



Vertical profiling of the troposphere: Innovation, optimization and application, Part I (VITAL I)

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Abstract. Within VITAL I, a two-week data-set of novel types of Atmospheric Boundary Layer (ABL) profilers, that are being considered for the next-generation German Meteorological Service DWD observational network is made available. The data set is thoroughly tested and evaluated in the context of the WMO Rolling Requirements Review for short-term / high-resolution weather forecasting. VITAL I took place in August 2024 at the Jülich Observatory for Cloud Evolution JOYCE, which is a National Facility of the ACTRIS European Research Infrastructure Consortium. VITAL I is a core activity of the Hans Ertel Centre for Weather Research, a joint research initiative between German atmospheric research institutions and the German Meteorological Service DWD. Vertical profiling data sets of temperature, humidity and wind using multi-copter uncrewed aerial systems and the ground-based remote sensing profilers Doppler lidar, water vapor lidar and microwave radiometer were created and evaluated against radiosondes and data from a 120 m meteorological tower. Comparisons were also carried out against satellite sounders. Most tested ground-based systems are shown to fulfill the WMO RRR breakthrough requirements and are suited for capturing the diurnal cycle of the ABL. VITAL I also encompassed an international summer school that was simultaneously held at JOYCE to educate students from the Bachelor to PhD level in Modern Methods in Atmospheric Profiling. Data measured during VITAL I is available via <https://doi.org/10.5281/zenodo.22960530>, (Löhnert et al., 2026).

1 Introduction

Currently, the global observing system does not meet the requirements for high-resolution numerical weather prediction on the km-scale as given by the WMO OSCAR Rolling Requirements Review (RRR) (World Meteorological Organization, 2026a).



This is especially relevant in the Atmospheric Boundary Layer (ABL), considering temperature, humidity and wind profiling. The upcoming generation of hectometer numerical weather prediction models will presumably require even more observational details to exploit their full potential.

20 Monitoring the ABL is challenging for several reasons, resulting in an observational gap. This gap exists because state-of-the-art observations are not able to provide consistent three-dimensional data due to temporal and spatial scarcity of profiling observations, e.g. from radiosondes or commercial aircraft. Satellite sounders from polar orbiting satellites deliver profiling typically only a few times daily. This deficit has recently been addressed through the new geostationary MeteoSat Third Generation Sounder (MTG-S1) satellite carrying the IRS (Infrared Sounder) as payload (Holmlund et al., 2021), which will soon
 25 provide continuous profiles of temperature and humidity over large parts of the European and African continents every 30 min. However, even this sounding satellite will continue to struggle in accurately measuring ABL conditions due to proximity to the surface and inherent low vertical resolution. These limitations affect weather forecasting accuracy, specifically on the convective scale.

However, recent years have brought forward significant progress in profiling the ABL from the surface upwards. This
 30 progress has fed into the Hans Ertel Centre for Weather Research (HERZ) (Hans Ertel Centre for Weather Research, 2026), a cooperation on fundamental weather and climate related research between the German Meteorological Service (DWD) and German universities, see also Simmer et al. (2016). One focus of the current HERZ funding phase is novel observations resulting in the two VITAL campaigns: Vertical profiling of the troposphere: Innovation, optimization and application. With this focus, HERZ and DWD collaborate in planning and designing a future observational system for the ABL.

35 The VITAL I campaign took place in August 2024 at Jülich Observatory for Cloud Evolution (JOYCE), Löhnert et al. (2015). JOYCE is situated on a 20 m high rooftop within Forschungszentrum Jülich (FZJ) at 111 m MSL (Fig. 1). It is operated jointly by the University of Cologne and FZJ. JOYCE is a National Facility of ACTRIS, the European Infrastructure Consortium for aerosols, cloud and trace gases (Laj and Coauthors, 2024). At JOYCE new and state-of-the-art ground-based active and passive remote sensing instruments for ABL vertical profiling, clouds and precipitation are continuously operated. These
 40 include cloud radars, microwave radiometers and Doppler lidar, among others. In addition, a 124 m meteorological tower, a permanently installed Vaisala radiosonde launching system and multiple radiation observations are available, including an AERONET (Holben et al. (1998), Giles et al. (2019)) sun photometer retrieving, among others, Aerosol Optical Depth (AOD). The ACTRIS Cloudnet (Illingworth and Coauthors, 2007) algorithms are continuously applied to JOYCE, delivering a cloud classification as well as an ABL classification product.



Figure 1. JOYCE platform at Forschungszentrum Jülich during VITAL I with an array of ground-based remote sensing profilers (front) and in about 300 m distance the 124 m meteorological tower (red/white). Foto credits: Andreas Platis, University of Tübingen

45 The main VITAL I objectives were the following:

1. Resolve, assess and compare summer daytime evolution of the ABL with state-of-the-art and novel observing systems
2. Educate early career atmospheric scientists in modern observational methods in meteorology

For the first objective, we focus on temperature, humidity and wind observations from Aug. 12-23 with the best possible temporal resolution, i.e. from a few hours to minutes. These include Uncrewed Aircraft Systems (UAS), MicroWave Radiometers (MWR), ceilometer, Water Vapor Differential Absorption Lidar (WV-DIAL) and Doppler Lidar (DL), but also radiosondes, satellite sounders and instruments mounted at the 124 m meteorological tower. While the ground-based remote sensing systems



and tower instruments were measuring continuously during the whole month of August 2024, only the VITAL I period from Aug. 12-23 is considered in the analyses presented in this paper.

During the VITAL I period, UAS observations contributed to the WMO UAS Demonstration Campaign (World Meteorological Organization, 2026b), an international effort to demonstrate the current capabilities of a range of UAS and to assess their capacity to contribute to meeting operational requirements for upper-air observations.

To meet the second objective, the HErZ Summer School on Modern Methods in Atmospheric Profiling with more than 50 international participants was held from Aug. 12-23. The students were educated through key-note lectures and carrying out guided scientific projects, which included hands-on experience in performing measurements and contributing actively to the VITAL I campaign.

This paper assesses ground-based and space-based remote sensing and UAS in-situ ABL observations against the reference observations radiosonde and meteorological tower. First, a statistical analysis for the different measurement systems is presented, then a case study is discussed to show the potential to resolve the ABL diurnal evolution. The obtained results are set into context to the requirements of WMO RRR for high-resolution NWP. The RRR discriminates between "threshold", "breakthrough" and "goal" requirements. "Threshold" denotes a minimum requirement to be met to ensure that data are useful, whereas the "goal" requirement is an ideal requirement above which further improvements are not necessary. Reaching the intermediate "breakthrough" level would result in a significant improvement for high-resolution NWP. With the analyses here, we assess the fulfillment of "breakthrough" requirements regarding uncertainty, vertical, horizontal and temporal resolution within the limited VITAL I time period.

Specifically, the paper is organized as follows: First, Section 2 describes the reference observations. In Section 3, for contextualization of the observations, a concise characterization of the weather conditions during VITAL I is given. Then, the assessment of the observations is divided into a thermodynamic (Section 4) and a wind profiling (Section 5). These sections include a short description of the different instrument systems and measurement principles, followed by statistical analyses of the performed comparisons. Section 6 then analyses one day with a marked ABL development bringing together all available observations. Finally, the main results of VITAL I are summarized in Section 7.

2 Reference Observations

In the following, the radiosonde and meteorological tower observations are shortly introduced. These are used as reference observations to assess the UAS and remote sensing ABL observing systems in Sections 4, 5 and 6.

2.1 Radiosondes

During VITAL I, 44 radiosondes were launched (Fig. 2) in total. The soundings were performed using state-of-the-art Vaisala RS41 sondes (Jensen et al., 2016), which provide profiles of temperature, relative humidity as well as wind speed and direction as a function of height. The soundings typically reached heights of 16 to 20 km.



On most days with UAS flights (Fig. 2), two to three radiosondes were launched daily. On three days with an explicitly well developed ABL (15, 19, 21 August), eight to ten radiosondes were launched per day. The evolution of the ABL from stable conditions in the early morning to the well-mixed conditions in the afternoon back to stable conditions in the evening could be covered. These high-frequency radiosonde launches with about one sounding per hour are key to describe the diurnal ABL evolution and provide a reference for validating the other in-situ and remote sensing systems. For the Vaisala RS41 sondes uncertainties of relative humidity measurements are given to be less than 4 %, while uncertainties of temperature measurements are within 0.3 K below 16 km height (Jensen et al., 2016). Height-resolved horizontal wind vector observations are derived from radiosonde position tracking via the GNSS. According to the manufacturer, the uncertainty of the wind measurement (Vaisala Oyj, 2017) is 0.15 m s^{-1} for wind speed and 2° for wind direction (for wind speeds $> 3 \text{ m s}^{-1}$).

2.2 Meteorological Tower

The meteorological tower at FZJ was built in 1963 and 1964 based on the model of the towers in Brookhaven (USA) and Risoe (Denmark). Its purpose is to continuously record the current weather situation and atmospheric dispersion conditions in order to fulfill the requirements of the directive on emission and immission monitoring of nuclear facilities, which is necessary for research involving radioactive substances. It has a total height of 124 m with seven accessible platforms. It is located in the northwestern part of the FZJ with a distance of $\approx 300 \text{ m}$ to the JOYCE platform. It is surrounded by a $\approx 24 \text{ m}$ high forest. The instrumentation allows measurements of wind speed, temperature and humidity at eight heights (2 m, 10 m, 20 m, 30 m, 50 m, 80 m, 100 m and 120 m) above the ground, wind direction at three heights (30 m, 50 m and 120 m), the global and outgoing radiation at two heights (30 m and 120 m) to provide the required, local information on wind, air temperature, relative humidity, (net) radiation, and air pressure. Additionally, precipitation is registered at ground level. An overview of all tower sensors is given in Tab. 1. For details, weather and climate diagrams as well as general data access, please refer to FZJ (Forschungszentrum Jülich GmbH, 2025).

In addition, an Eddy Covariance (EC) system is mounted at the 120 m platform. It includes an open path humidity sensor (LI7500, Licor) and a combined temperature and humidity probe (HMP45C, Vaisala). The humidity probe is based on a capacitive humidity sensor (HUMICAP 180, Vaisala) and we use it here as a reference for the UAS measurements. The LI7500 has been calibrated by use of a dew point generator prior to the campaign. Measurements between these humidity probes agree well within their accuracies.



Table 1. List of sensors located at and on the meteorological tower of Forschungszentrum Jülich

Variable	Sensor	Measurement height (m)	Accuracies	Temporal resolution
Air temperature	Ventilated PT-100	2, 10, 20, 30, 50, 80, 100, 120	$\pm 0.05\text{ }^{\circ}\text{C}$ at $0\text{ }^{\circ}\text{C}$	10 min average
Humidity	Vaisala HMP45C	120	$\pm 2\%\text{RH}$ for $\text{RH} < 90\%$, $\pm 3\%\text{RH}$ for $\text{RH} > 90\%$	10 min average
Wind velocity	Cup anemometer	2, 10, 20	$\pm 1\%$	10 min
Wind velocity	Cup anemometer	30, 50, 80, 100, 120	$\pm 1\%$, $< 0.2\text{ m s}^{-1}$	10 min
Wind velocity	Cup anemometer	30, 50, 80, 100, 120	$\pm 1\%$	10 min
Wind direction	Wind vane	30, 50	$\pm 2^{\circ}$	10 min
Wind direction	Wind vane	120	$\pm 1^{\circ}$	10 min
Sunshine duration	Pyrheliometer	20	$\pm 5\%$	10 min sum
Net radiation	Pyrradiometer	30, 120	$\pm 3\%$	10 min average
Precipitation	Rain gauge	1	-	10 min sum
Air pressure	Pressure transmitter	2	$\pm 2\text{ hPa}$	10 min average

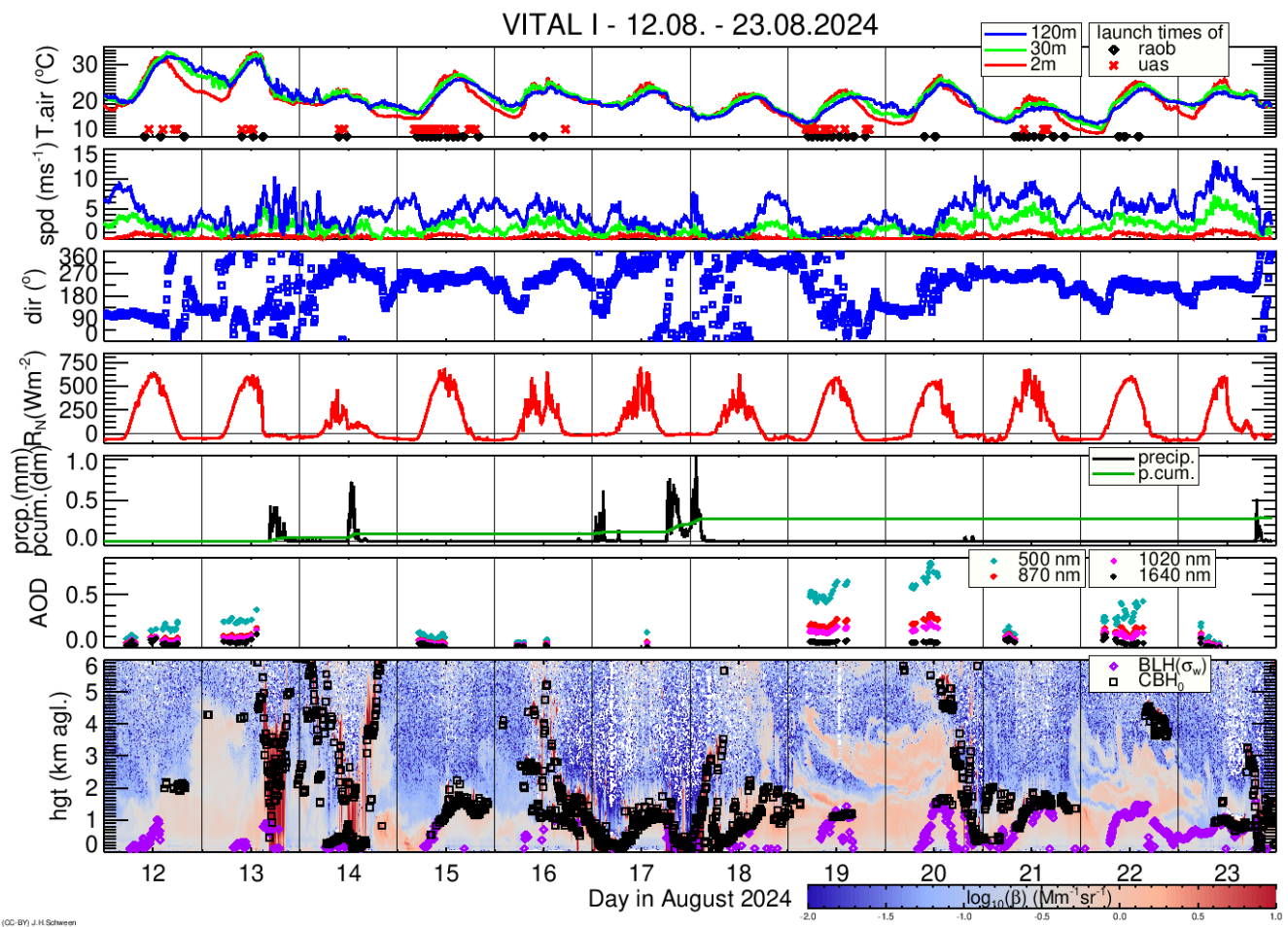


Figure 2. Overview of selected meteorological variables during VITAL I derived from the 124 m tower at Forschungszentrum Jülich and from the JOYCE platform. From top to bottom: Air temperature at 120 m (blue), 30 m (green) and 2 m (red) above ground, launch times of radiosondes (black symbols) and UAS (red crosses), wind speed at 120 m (blue), 30 m (green) and 2 m (red), wind direction at 50 m (blue), net radiation at 120 m (red), precipitation (black) and cumulative precipitation (green) at the base of the tower. Aerosol optical depth (AOD) from the Aeronet sun photometer with ID FZJ-Juelich for four different wavelengths. Attenuated backscatter coefficient β (color shading), lowest cloud base height (CBH_0) from the CHM15k ceilometer and boundary layer height ($BLH(\sigma_w)$) from vertical velocity measured by the Doppler wind lidar as described in Schween et al. (2014). All data are 10 min averages. Vertical lines mark 00 UTC of the respective day.

3 Characterization of VITAL I weather conditions

110 The meteorological conditions in August within the campaign area were warmer than average with occasional hot days and above-average hours of sunshine, although there was also above-average humidity and precipitation. The high pressure over Central Europe was frequently disturbed by depressions of low pressure systems over the North-East Atlantic. These me-



andering patterns caused the weather to alternate between warm to hot sunny days and warm, humid weather with rainfall, occasionally in convective form accompanied by thunderstorms.

115 During VITAL I from 12 until 23 Aug., the study area was characterized by relatively high air temperatures with daily maximums above 20°C (up to 33°C on 13 Aug.). During night, the air did not cool below 10°C. The average temperature was 19.9°C (16.9°C from 1961 - 1990). The condition with temperatures above 30°C at the beginning of the campaign ended on the evening of 13 Aug. with the passage of a low-pressure trough from Benelux accompanied by thunderstorms.

120 While the wind blew mostly from easterly and northerly directions under the influence of high pressure, the prevailing wind direction in the study area was south-westerly to westerly under the impact of low pressure. Wind speed was generally low, averaging 2 m s⁻¹ with maximum gusts of 9 m s⁻¹. Towards the end of the campaign, the wind increased to an average of 8 m s⁻¹ and 15 m s⁻¹ in gusts. During VITAL I, the precipitation totaled 29 mm, distributed over six days.

A meteorological overview from different in-situ and remote sensing instruments is given in Fig. 2. A well developed ABL is clearly visible in the course of August 12, 15, 19, 21 and 22 including the typical life cycle of shallow Cu clouds.

125 A noteworthy event during that period was the advent of a transcontinental plume of biomass burning aerosols on Aug. 19 and 20, originating from Canadian wildfires. These two days were characterized by a hazy, yellowish sky and aerosol optical depths ranging between 0.43 and 0.80 at 500 nm (Fig. 1, AOD panel). Ceilometer data revealed backscatter from aerosol layers in the free troposphere between 2 km and 5 km that were gone on Aug. 21 (Fig. 1, bottom panel), while aerosol optical depths decreased to around 0.15, a typical value for the site.

130 4 Thermodynamic Profiling Assessment

In the following section, the thermodynamic profiling capability (i.e. temperature and/or humidity) of state-of-the-art satellite sounders, UAS, ground-based MWR as well as WV-DIAL are jointly assessed based on VITAL I data. Following the WMO RRR for high-resolution NWP, a breakthrough would be reached if temperature Root Mean Square Error (RMSE) were 1 K with a vertical resolution of 250 m, a horizontal resolution of 2 km and were available every 60 min. For specific humidity 135 the corresponding requirements are given as 5 g kg⁻¹ RMSE with a vertical resolution of 200 m, a horizontal resolution of 5 km every 60 min. The humidity RMSE value seems to be unfitting, however, considering typical near-surface values 7-8 of g kg⁻¹ over Europe, with estimated hour-to-hour variations of 0.1-1 g kg⁻¹ and daily variations on the order of 1-3 g kg⁻¹. Thus we find a value of 0.5 g kg⁻¹ RMSE (division by a factor of 10) more suited, which is actually given also as a WMO RRR breakthrough requirement for the application area Atmospheric Climate Monitoring.

140 4.1 Satellite overpasses

The InfraRed Sounder (IRS) onboard the geostationary MTG-S1 satellite is the first instrument in a geostationary orbit over Europe to perform hyperspectral infrared measurements (Holmlund et al., 2021). It delivers an unprecedented three-dimensional view of atmospheric temperature and humidity, with a temporal resolution of 30 min and a horizontal resolution of 7-8 km over Central Europe. IRS therefore comes close to meeting the WMO breakthrough requirements for high-resolution NWP in terms



145 of temporal and horizontal resolution. In this context, it is important to assess the accuracy of satellite remote sensing in the ABL.

Up to the VITAL I time period, temperature and humidity profiles have been retrieved from hyperspectral infrared observations by Low Earth-Orbiting (LEO) satellites. E.g., EUMETSAT Datastore provides the Infrared Atmospheric Sounding Interferometer (IASI) Combined Sounding Product based on MetOp-B and MetOp-C satellite measurements.

150 Unlike the IRS, which relies solely on infrared observations, this product combines infrared and microwave measurements. IASI infrared spectra between 645 and 2760 cm^{-1} are combined with 15 channels of the Advanced Microwave Sounding Unit-A (AMSU-A, 15-90 GHz) and five channels of the Microwave Humidity Sounder (MHS, 89-190 GHz) observations (EUMETSAT, 2017). This infrared–microwave synergy improves vertical profiling accuracy in cloudy and partly cloudy environments (Hultberg and August, 2014). The product provides two profile types. The first set (the "first guess") is obtained
 155 using a statistical regression retrieval algorithm trained on ECMWF reanalysis and serves as the initial state for subsequent physical retrievals under clear-sky conditions. Details on the instruments and processing are given in EUMETSAT (2017).

MetOp-B and MetOp-C overpass JOYCE daily between 9-11 UTC and 19-21 UTC. From each overpass, the profile from the nearest field of view was selected, with a mean distance of 13 km from JOYCE. Fig. 3 shows the performance of the IASI statistical retrievals compared to the VITAL I radiosondes. The dataset consists of 35 satellite based profiles and corresponding
 160 radiosondes (19 clear sky, 16 cloudy) launched within one hour before or after the satellite overpass. For the calculation of statistics, the radiosonde profiles were interpolated to the pressure grid of the satellite retrieval. In the lowest 2 km, IASI retrievals show median temperature differences of up to 1 K. For specific humidity, the median difference shows values of down to -1 g kg^{-1} . Following downward from 5 km, the RMS (Root Mean Square) difference of temperature and humidity increases towards the surface from 1.5 to over 2 K and 1 to 2 g kg^{-1} , respectively. These errors translate into relative humidity RMS
 165 difference of roughly 10-20%. Because of its coarser spectral resolution, IRS is expected to have one degree of freedom for signal less in the troposphere than the IASI instrument (EUMETSAT, 2021). In addition, the lack of a microwave companion in geostationary orbit will make IRS retrievals more sensitive to clouds. Using IASI as a proxy therefore suggests that IRS may not meet the RRR breakthrough uncertainty requirements for temperature (1 K) nor the more strict specific humidity requirements (0.5 g kg^{-1}) in the ABL. However, the higher horizontal and temporal resolution of geostationary IRS observations would
 170 enable a fairer comparison with radiosondes than is possible with the polar-orbiting IASI.

4.2 Microwave Radiometers

Humidity And Temperature PROfilers (HATPRO) are ground-based passive microwave radiometers with all-sky scanning capabilities, manufactured by Radiometer Physics GmbH. Two MWR systems (JOYHAT of University of Cologne and HAMHAT of University of Hamburg) were installed on and around the JOYCE platform, respectively. They measure brightness tempera-
 175 tures in seven channels along the slope of the water vapor absorption line at 22 GHz and in seven channels along the slope of the oxygen absorption complex at 60 GHz, allowing retrieval of Integrated Water Vapor (IWV), cloud Liquid Water Path (LWP), as well as tropospheric temperature and coarsely resolved humidity profiles (Rose et al., 2005). These variables are available with a temporal resolution on the order of minutes (easily fulfilling the RRR goal requirements), constrained, however, to the

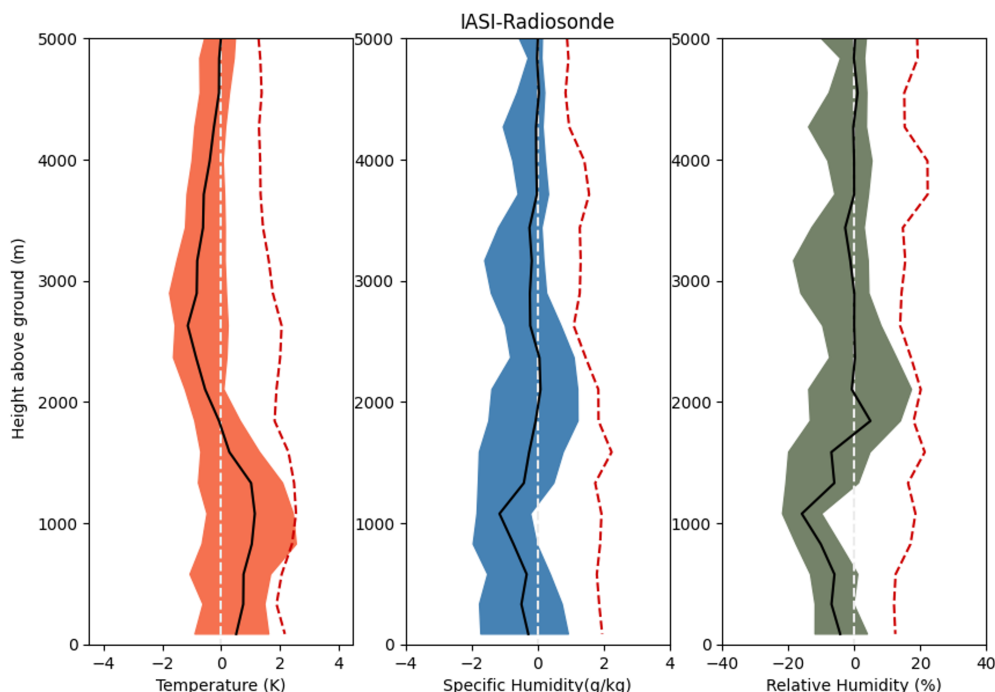


Figure 3. Profiles of median differences (black lines), RMS difference (red dashed lines), and inter-quartile range (colored shadings) of temperature (left), specific humidity (middle), and relative humidity (right) between IASI and 35 radiosondes during 12-23 August 2024.

fixed location of their measurement site, as all ground-based remote sensors. Thus, a large number of sensors would need to be installed, to meet the horizontal resolution requirements of 2-5 km.

MWRs can retrieve IWV with an accuracy similar to that derived from radiosondes while being able to continuously measure and capture the temporal evolution. To demonstrate this strength, the IWV retrieved from JOYHAT and HAMHAT (with MWRpy processing and quality control, Marke et al. (2024)) is compared with all corresponding launches during Aug. 12-23 (Fig. 4). In this analysis, nearest neighbor radiosonde values are utilized with respect to the MWR retrieval height grid, and MWR values closest to radiosonde launch times are selected. Although JOYHAT was located on the roof platform of JOYCE (19 m above ground) and HAMHAT was deployed nearby on the ground, the same retrieval setup was used for both radiometers. The VITAL I period shows highly variable humidity conditions, covering IWV values of 13-49 kg m^{-2} . For comparison, derived values from the radiosonde profiles are subtracted from IWV observations of the two MWRs. The mean absolute IWV differences of 0.86 kg m^{-2} (JOYHAT, 35 radiosondes) and 0.58 kg m^{-2} (HAMHAT, 43 radiosondes) convert into relative deviations of 3.5 % and 2.5 %, respectively. On average, both radiometers differ by 0.32 kg m^{-2} in IWV and 8.6 g m^{-2} in LWP during the VITAL I period. These differences are within the uncertainty range, which is approximately 0.5 - 1.0 kg m^{-2} for IWV and 20 - 30 g m^{-2} for LWP (Crewell and Löhnert, 2003).

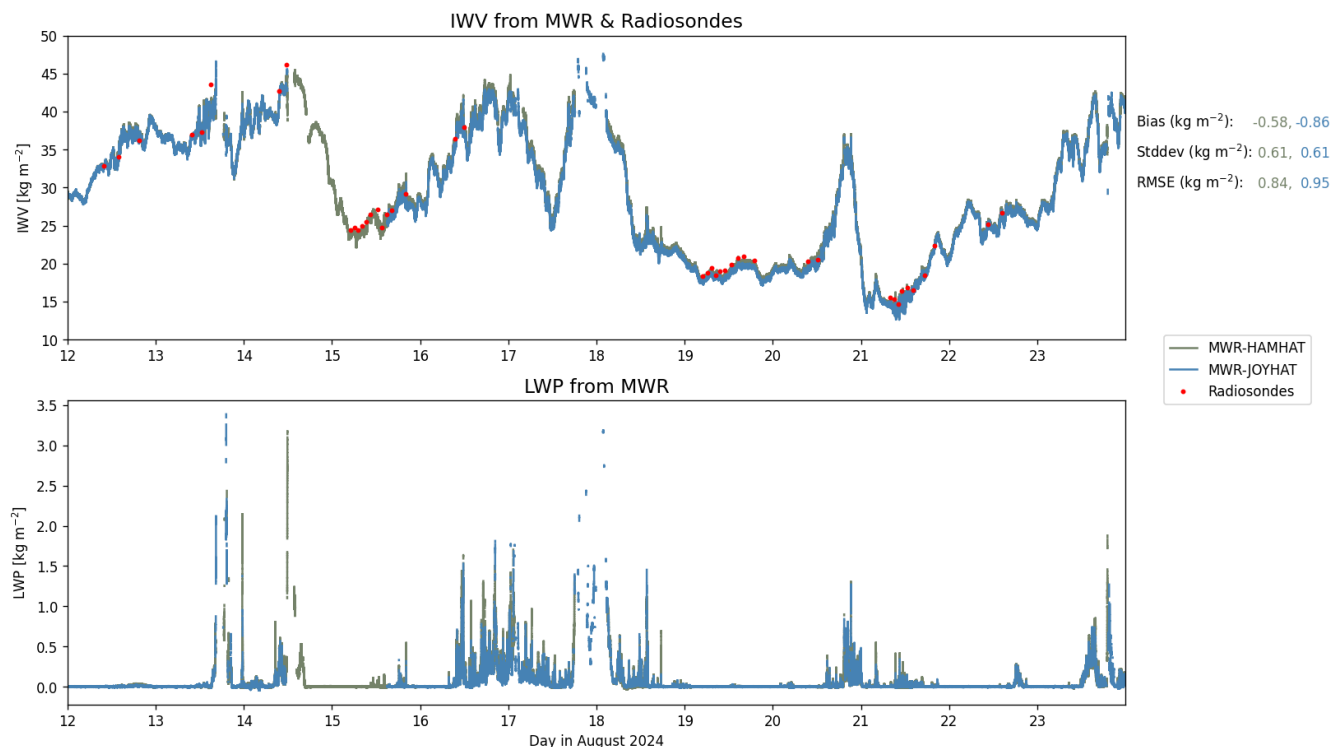


Figure 4. Timeseries of Integrated Water Vapor, IWV (top) and Liquid Water Path, LWP (bottom) retrieved from JOYHAT (blue line) and HAMHAT (green line), and IWV derived from radiosondes (red dots) during 12–23 Aug. 2024. Also shown are the IWV bias, standard deviation and RMS difference for both instruments with respect to the radiosondes (MWR – radiosondes).

In contrast, profile information on the vertical thermodynamic structure of the atmosphere is limited. The rather smooth profiles of the MWR can not represent sharp gradients or inversions. The number of degrees of freedom for signal is slightly greater than 3 in the lowest 2 km (Löhnert and Maier, 2012), resulting in a vertical resolution of a few hundred meters in the ABL. Thus, in this region, the highest median difference for retrieved temperature, specific humidity, and derived relative humidity are 0.8 K, -1.3 g kg^{-1} , and -15.3% , respectively (Fig. 5). Exploitation of angular elevation scans from the most opaque frequencies in the V-Band (51–58 GHz) is applied here and has been shown to improve the accuracy of temperature profiles in the lower atmosphere (Crewell and Löhnert, 2007). Without using these elevation scans and only relying on zenith measurements, the highest temperature bias in the lowest 2 km increases to almost 2 K (not shown). The RMS difference in temperature and specific humidity with respect to the radiosonde are on the order of 1–1.5 K, respectively 1 g kg^{-1} throughout the lowest 2 km, thus partially (i.e., in the lower 1000 m) fulfilling the WMO breakthrough requirements considering accuracy.

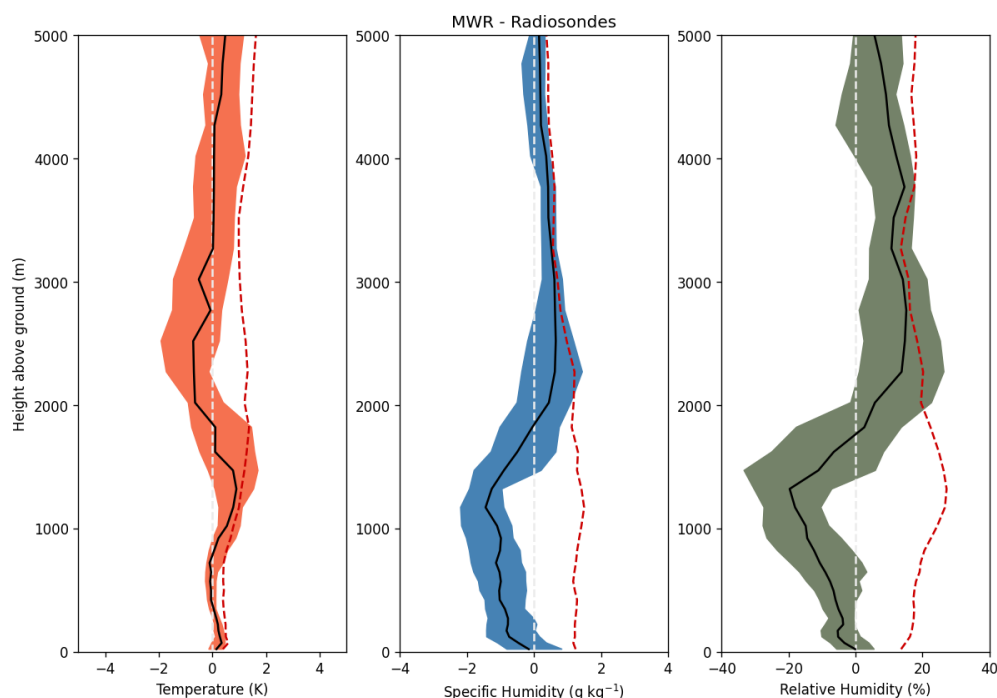


Figure 5. Height profiles of median differences (black lines), RMS difference (red dashed lines), and inter-quartile range (colored shadings) of temperature (left; from elevation scan observations), specific humidity (middle; zenith only), and relative humidity (right; derived from elevation scan temperature profiles and zenith humidity profiles) between JOYHAT (closest profile to launch time) and 35 radiosondes during 12 - 23 August 2024.

4.3 Water Vapor DIAL

The Water Vapor Differential Absorption Lidar (WV-DIAL) provides continuous and unattended real-time water vapor profiles within the ABL, as well as profiles of attenuated backscatter throughout the troposphere. The instrument (provided Karlsruhe Institute of Technology (KIT)) deployed during VITAL I is a commercially available Vaisala DA10 system (Vaisala, 2024; Newsom et al., 2020). The lidar simultaneously transmits and receives aerosol-backscattered radiation in two near-infrared bands with different water vapor absorption characteristics. The Lidar principle allows to assign the received backscattered light to a range or distance. The differential absorption in the two bands can directly be related to the along-sight water vapor distribution. The system contains two separate measurement units, with telescopes for far-range and near-range, corresponding to heights of above, respectively below 500 m above the instrument. Merging of both units allows water vapor profiling through the entire boundary-layer up to maximum height of ≈ 4 km, depending on the availability of aerosol as backscatterer. The instrument also provides cloud base heights and a fog detection flag. Water vapor profiles are generated every minute based on the data collected during the previous 20 min and every 9.6 m in the vertical. Thus, concerning vertical resolution and temporal cycling, the WV-DIAL fulfills the WMO breakthrough requirements.

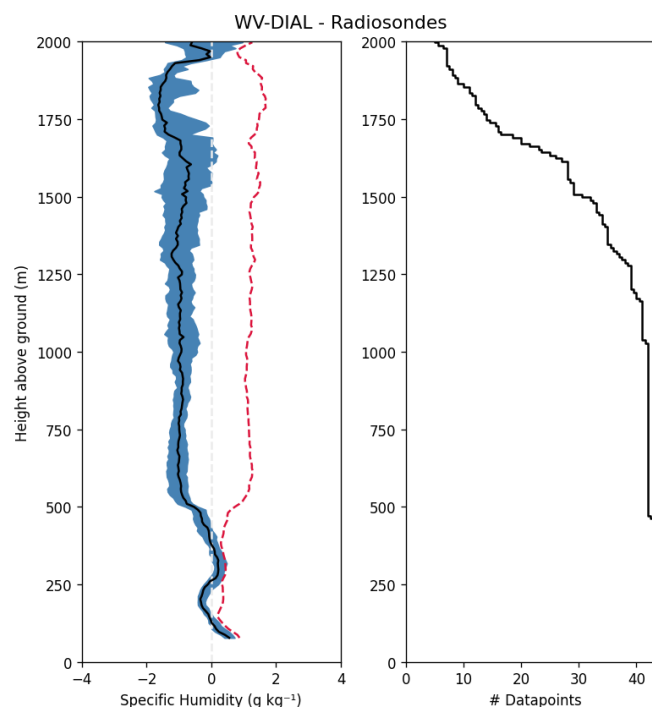


Figure 6. Height profiles of the median (black line), interquartile range (blue shading) and RMS difference (dashed red line) of the difference in specific humidity between WV-DIAL and 44 radiosondes during VITAL I (left). In addition the number of available measurements per DIAL height level is shown (right).

In Fig. 6 the WV-DIAL (system of Karlsruhe Institute of Technology, KIT) measurements are compared to the 44 radiosonde launches in terms of the median and inter-quartile range of the difference in specific humidity. For comparison, each height level in the WV-DIAL profile temporally closest to radiosonde launch time is compared to the vertically closest sonde measurement within the instrument's reliable height range (determined internally through the Vaisala software). WV-DIAL availability decreases above 1000 m due to decreasing presence of aerosol backscatter. An increase in the median difference to -1 g kg^{-1} can be seen above 500 m, which corresponds to the transition region between near and far field, otherwise the median difference is on the order of $\pm 0.5 \text{ g kg}^{-1}$ in the lowest 500 m above the instrument. In this region the RMS difference is also around -0.5 g kg^{-1} increasing to about 1.5 g kg^{-1} above 500 m. The strict breakthrough criterion of 0.5 g kg^{-1} is thus fulfilled in the lowest 500 m, whereby a simple bias correction would suffice to also fulfill this criterion at least up to 1500 m.

225 4.4 UAS - Uncrewed Aircraft Systems

Due to their mobility, UAS constitute a valuable platform for atmospheric profiling. Their typical flight range includes the ABL and lower troposphere. UAS can perform in-situ measurements with multiple sensors at precisely the region of interest, along horizontal or vertical lines, arbitrary flight patterns or simply by hovering permanently at a fixed location. Unlike remote



Figure 7. Multicopter “Flik” (left, DJI Mavic 3 Enterprise) and “Hopper” (right, DJI Matrice 300 RTK) with custom PARASITE payloads, both operated by the University of Tübingen. Foto credits: left: Lenu Piasecki, University of Cologne, right: Andreas Platis, University of Tübingen

sensing approaches, in-situ measurement accuracy is mostly independent of the probed location, rendering UAS also an ideal
 230 validation measure for other atmospheric profiling methods.

During VITAL I, two UAS of type multicopter were operated by the University of Tübingen. The two UAS – henceforth referred to as “Flik” and “Hopper” – are based on the DJI Mavic 3 Enterprise and the DJI Matrice 300 RTK model (Fig. 7), with dimensions measuring 350 mm × 290 mm and 810 mm × 670 mm, a total take-off weight of 1 kg and 8 kg, and flight endurance of about 25 min and 35 min, respectively. During the intensively probed days with pronounced ABL diurnal development,
 235 UAS were launched roughly every 30 min (one ascent took around 20 min), thus were shown to be able to fulfill the RRR breakthrough requirements with respect to temporal resolution. Due to air space restrictions, the UAS were used to profile the lower atmosphere up to 1850 m above ground level.

Each UAS has a custom meteorological sensor package with data processing unit attached, codenamed the **P**ortable **A**ircraft **R**ucksack for **A**tmospheric **S**ensing and **I**n-situ **T**urbulence **E**stimation (PARASITE). The three-dimensional wind vector is
 240 derived without a dedicated sensor from various meteorological and aircraft data such as attitude, rotor frequencies, ground speed velocity and air density based on a method improving the work of Bramati et al. (2024) with machine learning.

The smaller UAS “Flik” was part of the WMO Global UAS Demonstration Campaign. It measures temperature with a custom NTC-thermistor, and relative humidity with a capacitive iST HYT.R.411 sensor. During the course of VITAL I, approximately 100 vertical profile measurements were conducted to contribute to the WMO campaign. An essential requirement of the WMO
 245 is the system’s capability to transfer a processed data product (BUFR format, Binary Universal Form for the Representation of Meteorological Data) to a server in a matter of minutes after flight. With the PARASITE system’s immediate data upload this workflow could be demonstrated successfully.

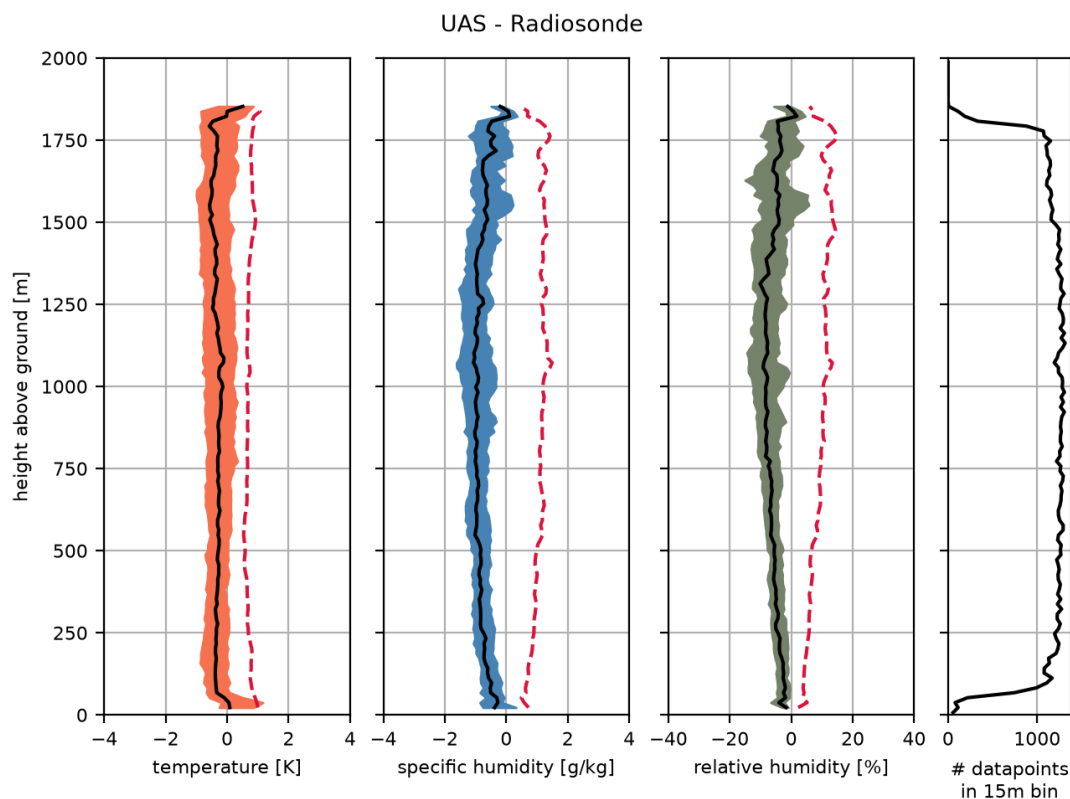


Figure 8. Vertical profiles of median differences (black line), inter-quartile-range (shaded area), and RMS difference (red dashed line) of temperature, specific humidity (derived), and relative humidity between 53 “Flik” UAS and radiosonde ascend pairs.

To optimize temperature and relative humidity measurements, offsets derived from flights near the Jülich tower were subtracted from raw “Flik” UAS measurements: 2.1 K against the ventilated PT-100 for temperature and +9.2 % against the Vaisala HMP45C for relative humidity (Tab. 1). The UAS’s capacitive humidity sensor underestimates nonlinearly at high humidities, but tower comparison data above 90 % RH were sparse, so this could not be fully quantified. As a result, even with the aforementioned RH offset correction, UAS humidity measurements can be expected to underestimate high humidity levels. With this bias correction, the uncertainties derived for temperature and humidity profiling of UAS compared to radiosondes are shown in Fig. 8. Only profiles are taken into account that are at most 60 min apart, each averaged in bins of 15 m height. UAS measurement frequency was 10 Hz during flight, compared to the radiosonde measurement frequency of 1 Hz during ascent. The UAS tends to measure slightly lower temperatures (-0.3 K) than the radiosonde with RMS difference values below 1 K and a median of 0.68 K, which is in line with WMO OSCAR breakthrough requirements of uncertainty for high-resolution NWP in the ABL. An explanation for the lower UAS temperature measurement could be that radiosondes can be expected to follow the convergence in the lower boundary layer towards convective plumes which are slightly warmer than their surroundings, while the UAS followed an independent, strictly vertical flight path. UAS relative humidity measurements show a height-averaged



underestimation of around 10 %, which is broadly distributed at heights around 1000 m, roughly coinciding with the height of the ABL during VITAL I (Fig. 2). Generally, the highest relative humidity values were measured at the top of the ABL, below the inversion, reaching values as high as 100 % as reported by the radiosondes. As explained above, the UAS humidity sensor underestimates these high relative humidity levels, which is not corrected by the performed offset subtraction. Resulting
 265 RMS difference values of specific humidity are around 0.5 to 1.5 g kg⁻¹ with a height-averaged value of 1.1 g kg⁻¹ thus only partially fulfilling the strict breakthrough requirements of uncertainty for high-resolution NWP in the ABL. A thorough, non-linear relative humidity correction with longer tower comparison time series including high humidity levels can be expected to remove these remaining biases.

5 Wind Profiling Assessment

270 Following the WMO RRR for high-resolution NWP, a breakthrough would be reached for ABL horizontal wind observations if the uncertainty of the horizontal wind vector were 2 m s⁻¹ with a vertical resolution of 200 m every 60 min and a horizontal resolution of 2 km. Here, the horizontal wind vector difference with respect to the radiosonde (RS) is calculated as

$$\|\delta \mathbf{v}_h\| = \|\mathbf{v}_i - \mathbf{v}_{RS}\| = \sqrt{(u_i - u_{RS})^2 + (v_i - v_{RS})^2} \quad (1)$$

with wind vector components u_{RS} and v_{RS} from the radiosonde and u_i and v_i from DL and UAS, respectively. This quantity
 275 will always be equal or larger than zero. The difference vector can be split into its components $\delta v_{\parallel}$ along and $\delta v_{\perp}$ perpendicular to the windvector. For small differences the latter is in good approximation proportional to the difference angle $\delta\phi$ of the wind direction and accordingly it is $\|\delta \mathbf{v}\| \simeq \sqrt{\delta v_h^2 + \pi/180^\circ \overline{v_h} \delta\phi^2}$ with v_h and δv_h the horizontal wind speed and its difference to the radiosonde reference, respectively.

Our main goal is to assess the performance of multi-copter UAS wind profiling as a novel measurement system. In the
 280 last years, Doppler Lidars (DL) have been shown to perform very accurately in the ABL (Mariani et al., 2020; Dai et al., 2020; Boverter et al., 2024; Morrison et al., 2025; Zhang et al., 2025). In the following, both systems are compared against radiosondes and against each other. An assessment of UAS against continuous DL measurements has the advantage, that a temporally matching DL wind profile is available for each UAS ascent.

The three-dimensional wind vector is derived from PARASITE UAS ascents in a two-step process: First, a rough physical
 285 estimate of the 3D wind vector is calculated from UAS attitude and rotor speeds, loosely based on Bramati et al. (2024). In the second step, a machine-learning model trained on calibration flight patterns during calm wind conditions adjusts the initial estimate to improve accuracy. The effects of density on UAS lift and drag are accounted for in the process. DL typically transmit laser pulses in the near infrared and use the backscattered radiation from aerosols for wind profiling. Via the Doppler effect, a frequency analysis of the received backscattered laser light allows derivation of the radial speed of the aerosols and
 290 accordingly the radial wind speed. Like the WV-DIAL, DL rely on air with sufficient aerosol content which is in most cases given in the ABL. To derive the horizontal wind speed a combination of beams in different azimuth directions is required (Päschke et al., 2015). During VITAL I a WLS200s DL (Vaisala) provided by Karlsruhe Institute of Technology (KIT) was

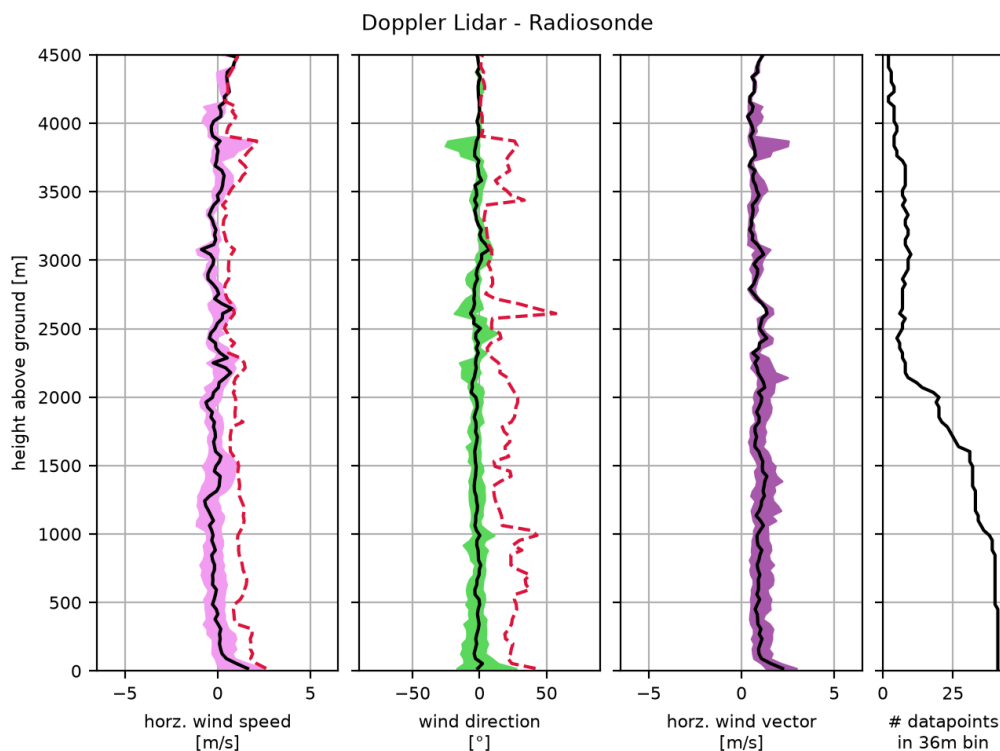


Figure 9. Doppler Lidar minus radiosonde, columns from left to right: Height profiles of the median difference (black line), RMS difference (red dashed line) and inter-quartile ranges (color shaded) of horizontal wind speed and wind direction. Also shown are median and inter-quartile range of horizontal wind vector differences (Eq. 1) and the number of data points available for the comparison between DL and 41 suited radiosondes.

used. Range resolution was set to 50 m, maximum range to 7050 m. Velocity resolution was 16 cm s^{-1} with a maximum unambiguous Doppler velocity of 36 m s^{-1} . The instrument was set up to perform a six-beam scan as described in Sathe et al. (2015) with measurements at azimuth angles of $\phi = 0^\circ, 72^\circ, \dots, 288^\circ$ at an elevation angle of $\theta = 45^\circ$ and a subsequent measurement in the vertical direction. The scan was performed once every minute.

5.1 Doppler Lidar vs. Radiosonde

First, wind profiles from the scans of the DL with those from radiosonde profiles are compared. For every radiosonde measurement below 5000 m above ground, the closest (in time) DL profile is used. The derived DL wind vector components are interpolated to the height of the balloon, which carries the radiosonde, as the balloon is the probing device for the wind. Then, horizontal wind vector differences are determined (Eq. 1), as well as differences in wind speed and direction. For horizontal wind speed and direction median differences, inter-quartile-ranges and RMS differences are calculated, as well median and inter-quartile range of the wind vector differences (Fig. 9).



The median difference in wind speed is typically lower than 1 m s^{-1} with low inter-quartile ranges ($1 - 2 \text{ m s}^{-1}$). The offset in the lowest 150 m is attributed to the incomplete Lidar overlap in the near field. The wind direction retrieval is basically without a systematic offset and shows very low RMS differences, specifically at the upper end of the maximum detection range (4 - 5 km) both pointing to a sufficient accuracy even under low backscatter conditions. The six beam scans used allow for a wind vector retrieval even if not all beams provide Doppler speeds (at least three beam directions are needed). The low uncertainties, with respect to the radiosonde wind speed and direction also point to less turbulent conditions in the free troposphere enabling a more accurate wind vector retrieval, despite the fact that the radiosonde is then typically already at a horizontal distance of few km from the DL. One can see, however, that the number of available data points strongly decreases above 2 km due to missing sufficient aerosol backscatter. The horizontal wind vector difference (Eq. 1) is less than 2 m s^{-1} throughout the shown measurement range. Thus, based on VITAL I and using the radiosonde as reference, DL clearly fulfills the RRR breakthrough requirements for wind profiling considering uncertainty, vertical and temporal resolution.

5.2 UAS vs. Radiosonde

In a next step, the wind vector assessment of UAS ascents is carried out to those matching to the radiosonde profiles. As for the temperature and humidity comparisons, all matching UAS data are collected in bins of 15 m height, at maximum 60 min from the radiosonde launch time and up to the maximum UAS flight height of 1800 m.

Above 100 m up to the maximum measurement height of 1850 m, the UAS horizontal wind vector derivation is well in line with the radiosonde measurement concerning wind speed (Fig. 10) with RMS differences around 1.5 m s^{-1} above 100 m. In the lowest 100 m, the UAS measures wind speeds around 2 m s^{-1} , higher than the radiosonde on average. These high deviations can be partially explained by strong turbulence in the convective ABL, leading to different sampling of stronger turbulent eddies. On the 19 August 2024, the overall wind speed was very low (mostly below 2 m s^{-1} to 1500 m, see Figure 2 and Figure 15), except for a narrow band of high wind speed at around 1000 m height. This explains the rather high deviations within the lowest 1000 m, where RMS differences in wind direction are up to 50° , and the wind vector difference has a median of 1.7 m s^{-1} . These values are significantly reduced, if Aug. 19 is excluded from the analysis (not shown), pointing to the challenge of accurate wind direction retrieval on days with overall low wind speeds and turbulence dominating the wind vector. Thus, UAS also fulfill the RRR breakthrough requirements for wind profiling considering uncertainty and vertical resolution. If they are launched regularly, the requirement for temporal resolution (every 30 min) can be reached additionally.

5.3 UAS vs. Doppler Lidar

Finally, the differences between UAS and DL derived horizontal winds are assessed (Fig. 11). At heights between 200 m and 1600 m the UAS and DL horizontal wind speed are practically unbiased, with a median difference of 0.2 m s^{-1} . RMS differences are rather constant with height with median of 1.1 m s^{-1} . The inter-quartile-ranges show that the UAS has a tendency to intermittently measure slightly higher wind speeds than the DL, which can be explained by its higher measurement frequency and greater sensitivity to gusts. Additionally, the DL has to perform scans to provide the information necessary to retrieve the wind vector. That means it averages over a certain volume and averages out gusts. Overall, UAS and DL wind

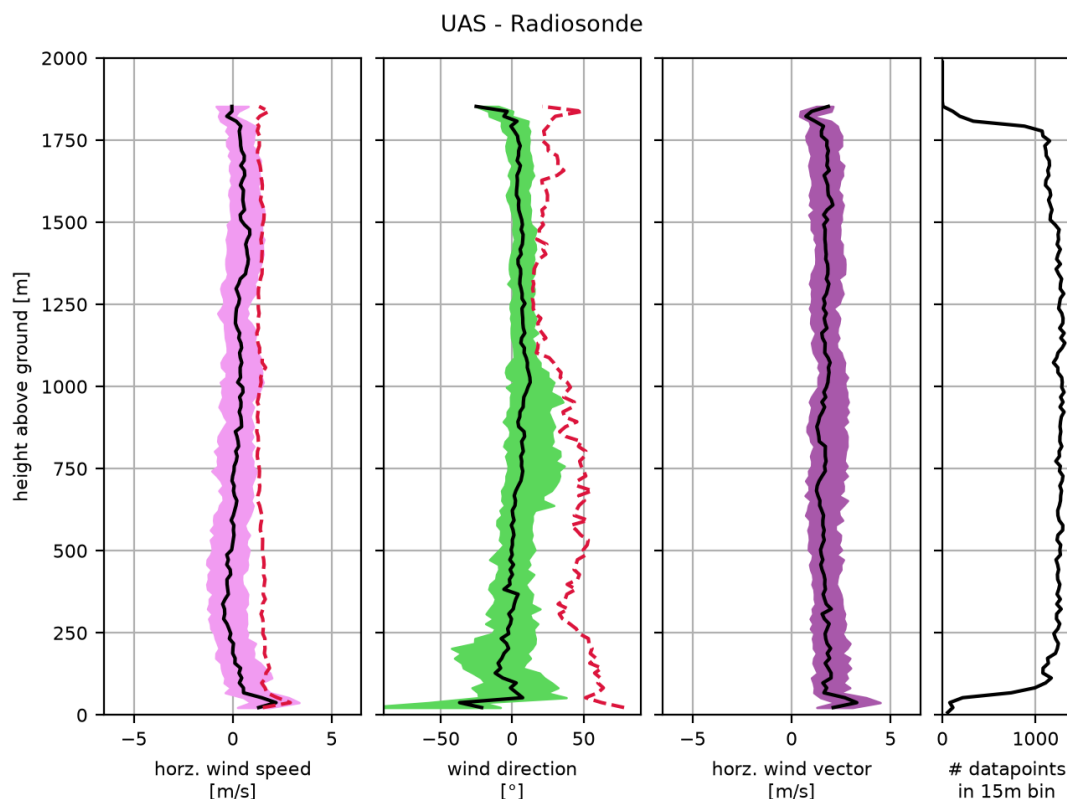


Figure 10. “Flik” UAS minus radiosonde, columns from left to right: Height profiles of the median difference (black line), RMS difference (red dashed line) and inter-quartile ranges (color shaded) of horizontal wind speed and wind direction. Also shown are median and inter-quartile range of horizontal wind vector differences (Eq. 1) and the number of data points available for the comparison between DL and 53 suited UAS ascents. UAS measurement frequency was 10 Hz during flight, radiosonde measurement frequency was 1 Hz during ascent.

measurements agree very well in the ABL. The median of the vector differences is 1.4 m s^{-1} with an inter-quartile range around 1 m s^{-1} , thus showing a similar accuracy of both wind profiling approaches. The higher uncertainties in lowest 100 m is attributed to near-surface turbulence sampling as well as incomplete lidar overlap in the near field of the telescope. In addition to radisondes, UAS and DL both have the capability of deriving vertical wind speeds. As can be drawn from Figure 11, both agree to a median difference less than 0.1 m s^{-1} . This is different to the findings of Dai et al. (2020) who observed no correlation between vertical wind speeds from a scanning DL and in-situ measurements on a tower 20 m away.

6 Case study: Combined analysis

In addition to the statistical uncertainty analysis provided in the prior sections, this section presents a comparative analysis of the diurnal cycle on Aug. 19, 2024. Central Europe was under influence of a strong low pressure system over the North

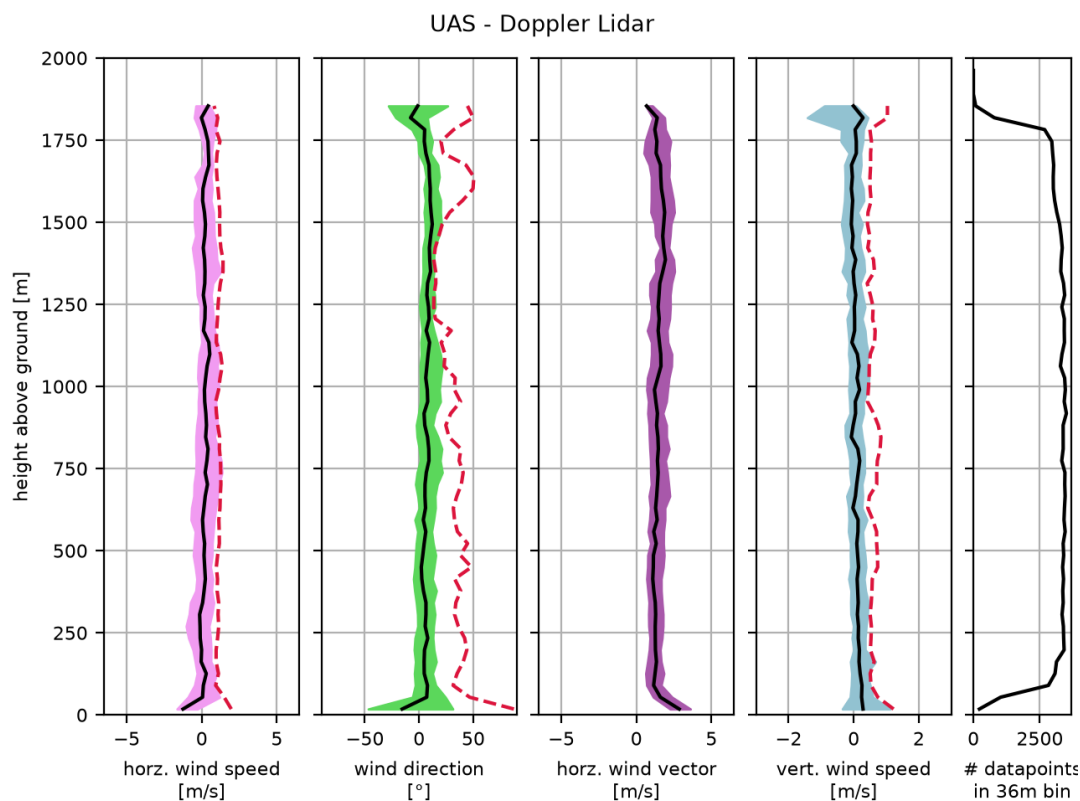


Figure 11. “Flik” UAS minus Doppler lidar, columns from left to right: Height profiles of the median difference (black line), RMS difference (red dashed line) and inter-quartile ranges (color shaded) of horizontal wind speed, wind direction. Also shown are median and inter-quartile range of horizontal wind vector differences (Eq. 1), median difference and inter-quartile range and RMS difference of vertical velocity and the number of data points available for the comparison between DL and suited UAS ascents. UAS measurement frequency was 10 Hz during flight, DL profiles are available every minute.

Atlantic and a high-level low pressure region over Italy. In between a weak high-pressure bridge evolved, ranging from France over central Germany to the Baltic states. Thus, a largely surface-driven ABL evolved, involving scattered Cu clouds with base heights up to 1500 m. Weak near-surface winds turned from initially north-westerly to easterly directions during the day.

Ten radiosondes were launched during the course of the day, starting at 5 and ending at 19 UTC (corresponding to 7 and 21 LT, respectively). The development of the ABL on this day is well depicted by the profiles of potential temperature (θ) and water vapor mixing ratio (m). The first sonde was launched at 04:59 UTC when stable nighttime conditions were still present (astronomical sunrise was at 04:28 UTC). θ and m profiles show a typical, almost text-book-like evolution of a convective ABL under weak synoptic influence (Fig. 12, left panel). The first sonde shows a θ increase of 5 K in the lowest 200 m, indicating a night time inversion, which dissolves in the following hours from the surface through radiative heating, leading to a well mixed ABL up to 900 m in the 08:21 UTC sonde. From that point onwards, the well-mixed ABL warms (up to θ values of

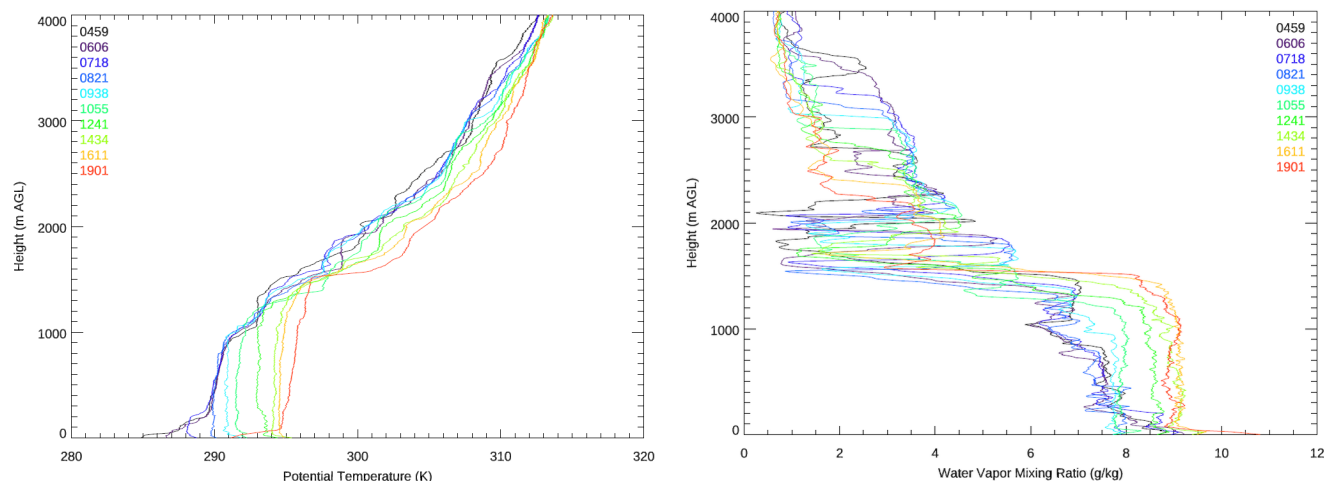


Figure 12. Profiles (referred to height above ground) of potential temperature (left) and water vapor mixing ratio (right) of the lower troposphere from 19 August 2024 from radiosondes. Colors refer to different launch times (in UTC) provided in the figure.

295 K) and extends vertically (up to 1500 m) until the 16:11 UTC sonde. The sonde at 19:01 UTC already shows the onset of a strong, radiatively driven night-time inversion. A warming of the free troposphere is also observed over the day, indicating the increased influence of the high-pressure bridge and thus presumably large-scale subsidence.

Corresponding behavior can be seen in the evolution of the m profile (Fig. 12, right panel). In the first three hours humidity is largely unchanged in the lowest kilometer. Then from the 08:21 UTC sonde on, the moment when the θ profile indicates a well mixed ABL up to 900 m, m is distributed more or less equally in the same vertical range. The humidity excess of the first three hours in the lowest hundreds of meters is reduced, whereas the humidity deficit from 400 to 900 m is also reduced. During the following hours of the day, until the sonde at 14:34 UTC, m is enhanced through evapotranspiration (latent heat flux) and well-mixed up to heights corresponding to the θ increase at the top of the mixed layer. The humidity enhancement in the ABL is accompanied by a drying in the free troposphere, thus leading to a fairly constant IWV value over the course of the day (Fig. 4).

The radiosonde timeseries analysis shows the importance of temporally highly resolved thermodynamic profiling. Minutes can decide on whether clouds or even precipitation can form. However, typical radiosonde stations only measure profiles once-a-day, discarding completely the diurnal evolution. In the following, the different profiling methods presented in the sections above are assessed for their potential of capturing the ABL diurnal cycle on Aug. 12, 2024.

We compare temperature, humidity, wind speed and direction to the radiosonde profiles at four height levels above the surface (100 m, 500 m, 1000 m and 1500 m). At 100 and 500 m heights, the evolution of the diurnal temperature spanning an amplitude of 7, respectively 6 K is nicely reproduced by MWR profiling (Fig. 13), compared to both the tower and radiosonde observations. At 1500 m from 9 UTC to 20 UTC, UAS temperature is positively offset by about 1 - 2 K (Fig. 8) compared to the radiosonde, both however, showing fairly constant values and thus not reflecting a diurnal cycle as seen in lower levels. This



Table 2. WMO RRR fulfillment of breakthrough requirements for VITAL I ABL profiling with reference to the radiosonde launches. Evaluated are values for uncertainty, vertical resolution and measurement cycle (temporal). See text for discussion.

	T uncert.	T vert. res.	T cycle	q uncert.	q vert. res.	q cycle	v uncert.	v vert. res.	v cycle
UAS	yes	yes	yes	possible	yes	yes	yes	yes	yes
MWR	partially	partially	yes	no	no	yes	-	-	-
WV-DIAL	-	-	-	possible	yes	yes	-	-	-
DL	-	-	-	-	-	-	yes	yes	yes
IASI (sat.)	no	no	no	no	no	no	-	-	-

feature of constant temperature at 1500 m is also visible in Fig. 12, marking the upper level of the well mixed layer and the transition to the free troposphere. Compared to UAS and radiosonde, the MWR temperature retrieval at 1500 m clearly shows a gradual temperature increase of 3.5 K in this time window, marking the limited vertical resolution of the MWR already at this level. It is difficult to extract a diurnal temperature profile evolution from the five IASI temperature points at each height
 380 level. It seems that some points match the radiosonde by chance, others not.

For humidity the situation is as follows (see Fig. 14). In the lowest three levels, the WV-DIAL nicely reproduces the general evolution of the radiosonde humidity, except for an offset of -0.5 - 1 g kg^{-1} above 500 m, indicated also in Fig. 6. At 1500 m the humidity is highly variable during the course of the day, which the WV-DIAL can only partially reproduce, possibly due to decreasing aerosol concentration and a general loss of SNR at higher levels. However, the general trend is reproduced,
 385 especially the drying after 19 UTC. While the MWR delivers a high-accuracy IWV (Fig. 4), the vertical resolution for water vapor is low, so that it can only cover the gradual humidity increase in the ABL over the course of the day. UAS profiling, in spite of the small positive bias (Fig. 8), best captures the diurnal ABL humidity evolution and its strong variability compared to the radiosonde, e.g. at the end of the day at 1500 m height. For IASI, again as in the temperature case, it is difficult to extract a diurnal humidity profile evolution, underlining the limitations for ABL profiling by means of satellite.

390 The diurnal cycle of wind speed (Fig. 15) and direction (Fig. 16) is mostly consistently captured with radiosonde, UAS and DL. While UAS matches the other two sensors nicely at 1000 and 1500 m height, a rather large relative scatter between UAS and radiosonde, respectively DL can be observed at lower heights. Here, all sensors display low winds speeds around 1 - 3 m/s during day time. The low winds speeds and the highly variable wind direction at 100 and 500 m are associated with the turbulence created through surface-induced friction and the match is good as to be expected. A significant increase in wind
 395 speed in the afternoon, first visible around 14 UTC at 1500 m (here from 2 to 9 m s^{-1}) and then later also at the lower heights, is captured by all sensors.

7 Summary and Outlook

While ground-based in-situ, respectively remote sensing ABL profiling cannot fulfill the WMO requirements for short-term / high-resolution weather forecasting concerning horizontal coverage, they do provide high potential for fulfilling the require-

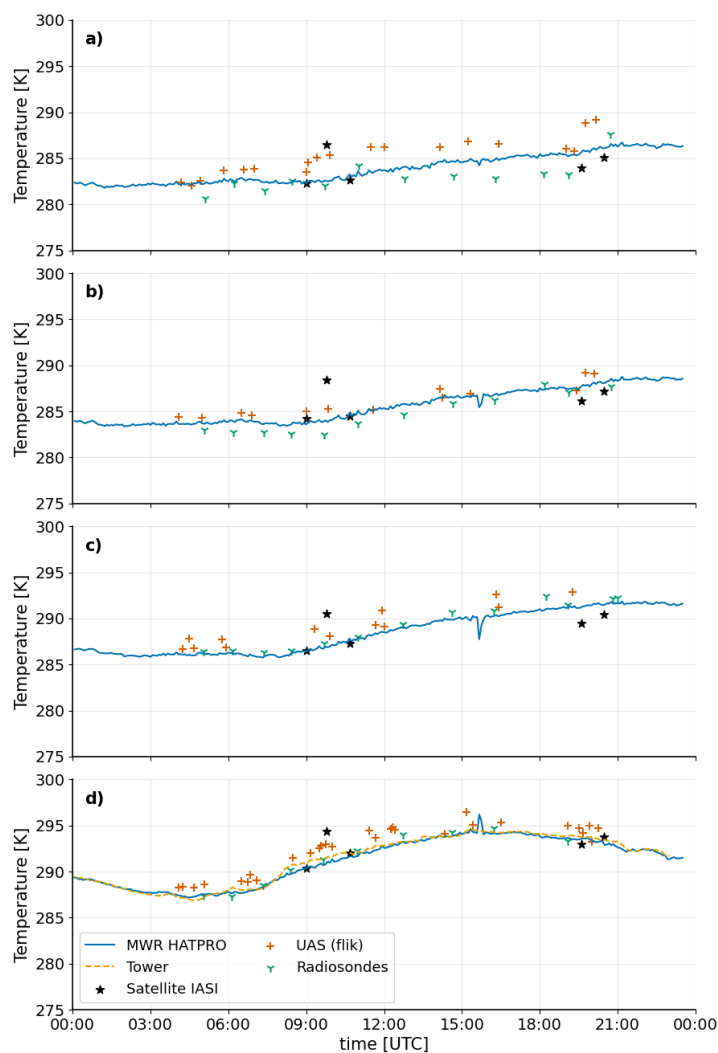


Figure 13. Time series of temperature at 1500 (a) 1000 (b), 500 (c), 100 m (d) above the surface at JOYCE on August 19, 2024. Shown are observations from Jülich tower (100 m), UAS, radiosondes, ground-based MWR and IASI (satellite sensor). Temperature is given on a 5 min temporal and 20 m vertical grid. Radiosonde, MWR and IASI observations are assigned to the nearest neighbor grid-point. UAS data are averaged to the spatial-temporal grid. The alternating number of available UAS observations from level to level is due to different flight patterns, i.e. constant height hovering vs. vertical profiling.

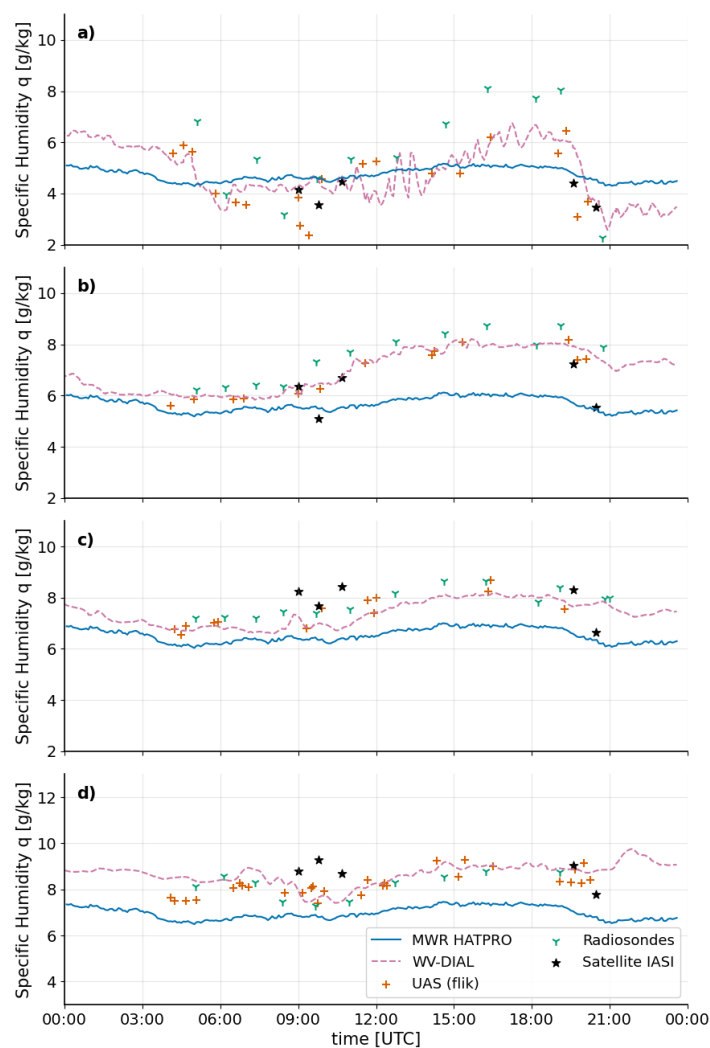


Figure 14. Time series of specific humidity at 1500 (a) 1000 (b), 500 (c), 100 m (d) above the surface at JOYCE on August 19, 2024. Specific humidity is given on a 5 min temporal and 20 m vertical grid. Radiosonde, MWR, WV-DIAL and IASI observations are assigned to the nearest neighbor grid-point. UAS data are averaged to the spatial-temporal grid. The alternating number of available UAS observations from level to level is due to different flight patterns, i.e. constant height hovering vs. vertical profiling.

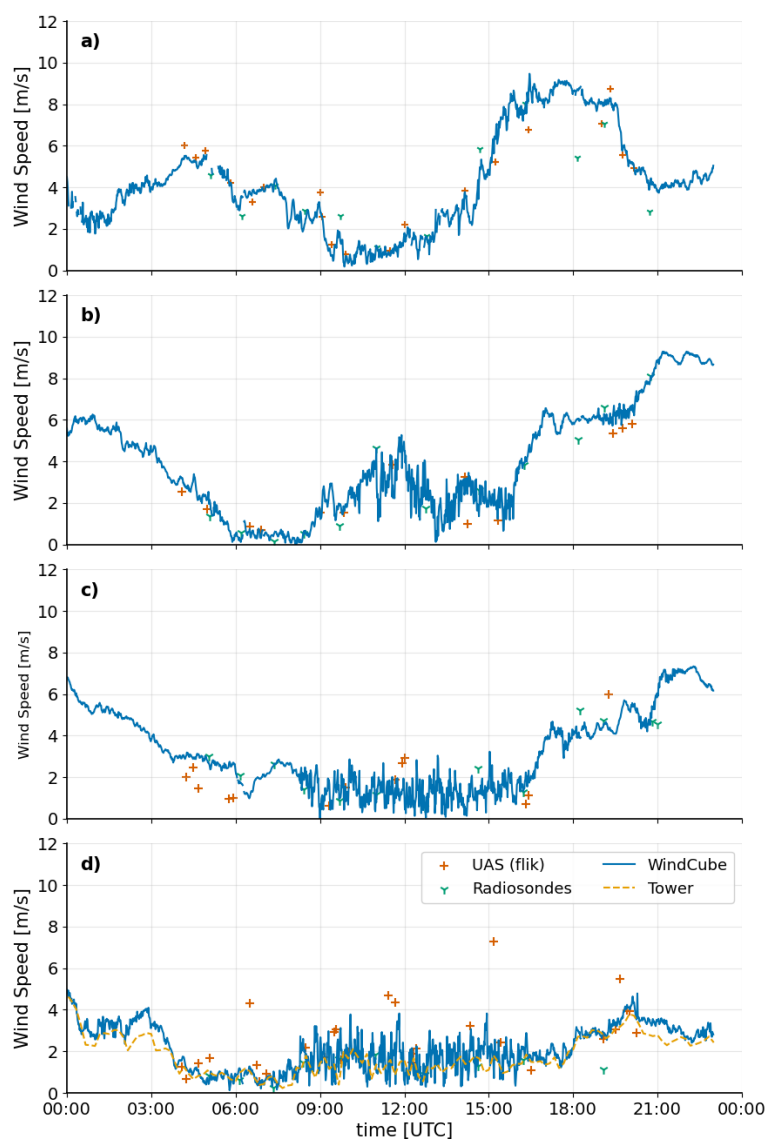


Figure 15. Time series of wind speed at at 1500 (a) 1000 (b), 500 (c), 100 m (d) above the surface at JOYCE on August 19, 2024. Jülich tower (100), radiosonde and DL (WindCube) observations are assigned to the nearest neighbor grid-point. UAS data are averaged to the spatial-temporal grid. The alternating number of available UAS observations from level to level is due to different flight patterns, i.e. constant height hovering vs. vertical profiling.

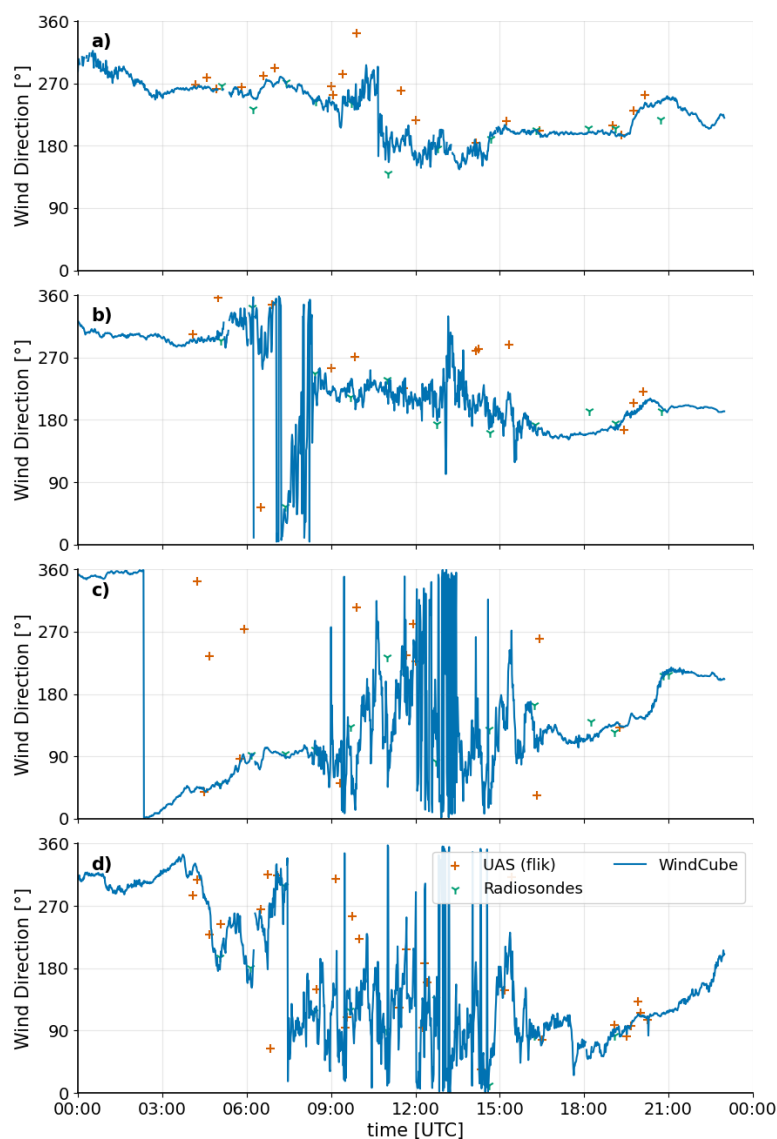


Figure 16. Time series of wind direction at at 1500 (a) 1000 (b), 500 (c), 100 m (d) above the surface at JOYCE on August 19, 2024. Radiosonde and DL (WindCube) observations are assigned to the nearest neighbor grid-point. UAS data are averaged to the spatial-temporal grid. The alternating number of available UAS observations from level to level is due to different flight patterns, i.e. constant height hovering vs. vertical profiling.



400 ments for uncertainty, vertical resolution and temporal resolution (Tab. 2). In this context, VITAL I can be regarded as a step forward in evaluating state-of-the-art measurement systems for the future operational observation of the vertical ABL structure.

Although the analyzed period covers only 12 days, an innovative emerging UAS profiling system could be assessed against novel and state-of-the-art remote sensing approaches - both evaluated against radiosondes. From VITAL I we draw the conclusion, that UAS ABL profiling of temperature, humidity and winds has a high potential for fulfilling the WMO breakthrough requirements for short-term / high-resolution weather forecasting, considering accuracy, vertical and temporal resolution. In addition, the ability for capturing the vertically-resolved diurnal cycle of ABL temperature, humidity and winds for the novel ABL sensors was shown.

UAS horizontal wind observations provide the most convincing results, while temperature and humidity observations show low spread (inter-quartile range) around the median difference, but currently require specifically adapted bias corrections.

410 As expected, the performance of the DL system for ABL wind profiling is similar to the UAS. The DL system has the advantage of a 24/7 continuous operation, with no need for flight permissions, as in case of the UAS. However, the UAS can profile simultaneously temperature, humidity and wind and autonomous launching systems are currently under testing.

The novel and recently also commercially available WV-DIAL system was shown to deliver satisfactory humidity profiles, fulfilling breakthrough requirements with respect to temporal and vertical resolution. Considering uncertainty, performance was excellent based on the inter-quartile range around the median deviation, however, at least above 500 m (far field receiver), a bias correction was shown to be necessary in our case in order to fulfill the WMO requirements.

The ground-based MWR system delivers, as expected, very limited information on the vertical water vapor distribution, however, excellent performance concerning column-integrated water vapor, in clear as well as in cloudy cases. With respect to temperature, WMO breakthrough requirements are met in the lowest 1000 m, using a retrieval algorithm that makes use of zenith as well as off-zenith brightness temperature observations. It must be emphasized, that ground-based MWR currently represent the only remote sensing system suited for operational measurements, that have the potential for deriving ABL temperature profiles. As the WV-DIAL systems, MWR can also operate in a 24/7 unattended manner.

Our analyses confirm, that satellite-based sounders provide only very limited information on ABL thermodynamic structure. IRS data from MTG-S1 is expected to perform similarly, however Toporov and Löhnert (2025) have shown that a synergy of ground-based and satellite-based remote sensing can be beneficial for deriving the thermodynamic state of the full troposphere.

Clearly, this study only provides a snapshot for instrument system evaluation and the results should not be generalized, but rather be seen as a starting point for further comparative evaluations. Here, only mid-European summertime conditions have been considered. However, open-access, combined data sets of UAS, remote sensing and radiosonde profiling are still rare, further long-term analyses and measurement campaigns will provide valuable insights in the potential of the upcoming generation of ABL profilers.

430 In this context, the HERZ VITAL II campaign (HERZ Bonn/Cologne/Tübingen/Hamburg, 2026), which ran from June to September 2026 in the Cologne Bay area in Germany, operated eight distributed profiling sites with MWR, WV-DIAL and DL. More than 100 radiosondes were launched with the goal to evaluate combined IRS and ground-based thermodynamic profiling algorithms during different weather scenarios. Additionally, during a two-week intensive observation period, an auto-launcher



435 for ABL UAS profiling was tested. This data set will show to what degree the synergy of ground-based and satellite observations
 may enhance the information content for thermodynamic ABL profiling at distinct locations. These detailed observations
 of vertical atmospheric structures are supplemented by a dense network of 54 ground stations - the second generation of
 Autonomous Cold Pool Loggers APOLLO (Kirsch et al., 2022) - to place severe weather related strong jumps in atmospheric
 profiles, particularly those caused by convective cold pools, within the context of spatial weather development. Future research
 440 needs to address the impact of ground-based ABL remote sensing on short term / high-resolution weather forecasting and what
 type of observation network structure and density is required to make a significant impact.

The presented data set and the given analyses may also prove valuable for students, lecturers as well as future operators and
 users of the new systems, but also provide helpful feedback to manufacturers.

Data availability. Data measured during VITAL I is available via <https://doi.org/10.5281/zenodo.22960530>, (Löhnert et al., 2026). The IASI
 445 combined sounding product is available in the EUMETSAT Datastore under the following number: EO:EUM:DAT:METOP:IASSND02
 (<https://data.eumetsat.int/product/EO:EUM:DAT:METOP:IASSND02>).

Author contributions. UL, LE, APla, MA, MSak, FA conceptualized the study. UL, BB, YB, TM, APla, BP, FA, JS and AR designed the
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 (WV-DIAL, radiosondes), JS (DL), AW (DL, WV-DIAL) performed the measurements and operated the instruments. YB, MSch, LvG, LH,
 450 TM, MM, BP, APsch, JS, YG and MT processed and analysed the observational data and prepared the figures. UL, JB, APla, BB, FA and
 JS supervised the scientific analysis. UL prepared the original manuscript. All authors contributed to the interpretation of the results and
 reviewed and edited the manuscript.

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