Guidance documents on measurements and modelling of novel air quality pollutants:

Atmospheric boundary layer dynamics

with the support of:

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Research Infrastructures Services Reinforcing Air Quality Monitoring Capacities in European Urban & Industrial AreaS (RI-URBANS)

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Abbreviations

ABL	Atmospheric boundary layer
ABLH	Atmospheric boundary layer height
ACTRIS	Aerosols, Clouds and Trace gases Research InfraStructure
ACTRIS-CCRES	ACTRIS Centre for Cloud Remote Sensing
ALC	Automatic lidars and ceilometers
AQ	Air quality
AQMN	Air quality monitoring networks
BC	Black carbon
DBS	Doppler beam swinging
CAL	Continuous aerosol layer
DWL	Doppler wind lidars
EAL	Elevated aerosol layer
EC	Elemental carbon
LOS	Line of sight
MAL	Mixed aerosol layer
MLH	Mixed layer heigth
PM	Particulate matter
QA/QC	Quality assurance and quality control
RI-URBANS	Research Infrastructures Services Reinforcing Air Quality Monitoring Capacities in European Urban & Industrial AreaS EU-project
SNR	Signal-to-noise ratio
VAD	Velocity azimuth display
WHO	World Health Organization

1. ABOUT THIS DOCUMENT

This document is connected to the Directive of the European Parliament and of the Council on ambient air quality and cleaner air for Europe (recast). This document was prepared as part of the "Research Infrastructures Services Reinforcing Air Quality Monitoring Capacities in European Urban & Industrial AreaS" (RI-URBANS) EU-project that connects the atmospheric observation expertise from the Aerosols, Clouds and Trace gases Research InfraStructure (ACTRIS), as well as the urban air quality observation capacities of the regulatory air quality monitoring networks.

The proposed directive underlines the emerging importance of pollutants to air quality and the well-being of citizens. Particulate matter (PM), and in particular some of its components such as ultrafine particles (UFPs), black carbon (BC) and elemental carbon (EC), need to be monitored in both rural and urban supersites in order to support the scientific understanding of their effects on health and the environment, as recommended by WHO.

Currently, most Air Quality Monitoring Networks (AQMNs) miss information about important processes and quantities in the vertical dimension that are necessary to better understand surface-level pollution data. The vertical dimension is especially relevant when considering potential non-local sources of aerosols (e.g. those arriving via medium-to-long-range transport) and for evaluating vertical dilution of locally emitted pollutants and, in specific conditions, episodes associated with new particle formation and related particle growth processes.

Several atmospheric products can efficiently complement regulated in situ air quality measurements for different applications, including assessment, monitoring, and forecast. Here we highlight the added value provided by knowledge of the dynamics of the atmospheric boundary layer that can be traced through measurements of atmospheric boundary layer heights and profiles of wind and turbulence. To provide an overview of the underlying measurements that allow for the monitoring of boundary layer dynamics, we introduce the core instruments and briefly outline operation requirements. Finally, the document presents a few selected examples of measurements and retrievals that are applied in different RI-URBANS pilot cities and beyond.

This is a RI-URBANS/ACTRIS guidance for this specific service tool that is part of the RI-URBANS deliverable D46 (D6.1, containing guidance for all service tools provided in the project) with the support for publication from AXA Research Fund to build up the final dissemination D55 (D7.6). Any dissemination of results must indicate that it reflects only the author's view and that the European Commission is not responsible for any use that may be made of the information it contains.

2. VARIABLES TO TRACK ATMOSPHERIC BOUNDARY LAYER DYNAMICS

The Atmospheric Boundary Layer (ABL) is the lowest part of the atmosphere that is directly affected by the Earth's surface at time scales of < 24 h. When the ABL is not well mixed, which may frequently be the case during the day-night transition and several hours around those times, multiple sublayers can have distinctly different composition characteristics. In clear sky conditions, buoyant mixing during the day dilutes pollutants within the so-called convective boundary layer that increases in height during the morning and decays around sunset. At night, the vertical buoyancy is absent or weak, leading to a relatively shallow nocturnal layer close to the ground. The air diluted within the daytime convective boundary layer remains aloft and forms the residual layer. The height of the total atmospheric boundary layer (ABLH) represents the height of the residual layer at night and during morning while the convective boundary layer extends over the entire ABL in the afternoon. To define the volume for pollution dispersion and distribution near the ground, the continuum of the shallow nocturnal layer and the daytime convective boundary layer can be considered as the **mixed layer height (MLH)**. The cloud-topped ABL can generate its own turbulent mixing which may be sufficient for a deep MLH to persist whether day or night.

Transport processes in the atmospheric boundary layer can significantly affect the spatial distribution (horizontal and vertical) of aerosols and trace gases. While the **horizontal wind** is an important variable that drives horizontal advection between neighbourhoods or between the city and its surroundings, atmospheric **turbulence** is responsible for the mixing of the atmosphere, the vertical dilution of pollutants as well as the potential entrainment into the convective boundary layer. If fresh air is entrained, this can improve near-surface air quality, while entrainment of residual layer air or pollutants from elevated aerosol layers (e.g. Saharan dust, forest fire plumes) may have negative effects.

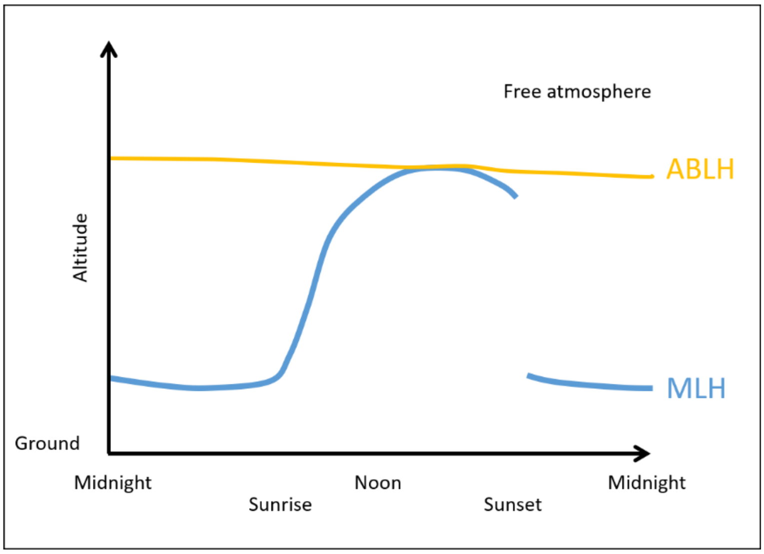

Figure 1: *Schematic diurnal evolution of the mixed-layer height (MLH) and the atmospheric boundary layer height (ABLH) above ground on a cloud-free day, driven by surface-based vertical mixing.*

3. MEASUREMENT METHODS AND QUALITY CONTROL OF BOUNDARY LAYER DYNAMICS

MLH can be derived from different atmospheric profile observations, using thermodynamic (based on temperature/humidity), dynamic (based on wind or turbulence variables), trace gas-based (e.g. ozone) or aerosol-based approaches (Kotthaus et al. 2023). Synergy approaches that combine multiple sources of information are also being developed. Algorithms for the retrieval of layer heights from profile observations are becoming increasingly advanced, now often including checks for temporal consistency or automatic quality control procedures. For RI-URBANS, advanced processing algorithms have been implemented that derive MLH (and ABLH) from automatic lidar and ceilometer (ALC) observations using tailored aerosol-based retrieval approaches.

The dynamics in the ABL can be observed continuously at high temporal (< 1 h) and vertical resolutions (~ 5-30 m) using ground-based Doppler wind lidars (DWL). Doppler wind lidars can be operated in different scanning modes to monitor the atmospheric variables of interest: such as the vertical profile of horizontal wind speed and wind direction or different turbulence variables (e.g. variance of the vertical velocity, eddy dissipation rate).

3.1. State of harmonisation

Numerous ALC and DWL model types from different manufacturers are being operated across Europe. To ensure results are comparable between sites and over time, the ACTRIS Centre for Cloud Remote Sensing

(CCRES) has formulated a set of instrument-specific operation guidelines that describe best practices for instrument settings and maintenance. While ACTRIS-CCRES is currently formulating best-practice guidelines for the scanning schedule of DWL, a general agreement has been reached on the recommendations for ALC operations between several European measurement networks. Valuable sources of information are the overview documents recently compiled by the EU COST Action PROBE with significant contributions from ACTRIS (ALC: Wagner et al., (2024); DWL: Preissler et al., (2024)). In addition to standardised instrument operations, careful processing and quality control procedures need to be implemented to ensure the harmonisation of measurements across diverse sensor networks.

3.2. Instrument summary and standard operating procedures

3.2.1. Automatic lidars and ceilometers (ALC)

Automatic lidars and ceilometers (ALC) are compact, low-power lidars that require very little maintenance. ALC operate an eye-safe laser in the near-infrared region of the electromagnetic spectrum. Laser pulses with low power and a high repetition frequency are emitted into the atmosphere, the backscattered light is captured by a receiver and a profile is obtained using the round-trip time. ALC can be operated autonomously both in rural and urban settings. In the city, they are often installed on rooftops or in backyards. Their field of view should not be obstructed at any time (e.g. by trees). Given their small field of view, ALC can be placed below the average ground level (see Figure 2). Such a placement is advantageous compared to a rooftop location as it allows to discard the first measurement levels from the layer detection analysis without losing information near the surface. For most ALC, measurements in the very first range gates show higher levels of uncertainty which can translate into errors in the detection of shallow layer heights. If more than one ALC with the same laser wavelength is installed at the same site (e.g. during inter-comparison), a minimum distance of approximately 8-10 m or tilting is needed to avoid possible optical interference.

Figure 2. *Placement of an ALC in an urban setting below ground level. Such a placement allows to discard the first measurement levels from the analysis without losing information near the surface. Given measurements in the first levels have a relatively high uncertainty for many ALC, this can improve the detection of shallow layer heights. Photo: M. Haeffelin.*

Site requirements defined by ACTRIS:

- **Environment surrounding the instrument:** Secure, stable, levelled-surface (e.g. concrete base). Open view to the sky (e.g. no tree branches).
- **Reliability of the internet and stability of electric power** (UPS) is required.
- **Local safety and security rules:** ALC operate eye-safe lasers that do not require specific security clearance in most cases. Regulations applicable for the specific measurement location should be checked.

Technical and operational requirements defined by ACTRIS:

- Instrument set-up and operations should follow the ACTRIS ALC Standard Operating Procedures. Note this may include instrument-specific settings and the operation of certain firmware versions.
- It is recommended (not mandatory) to install ALC with a tilt angle of 3° off-zenith to reduce specular reflection from ice clouds and pointing northward to minimize solar background radiation. Some ALC models have this tilt angle implemented internally.
- Data range resolution is either 5, 10, 15, or 20 m and temporal resolution is either 5, 15, or 30 s.
- Use UTC if possible (no changing with Summer Time), use NTP time server (ntpd) or GNSS (e.g. GPS) reference.

- Housekeeping data should be collected at the same frequency as the data resolution and should be monitored regularly.
- ALCs can be configured via a web interface, a serial connection or SSH. Data transfer is usually realized via a serial interface or an ethernet connection and data is pushed via FTP/SFTP in NetCDF format or is recorded with an acquisition software when using a serial connection.
- It is important to use an accurate system clock to get correct timestamps. For some systems a time server (NTP) can be defined. For instruments that rely on the correct time of the operating system on which the acquisition software is running, the operating system time needs to be synchronized with a NTP-server.

Maintenance procedures recommended by ACTRIS:

Maintenance requirements and frequency can highly depend on the measurement conditions (e.g. high pollution, aerosol deposition, snowfall, high humidity).

- **Preventive maintenance:** Clean window at least once a week/month or when window condition (as indicated by the housekeeping data) is less than ideal. Certain models (e.g. Ott Hydromet/Lufft ALC) require replacement of drying agent.
- **Component monitoring and replacements:** A failing laser will cause deterioration of the signal and loss of sensitivity. Laser power housekeeping data should be monitored continuously. The lifespan of lasers varies (~ 5-8 years).
- **Likely software issues, software upgrades:** Ensure firmware is appropriate for specific hardware. Always follow ACTRIS-CCRES firmware update recommendations.

Quality assurance, quality control and measurement uncertainty

The quality assurance and quality control of ALCs can be realized in two complementary ways.

- It is important to monitor the housekeeping data that track the status of the device in order to detect possible malfunctions or signs of ageing which might affect the measurement quality.
- The actual measurement data can be used to apply calibrations and correction procedures. These are useful to monitor and improve the product quality and consistency.

Currently, a full processing chain for ALCs with QA/QC procedures is set up by ACTRIS-CCRES at the Cloud Remote Sensing data centre (Cloudnet data portal) in exchange with experts from the ACTRIS Centre for Aerosol Remote Sensing (ACTRIS-CARS). Important housekeeping data parameters and their critical thresholds have been identified by experienced operators and researchers for the most commonly used

ALC models. ACTRIS developed an application to monitor all identified housekeeping data variables, currently implemented at the ACTRIS National Facilities. The monitored variables will be accessible and visualized through web dashboards. Alerts will be sent to instrument operators when housekeeping data parameters cross predefined threshold values. This shall allow stations to get the best uptime possible and data with the best quality.

In the post-processing step, the recorded range-corrected signal needs to be corrected for instrument-specific artefacts, such as the instrument-related background (Kotthaus et al., 2016) or uncertainties in the optical overlap correction (Hervo et al., 2016). Finally, the range-corrected signal is converted into a physical value of attenuated backscatter using an automatic calibration procedure that utilises the response of the signal to atmospheric conditions (e.g. liquid water clouds, Hopkin et al., (2019); O'Connor et al., (2004)); or molecular scattering (Wiegner & Geiß, (2012)).

3.2.2. Doppler Wind lidars (DWL)

Doppler wind lidars (DWL) are active remote sensing systems similar to aerosol backscatter lidars but with the capability to monitor wind velocities. Most DWL that are used to probe the atmospheric boundary layer employ solid-state fibre optic technology and coherent heterodyne detection. Systems that cover the full depth of the boundary layer commonly send pulsed laser signals and then use the round-trip time to determine the range information along the line of sight (LOS). Typically operating at wavelengths between 1.5-2.0 µm, DWL use aerosol, cloud droplets or ice particles as tracers to determine the radial Doppler velocity based on the detected Doppler shift between the emitted and backscattered signal along the laser beam direction. By combining beams in multiple directions, the three wind components (u,v,w) can be derived along the profile. DWL can be operated with different scan patterns. To determine the vertical profile of horizontal wind, the Doppler beam swinging (DBS) or velocity azimuth display (VAD) mode can be applied. From continuous stare in a fixed direction (usually in the vertical), high-frequency fluctuations in the wind field can be observed and used to derive turbulence indicators, such as the variance of the (vertical) velocity. Further details on DWL capabilities and limitations are summarised in Kotthaus et al. (2023) and Preissler et al. (2024).

Instrument set-up and operations should always follow the ACTRIS DWL Standard Operating Procedures.

Site requirements defined by ACTRIS:

- **Environment surrounding the instrument**: Secure, stable, levelled-surface (e.g. concrete base). Open view within a cone of specified angle from zenith (~30°) necessary to obtain a wind profile, and preferably open view to horizon to enable low-elevation scans.

Technical and operational requirements defined by ACTRIS:

- Keep the instrument powered. This ensures permanent temperature stabilization.
- Use UTC if possible (no changing with Summer Time), use NTP time server (ntpd) or GNSS (e.g. GPS) reference.
- For scanning instruments provide azimuthal correction from the north (see instrument manual). Ensure horizontal alignment of the instrument. Hard target measurements are advised at installation for velocity calibration and pointing angle alignment.
- For scanning systems: For instruments with a reliable, internal DBS retrieval, this can be applied to derive vertical profiles of horizontal wind. To utilise ACTRIS-CCRES retrieval algorithms, VAD scans should be performed with a sufficient number of azimuth angles. Both for DBS and VAD, scans at two complementary elevation angles (e.g. one high (~70°), one low (~10°) elevation) are advised to enable retrieval of the wind field across the entire boundary layer. Continuous segments of vertical stare mode are necessary to derive turbulence indicators. To determine the variance of the vertical velocity, vertical stare mode at a high temporal frequency (< 5 s) should be operated for several continuous minutes.
- Store data at highest possible temporal resolution.
- Store all raw data: signal and velocity, background measurements, spectra (if possible).

The following maintenance is recommended by ACTRIS:

Maintenance requirements and frequency can highly depend on the measurement conditions (e.g. high pollution, snowfall, high humidity). It is critical to monitor instrument stability using housekeeping data.

- **Preventive maintenance:** Occasional cleaning of the telescope (not less than every 6 months). Certain systems (Vaisala) need regular changes of desiccant to prevent lens fogging.
- **Component monitoring and replacements:** Amplifiers can degrade - usually, this is very rapid. We recommend the check at least once a month.

- **Likely software issues, software upgrades:** Ensure firmware is appropriate for specific hardware. Always follow ACTRIS-CCRES firmware update recommendations.
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3.3. Boundary layer height detection

Given that the distribution of aerosol particles and moisture is (amongst others) affected by mixing processes, attenuated backscatter profiles from ALC can be exploited to track the recent history of ABL dynamics. Layer boundaries can be detected if aerosol properties differ between the probed atmospheric layers. The most pronounced layer edge usually marks the height of the total ABL (ABLH) because aerosol concentrations and humidity tend to be significantly higher within the ABL than in the free troposphere above. Within the ABL, mixing dynamics and advection can lead to contrasting aerosol properties between different layers so that often the height of the mixed layer (MLH) can be determined based on aerosol backscatter profile data. The performance of aerosol-based layer height retrieval algorithms significantly depends on the quality of the attenuated backscatter analysed (Kotthaus et al., 2023).

RI-URBANS contributes to the ABL testbed project implemented at the French AERIS data centre in a collaboration between multiple networks and partners (RI-URBANS, ACTRIS, ICOS, E-PROFILE, EU COST Action PROBE). To exploit the signals from different ALC models most effectively, the ABL testbed evaluates the application of layer detection algorithms that can be adjusted according to the measurement capabilities of a given ALC. In accordance with results from the ABL testbed project, RI-URBANS is now recommending the use of the automatic layer tracking algorithm **STRATfinder** (Kotthaus et al., 2020), a tool that is freely available from the ABL testbed project. Note that the retrieval algorithms are continuously under development and are being refined. Recommendations may be updated in the future.

First results from the ABL testbed confirm conclusions from previous studies (Kotthaus et al., 2023): the quality of the attenuated backscatter input into the algorithm has a decisive impact on the reliability of detected layer heights. A critical limitation for detection of deep ABL layer heights is the signal-to-noise ratio (SNR). Data from ALC with relatively high SNR (e.g. Ott Hydromet/Lufft CHM15k, Vaisala CL61) are suitable for the detection of layer heights even greater than 3 km, while those with a relatively low SNR can be challenged when layer heights exceed ~ 1.5 km. To detect shallow MLH (< 250 m) that are frequent at night and during winter, good optical overlap capabilities in in the near-range are required.

A detailed quality control procedure was developed by the ABL testbed to flag results that display physically unreasonable temporal discontinuities. It is very challenging to quantify the uncertainty of boundary layer height products, given the lack of an “absolute truth” that can be used for comparison. In a first instance, layer products are assessed through visual comparison to the input data (e.g. field of attenuated backscatter). The analysis of daily quicklooks (see ABL testbed) reveals that layer tracking algorithms such as STRATfinder generally perform well at times when the diurnal cycle of ABL dynamics is mostly responding to local, surface-driven variations in atmospheric stability and thermal buoyancy. This can be explained by the fact that the tested algorithms work with a preconception of the idealised ABL diurnal evolution with a growth of the MLH in the morning and an evening decay around sunset. For locations where boundary layer dynamics are largely influenced by horizontal advection (e.g. driven by land-sea breezes or topographic flow regimes) the tracking of MLH is more challenging mostly because the daytime convective boundary layer is not the predominant feature in the ABL evolution. Other tools, such as the ABL classification into advection regimes, can be more beneficial for the interpretation of air pollution transport in such locations (Diémoz et al., 2019).

3.4. Data management summary

3.4.1. Data formatting

Given that various ALC models from different manufacturers are being operated, this results in a range of output data formats. Raw data are increasingly stored by the instrument firmware in NetCDF format, but also other formats (e.g. text files) are being used. Through a collaboration between ACTRIS, E-PROFILE and the EU COST Action ToPRof (ES1303), the *Raw2L1* software has been developed. Raw2L1 produces a standardized and harmonized data and file format with necessary information added that is not provided for all ALCs in the manufacturer's raw data (e.g. instrument settings, overlap function, geolocation information). The NetCDF output follows CF-conventions. The tool (Python code) is available on the ACTRIS-CCRES Github (https://github.com/ACTRIS-CCRES/raw2l1) and development is still ongoing for further improvements. The same tool is implemented in the E-PROFILE data hub, which centralises most of the ALC operated across Europe.

Several tools do exist to format and process observations from DWL (Preissler et al., 2024). Given output from DWL varies greatly not only between instrument models but also in relation to the scanning strategies, no common “raw” file format has yet been established within ACTRIS. ACTRIS-CCRES is working on common guidelines for scanning procedures and retrieval methods.

3.4.2. Correction procedures

Instrument-specific corrections (temperature-dependent overlap correction, background correction, near-range artefacts) are being implemented by ACTRIS-CCRES to ensure harmonised processing across the diverse ALC models in the network. The ACTRIS-CCRES ALC processing is similar to the procedure implemented by the AERIS-ABL testbed demonstrator project with support from RI-URBANS.

ACTRIS-CCRES has similar procedures implemented for the harmonised retrieval of horizontal wind and turbulence indicators from DWL, which include instrument-specific background correction, telescope focus correction and uncertainty estimators.

3.4.3. Boundary layer height detection

The detection of the MLH and ABLH are currently not implemented in the ACTRIS data centre. ACTRIS-CCRES, ACTRIS-CARS and RI-URBANS are strongly supporting developments of boundary layer height detection with the STRATfinder algorithm (Kotthaus et al., 2020) in the framework of the ABL testbed demonstrator project implemented at the AERIS data centre. The ABL testbed is comparing aerosol-based MLH results obtained with the STRATfinder algorithm to turbulence-based layer heights obtained from processing vertical velocity variance profiles measured with DWL using the vertical stare mode. A turbulence-based layer tracking algorithm is still under development at IPSL-CNRS.

4. BOUNDARY LAYER HEIGHT DETECTION AT EUROPEAN AND REGIONAL SCALES

4.1. Introduction

The ABL testbed demonstrator project is currently processing data from 17 measurement sites (21 ALC) across Europe, including several sites relevant to RI-URBANS pilot cities: Bucharest (2 sites), Helsinki (2 sites), Aosta - St Christophe that is influenced by Milan (1 site), Paris (2 sites), and Rotterdam (2 sites), with daily quicklooks (Figure 3) freely accessible:

- ABL testbed – European: https://observations.ipsl.fr/aeris/e-profile/

Multiple years of measurements have been processed by the ABL testbed spanning from 2018-present for most sensors.

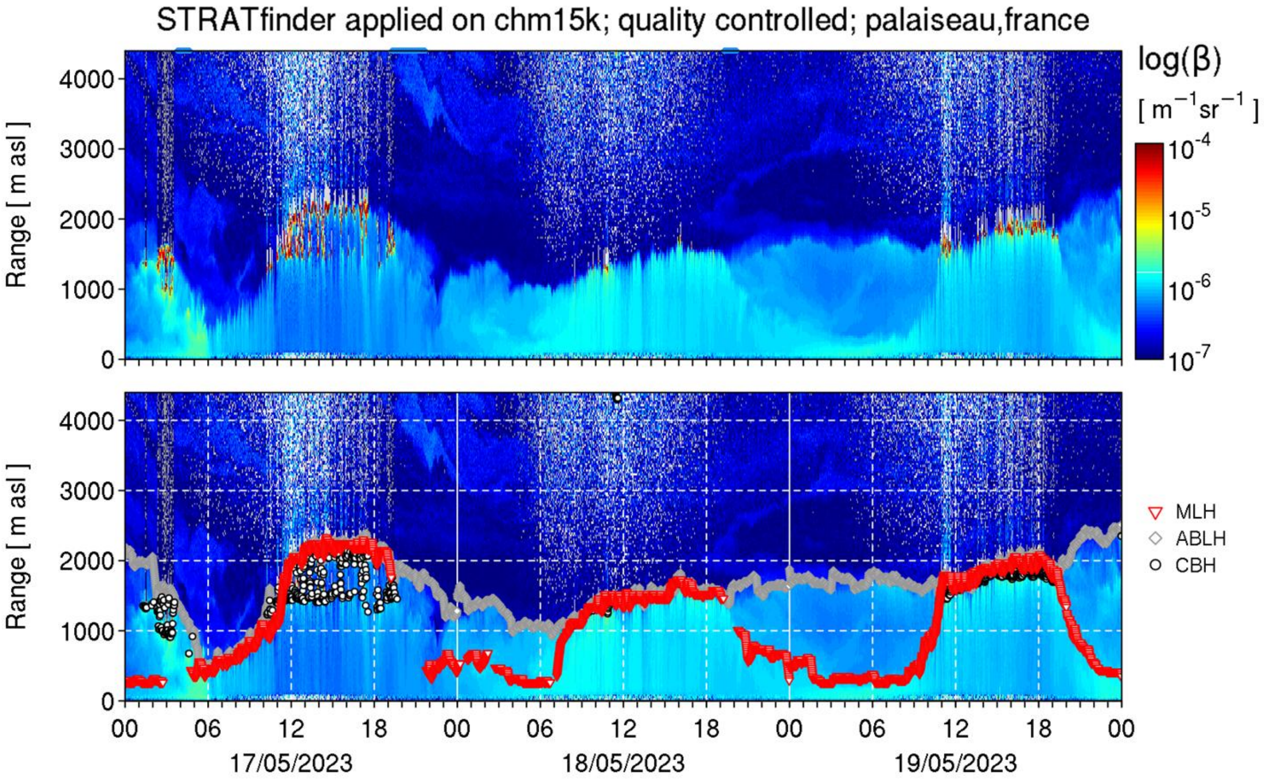

Figure 3. *Daily quicklook from the ABL testbed: overlap-corrected and calibrated attenuated backscatter observed with an ALC (Lufft CHM15k) at the SIRTA observatory at Palaiseau near Paris over a three-day period. Bottom figure also shows the cloud base height (CBH) and the mixed layer height (MLH) and atmospheric boundary layer height (ABLH) detected with the STRATfinder algorithm.*

In addition, the Italian ALC network ALICEnet (www.alice-net.eu) is also testing detection of the MLH at EU urban sites (e.g. Paris, Milan and Rome) using the STRATfinder algorithm, comparing it to the output of an original further tool (ALADIN, Aerosol LAyer DetectIoN) developed by the Alicenet team within the RI-URBANS activities. In particular, ALADIN was designed to identify automatically different aerosol stratifications based on ALC data (Bellini et al., 2024a). In fact, ALADIN output includes: 1. the Continuous Aerosol Layer (CAL): it is the layer extending from the ground level and characterised by the continuous presence of aerosols; 2. the Mixed Aerosol Layer (MAL): it is a CAL sublayer within which aerosols are mixed by surface-driven turbulent fluxes; 3. Elevated Aerosol Layers (EALs): they are lofted aerosol layers which lie above the MAL and may intrude into it, thus in turn affecting AQ measurements at the ground.

Examples of the ALADIN tool application on ALC data collected in Rome and Paris are provided in Figure 4 and Figure 5, respectively. In the second case, comparison with Stratfinder is also included.

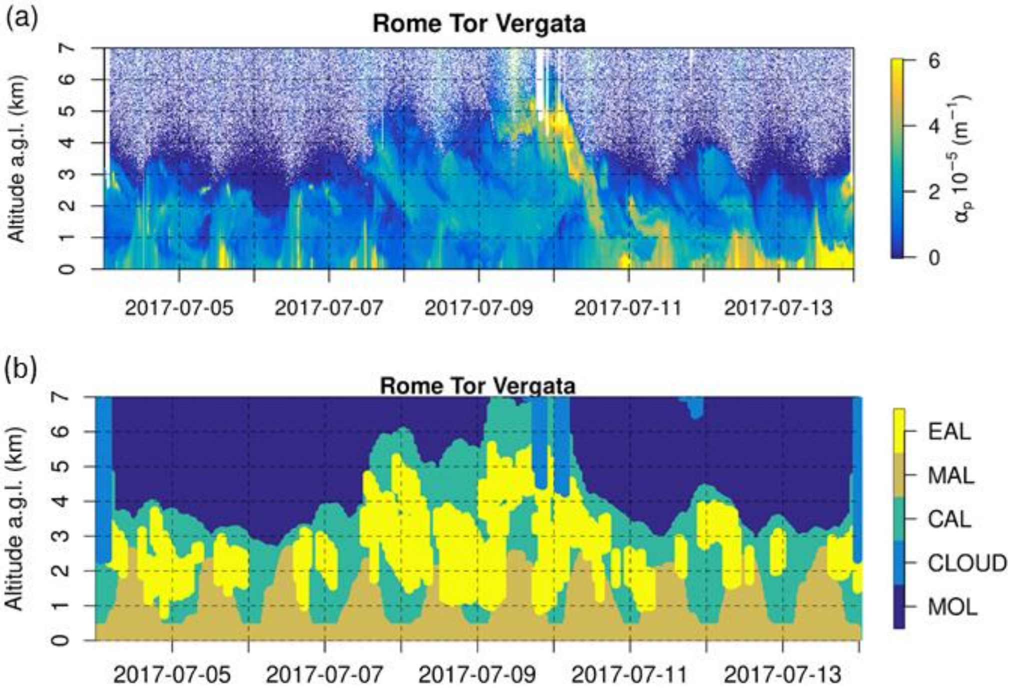

Figure 4: *a) Aerosol extinction profiles at 1064 nm as derived by ALC in Rome-Tor Vergata using the Alicenet inversion scheme in the period 4-13 July 2017; b) corresponding aerosol layering mask derived from the Alicenet-ALADIN processing, discriminating the continuous aerosol layer (CAL), the mixed aerosol layer (MAL) and elevated aerosol layers (EALs). Aerosol-free (i.e., molecular, MOL) or cloud-affected (CLOUD) regions are also identified. Adapted from Bellini et al., (2024a).*

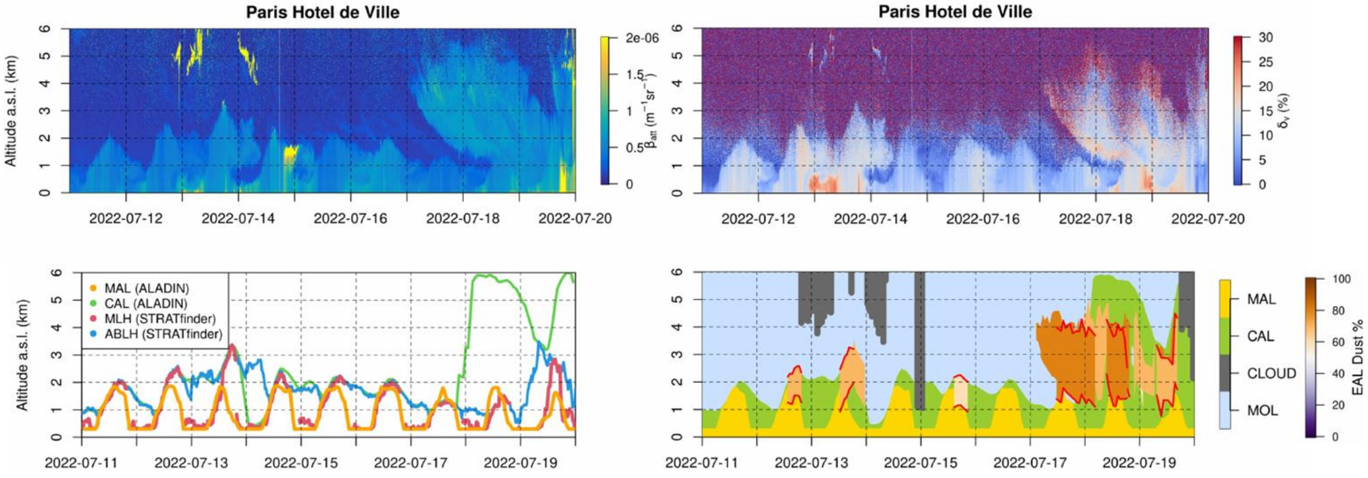

Figure 5*: (Top panels): (left) Aerosol Backscatter and (right) depolarization values recorded in Paris (Hotel de Ville; Vaisala CL61 loaned from manufacturer) in the period 11-19 July 2022. (Bottom panels): (left) relevant output of the STRATfinder and ALICENET-ALADIN algorithms in terms of MLH/ABLH and MAL/CAL respectively and (right) ALICENET-ALADIN atmospheric scene classification, including the Aerosol-free (molecular, MOL) region, the cloud-affected (CLOUD) screened profiles, and the aerosol layering: MAL, CAL plus elevated aerosol layers (EALs), these being coloured according to the estimated percentage of mineral dust (see colour scales). Thin red lines highlight likely intrusion of EAL aerosol into the MAL. Adapted from Bellini et al., (2025), in preparation.*

4.2. ABL height variability (temporal & spatial)

Using the long-term MLH results detected by the ABL testbed project at the RI-URBANS pilot cities, the variability of ABL dynamics can be assessed at different temporal scales, from diurnal cycles to monthly or seasonal variations to inter-annual differences. The monthly median diurnal MLH at the SIRTA observatory at Palaiseau near Paris derived from a 6-year dataset (**Figure 6**) reveals that vertical buoyancy commences three hours after sunrise (SR) independently of the season. The mixed layer decays on average several hours after sunset. As expected, month-to-month variations are detected with peak daytime developments in July and August and most shallow layer heights in December and January. Note that median MLH developments are quite similar for the four months of April, May, June and September, despite large differences in daylight duration and peak solar elevation. Similar analyses are being performed for other locations in or near RI-URBANS pilot cities (Paris, Bucharest, Helsinki, Rotterdam/Cabauw, Aosta/Milan, and Rome). Such information is highly relevant for the assessment of air pollution observations and forecasting.

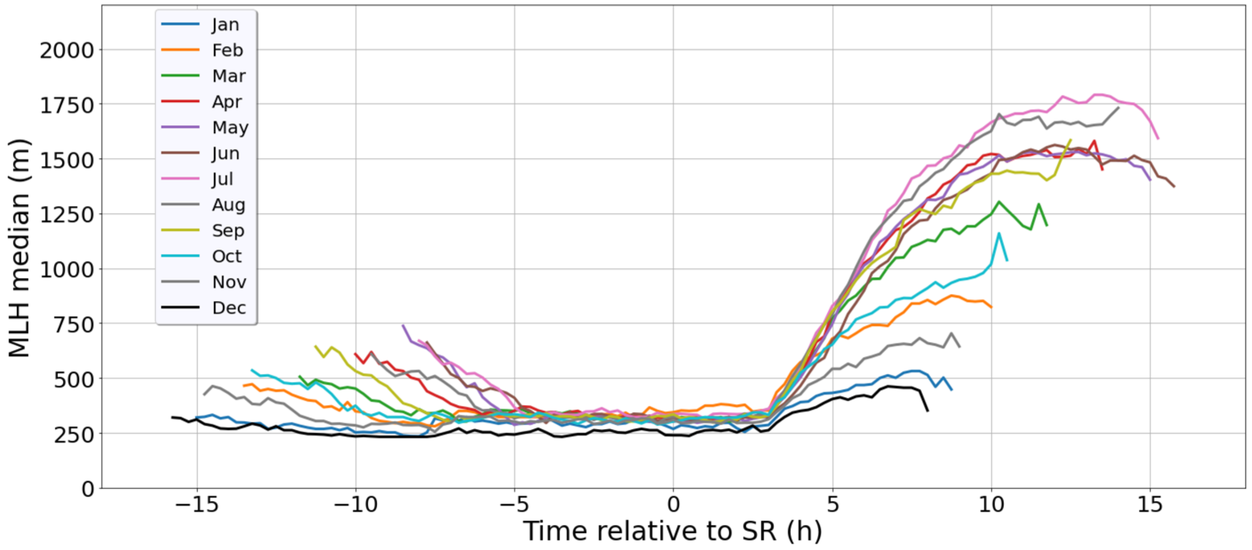

Figure 6. *Monthly median mixed layer height (MLH) against time relative to sunrise (SR) derived from ALC profile observations (Ott Hydromet/Lufft CHM15k) at the SIRTA observatory at Palaiseau near Paris, France, with the STRATfinder algorithm for the period 2015-2021.*

As the daytime MLH tends to trace the diurnal evolution of the convective boundary layer, it responds to the surface induced buoyancy and is also affected by the atmospheric stability conditions in the free troposphere above the ABL, hence the synoptic scale conditions. Atmospheric boundary layer dynamics hence change depend on surface cover characteristics and geographic settings. A long-time comparison between the median diurnal cycle of the MLH derived at three RI-URBANS pilot cities, namely Paris, Rotterdam and Bucharest (**Figure 7**), reveals that boundary layer dynamics vary considerably across Europe, with the average MLH over Bucharest being about 1 km higher than over Rotterdam.

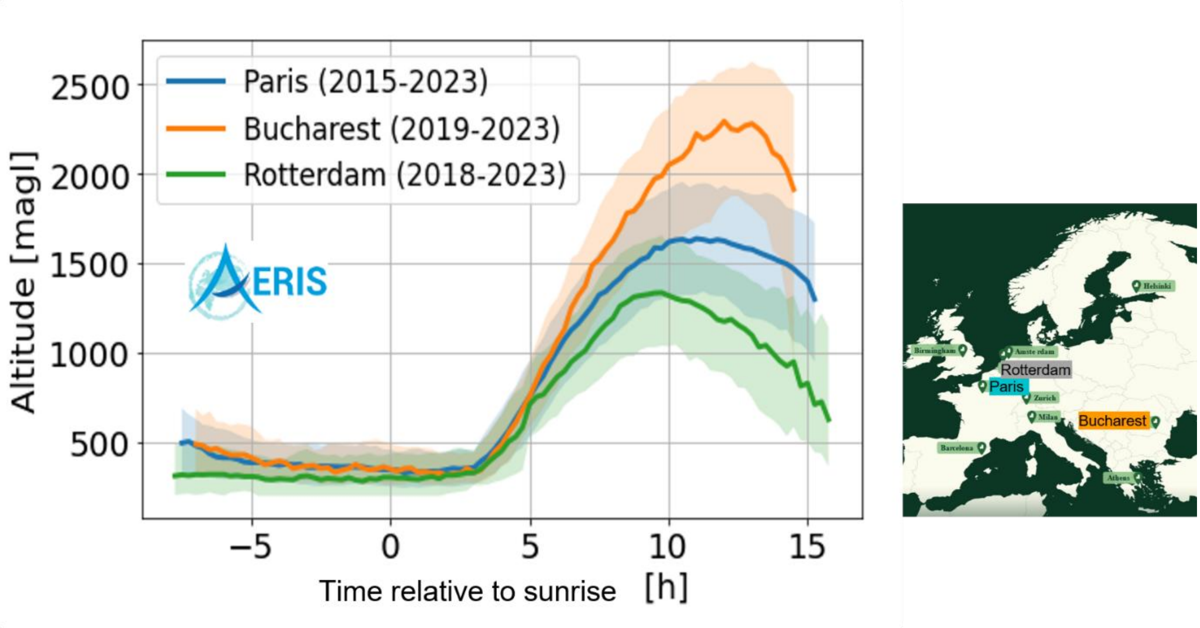

Figure 7. *Median diurnal mixed layer height (MLH) against time relative to sunrise with shading the inter-quartile range derived from ALC profile observations (Ott Hydromet/Lufft CHM15k) with the STRATfinder algorithm for all available data in the indicated period for three RI-URBANS pilot cities: Paris (suburban site Palaiseau), Bucharest (urban site Măgurele) and Rotterdam (rural site Cabauw).*

And also, at the regional scale (i.e. across an urban area), significant differences in MLH are detected. A comparison between the MLH detected at the SIRTA observatory in a sub-urban location 20 km Southwest of the Paris city centre and the central urban Paris site QUALAIR-SU (**Figure 8**) shows that the MLH tends to be greater over the city during daytime by several tens to hundreds of meters. With SIRTA being located on a Plateau (80-100 m relative to the city centre), part of this difference could be explained by topographical effects. However, even when comparing height relative to sea level, the MLH is consistently higher over Paris. Where urban ALC measurement networks are set up with sufficient site density to capture the rural–suburban–urban transect, such spatial variations can be detected and quantified with the automatic procedures implemented by RI-URBANS.

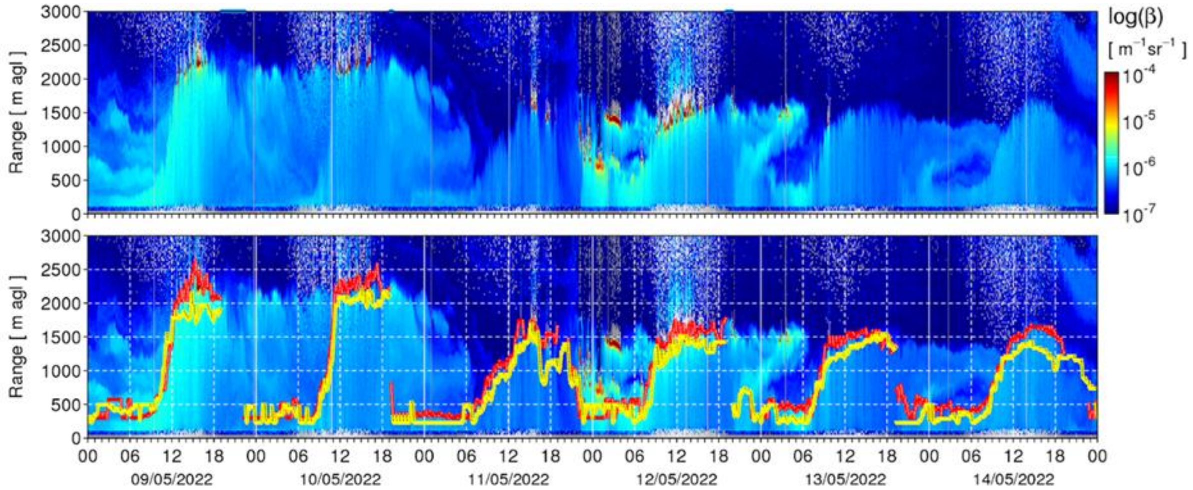

Figure 8. *Attenuated backscatter profiles observed with an ALC (Ott Hydromet/Lufft CHM15k) at the central Paris site of QUALAIR-SU between 9-15 May 2022. The bottom figure shows also the STRATfinder-derived MLH at Paris/QUALAIR-SU (campus of Sorbonne Université - red curve) in the city centre and the suburban site of SIRTA/Palaiseau (yellow curve), located 20 km SW of the Paris city centre.*

A long-term analysis (2016-2022) of the ALC-based data collected at the urban sites of Milan and Rome was also performed within RI-URBANS (Bellini et al., 2024b), this including evaluation of the monthly- and daily-resolved variability of the MAL and CAL heights, as derived from the Alicenet-ALADIN tool. The results of this aerosol stratification statistics are shown in Figure 9.

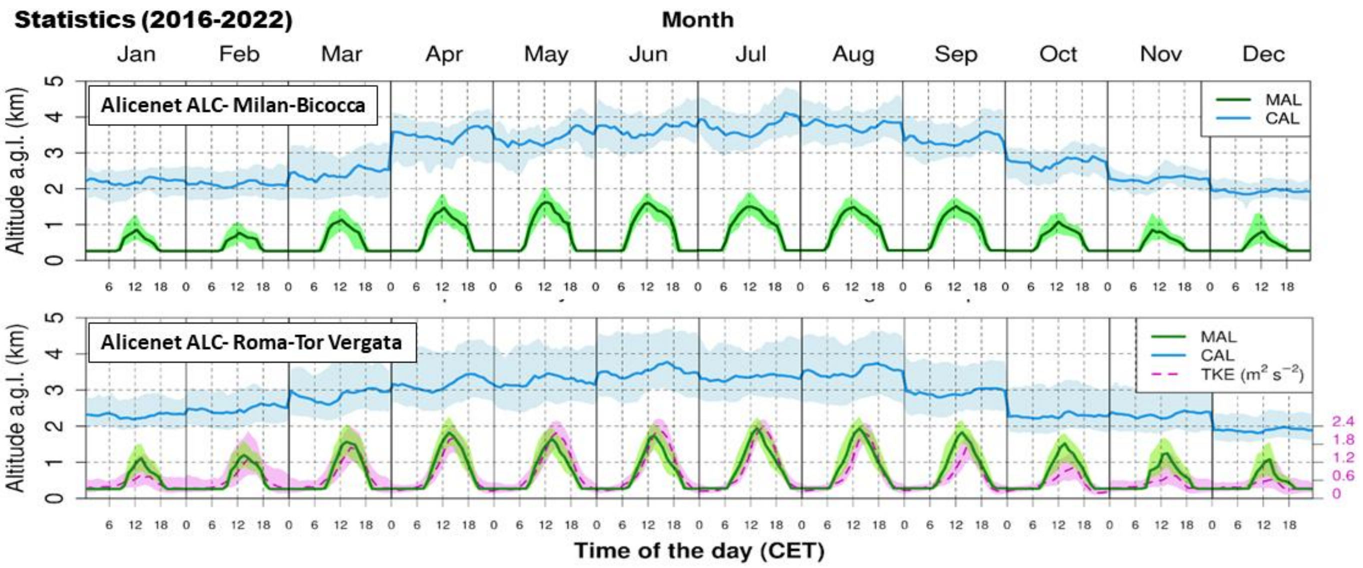

Figure 9: *Long-term (2016-2022) statistics (median, and 25-75 percentiles) of the monthly- and daily-resolved cycles of the MAL and CAL heights (left y-axis) derived from the ALICENET-ALADIN tool applied to ALC data in Milan (top) and Rome (bottom). For the Rome case, similar statisticS of the Turbulent Kinetic Energy (TKE) derived from a co-located ultrasonic anemometer (violet) is also added (right y-axis) as a proxy of convection intensity/timing (adapted from Bellini et al., 2024a, b).*

4.3. Wind profiles and turbulence

Horizontal wind speed and direction in the atmospheric boundary layer are a result of the interactions between the geostrophic flow in the free troposphere and the surface drag force. Examples of horizontal wind fields (speed and direction) as retrieved by DWL in the urban areas of Paris and Rome are given in Figures 10 and 11, respectively. In Paris, the horizontal wind in the ABL is often stronger at night, while vertical movements driven by turbulent eddies of different sizes dominate daytime momentum transport. In Rome, horizontal wind profiles clearly reveal the sea breeze regime affecting the area. In general, vertical profiles of horizontal wind aid the interpretation of advection processes, while measures of vertical turbulence (e.g. variance of vertical velocity) provide information on the intensity and vertical extent of atmospheric (vertical) mixing. The turbulence-based MLH (Figures 10, 11) is usually in rather good agreement with the MLH determined through analysis of the ALC attenuated backscatter at a nearby site in the Paris region (e.g., Figure 3). When clouds form within the ABL (e.g. Paris, 17th May 2024), detection and layer interpretation become more challenging.

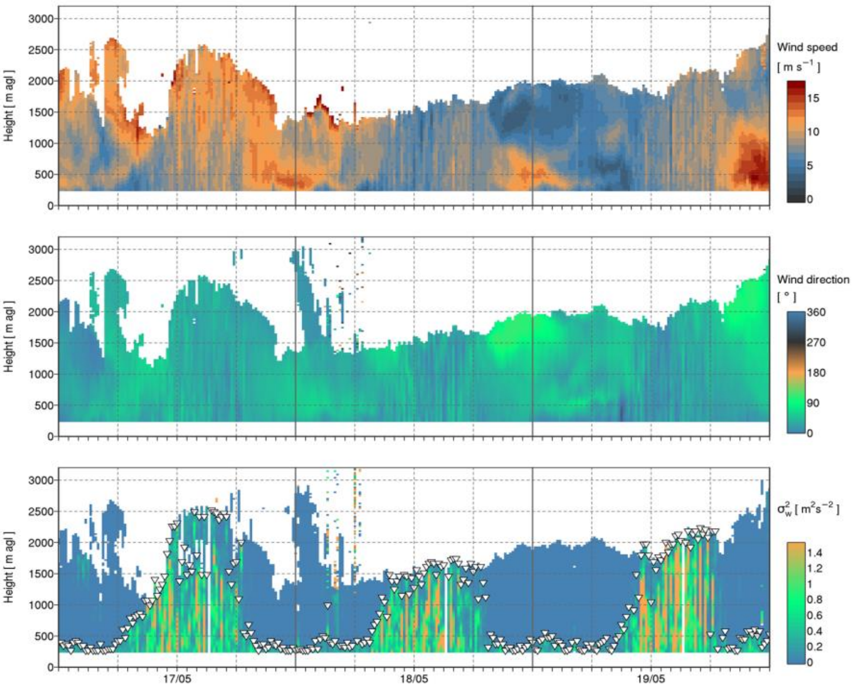

Figure 10. *Observations obtained with a Doppler wind lidar (Vaisala WindCube 400s) at the QUALAIR-SU site in central Paris for 17-19 May 2024, i.e. the same period as shown in Figure 3: (top) horizontal wind speed, (middle) horizontal wind direction, (bottom) vertical velocity variance with (symbols) the turbulence-based height of the mixing layer. As visible from ALC measurements in Figure 3, clouds formed at the top and within the ABL on the 17th May in the Paris region, which can cause considerable variations in the retrieved layer heights.*

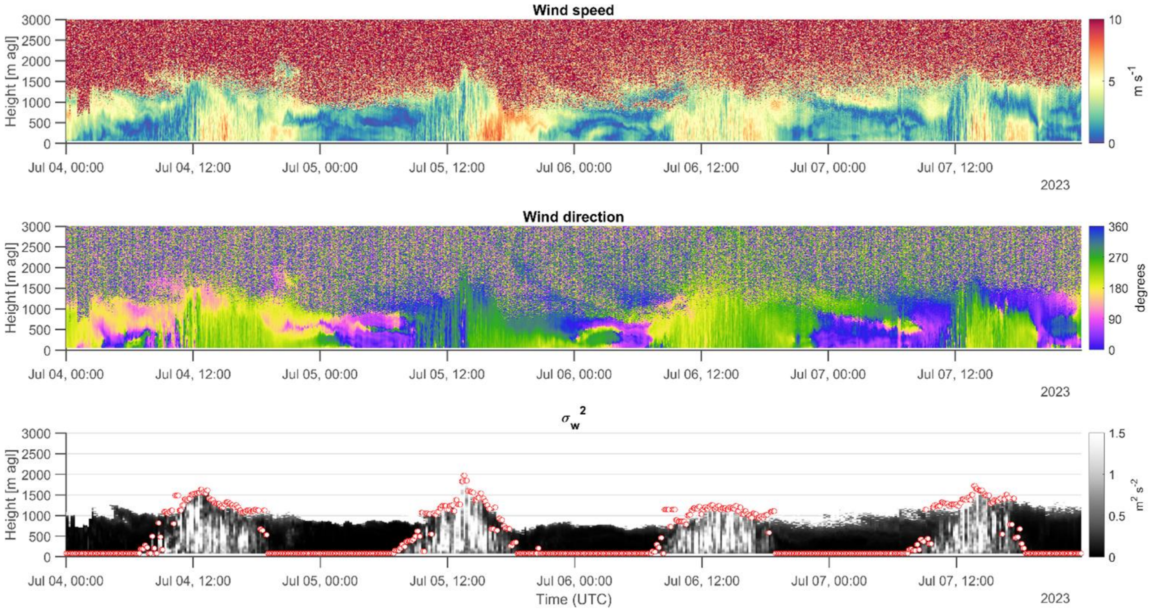

Figure 11. *Observations obtained with a Doppler wind lidar (Halo Photonics Streamline XR) in Rome-Tor Vergata from July 4 to 7, 2023: (top) horizontal wind speed, (middle) horizontal wind direction, and (bottom) variance of vertical velocity with red markers indicating the turbulence-based height of the mixing layer.*

5. RECOMMENDATIONS

With advances in compact ground-based measurement technology, profiling instruments are increasingly operated near urban areas or even in downtown settings to monitor the dynamics of the atmospheric boundary layer (ABL). Due to their relatively low maintenance and automatic operations, both Automatic Lidars and Ceilometers (ALC) and Doppler Wind Lidars (DWL) provide valuable and complementary information.

- Using ALC profile observations of range-corrected signal, automatic procedures are available to track layer heights in and above the ABL, such as the height of the mixed layer or the total height of the ABL, or the presence of elevated aerosol layers.
- Combining layer heights with profiles of horizontal wind (speed and direction) observed with DWL, provides additional insights into horizontal transport and advection processes.
- The mixing layer height (MLH) can also be traced based on DWL observations of the vertical velocity variance profile using turbulence-based methods. Not that only DWL with scanning capabilities can be used to collect information on vertical mixing processes in addition to the vertical profile of horizontal wind.

To utilise such advanced products from ABL remote sensing instruments, the measurement network should be designed carefully and instruments should be selected according to specific user needs.

5.1. Instrument operations

A large range of makes and models is currently available for both DWL and ALC with considerably different capabilities and limitations:

- To ensure **deep daytime convective layers** can be monitored effectively, it is critical to operate sensors with sufficient signal strength.
- The **monitoring of shallow layers** (< 250 m a.g.l.) at night and during winter can be of interest for air quality applications in cities. Sensors with good optical capabilities in the lowest measurement levels (good optical overlap, low blind zone) should be selected. Profiling Doppler lidars (with no scanning head) or automatic aerosol lidars should be operated from below average ground level where possible.

For scanning Doppler lidar systems, one should consider combining the standard VAD or DBS scan mode (high elevation angle from horizontal) with a shallow scan mode that can help to extend the vertical profile of horizontal wind down to within the standard blind zone.

Further details and recommendation on model capabilities and limitations are provided by Wagner et al. (2024) for ALC and by Preissler et al. (2024) for DWL (guidelines compiled by the “PROBE” European COST action).

To trace the effects of urban-induced buoyancy and potential horizontal advection mechanisms at the regional scale, multiple ALC and/or DWL can be operated simultaneously e.g. along a rural – suburban – urban transect. The prevailing wind direction under the conditions of interest should be considered carefully when selecting locations for measurement sites. For example, if pollution events predominantly occur under flow from certain wind directions, it could be beneficial to place the rural reference sensor somewhere upwind of the city along this flow.

All instrument setup and operations should strictly follow the ACTRIS guidelines.

5.2. Data processing and quality control

Both for ALC and DWL, a set of correction and harmonising steps needs to be implemented in the data processing. While certain tools are freely available and can be implemented individually, it is highly beneficial to join existing European networks (e.g. EUMETNET E-PROFILE). This ensures data quality is monitored continuously and new recommendations on instrument operations are readily accessible. The value of measurements at individual sites clearly increases through contributions to a harmonised network, as this enables also the monitoring of spatial variations in ABL dynamics.

5.3. Data management

Both ALC and DWL at ACTRIS measurement sites are processed by the ACTRIS Cloud Remote Sensing data centre (Cloudnet data portal), with clear guidelines and quality assurance. RI-URBANS is discussing with various stakeholders how DWL and ALC from urban monitoring networks could be efficiently processed to ensure data are harmonised through dedicated quality control procedures so that advanced products (such as boundary layer heights) can be obtained automatically at a large number of stations.

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