



Evaluating the scanning capabilities of an MWR to estimate temperature and humidity advection from a single site

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Abstract. Advection plays a fundamental role in the transport of heat and moisture within the Atmospheric Boundary Layer (ABL). Recently, horizontal advection has been quantified using ground-based remote sensing networks deployed at multiple locations. This study presents a novel single-site methodology to estimate horizontal temperature and humidity advection. Horizontal gradients are derived from a microwave radiometer (MWR) by exploiting its azimuthal scanning capability, while wind components are obtained from a Doppler wind lidar (DWL). Advection is estimated and a comprehensive uncertainty quantification framework is developed, based on standard error propagation and a Monte Carlo approach that accounts for correlated uncertainties in the MWR's observations. The resulting uncertainties are evaluated relative to the magnitude of advection over a range of horizontal gradients and wind speeds.

For typical ABL conditions, the uncertainty associated with humidity advection is approximately 60% of its estimated value, while temperature advection uncertainties reach 140%. However, under conditions characterized by strong horizontal gradients and high wind speeds, the observed magnitude of advection exceeds its uncertainties, enabling the detection of significant events such as frontal passages. As proof of concept, two strong advection episodes are analyzed. On 19 June 2022, a pronounced cold advection event was observed, and the current estimation captured intense cooling throughout the ABL, with vertically averaged values reaching -10 K h^{-1} , with relative uncertainties generally below 40%. A second case, on 8 October 2021, highlights humidity advection, with dominant zonal contribution at around 2300 UTC. The height-averaged estimated humidity advection reached $-10 \text{ g kg}^{-1} \text{ h}^{-1}$, with uncertainties typically below 30%. The present study provides a novel advection estimate and its robust assessment of capabilities and limitations, highlighting the clear identification of strong advection events in the ABL, reducing the logistic complexity of capturing this variable.



20 1 Introduction

The atmospheric boundary layer (ABL) is the lowest part of the troposphere directly influenced by the Earth's surface. Diurnal surface heating and cooling, driven by solar radiation, induce turbulent transport processes within the ABL (Stull, 1988). Interactions with the surface impose additional forcings—including aerodynamic drag, evapotranspiration, sensible and latent heat exchange, terrain-induced flow modification, and pollutant emissions—that modulate the ABL structure on hourly time scales and typically extend around two kilometers vertically (Schween et al., 2010; Marke et al., 2020; Jiang et al., 2022). Turbulent mixing highly impacts the transport and distribution of water vapor, momentum, and heat, shaping mass and energy exchanges between the surface and the atmosphere (Santanello Jr et al., 2018; Helbig et al., 2021). At a fixed location, the thermodynamic evolution of the ABL reflects both local surface-driven processes and the arrival of air masses with distinct properties. This latter mechanism—advection—often plays a central role in redistributing scalar quantities (Wang and Li, 2019; Rey-Sanchez et al., 2021) and is essential for closing local energy and moisture budgets (Wagner et al., 2022). Despite its importance, direct measurements and detailed characterization of ABL advection remain relatively scarce (Rey-Sanchez et al., 2021).

While large-scale thermodynamic mechanisms in the atmosphere are widely investigated via reanalysis datasets (Bieli et al., 2015; Zschenderlein et al., 2019), and temperature advection in the troposphere is generally well represented in numerical models (Naakka et al., 2021; You et al., 2021); processes occurring in the ABL are often more accurately characterized through ground-based observations (Kotthaus et al., 2022). Moreover, the increasing availability of high-quality ground-based remote sensing data across Europe, through research infrastructures such as the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) (Laj et al., 2024), further expands the capacity for such detailed investigations. Integration of multiple sensors within these networks is particularly valuable both for evaluating numerical models and for investigating mechanisms such as advection (Kotthaus et al., 2023).

Several strategies have recently emerged to derive advection estimates from ground-based observations. Rey-Sanchez et al. (2021) estimated potential temperature and specific humidity advection at wetland sites in the United States using meteorological station measurements combined with mean wind velocities, demonstrating the influence of advection on the seasonal variability of coastal ABL height. Vertically and temporally resolved advection estimates were later obtained at the Atmospheric Radiation Measurement (ARM) site in the Southern Great Plains site using remote sensing data (Wagner et al., 2022). In that study, a polygonal network of five observation nodes enabled the application of Green's theorem to relate line integrals to horizontal spatial derivatives, yielding temperature and humidity advection fields derived from an Atmospheric Emitted Radiance Interferometer (AERI) (Knuteson et al., 2004) and with the retrieval algorithm called Tropospheric Remotely Observed Profiling via Optimal Estimation retrieval (TROPOe) (Turner and Löhnert, 2014). An accompanying evaluation and uncertainty assessment confirmed strong qualitative agreement with model estimates (Wagner et al., 2022). A subsequent study further quantified the information content and propagated uncertainties from six contributing instruments (three AERIs and three Doppler lidars) to assess confidence in the retrieved advection fields (Turner et al., 2025).



Because advection estimation requires horizontal gradients, the most direct approach relies on spatially distributed measurements, as in the aforementioned studies. However, the full azimuth–elevation scanning capability of a passive microwave radiometer (MWR) allows temperature and humidity retrievals at multiple horizontal directions using a single instrument. Schween et al. (2010) demonstrated this concept by deriving gradients of absolute humidity and their direction with ~20-min resolution. They showed that persistent humidity gradients during a summer day over Jülich, Germany, coincided with the increase of winds, which suggested the horizontal transportation of humidity. The observed variability in this study could not be attributed to instrumental noise, which highlighted the potential of scanning MWRs to detect horizontal inhomogeneities. Moreover, Marke et al. (2020) detected spatial integrated water vapor (IWV) deviations and compared them with satellite-derived variations to link them to different land-uses. However, to our knowledge, no further studies have estimated advection from systematically assessing vertically-resolved horizontal gradients from a single scanning MWR.

The present study investigates the capability of a scanning MWR to detect horizontal inhomogeneities in both humidity and temperature to derive associated advection estimates. We combine MWR-derived thermodynamic fields with wind measurements from a Doppler wind lidar (DWL) to obtain temperature and humidity advection. A detailed evaluation and uncertainty analysis identifies the regimes of horizontal contrast and wind speed in which the advection estimates are reliable. Finally, two extreme advective events over Jülich are examined as proof of concept, demonstrating physically consistent temperature and humidity advection. This work establishes a foundation for broader exploitation of MWR scanning capabilities, which could be implemented at larger scales within MWR networks installed within ACTRIS.

2 Methods

The present investigation utilizes remotely-sensed temperature and humidity fields from a MWR and horizontal wind components from a DWL; both instruments in Jülich, Germany. The resulting advection estimate and its evaluation require multiple calculations in the current Section.

2.1 Site

The Jülich Observatory for Cloud Evolution (JOYCE) (Löhnert et al., 2015) is located within Forschungszentrum Jülich (FZJ) and constitutes an ACTRIS cloud remote sensing National Facility. JOYCE is located in western Germany at 50°54' N, 6°24' E, 111 m above mean sea level. The terrain around JOYCE is mostly flat, and includes small villages, farming and forested areas. The climate in Jülich is temperate and humid with monthly average temperatures between 3.1°C in January and 18.1°C in July (Löhnert et al., 2015).

2.2 Instruments

The present subsection details the instruments and data acquired by them. Furthermore, the temperature and humidity measurements are brought to the same horizontal and vertical grids as the wind. The data processing and methodological considerations required for the estimation of advection are also described



2.2.1 Microwave radiometer

- 85 MWR are passive sensors designed to detect electromagnetic radiation emitted from the atmosphere (Löhnert and Crewell, 2003; Crewell et al., 2021). We utilize the *Humidity and Temperature Profiler* HATPRO-G5 (RPG, Rose et al. (2005)). A retrieval based on a multi-variate linear regression algorithm and including a radiative transfer model (Mech and Löhnert, 2023), provides temperature and water vapor profiles along the line of sight (Marke et al., 2024). Retrieved temperature and humidity profiles are obtained every 15 minutes and vertically-resolved on a grid that has a spacing of 50 m between 0 and 1450 m, 200 m at 2 km, and decreasing beyond. Vertical temperature profiles are often retrieved utilizing zenith and off-zenith observations in the V-band, assuming horizontal homogeneity (Böck et al., 2024). In the present work however, we do not utilize this generally more accurate approach. Instead, we independently retrieve along-site temperature and humidity profiles at defined elevation and azimuthal angles. This enables the detection of horizontal inhomogeneities in temperature and humidity, which in turn provides the computation of advection in the ABL.
- 95 Key processes governing the dynamics of the ABL—including vertical mixing, turbulence, and the transport of heat and moisture—are more appropriately described using thermodynamic variables that remain conserved under adiabatic conditions. Because temperature and absolute humidity vary during vertical displacements, in the present study, we utilize potential temperature, θ and specific humidity q . These variables are obtained employing the standard Poisson equation for dry air and the thermodynamic definition of water vapor mass fraction as in Wallace and Hobbs (2006).

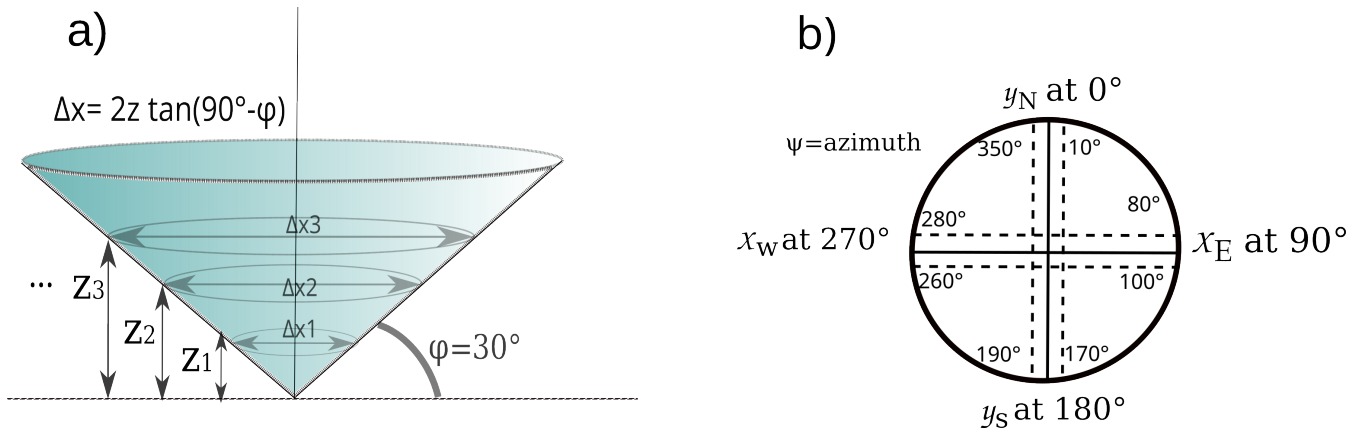


Figure 1. Schematic illustration of the 30° elevation scan of the MWR. a): Scanning pattern, at each height z there is a horizontal distance $\Delta x = 2z \tan(90^\circ - \varphi)$ between the North-South and East-West measurements. b): Azimuth angles at which the temperature and humidity horizontal differences are calculated

- 100 In order to investigate the horizontal variability of θ and q using the scanning capabilities of the MWR, the 30° elevation (φ) scans are utilized in the four cardinal directions (Fig. 1). This provides temperature and humidity at different horizontal locations, to estimate horizontal gradients at different heights from a single MWR. The temperature and humidity measurements are used in the four cardinal directions, North ($\psi = 0^\circ$), South ($\psi = 180^\circ$), East ($\psi = 90^\circ$), and West ($\psi = 270^\circ$). Moreover,



to reduce the noise, an averaging is performed around $\pm 10^\circ$ of each cardinal direction. That is, θ_E is calculated averaging θ at 80, 90 and 100° (Fig. 1b). Then, the differences are estimated:

$$\frac{\Delta\theta}{\Delta x} = \frac{\theta_E - \theta_W}{x_E - x_W} \quad \text{and} \quad \frac{\Delta\theta}{\Delta y} = \frac{\theta_N - \theta_S}{y_N - y_S}. \quad (1)$$

Estimations are likewise performed in zonal and meridional components to derive humidity gradients. To illustrate that horizontal variations can be captured by the MWR scanning, Fig. 2a) displays the azimuthally distributed evolution of air mass corrected slant-path-integrated absolute humidity up to 2 km on 8 October 2021, derived from MWR scans at 30° elevation. The gray areas correspond to the flagged data that were disregarded because they are not reliable at those directions. A clear moistening signal is detected after 1200 UTC in all azimuths; later at ~ 2230 UTC, a clear drying also takes place in all directions (Fig. 2 a). Given that the temporal variability dominates over azimuthal variability, we emphasize horizontal differences (Fig. 2b), where deviations relative to the azimuth-ally averaged values are presented. The deviations reveal clear azimuthal gradients, coinciding with the moistening and drying episodes. Between 0800 and 1200 UTC, moister conditions occur in the southern-directions than in the northern-ones. Similarly, after 2100, the directions $220^\circ < \Psi < 360^\circ$ (corresponding to the West) are moister than the eastern azimuthal angles. These detectable behaviors motivate further analysis of the horizontal inhomogeneities that can be deduced from the scanning capabilities of the MWR.

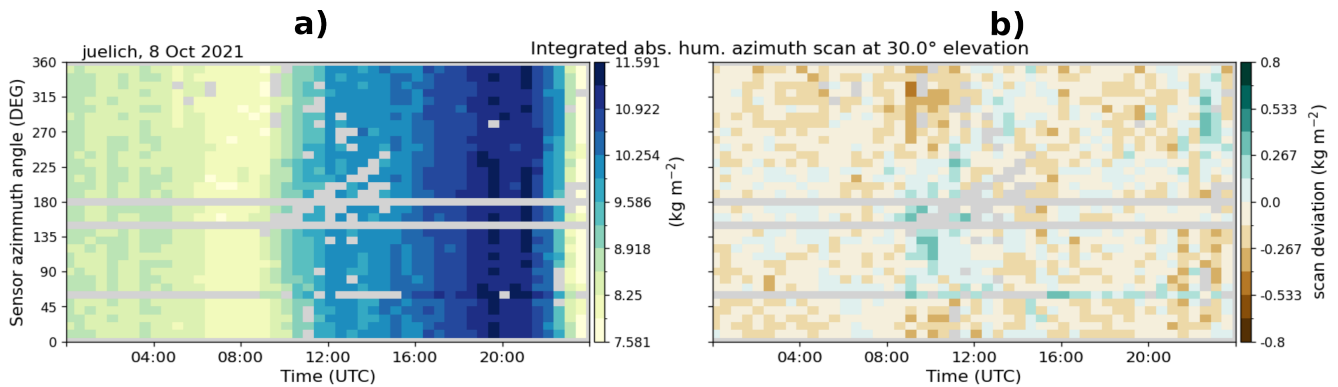


Figure 2. Integrated absolute humidity obtained from the 30° elevation scan from the surface to 2 km, approximately coincident with the ABL height. a): Air mass corrected slant-path-integrated absolute humidity on October 8, 2021. b): Deviations from the azimuthally averaged values from a)

2.2.2 Doppler Wind Lidar

Doppler wind lidars (DWLs) are active remote sensors that utilize the Doppler shift of elastically backscattered light to measure wind speed. The Doppler shift provides the wind speed along the beam, and measurements from multiple beam directions allow the three components of the wind vector to be estimated. The DWL at JOYCE is a Streamline XR pulsed lidar from HALO



Photonics that operates at a wavelength of 1500 nm with an average pulse energy of 100 μ J (Pearson et al., 2009). This instrument is capable of providing full hemispheric scans and range-resolved profiles of backscatter and Doppler velocity. Our measurement configuration consists of a 75° elevation velocity azimuth display (VAD) scan with 36 beams performed every 15 minutes, interspersed with vertical-stare measurements at 30 m vertical resolution.

2.3 Estimating advection

In the present work, advection is obtained via the scanning capabilities of the MWR (estimating the horizontal gradients via Eq. 1) and velocities from the VAD scan of the DWL (subsection 2.2.2), then the following equation is employed:

$$\mathbf{v} \cdot \nabla \theta = -\left(u \frac{\partial \theta}{\partial x} + v \frac{\partial \theta}{\partial y}\right) \approx -\left(u \frac{\Delta \theta}{\Delta x} + v \frac{\Delta \theta}{\Delta y}\right), \quad (2)$$

where $\mathbf{v} = (u, v)$ is the horizontal velocity vector with the zonal and meridional components. It should be noted that the wind vector we derive in this manner is assumed to be representative over the horizontal distances used for calculating the gradients. The humidity advection is estimated just as in Eq. 2, but replacing θ by q . A matching of measurements from MWR and DWL is performed with a common averaging over 30 minutes and vertically ranging in the same manner as the MWR resolution. These estimates are finally averaged vertically within the ABL in order to obtain the evolution of representative advection values. Additionally, to reduce the influence of instrumental noise, a temporal smoothing is applied to the advection via a moving average.

2.4 Assessment of uncertainties

Because the current advection estimate is a novel approach, the estimation of uncertainties in the final calculation is crucial. Given the estimate via Eq. 2, traditional uncertainty propagation methods are required (Taylor, 2022). However, the correlation between temperature and humidity measurements from the MWR in different directions needs to be considered and assessed accordingly, as presented in Subsect. 2.4.1. The assessment of advection uncertainties also requires the variables presented in Table 1.

2.4.1 Uncertainties of horizontal inhomogeneities

As shown by Böck et al. (2024), uncertainties of scanning MWR include pointing errors caused by a tilt of the instrument, the influence of physical obstacles in the line of sight of the instrument, and retrieval inaccuracies. As we obtain horizontal temperature and humidity differences from these MWR measurements, traditional uncertainty propagation methods are required (Bevington and Robinson, 2003; Taylor, 2022). However, since the horizontal inhomogeneities are estimated from a single MWR at different directions, their mutual correlation must be considered before applying the standard uncertainty propagation. Under typical atmospheric conditions, the temperature and humidity fields within the MWR scanning domain (radius < 5 km) do not show a pronounced spatial variability that highly influences the error. Consequently, it can be assumed that the atmospheric state induces the same errors in every azimuthal direction during MWR scanning. This assumption leads to the partial cancellation of retrieval errors when computing zonal and meridional differences (see Eq. 1). However, the random error



introduced by radiometric noise during the retrieval of thermodynamic profiles from T_B measurements in different directions remains. To isolate and quantify the influence of this noise, we implement a Monte Carlo approach following Blumberg et al. (2017), utilizing the error covariance matrix $\mathbf{S}$ to produce perturbed brightness temperatures ($\hat{\mathbf{T}}_B$) via the equation:

$$\hat{\mathbf{T}}_B = \mathbf{S}^{1/2} \mathbf{Z} + \mathbf{T}_B, \quad (3)$$

where $\mathbf{Z}$ is a normally distributed random number, and the specific values in the $\mathbf{S}$ matrix can be found in Fig. A1 (Appendix A); these values are consistent with the error analysis provided by Böck et al. (2025). Error covariance matrices are derived by viewing the MWR internal cold and ambient calibration targets. Given that the K-band (channels 1-7) corresponds to the water vapor absorption line, the cold load $\mathbf{S}$ is utilized for humidity retrieval. Correspondingly, the V-band, being in the oxygen absorption line, influences the temperature retrieval more strongly; thus, for channels 8-14, the ambient load $\mathbf{S}$ is utilized. By implementing Eq. 3, 500 Monte Carlo samples are derived for the T_B at each direction. Then, the horizontal difference between retrieved profiles (e.g. $T_E - T_W$) is estimated and plotted in Fig. 3. Finally, the influence of the radiometric uncertainty on the profile retrievals is estimated as two times the standard deviation from the mean profile (shown in black '+' signs in Fig. 3). This results in uncertainties of $\widetilde{\Delta\theta_{MC}}=0.4$ K for temperature and 0.18 gm^{-3} (equivalent to $\widetilde{\Delta q_{MC}}=0.13 \text{ g kg}^{-1}$) for humidity. These values are reported in Table 1 and propagated to the advection calculation.

Table 1. Typical values of variables for estimating the uncertainties of temperature and humidity advection

variable	symbol	value	obtained from
typical height	h^*	0.8 km	averaged inside ABL
typical horizontal distance	Δx	3 km	mean distance for horizontal diff.
uncertainty of θ	$\tilde{\theta}$	1 K	MWR retrieval
uncertainty of q	$\tilde{q}$	0.5 g kg^{-1}	MWR retrieval
typical temperature difference	$\Delta\theta/\Delta x$	0.1 K km^{-1}	estimated from MWR
typical humidity difference	$\Delta q/\Delta x$	$0.1 \text{ g kg}^{-1} \text{ km}^{-1}$	estimated from MWR
radiometric uncertainty of $\Delta\theta$	$\widetilde{\Delta\theta_{MC}}$	0.4 K	Monte Carlo sampling
radiometric uncertainty of Δq	$\widetilde{\Delta q_{MC}}$	0.13 g kg^{-1}	Monte Carlo sampling
typical horizontal velocity ABL	$\bar{v}$	4 m s^{-1}	DWL measurements
uncertainty velocity	$\tilde{v}$	1.5 m s^{-1}	DWL retrieval
typical temperature advection	$\overline{\mathbf{v} \cdot \nabla \theta}$	1.4 K hr^{-1}	estimated synergistically
typical humidity advection	$\overline{\mathbf{v} \cdot \nabla q}$	$1.4 \text{ g kg}^{-1} \text{ hr}^{-1}$	estimated synergistically
uncertainty temperature advection MC	$(\overline{\mathbf{v} \cdot \nabla \theta})_{MC}$	1.9 K hr^{-1}	propagating via Eq. 4
uncertainty humidity advection MC	$(\overline{\mathbf{v} \cdot \nabla q})_{MC}$	$0.8 \text{ g kg}^{-1} \text{ hr}^{-1}$	propagating via Eq. 4

To propagate the radiometric uncertainties into advection formulation, the radiometric uncertainties of θ and q differences ($\widetilde{\Delta\theta_{MC}}$ and $\widetilde{\Delta q_{MC}}$) are divided by the typical horizontal separation, $\Delta x = 3$ km. Then, since horizontal advection is computed

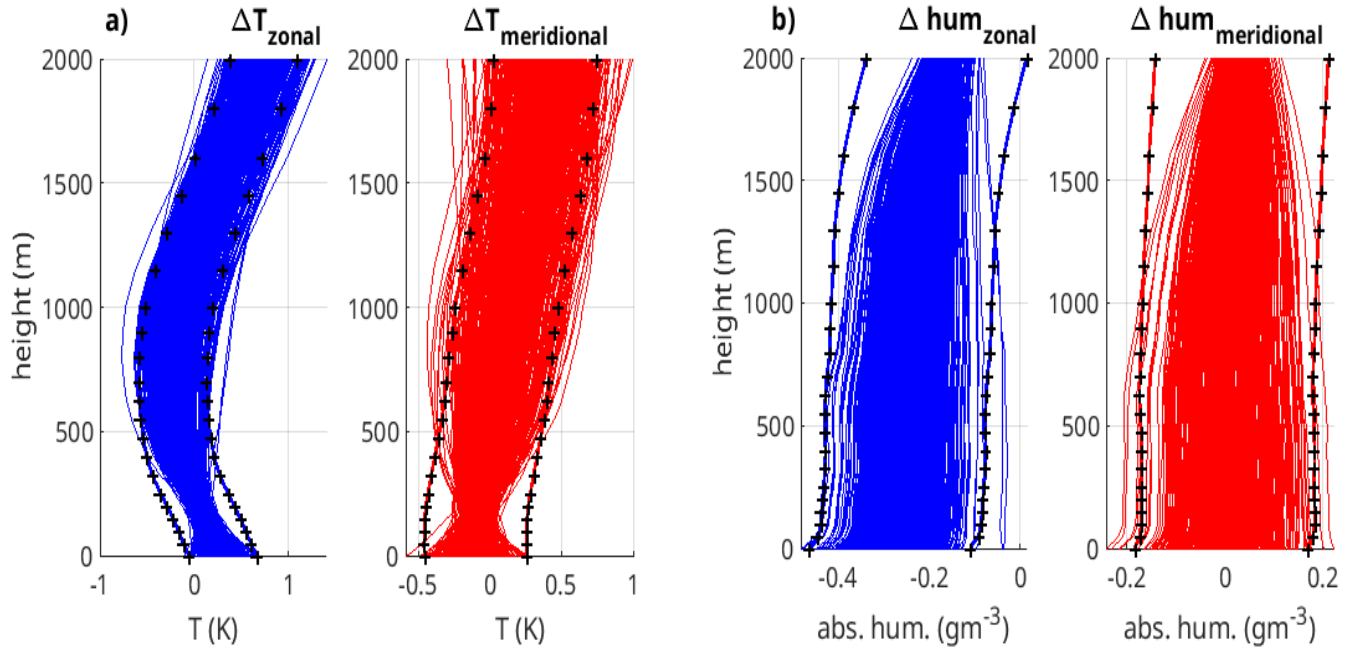


Figure 3. a): Perturbed temperature difference retrievals based on 500 T_B Monte Carlo samples. Blue profiles correspond to $\Delta T_{zonal} = T_E - T_W$ and red ones to $\Delta T_{meridional} = T_N - T_S$. The thicker lines with black '+' signs correspond to the standard deviations taken to estimate the radiometric uncertainties. All plots here correspond to 19 June 2022 at 1200 UTC. b): As in a) but for humidity retrievals

as the product of the horizontal gradient and the wind velocity (Eq. 2), the associated uncertainties of advection are propagated
 170 (Taylor, 2022), utilizing the equation:

$$\widetilde{\mathbf{v} \cdot \nabla \theta} = [(\widetilde{v(\Delta \theta / \Delta x)})^2 + (\widetilde{v(\Delta \theta_{MC} / \Delta x)})^2]^{1/2} \quad \text{and} \quad (4)$$

$$\widetilde{\mathbf{v} \cdot \nabla q} = [(\widetilde{v(\Delta q / \Delta x)})^2 + (\widetilde{v(\Delta q_{MC} / \Delta x)})^2]^{1/2},$$

where the meaning and typical values of all the variables can be found in Table 1. The resulting typical uncertainties of
 175 temperature and humidity advection are on the same order of magnitude as the advection itself (Table 1). In particular, the temperature advection uncertainty is $\sim 140\%$ of the temperature advection value and the humidity one is $\sim 60\%$ of the advection value.



2.4.2 Applicability regimes of advection estimate

As presented in Subsect. 2.4.1, the uncertainties of advection are estimated (Table 1) and typically reach $(\widetilde{\mathbf{v} \cdot \nabla \theta})_{MC} = 1.9 \text{ K hr}^{-1}$ and $(\widetilde{\mathbf{v} \cdot \nabla q})_{MC} = 0.8 \text{ g kg}^{-1} \text{ hr}^{-1}$. Despite these large values, the detectability of strong humidity gradients is clearly shown in Fig. 2; hence motivating the implementation of MWR scans to detect horizontal inhomogeneities, and subsequently estimate advection. The magnitudes of the advection and their uncertainties are dependent on the wind speed and the horizontal gradients of θ and q (Eq. 4). Thus, the present subsection explores how large the uncertainties are with respect to the temperature and humidity advection magnitudes for different regimes of horizontal inhomogeneities and wind speeds.

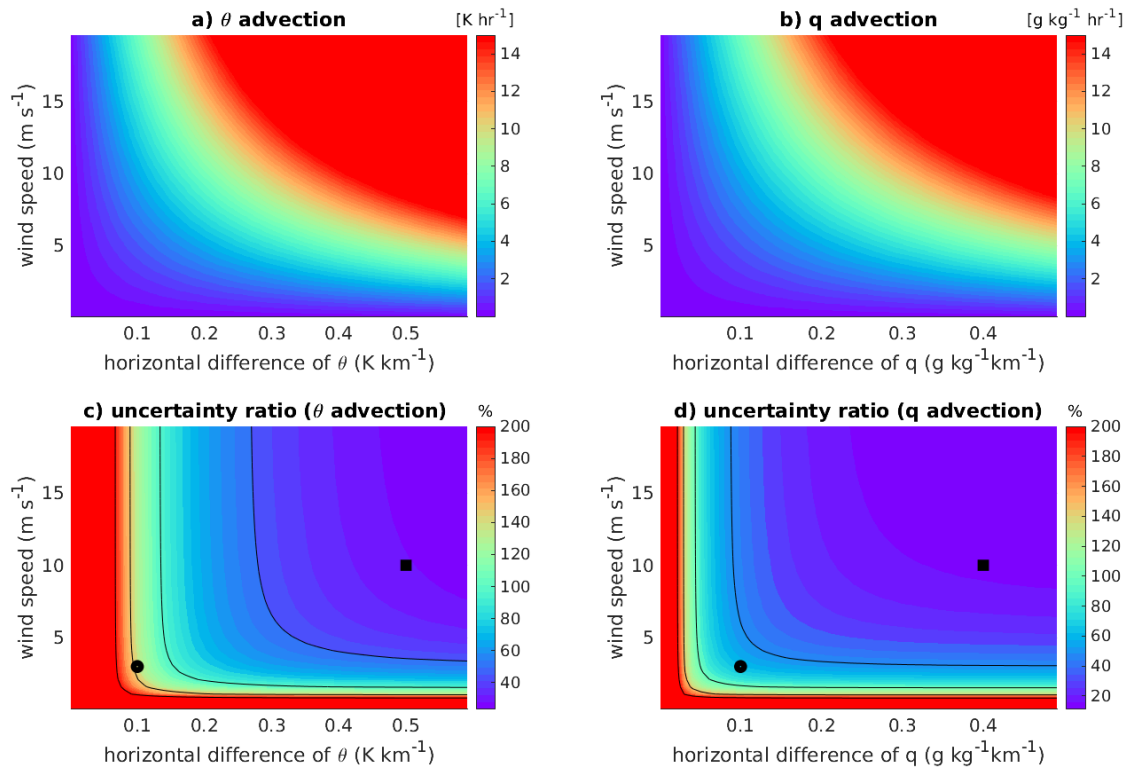


Figure 4. a) Magnitude of temperature advection for a range of temperature contrasts and wind speeds. b) Magnitude of humidity advection for a range of humidity contrasts and wind speeds. c) Relative uncertainty of temperature advection for the same ranges as in a), the black contours correspond to 50, 100 and 150 and 200%; the black circle represents an advection case for typical values of Table 1, and the square represents an extreme temperature advection case. d) Relative uncertainty of humidity advection for the same ranges as in b), black contours as in c), black circle represents a typical humidity advection case and black square an extreme episode

Figure 4 illustrates the magnitudes of horizontal advection (panels a and b) together with the relative uncertainties (panels c and d). For temperature advection, uncertainties increase substantially—by up to a factor of two—when horizontal temperature



gradients are smaller than 0.1 K km^{-1} and wind speeds are below approximately 1 m s^{-1} . The typical values listed in Table 1, result in a temperature advection of $\mathbf{v} \cdot \nabla \theta = 1.4 \text{ K hr}^{-1}$, corresponding to $\sim 140\%$ relative to the advection magnitude, as indicated by the black circle in Fig. 4c. In contrast, for horizontal temperature gradients exceeding 0.2 K km^{-1} and wind speeds greater than 3 m s^{-1} , the associated uncertainties become smaller than the magnitude of the temperature advection itself. This indicates that strong temperature advection events are detectable using the current methodology. When temperature gradients exceed 0.4 K km^{-1} and wind speeds are greater than 5 m s^{-1} , uncertainties are reduced to less than 50% of $\mathbf{v} \cdot \nabla \theta$.

For humidity advection, horizontal moisture gradients smaller than $0.05 \text{ g kg}^{-1} \text{ km}^{-1}$ combined with wind speeds below 2 m s^{-1} lead to uncertainties exceeding the estimated advection magnitude. However, such conditions correspond to extremely weak gradients. Even for the typical horizontal humidity contrasts and wind speeds reported in Table 1, the uncertainty remains moderate at approximately 60%, as shown by the black circle in Fig. 4d. This suggests that humidity advection is detectable even under non-extreme, representative atmospheric conditions. Moreover, when horizontal humidity gradients exceed $0.2 \text{ g kg}^{-1} \text{ km}^{-1}$ and wind speeds are greater than 5 m s^{-1} , the uncertainty in the humidity advection estimate decreases to below 50% of the advective magnitude. Overall, Fig. 4 provides a comprehensive assessment of the parameter space in which the MWR scanning-based approach for estimating horizontal advection produces reliable results. The figure clearly delineates the regimes where this novel methodology is expected to perform robustly.

3 Results

Given that the advection estimate is only smaller than its uncertainty for large horizontal contrasts and wind speeds, here we analyze two distinctively strong episodes (one for temperature and one for humidity advection) as proof of concept of our methodology. The thermodynamic structure and evolution of the ABL during these episodes are discussed, and the subsequent advection is estimated and analyzed accordingly.

3.1 Temperature advection estimate during strong temperature decrease

On 19 June 2022, at around 0300 UTC, an abrupt and strong temperature drop ($\sim 10 \text{ K}$ decrease in less than three hours) was detected by the MWR measurements (Fig. 5). Additionally, the horizontal winds reached velocities greater than 10 m s^{-1} and changed direction at that same time. The synoptic conditions from maps generated by the German Meteorological (*Deutscher Wetterdienst*, DWD), show an analyzed front that appears to be occluded or quasi-stationary over the area northern than Jülich at 0000 UTC. However, the actual temperature gradient can be displaced by ten up to perhaps hundreds of kilometers. Moreover, weak frontal waves often develop secondary frontal segments, in the present study we are likely detecting such a secondary circulation. Our analysis with the temperature gradients and wind velocities clearly points toward a cold advection event, as shown in the following subsections.



3.2 Temperature structure and wind fields

Figure 5 a,b,d and e illustrate the evolution of θ profiles in the four cardinal directions at 30° elevation from 18 June at 2100 UTC to 19 June 2022 at 1000 UTC. Higher θ values are reached at higher heights, as expected, given a stable stratification. A prominent feature, however, is the pronounced and rapid cooling during the first hours of 19 June. Specifically, θ decreases from approximately 306 K to 296 K between 0200 and 0400 UTC. This sharp and consistent cooling took place independently of the sunrise at 0518 UTC; which suggests that a non-diurnal cycle mechanism had a dominant role in cooling the ABL. Panels c) and f) of Fig. 5 present the zonal and meridional horizontal differences of θ , respectively, normalized by the corresponding separation distances (see Fig. 1). These gradients exhibit pronounced temperature contrasts around 0300 UTC. In particular, below 600 m, zonal differences reach 0.5 K km^{-1} (panel c), while meridional contrasts attain about 0.25 K km^{-1} (panel f). The meridional differences are also weaker and less persistent than their zonal counterparts.

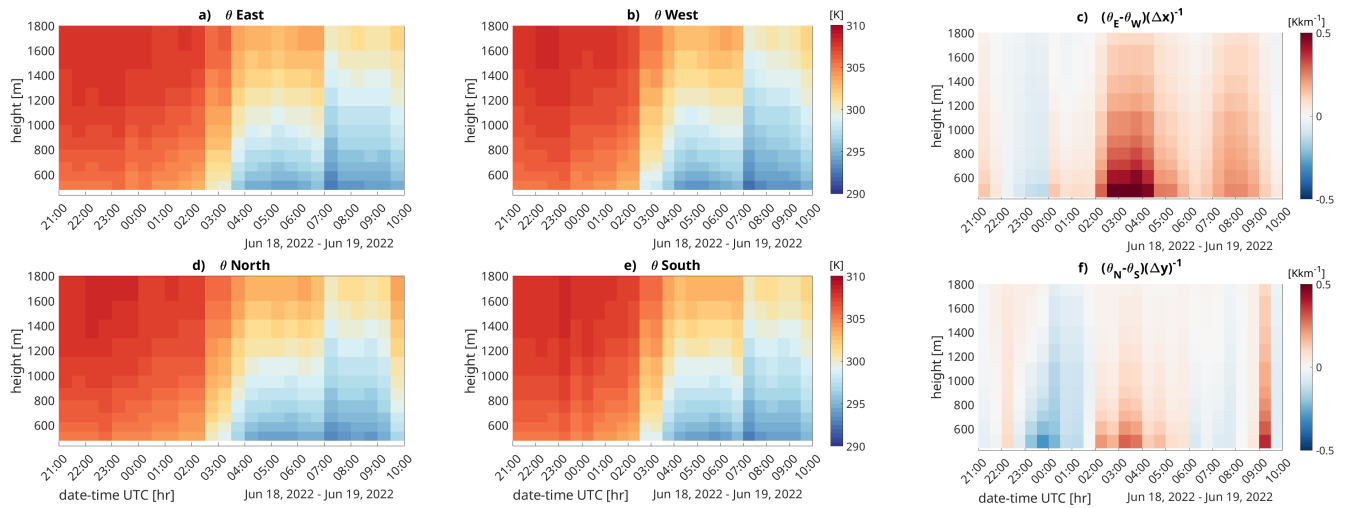


Figure 5. Temperature profile evolution in the ABL from 18 June at 2100 UTC to 19 June 2022 at 1000 UTC, derived from MWR scans observing towards the a) East, b) West, d) North and e) South directions. The horizontal differences scaled by the distance between them are shown for the zonal component in panel c) and for the meridional one in f)

It should be noted that the current approach has the difficulty of measuring weak horizontal gradients. Given the conical pattern of the scan (Fig. 1a), measured differences close to the surface in all azimuthal directions are performed closer together horizontally, and thus true small horizontal gradients may be difficult to discern given the uncertainties $\widetilde{\Delta\theta_{MC}}$ and $\widetilde{\Delta q_{MC}}$ (Table 1). Thus, it is necessary to introduce a minimum horizontal distance Δx_{min} for which we perform the estimations. To select a proper value Δx_{min} , we consider that the zonal and meridional differences in Figs. 5 and 9 range between $0.1\text{--}0.5 \text{ K km}^{-1}$ and $0.1\text{--}0.4 \text{ g kg}^{-1} \text{ km}^{-1}$ correspondingly. Thus, within a distance of $\Delta x_{min}=1500 \text{ m}$, we assure that both the temperature and humidity contrasts are larger than these values and therefore detectable according to Fig. 4. The relation between the horizontal distance Δx and the height z is given by $\Delta x = 2z \tan(90^\circ - \varphi)$ thus, below $z=433 \text{ m}$, the horizontal



distance is smaller than 1500 m and the corresponding measurements are disregarded. Above this height, we provide height-
235 resolved horizontal gradients that are later matched with the vertically resolved wind.

In addition to the temperature evolution in the ABL, the wind field represents a key variable in interpreting the observed abrupt cooling. The horizontal wind components in the zonal and meridional directions are presented in Fig. 6 a and b. Wind speeds generally increase with height, with the strongest velocities occurring aloft and weaker winds near the surface, consistent with friction and interaction with the surface. A period of particularly strong southerly flow, with wind speeds reaching up to 15
240 m s^{-1} above 600 m, occurs from 0000 to ~ 0200 UTC. Later, from ~ 0200 to ~ 0400 UTC, when the sharp drop of temperature is observed (Fig. 5), strong southwesterly flow predominates, reaching more than 15 ms^{-1} . To further elucidate the wind direction during this period, Fig 6 c presents a wind-rose considering winds during the period 0200-0400 UTC, and between 433 and 1300 m, which clearly shows the southwesterly wind. The southwesterly flow continues until ~ 0800 UTC, the zonal component continues reaching more than 10 ms^{-1} . After 0800 UTC, both the zonal and meridional components are weaker,
245 generally reaching less than 10 ms^{-1} .

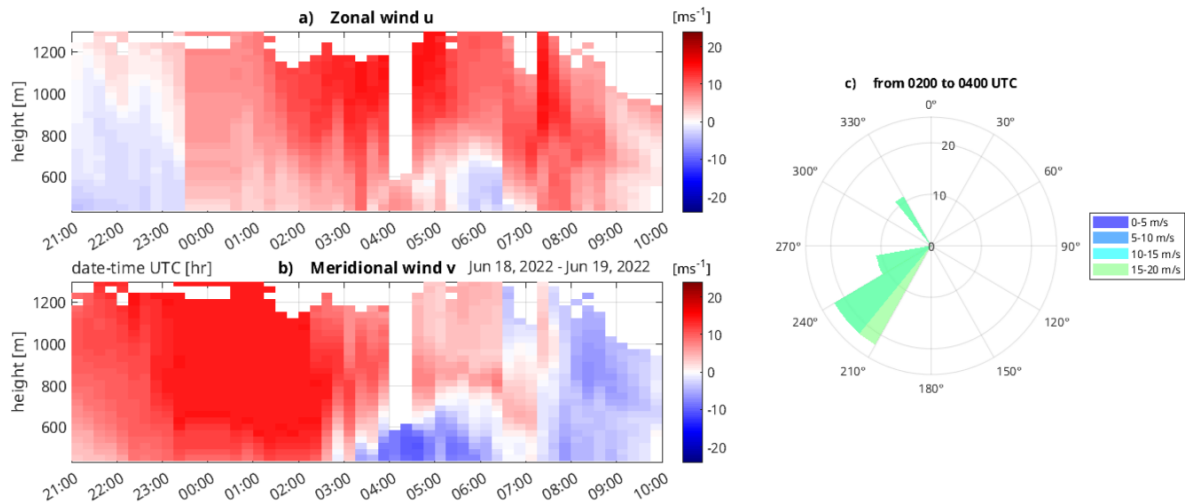


Figure 6. a) Zonal and b) meridional velocity components every 15 minutes from DWL from 2100 UTC on 18 June to 1000 UTC on 19 June 2022. Red tones represent eastward (and northward) directions, blue tones denote western (and southern) directions. c) Wind-rose showing the direction of wind magnitudes from 0200 to 0400 UTC on 19 June, and between 433 and 1300 m

The temporal coincidence of the strongest winds (Fig. 6) and the largest horizontal θ gradients (Fig. 5, panels c and f) at around 0300 UTC, points towards the detection of a strong temperature advection episode. Before 0500 UTC θ decreases ~ 10 K in all directions. In the meridional component, a distinguishable $\theta_S > \theta_N$ pattern is observed between 0000 and 0200 UTC. During this period, the wind is predominantly directed northward, which implies warm advection in the meridional component
250 during this short early period. However, between 0200 and 0800 UTC, θ_E consistently exceeds θ_W , coinciding with strong westerly flow. This very persistent behavior, which peaks between 0200 and 0400 UTC, indicates strong cold advection. This



interpretation suggests a dominant role of the zonal temperature difference and winds in substantially cooling the ABL (Fig. 5).

3.3 Advection estimate during strong cooling episode

255 MWR and DWL resolution is matched on a common grid (Subsect. 2.2.1), to estimate height and time-resolved temperature advection within the ABL (Eq. 2). Figure 7 presents both the behavior of θ within the ABL (averaged between 433 and 1300 m in panel a, and height-resolved in panel b), and the resulting evolution of advection. Panels c and d present the zonal ($u \cdot \Delta\theta/\Delta x$) and meridional ($v \cdot \Delta\theta/\Delta y$) components respectively. Finally, the total horizontal temperature advection ($\mathbf{u} \cdot (\Delta\theta/\Delta x + \Delta\theta/\Delta y)$) is shown in panel e. Panels a and b clearly elucidate the strong drop of temperature from 0200 to 0400

260 UTC. A pronounced warm meridional advection prior to 0200 UTC is detected in panel d, particularly above 600 m. However, after 0200 UTC, the advection regime shifts strongly to cold advection, with the zonal component (panel c) reaching values stronger than -5 K h^{-1} . Even stronger and more persistent cooling is observed in the total advection field (Fig. 7 e), reaching -10 K h^{-1} . The most intense phase of this cold-advection episode concludes around 0500 UTC; however, weaker but persistent cooling continues until approximately 0900 UTC.

265 To quantify the net impact of advection within all the ABL, vertical averages (within 433-1300 m) are computed, yielding time series of temperature advection and its uncertainty (Eq. 4) in Fig. 8. Periods of stronger wind speed result in increased advection uncertainty; nevertheless, the sign and temporal evolution of the advection remain robust during the cold advection episode. A pronounced negative (cooling) peak is evident at approximately 0300 UTC, particularly in the zonal component, with total advection reaching values more than -10 K h^{-1} . A secondary, weaker cooling peak of approximately -5 K h^{-1} occurs

270 near 0800 UTC. Meridional advection is strong only prior to 0200 UTC and is characterized by warm advection exceeding 5 K h^{-1} , but it only occurs before 0200 UTC. Subsequently, a rapid cooling ensues later in the day, consistent with the observed temperature evolution shown in Fig. 5.

Despite the relatively large uncertainties discussed in subsections 2.4.1 and 2.4.2, the strong cold advective event on the early hours of 19 June clearly exceeds the detection threshold. This can be identified in Fig. 4, where temperature contrasts of

275 0.5 K km^{-1} (such as those in Fig. 5 c) and velocities reaching 10 m s^{-1} (as in Fig. 6) result in smaller uncertainties than the advection values. This case is identified as the black square in Fig. 4c, which corresponds to uncertainties of less than 40%.

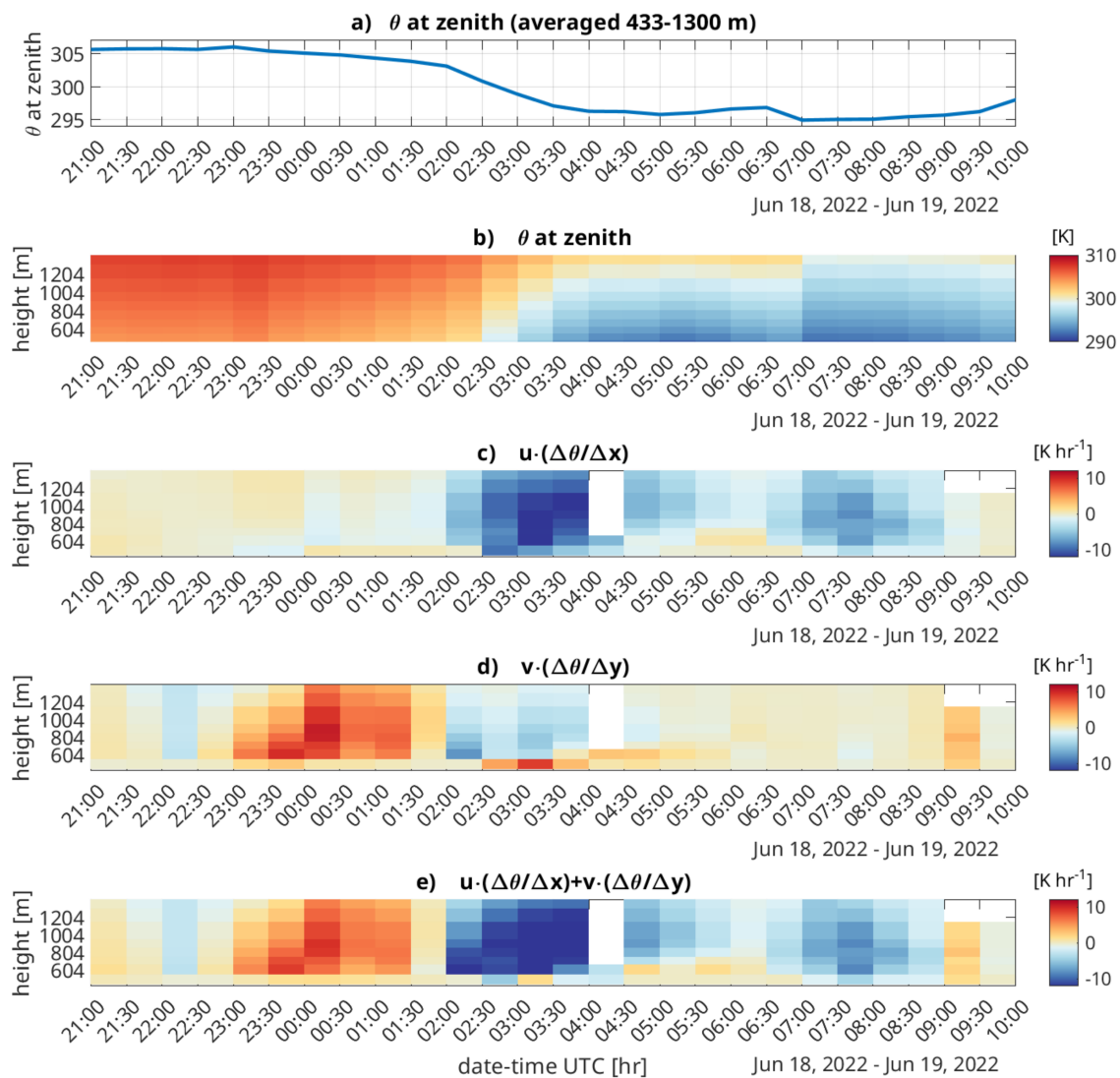


Figure 7. Temperature evolution in the ABL from 2100 UTC on 18 June to 1000 UTC on 19 June 2022. a) Time series of θ at the zenith, and averaged from 433 to 1300 m. b) Height-resolved θ evolution at zenith. c) Zonal and d) meridional vertically-resolved temperature advection evolution. e) Evolution of the total horizontal temperature advection

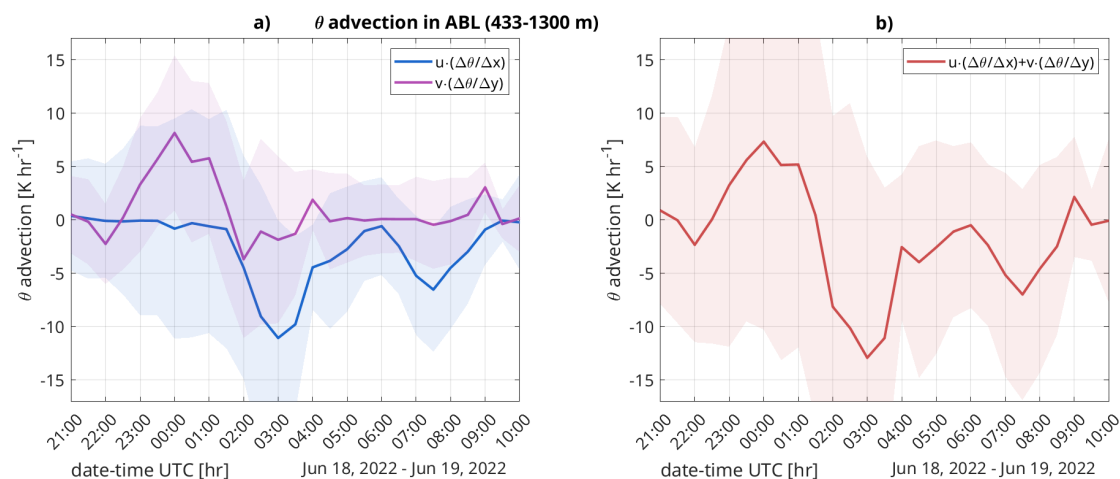


Figure 8. a) Time series of temperature zonal (blue) and meridional (purple) advection vertically averaged from 433 to 1300 m. The shadows correspond to the time-resolved uncertainties. b) Time series of the total advection (and its uncertainty), adding up components in a)

3.4 Strong drying case

During the last hours of October 8 and early October 9, 2021, a strong drying in the ABL was detected by the MWR observations; this coincided with the occurrence of very strong winds measured by the DWL. The synoptic conditions provided by the DWD show a high pressure system relatively stationary over Germany around 0000 UTC on 9 October, a detailed frontal passage cannot be clearly detected by this synoptic analysis. However, ABL processes are better characterized via ground-based remote sensors, and strong horizontal contrasts were already detected during the last hours of October 8, as shown in Fig. 2. Here, we illustrate that the MWR humidity measurements within the ABL detect a clear feature, as shown in each direction in Fig. 9 a,b,d and e. A strong decrease in specific humidity is elucidated from 2200 on October 8 to 0100 UTC on October 9, transitioning from $\sim 7 \text{ g kg}^{-1}$ to $\sim 3 \text{ g kg}^{-1}$. Although this behavior is consistent in all directions, it presents slight variations. The differences are more clearly shown in the Fig. 9 c and f, where the zonal and meridional contrasts are plotted correspondingly. From 2100 to 0100 UTC, dryer conditions in the East than in the West predominate. Similarly, from 2100 to 0000 UTC, the North direction appears moister than the southern MWR measurements. These strong gradients reach 0.5 g kg^{-1} in the zonal component, and they are smaller ($\sim 3 \text{ g kg}^{-1}$) for the meridional one.

Similarly to the temperature advection case, the structure and evolution of the horizontal winds are analyzed to understand their role in the drying of the ABL. Figure 10 presents the zonal and meridional wind components. The overall wind evolution reveals a persistent easterly flow that strengthens from 2100 to 2330 UTC on October 8. The meridional wind exhibits a consistent southerly direction after 2300 UTC. Moreover, the wind rose in panel c illustrates a very strong primarily easterly from 2100 to 0000 UTC. The concurrent examination of panel Fig 9c and Fig 10a from 2100 to 2330 UTC points towards the drier conditions in the East being transported to the West, which provokes a negative (dry) advection. In the meridional component (Fig 9f and Fig 10b), the northern measurements show moister conditions than those in the South, and although the

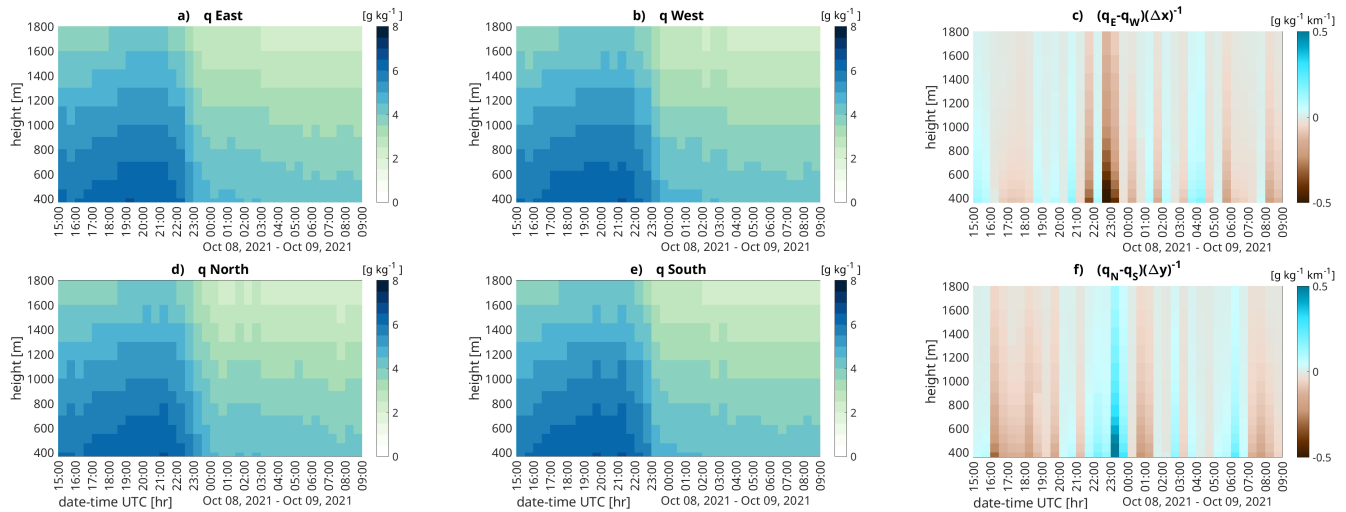


Figure 9. Evolution of q profiles at 30° elevation in all the different cardinal directions in the ABL from 1500 UTC on October 8 to 0900 UTC on October 9, 2021, derived from MWR a) East, b) West, d) North and e) South directions. The horizontal humidity differences scaled by the distance between them are shown for the zonal c) and meridional f) components

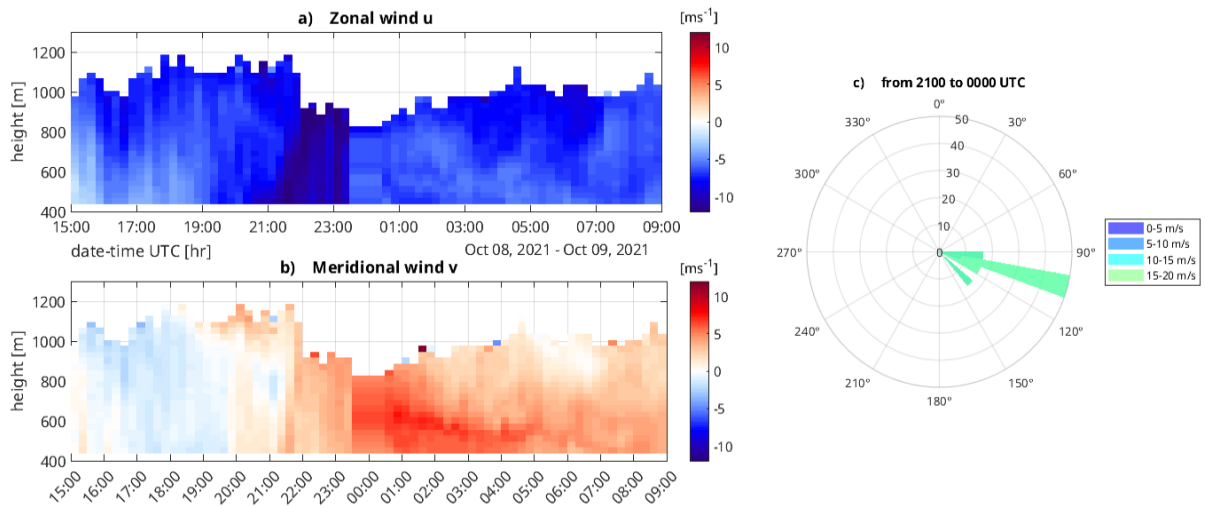


Figure 10. a) Zonal and b) meridional velocity components every 15 minutes from DWL from 1500 UTC on 8 October to 0900 UTC on 9 October 2021. c) Wind-rose showing wind direction from 2100 to 0000 UTC on 8 October, and between 433 and 1300 m

horizontal contrasts are not as strong as in the zonal case, the concurrent behavior with the southerly winds implies drier air in the south being transported to the North, which is also consistent with dry advection.



3.5 Humidity advection estimates

300 The humidity contrasts and wind speeds described in Subsect. 3.4, clearly point towards drying episode between 2100 and 0000 UTC. Here, we present the advection estimates via Eq. 2. The humidity advection is estimated height-resolved and the resulting evolution is presented in Fig. 11. Firstly, panel a shows the time series of integrated water vapor (IWV), during the complete investigated period. These values correspond to the vertically integrated amount of water vapor from the surface to the top of the troposphere; however, usually, most of the water vapor is close to the surface. Moreover, the evolution of IWV
305 clearly shows a significant drop from ~ 2130 to 2330 UTC; revealing that the amount of water vapor was decreasing rapidly in the whole atmospheric column. The absolute humidity at the zenith is plotted vertically-resolved in the ABL in panel b, which also points toward a strong drying on this lower sector of the atmosphere from 2230 to 2330 UTC.

The advection estimates are presented in the last three panels of Fig. 11. The zonal component (panel c) shows a drying tendency that reached $\sim 3 \text{ g kg}^{-1}\text{hr}^{-1}$ at 2200 . Later, there is a slight and short moistening, followed by consistent drying
310 reaching $\sim -5 \text{ g kg}^{-1}\text{hr}^{-1}$ and ending at 0000 UTC. The meridional advection is rather low but also shows a slight consistent drying at around 2330 UTC (panel d). Finally, the total horizontal advection in panel e points towards consistent drying from 2130 to 0000 UTC, reaching more than $5 \text{ g kg}^{-1}\text{hr}^{-1}$. Thus, despite the relatively large uncertainties assessed in Subsect. 2.4.2, Fig. 11 shows that the current advection estimate does capture this strong dry advection episode in the ABL.

The vertically-integrated ($433\text{--}1300$ m) humidity advection in the ABL and its uncertainties (Eq. 4) are presented in Fig. 12.
315 The clear drying from 2100 to 0100 UTC is captured because it exceeds its uncertainties. It is observed that the zonal advection has a major role in this drying; however, it has a positive peak at 2200 UTC, but later the drying tendency becomes stronger. Moreover, the meridional component also shows clear negative advection from 2230 to 2330 UTC, resulting in a total humidity horizontal advection that reaches $-10 \text{ g kg}^{-1}\text{hr}^{-1}$. This episode is identified as the black square in Fig. 4d, which corresponds to uncertainties of less than 30% . The overall behavior of q in Fig. 12 is very clear and the corresponding shaded uncertainties
320 are small enough to provide a confident humidity advection measurement during this very strong drying episode.

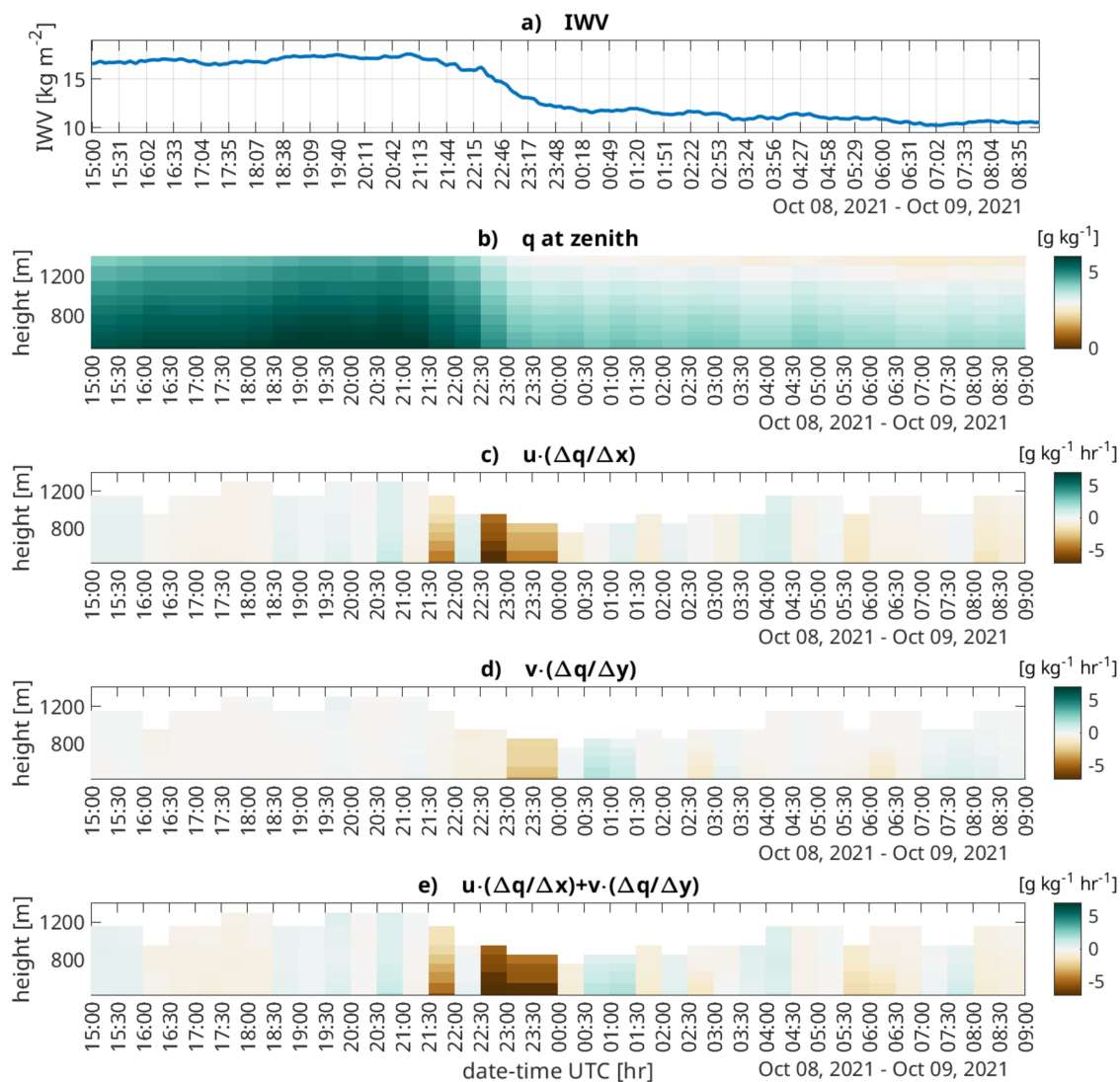


Figure 11. Evolution of variables from October 8, 2021 at 1500 UTC to October 9 at 0900 UTC. a) IWV over the troposphere. b) height-resolved q at zenith from 433 to 1300 m. c) Zonal vertically-resolved humidity advection evolution. d) Meridional vertically-resolved humidity advection. d) Sum of total horizontal humidity advection

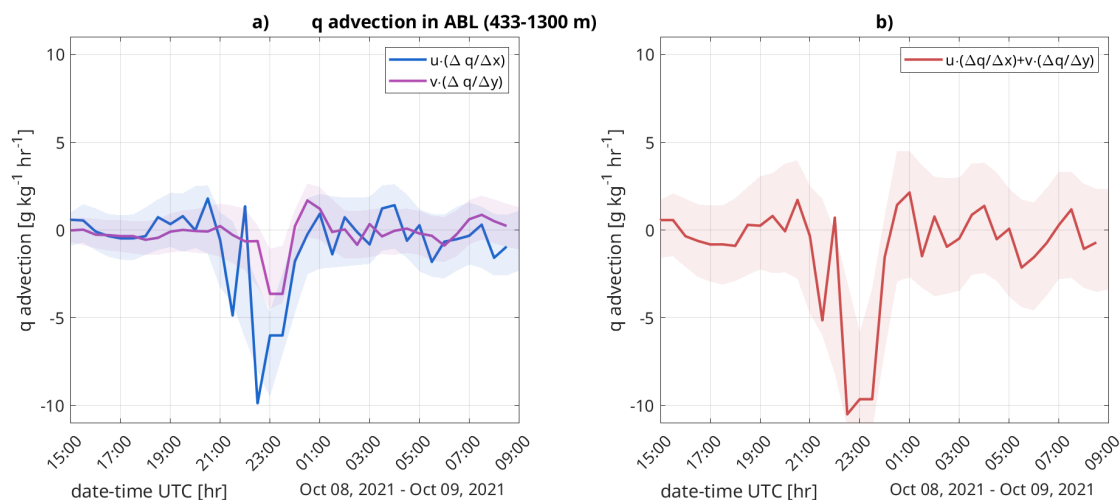


Figure 12. a) Time series of the zonal (blue) and meridional (purple) vertically-averaged humidity advection and their uncertainties. b) Time series of the total horizontal advection and its uncertainty

4 Conclusions

The present study utilizes remotely-sensed temperature, humidity, and horizontal wind components measured at a single site to synergistically estimate temperature and humidity horizontal advection. Given that advection inherently depends on spatial gradients of temperature and humidity, the present single-site estimation relies on the scanning capabilities of a MWR to estimate these gradients. This constitutes a methodological innovation that could significantly reduce logistical complexity for local advection estimates. As such, this new advection estimate is carefully evaluated, characterized, and tested in order to provide a useful assessment of capabilities and limitations for future investigations.

Temperature and humidity advection are estimated using 30° elevation scans from the MWR, which provide spatially distributed thermodynamic observations, combined with horizontal wind vectors from the DWL. Advection is computed directly using vector calculus; consequently, the associated uncertainties are representative and quantified through standard error-propagation methods that account for the intrinsic uncertainties of each remote sensor. Additionally, the correlation among MWR measurements at different azimuths has been considered. To this end, a Monte Carlo approach is applied using the full MWR channel correlation matrix. The resulting uncertainties in horizontal temperature and humidity differences are then propagated. Because advection uncertainty depends on both horizontal gradients and wind speed, the ratio of advection magnitude to its uncertainty is analyzed as a function of these variables. For typical ABL conditions at Jülich, humidity advection uncertainties are on the order of 60% of the estimated magnitude, increasing to approximately 140% for temperature advection. Nevertheless, during periods characterized by strong horizontal gradients and high wind speeds, advection intensifies and relative uncertainties decrease to below 50% for both temperature and humidity advection. These results reveal that when ad-



vection dominates atmospheric processes—such as during frontal passages—its quantification using the present methodology
340 is robust.

Two case studies—one focusing on temperature and the other on humidity—are presented as a proof of concept. The first case study examines the night of 18 June and the early hours of 19 June 2022, when ABL temperatures exceeding 305 K were observed over JOYCE. These anomalously warm conditions ended abruptly with the eastward passage of a cold front. Temperature measurements from the scanning MWR revealed persistently lower temperatures to the west than to the east
345 between 0200 and 0800 UTC, together with westerly winds (from DWL) exceeding 10 m s^{-1} . This configuration resulted in pronounced cold advection, which was most intense between 0200 and 0400 UTC and was clearly captured by the proposed methodology. During this period, the relative uncertainty of the temperature advection estimate remained below 40% of its magnitude.

The second case study focuses on humidity advection during the afternoon and night of 8 October and the first nine hours of
350 9 October 2021, when a pronounced drying of the ABL over JOYCE occurred around 2300 UTC. This drying was accompanied by strong south-easterly winds, which peaked between 2200 and 0100 UTC. The resulting humidity advection estimates clearly captured this event, with the strongest advection occurring in the zonal direction and near the surface. The total estimated advection during this period elucidates the evident drying, and the height-averaged advection time series confirmed this situation, reaching a drying rate of $-10 \text{ g kg}^{-1} \text{ hr}^{-1}$. Moreover, the corresponding uncertainties generally remained below 30%,
355 providing confidence in the detected drying episode and demonstrating that, under conditions of strong horizontal gradients, the scanning capabilities of the MWR enable the detection of horizontal advection from a single observation site.

In the context of the increasing availability and resolution of ground-based remote sensing observations, this study highlights the potential of synergistic single-site measurements for advancing the quantification of advective transport. The innovative framework presented here is accompanied by a careful assessment of its uncertainties, providing insight into its operational
360 applicability and the reliability of the proposed advection estimates. This framework also offers opportunities for future applications to better characterize the ABL dynamics. In particular, the derived advection terms could be integrated into mixing-diagram approaches to quantify the contribution of horizontal transport to the ABL energy budget and to distinguish local from advective influences on ABL evolution. Ultimately, this approach contributes to a pathway toward routinely incorporating advective transport into observation-based assessments of ABL budgets using measurements from a single ground-based site in
365 networks such as ACTRIS.

Appendix A: T_B error covariance matrices

Figure A1 shows two brightness temperature (T_B) error covariance matrices that are utilized to retrieve the Monte Carlo samplings of perturbed temperature and humidity profiles via Eq. 3 (Fig. 3). These T_B matrices correspond to HATPRO-G5, as assessed by Böck et al. (2025). First, the cold load covariance matrix is shown, it corresponds to channels 1-7 (table A1) and,
370 given that the frequencies correspond to the water vapor absorption K-band, it is utilized to perform the humidity retrievals.



Secondly, the hot load error covariance matrix, corresponding to channels 8-14, is utilized for temperature retrievals, given that these frequencies correspond to the oxygen absorption V-band.

Channel	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Frequency (GHz)	22.24	23.04	23.84	25.44	26.24	27.84	31.40	51.26	52.28	53.86	54.94	56.66	57.30	58.00

Table A1. Center frequencies of the 14 HATPRO channels (RPG-Radiometer Physics GmbH, 2015). Values as in Böck et al. (2024)

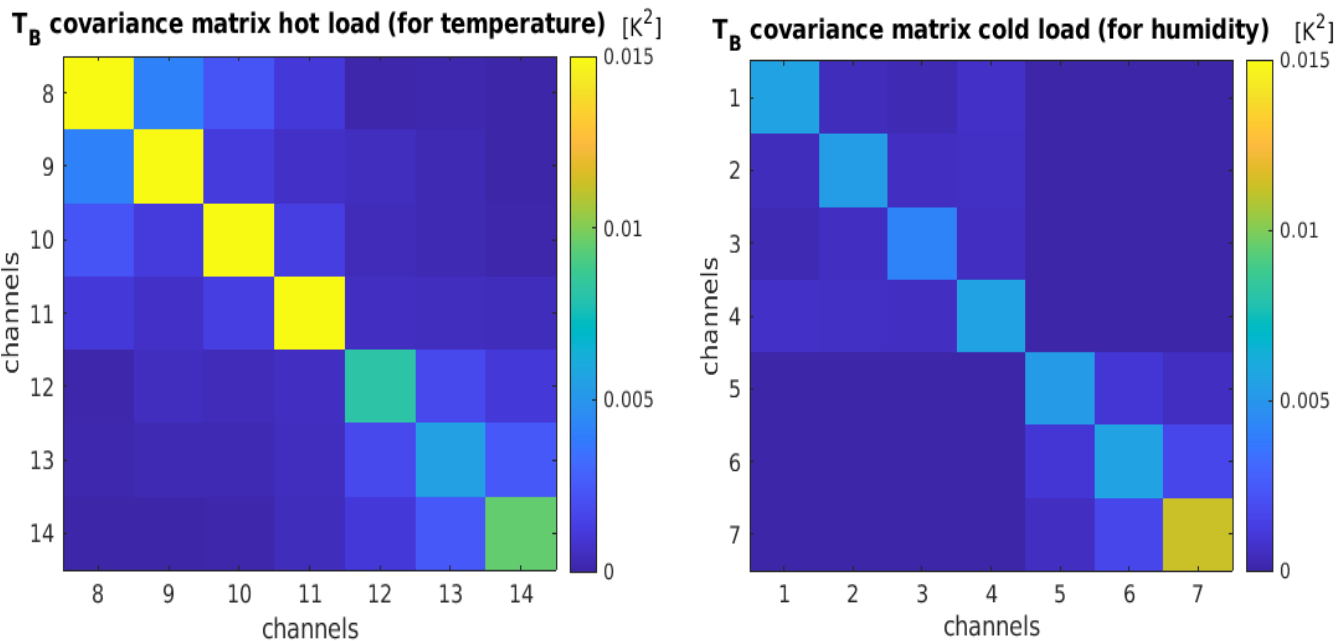


Figure A1. T_B error covariance matrices of the HATPRO-G5. The cold load (channels 1-7) is on the left and hot load matrix (channels 8-14) on the right side

Code and data availability. The data used in this study are generated by the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) and are available from the ACTRIS Data Centre using the following link: <https://doi.org/10.60656/da12e7a9142b45ad>. Given
375 that some products are not currently processed in the ACTRIS Data Center, all specific data for this investigation can also be found via Zenodo: <https://doi.org/10.5281/zenodo.21940721>. The analysis code used in this study is available at the GitHub repository https://github.com/andreaburgoscuevas/advection_estimate_MWR_scanning



Author contributions. ABC: Conceptualization, methodology, software, formal analysis, visualization and writing original draft. UL: Conceptualization, methodology and critical input in the analysis. DDT: Conceptualization, methodology and critical input on the analysis. JHS: Methodology and interpretation of the analysis. TM: Visualization and assisted with the preparation and formatting of data. TB: Validation of the analysis and provided matrices for verification of the results presented in the appendix. All authors contributed to reviewing and editing the manuscript and approved the final version.

Competing interests. The authors declare no competing interests.

Disclaimer. The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect those of NOAA or the Department of Commerce.

Acknowledgements. The work presented in this manuscript was funded by ACTRIS-D, the German infrastructure component for ACTRIS ERIC (European Research Infrastructure Consortium for Aerosols, Clouds and Trace Gases), through the German Federal Ministry of Research, Technology and Space (BMFTR) under grant agreements 01LK2001G & 01LK2002F. JOYCE is an ACTRIS National Facility for cloud remote sensing. In addition, JOYCE is a central measurement infrastructure of CPEX-LAB (Cloud and Precipitation Exploration Laboratory), supported through Geoverbund ABC/J (<https://www.geoverbund-abcj.de>, last access: 13 August 2026).



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