VITAL Campaigns

Vertical profiling of the troposphere:
Innovation, optimization and application

VITAL II Concept Paper
Vertical Profiling of the Troposphere: Innovation, Optimization and Application II

Ulrich Löhnert(1), Felix Ament(3), Andreas Platis(5), Mirjana Sakradzija(6), Maria Toporov(1), Maike Ahlgrimm(2), Frank Beyrich(2), Birger Bohn(8), Yann Büchau(5), Leonie Esters(4), Jan Handwerker(9), Luise Helmstreit(1), Peter Knippertz(9), Tobias Marke(1), Marcus Müller(8), Anika Obermann-Hellhund(2), Annika Oertel(9), Bernhard Pospichal(1), Alexander Pschera(1), Anja Rapmund(3), Leonhard Scheck(2), Vera Schemann(1), Jan H. Schween(1), Jaydeep Singh(7), Sabrina Schnitt(1), Andreas Wieser(9)

Version of October 23, 2025

(1): University of Cologne (UoC, HErZ HIRES-APP), (2): German Meteorological Service (DWD), (3): University of Hamburg (UHH, HErZ OceanWeather), (4): University of Bonn (UB, HErZ HIRES-APP), (5): University of Tübingen (UT, HErZ HIRES-APP), (6): LMU Munich (LMU, HErZ SCALABLe), (7): University of Frankfurt (UF, HErZ SCALABLe), (8): Forschungszentrum Jülich (FZJ), (9): Karslruhe Institute for Technology (KIT)

Correspondence to ulrich.loehnert@uni-koeln.de

Abstract

The VITAL (Vertical profiling of the troposphere: Innovation, opTimization and AppLication) concept is part of the Hans Ertel Centre for Weather Research (HErZ) and focuses on novel observations of the vertical structure of the troposphere. It is a common, networking effort of four HErZ projects, DWD observational and modeling experts as well as different external partners. The concept consists of two measurement campaigns: VITAL I and VITAL II. The VITAL I campaign took place in August 2024 at the Jülich Observatory for Cloud Evolution (JOYCE). It generated near-surface and vertical profiling data sets in the ABL to assess instruments and methods for the next-generation German Meteorological Service (DWD) observational network, including Uncrewed Aerial Systems (UAS), water vapor lidar and microwave radiometer. VITAL I results are transferred to VITAL II which is planned for 2026 and will take place from June 1 – August 31 in the Cologne Bay region between the west German cities of Cologne, Bonn and Aachen employing and installing up to seven profiling sites. During this time, first data from the Meteosat Third Generation Sounder (MTG-S1) satellite will become available providing continuous 3D observations of temperature and humidity over large parts of Europe and Africa with a temporal resolution of 30 min. However, deficits will remain in observing the atmospheric boundary layer (ABL). VITAL II will leverage the use of these novel satellite sounder observations by combining them with surface-based in-situ and remote sensing observations to significantly enhance the observed information content in the ABL. VITAL II also extends upon the success of the FESSTVaL, a 2021 field experiment at DWD's Richard-Assmann-Observatory, which focused on the meso-γ-scale (2-20km) providing a high-density surface observation network paired with continuous, ground-based atmospheric profiling at three distinct locations within 6 km of each other. VITAL II will extend profiling and dense near-surface observations to the meso-β-scale (20-200km). Up to 50 surface stations of the updated autonomous cold pool logger 2 (APOLLO 2.0) will be installed within Cologne Bay. The planned observational setup, in synergy with the MTG-S1 measurements, will provide important elements in enhancing our understanding of the evolution of the stable and convective ABL as well as convective cold pools. The observations will be used for assessing and improving the DWD Numerical Weather Prediction (NWP) model ICON land surface and ABL parameterization schemes. In addition, data assimilation experiments with the novel data are planned.

1 Motivation

The geostationary Meteosat Third Generation Sounder (MTG-S1) satellite was successfully launched on July 1, 2025. It will be the first satellite to provide continuous 3D observations of temperature and humidity over large parts of Europe and Africa with a temporal resolution of ∼30 min. However, deficits will remain in observing the Atmospheric Boundary Layer (ABL). This layer plays a crucial role for weather, climate, and air quality due to its complex interactions with the surface considering heat, moisture, momentum and mass exchange. Monitoring the ABL is challenging for several reasons, resulting in observational gaps. Observational gaps in the ABL exist because ground-based instruments are not able to provide consistent 3D data, and satellites, including MTG-S1, struggle to accurately measure ABL conditions due to the proximity to the surface. This limitation affects weather forecasting accuracy, specifically on the convective scale, and also air quality forecasts.

Within the Hans Ertel Centre for Weather Research (HErZ), scientists acting within the cluster Novel Observations aim to reduce these limitations, which is essential for enhancing process understanding, data assimilation, model assessment and ultimately model improvement. The **VITAL II campaign will leverage the use of novel and state-of-the-art satellite sounder observations in synergy with surface-based in-situ and remote sensing observations**. First important steps in this direction were made during VITAL I in 2024 (see Sec. 2). Novel machine learning algorithms which will synthesize the first MTG-S1 data with surface-based observations, will be applied to and assessed by a multitude of additional profiling observations. The objective is to significantly enhance the observed information content in the ABL.

VITAL II also extends upon the success of FESSTVaL (Field Experiment on submesoscale spatio-temporal variability in Lindenberg, Hohenegger et al. [2023]), which focused on the meso-γ-scale (2-20km) providing a high-density surface observation network paired with continuous, ground-based atmospheric profiling at three distinct locations within 6 km of each other. VITAL II will extend profiling and dense near-surface observations to the meso-β-scale (20-200km = regional scale). The planned observational setup, in synergy with the MTG-S1 measurements, will provide important elements in **enhancing our understanding of the evolution of the stable and convective ABL as well as convective cold pools**. The observations will be used for assessing and improving the German Meteorological Service (DWD) Numerical Weather Prediction (NWP) model ICON [Zängl et al., 2015] land surface and ABL parameterization schemes. In addition, data assimilation experiments with the novel data are planned, e.g. within the HErZ project HIRES-APP.

2 VITAL II Setting

VITAL II will operate a dense network of atmospheric profilers in addition to a dense near-surface network on the meso-β-scale and combine these observations with the novel MTG-S1 observations (Sec. 5). This setting allows addressing research objectives and research questions related to sensor synergy, ABL evolution, and convective cold pools (Sec. 4). Building upon FESSTVaL, VITAL II also includes a modeling strategy for convective ABL and cold pool cases (Sec. 4.3) which will employ high-resolution ICON modeling to assess ABL parameterizations based on the intensive observations.

VITAL II is planned for **June 1** - **August 31 of 2026**. It is divided into an IOP (Intensive Observation Period, four week time window between July and August 2026) and a GOP (General Observation Period, the remaining time between June 1 and August 31, 2026). The time setting is rather late within the fourth HErZ funding phase which runs until the end of July 2027. However, this allows the inclusion of first available MTG-S1 satellite data.

VITAL II will focus on the **Cologne Bay (CB)** area (Fig. 1). CB is a low-lying geographical region in Germany situated between the cities of Bonn, Aachen, and Düsseldorf, in the south marking the transition to the Rhenish Massif. It is a densely populated region with more than 2100 inhabitants per km^2 along the Rhine River with Cologne being the largest city in western Germany with about one million inhabitants. Thus, CB is heavily dependent on accurate forecasts of high-impact weather, such as convective storms, flooding, fog, heat waves or weather conditions that significantly influence the regional air quality. Regional flow patterns are determined by the heterogeneous, low mountain landscapes and especially the Rhine River valley (e.g. wind channeling effect, Hartwig et al. [2022]). A large heterogeneity in land surface types and land use exists, including forests, high-density agricultural use, urban and suburban areas, wide-spread traffic infrastructure, petro-industry, large lignite mines, and major power plants which all present a challenge for state-of-the-art km- and sub-km-scale modeling.

Instrumentation
Within CB, a ground-based measurement infrastructure - including different types of novel/exploratory remote sensing observations - is already in place (see Fig. 1). CB includes the Jülich Observatory for Cloud Evolution (JOYCE, Löhnert et al. [2015], www.joyce.cloud), a ground-based remote sensing station in the City of Cologne and DWD's pilot

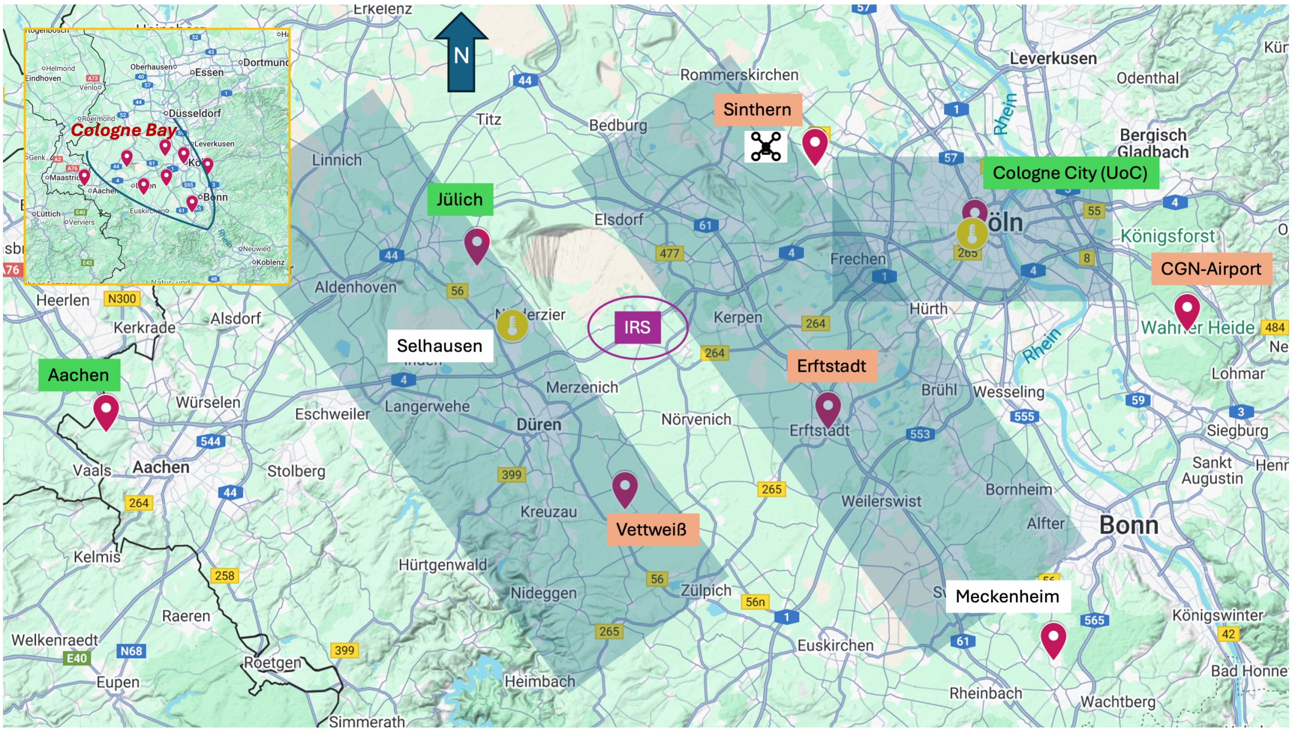

Figure 1: VITAL II (June-August 2026) observational setup concentrated in the Cologne Bay (CB, see inset figure, upper left). Red markers indicate VITAL II ground-based remote sensing profiling sites for wind, turbulence, temperature and humidity. All profiling sites are equipped with near-surface meteorology measurements (including radiation). Profiling sites with green background are existing, with a peach background are planned for VITAL II. ∼100 Radiosondes will be launched on demand in the CB area. UAS Multicopter profiling sites are planned in Sinthern during the IOP between July and August 2026. VITAL II will operate an energy balance station at Sinthern, also available at Selhausen. Additional ∼50 near-surface measurements of temperature, pressure and humidity will be available from the autonomous cold pool logger 2 (APOLLO 2.0) network to be set up in the gray-shaded areas. The purple oval indicates an MTG-S1 IRS pixel size. IRS coverage is available over the whole domain. Source of the map: Google Maps

station for ground-based remote sensing at Aachen-Orsbach to the west of CB. These stations operate state-of-the-art profiling instruments for deriving vertical information on temperature, water vapor, winds, turbulence and clouds. For VITAL II, the measurement infrastructure will be extended by further remote sensing profiling sites, Uncrewed Aerial System (UAS) profiling and a dense near-surface observation network. At least 50 so-called autonomous cold pool loggers (APOLLO 2.0) measuring near-surface temperature, pressure and humidity will be set up in the areas of the Rur and Erft catchments as well as within the City of Cologne and to the east of the city.

VITAL I successfully demonstrated the simultaneous operation of UAS profiling and ground-based remote sensing during two weeks in August 2024 at JOYCE. This campaign focused on wind and turbulence profiling compared to Doppler wind lidar and radiosondes measurements as well as humidity profiling assessment from four different approaches, including a new water vapor differential absorption lidar. The wind estimation by UAS showed very good agreement with the radiosonde profiles and ground-based observations such as DWL and anemometers on a meteorological tower with deviations for the mean wind below 0.5 m/s. Temperature measurements initially showed a bias between the UAS and the radiosonde. However, this has now been minimized by optimizing the measurement system with better ventilation of the temperature sensors. The water vapor observations showed good agreement with the radiosonde profiles, a data publication is currently being drafted. Additionally, during VITAL I, a network of twelve stations equipped with both APOLLO 2.0 prototypes for testing and Vaisala WXT sensors for reference was deployed. A similar setup was used in summer 2025 during a student field trip on the island of Fehmarn. Both experimental datasets were highly valuable for optimizing the design of APOLLO 2.0, as outlined in more detail in Sec. 5.1.6.

Data from an EC station will be available from the TERENO [Zacharias et al., 2024] site Selhausen (Fig. 1), e.g. for regional background information concerning the Bowen ratio. Additional, publicly available near-surface temperature, humidity, pressure and precipitation data from regional networks of DWD, the Federal State of North-Rhine-Westphalia, as well as through a data exchange partnership with the City of Cologne will be available and employed.

A further key factor for VITAL II will be the availability of MTG-S1 sounder measurements. The combination of these spatially and temporally highly resolved satellite observations carrying temperature and humidity profile information, in synergy with the dense surface and ground-based remote sensing network, will provide an unprecedented array of meteorological observational systems for characterizing the 3D development of the lower troposphere on the meso-β-scale. Details on the VITAL II observational strategy are given in Sec. 5.

Figure 2: JOYCE at Forschungszentrum Jülich (left), UT UAS over JOYCE (right), both during VITAL I in Summer 2024

Modeling

The VITAL II observational strategy is aligned with a nested modeling setup over the CB area (Table 1, Fig. 1). To achieve this setup, we adapted the modeling framework previously used in FESSTVaL [Sakradzija et al., 2025] and also applied around JOYCE since 2020 (at the University of Cologne) to cover the CB area with a grid refinement of down to 30 m of grid spacing. The aim is to capture processes that span from meso-β-scales to micro-scales with horizontal grid-spacing from 1 km down to 30 m using the same model, ICON [Zängl et al., 2015] in its Numerical Weather Prediction (NWP) and Large-eddy simulation (LES) configurations. For the NWP configuration, two nested domains with approximately 1 km (N1) and 500 m (N2) grid spacing are planned. ICON will be run in LES mode for five nests (L1, L2, L3, L4, L5) embedded within the ICON-NWP model grids. The outer LES domain has a horizontal extension of 180 km and is thus more than twice as wide as the observational domain. Both ICON-NWP and -LES will be forced by the operational ICON-D2 initialized analysis and forecasts with 2.2 km mesh size.

LES will be used in synergy with the campaign observations as a reference for NWP model evaluation and ABL process understanding related to the initialization of deep convection. Combining the VITAL II observation strategy with modeling will make it possible to assess and possibly adapt novel turbulence and land surface schemes developed together with DWD. Further details on the ABL and cold pool modeling in VITAL II are given in Sec. 4.2 and 4.3, respectively.

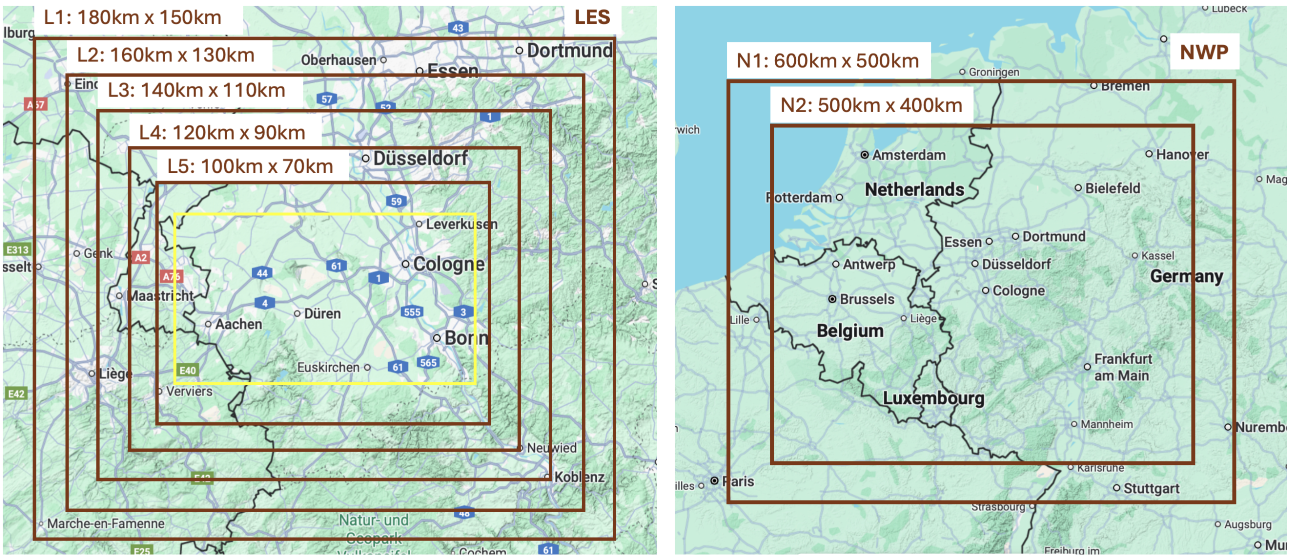

Figure 3: VITAL II model setup concentrated around the Cologne Bay (CB) area. The right panel shows the nested NWP model configuration, the left panel the nested LES configuration. The yellow box indicates the area of the VITAL II observational setup. Source of the map: Google Maps

Table 1: Setup of the modeling domains for ICON-LES and -NWP in VITAL II.

Domain abbreviation	Grid spacing (m)	Domain size E-W (km)
LES		
L1	600	180
L2	300	160
L3	150	140
L4	75	120
L5	30	100
NWP		
N1	1200	600
N2	600	500

3 VITAL II Partners and Support

Within HErZ, the projects **HIRES-APP**, **OceanWeather** and **SCALABLe** are currently actively contributing to VITAL II. Their contributions are coupled to project specific research objectives and research questions (Sec. 4) whose success relies on a successful campaign. Further, **HErZ-DA** will contribute to VITAL II with the self-built cloud camera system ATMOCORDER.

VITAL II partner IMKTRO (Institute of Meteorology and Climate Research Troposphere Research) of the Karlsruhe Institute for Technology (**KIT**) is contributing parts of the unique mobile atmosphere observation platform KITcube for ground-based remote sensing and in-situ observations of the lower atmosphere. Specifically, two meso-stations of the KITcube, including remote-sensing instruments for water vapor and wind profiling, are currently confirmed, and key to the VITAL II observational setup (Fig. 1, see also Sec. 5). IMKTRO is especially interested in scientific collaboration concerning novel approaches for 3D atmospheric profiling in the ABL, convection initiation and convective cold pool formation as well as high-resolution data assimilation (DA) over the heterogeneous, strongly human-shaped landscape of the Cologne Bay. Potential extensions for VITAL II observations as well as their use for high-resolution data assimilation with ICON are currently discussed (Sec. 9).

Also, VITAL II is partnering with DWD Technical Infrastructure (TI) division: the mobile measurement unit (MME) from Potsdam is contributing a Doppler lidar system to be located at CGN-Airport. VITAL II especially profits from collaboration with the Richard Aßmann Observatory in Lindenberg (RAO). The successful partnership established during FESSTVaL is continued in terms of exchange on optimal measurement configuration, processing and interpretation. Through this partnership, access to the instruments at Aachen-Orsbach is possible.

VITAL II will take place within the Geoverbund ABC/J region. Geoverbund ABC/J (Aachen-Bonn-Cologne-Jülich) is the network of all scientists and students working in geosciences and related disciplines, coordinating new ideas for large research initiatives, facilitating access to universities and measurement infrastructures as well as providing contacts to experts, informing the public and acquiring new students in geosciences. VITAL II will profit from this network by taking advantage of existing cooperation and measurement infrastructures.

Carrying out VITAL II would not be possible without UoC participation within the ACTRIS ERIC research infrastructure. The network of atmospheric profilers to be installed during VITAL II enormously profits from the deployment and operating procedures as well as the data processing software developed with the ACTRIS Centre for Cloud Remote Sensing (CCRES). Major parts of the remote sensing infrastructure at JOYCE have been supported through the German branch of ACTRIS (ACTRIS-D, funded by Federal Ministry of Research, Technology and Space) to implement the ACTRIS national facility for cloud remote sensing JOYCE-NF.

4 VITAL II Research Focus

Based on the HErZ IV proposal, the research associated to VITAL II will focus on:

- **Novel Observations**: Compilation and assessment of an unprecedented data set of combined satellite and ground-based observations for weather and climate research (**HErZ HIRES-APP**)
- **Improving ABL Modeling**: Test and improve different ABL parametrization schemes within the ICON framework (**HErZ SCALABLe**)
- **Cold Pools**: Observe and model convectively driven cold pools on the meso-β-scale (**HErZ OceanWeather**)

Related VITAL II research objectives are highlighted below.

4.1 Novel Observations

The geostationary Meteosat Third Generation Sounder (MTG-S1) with the Infrared Sounder (IRS) payload on board was successfully launched on July 1, 2025. For the first time in geostationary orbit, this sensor will provide high-resolution infrared spectra over Europe every 30 min with a horizontal spacing of ∼7-9 km. The level 2 product based on these spectra will include among other quantities the vertical profiles of temperature and humidity over Europe [EUMETSAT, 2021]. However, from the experience with the hyper-spectral IR sensors onboard polar-orbiting satellites, such as Metop-IASI, even hyper-spectral observations leave a gap in the ABL mainly due to the limited vertical resolution of the satellite, the strong influence of the varying land surface emissivity as well as the cloudiness. For polar-orbiting IR observations, the limiting effect of clouds is mitigated by using the microwave observations from collocated Metop-AMSU-A/MHS instruments. However, on board of geostationary satellites, no microwave sensors are planned.

The accuracy of temperature retrievals (RMSE relative to ECMWF analyses) based on IASI observations over the land surface is typically 0.7-1.0 K between 200-800 hPa and increases up to 2.5-3.5 K at lower atmospheric levels. The water vapor retrievals perform differently depending on the scene and the overall water vapor content. For relative humidity, the RMSE departures from ECMWF analyses are around 10% in the layers above 800 hPa and increase to 20% in the boundary layer [August et al., 2012]. For the MTG-IRS sensor, the errors can be expected to be in a similar range.

One HErZ HIRES-APP objective is to improve these accuracies. The project will compile a temporally continuous and spatially dense data set of temperature and humidity profiles in the ABL and mid-troposphere over the CB area. This will be achieved by combining MTG-S1 satellite and ground-based observations. For this, novel synergy algorithms, based on machine learning are currently developed [Toporov and Löhnert, 2025, 2020] and will be applied to the wealth of data collected during VITAL II. These synergy algorithms collocate the IRS radiances with (1) either the dense in-situ network of near surface observations of temperature and humidity and/or (2) with downwelling radiances measured by ground-based microwave radiometers (MWR) by using water vapor and temperature sensitive absorption bands and/or profiles of water vapor (WV) from differential absorption or Raman Lidar. In the unexpected case that IRS data are not available for VITAL II, EPS and NOAA polar orbiter satellite overpasses with on-board infrared and microwave sounders (up to six daily overpasses of the CB area) will be used to fill the gap. HIRES-APP is also developing machine learning algorithms for these sensors. Thus, the first two VITAL II research objectives considering novel observations are stated as

RO-NO1: Apply state-of-the-art retrieval algorithms to continuous time series MTG-S1 IRS radiances over relevant VITAL II measurement locations for retrieving satellite-based temperature and humidity profiles

RO-NO2: Combine continuous time series of quality-controlled observations of ground-based near-surface temperature and humidity observations, ground-based remotely sensed microwave radiances and profiles of WV from lidar with the MTG-S1 IRS radiances to enhance the information content over the relevant VITAL II measurement locations

The required observation strategy for the MWR and WV lidar is given in Sec. 5. The required ground-based observations will be performed continuously in time over the full period of the campaign at all profiling sites shown in Fig. 1.

Through this type of sensor synergy, an increase in information content and retrieval accuracy is expected - compared to the satellite observations alone. Additional in-situ VITAL II observations from UAS profiling during the IOP and radiosonde ascents during the whole VITAL II period will be used to assess the accuracy of the derived synergy profiles. The goal is to assess satellite-only vs. ground-based-only vs. satellite / ground-based-synergy compared to the in-situ measured profiles by UAS and radiosonde. For this assessment to be meaningful, an observation strategy for the in-situ sensors strategy is defined in Sec. 5.2.1 and Sec. 5.2.2, respectively. Performance of the profiling methods will be evaluated under different environmental condition: clear-sky, different ranges of water vapor column and different types of cloudiness (i.e liquid vs. ice vs. mixed-phase clouds). Thus, the third VITAL II research objective considering novel observations is stated as

RO-NO3: Perform in-situ-based profiling based on frequent UAS and radiosonde ascents for a representative assessment of the synergistic satellite-ground-based temperature and humidity retrievals

All data recorded during VITAL II and given in the observational strategy will be archived (Sec. 11, Data Management Plan) and made available to the scientific community.

Preliminary results of temperature and humidity retrievals derived from simulated IRS and MWR observations are shown in Fig. 4. These observations were generated using ERA5 reanalysis profiles and radiative transfer models

RTTOV for IRS and a line-by-line model for MWR. Neural networks were trained with the simulated observations as input and the ERA5 temperature and humidity profiles as targets, and subsequently applied to an independent set of simulated observations. The figure displays statistics comparing the retrieved profiles with the corresponding "true" ERA5 profiles. The combined retrievals MWR+IRS show improved performance relative to IRS alone, particularly within the lowest 8 km for humidity and the lowest 5 km for temperature. These findings represent rather the optimal performance achievable under ideal conditions, since the simulated observations were not yet perturbed by noise.

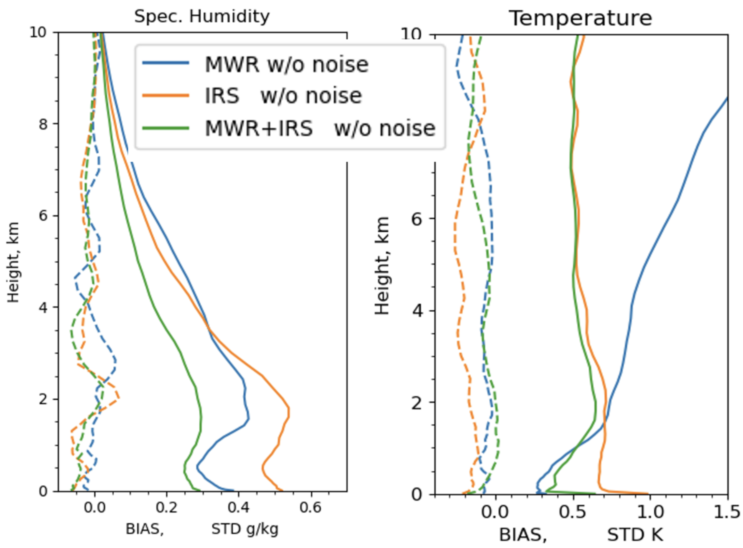

Figure 4: Bias and standard deviation of humidity and temperature retrievals from simulated IRS, MWR and combined IRS+MWR observations.

4.2 Improving ABL Modeling

In collaboration with SCALABLe, DWD is currently testing different turbulence schemes to better represent the diurnal cycle of the ABL development during day and night in ICON-NWP. Here, VITAL II observations, together with realistic, fine-scale LES are suited to assess ICON-NWP ABL development (e.g. mixing layer height) over different land-surface types, such as agricultural areas, grassland, forests, and urban areas with settlements and industry.

Based on VITAL II, SCALABLe will further develop and evaluate the Two Turbulent Energies Scheme coupled to the Assumed PDF method (2TE+APDF) [Bašták Ďurán et al., 2022] and the stochastic cloud scheme of Sakradzija et al. [2016]. The planned VITAL II measurement set-up will allow the observation of ABL structure and variability over different parts of the CB area. The sensitivities of the applied turbulence schemes to the diurnal cycle of the mixing layer height (MLH), lower tropospheric stability and ABL winds will be investigated. Specifically, at the profiling sites (Fig. 1) synergistic ground-based (and satellite) retrievals of temperature and humidity, together with DWL-derived wind profiles will allow comparing the Bulk-Richardson number, describing buoyant to shear production of turbulence, directly to model output. DWL-derived Eddy Dissipation Rate will also be applied to characterize the MLH. Applying MLH detection methods to profiling observations is not part of current HErZ funding, however a master student at UoC has committed to this analysis. In addition, cooperation shall be established on this theme with the SynABLH project (DWD IAFE funding scheme) at RAO.

The VITAL modeling strategy will also include the representation of the urban land cover type in the land surface model, TERRA-URB (Jan-Peter Schulz, DWD) to accommodate the landscape of the VITAL II field experiment. With the further development of ICON-Land at DWD, the possibility of bridging between the LES scales planned for VITAL II and the scales used in ICON-Seamless is open for the next HErZ stage.

An overview of the corresponding modeling strategy is given in Fig. 3 and Table 1. Here, the VITAL II ABL-related research objectives and research question are formulated to:

RO-ABL1: Apply the VITAL II modeling strategy to a set of classical ABL days with pronounced diurnal cycle over the different profiling sites

RO-ABL2: Apply suited ABL diagnostics (e.g. for MLH) to the model output and the corresponding observations

RO-ABL3: Investigate how different ABL and land surface schemes applied in ICON-NWP influence the diurnal cycle of MLH (especially the growth/decay rates during morning/evening transition) over heterogeneous land-surface types in the CB area in comparison to the observations

4.3 Cold Pools

Observations
In 2020, the HErZ campaign FESST@HH successfully pioneered an approach to measure and depict the horizontal structures of cold pools at the surface, despite taking place under pandemic conditions.

Kirsch et al. [2022] present a data set of 103 stations randomly distributed over the urban region of Hamburg recording temperature and pressure with at least 10 s resolution. They were able to observe 37 cold pool events and to record their spatial and temporal evolution. This effort was extended by the FESSTVaL campaign [Hohenegger et al., 2023], where cold pools were observed with a regular distributed dense station network across an approximately circular region with about 30 km diameter centered around Lindenberg. Kirsch et al. [2024] describe the morphology of about 40 observed cold pool events from this campaign, focusing primarily on 2D features, such as the area and intensity (in terms of surface temperature perturbation) of the cold pools. However, a triangle of three "supersites", equipped with profiling instruments (mainly DWL and MWR) provided already first insights into the vertical structure of cold pools. Steinheuer et al. [2025] describes the vertical depth of cold pools and their edged structure in terms of wind gust profiles, derived using novel DWL retrievals [Steinheuer et al., 2022], and temperature profiles obtained from the MWR.

Classical analysis of cold pools at single, isolated stations always lacks spatial and temporal context – while registering the cold passage its age and size remains unknown. However, characterization of cold pools strongly depends on age and location relative to the cold pool center. Likewise, model evaluation requires a Lagrangian coordinate system relative on cold pool age and center. Only spatial observations, like a dense station network, can provide this key information. While VITAL II will focus on the vertical structure of cold pools and their edges by exploiting DWL, MWR and UAS measurements, we need to maintain the heritage of FESSTVaL by putting the profile measurement in spatial and temporal context. Spatial and temporal coverage will be complemented by remote sensing measurements (DWD radar network, MTG-S1), but ground based near surface observations will still form the backbone. The operational weather stations of DWD with ten stations in the CB will be upgraded during VITAL II by additional APOLLO 2.0 stations, which, in addition to temperature and pressure, also observe near surface humidity.

We aim at a station separation on the order of 5 to 10 km. This is less dense than the FESSTVaL and FESST@HH networks but will allow us to cover a larger domain ranging at least from Jülich to Cologne. This intermediately dense network in synergy with operational DWD measurements will provide the context for the detailed vertical profiling observations at the VITAL II profiling sites. The larger domain will allow us to study more of the cold pool life cycle because we are less prone to cold pools eventually exceeding the observational domain. VITAL II will extend our record of cold pool observations during FESST@HH and FESSTVaL and will in particular allow OceanWeather to address the following cold pool related research objectives:

RO-CP1: Characterize the vertical structure of a cold pool and in particular its edges. How does this change throughout the cold pool life cycle?

RO-CP2: Investigate how different land surfaces (farm land, urban fabric, Rhine Valley channeling) impact cold pool evaluation

RO-CP3: Characterize the humidity structure of cold pools. Can we confirm modeled features like the moisture ring structure at cold pool edges?

RO-CP4: Investigate how dense/sparse a network is sufficient to reliably detect cold pools. How can we complement the operational observational networks of DWD?

Detailed observational strategies for observing the horizontal and vertical structure of cold pools are presented in Section 5. Here, the research objective is formulated

RO-CP5: Identify, observe, compile and depict a data set of cold pools during the GOP and IOP which can be used for detailed physical analysis as well as for model evaluation and improvement.

Cold Pool Modeling
Next to observationally driven research, VITAL II will continue to focus on cold pool modeling. ICON was used in NWP and LES mode to simulate cold pools for FESSTVaL [Sakradzija et al., 2025]. Requirements in terms of model resolution and domain size were tested and needed to be reconsidered to find a satisfactory configuration for the LES setup. First statistics of cold pools resolved in ICON-LES and ICON-NWP were compared to the observed morphology of cold pools derived from the surface observational network used in FESSTVaL. Qualitatively, the area and intensity of the simulated and observed cold pools match quite well when these properties are normalized by precipitation (the "driving force" for cold pools) (Fig. 5).

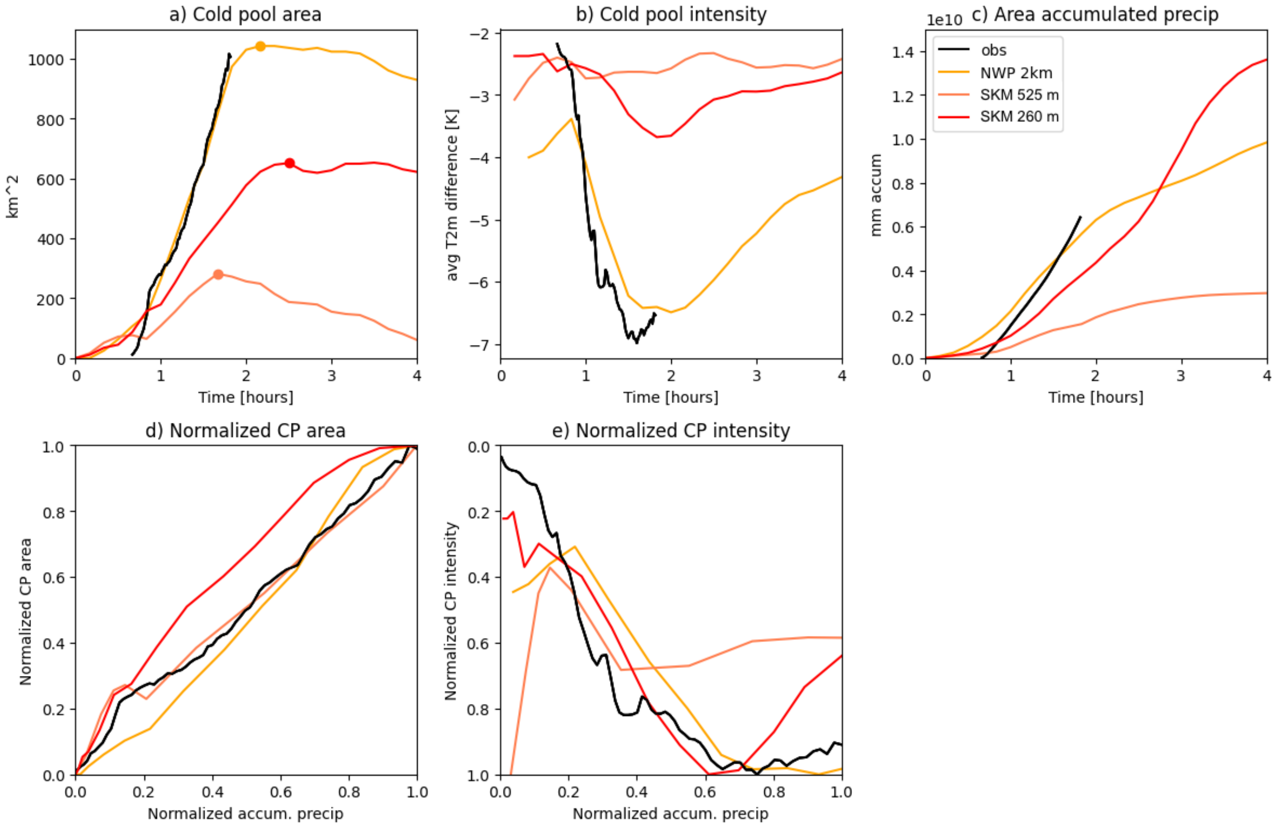

Figure 5: Figure showing a) CP area, b) CP intensity and c) accumulated precipitation for the observed CP "Jogi" (black) and simulated cold pools from the ICON-NWP and sub-km simulations on June 29, 2021. The bottom row shows d) CP area and e) intensity vs. accumulated precipitation, normalized over the growth phase of the CPs only. Reproduced from Sakradzija et al. [2025].

The FESSTVaL LES made clear that cold pool dynamics require significantly larger domains compared to the domains used for other ABL processes. One of the main limitations of the nesting setup used in LES is the advection of convective systems from the outer coarser-resolution domains into the child domains superimposing local convection and cold pool development. A setup using a considerably larger domain size and minimal gaps between outer and inner domains ensures undisturbed local development of the storms within the inner-most domain that is not affected by the features inherited through lateral-boundaries. In order to guarantee this, a VITAL II modeling strategy is proposed in Sec. 2.

In addition to the existing experiments based on FESSTVaL, SCALABLe will use VITAL II cold pool case studies for sensitivity studies on ABL parametrization and land-surface model influence of deep convection over heterogeneous land cover. Thus, a further cold pool related research question with respect to model development is

RO-CP6: Investigate how the representation of land-cover, ABL turbulence and shallow convection influences the onset and development of resolved deep convection, precipitation and cold pools

5 Observational Strategy

Within the CB area, we take advantage of an already existing measurement infrastructure of observational networks of near-surface variables as well as vertical profiling sites and augment these with additional observations. The VITAL II observations can be classified into continuous and non-continuous. Continuous observations will be operated throughout the campaign from June 1 to August 31, 2026 (GOP and IOP). The non-continuous observations will be performed within the VITAL II IOP in a four-week time window between July and August 2026.

The different observations types, the planned measurement modes as well as the spatial configuration of the measurements conceptualized to address the in total nine VITAL II research objectives related to novel observations (RO-NO), ABL modeling (RO-ABL) and convective cold pools (RO-CP) are given below.

Table 2: VITAL II profiling observations for the Cologne Bay area. A graphical overview of the locations is given in Fig. 1.

Instrument	ABL Variables	Locations	Vert. Res.	Temp. Res.	Operation time
DWL	horz. wind vector profile, vertical vel. profile	Aachen, JOYCE, Vettweiß, Sinthern, Erftstadt, UoC, CGN-Airport	30 m	sec to min	01/06/26 - 31/08/26
MWR	T-profile, IWV, LWP	same as DWL	100-500 m	sec to min	01/06/26 - 31/08/26
WV-DIAL	q-profile, particle backscatter	Aachen, Sinthern, UoC	100 m	30 min	01/06/26 - 31/08/26
Raman Lidar	T-profile, q-profile	JOYCE	30 m	10 min	01/06/26 - 31/08/26
Differential Absorption Radar (DAR)	IWV partial columns	JOYCE	cloud dependent	1 min	01/06/26 - 31/08/26
Meteorological Tower (130 m)	2D wind vector, T, q	JOYCE	30 m	10 min	01/06/26 - 31/08/26
UAS-MC	high-resolution (5Hz) 3D wind vector, turbulence (σ_w, TKE, momemt. flux), T, q	Sinthern	5-20 m	5 Hz	IOP (Jul/Aug 2026)
Radiosonde	horz. wind vector profile, T-profile, q-profile	JOYCE, variable	10-50 m	on demand	01/06/26 - 31/08/26
MTG-S1 IRS	T-profile, q-profile above clouds	every ∼7 km	500-1000 m	every 30 min	01/06/26 - 31/08/26
MW and IR sounders on polar orbiters	T-profile, q-profile above clouds (IR)	swath dependent	500-1000 m	∼4-6x daily	01/06/26 - 31/08/26

5.1 Continuous Observations

VITAL II plans to operate seven ground-based vertical profiling sites (Tab. 2). Continuous profiling capability at each station is obtained through observations of at least a Doppler wind lidar (DWL) and a microwave radiometer (MWR). DWL provide 3D wind vector and turbulence starting at ∼100 m above the surface to the top of the ABL, whereas MWR provide columnar water vapor and liquid water retrievals as well as low-resolution information on ABL temperature profiles. At at least four sites, these observations will be supplemented with water vapor lidar, which can provide humidity profiles within the ABL. VITAL II will also distribute a network of self-developed ∼50 near-surface stations measuring pressure, temperature and humidity over the CB area (Fig. 1). These will significantly enhance the observational density of the existing near-surface observations of DWD, federal state and local authorities. During the full length of VITAL II, we plan to access first geostationary MTG-S1 radiance data, available every ∼7 km over the CB area. We will also collect polar-orbiting satellite sounder radiance data during the campaign. The continuous observation types as well as the foreseen measurement modes of the VITAL II installed systems are described below.

5.1.1 Doppler Wind Lidar

DWL will be employed to derive continuously vertical profiles of the 3D wind vector (Tab. 2). These are required for observing cold pools dynamics as a function of height (RO-CP). In addition turbulence measures such as eddy dissipation rate (EDR) or the Reynolds stress tensor can be derived, which are used to describe the turbulent structure of the ABL (RO-ABL). The full potential of the DWL observations will be exploited when combined with the thermodynamic profiling from the MWR and DIAL, e.g. to retrieve the Bulk-Richardson number expressing the ratio of the buoyant to shear stress turbulence production. This turbulence measure can directly be compared to NWP model output (RO-ABL).

During the pre-FESSTVaL campaign FESST@MOL Steinheuer et al. [2022] assessed a variety of DWL scan patterns for different meteorological applications. Based on the experience of VITAL I, we have decided to use two alternating scan patterns to capture cold pool features and the ABL dynamic structure. We have decided to use – as far as possible – identical scan configurations across the VITAL II profiling network since we will be simultaneously observing similar (or even the same) atmospheric phenomena which facilitates model comparisons and the interpretation in general.

A scan with six beams (one vertical and five at evenly distributed azimuths and an elevation of 45°) will be used to derive 3D wind vectors at a temporal resolution of at least one minute as well as the terms of the Reynolds stress tensor [Sathe et al., 2015]. Through the directly measured vertical velocity component the EDR will be derived [O'Connor et al., 2010] based on averaging over ∼30 min. The skewness of the vertical wind velocity distribution will be used to infer the type of ABL turbulence (e.g., surface or cloud driven) as successfully shown by Manninen et al. [2018] within the ACTRIS [Laj and Coauthors, 2024] network. Note, that while this scan provides the 3D wind vector every minute with an averaging time of ∼30 s, we will not be able to capture gusts with a temporal resolution of 3.4 s as performed during FESSTVaL [Steinheuer et al., 2025]. This is due to the following: (1) these rapid scans are only possible with HALO Streamline Doppler lidars of which we only have two in the VITAL II network (2) we would like to run homogeneous scan patterns over the VITAL II domain.

This 6Beam scan will be carried out in alternation with a quick continuous VAD (velocity azimuth display) scan lasting also about 30 s and providing along beam Doppler wind speeds in 10 sectors. Depending on the situation of obstacles around the site, this scan will be carried out at 30° elevation or even lower to sense winds below 100 m height. We thereby prioritize achieving lower heights against an only slightly higher theoretical uncertainty in the wind retrieval compared to that at an elevation of 35° [Teschke and Lehmann, 2017] and an larger area covered by the scan especially at higher levels. The extension of the observed vertical range towards the surface is important since cold pools as density flows are significantly influenced by surface friction leading to strong shear especially in the lowest 100 m.

These scans also allow a better detection of low level jets (LLJ) which have been shown to be related to cold pools [Luiz and Fiedler, 2023] or often appear within or above the nocturnal ABL and can influence the onset of daytime convection.

5.1.2 Microwave Radiometer

The MWRs at the profiling sites will deliver thermodynamic variables (Tab. 2). First, a coarsely resolved temperature profile in the ABL can be retrieved, in addition to the along-sight integrated water vapor (IWV) content and the liquid water path (LWP), the latter with high accuracies of ~ 0.5 kg m^{-2}, respectively ~ 15 g m^{-2}. In conjunction with the wind profiles, the temperature profiles will be essential for characterizing atmospheric stability over different location in the CB (RO-ABL) as well as detecting and analyzing cold pools, e.g. the evolution of cold pool depth over the VITAL II domain (RO-CP). The LWP measurements provide cloudiness and rain occurrence where the IWV measurements give information on the moist processes of cold pools. The raw microwave radiance data in the K-band (water vapor) and V-band (oxygen, temperature sensitive) will be combined with the satellite radiance observations to obtain a synergistic product at all profiling sites (RO-NO).

For the MWR observations, we have decided to perform so-called boundary layer scans down to 5° in one suited, obstacle-free azimuth direction every 5 min to accurately measure the ABL temperature profile. One scan takes about 2-3 min. In between, vertical-stare observations (2 s temporal resolution) will make possible the retrieval of IWV and LWP.

Additionally, the five sites Aachen, Jülich, Vettweiß, Sinthern and CGN Airport are suited for low level azimuth scans around 10-30° elevation, at least in most azimuth directions. Azimuth scans at a suitable, constant elevation angle will be carried out with an azimuth angle spacing of 10°. These scans take ~5 min and will be carried out once at the beginning of every hour. They can be used to characterize spatial water vapor and temperature inhomogeneity relevant for interpreting the MSG-S1 observations. In case of strong gradients, in synergy with the DWL, they also provide water vapor advection estimates. Within the DWD-funded EMF-project WV-ENHANCE, these data will be assimilated into ICON-NWP and compared to the case when assimilating only vertical observations.

5.1.3 Water Vapor Lidar

Two types of water vapor lidar are employed during VITAL II. The water vapor differential absorption lidar (WV-DIAL) [Newsom et al., 2020] is vertically pointing and emitting in the near-infrared and provides specific humidity profiles up to the ABL height every ~30 min (Tab. 2). The DA-10 system from Vaisala has now been commercially available for about two years. The DWD pilot station in Aachen is planning to obtain such a system before the end of 2025, two further system from our partner KIT will be installed at Sinthern and at the City of Cologne (UoC). At Jülich, JOYCE operates an experimental Raman lidar from Raymetrics within the ACTRIS ERIC research infrastructure. The system is also vertically pointing and the laser emits at a wavelength of 355 nm with two rotational Raman channels as well as one vibrational water vapor channel enabling the retrieval of temperature and water vapor profiles from ~400 m up to ~3 km above the ground.

The WV lidar systems present a valuable addition to the remotely sensed column amounts of water vapor derived by the MWR because they can vertically resolve the water vapor distribution in the ABL (RO-ABL). In synergy with the MWR, free-tropospheric and ABL water vapor content can be derived and effectively distinguished. Next to water vapor profiles, the lidars also provide backscatter (at JOYCE extinction and de-polarization) profiles every 30 s enabling the detection (and classification) of aerosols (i.e. the height of the ABL during daytime) and liquid as well as ice clouds, the latter if not obscured through low-level liquid clouds.

At the sites with WV-DIAL or Raman lidar, ABL water vapor profiles will be combined with the satellite and ground-based MWR radiances to derive an advanced thermodynamic profile with maximum information content (RO-NO). If not used directly in the retrieval, the WV lidar can also be used as an independent evaluation for the synergistic ground-based / satellite retrieval (RO-NO).

5.1.4 CO_2 Sensors

Low-cost non-dispersive infrared (NDIR) carbon dioxide (CO_2) sensors integrated into SenseBoxes (https://sensebox.de/) will be installed at each of profiling sites to test their suitability for observing CO_2 during the ABL diurnal cycle. Especially, the CO_2 concentrations during cold pool passages will examined. Although these sensors do not provide highest accuracy, VITAL II aims to show that they offer a cost-effective alternative way to explore a part of the carbon cycle.

5.1.5 Satellites

Because MTG-S1 was only launched on July 1, 2025, no public distribution of IRS data can be expected by the beginning of VITAL II. However, for the VITAL II team, early access to MTG-S1 data is highly important. Contacts with DWD and EUMETSAT are established and inquiries are on-going to receive IRS radiance data as soon as possible before VITAL II. Currently, a proposed option is for VITAL II to be part of the IRS cal/val phase, which would enable early data access.

In parallel, data from overpasses of polar orbiting satellite with on-board microwave and infrared sounders over the CB area will be accessed in due time before and during the campaign. This procedure was successfully carried out during VITAL I: atmospheric temperature and humidity profile products from four LEO satellites of two missions were downloaded: Metop B and C and NOAA 20 and 21. The first includes the Infrared Atmospheric Sounding Interferometer (IASI) Combined Sounding Product provided by EUMETSAT. The second, provided by NOAA, is the Unique Combined Atmospheric Product System (NUCAPS). In contrast to the IRS, both products utilize the measurements of atmospheric emission in the infrared and microwave bands. The IASI infrared spectra between 645 and 2760 cm^{-1} are combined with 15 channels of Advanced Microwave Sounding Unit-A (AMSU-A, 15-90 GHz) and five channels of Microwave Humidity Sounder (MHS 89 to 190 GHz) observations [EUMETSAT, 2017]. The NUCAPS algorithm is based on the Cross-track Infrared Sounder (CrIS, 655-2550 cm^{-1}) and Advanced Technology Microwave Sounder (ATMS, 22 channels between 23-183 GHz) measurements [NOAA, 2021]. This infrared–microwave synergy allows for improved accuracy of vertical profiling in cloudy and partly cloudy environments.

The single instrument and synergistic retrieval algorithms developed in HErZ project HIRES-APP will be applied to the satellite and/or ground-based radiance data collected during VITAL II to retrieve temperature and humidity profiles (RO-NO). These profiles from the different data sources will be evaluated against the numerous VITAL II radiosondes (during GOP and IOP) and UAS profiles (during IOP) measured over the CB area (RO-NO). Especially the performance and information gain of the synergistic algorithms in the vertical transition region from ABL to free troposphere, where typically large gradients in temperature and humidity exist, is targeted. The evaluation scenarios for the synergistic retrievals are planned for

- clear sky cases under varying water vapor columns (from 15 - 40 kg m^{-2}),
- clear sky cases under varying aerosol optical depths (from 0.5 to 3),
- transitions between clear-sky stable ABL and daytime convective ABL,
- low-level and mid-level cloudy cases with varying cloud cover and optical thickness,
- high-level cloud with varying cloud cover and optical thickness

Note, comparisons will also be carried out against NWP analyses (always available) and against the satellite products provided by EUMETSAT and NOAA, when available.

5.1.6 APOLLO 2.0

A dense network of self-built Autonomous Cold Pool Loggers (APOLLO) sensors measuring 2 m temperature, pressure and humidity will provide the backbone of tracking and later analyzing cold pools as they propagate over the CB area (RO-CP). In addition, these data can by used in synergy with MTG-S1 satellite observations available every $\sim$ 7-9 km over the CB area, i.e. they provide a constraint on the lowest temperature and humidity values of the satellite retrieval (RO-NO). The first generation of APOLLO was used very successfully during FESST@HH and FESSTVaL. They will be reused in a revised form for VITAL II. The redesigned APOLLO 2.0s will have an external humidity sensor (SHT85) and an autonomous solar power supply. They will also transfer status information and measured data via LTE mobile communication. These features will drastically reduce maintenance requirements and enable the operation of a larger network. APOLLO 2.0 is currently being developed and tested in preparation for VITAL II.

For VITAL II, UHH is planning to install the stations on protected sites. In addition to installation at the profiling sites, further DWD stations and research institutions in the area, installation support comes from the local water management associations. Since previous studies did not find any significant differences between an opportunistic network design (FESST@HH) and a regular geometric one (FESSTVaL), the VITAL II team from UHH assumes that the slightly irregular station distribution will not influence the results. A station spacing of 5 to max. 10 km is planned with the aim to cover a representative area of the CB with $\sim$ 50 stations and to capture the transition from agricultural to urban land surfaces. The local Erft Verband and Bachverband will enable VITAL II to place APOLLO 2.0 stations along the Erft river and tributaries in a NW-SE orientation straight through the central CB area. A similar setup is planned along the Rur River in the more western part of the CB, also in NW-SE orientation (Fig. 1). In order to obtain sufficient statistics, measurements will be carried out over the entire duration of the campaign.

5.1.7 ATMOCORDER - Camera

The project HErZ-DA will contribute to VITAL II with two low-cost cloud cameras. The so-called ATMOCORDER was developed by Leonhard Scheck (LMU) as a ground-based camera for cloudy sky observations. The camera is based on a Raspberry Pi computer and camera. A prototype forward operator based on libRadtran 3D Monte-Carlo radiative transfer solver is also in development and will make it possible to assimilate these data into ICON-NWP, providing complementary information to satellite images. The system was successfully tested during VITAL I. One camera will be positioned at Sinthern, the second at UoC. This will allow further tests of the camera (with upgraded control software) and could certainly be beneficial for the cold pool research regarding the visual impressions of the convective system giving rise to the cold pool.

5.1.8 Eddy Covariance Measurements

In general, energy exchange processes between Earth surface and ABL are highly important for ABL and convective cold pool evolution but also highly variable in space and time. Because of limited resources, VITAL II will not be able to provide a representative coverage of surface fluxes over the CB area. However, VITAL II will access surface fluxes of momentum, heat and water vapor from the EC-station at Selhausen (operated by Forschungszentrum Jülich), just $\sim$5 km in the SSE of JOYCE. This will provide a background on Bowen ratio (quotient of sensible to latent heat flux) and thus characterize the overall surface influence on the convective activity, relevant for all VITAL II research objectives. Selhausen is integrated into ICOS and also part of the global FLUXNET.

5.1.9 Access to Public and Private Networks

The publicly available data from the DWD polarimetric C-Band radar network will provide essential input for identifying convective precipitation and thus the possible existence of cold pools (RO-CP). Established contacts with "Stadtentwässerungsbetriebe Köln" (STEB) will bring forward precipitation measurements from more than 15 stations within the Cologne city area. Additional, publicly available near-surface temperature, humidity, pressure and precipitation data from DWD, regional networks of the Federal State of North-Rhine-Westphalia, as well as through a data exchange partnership with the city of Cologne will be available and employed for cold pool analyzes and synergistic retrieval application.

5.2 Non-continuous Observations

In addition to the continuous observations described above, non-continuous atmospheric profiling observations will be carried out, respectively be available. These will state independent evaluation measures for the synergistic satellite / ground-based retrievals (RO-NO). In addition, they will provide details on the vertical structure of wind, temperature and humidity and give valuable information on the stability and turbulent structure of the ABL, e.g. before and after cold pool passages (RO-ABL, RO-CP). These observations include UAS profiling at Sinthern during the IOP in July/August 2026. Further, radiosondes will be launched on demand at Jülich (fixed launching site) and at variable, suitable profiling sites within the CB area by means of a mobile radiosonde launching system. Commercial aircraft data from Cologne-Bonn airport providing wind and temperature as a function of height during ascent and descent procedure will also be exploited.

5.2.1 UAS

We will equip the Sinthern site (∼13 km to the NW of Cologne) with a UAS multi-copter (UAS-MC) launching station during the VITAL II IOP. The VITAL II UAS-MC system supplied and operated by University of Tübingen (UT) consists of two identical multi-copters which guarantees uninterrupted observations without break during observational periods due to battery exchange measures.

The UAS-MC can measure high-resolution vertical profiles of temperature and water vapor and thus states an ideal opportunity for evaluating the combined synergistic satellite / ground-based algorithms (RO-NO). During the IOP, evaluation flights will target to cover atmospheric cases for the scenarios depicted in Sec. 5.1.5. In contrast to radiosondes, UAS ascents are limited in height ($<$ 2 km MSL), however can be performed continuously thus providing the possibility to evaluate the synergistic retrievals over the diurnal cycle.

Very recently UAS-MC measurements have not only shown to accurately measure the horizontal wind, but also the turbulence spectrum up to 5 Hz [Büchau et al., 2025] by means of attitude adjustments [Bramati et al., 2024] resulting in the derivation of TKE or momentum flux (see comparison with tower observations in Fig. 6). These characteristics make UAS-MC profiling and/or hovering at a constant height very valuable for capturing the ABL dynamic and thermodynamic diurnal evolution above a rural site (RO-ABL) or before cold pool passages (RO-CP).

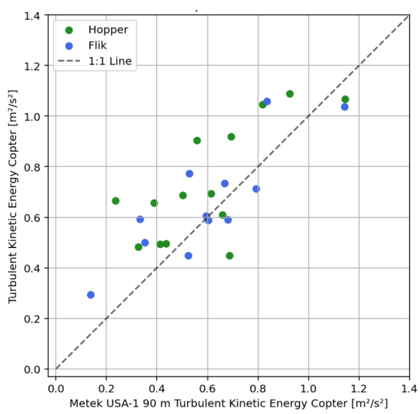

Figure 6: TKE measured by two UAS-MC called 'Flik' and 'Hopper' (vertical axis) versus sonic observations (horizontal axis) at a height of 90 m at the 99-m met-mast operated by the German Met Service at Falkenberg, Germany in February 2025. Each data point is a 2-min average, adapted from Büchau et al. [2025].

During the IOP, daily weather briefings (see Sec. 7) will decide if UAS-MC flights will be carried out on the following day of the IOP. The VITAL II science team will decide on one of two predefined strategies:

Flight Strategy 1: Vertical profiling to capture ABL characteristics. UAS-MC ascends vertically at 1 m/s up to 2 km, collecting continuous in-situ measurements of temperature, humidity, wind (speed and direction) with a vertical resolution of 1 m. The ascent thus takes about 30 min, after which the second UAS-MC can be launched so that profiles can be derived every ∼30 min These profiles allow calculation of wind, lapse rates and Bulk Richardson number. Turbulent quantities such as TKE and momentum fluxes will be derived using 60 m vertical averaging.

Flight Strategy 2: The UAS will hover at constant heights within the ABL. This enables the temporal variability of meteorological variables and turbulence to be captured at distinct heights. As the battery life of one UAS-MC is limited, it is continuously alternated with a second UAS-MC. During this time, the first UAS-MC can land, change batteries and ascend as soon as the second UAS has to land again. This will enable us to observe locally and continuously ABL transitions, e.g. from the well mixed ABL to a more stable ABL during cold-pool passage or the transition from the nocturnal stable ABL to the well-mixed convective ABL or vice-versa.

Due to regulatory requirements for drone operations, the applicants are in close contact with the civil aviation authorities and bring extensive experience conducting complex UAS missions, also over urban areas (e.g., UNLUBW project, www.unlubw.de). Existing concepts of operations and Specific Operational Risk Assessments from previous missions in Stuttgart will be adapted for the current project sites. Permissions for flights up to 2 km MSL (as carried out during VITAL I above Jülich) are being coordinated.

5.2.2 Radiosondes

A further independent measure of evaluation for the satellite / ground-based retrievals will be radiosondes (RO-NO). These will also be used to characterize the overall synoptic situation, as benchmark measurements for the ABL vertical structure compare for model assessment (RO-ABL) and for describing the atmospheric stability before and after the passage of cold pools (RO-CP). While UAS-MC launches will only be available during the IOP, radiosondes will be available throughout the whole campaign duration (GOP and IOP).

The permanent launching facility (Vaisala) for radiosondes at JOYCE can be accessed on demand for which at least 50 radiosondes are available. In addition, UoC has a mobile radiosonde launching system which will be made use of. Permissions for launching at the profiling stations Aachen, Sinthern, Erftstadt and Cologne City will be applied for, as has been done frequently for teaching and research projects. At least 50 launches are planned with the mobile system.

Of the available radiosondes mentioned above, at least ∼30 radiosonde ascents are explicitly planned within the GOP for synergistic retrieval evaluation at Jülich in addition to at least ∼30 radiosonde ascents above the Cologne City

(UoC) site. Radiosonde use is planned to be equally distributed for the different evaluation scenarios (Sec. 5.1.5). Further ∼20 ascents are planned at Jülich and ∼20 distributed at the sites Sinthern, Erftstadt and Cologne City (UoC) site (1) for characterizing the atmospheric vertical structure before, during and after convective cold pool events throughout the whole campaign and (2) for intensifying the IOP observations. These latter ascents will be carried out in coordination with UHH and the UAS profiling group.

All radiosonde ascents are planned to be submitted into the GTS (Global Telecommunication System) to make possible their use in real-time data assimilation applications.

5.2.3 Aircraft data

Additionally, VITAL II will access commercial aircraft data of winds and temperature measured during ascents from and descents to Cologne-Bonn airport via the EUMETNET E-ABO.

5.3 Observational Locations

In the following the existing and planned profiling sites (Fig. 1) are briefly described. In space, these span observations over the meso-β-scale. For the presented sites, the minimum operation requirements including external power supply, (mobile) network connection, non-obscured elevation scans down to 30° in all directions (unless specified otherwise) and a not too (human-activity) exposed location can be confirmed. Detailed site information, instrumentation specification and status as well as links to data and quicklooks are continuously updated on our VITAL wiki.

5.3.1 Aachen

In Aachen-Orsbach, DWD is running a pilot station for ground-based remote sensing. It is the only VITAL II station located not directly within the CB, but rather on the northern edge of the Eifel low mountain range, bordering the lowlands of the Lower Rhine Bay. It is located at 232 m MSL on a grass field in a flat terrain surrounded by agricultural fields. Available instruments include a DWL, a MWR, a ceilometer as well WV-DIAL (installation planned within 2025). These instruments measure automatically and continuously following DWD protocol. The VITAL II team is currently connecting with DWD colleagues from the Meteorological Observatory of Lindenberg (MOL) to clarify if the measurement modes of the instruments can be adapted to the VITAL II measurement modes during the campaign. In addition, Aachen-Orsbach is within the synoptic observation network of DWD, thus including high-quality near-surface meteorological observations.

DWL observations of winds, MWR profiling of temperature and WV-DIAL humidity profiles will provide the most western corner stone for characterizing cold pool vertical structure. The derived ABL profiles will represent diurnal developments of a mostly rural area, with the low-mountain Eifel region in the South and the city of Aachen 10 km in the Southeast.

5.3.2 JOYCE

The ACTRIS National Facility for cloud remote sensing JOYCE (Jülich Observatory for Cloud Evolution, Löhnert et al. [2015], www.joyce.cloud) will be an anchor profiling site of VITAL II. It is operated jointly by UoC and Forschungszentrum Jülich. JOYCE is situated on the rooftop of a 20 m building at 111 m MSL. The derived ABL profiles will represent diurnal developments over a mostly rural area, influenced by large lignite open pit mines in the surrounding 10–20 km.

JOYCE has been operative since 2011 being a major contributor in progressing ground-based active and passive microwave remote sensing. At JOYCE, the PLs of HIRES-APP successfully hosted the VITAL I campaign, including the HErZ 2024 Summer School on *Modern Methods in Atmospheric Profiling*.

At JOYCE the group of PL Löhnert operates a multitude of new and state-of-the-art ground-based active and passive remote sensing instruments for ABL vertical profiling and cloud and precipitation observations. This includes cloud radars, microwave radiometers, Doppler lidar, Raman Lidar (with water vapor and temperature profiling capability) among others. In addition, a 130 m meteorological tower, a permanently installed Vaisala radiosonde launching system and multiple radiation observations are operated continuously. Horizontal cloud inhomogeneities can be inferred from total sky imager and scanning MWR. A complete overview of the JOYCE instruments can be found on this website.

DWL observation of winds, MWR profiling of temperature and humidity and profiles from the 130 m meteorological tower as well as frequent radiosonde ascents will provide an important corner stone for the synergistic ground-based satellite retrieval application and evaluation as well as for characterizing cold pool vertical structure.

In addition, during VITAL II JOYCE will host the G-band Radar for Water vapor and Arctic Clouds (GRaWAC). GRAWAC is a FMCW Doppler-capable dual-frequency radar which transmits and receives simultaneously at 167.3 and 174.7 GHz. The unique frequency combination allows the application of the Differential Absorption Radar (DAR) technique [Lebsock et al., 2015] to continuously profile water vapor in cloudy and precipitating conditions. A synergy with MWR measurements further advances the retrieval of humidity profiles [Schnitt et al., 2020].

5.3.3 Vettweiß

An ideal profiling site for the VITAL II objectives has been identified in Vettweiß-Soller at a local ultra-light air field. This is the southern most profiling site in the SW of Cologne (33 km) and the ESE of Aachen (39 km). The local hosts (including flight club and airfield landlord) are supportive of installing VITAL II instrumentation. The District Government in Düsseldorf has cleared the operation of the VITAL II remote sensing instrumentation on a secure part of the airfield. The surrounding area is a flat, rural domain under agricultural use. Except for the farm house of the landlord at ∼100 m distance, the horizon is basically obstacle free. Thus, the site is ideally suited for low-elevation (<30°) scans with DWL and/or MWR. Currently, a MWR from UoC has been secured to be installed here. Different options for the installation of a DWL and standard meteorological observations are currently under consideration.

5.3.4 Sinthern

At Sinthern, the VITAL II team is collaborating with *Bachverband Pulheim*, the regional water management association. Sinthern is located within CB, about 13 km to the northwest of Cologne and is the northern most site. During summer, this frequently corresponds to down-wind conditions with respect to the city of Cologne, mostly due to the Rhine Valley channeling effect. The site is situated at 73 m MSL, a grass meadow within a rainwater retention basin with higher trees at ∼120 m and power lines at ∼200 m distance, respectively, towards the southwest. *Bachverband Pulheim* has agreed to support VITAL II through providing power and a platform suitable for placing an MWR, DWL and WV-DIAL in combination with a meteorological near-surface station. For the VITAL II campaign, the team plans to install a DWL (Vaisala Wind Scanner), as well as a Vaisala WV-DIAL in collaboration with our partner KIT. An MWR will be provided by KIT as well as standard meteorological observations by UoC. Sinthern will be the anchor site for UAS profiling. The VITAL II team from UT is currently applying for permissions to launch UAS of type multi-copter for on-demand profiling of temperature, humidity, wind and turbulence.

5.3.5 Erftstadt

GWU GmbH, a distributor of meteorological lidar systems, has confirmed the possibility of using their meteorological measurement field in Erftstadt-Lechenich. This site is located within the CB about 18 km to the Southwest of Cologne city in a business park surrounded by a mostly flat, rural environment. The height above MSL is 116 m. Elevation scans lower that 30° are possible in easterly directions. Surface-based meteorological measurements as well as possibly DWL observations will be available through GWU as such measurements are carried out there independently of VITAL II. For the VITAL II campaign it is foreseen to install an MWR from our partner KIT.

5.3.6 Cologne City (UoC)

The new remote sensing site in the southern part of the City of Cologne "Südstadt" is located on the central university campus. This station represents near surface and ABL observations in an urban environment, located in the Rhine river valley. A MWR and a DWL are currently installed on the roof of the Biochemistry building allowing for low-elevation scans in northwesterly direction. The DWL here is a WindCube, allowing to profile the wind vector only up to 400 m above the ground. For the VITAL II campaign, we plan to install a DWL (Vaisala Wind Scanner) with a higher maximum range, as well as a Vaisala WV-DIAL with our partner KIT.

At just 200 m distance, UoC is operating a weather station within the City of Cologne, including observations of temperature, humidity, wind, precipitation, four-component radiation and ozone concentration. A Vaisala CL51 ceilometern complements the remote sensing instrument suite.

5.3.7 CGN-Airport

The most eastern VITAL II station is planned within the secured area of Cologne-Bonn (CGN) Airport, located 17 km southeast to Cologne city (92 m MSL) in the Wahner Heathland. This area is at the eastern boarder of the CB denoting the transition to the low-mountain area "Bergisches Land". Channeling of the Rhine River valley leads to frequent SE flow in summer time so that this site is often upstream of the City of Cologne.

Currently, the VITAL team is clarifying with the responsible DWD administration under what conditions the instrumentation can be set up next to the DWD airport measurement station. Strict security procedures are required. For the VITAL II campaign, the team plans to install a DWL (HALO Streamline) from DWD's mobile observation unit in Potsdam (confirmed through F. Beyrich), as well as an MWR of UoC. Meteorological data will be available through the standard DWD observations on-site.

5.3.8 Meckenheim

If successful, we do consider the (challenging) realization of seven sites already a success, more than doubling the amount of profiling sites compared to FESSTVaL with a far lower VITAL II budget. Nevertheless, we are open for further collaboration with external non-HErZ partners. One possibility would be to extend the observations towards the southern part of the CB.

A further, eighth profiling station could be located at Radiometer Physics (RPG, a Rohde and Schwarz company). It is located in the business park of Meckenheim, south-south-west of the city of Bonn and lies in the southern part of CB. Observations at RPG represent a mostly rural environment, located above the Rhine river valley surrounded by the forest of the Ville in the East and agricultural fields in the West.

RPG has confirmed that VITAL II could use their observational platform, where more than one MWR is continuously operated, which could be used for scientific purposes. For this location, we have not yet identified a DWL system, but are open for further external participation.

6 Campaign Preparation

As depicted above, the preparations for instrument installation are currently on-going. A joint site visit of all VITAL II PIs and partners is planned in conjunction with an in-person workshop at UoC in February 2026. During the VITAL II planning phase all relevant information for each site and measurement type is inserted in and displayed through the VITAL II wiki. In the month of May 2026, the profiling and near-surface sensors will be installed at the planned locations. Each type of observational system described in Sec. 5 will be assigned to a group of one to two responsible scientists (instrument curators, IC) from UoC, UT or UHH. The ICs will be responsible for implementing the measurement strategy as given in Sec. 5, establishing a remote connection to the systems and guaranteeing continuous data transfer to servers at UoC, UT and UHH, respectively. Note, the IC team for the radiosondes will consist of a larger number of team members (4-5) so that launches with a lead time of one day will be generally possible.

In a further step, the ICs will be responsible for preparing the processing of the data to meteorological variables (if applicable), transferring the data to ATRIS (ATmospheric Research Data Information System, see Sec. 11) and displaying these via a VITAL II quicklook browser. As soon as the systems are installed, this data life cycle will be activated and tested step by step to be fully functional when the VITAL II campaign begins. Within the VITAL wiki, a separate logbook page for each instrument will be created to document the performance of each system. Additionally a measurement availability table will provide an overview over the status of each system.

7 Campaign Execution

During the course of the full campaign, a scientist in charge (SIC) will be assigned to each full week. The SIC will be the main point of contact for all scientific and public-relation issues during the corresponding week.

All relevant VITAL II reports, site and measurement information will be continuously updated and available through the VITAL II wiki.

7.1 General Obnservation Period - GOP

During the GOP the focus is on continuous (24/7) observations. The only non-continuous observations carried out by the VITAL II team during the GOP will be radiosonde ascents. Continuous surveillance (via remote access) and the ability to perform instrument maintenance on demand is required. The ICs will update the measurement availability table as well as the logbook (if required) daily, latest at 10:00 LT of the next working day for the past day. If necessary, the corresponding ICs will organize, as soon as possible, a maintenance visit to the affected instrument.

Reporting
The SIC will issue a short, daily report at 17:00 LT via the wiki. Depending on the weather situation, the two weekend days can be summarized in one report. The ICs and all other campaign participants are asked to deliver any noteworthy information to the SIC until 16:00 of every day. The report (2-3 pages max.) shall include information about the previous 24 h concerning

- general campaign activities (e.g. visits, common events, overflights, etc.),
- synoptic situation,
- local weather summary (e.g. ABL development, clouds and precipitation, radiation, etc.),
- changes in instrument status (e.g. addition of new instruments, instrument failure, problems, radiosondes launched, etc.),
- extraordinary/noteworthy events (if any, e.g. cold pools, LLJ, heat wave, etc.)
- weather forecast for next day and week

Radiosondes
The compilation of an evaluation data set for the synergistic temperature and humidity retrievals will be carried out during the GOP at Jülich and City of Cologne (UoC) with a planned number of ∼60 radiosondes (Sec. 5.2.2). The satellite ICs will continuously keep an eye on the forecasts and identify scenarios to fulfill the evaluation strategy as defined in Sec. 5.1.5. In case a suited scenario is forecast, the satellite ICs will contact SIC and the radiosonde ICs to organize corresponding ascents.

If potential for convective cold pool passages over the CB areas are identified from the forecasts for the upcoming days, the SIC will be in continuous contact with the PIs from UHH and the radiosonde ICs to plan radiosonde ascents at certain times and locations. Radiosondes can be launched from the profiling sites Aachen, Sinthern, Erftstadt, Cololgne City (UoC) with the mobile Graw launching system and from JOYCE with the fixed Vaisala launching system. If both UHH and satellite ICs have demands for radiosonde ascents on one and the same day, the SIC will decide on prioritization in consultation with all parties involved. Naturally, all cold pool radiosondes can also be used for synergistic retrieval evaluation.

7.2 Intensive Observations Period - IOP

Continuous observations will be operated during the IOP in the same manner as during the GOP. In addition to the GOP, regular UAS profiling will be carried out at Sinthern combined with intensified radiosonde ascents. If at the sites JOYCE, Aachen, Erftstadt, Sinthern and City of Cologne (UoC) with the fixed radiosonde system in Jülich and one mobile system for ascents at the other (variable) locations.

Reporting
In addition to issuing the short daily report as planned during the GOP, during the IOP, the SIC will organize a short on-line briefing at 17:00 LT where the daily report is presented.

UAS Profiling and Radiosondes
Based on this presentation, PIs from UT, UoC and UHH will decide upon the number and/or time span of UAS launches and the flight strategy (Sec. 5.2.1) for the next day, in addition to the number of radiosonde to be launched at which locations.

8 Partnering Campaigns

8.1 Zeppelin Campaign

In parallel to VITAL II, the PEGASOS Zeppelin-NT campaign by Forschungszentrum Jülich will be carried out under Georgios Gkatzelis (ERC Starting Grant) and Eva Pfannerstil (Helmholtz Investigator Group). The aim of the Zeppelin campaign is: a) to gain a better understanding of the exchange of organic trace gases between stressed forests and the atmosphere, and the resulting consequences for air pollution (ozone and particle formation), and b) to measure the exchange of organic trace gases between cities and the atmosphere, in particular mapping typical emissions that have received little attention in the past, such as "volatile chemical products" (household chemicals and solvents) as well as emissions from cooking, and their impact on air quality. The data will later be compared with emission inventories in order to improve them and thus ensure better air quality predictions and a better understanding of interactions between climate and air quality.

To this end, the Zeppelin campaign will be conducting direct emission flux measurements using airborne eddy covariance coupled with time-of-flight mass spectrometry, which provides spatially resolved (1-2 km resolution) emission and deposition data for hundreds of organic trace gases simultaneously.

Because the target regions for the measurement flights are the Rhine-Ruhr area, the Netherlands, Eifel, and Pfälzerwald the Zeppelin will also pass over the CB area. The VITAL II team is collaborating with the Zeppelin team to enable simultaneous UAS launches and Zeppelin overflights at Sinthern to independently evaluate the newly developed wind measurement system of the Zeppelin NT externally. The coordinated overpasses are planned for the first two weeks of August, the exact day depending on the weather situation.

8.2 C3SAR Campaign

The recently established DFG Research Unit C3SAR - Cloud 3D Structure and Radiation will perform a measurement campaign simultaneously to VITAL II at RAO Lindenberg in eastern Germany. The campaign also uses state-of-the-art ground-based and satellite remote sensing approaches to investigate 3D-cloud effects and is thus complementary to VITAL II. In order to understand the 3D-cloud effects this campaign addresses the need for synergetic studies combining in-situ, satellite observations and model projections. The PIs of both campaigns have been collaborating concerning the exchange of instrumentation and intend to coordinate their organization, if applicable. C3SAR is also conducting a summer school, where also VITAL II research objectives and methodologies can be presented and discussed.

9 Potential VITAL II Extensions

9.1 Nocturnal ABL Focus

The planned VITAL II measurement set-up bears a high-potential for addressing research questions that go beyond those posed in the current HErZ phase. The JETRANSIT (Illuminating Low-Level-Jets over a Rural-Urban Transition) proposal has been submitted jointly through HErZ PIs Sakradzija (SCALABLe), Platis and Löhnert (HIRES-APP) to DFG in September 2025 and aims for an improved understanding and modeling of low levels jets in the nocturnal Stable Boundary Layer (SBL) above the Cologne rural-urban transition. If supported, this project would exploit the VITAL II efforts for night-time observations of the SBL in terms of an already in-place unique measurement set-up. In this case, UAS and radiosonde observations up-wind, above and down-wind of the City of Cologne would be enhanced.

9.2 Airborne Lidar

A further, innovative possibility to probe the LLJ over the urban-rural transition would be via airborne 2D "wind-curtains". KIT plans to discuss with colleagues at the Technical University Braunschweig the possibility to conduct research flights with their Cessna aircraft, for which KIT has recently established the powerful five beam wind lidar system AIRborne fixed-beam lidar for wind measurements AIRflows that allows to measure the 3D wind in an unprecedented resolution of about 100 m in the vertical and horizontal direction.

9.3 Data Impact Experiments

The dense profiling measurements of the dynamic and thermodynamic structure of the ABL offer substantial potential for improving initial conditions for weather forecasts through their assimilation. Dedicated data impact experiments, specifically focusing on assimilating vertical profiles of wind and humidity, can provide valuable insights into the role of such profiling networks for convective-scale NWP. While these experiments could, in principle, be conducted in near-real time, it is more likely that the campaign observations will require careful post-processing and calibration before they can be assimilated. Consequently, such experiments do not necessarily need to be carried out simultaneously with the measurement campaign. VITAL II partners, together with KIT, will discuss the feasibility of conducting data impact experiments focusing on convective conditions. Such experiments could also contribute to the modeling strategy by providing improved analysis data used as initial and boundary conditions.

9.4 External Participation

Further external participation is welcome, especially concerning completing the measurement sites at Vettweiß, Erftstadt and Meckenheim with Doppler lidars reaching higher than ∼400 m. Currently, discussions with further potential partners are on-going

10 Education and Outreach

VITAL II will present an ideal environment for triggering Bachelor and Master theses at the HErZ partner universities. Ideas for such theses are currently emerging and will be brought together during the planned in-person 2026 VITAL II workshop.

While the HErZ 2024 Summer School during VITAL I was very successful and questions about a repetition were posed, there is currently no such event planned due to unavailable personnel resources. Nonetheless, practical courses from the HErZ partner universities can be integrated and planning is on-going. E.g., a Master module on "Observing the ABL over a wide Range of Terrain" is currently considered in conjunction with the LMU and parallel observations at the Zugspitze mountain. Also, the Bachelor "Storm Chaser" practical course, carried out together by UoC and UB, is planned to be integrated in VITAL II. Further, the DFG Research Unit C3SAR (Cloud 3D Structure And Radiation) is planning a measurement campaign integrating a summer school at RAO in Summer 2026. The VITAL II team aims to be present at the summer school and will advertise it within the HErZ network.

11 Data Management Plan

Our research data, consisting of the meteorological variables within the ABL, will be treated according to the FAIR (Findable, Accessible, Interoperable, and Reusable) principles. Access information to all publicly available research data will be provided through the HErZ website www.hans-ertel-zentrum.de. Observational data collected through the UoC, KIT, UHH or UoT instruments are transferred to institute servers for archiving of raw data and further processing within minutes of the observation. Processed data will be publicly displayed in near-real-time on a UoC web server.

All processed data will be made available to VITAL II community in near-real-time via ATRIS (ATmospheric Research Data Information System) which was successfully tested and applied during HErZ VITAL I. ATRIS is a data management system designed for comprehensive and reproducible management of atmospheric research data based on Forgejo. It keeps track of changes to contents and organization of files and provides secure remote access to hosted data by utilizing git, git-annex and DataLad. This service is hosted by the Institute of Climate and Energy Systems - Stratosphere (ICE-4) at Forschungszentrum Jülich. Processing and data quality control relies on the long-term research experience of the PIs. Established data life cycle procedures will be applied: UoC uses and develops Cloudnet processing, which is part of the European Research Infrastructure Consortium ACTRIS www.actris.eu, which will be applied to the remote sensing profiling observations. Once the data has reached a final form to be published, permanent data storage and DOIs will be established. We plan to make these data publicly available 12 months after the end of VITAL II. Currently VITAL II data archiving possibilities are considered at DWD or at the ICDC (Integrated Climate Data Center), where FESSTVaL data has been archived.

Modeling data used for driving the model runs will be publicly available for use in research free of charge via DWD (opendata.dwd.de). The final model data generated will be published through the World Data Center for Climate (WDCC) long-term open-access archive hosted by the German Climate Computing Center (DKRZ) in Hamburg. Raw data and intermediate model output will be stored at the DKRZ Tape Archive and available upon request. Detailed technical information and analysis scripts will also be provided on request for research purposes. Within 12-15 months after VITAL II, we plan to submit a common data publication with all VITAL II scientists.

References

Thomas August, Dieter Klaes, Peter Schlüssel, Tim Hultberg, Marc Crapeau, Arlindo Arriaga, Anne O'Carroll, Dorothée Coppens, Rose Munro, and Xavier Calbet. Iasi on metop-a: Operational level 2 retrievals after five years in orbit. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 113(11):1340–1371, 2012. ISSN 0022-4073. doi: https://doi.org/10.1016/j.jqsrt.2012.02.028. URL https://www.sciencedirect.com/science/article/pii/S0022407312000921. Three Leaders in Spectroscopy.

I. Bašták Ďurán, M. Sakradzija, and J. Schmidli. The Two-Energies Turbulence Scheme Coupled to the Assumed PDF Method. *Journal of Advances in Modeling Earth Systems*, 14(5):e2021MS002922, 2022. doi: https://doi.org/10.1029/2021MS002922. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021MS002922. e2021MS002922 2021MS002922.

Matteo Bramati, Martin Schön, Daniel Schulz, Vasileios Savvakis, Yongtan Wang, Jens Bange, and Andreas Platis. A versatile calibration method for rotary-wing UAS as wind measurement systems. *J. Atmos. Oceanic Technol.*, 41(1): 25–43, 2024.

Yann Büchau, Martin Schön, Kjell zum Berge, Samantha Gallatin, Jens Bange, and Andreas Platis. Enhancing High Resolution Atmospheric Profiling Using UAS: Deployment and Validation of the PARASITE Sensor Package. In *EGU General Assembly 2025, Vienna*, volume EGU25-11744, 2025. doi: 10.5194/egusphere-egu25-11744.

EUMETSAT. IASI Level 2: Product Guide , EUMETSAT document No:EUM/OPS-EPS /MAN/04/0033, 2017. URL http://www.eumetsat.int.

EUMETSAT. Algorithm Theoretical Baseline Document (ATBD) [EURD], EUMETSAT document No: EUM/RSP/TEN/17/935387, 2021.

C Hartwig, Y Wieczorrek, S Birkenstock, M Langen, S Ginzel, and M Kossmann. Lokale und regionale Windsysteme in der Kölner Bucht sowie der kanalisierende Effekt des Rheintals. *Imissionsschutz*, 2022. doi: 10.37307/j.1868-7776.2022.01.03.

Cathy Hohenegger, Felix Ament, Frank Beyrich, Ulrich Löhnert, Henning Rust, Jens Bange, Tobias Böck, Christopher Böttcher, Jakob Boventer, Finn Burgemeister, Marco Clemens, Carola Detring, Igor Detring, Noviana Dewani, Ivan Bastak Duran, Stephanie Fiedler, Martin Göber, Chiel van Heerwaarden, Bert Heusinkveld, Bastian Kirsch, Daniel Klocke, Christine Knist, Ingo Lange, Felix Lauermann, Volker Lehmann, Jonas Lehmke, Ronny Leinweber, Kristina Lundgren, Matthieu Masbou, Matthias Mauder, Wouter Mol, Hannes Nevermann, Tatiana Nomokonova, Eileen Päschke, Andreas Platis, Jens Reichardt, Luc Rochette, Mirjana Sakradzija, Linda Schlemmer, Jörg Schmidli, Nima Shokri, Vincent Sobottke, Johannes Speidel, Julian Steinheuer, David D. Turner, Hannes Vogelmann, Christian Wedemeyer, Eduardo Weide-Luiz, Sarah Wiesner, Norman Wildmann, Kevin Wolz, and Tamino Wetz. Fesstval: The field experiment on submesoscale spatio-temporal variability in lindenberg. *Bulletin of the American Meteorological Society*, 104(10):E1875 – E1892, 2023. doi: 10.1175/BAMS-D-21-0330.1. URL https://journals.ametsoc.org/view/journals/bams/104/10/BAMS-D-21-0330.1.xml.

B. Kirsch, C. Hohenegger, D. Klocke, R. Senke, M. Offermann, and F. Ament. Sub-mesoscale observations of convective cold pools with a dense station network in hamburg, germany. *Earth System Science Data*, 14(8): 3531–3548, 2022. ISSN 1866-3508. doi: 10.5194/essd-14-3531-2022. URL https://essd.copernicus.org/articles/14/3531/2022/essd-14-3531-2022.pdf.

Bastian Kirsch, Cathy Hohenegger, and Felix Ament. Morphology and growth of convective cold pools observed by a dense station network in germany. *Quarterly Journal of the Royal Meteorological Society*, 150(759):857–876, 2024.

P. Laj and Coauthors. Aerosol, Clouds and Trace Gases Research Infrastructure – actris, the European research infrastructure supporting atmospheric science. *Bulletin of the American Meteorological Society*, 2024. doi: 10.1175/BAMS-D-23-0064.1. URL https://journals.ametsoc.org/view/journals/bams/aop/BAMS-D-23-0064.1/BAMS-D-23-0064.1.xml.

M. D. Lebsock, K. Suzuki, L. F. Millán, and P. M. Kalmus. The feasibility of water vapor sounding of the cloudy boundary layer using a differential absorption radar technique. *Atmospheric Measurement Techniques*, 8(9):3631–3645, 2015. doi: 10.5194/amt-8-3631-2015. URL https://amt.copernicus.org/articles/8/3631/2015/.

E. W. Luiz and S. Fiedler. Can convective cold pools lead to the development of low-level jets? *Geophysical Research Letters*, 50(11):e2023GL103252, 2023. doi: https://doi.org/10.1029/2023GL103252. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2023GL103252. e2023GL103252 2023GL103252.

U. Löhnert, J. H. Schween, C. Acquistapace, K. Ebell, M. Maahn, M. Barrera-Verdejo, A. Hirsikko, B. Bohn, A. Knaps, E. O'Connor, C. Simmer, A. Wahner, and S. Crewell. Joyce: Jülich observatory for cloud evolution. *Bulletin of the American Meteorological Society*, 96(7):1157 – 1174, 2015. doi: 10.1175/BAMS-D-14-00105.1. URL https://journals.ametsoc.org/view/journals/bams/96/7/bams-d-14-00105.1.xml.

A. J. Manninen, T. Marke, M. Tuononen, and E. J. O'Connor. Atmospheric Boundary Layer Classification With Doppler Lidar. *Journal of Geophysical Research: Atmospheres*, 123(15):8172–8189, August 2018. ISSN 2169897X. doi: 10.1029/2017JD028169.

R. K. Newsom, D. D. Turner, R. Lehtinen, C. Münkel, J. Kallio, and R. Roininen. Evaluation of a compact broadband differential absorption lidar for routine water vapor profiling in the atmospheric boundary layer. *J. Atmos. Oceanic Technol.*, 37(1):47 – 65, 2020. doi: 10.1175/JTECH-D-18-0102.1. URL https://journals.ametsoc.org/view/journals/atot/37/1/jtech-d-18-0102.1.xml.

NOAA. Noaa unique combined atmospheric processing system (nucaps). algorithm theoretical basis document. version 3.1, 2021. URL http://www.eumetsat.int.

Ewan J. O'Connor, Anthony J. Illingworth, Ian M. Brooks, Christopher D. Westbrook, Robin J. Hogan, Fay Davies, and Barbara J. Brooks. A method for estimating the turbulent kinetic energy dissipation rate from a vertically pointing doppler lidar, and independent evaluation from balloon-borne in situ measurements. *Journal of Atmospheric and Oceanic Technology*, 27(10):1652 – 1664, 2010. doi: 10.1175/2010JTECHA1455.1. URL https://journals.ametsoc.org/view/journals/atot/27/10/2010jtecha1455_1.xml.

M. Sakradzija, A. Seifert, and A. Dipankar. A stochastic scale-aware parameterization of shallow cumulus convection across the convective gray zone. *Journal of Advances in Modeling Earth Systems*, 8(2):786–812, 2016. doi: https://doi.org/10.1002/2016MS000634. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016MS000634.

M. Sakradzija, M. Ahlgrimm, F. Beyrich, C. Heerwaarden, E. Päschke, U. Görsdorf, B. Kirsch, J. Schmidli, and N. Dewani. Where numerical weather prediction meets large-eddy simulations in a convective boundary layer during the FESSTVaL field experiment. *Quarterly Journal of the Royal Meteorological Society*, e70037, 2025. doi: https://doi.org/10.1002/qj.70037.

A. Sathe, J. Mann, N. Vasiljevic, and G. Lea. A six-beam method to measure turbulence statistics using ground-based wind lidars. *Atmospheric Measurement Techniques*, 8(2):729–740, 2015. doi: 10.5194/amt-8-729-2015. URL https://amt.copernicus.org/articles/8/729/2015/.

Sabrina Schnitt, U Löhnert, and R. Preusker. Potential of dual-frequency radar and microwave radiometer synergy for water vapor profiling in the cloudy trade wind environment. *Journal of Atmospheric and Oceanic Technology*, 37(11):1973 – 1986, 2020. doi: 10.1175/JTECH-D-19-0110.1. URL https://journals.ametsoc.org/view/journals/atot/37/11/JTECH-D-19-0110.1.xml.

J. Steinheuer, C. Detring, F. Beyrich, U. Löhnert, P. Friederichs, and S. Fiedler. A new scanning scheme and flexible retrieval for mean winds and gusts from doppler lidar measurements. *Atmospheric Measurement Techniques*, 15(10):3243–3260, 2022. doi: 10.5194/amt-15-3243-2022. URL https://amt.copernicus.org/articles/15/3243/2022/.

Julian Steinheuer, Frank Beyrich, and Ulrich Löhnert. Exploiting the full potential of doppler lidars: High-resolution wind-gust profiling in significant weather. *Quarterly Journal of the Royal Meteorological Society*, 151(769):e4961, 2025. doi: https://doi.org/10.1002/qj.4961. URL https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.4961.

G. Teschke and V. Lehmann. Mean wind vector estimation using the velocity–azimuth display (vad) method: an explicit algebraic solution. *Atmospheric Measurement Techniques*, 10(9):3265–3271, 2017. doi: 10.5194/amt-10-3265-2017. URL https://amt.copernicus.org/articles/10/3265/2017/.

Maria Toporov and Ulrich Löhnert. Synergy of satellite- and ground-based observations for continuous monitoring of atmospheric stability, liquid water path, and integrated water vapor: Theoretical evaluations using reanalysis and neural networks. *Journal of Applied Meteorology and Climatology*, 59(7):1153 – 1170, 2020. doi: 10.1175/JAMC-D-19-0169.1. URL https://journals.ametsoc.org/view/journals/apme/59/7/jamcD190169.xml.

Maria Toporov and Ulrich Löhnert. Monitoring regional atmospheric stability with hyperspectral satellite observations enhanced with a potential network of ground-based microwave radiometers. *Journal of Applied Meteorology and Climatology*, 2025. doi: 10.1175/JAMC-D-24-0212.1. URL https://journals.ametsoc.org/view/journals/apme/aop/JAMC-D-24-0212.1/JAMC-D-24-0212.1.xml.

Steffen Zacharias, Henry W. Loescher, Heye Bogena, Ralf Kiese, Martin Schrön, Sabine Attinger, Theresa Blume, Dietrich Borchardt, Erik Borg, Jan Bumberger, Christian Chwala, Peter Dietrich, Benjamin Fersch, Mark Frenzel, Jérôme Gaillardet, Jannis Groh, Irena Hajnsek, Sibylle Itzerott, Ralf Kunkel, Harald Kunstmann, Matthias Kunz, Susanne Liebner, Michael Mirtl, Carsten Montzka, Andreas Musolff, Thomas Pütz, Corinna Rebmann, Karsten Rinke, Michael Rode, Torsten Sachs, Luis Samaniego, Hans Peter Schmid, Hans-Jörg Vogel, Ute Weber, Ute Wollschläger, and Harry Vereecken. Fifteen Years of Integrated Terrestrial Environmental Observatories (TERENO) in Germany: Functions, Services, and Lessons Learned. *Earth's Future*, 12(6):e2024EF004510, 2024. doi: https://doi.org/10.1029/2024EF004510. URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2024EF004510.

Günther Zängl, Daniel Reinert, Pilar Rípodas, and Michael Baldauf. The ICON (ICOsahedral Non-hydrostatic) modelling framework of DWD and MPI-M: Description of the non-hydrostatic dynamical core. *Q. J. R. Meteorolog. Soc.*, 141(687):563–579, 2015. doi: 10.1002/qj.2378.