywords: PBL entrainment of advected aerosol layers, exposing deposition related processes

In Belgium, air quality is a legal regional competence but in order to strengthen efforts in monitoring air quality in Belgium, there is an interregional agency (IRCELINE) which coordinates the monitoring of air quality for Belgium. Often when IRCELINE detects high pollutant concentrations and it cannot determine with certainty the source, it generally contacts the Royal Meteorological Institute of Belgium (RMI) that manages ALC network, to find out if an aerosol plume has been detected by the ALCs network and if it is linked to the atmospheric layers close to the ground. IRCELINE has access in real-time to the image of ALCs but often the interpretation of these plots can be complicated without the help of an ALC expert.

One of main questions from IRCELINE for RMI when an aerosol plume (dust, smoke…) is forecasted by CAMS is **whether the plume will impact the air quality**. **Most often, aerosol plumes pass aloft without interacting with the atmospheric boundary layer, but sometimes there is interaction and PM measurements on the ground can increase significantly.**

In 2023, especially during the summer, severe wildfires have affected central regions of Canada since May 2023. Several smoke plumes coming from these wildfires were detected with ALC and potentially impacted the air quality in Belgium. During summertime, three significant events clearly impacted PM2.5 concentrations and/or black carbon (BC) at several air quality stations. Once detected by an ALC, it is possible to retrieve the source location of the plume using a backward atmospheric dispersion model but this is not enough to explain how the aerosols plume sometimes ends up on the ground.

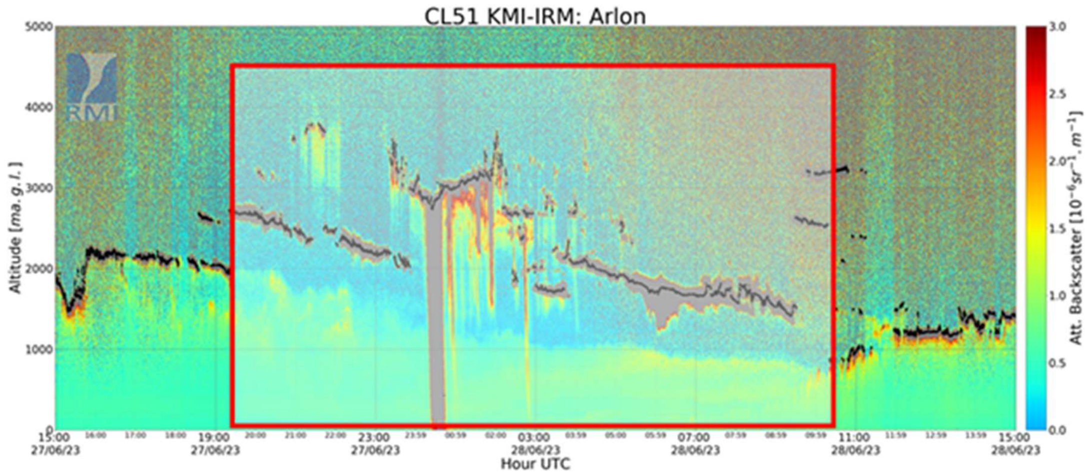


Figure 14 Attenuated backscatter profile as a function of time observed on June 27-28 2023 at Arlon (Belgium). The black dots correspond to the detection of the cloud base. The red box illustrates the time when a smoke plume passed over the measurement site.

To have a complete interpretation of the ALC profiles, you need both an expert in the interpretation of ALC plots but also in knowledge of the atmospheric mechanisms which can cause this interaction between the plume located in altitude and the first atmospheric layers. On June 26 2023 a large-scale smoke plume over the Atlantic ocean was observed by satellites and well forecasted by CAMS. But as is often the case, aerosol plumes can be associated with clouds and it is sometimes difficult to detect them distinctly with an ALC instrument. To illustrate our remarks, we have in *Figure 14* the ALC profile measured during June 27-28 2023 in Belgium (Arlon). In this case, the signature of the smoke plume in the backscatter profile is visible by a change in the physical structure of the cloud base height (located by the black point) in the rectangle compared to before and after the passage of the smoke plume. This signature is often observed in autumn-winter-spring period due to the presence of ice crystals at the base of the cloud but in this case no ice crystal were present because the 0°C isothermal level was higher than 3 km (ECMWF data) and the cloud is located below this altitude. Another interesting observation can be seen on ALC plot (Figure 15A) that shows the presence of virga (precipitations that evaporate or sublimate before reaching the ground) below this cloud layer. If a cloud is heavily loaded with aerosol, the formation of virga under it generates potentially aerosol layers after its evaporation which remain in suspension and which sometimes reach the ground (depending on the virga length and where is located the air temperature inversion). Virga formation is very heterogeneous spatially and temporally. If we compare the plots of two ALCs close to each other, on the Figure 15A, several virga were present in altitude but also close to the ground. On the figure 15B, virga is also detected by the second ALC but their length is shorter and also their frequency. In the measurements of PM2.5 and BC (Figure 15C) of the station closest to the two ALCs, a peak was detected in the same time slot the virga producing aerosol layer close to the ground was detected by ALC. This case illustrates the great heterogeneity existing in the formation of virga within the same area, often making it difficult to establish the link between virga and ground PM measurement.

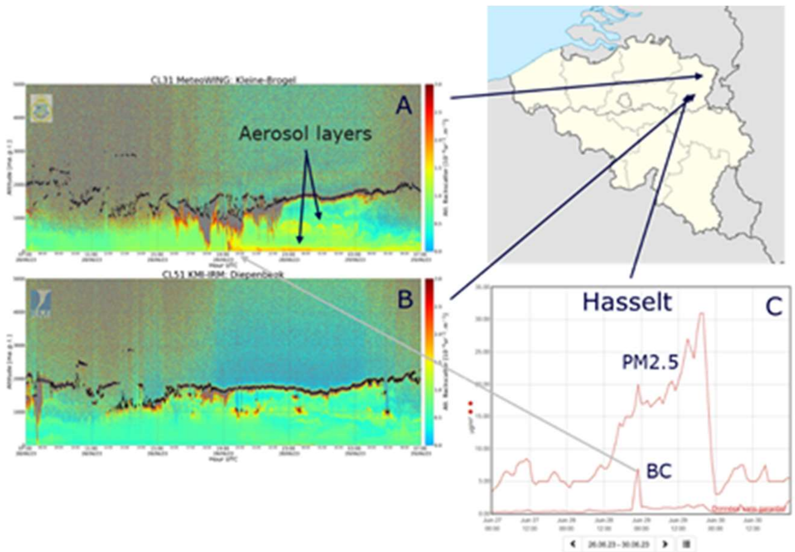


Figure 15: Attenuated backscatter profile as a function of time observed on June 28 2023 at Kleine-Brogel (A) and Diepenbeek (B). (C) Surface measurement of BC and PM2.5 concentrations at Hasselt provided by IRCELINE (https://www.irceline.be).

Up to now, only one study (Karle et al., 2023), provided an initial investigation into virga's impact on ground-level PM concentrations. This study investigated and characterised virga events using a combination of ground-based remote sensing instruments and PM ground measurements and analysed its impact on local air quality. The quantification of the relationship between virga and the aerosol loading in the lower troposphere is an important new research question for atmospheric chemistry. This case study in June 2023 illustrated the need to obtain expertise concerning atmospheric dynamics combined with near-real-time operational monitoring of aerosol plumes by ALC to quickly answer questions from air quality agencies.

5.4 Improved aerosol monitoring with polarisation ALCs

dr. Quenting Laffineur, Royal Meteorological institute of Belgium (RMI)

Keywords: monitoring advected aerosol layers PBL entrainment, aerosol classification

In order to respond as quickly as possible to the needs and expectations of stakeholders including IRCELINE and avoid waste of time and the assumptions that must be made in the interpretation of traditional ALC data on the nature of aerosols. RMI purchased a new recently developed commercial ACL (CL61, VAISALA) with the depolarisation measurement function allowing straightforward identification of liquid and ice clouds, precipitation type and melting layer, as well as having improved potential for monitoring aerosols, smoke, dust, and volcanic ash. This new instrument very quickly met IRCELINE's expectations after its installation as illustrated in the following case.

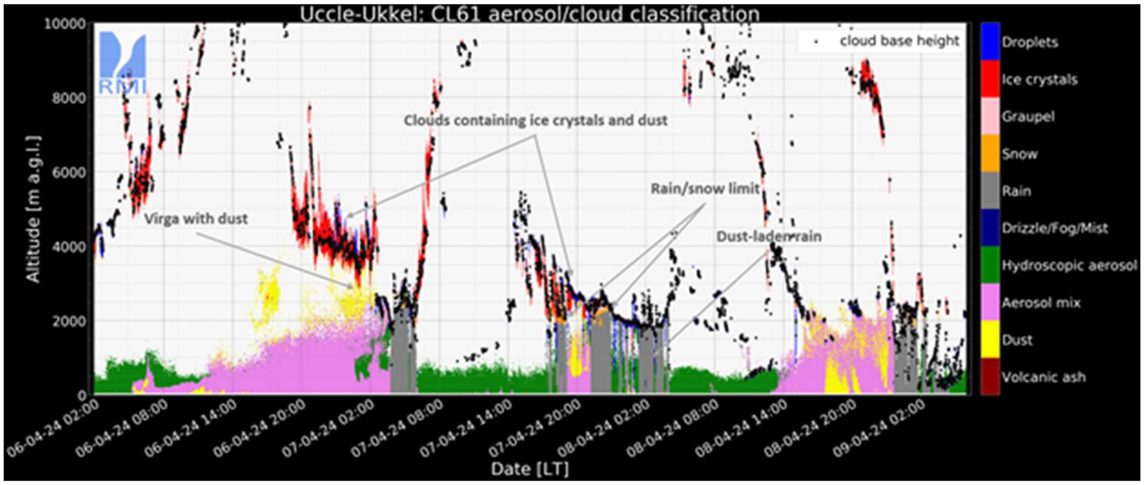


Figure 16. Example of output of the RMI in-house algorithm based on the measurement of the backscatter and the depolarization ratio between April 6 and 8, 2024 allowing to support the identification of the passage of three dust plumes over Brussels (Belgium).

Between April 6 and 8, 2024, three dust plumes coming from Saharan were detected by CL61 above the Brussels region (Uccle) as illustrated in Figure 16. In order to provide a first rapid response on the nature of aerosols present in the atmosphere, RMI has developed an algorithm based on the measurement of the backscatter and the depolarization ratio which automatically determines the nature of aerosols and hydro-meteors. As illustrated in Figure 16, this algorithm allows us to obtain a direct visualisation of the structure of dust plumes that didn't have the same characteristics. The first plume was probably present at altitude (the detection of a virga by ALC with the presence of dust after its evaporation seems to confirm that) and another part was present in the ABL mixed with other aerosols causing a slight increase in PM10 as illustrated in Figure 17. There is a PM10 measuring station near CL61 but it was out of service during this period. The second dust plume was essentially present at altitude in connection with the cloud cover which locally produced some precipitation containing sand (confirmed visually) without inducing an increase in PM10. It is possible that during this episode virga at the front of the precipitation zone were close to the ground and caused an increase in PM10 locally before being washed out by rain. The last plume, also present at altitude, interacted strongly with ABL, bringing a significant quantity of dust to the ground, locally causing a strong increase in PM10. The output of this automatic algorithm allows the user to obtain better confidence on the nature of the aerosols. However, human expertise is still required regarding the output of this algorithm in combination with other identification methods. Indeed, polarisation ALCs operating in one wavelength can't provide independent, unambiguous aerosol type identification.

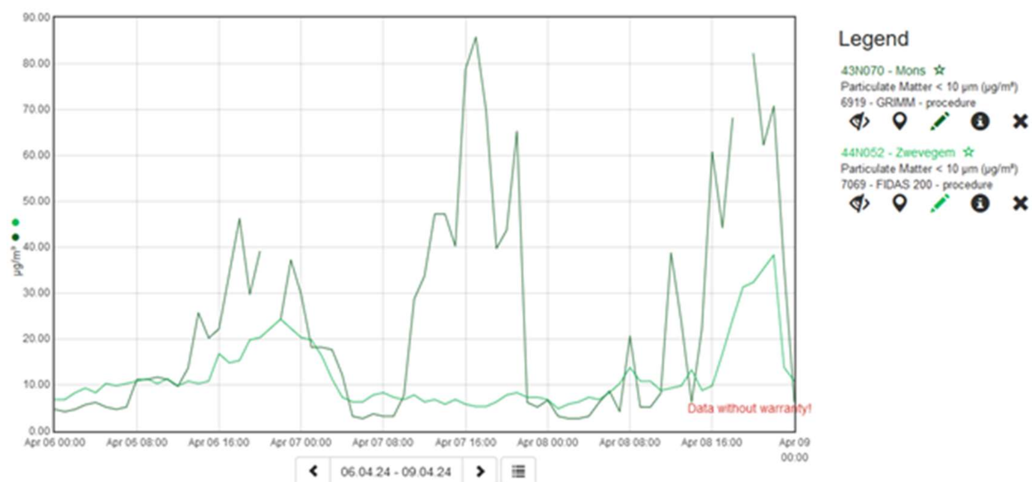


Figure 17. Surface measurement of PM10 concentrations at Mons and Zwevegen provided by IRCELINE (https://www.irceline.be).

5.5 Aerosol advection and influence on the local air quality

Keywords: local air quality, trans-regional advection, real time monitoring of aerosol dynamics

Several publications (Diémoz et al, 2019; Bellini et al, 2024; Diémoz et al, 2021;Gobbi et al, 2019; Barnaba et al, 2010; Ferrero et al, 2019) analysing high pollution episodes at surface using vertical profiles of aerosols and modelling tools were published. They show the importance of ground based remote sensing automated lidars and polarisation lidars in the process of interpreting, validating or complementing modelling results. Vertically resolved aerosol profiles give a direct insight into the dynamics and composition (using polarisation) of the aerosol layers.

With the use of ground based remote sensing data from the ALICENET network (Diémoz et al, 2019; Bellini et al, 2024; Diémoz et al, 2021; Bellini et al, 2024) extensive analysis of specific situations that lead to air quality pollution events in the Alpine valleys of northern Italy was possible. The analysis showed an important link of intense air quality pollution events in northwestern Alps with the aerosol sources in the Po basin in specific meteorological conditions. The multisensory approach accompanied with meteorological, chemical and transport models proved to be successful in determining the locations of sources and analysing time evolution of emitted particles, their vertical distribution and influence on the trans-regional air quality. Vertical profiles of backscatter signal from aerosols in the atmosphere elucidated the particle source regions and exposed actual timing of the advection and mixing processes, which could otherwise be wrongly attributed to local emitters. Profiler data also complemented quantified evaluation of the particulate matter load at the surface compared to the model outputs.

A long-term study of aerosol pollution in the northwestern Alps was possible using 3 years of data of vertically resolved aerosol profiles, vertically integrated extinction coefficient (AOD - aerosol optical depth), CTM (chemical transport models), NWP (numerical weather prediction) models and in-situ surface measurements of aerosol properties (Diémoz et al, 2019). The research study showed long-term impact on air quality in the alpine regions of the northwestern Alps. The study was able to evaluate frequency of occurrence of trans-regional surface pollutant advection events, optical and physical properties of the advected pollutant aerosols and the contribution of the advected aerosol layers at surface and aloft to the local in-situ measured PM values.

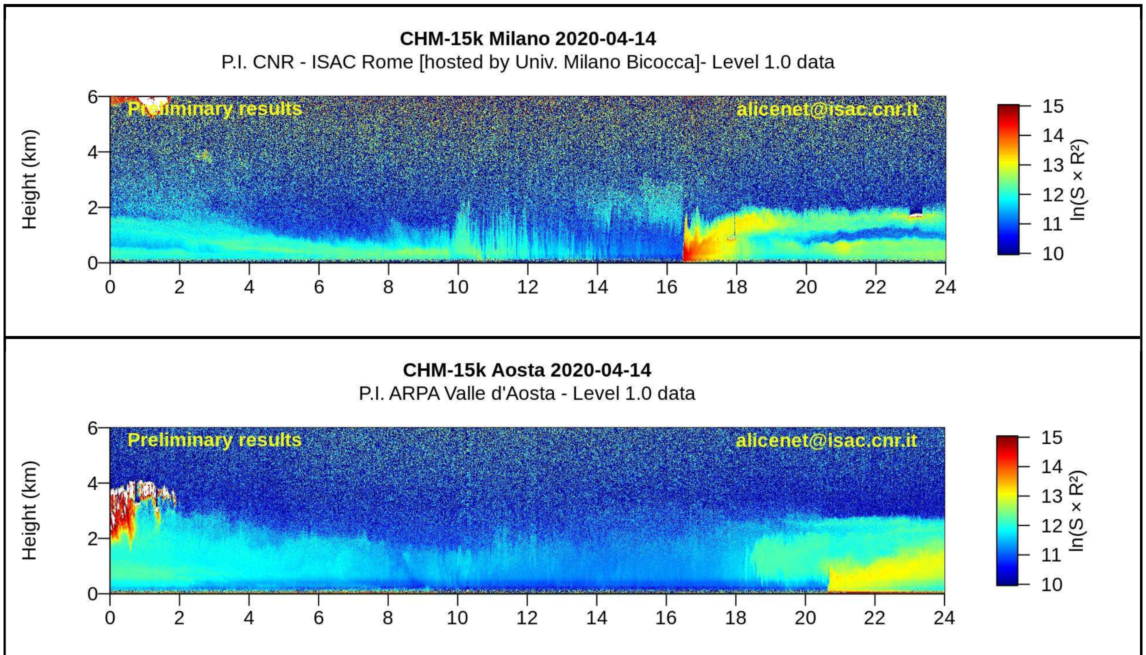


Figure 18: Example of ALC profile at Milano (upper plot) and Aosta (lower plot) ALICENET stations showing the arrival of the gust front transporting resuspended coarse aerosol particles (PM) from the Po Valley towards northwestern Italy. https://www.alice-net.eu/, accessed 5.5.2024

5.6 Meteorological support during industrial accident

dr. Massimo Enrico Ferrario, ARPA Veneto, Italy

Keywords: PBL dynamics, pollutant dispersion, industrial accidents

Introduction

The ARPAV Agency (Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto - Regional Agency for Environmental Prevention and Protection in Veneto) has been active in the north-eastern part of Italy since 1996. The Agency deals with many issues related to pollution from various sources and has an internal structure dedicated to Meteorology and Climatology: the Meteorological Centre at Teolo in the province of Padua. The various Operational Units of ARPAV therefore actively collaborate and interact with the Meteorology and Climatology Operational Unit, offering the possibility of analysing and studying pollution events and episodes in an effective and expeditious manner.

In 2005, thanks to the DOCUP project financed by the European Community, ARPAV was equipped with four SODARs and four radiometers to study PBL. These atmospheric profiling instruments provided important information on the state of stability of the atmosphere and the degree of air mixing near the ground. The four SODARs, albeit with relocations and displacements, are still active and produce hourly data available to the public at four sites of the wind intensity and direction in the first 500 m of altitude. Three of these stations are in the plains and one in a valley of the Alps (Pre-Alps). As far as radiometers are concerned, only one remains active, also in a valley of the Alps (Pre-Alps), the others being broken down irreparably after more than 10 years of operation.

These instruments have proved useful in the study of both acute and chronic air pollution, providing information that no other meteorological instrument could provide, either from the ground through conventional weather stations or meteorological radar, or from space through geostationary or polar meteorological satellites.

This is why ARPAV continues to invest in this sector, keeping all the profiler instruments in its possession active and calibrated where possible. In addition, with recent PNRR-PNC (*Piano Nazionale di Ripresa e Resilienza*) funding derived from post-COVID refreshments, the purchase of a new radiometer is planned, which will be able to perform thermal profiling of the atmosphere up to an altitude of 10 km.

SODAR operational use

On 18 April 2017 at around 13:00 hours, a large fire broke out in a warehouse of a factory producing electrical appliances near Treviso. The flames quickly devoured all the material present and a very high column of black smoke rose into the atmosphere (Fig.19) and was visible even from a great distance (Fig 20 a). The event was so great that the pyro-cumulus was also visible from Satellite (Fig. 21). The industrial area was completely destroyed (Fig 20 b).

Figure 19: The fire in the first few minutes as seen from the Treviso motorway (tangential).

Figure 20 a b The fire was visible from tens of kilometres away. The industrial area was completely destroyed.

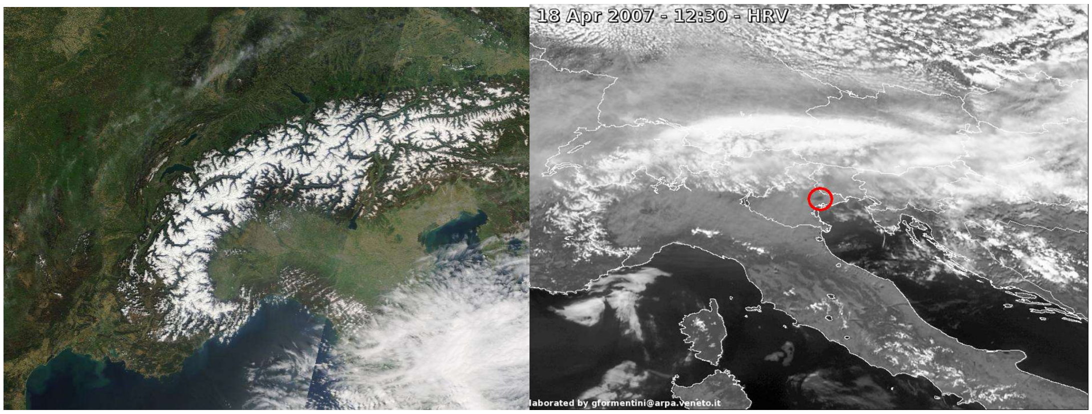


Figure 21: LEFT: Satellite image around 10:00 UTC of the MODIS satellite showing the absence of clouds over all of northern Italy. RIGHT: satellite image at 12:30 UTC (14:30 LT) MSG - HRV, note "red circle" of the pyro-cumulus in the eastern part of the Veneto region.

At that time, the SODAR in Padua (40 km from Treviso) was active and continuously measured wind intensity and direction data (Fig. 22). During the hours of the accident the SODAR measurements showed the presence of a south-easterly sea breeze, active up to about 200 m altitude and with maximum values around 5 m/s.

The spring-like situation with mostly sunny skies and high pressure on the ground had already activated the thermal difference between the sea (still 'cold' from the winter that had just passed) and the land, which warmed up very quickly. These penetrated the lowlands, following the same shape as the coastline, up to 30-40 km from the beach. Hourly wind data made it possible to constantly monitor the evolution of the wind situation.

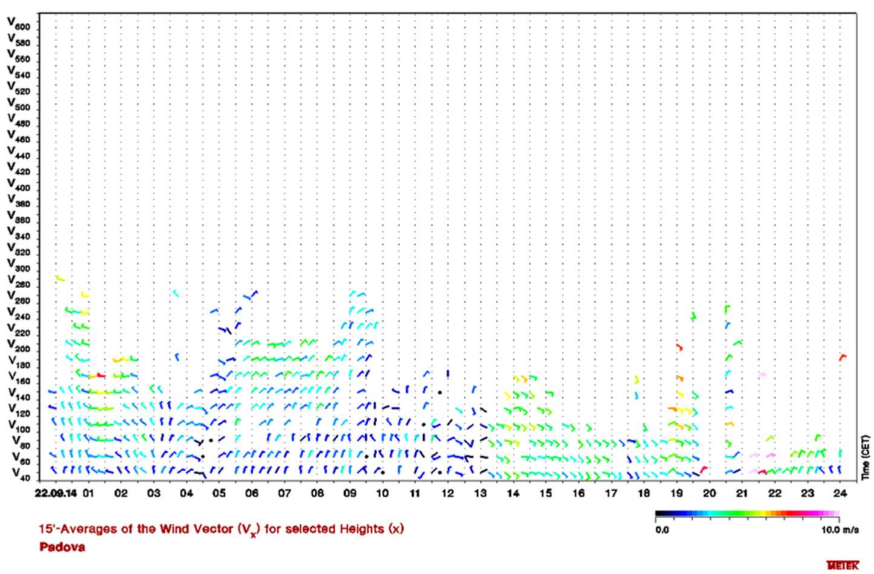


Figure 22 SODAR wind chart of Padua, note how from 13:00 LT (UTC+2) the sea breeze reaches the city of Padua and remains active until the evening.

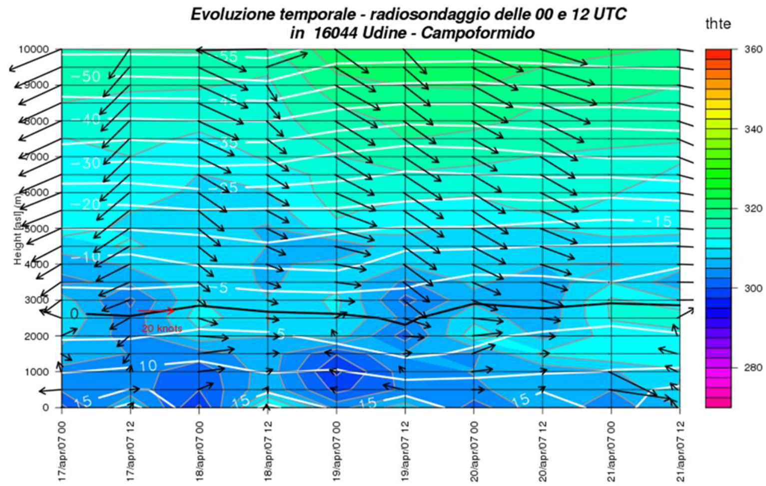


Figure 23 SODAR wind chart of Padua, note how from 13:00 LT (UTC+2) the sea breeze reaches the city of Padua and remains active until the evening.

The moderate sea breeze was therefore responsible for the north-westerly bending of the plume, but after a certain altitude the pyro-cumulus was intercepted by the currents at high altitude and turned eastwards. This was due to winds between 1000 and 2000 m blowing from the west, as witnessed by the radio-sounding at Campoformido in the province of Udine, 100 km east of Treviso (Fig. 23).

Conclusions

In this particularly serious and extensive industrial accident SODAR was useful for estimating wind speeds at the surface and in the first layers of the atmosphere. Through the evolution of the situation, it was possible to carry out a form of 'nowcasting' of the ventilation and better understand which areas of the city of Treviso needed to be evacuated or subjected to particular restrictions. The SODAR also made it possible to assess at what altitude the winds were changing direction and to have a quantitative feedback of the wind strength at different heights.

5.7 Operational use of microwave radiometers

dr. Massimo Enrico Ferrario, ARPA Veneto, Italy

As part of the European DOCUP project ARPAV purchased three MTP5-HE radiometers (ATTEX) in 2005 to perform temperature profiling in the first 1000 m of altitude.

Figure 24: Example of operational MTP5-HE microwave radiometer in the ARPA Veneto profiler network. Picture provided by Massimo E. Ferrario, ARPA Veneto.

These instruments have been very long-lived and reliable, working with great continuity. Even today one of these radiometers is perfectly functional in Feltre and produces an important temperature profile every 5 minutes for the study the evolution of thermal inversions and the phase transition from rain to snow (level of 0° C) during the winter period in the Belluna valley. In some cases, it also monitors freezing rain, a very rare phenomenon, but one that is also possible in Italy. They give important information on the stratification of the atmosphere and the diurnal temperature cycle not only on the ground, but at all levels.

These radiometers are very useful in the cold season when the ABL is only a few hundred metres high, while they are less effective in the summer when the atmospheric boundary layer reaches 2-3 km in height.
Possessing three of these instruments at the same time made it possible between 2005 and 2020 to make important comparisons of ABL in different areas of the Po Valley. In addition to the above-mentioned meteorological applications, ARPAV used these radiometers to compare atmospheric stability and air quality.

In particular, in the city of Padua, in the centre of the Veneto Po Valley, one of these radiometers and an air quality monitoring station have been co-located for many years. By comparing the number of hours of inversion, inversion strength and daily PM10 concentrations, it was possible to constantly monitor the evolution of air quality in the urban environment (Fig 25).

These very reliable radiometers with a simple structure have proved to be very versatile and have provided many indications in various fields of meteorology and air quality over the years.

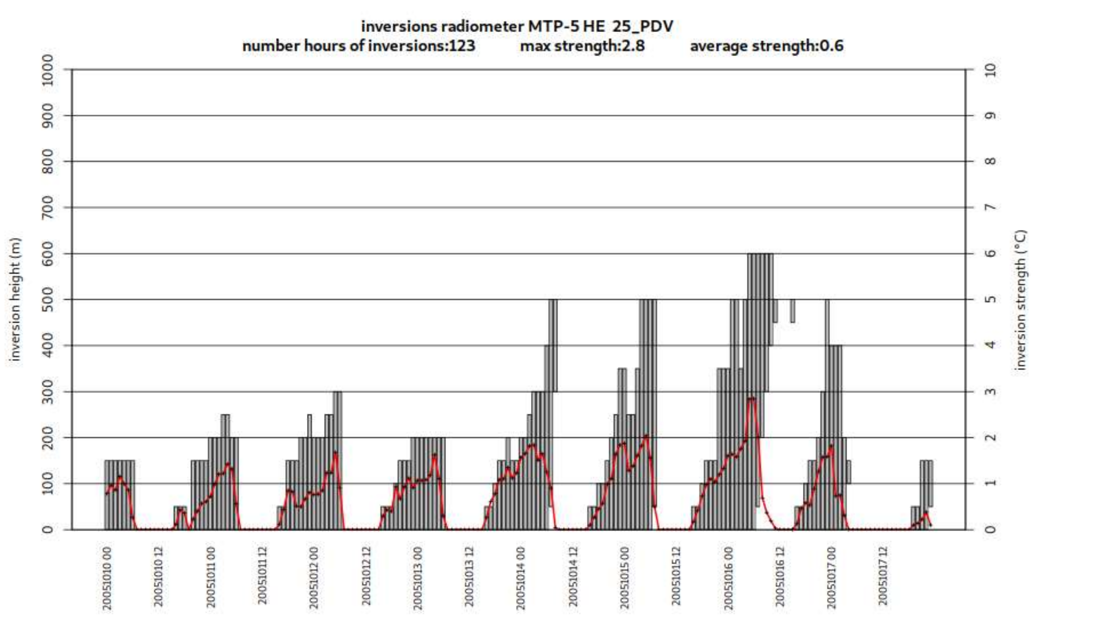


Figure 25. Hourly evolution of thermal inversions (gray bar height - left, red line strength - right) and PM10 concentrations in Padua from 10 to 18 October 2005. Note how on the last day the arrival of a synoptic disturbance (wind and rain) reduces inversions and pollutant concentrations.

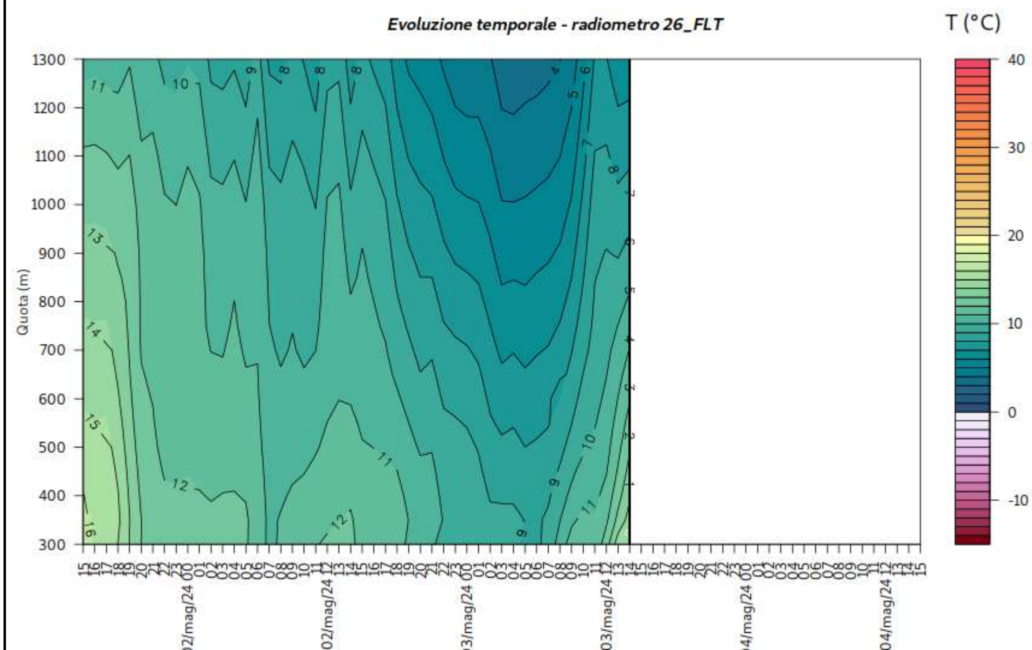


Figure 26: Example of MWR temperature near-real-time profiles in the ARPA Veneto ground based profiler network. https://www.arpa.veneto.it/dati-ambientali/dati-in-diretta/radar/profilatori, accessed 4.5.2024

5.8 Pollen detection in the ABL

Keywords: aerosol pollen events, lidar detection and classification

Part of aerosol content in the atmosphere are bioaerosols, which include algae, bacteria, plant debris and also pollen. Health related pollen allergies are highly correlated with the occurrence of different pollen during the pollination seasons which are strongly influenced by meteorological parameters, like temperature, humidity, wind, solar radiation. Climate change will influence the yearly cycles of pollination, dispersion and transport of the pollen grains (Rascado, Cost action PROBE-VMG, 2022).

Results of a study (Filioglou et al, 2023) showed spectral dependence of linear particle depolarisation ratios on different pollen types, specifically birch and pine, using a combination of single wavelength and multiwavelength depolarisation lidars. The results show good evidence for using multiwavelength aerosol profiles or depolarisation aerosol profiles to detect pollen and classify pollen types with accompanying uncertainty.

Another study (Rascado, Cost action PROBE-VMG, 2022) explored the influence of meteorological factors on the occurrence and intensity of pollen events, like PBL stability, atmospheric boundary layer heights (ABLH) and inversions, using microwave radiometers (MWR). Thermal inversions and their strengths were determined from MWR temperature profiles. Additionally ABLH and stability indices were also calculated, like Lifted index, K index, Showalter index and CAPE (convective available potential energy). The study showed the largest correlation of pollen events with ABLH parameter. Other variables, like inversion height, strength and duration also showed relation to surface pollen concentration, but the results were not homogeneous between test sites.

5.9 Saharan dust and fire smoke events

Keywords: saharan dust advection, fire smoke plumes, vertical mixing, PBL entrainment, surface PM loads

Advection of Saharan dust is a common phenomenon in southern Europe, often reaching central Europe. In recent years large fires due to summer droughts have also become more and more common. The global circulation drives the fire plumes around the globe. The Canadian fires in summer 2023 reached Europe. The contribution from elevated layers of Saharan dust advection or fire smoke plumes can have a major contribution to surface PM concentrations. Study of the entrainment processes of elevated aerosol layers into the PBL and quantification of the contribution those processes have on the surface PM load is thus important for understanding the air quality dynamics at the surface (Gobbi et al, 2019).

Saharan dust and fire smoke plumes can be studied using automated lidars and ceilometers, some with polarisation capabilities. The global models, like CAMS (ECMWF) provide good forecasts of the advection and evolution of the elevated Saharan dust and fire smoke plumes in the free atmosphere above ABL. However the actual timing and entrainment of the aerosols from aloft into the ABL is greatly improved by observations from lidar, ceilometer profilers (Gobbi et al, 2019).

Polarisation capabilities enable classification of the aerosol layers and advected dust or smoke plumes which can serve as a complementary information to the models outputs, providing real time picture of the forecasted dust or fire smoke events. Thresholds for the depolarisation ratio have been assessed for indication of presence of dust in the observed layer (Gobbi et al, 2019).

Polarisation lidars have also been proven to provide information about the influence of clouds and precipitation on the dust entrainment and vertical mixing (Karle et al, 2023). Dust particles induce higher depolarization ratios, thus enabling the interested user to follow the location of the dust in the ABL. The processes that influence the vertical redistribution of dust can be observed or their impacts can be evaluated, like scavenging of dust particles by rain, role of virga and mixing layer height. This enables users to view in real time and to understand the processes behind observed PM loads at the surface (Bellini et al, 2024).

5.10 Volcanic ash plumes events

Keywords: volcanic ash detection and monitoring

The importance of volcanic aerosols has been exposed with the eruption of Eyjafjallajökull volcano, exposing the whole air traffic sector to great uncertainty. Automatic lidars and ceilometers proved to be of great value at that time, providing information on the location, horizontal spread and vertical distribution of the volcanic ash clouds.

Regular monitoring is now provided by a large network framework of different types of lidars that monitor atmospheric profiles 24/7 (Bellini et al, 2024).

An example of surveying a volcanic eruption is the Etna volcano, erupting on the night from 13th to 14th of August 2023 (Bellini et al, 2024). Volcanic ash was detected with the ALICENET lidars that provided real time monitoring of the evolution of the volcanic cloud, when also VONA (Volcano Observatory Notice to Aviation) was issued. The ash plume was detected and identified also by depolarisation capabilities of the lidars in the ALICENET network, enabling the parties involved to follow the advection and deposition of the ash particles that reached the ground shortly after the event.

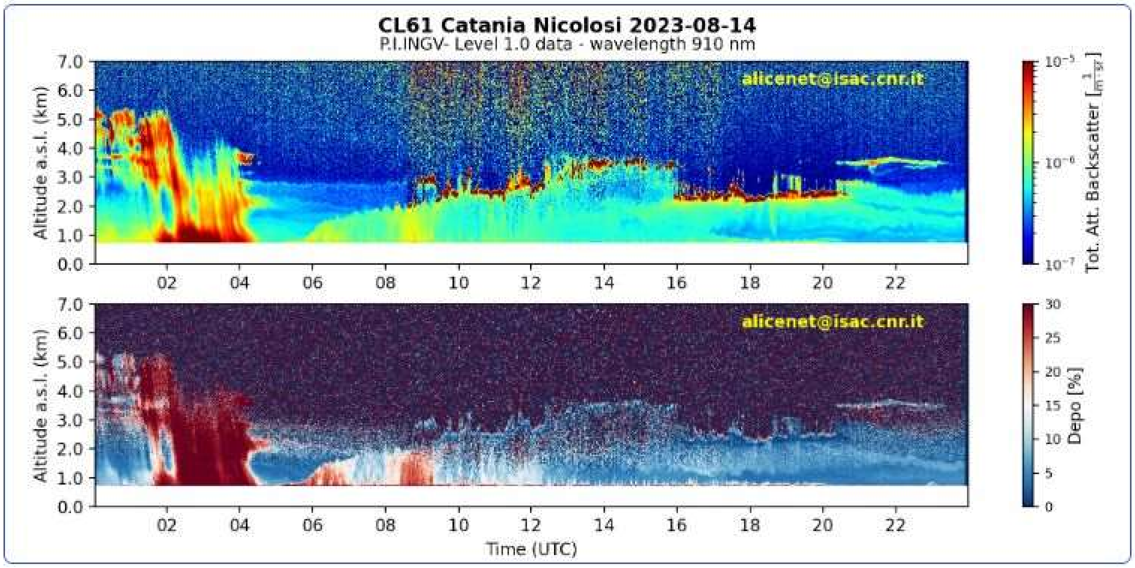


Figure 27: https://www.alice-net.eu/; access: 25-04-2024; Volcanic ash plume from Etna volcano reaching the ground.

5.11 Aerosol optical properties and mass concentration retrieval

Keywords: advanced optical and quantitative aerosol properties, derivation algorithms

The level of maturity of ALC networks around Europe now enables derivation of advanced end user products that provide quantitative optical and physical properties of aerosols, like *backscatter, extinction and mass concentration* (Bellini et al, 2024).

Different European institutions and programs (ALICENET, MetOffice, MetNorway, DWD, ACTRIS) involved with ALC aerosol profiling have developed processing chains for the derivation of advanced optical and physical aerosol properties which are of benefit to research, environmental, meteorological and health related public services (Bellini, Cost action PROBE-VMG, 2022). Processing steps include signal correction, calibration, calculation of backscatter and extinction coefficients and derivation of aerosol mass concentrations. The methodologies and assumptions differ between institutions and include functional relationships, aerosol backscatter data, aerosol volume estimation, aerosol density assumptions and sun photometer measurements (Bellini, Cost action PROBE-VMG, 2022). Some institutions provide visualisation products at their internet sites (Chapter 6).

There is ongoing work to improve derivations of advanced products, such as including new information from ALC polarisation measurements where available. A research study comparing the UAS (unmanned aircraft system) measurements with data from ALC profilers showed a positive synergistic effect when deriving mass concentrations of different aerosol types with improved uncertainty (Mamali et al, 2018). Intercomparison of different methodologies is also an active area of research trying to understand uncertainty contributions of different parameters.

6 Online near real-time visualization tools

The span and density of ground based remote sensing instrument networks is increasing at the national level and many of them are integrated into international frameworks that provide guidelines for standardisation on the operation, calibration and maintenance of different profilers, and also processing chains and tools for deriving end user products.

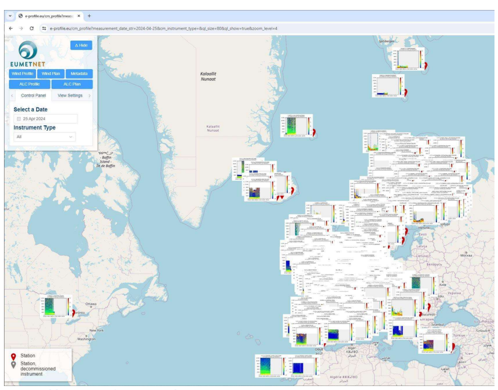
Many countries have been involved in developing their own processing chains and provide visualisations for different instruments that are part of international or national measuring networks.

The most advanced processing chains are currently available for ALCs (automatic lidars and ceilometers), but also wind profilers and microwave radiometers are following their path. Some of the instrument networks provide visualisation also for wind profilers and microwave radiometers.

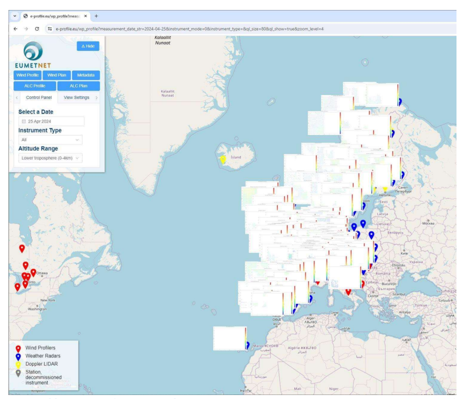
The processing chains are constantly developing. Some of them provide information on the stratification of the atmosphere and the presence of different aerosols. Advanced products are also available, like extinction coefficient profiles, AOD (aerosol optical depth) and mass concentration profiles.

Some of web platforms that provide online data from remote sensing instruments are presented below on figures showing the front pages of the web interfaces.

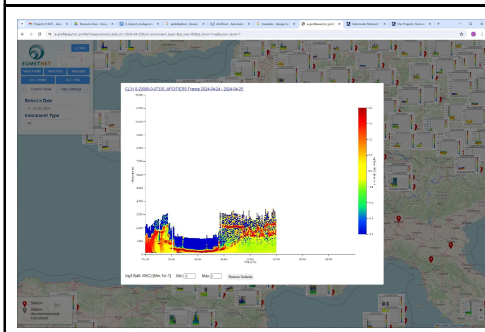
E-PROFILE online visualisation tool



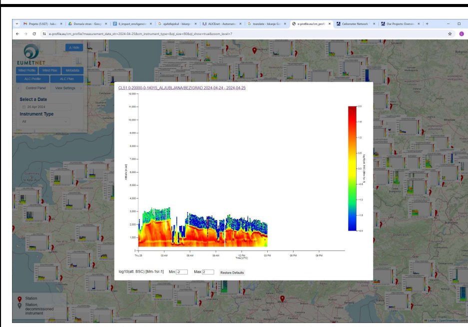
https://e-profile.eu/; Visualisation page for aerosol profiles from integrated ALC network; access 25-04-2024



https://e-profile.eu/; Visualisation page for aerosol profiles from integrated Wind profiler network; access 25-04-2024



Example of near real time ALC quicklook from Poitiers, France (accessed 25-04-2024).
We can see the onset of surface fog period during the night and breakout of fog layer in the next day.

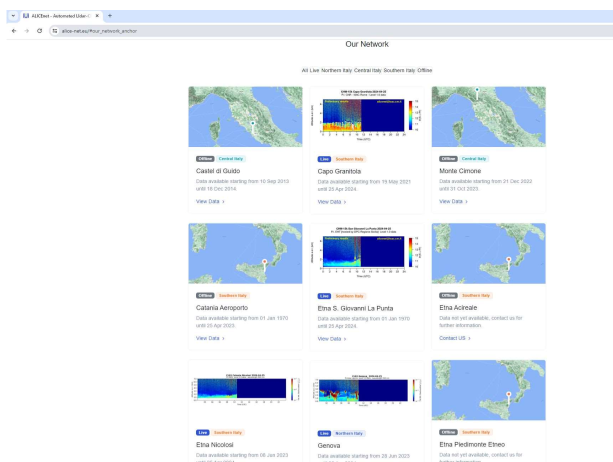


Example of near real time ALC quicklook from Ljubljana, Slovenia (accessed 25-04-2024).
We can see pronounced horizontal line in the saturated signal of precipitation (red colour), which is due to melting layer (snow to rain).

V-PROFILES online visualisation tool

https://vprofiles.met.no/; Norwegian meteorological institute page for visualisation of ALC instrument profiles and derived quantitative products; example for Payern ALC instrument; accessed 25-04-2024

ALICENET online visualisation tool



https://www.alice-net.eu/; Main page of Italian ALC network ALICENET providing visualisations of aerosol profiles and quantitative products; accessed 25-04-2024

CloudNet online visualisation tool

https://cloudnet.fmi.fi/; CloudNet framework, example visualisation for station Payerne, Switzerland, providing measurements on cloud, water vapour, temperature and aerosol properties together with model simulations; accessed 25-04-2024

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