We thank the reviewer for their thorough assessment, feedback and comments on our manuscript. Please find our answers to the comments below with the original comment in *italics with light grey shading*, followed by our reply.

General Comments

1. *This paper nicely shows the potential of a sub-meso-scale observation network for providing insights to the initialization, evolution and decay of local Heavy Precipitation Events (HPE) over a hilly landscape in the south-east of Austria. In-situ and remotely measured meteorological variables are set into context with the precipitation development. However, I do see important factors missing in the data interpretation, which I outline in the Specific Comments below. These include the consideration of convective cold pools, advection and the synoptic situation.*

2. *This paper deals with observations. However, measurement principles and errors are not discussed at all. For each observation type and variable, the authors need to provide a sound physical background, including relevant references. The resulting uncertainties should be included in the discussion of the results. This is especially true for all variables derived from the MWR and the GNSS water vapor retrievals.*

   In order to provide a better overview of the measurement technique behind each variable, we expanded section 2.1. with a detailed listing and corresponding references. In addition, we added a reference to the data description preprint (Kvas et al. 2025), where details concerning quality control and inter-technique comparisons in the WEGN3D Open-Air Lab, specifically GNSS and MWR water vapor retrieval, are given.

3. *The MWR observations need to be interpreted in a more critical manner. Please quantify vertical resolution of the MWR retrievals and discuss the implication of vertical resolution of the MWR retrievals of the temperature and humidity profiles on the your interpretations.*

   Thank you for this comment. We amended the manuscript with a paragraph discussing the coarse (and varying) vertical resolution of the MWR retrievals on the temperature and humidity profiles, to put the observations in a better physical context. Specifically, we added

   L81: *Their main drawback is a comparatively coarse vertical resolution, especially for humidity retrievals (Barrera-Verdejo et al., 2016; Walbröl et al., 2024; Blumberg et al., 2015). Thus, MW radiometers trade vertical resolution and vertical coverage with temporal resolution compared to radiosondes (Rose et al., 2005).*

   to the dataset description in section 2.1 and

   L212: *The comparatively coarse vertical resolution of the radiometer-derived WEGN temperature and humidity profiles is evident, with very little vertical variation visible above 1.5 km - 2 km.*

   to our interpretation of the temperature and humdity anomaly profiles (section 3.1).

   For details concerning the impact of the vertical MWR resolution on the derived CAPE values, please see our response to your specific comment No. 2.

Specific Comments

1. *Table 1: If I understand correctly, only one station provides wind speed information? If so, please indicate this in Fig. 1 and/or clarify.*

   Thank you for bringing that to our attention. The station we chose to get our wind speed information from is not the only one in the WEGN3D that provides wind speed, however, it is the one that is located closely to our radiometer station. By using this station we ensure that our wind speed data is linked to the same precipitation systems as the parameters we obtain from the radiometers. To clarify this also in the manuscript we added the following sentence:

   L98: *For this study we decided to use the wind speed sensor that is located closest to the radiometer site to ensure that the measured wind speeds and the parameters obtained from the radiometers are connected to the same precipitation systems.*

2. *The observed CAPE values from the MWR in Fig. 3 are significantly smaller than the ERA5 values and also smaller than one would expect for HPE. CAPE values over 1000 J/kg are not exceptional over Europe. Please discuss where this originates from. And in this respect, describe in detail, how and what type of CAPE you have calculated. How do the values of the nearest radiosonde stations (Zagreb?) compare? Also, MSG-Seviri (and maybe already MTG?) provides a CAPE product which you should compare to.*

   Thank you for this observation. We attribute the lower CAPE values to the comparatively coarse resolution of the MWR-derived temperature and humidity profiles. To verify this assumption, we computed "MWR-like" profiles from Zagreb radiosonde data by adaptive smoothing to resemble the vertical resolution of the MWR (see Figure R1). The smoothing is implemented by aggregating all values within an altitude-dependent range according to Blumberg et al. 2015. We then compared surface-based CAPE values derived from the original radiosonde profiles to the "MWR-like" ones over a 4 year time span and found a CAPE reduction of 36% (see Figure R2). This behavior is also consistent with previous studies (e.g., Gartzke et al. 2017).

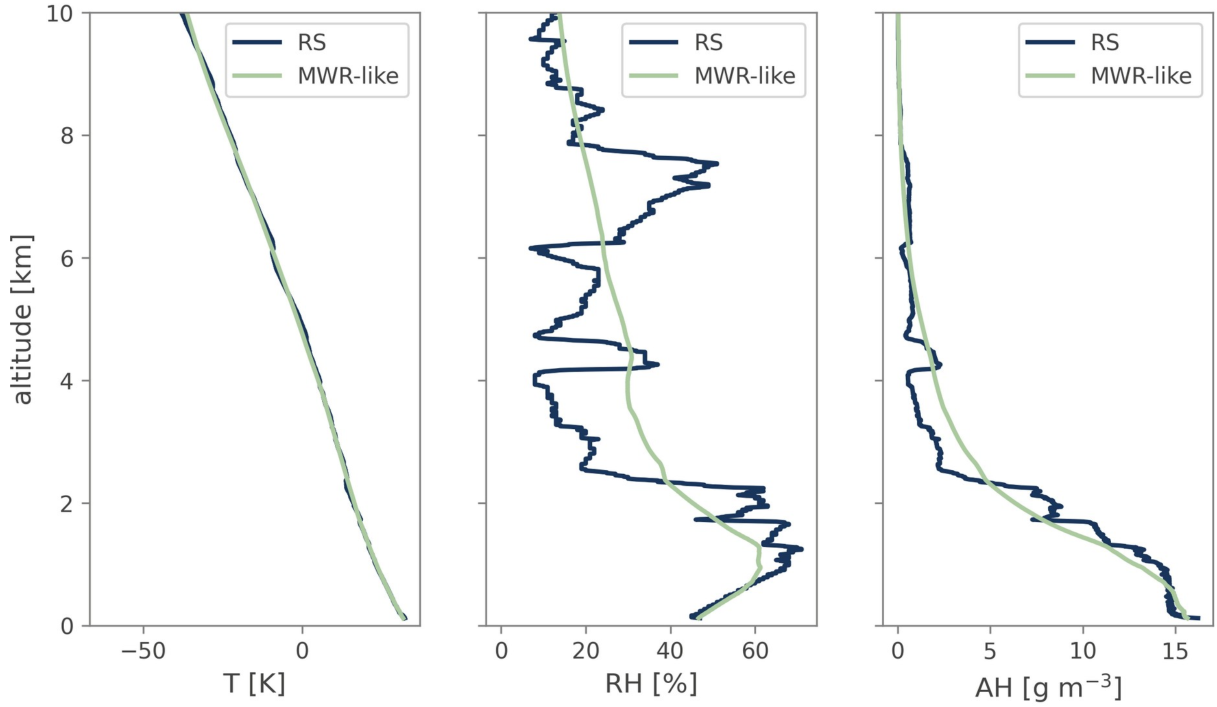

Figure R1: Comparison of original radiosonde (RS) and smoothed "microwave radiometer (MWR)-like" profiles of temperature (T), relative humidity (RH), and absolute humidity (AH) for a single launch at Zagreb 2024-07-28 12:00.

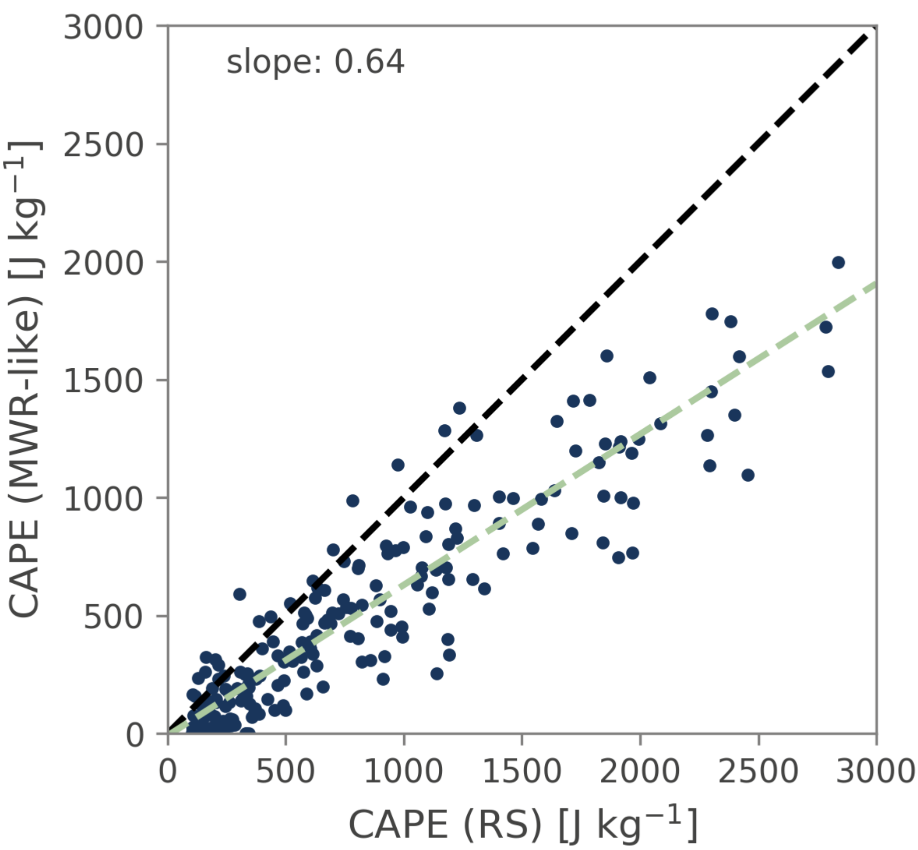

Figure R2: Scatter plot of surface-based CAPE values derived from radiosonde (RS) and smoothed, "mircowave radiometer (MWR)-like" profiles over a 4 year time span.

To better communicate this effect, we amended section 2.2.2. with the following paragraph:

L129: *Note that due to the comparatively coarse resolution of the radiometer-derived temperature and humidity profiles, the resulting CAPE values are lower than, for example, radiosonde-derived ones (e.g., Gartzke et al. 2017). We thus focus on the temporal evolution of CAPE, rather than absolute values.*

We calculate the (surface-based) CAPE using the cape_cin function (https://unidata.github.io/MetPy/latest/api/generated/metpy.calc.cape_cin.html) of the MetPy package, which follows the formula by Hobbs (1977):

$$CAPE = \int_{SL}^{LFC} R_d (T'_v - T_v) \, d\ln(p)$$

$CAPE$ … convective available potential energy

LFC … pressure of level of free convection

SL … pressure of surface level

R_d … gas constant

T'_v … parcel virtual temperature

T_v … environment virtual temperature

p … atmospheric pressure

We amended section 2.2.2 to make it clear that surface-based CAPE is used throughout the study.

3. *In Section 3.1 you write: Another effect of the convective nature of HPEs is the deepening of the convective cloud system, represented by a decrease in the CBH anomaly of about 1000m prior to the event onset. Once the air parcels have enough energy to reach the level of free convection, a deep convective system will develop and CTH will rapidly increase. Please explain in a physically plausible way, why you think the lowering of CBH is an indicator of a developing deep convective system.*

Thank you for pointing that out. After reading your comment and checking the development of our HPEs again, we agree that the lowering of the CBH anomaly is probably not connected to the deepening of the convective core. Since most of the investigated HPEs do not form within the 22 km x 16 km covered by the WEGN, we assume that the drop in CBH anomaly we observe stems from the displacement of no clouds/fair weather clouds with cumulus clouds that move into the study region close to a HPE. We changed the corresponding sentences in the manuscript and replaced the term 'deepening of the convective system' with 'arrival of the convective system'. In addition we changed the following sentences:

L140: *Another effect of the convective nature of HPEs is the deepening of the convective cloud system, represented by a decrease in the CBH anomaly of about 1000 m prior to the event onset.*

[changed to]

L169: *Most HPEs observed do not form within the comparatively small region of the WEGN. This means that before a HPE the sky is either clear or filled with some fair weather clouds which get displaced by cumulus clouds close to the actual event. This is represented by a decrease in the CBH anomaly of about 1000 m prior to the event onset.*

4. *Fig. 4a: The vertical structure of the temperature anomaly is not discussed. I suggest analyzing the lapse rate anomalies before and after the HPE and discuss the mixing processes in the troposphere.*

Thank you for this interesting suggestion. We investigated the LR and added a plot similar to Fig. 4 in the appendix. We also added a few sentences describing the findings of this analysis to the main paper:

L184: *As an indicator for the atmosphere's stability, we additionally investigate the environmental lapse rate (LR), shown in Appendix B, Fig. B1. Before the event onset, we observe high LR values that point towards an unstable, and hence a thunderstorm favoring, atmosphere (Daidzic, 2019). In the hours after the event, we observe decreased LR values. At lower altitudes, the difference between pre and after event LRs is highest, which we attribute to the increased moisture at these levels. At higher altitudes the decrease in LR values might be connected to the release of latent heat during the rainfall event.*

Concerning the suggestion to discuss the mixing processes in the troposphere we consider this beyond the scope of our observation-based study.

5. *In Section 3.1 you write: Using the lower contour of the 80-90% RH area as a proxy for the CBH, we see a decrease in CBH of about 1 km in the 8 h before the event. This is in line with the drop in CBH anomaly already detected in Fig. 3d. Is this really true? The strong decrease of CBH in Fig. 3 is only seen 1-2 hours before the HPE. Also, please confirm with the actual CBH MWR/IRT retrieval that the CBH corresponds to your 80-90% contour.*

During the review we found a bug in our plot script. Accidentally, not the 8h before the event were shown in the vertical plots but only about 1.5 hours. After comparing the actual CBH to the 80 % RH contour (see Figure R1 below), we find that our findings remain the same. Even though the CBH is located a few meters below the 80 % contour line, both the 80 % RH contour and the CBH decrease in the hours before the event onset. The strongest decrease in the 80 % RH contour line sets in ~2 h before the event onset which is in-line with the decrease in CBH anomaly shown in Figure 3 of the manuscript. To clarify this in the manuscript we changed the corresponding line to:

L157: *Using the lower contour of the 80-90 % RH area as a proxy for the CBH, we see a decrease in CBH of about 1 km in the 8 h before the event. This is in line with the drop in CBH anomaly already detected in Fig. 3d.*

[changed to]

L193: *Using the lower contour of the 80-90 % RH area as a proxy for the CBH, we see a decrease in CBH of about 2 km in the 2 hours before the event. This roughly corresponds to the drop in CBH anomaly already detected in Fig. 3d.*

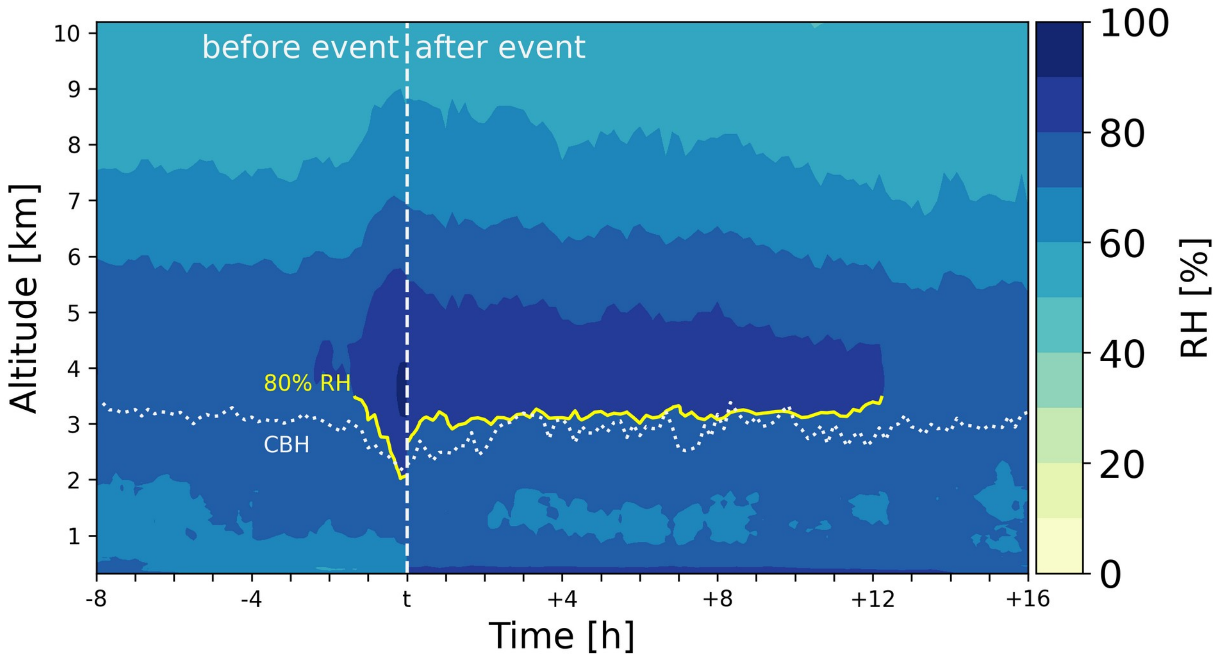

Figure R3: Median vertical structure of relative humidity for WEGN3D (as shown in panel b of Figure 4 in the main paper). The yellow line indicates the 80% RH contour line, the dotted white line marks the CBH.

6. *Fig. 5 interpretation: the increase in temperature variability goes along with the decrease of the mean temperature (Fig. 3). Relating this to clouds is probably only one part of the story. You should consider the effect of convective cold pools originating from evaporative cooling of precipitation and downward transport of upper tropospheric air (see Kirsch et al. https://doi.org/10.1002/qj.4626). Cold pools are often encountered before the actual HPE passes over the specific location. Your data are highly suited for analyzing spatial temperature variability and associated wind speeds with respect to the origin of the HPE.*

Thank you for this interesting suggestion. After reading your comment, we checked the HPEs for cold pool occurrences. Though we do find cold pools prior to the events for some of the HPEs (Figure R2), we have the reoccurring issue that most of our events do not form within the comparatively small region covered by the WEGN. To acknowledge that the observed temperature variability does not solely stem from cloud formation, we added the following sentence to our manuscript:

L221: *Another reason for the increase in temperature variability might come from convective cold pools (Kirsch et al., 2024) which are often detected at the location of HPEs before the event onsets. While we do find indications of such cold pools for a few of the investigated HPEs (not shown), most of the HPEs do not form directly in the region covered by the WEGN, which means that potential cold pools cannot be found in that area as well.*

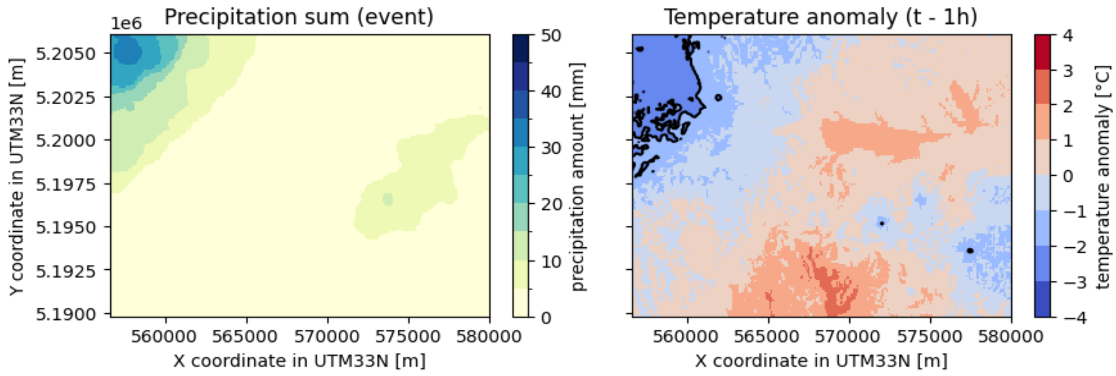

Figure R2: Event precipitation amount (left panel) and temperature anomaly 1 h prior to the onset of the 2021-07-30 HPE. Areas with temperature anomalies <= -2°C (i.e. possible cold pools) are marked with the black contour lines in the right panel.

7. *Fig. 7 interpretation: Please clarify in detail how you define the maximum precipitation amount? It is given in mm. What spatial and temporal extent does this amount refer to?*

The maximum precipitation amounts shown in Figure 7 are the maximum 5 min amounts recorded during the event, which correspond to an individual station. Meaning that for each time step during the event the 5 min precipitation amount of the station with the highest value is selected. To state this more clearly in the manuscript, we added this information in the following sentence:

L199: *Figure 7 depicts the development of the maximum precipitation amount (PAx), 2 m air temperature anomaly, and IWV anomaly during the event, as well as, the spatial variability of these parameters.*

[changed to]

L238: *Figure 7 depicts the development of the maximum 5 min precipitation amount (PAx), 2 m air temperature anomaly, and IWV anomaly during the event, as well as, the spatial variability of these parameters.*

8. *In the discussion you write: The energy build-up, which is also linked to the rise in temperature, is reflected by the increase of CAPE in the hours prior to the event onset (Fig. 3c). Isn't it the airmass which is associated to a certain CAPE value and this potential energy can be set free when the surface heats or orographic lifting occurs? Wouldn't you think that the CAPE increase you see in the hours prior to the HPE is most probably due to advection of a warm and humid airmass? I suggest to check this through a more thorough characterization of the synoptic situation, e.g. by using the concept of a circulation weather type: (https://www.dwd.de/EN/research/weatherforecasting/met_applications/nwp_applications/grosswetterlagen_forecast.html) This would provide a more comprehensive way of contextualizing your observations.*

Thank you for that input. We agree that the observed rise in CAPE is probably not directly linked to the HPEs themselves. As already mentioned in our answer to specific comment #3, most of the investigated HPEs do not actually form within the region of the WEGN3D and the CAPE values observed by the WEGN3D are therefore not representative for the events themselves.

To emphasize this also in the manuscript, we changed the corresponding sentence to:

L278: *The energy build-up, which co-occurs with a rise in temperature, is reflected by the increase of CAPE in the hours prior to the event onset (Fig.3c).*

We followed your suggestion of checking the weather types and found that many of our events occurred on days with the BM (*"Hochdruckbrücke Mitteleuropa"*) synoptic situation (see Fig. R3), which is characterized by a band/area of high pressure over Central Europe. This is a very curious finding, since the HB situation is not very common over the year and only ~7% of all days exhibit this synoptic condition:

https://www.pik-potsdam.de/en/output/publications/pikreports/.files/pr119.pdf

Though we find this topic highly interesting, we consider it beyond the scope of this study, where we focus on the observation-based life-cycle of rainfall events. However, we are currently in the process of planning further studies that focus on the drivers of HPEs on different scales, where we will also investigate the circulation patterns connected to these events with the amount of attention and detail required by this topic.

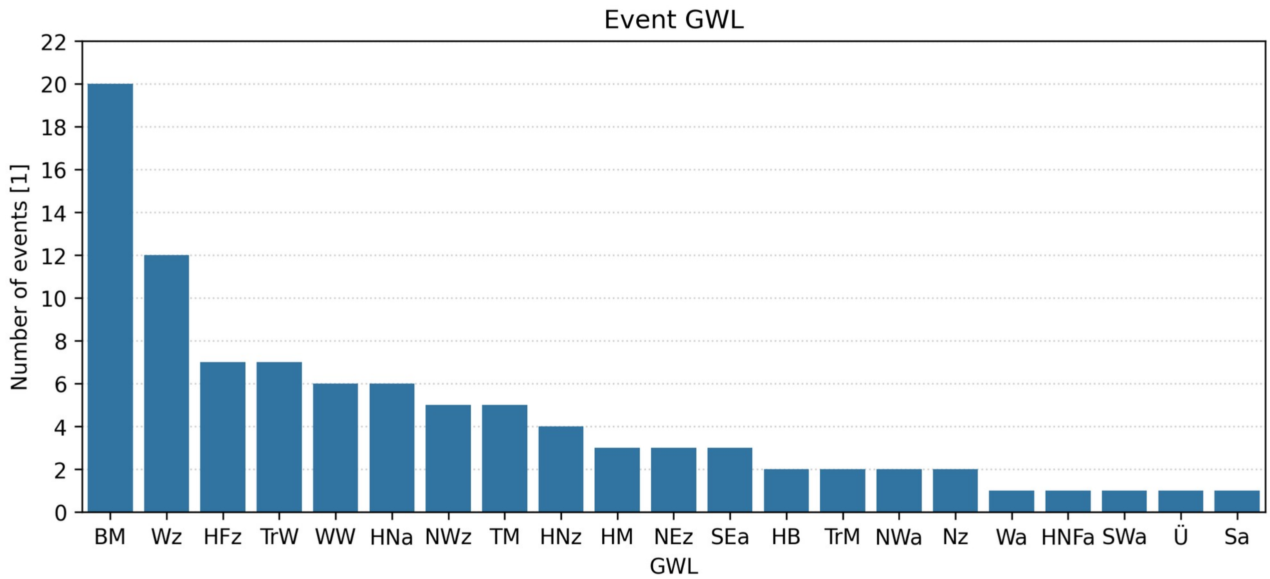

Figure R3: Number of Großwetterlagen (GWL) connected to the HPEs investigated in the study.

REFERENCES

Gartzke, J., R. Knuteson, G. Przybyl, S. Ackerman, and H. Revercomb, 2017: Comparison of Satellite-, Model-, and Radiosonde-Derived Convective Available Potential Energy in the Southern Great Plains Region. *J. Appl. Meteor. Climatol.*, **56**, 1499–1513, https://doi.org/10.1175/JAMC-D-16-0267.1.

Hobbs, P. V., and J. M. Wallace, 1977: *Atmospheric Science: An Introductory Survey*. Academic Press, 350 pp.

Kvas, A., Kirchengast, G., and Fuchsberger, J.: High-resolution atmospheric data cubes from the WegenerNet 3D Open-Air Laboratory for Climate Change Research, Earth Syst. Sci. Data Discuss. [preprint], https://doi.org/10.5194/essd-2025-176, in review, 2025.

Blumberg, W. G., Turner, D. D., Löhnert, U., & Castleberry, S. (2015). Ground-Based Temperature and Humidity Profiling Using Spectral Infrared and Microwave Observations. Part II: Actual Retrieval Performance in Clear-Sky and Cloudy Conditions. *Journal of Applied Meteorology and Climatology*, *54*(11). https://doi.org/10.1175/JAMC-D-15-0005.1