Author's response to:
RC#1 from Raphaela Vogel
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Dear Raphaela Vogel,

Thank you for carefully reading the manuscript and pointing out several issues where the description needs to be improved for understanding. The requested clarifications and references to ambiguities contribute to the improvement of the manuscript.

In order to separate the reviewer's comments and the author's response, we printed the comments in black and the response in blue. Excerpts of the manuscript with marked changes are pinned directly to the appropriate responses, with the indicated text location (e.g., line number) referring to the manuscript in preprint.

Sincerely, on behalf of all authors

Heike Kalesse-Los

Changes done to the manuscript:

- The Virga-Sniffer code was updated (v0.3.4 -> v1.0.0), with mostly minor changes (e.g., more flexible plotting routines). Nevertheless, there are two considerable additions, listed below. In particular, the handling of situations in which precipitation falls into lower cloud layers was changed compared to the first submitted manuscript. We now focus on avoiding misclassifications and therefore set the newly introduced configuration *cbh_connect2top* to False (see below).

  1. Adding a configuration flag "*lcl_replace_cbh*". When additional LCL data is provided, this flag changes the behaviour of the *add LCL* module for CBH preprocessing. In the default setting (True), the LCL data completely replaces the lowest ceilometer CBH layer. If False, the LCL data is merged with the lowest ceilometer CBH layer by replacing only missing values.
  2. Adding a configuration flag "*cbh_connect2top*". This flag changes how situations where precipitation falls in lower CBH layers are handled. In the default setting (False), the lowest CBH is retained and higher CBH layers are omitted from processing because no distinction can be made between clouds and precipitation from higher layers if there is a continuous radar signal in the profile. Therefore, the default setting is most conservative to avoid false detection of virga. For True, the top CBH layer is retained and the lower CBH layer is omitted from processing. This approach results in more precipitation data points, but it is prone to misclassification of cloud droplets as precipitation.

  The up-to-date version of the Virga-Sniffer is hosted on GitHub, see also its Changelog (Witthuhn et al., 2022). All results and figures have been updated according to the new version.

- The technical description of the Virga Sniffer (Sect. 3) has been significantly revised. Care has been taken to name optional data and default configurations explicitly in order to avoid ambiguities. In the course of this, the flowchart (Figure 2) and the illustration (Figure 3) were adapted.

- A new appendix (B) has been added, where the sensitivity of precipitation and cloud detection on setting parameters and optional data are analysed and discussed.

- In section 4.1, "Comparison with Cloudnet target classification", we have added another performance evaluation of the *Virga-Sniffer*. Here we analyse how many data points were evaluated as precipitation by CloudnetPy but not by the *Virga-Sniffer*.

- Many text passages, figures and tables were revised in consideration of review comments, as can be seen in the detailed responses.

Response to RC#1 of Referee Raphaela Vogel:

Major comment #1: Tool description

1. *I think the tool description can be improved. I couldn't follow the explanation in Section 3.1 as I was missing some crucial information: at what temporal resolution are these analyses done? What is a CBH layer?*

* In order to clarify the operation of the Virga-Sniffer including its temporal and vertical resolution, as well as the term 'CBH layer', we added the following bits:

> **Sect. 3., 1st paragraph (L140ff.)**:
>
> ---
>
> The *Virga-Sniffer* is a profile-based detection scheme for virga events. It is a self-developed Python package (Witthuhn et al., 2022). The detection is based on a set of empirical thresholds, which are manually tuned on the EUREC^{4}A data set (Sect. 2) and summarized with their default values in Appendix A. This package provides a tool for detecting ~~virga from profiles~~ precipitation, virga and clouds from profile-by-profile observations of vertically-pointing cloud radar reflectivity and ceilometer observations of cloud base height (CBH), taking into account multilayer cloud situations. The radar data serve as a basis, as they define the temporal and vertical resolution for the *Virga-Sniffer*, which in the case of the EUREC^{4}A data set is 1.6–2.9 s and 22–42 m, respectively (see Sect. 2.1). The main result are Boolean masks, which mark clouds, virga and/or precipitation on the radar coordinates (range-gates and time-steps). It is highly configurable, modular and therefore usable for different measurement setups. In addition, virga detection can be refined by additionally considering radar mean Doppler velocity, LCL, and surface rain detection. Example cases presented in the following are based on the default settings of the *Virga-Sniffer* to process the EUREC^{4}A data set.

Sect. 3.1, 1st paragraph (L150ff.):

The ~~input CBH layer data is~~ ceilometer provides the input values of the CBH. The variable CBH is a data product of the internal ceilometer processing. For multilayer cloud situations, multiple CBH are output, until the ceilometer signal is fully attenuated. Depending on the type of ceilometer and the underlying internal CBH determination algorithm, multilayer cloud situations can also be taken into account. In the *Virga-Sniffer* cloud layers are sorted within a processing interval, which depends on the given input data (here daily data). A cloud layer is identified in the *Virga-Sniffer* by its CBH, which on average differs from other layers over the processing interval by more than the set threshold of 500 m (*cbh_layer_thres*, see Appendix A). The term *layer* is used, if a variable is tied to a specific cloud layer, as the term CBH layer refers to the cloud-base height of one cloud layer.
The CBH input data from the ceilometer must be pre-processed ~~before it is~~ to achieve a sorted CBH layer data set before it can be used for virga and cloud detection (see Fig. 2 box 1). As the *Virga-Sniffer* is designed to work on the radar data coordinates, the CBH input data, on a temporal resolution of 30 s, is interpolated to the radar time-steps (1.6–2.9 s).

2. *L152: The module numbering in Sec 3.1 is a bit counter-intuitive: why not put the smoothing as module 1 (instead of 5) and thus start with module 1?*

* We agree, that the sorting of the modules is debatable, and it would make sense to put *smooth* either as module 1 or 5. In the current design of the Virga-Sniffer, an additional CBH smoothing step is applied before, but not as a part of, the pre-processing modules. The idea was to give the user the opportunity to alter the pre-processing but to also force smoothing beforehand, as it seems mandatory in order to have the pre-processing modules work correctly. Therefore, during 'pre-processing', the *smoothing* is actually only applied at the end. Following this logic, the modules are already sorted in order of occurrence, except *clean&sort* which is frequently applied after each individual pre-processing step. For clarification, we rephrased this paragraph (also see answers to #1.3. and #1.4.) as:

L151ff:

~~For this processing~~Prior to configurable pre-processing, CBH data is smoothed to avoid outliers in the input data that would complicate pre-processing. For the pre-processing, modular methods are applied to the CBH input data, which can be individually configured. In total~~five modules (described below) are available~~, five modules are available. These modules are named *clean & sort*, *split*, ~~used settings and thresholds~~ *merge*, *add LCL* and *smooth*. Flags and thresholds used to control in the modules, and their default values, are summarized in ~~Sect.~~Appendix A. ~~Prior to the configurable processing, the CBH data is smoothed, which corresponds to processing module five:~~

3. *L154: what does 5% mean here? 5% of a given time period? Or 5% of vertical extent?*

* Here, we refer to the number of data points of CBH in a cloud layer within the processing interval (see answer to #1.1.). For clarification, we have rephrased this description, also deleting "First,", as this might indicate, that this module is applied first, which it is not, see also the answer to the next remark.

> **L154ff**:
>
> 1. *clean & sort*: First, CBH layers with less valid The valid data-points of each CBH layers are counted and compared to the number of data-points for the total processing interval. If the number is lower than the given threshold of 5 % are by default, the data of this layer is removed (*clean*). Then, for After the cleaning, the remaining layers , the mean height of each layer is calculated. The CBH dataset is then re-indexed, by sorting the layers are sorted in ascending order by mean height comparing their mean height over the processing interval (*sort*). Note that cloud layers in the Virga sniffer are not sorted profile by profile, but by height for the processing interval. This results in gaps, for example in lower layers in broken cover, e.g., caused by trade wind cumulus clouds.

4. *L166-168: this is a very lengthy way of saying that 'two iterations of all 5 steps are made'*

* We agree, that the current phrasing is misleading. Actually, it is not two iterations of all five modules, but two iterations of [split, clean&sort, merge, clean&sort, add LCL, clean&sort] (config = [2, 1, 3, 1, 4, 2, 1, 3, 1, 4, 5], see also Appendix A), and these two iterations are followed by a final smoothing step. We have rephrased this paragraph as:

> **L166ff.**:
>
> For the pre-processing of the EUREC^{4}A RV *Meteor* CBH dataAs default, two iterations of the combination *split*, *merge*, *add LCL* are considered, followed by an additional smoothing step. The module *clean & sort* is applied in between each step to continuously filter outliers. After these two iterations, a last smoothing step is applied.

5. *L168: I thought that LCL data is optional (Fig. 2), but here it seems to be necessary.*

* Yes, the LCL data is optional, but for the processing of EUREC4A data we provide all optional data to foster the full potential of the tool. We agree, that the phrasing in L168 is therefore misleading, and modified this paragraph as:

L168ff.:

Note , that here additional data of LCL is required, which is that the *add LCL* module is used here, which utilizes the optional LCL data. With the additional information about the LCL, the lowest potential cloud layer can be estimated. This supplements the CBH data of the lowest cloud layer, filling in gaps that may occur in the ceilometer data. This ultimately leads to a more complete virga and cloud mask in the *Virga-Sniffer* output. Nevertheless, the use of the module and LCL data is optional, since the main CBH information is provided by the ceilometer. To use the full potential of the Virga-Sniffer, the LCL is included here. The LCL is calculated from surface observations of air atmospheric pressure, temperature, and humidity from the meteorological observation station on the RV *Meteor* using the method of Romps (2017) , which is build into the built into the utilities of the *Virga-Sniffer* packageutilities.

6. *L175: I don't remember a definition of 'valid radar reflectivity'.*

* We have added an explanation to the text accordingly.

175ff.:

After the pre-processing of CBH, the radar reflectivity values , specifically the Boolean mask of valid reflectivity values, is are used for the initial step of detecting precipitation, clouds and cloud-top heights (CTH) . This is done by successively iterating (see Fig. 2 box 2). A Boolean mask is created, which yields True if the radar reflectivity maskvalue is not a nan-value, meaning any kind of particles are detected by the radar in the given time and altitude. This mask is successively iterated, starting from each cloud-base in both up- and downward direction. To do this, the values of the cloud base must be mapped to the radar range-gate resolution, each of which has a certain vertical extent. Precipitation events are generally detected from the range-gate containing the measured cloud base, whereas clouds are detected from the next higher range-gate. This step is referred to as range-gate mapping in Fig. 2.Figure 3 shows a demonstration example for precipitation, virga and cloud detection.

7. *L200ff: These clarifications are helpful, but e.g. the minimum virga length requirement is only mentioned in Sec 3.3, and comes as a surprise here. These examples could thus be moved after Sec 3.3. Furthermore, instead of just writing 'maximum allowed gap for virga', the chosen default threshold could be mentioned again (I actually thought that 700m is a typo, it seemed too large for me – so repeating it would clarify this choice).*

* We added the default threshold values as well as a reference to Sect. 3.3 and the Appendix. Except for *minimum_rangegate_number* the sketch refers to maximum allowed gaps of virgas and clouds, and therefore mainly refers to Sect. 3.2. We opt to keep the Figure in place but added another schematic sketch as panel (b). The changes in the text are summarized in answer to #1.8.

8. *L204: What is rg19 then? Did the ceilometer miss this second cloud layer due to the strong rain? This should be discussed.*

* Yes, if the clouds in the lower layer are optically too thick, the clouds in the upper layer might not be detected by the ceilometer. This statement is added as shown below.

L199ff.:

Virga and cloud detection is sketched in Fig. 3 to highlight special cases and usage of certain thresholds . Special cases demonstrate the usage of thresholds handling gaps in the radar reflectivity signal. The specific cases of Fig. 3 panel (a) are:

- *time-step* = *1*: The standard case, when precipitation and cloud are detected from the observed CBH. No further considerations have to be made.
- *time-step* = *2*: The gap (range-gate (rg) 7–8) is smaller than maximum allowed gap for virga (*precip_max_gap* = 700 m) to count rg 6 as virga, but rg 6 is filtered since the requirement of minimum virga length of 2 rg is not met., which is a requirement of the virga mask refinement based on the threshold *minimum_rangegate_number* (see Sect. 3.4 and Appendix A).
- *time-step* = *3*: The gap (rg 7–8) is smaller than the threshold, therefore rg 3–6 are counted as virga.
- *time-step* = *4*: The In addition, the gap (rg 7–1117–18) is larger than the threshold, maximum allowed gap for clouds (*cloud_max_gap* = 150 m) therefore rg 3–6 are 19 is not counted as virga. In addition, the cloud. In this case, rg 19 could be a cloud, but since the *Virga-Sniffer* detection is tied to the CBH input data, rg 19 cannot be identified. Missing information about the second cloud layer can occur if the ceilometer signal is strongly attenuated by the clouds of the lower layer or by strong precipitation.

- *time-step* = *4*: The gap (rg 17–187–11) is larger than the maximum allowed gap for cloudsthreshold, therefore rg 19 is 1–6 are not counted as cloud. virga. Therefore, the rain flag at the surface has no effect, as the virga detected in rg 12–14 does not reach the first rg.
- *timetime-step* = *5*: Rain is observed Precipitation is detected from (rg 1–14) as the gap (rg 7–8) is smaller than the threshold. Due to the rain flag at the surface (either by the additional data of surface rain flag, or by exceeding the radar reflectivity threshold in the lowest rg)radar rg, therefore *ze_thres* = 0 dBz), no virga is assigned in this profile.
- *time-step* = *6*: Same as *time-step* = *5*. In addition, the gap (rg 17) is smaller than the maximum allowed gap for clouds, therefore rg 18–19 are counted as cloud. The surface rain flag doesn't lead to a reclassification of the detected virga towards rain, as the first rg has no data.
- *time-step* = *7*: Same as *time-step* = *6*. In addition, another CBH layer is observed right below rg 19. This CBH layer is not considered, as the gap at rg 17 is smaller than the maximum allowed gap for clouds, and it is not possible to distinguish between clouds and precipitation due to that. Therefore, the lowest CBH is assigned, as in time-step = 6 to initialize the detection of clouds and precipitation and the higher CBH is ignored per default (*cbh_connect2top* = False).

9. *L210: This step of virga mask refinement is thus not optional (as suggested in Fig. 2, part 3))?*

* Every step in the 'virga mask refinement' is entirely optional. This had not been made entirely clear previously and was now modified. We have separated step 3 into the mandatory virga detection using the radar-based rainflag given by the reflectivity in the lowest radar range gate and the optional virga mask refinement:

L145ff.:

The workflow of the virga detection is separated into three parts, as summarized in Fig. 2:

1. Preprocessing of CBH
2. Precipitation and cloud detection
3. Virga detection
   (a) Masking rain events
   (b) (Optional) ~~Virga detection~~ virga mask refinement

Note, all modules in the virga mask refinement are entirely optional (step 3b). In order to separate rain and virga events (step 3a) the *mask_rain_ze* module is used, which is based on the radar reflectivity values in the lowest range-gate. Potentially, the *Virga-Sniffer* can be used to mask both rain and virga by opt out of using the rain masks *mask_rain_ze* and *mask_rain*.

10. (Fig.) *4: what does 'filled cloud base' mean?*

* We added an explanation to the figure caption.

Fig. 4 caption:

LIMRAD94 reflectivity factor Z_e (panels (a), (c), (e)) , and *Virga-Sniffer* output for different cloud situations during EUREC[4][4]A based on RV *Meteor* observations ~~. The colorbar~~ (panels (b), (d), (f)). The colour bar on the right side panels ~~denote the maximumd~~ denotes the maximum number of cloud layers detected during the case study days (count starts at zero for the lowest layer). Panels (a) and (b) show ~~stratocumulus~~ stratiform cloud layers with virga and a warm precipitation system, panels (c) and (d) ~~altocumulus~~ stratiform cloud layers with virga, and panels (e) and (f) trade wind cumuli with virga. The dotted line labelled "filled cloud base" refers to either LCL values which fill in gaps during the CBH pre-processing or CBH gaps which are filled by interpolation (see Sect. 3.1 and Appendix A).

11. *L269: I don't see the multiple layers at 05:00 in Fig. 5. Is the 'filled cloud base' considered as a cloud? If so, I'd find this problematic, because there is obviously no cloud there.*

* You are correct, there are no multiple layers of clouds at 05:00 UTC, this might have sneaked in while preparing the manuscript, thank you for reading carefully and pointing this out. We have deleted 05:00 UTC from this sentence, as this

paragraph is dedicated to the 05:45 UTC time-step. No, the "filled cloud base" is not considered as a cloud, rather as a potential cloud base, from which the cloud and precipitation detection is initiated.

12. (Figures) *4&5: Zooming into the detected virga (e.g. Fig 5c, around 04:40 or 05:45), the sub-cloud layer virga is not continuously detected, potentially due to surface rain or (for stratiform inversion cloud) positive Doppler velocity. I find that a bit problematic, as physically these rainshafts should be considered as one object, and the on-off-virga detection is a bit arbitrary. See also my major comment #3.*

   * Yes, for some profiles, the radar reflectivity at the lowest level is larger than the threshold of 0 dBz, which is considered to have rain reaching the surface. We agree that the precipitation events recognized as "on-off Virga" and the intervening rain should be physically counted as one precipitation event from this cloud. The current version of the Virga-Sniffer does however not include temporal aggregation and segmentation of precipitation events. We focus here on the profile-by-profile evaluation of whether precipitation reaches the ground, or whether a particular time step can be considered virga. Therefore, the precipitation analysis is tied to time rather than a specific cloud or precipitation event (e.g., within an hour, there were 50% clear skies, 25% clouds with no precipitation, and 20% clouds with precipitation classified as virga, and 5% clouds with precipitation classified as rain). We agree that the identification of aggregated virga/precipitation events is very interesting and would allow for cloud/situation specific analysis of precipitation and could be implemented as an enhancement in the future.

13. *To clarify the reason why some sub-cloud layer rain is not classified as virga, it would be helpful if Fig. 4 & 5 could also show the surface rain flag.*

   * We agree and added the rain flag in both figures.

14. *The beginning of the summary section 5 mentions that profile-by-profile information is used. I think this information should come at the beginning of Sec. 3, together with information about the temporal resolution of the analyses (e.g., it is unclear what temporal resolution the ceilometer has), and reference to the appendix, which summarizes the configuration (I only realized after the summary that there is an appendix).*

   * We added this information to the beginning of Sec. 3 accordingly. The changes are summarized below the answer to #1.1.

15. *I also have some issues with Fig. 2, as (i) the gray thin lines in Fig. 2 are hard to see on my print out, and (ii) the figure claims some steps to be optional, which are discussed as necessary in the text (see above).*

   * (i) We increased the line width in Fig. 2. (ii) Indeed, all steps marked as optional in Fig. 2 are optional modules in the Virga-Sniffer algorithm. See answer to #1.9. Nevertheless, we have separated the obligatory virga detection based on the radar reflectivity value in the lowest radar range gate (Step 3a) from the optional virga mask refinements (Step 3b), although in principle it is up to the user whether to use it or not.

16. *For Figure 3, the coloring is ambiguous, because detected cloud and virga should also be partly green, because they have a valid Ze. So maybe make two masks (one input and one output), or hatch the boxes with valid Ze. It would also be nice to have an example of a multi-layered cloud situation here.*

   * We agree, and updated the figure to an unambiguous labelling. Note, we have also changed the colours for cloud and virga masks in related figures, and changed the label of "radar signal" to "unclassified".

Major comment #2: Cloud type classification

I have some issues with the cloud type classification here. During EUREC4A, I don't remember any situations of stratocumulus or stratus clouds. However, deeper trade cumulus clouds with extensive stratiform cloud layers were very frequent. But these stratiform cloud layers were at some point detrained from a cumulus core rooting in the sub-cloud layer. I.e., the convection and cloud formation was surface-driven and not cloud-top driven as in stratocumulus. From a ground-based single-point perspective, this distinction is of course not easily made, because you might only capture the stratiform part of a cloud.

Although the classifications used here might be in line with the Stratocumulus Cumulogenitus (CL = 4) class of the WMO cloud atlas, I would encourage the authors to reconsider their cloud type classification. In the broader EUREC4A or trade cumulus community, we usually use different names for this 'cloudiness aloft' components, which are often called 'stratiform (cloud) layers', 'stratiform inversion cloud', 'shallow anvils', or sheared edges of deeper trade cumuli. Nuijens et al. (2014) or Vial et al. (2019, https://doi.org/10.1029/2019MS001746) are good references for how to deal with these naming issues.

We acknowledge that in our initial manuscript version, the cloud classification terminology for stratiform clouds differs from the one generally used the trade wind community. When looking through the R/V Meteor sounding data, we saw cases where the radiosondes combined with radar and ceilometer measurements indicated the presence of stratocumulus clouds, given by an unstable layer or even elevated mixed layer aloft (i.e 21.01.2022 18:45 UTC or 24.01.2020 00:28UTC). In general, many moist layers below the trade inversion where rarely completely stable, but often showed at least some weak instability. As suggested by Vial et al. (2019), we decided to also follow the cloud classification nomenclature of the broader trade cumulus community and will call the Stratucumulus Cumulugenitus class of the WMO cloud atlas "stratiform cloud layers".:

L17ff.:
The most important virga-producing clouds were either anvils of convective cells or ~~stratocumulus clouds~~stratiform cloud layers.

L29ff.:
The other third consists of clouds bases above 1 km, mainly ~~stratocumulus, stratus~~ stratiform cloud layers or cloud edges near the trade wind inversion at 2–3 km (Nuijens et al., 2014, 2015).

L32ff.:
Therefore, precipitation generally occurs as light rain/drizzle from ~~stratocumulus and stratus~~ stratiform cloud layers or as showers from well-developed trade wind cumuli (Austin et al.,1995; Baker, 1993).

L319ff.:
In these heights, mostly ~~stratocumulus~~ stratiform cloud layers are present, reaching up to the base of the trade inversion.

L329ff.:
Those are mostly ~~stratocumulus~~stratiform cloud layers, cloud edges and anvils of convective cells spreading under the trade inversion. Virga depths smaller than 0.3 km often occur from shallow ~~stratocumulus~~ stratiform cloud layers with depths below 0.5 km

L334ff.:
Those clouds are mainly thick ~~stratocumulus~~ stratiform cloud layers and anvils below the trade inversion, with a cloud base that is high enough to produce deep virga.

L372ff.:
Clouds with bases between 1 km and 4 km, which are either cloud edges of convective cells or ~~stratocumulus~~ stratiform cloud layers forming below the trade inversion, were identified as important virga producers. ~~Stratocumulus and stratus~~ Stratiform cloud layers with their base around 1.5 km and 2.5 km frequently produce either virga with small depths up to 200 m or virga reaching the lowest radar range gate.

Major comment #3: Virga vs. evaporation from rainshafts that reach the ground

I miss the motivation for focusing only on virga rather than all rainshafts. Although raining clouds are less frequent than clouds with virga (your Table 3), in terms of their contribution to total rain evaporation they are likely still very important. So when the main reason motivating this study is to (eventually) investigate rain evaporation, why focusing only on virga? In my eyes, the only physical reason that distinguish virga from other rainshafts is that total versus partial re-evaporation is relevant for the isotopic signal (Torri 2021, https://doi. org/10.1029/2020JD033139). But e.g. from a moisture or heat budget point of view, it doesn't matter whether rain reaches the surface or not. It would be great if the authors could discuss their reasons for their focus on virga more explicitly.

The authors agree that from an atmospheric perspective, it is true that besides full rain evaporation (as in virga), partial rain evaporation that occurs when rainfall reaches the ground is important and also influences the atmospheric heat and moisture budget. To differentiate between both, we have made our wording more precise by adding "full vs partial rain evaporation" throughout the manuscript. However, for the hydrological cycle it does make a difference if rain evaporates fully or only partially. In marine settings, rain reaching the ground changes the surface water salinity and temperature. Rain reaching land surfaces is important for vegetation and can be stored in the soil. Since satellite precipitation products (like from CloudSat or GPM) have a blind-zone in the near-surface region, biases in total precipitation estimates occur. Knowing if rain reaches the ground or if it fully evaporates can thus also be important for evaluating satellite-based rain statistics. We have added this motivation in the introduction and the outlook:

L42f.:
While both - full subcloud evaporation of precipitation resulting in virga as well as partial precipitation evaporation in which rain still reaches the ground - are important, the focus of this manuscript is to introduce a tool that allows for identification of virga. Besides the need to distinguish partial vs. full evaporation due to their different implications for the biosphere, the tool could be used to evaluate satellite-based rain statistics which suffer from blind-zone effects in the near-surface region leading to biases in total precipitation estimates as shown e.g. by Valdivia et al. (2022).

L387f.:
Our virga identification tool might help to evaluate satellite-based surface precipitation statistics suffering from blind-zone effects as indicated by Maahn et al. (2014) and Valdivia et al. (2022).

Minor comments

- *Review of earlier approaches of virga detection or rain evaporation retrievals: In the introduction, I missed a review of earlier work focusing on virga and rain evaporation in the trades. E.g. Sarkar et al. (2020, DOI: 10.1175/MWR-D-19-0235.1) is a study that comes to my mind, but there are for sure others.*
- We acknowledge that there is much more work on precipitation evaporation retrieval that we have not included in the introduction. The reason for this is that our work is mainly focused on a technical approach to virga detection and the study of trade wind cumulus clouds here serves as a case study. The EUREC^{4}A dataset was used as a basis for the development of the tool, and in the future we plan to use the *Virga-Sniffer* at other geographical locations. For this reason, we prefer not to expand the introduction with papers focusing on the trade wind zone. Instead, the introduction favours papers that use cloud radar Doppler spectra for precipitation evaporation studies, such as the cited references by Xie et al. (2016) and Tridon et al. (2017). We have expanded the literature review of studies on rain evaporation via radar observations. For details please see our response to Comment 43 of reviewer 3.
- *Results for single cloud layers: Sec. 3.5 showed that most challenges and limitations pertain to multi-layer cloud situations. To increase the robustness of the results, it would be great to see how the results (e.g. in Fig. 8 and 9) change if only single-layer clouds are considered. These results will likely be more trustworthy.*
- It is true that mainly in situations with multilayer cloud cover sources of error of the *Virga-Sniffer* appear. However, the main problem is when the cloud layers are not clearly distinguishable from each other, such as in big convective rain systems, where the measured CBH is influenced by updrafts and downdrafts. Therefore, we find no significant deviations from the figures shown if we exclude (clearly delineated) multilayer cloud cover, as illustrated in Fig 1 below.
- *Comparison with Cloudnet target classification: How often does Cloudnet detect drizzle / rain when the VirgaSniffer doesn't detect anything? I think the comparison in both directions is important.*

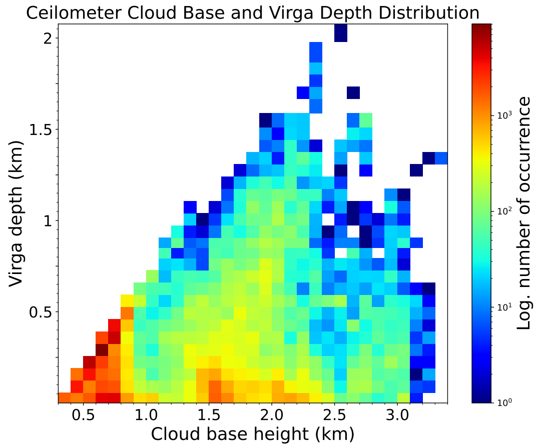

Figure 1. Single layer cases cloud base height and virga depth.

– We added an analysis according to your suggestions

> **L289f.**:
>
> It is also possible to assess the performance of the *Virga-Sniffer* by only taking into account situations without rain reaching the ground, no rain observed in the lowest radar range-gate and the virga classified by the *Virga-Sniffer*. During these situations the *Virga-Sniffer* misses 15 % of cloud and precipitation related Cloudnet targets (excluding clear sky, aerosols or insects targets). This is mainly due to the determination of the cloud base in the *Virga-Sniffer*. In certain situations, the cloud base used in the *Virga-Sniffer* is lower than the cloud base used in CloudnetPy. As a result, data points in between the cloud bases from CloudnetPy and the *Virga-Sniffer* are identified as the drizzle or rain Cloudnet class, but as cloud by the *Virga-Sniffer*. These situations include: (i) When precipitation connects multi layers of clouds, where the *Virga-Sniffer* retains the lowest CBH only (see Sect. 3.2); (ii) The LCL, which is usually lower than the observed CBH, replaces the lowest CBH layer of the *Virga-Sniffer* (see Sect. 3.1).

– *Commas: I'm not an expert on commas, but I feel that some additional commas would ease the reading. I made some suggestions in the annotated pdf.*

– Thank you, we have taken them into account.

Technical corrections

Please find some technical suggestions in the annotated pdf.

Thank you, we have taken the suggestions into account, which definitely improves readability.

References

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Author's response to:
RC#2 from Anonymous Referee #2
https://doi.org/10.5194/amt-2022-252-RC2

Heike Kalesse-Los[1], Anton Kötsche[1], Andreas Foth[1], Johannes Röttenbacher[1], Teresa Vogl[1], and Jonas Witthuhn[1]

[1]Leipzig Institute for Meteorology (LIM), University of Leipzig, Leipzig, Germany

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Dear Anonymous Referee #2,

We want to thank you for your suggestions and the thorough evaluation of the manuscript. We revised multiple parts of the previous submission and added more details, mostly according to the reviewer's suggestion. This revised version provides a better explanation of the used methods and results.
Thank you for carefully reading the manuscript and pointing out several issues where the description needs to be improved for understanding. The requested clarifications and references to ambiguities contribute to the improvement of the manuscript.

In order to separate the reviewer's comments and the author's response, we printed the comments in black and the response in blue. Excerpts of the manuscript with marked changes are pinned directly to the appropriate responses, with the indicated text location (e.g., line number) referring to the manuscript in preprint.

Sincerely, on behalf of all authors

Heike Kalesse-Los

Changes done to the manuscript:

- The Virga-Sniffer code was updated (v0.3.4 -> v1.0.0), with mostly minor changes (e.g., more flexible plotting routines). Nevertheless, there are two considerable additions, listed below. In particular, the handling of situations in which precipitation falls into lower cloud layers was changed compared to the first submitted manuscript. We now focus on avoiding misclassifications and therefore set the newly introduced configuration *cbh_connect2top* to False (see below).

  1. Adding a configuration flag "*lcl_replace_cbh*". When additional LCL data is provided, this flag changes the behaviour of the *add LCL* module for CBH preprocessing. In the default setting (True), the LCL data completely replaces the lowest ceilometer CBH layer. If False, the LCL data is merged with the lowest ceilometer CBH layer by replacing only missing values.
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  The up-to-date version of the Virga-Sniffer is hosted on GitHub, see also its Changelog (Witthuhn et al., 2022). All results and figures have been updated according to the new version.

- The technical description of the Virga Sniffer (Sect. 3) has been significantly revised. Care has been taken to name optional data and default configurations explicitly in order to avoid ambiguities. In the course of this, the flowchart (Figure 2) and the illustration (Figure 3) were adapted.

- A new appendix (B) has been added, where the sensitivity of precipitation and cloud detection on setting parameters and optional data are analysed and discussed.

- In section 4.1, "Comparison with Cloudnet target classification", we have added another performance evaluation of the *Virga-Sniffer*. Here we analyse how many data points were evaluated as precipitation by CloudnetPy but not by the *Virga-Sniffer*.

- Many text passages, figures and tables were revised in consideration of review comments, as can be seen in the detailed responses.

Response to RC#2 of Anonymous Referee #2:

General Points

There are a large number of thresholds used within the study, how sensitive is the output of the virga-sniffer to these thresholds? Some discussion of the parameters that the tool is sensitive to is necessary. Why are they set at their current values? How does changing them effect the results?

To address this comment, we added a new Appendix (B). In this Appendix, the effects of the Virga-Sniffer setting are discussed. Also, the sensitivity of the setting parameters is studied versus their default values, by comparing the number of data points and time-steps for which virga and clouds are detected.

There is some mention that the tool works without the inclusion of the LCL and the surface precipitation measurements. Some discussion of the differences in the results with and without these parameters would be useful.

Yes, the inclusion of LCL, surface precipitation measurements and mean Doppler velocity are optional. The new Appendix section (B3) addresses how the detection is affected when not using the optional data.

Minor comments

1. ***L98:*** *Are roll and pitch angles allowed to be negative? If so replace this with absolute angles. If not, why is the standard deviation so much greater than the mean, this implies a very skewed distribution?*

   * Yes, the attitude angles can be negative. We redid the calculation of the mean and standard deviations using absolute values as suggested. The mean and standard deviation of the pitch and roll angle then amounted to $0.36 \pm 0.31°$ and $0.19 \pm 0.16°$, respectively. We have changed the corresponding line in the manuscript:

L98f:
observed ~~roll and pitch angles experienced by the radar generally were less than $0.09 \pm 0.49°$~~ absolute values of roll and pitch angles experienced by the radar generally were less than $0.36 \pm 0.31°$

2. ***L100:*** *Together with the previous point, if there is a sizeable inclusion of horizontal wind the pointing is relevant for the Doppler velocity. Is there any treatment or removal of Doppler velocity at large roll/pitch angles?*

   * True, for large radar mispointings from zenith and high horizontal wind speeds, the influence of horizontal wind on the observed Doppler velocity is non-negligible. We do not account for this. Based on the radiosoundings, we did however do an analysis of the horizontal wind profile, for the relevant altitudes below the trade inversion height, the mean horizontal wind speeds had means of 5–8 $\mathrm{m\,s^{-1}}$. As stated in the manuscript, the highest Doppler velocity resolutions of the used chirp programs amounted to 5 and $5.7\,\mathrm{cm\,s^{-1}}$. The effect of the influence of horizontal wind on mean Doppler velocities for different radar mispointing angles is shown in Figure 1 of this reply. When considering the experienced values of roll and pitch angles (see answer to previous question) as well as the Doppler spectra resolution and the horizontal wind speed profiles, we conclude that filtering large attitude angles should not be needed often anyways. In

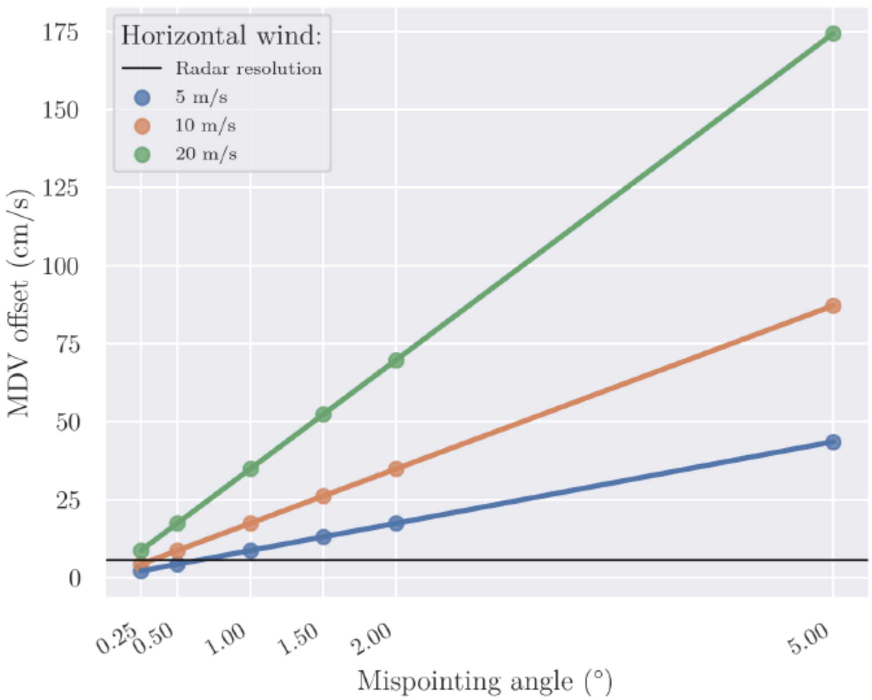

Figure 1. Influence of horizontal wind on mean Doppler velocity (MDV) caused by radar mispointing from zenith. Radar Doppler spectra resolution of 5.7 $\mathrm{cm\,s^{-1}}$ is indicated by black horizontal line.

fact, for mispointing angles less than 0.41°, no effect of typically experienced horizontal winds of 8 $\mathrm{m\,s^{-1}}$ magnitude are discernable in the radar Doppler spectra.

3. ***L196-198:*** *In this situation it is possible to have rain from another section of cloud blown in to the column and giving the impression of rain reaching the surface. Any consideration of this situation? Use of horizontal wind e.g.?*

* We agree, that the handling of tilted fall streaks in the Virga-Sniffer is one of the biggest challenges. In the current state, this is addressed by the implementation of the "*precip_max_gap*" threshold, which enables detection of precipitation which is not directly attached/connected to a detected cloud base. Of course it might happen, that a fall streak resulting in rain at the surface "enters" the profile just below the lowest radar range-gate (approx. 300 m) in which case, the proper virga event above the fall streak with rain will be masked out. We have added another sketch as panel (b) to Fig. 3 and the following text pieces to address this situation:

L183ff.:
Precipitation is detected at each range-gate of ~~valid radar reflectivity~~ the radar reflectivity mask iterating downward from CBH until a gap ~~(nan-value in radar reflectivity)~~ occurs, which is larger than the threshold *precip_max_gap* of 700 m per default (see Appendix A). This threshold is large by choice, to also capture precipitation which can be observed from fall streaks advected to the radar viewing volume by wind shear. At the same time, the threshold is still small enough to mask out any clutter or unidentified clouds close to the surface or a lower cloud layer, respectively. Since the detection of clouds and precipitation with the *Virga-Sniffer* is carried out for individual profiles and no horizontal linking (in the temporal sense) of these profiles takes place, the handling of fall streaks is one of the most challenging aspects and is realized exclusively by the threshold value of the allowed gap size.

L208ff.:
Figure 3 panel (b) demonstrates how rain flags influence the precipitation or virga detection. Since radar observations only provide data at a certain distance from the ground, there may be an offset between the rain flag observed on the surface and the rain flag obtained from the radar signal. The user is given a choice, but additional input data is required for the surface rain flag. In Appendix B3 it is shown how the choice of rain flag affects the virga and cloud detection based on the EUREC^{4}A dataset. In addition, Figure 3 panel (b) again shows the influence of the choice of the threshold for the maximum permissible gaps for the detection of precipitation and the handling of fall streaks.

4. ***L199:*** *How frequently do these special cases occur and how frequently does the virga detection work with little or no complications?*

* Thank you for your comment. The use of "special cases" may not be appropriate in this context or may be misleading, as Figure 3 shows cases that occur all the time. While the column at time-step=1 can be seen as a standard case where no further considerations need to be made, the other columns show "special cases" to describe how gaps in the radar signal are handled. However, this kind of gaps appear very often. Therefore, we changed the text to be more specific, see below. Also, Figure 3 now includes a 7th column to demonstrate the handling of multi-layer clouds.

L199ff.:

Virga and cloud detection is sketched in Fig. 3 to highlight special cases and usage of certain thresholds . Special cases demonstrate the usage of thresholds handling gaps in the radar reflectivity signal. The specific cases of Fig. 3 panel (a) are:

- *time-step* = *1*: The standard case, when precipitation and cloud are detected from the observed CBH. No further considerations have to be made.
- *time-step* = *2*: The gap (range-gate (rg) 7–8) is smaller than maximum allowed gap for virga (*precip_max_gap* = 700 m) to count rg 6 as virga, but rg 6 is filtered since the requirement of minimum virga length of 2 rg is not met., which is a requirement of the virga mask refinement based on the threshold *minimum_rangegate_number* (see Sect. 3.4 and Appendix A).
- *time-step* = *3*: The gap (rg 7–8) is smaller than the threshold, therefore rg 3–6 are counted as virga.
- *time-step* = *4*: The In addition, the gap (rg 7–1117–18) is larger than the threshold, maximum allowed gap for clouds (*cloud_max_gap* = 150 m) therefore rg 3–6 are 19 is not counted as virga. In addition, the cloud. In this case, rg 19 could be a cloud, but since the *Virga-Sniffer* detection is tied to the CBH input data, rg 19 cannot be identified. Missing information about the second cloud layer can occur if the ceilometer signal is strongly attenuated by the clouds of the lower layer or by strong precipitation.
- *time-step* = *4*: The gap (rg 17–187–11) is larger than the maximum allowed gap for cloudsthreshold, therefore rg 19 is 1–6 are not counted as cloud. virga. Therefore, the rain flag at the surface has no effect, as the virga detected in rg 12–14 does not reach the first rg.
- *timetime-step* = *5*: Rain is observed Precipitation is detected from (rg 1–14) as the gap (rg 7–8) is smaller than the threshold. Due to the rain flag at the surface (either by the additional data of surface rain flag, or by exceeding the radar reflectivity threshold in the lowest rg)radar rg, therefore *ze_thres* = 0 dBz), no virga is assigned in this profile.
- *time-step* = *6*: Same as *time-step* = *5*. In addition, the gap (rg 17) is smaller than the maximum allowed gap for clouds, therefore rg 18–19 are counted as cloud. The surface rain flag doesn't lead to a reclassification of the detected virga towards rain, as the first rg has no data.
- *time-step* = *7*: Same as *time-step* = *6*. In addition, another CBH layer is observed right below rg 19. This CBH layer is not considered, as the gap at rg 17 is smaller than the maximum allowed gap for clouds, and it is not possible to distinguish between clouds and precipitation due to that. Therefore, the lowest CBH is assigned, as in time-step = 6 to initialize the detection of clouds and precipitation and the higher CBH is ignored per default (*cbh_connect2top* = False).

5. ***L201:*** *Is this step included when the clutter filter described earlier is also in use? Is it necessary if there is already a clutter filter?*

* In Figure 2, time step 2, range gate 6 shows an isolated radar signal. This may or may not be clutter. In Virga sniffer, clutter is defined by the combination of high mean Doppler velocity and low radar signal, which is not always the case even for signals from isolated range gates. This signal at range gate 6 could just as well be a signal from precipitation blown into this column by the wind. At least for the EUREC4A dataset, we found that single isolated signals from a range gate often appear near the lowest range gates, which are likely clutter but which we cannot verify and whose combination of mean Doppler velocity and radar reflectivity value for the mask_clutter step does not fall under "clutter". Therefore, we introduced a minimum number of contiguous range gates within a profile. We reordered the text of Sect. 3.3 for clarification and clarified the intention to mask clutter.

> **L210 ff.**:
>
> ~~As a first step of virga mask refinement, virga events of each profile spanning less than two range-gates are excluded to remove false positive detection due to clutter (see Fig. 3, *time-step* = 2~~
> ~~). In addition, clouds and virga~~ Clouds and precipitation detection solely based on radar reflectivity and CBH is refined by using additional data of mean Doppler velocity and surface rain flag.
>
> [...]
>
> A data point is considered virga only if Eq. 1 is fulfilled. With default configuration (m = 4 and c = -8) unusual combinations of low Z_e and V_m are filtered (*mask_clutter*, see Fig. A1).
> In addition to the clutter mask based on the mean Doppler velocity, isolated precipitation events spanning less than two range-gates are excluded to remove false positive detection due to clutter, which cannot be identified by the combination of high mean Doppler velocity and low radar signal (see Fig. 3, *time-step* = 2).

6. ***L208-209:*** *As previous comment about wind-blown rain detected at the surface.*

* The differences of using the surface observed rain flag and the rain flag from the first radar range-gate are discussed in the new Appendix section B3. In a situation of wind blown rain, both rain masks are likely shifted as it is sketched in new added Fig. 3 panel (b) in the manuscript (see also answer to comment #3.)

7. ***L237:*** *Include some discussion of how frequently these limitations occur and the impact they are likely to have on the overall data quality.*

* We have added the following paragraph to the end of section 3.5:

L275ff.:

The limitations identified in this section strongly depend on the input data and atmospheric situation. They can occur at any time. This section is intended to alert potential users of the software of these pitfalls, which may occur to varying degrees on their data set. To be more precise: The issues with "noncontinuous radar signal" and "cloud detection" originate from the facts, that (i) CBH data might be incomplete and (ii) the radar reflectivity might have some gaps if very small cloud droplets are not seen by the radar. The "cloud layer transition" problem is a bit more tangible. It does not occur very often when cloud layers in the atmosphere are clearly separable (as it is the case for the EUREC^{4}A RV *Meteor* dataset). It can become a frequent problem when cloud layers have very large height variations over the course of a measurement period and/or are vertically not well separated.

8. ***L252-253:*** *Could neighbouring columns be included to mitigate this? Allowing a large vertical gap for virga seems to lead to unlikely results at times (e.g. part of the lower cloud being labelled as virga at 3.4 in Fig. 5)*

* We agree, that the allowed vertical gap for virga is a sensitive threshold in the configuration of the Virga-Sniffer. As it is stated in the text, it should be set to zero to avoid False-Positive detection of Virga. Nevertheless, allowance for gaps is virga is required in order to catch fall-steaks advected into the radar volume, as checking neighbouring profiles is not implemented in the Virga-Sniffer. We have strongly considered it though along with moving to aggregation of virga events to be able to characterize connected events. At this stage, this is out of the scope of the Virga-Sniffer, but might as well be an extension in the future. Nevertheless, even allowing an infinitely large gap for virga detection does not add a large amount of false data points. As clouds are detected first, precipitation is limited between the cloud layers. This is shown in the newly added Appendix B2.

9. ***L263:*** *Due to what?*

* This might occur due to low liquid water content and small droplets in clouds which are detected by a LIDAR system but not by the radar system.

10. ***L280:*** *If I understand this correctly the categories on the inner ring are a subset of the outer ring? If so, why do they not align for aerosols?*

* This seems to be an optical illusion. We double-checked all values, they do align.

11. ***Fig. 6:*** *Annotate the larger classes in the inner ring with the percentages*

* Done as suggested.

12. ***L313:*** *What are the horizontal lines on Figure 8?*

* The values of the virga depth calculated by the *Virga-Sniffer* can only assume certain values. This depends on the radar range-gate resolution (here about 30 m). The horizontal lines resulted from the fact that at certain distances the bins of the histogram spanned several possible values of the virga depths. This issue is resolved in the new version of the figures, which were plotted using different bin widths.

13. ***L313:*** *Given the large number of virga reaching 300 m it would be interesting to see any meteorological observations both surface based or radio/dropsondes to look at profiles of humidity and temperature.*

* This was done, but because the paper is more focused on the technical nature of the virga sniffer, it was not included.

14. ***L325:*** *By eye there appears to be a loose trend along a line from approx. (0, 0.2) to (1, 1.5). Have you looked at any statistics for these data?*

* No, we did not consider this trend to be significant.

15. ***Fig. 8, 9b:*** *The y-axis scale is irregular, I assume it should be 250 m per label. Add the extra sig fig to make this clearer*

* This issue is resolved in the new version of the figures.

16. ***Fig. A1:*** *needs colorbar*

* A colorbar is now added to Fig. A1.

Spelling/Grammar/Typos

- ***L19(x2), 20, 31, 197:*** *Using above/below is ambiguous when talking about the atmosphere, especially in relation to temperature which changes with height. Use greater than, less than etc.*
- ***L112:*** *Define MPI before use*
- ***L154:*** *less -> fewer*
- ***L261:*** *remove the comma*
- ***L334:*** *1.5 m -> 1.5 km*
- ***L357:*** *pixel -> pixels*
- ***L363:*** *"As application", I'm not sure what was intended here*
- ***L403:*** *suses -> uses*
- ***L404:*** *remove comma*
- ***L457:*** *remove paragraph*

Thank you for carefully reading and pointing this out, these remarks have been corrected in the text.

References

Witthuhn, J., Röttenbacher, J., and Kalesse-Los, H.: Virga-Sniffer (v1.0.0), https://doi.org/10.5281/zenodo.7433405, 2022.

Author's response to:
RC#3 from Anonymous Referee #3
https://doi.org/10.5194/amt-2022-252-RC3

Heike Kalesse-Los[1], Anton Kötsche[1], Andreas Foth[1], Johannes Röttenbacher[1], Teresa Vogl[1], and Jonas Witthuhn[1]

[1]Leipzig Institute for Meteorology (LIM), University of Leipzig, Leipzig, Germany

Correspondence: heike.kalesse-los@uni-leipzig.de

Dear Anonymous Referee #3,

We appreciate the time you used for an in-depth read of the manuscript. You spotted many small issues in the manuscript that needed improvement and clarifications. We have addressed those issues carefully and extensively.

In order to separate the reviewer's comments and the author's response, we printed the comments in black and the response in blue. Excerpts of the manuscript with marked changes are pinned directly to the appropriate responses, with the indicated text location (e.g., line number) referring to the manuscript in preprint.

Sincerely, on behalf of all authors

Heike Kalesse-Los

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- Many text passages, figures and tables were revised in consideration of review comments, as can be seen in the detailed responses.

Response to RC#3 of Anonymous Referee #3:

Comments on the description of the Virga-Sniffer (Sections 3 – 3.3)

1. *It is not clear what processing is optional and which steps are always performed, and which of the description applies specifically to the processing of the EUREC4A data set. The authors might need to make a more clear separation of the general description of the algorithm and the EUREC4A specific processing. The authors should also check that the optionality of different steps is clear and uniformly presented across the manuscript.*

* For clarification, we added more explanation to the beginning of Sect. 3. In addition, we have separated step 3 into virga detection based on radar reflectivity threshold in the lowest range gate (mandatory) and the optional virga mask refinement. We have also revised the manuscript to ensure that any user-definable settings are identified as such and their default values are specified.

> **L142ff.**:
>
> It is highly configurable, modular and therefore usable for different measurement setups. In addition, virga detection can be refined by additionally considering radar mean Doppler velocity, LCL, and surface rain detection. Example cases presented in the following using the default settings to process the EUREC^{4}A dataset.
>
> The workflow of the virga detection is separated into three parts, as summarized in Fig. 2:
>
> 1. Preprocessing of CBH
> 2. Precipitation and cloud detection
> 3. Virga detection
>   (a) Masking rain events
>   (b) (Optional) ~~Virga detection~~ virga mask refinement
>
> Note, all modules in the virga mask refinement are entirely optional (step 3b). In order to separate rain and virga events (step 3a) the *mask_rain_ze* module is used, which is based on the radar reflectivity values in the lowest range-gate. Potentially, the *Virga-Sniffer* can be used to mask both rain reaching the surface and virga by opting out of using the rain masks *mask_rain_ze* and *mask_rain*.

2. *It is also not clear which of the many thresholds given are user-configurable, and I kindly ask the authors to clarify whether some thresholds (if any) can not be chosen by the user.*

* All thresholds, flags and special configuration options listed in the appendix and referred to in the text are freely user-configurable.

Appendix A, first paragraph (L392ff.):

The *Virga-Sniffer* utilizes a variety of flags and thresholds to detect virga from the given input data. The configuration ~~can be set~~ is freely user-configurable via a configuration dictionary, which will be merged with the default values. In the following all default values of configuration flags, thresholds and settings are summarized. ~~A full description~~ This default setup is used to process the EUREC[4]A dataset described in Sect. 2. A full description of each configuration parameter can be found in the documentation (https://virga-sniffer.readthedocs.io, last access 19 August 2022) (Witthuhn et al., 2022).

3. *There seems to be discrepancies between the text and Fig. 2, which shows the workflow of the algorithm. I first got the impression that Sections 3.1-3.3 correspond to the three orange boxes in Fig. 2, each section describing one box, however parts of the text describe processing that is shown in a different orange box. Furthermore, there is processing described in the text that is not included in the figure, and elements in the figure that are not included in the text, as far as I can tell. Specifically, I am missing the description of the Range-gate mapping (orange box 2), the smoothing that is presented in the ellipse below orange box 1, and the Count valid data (orange box 3) in the text. Could the authors add the description of these algorithms in the text, or make it more clear where a certain algorithm description is related to the corresponding element in Fig. 2? I urge the authors to check that the Fig. 2 and text logically relate to each other, and suggest the authors use Fig. 2 more to guide the reader through the multiple processing steps.*

* We have revised the text and have added several references pointing to methods shown in the flowchart. As the flowchart has also been revised and some text part have been re-sorted to another section for clarification, the reviewer is kindly asked to review the changes in the tracked-changes document.

4. *P. 7 L. 140-148. The description of the overall structure of the VirgaSniffer could be extended. I believe providing some more top level description of the processing chain would be helpful to understand the following sections and the context in the processing chain that these occur in. Although the three parts of the virga detection (somehow related to the 3 orange boxes in Fig. 2) are introduced, introducing also what happens outside these boxes, and where in the manuscript these different parts are described, would be helpful for the reader.*

* The methods boxes in Fig. 2 are connected by arrows, which show the data flow within the *Virga-Sniffer* (we made the lines thicker in the revised versions some reviewers had problems seeing them on print-outs). Outside these boxes nothing happens to the data. In addition to changes shown in the answer to comment #1, the following text has been added to the beginning of Sect. 3 and the Fig 2 caption:

Sect. 3., 1st paragraph (L140ff.):

The *Virga-Sniffer* is a profile-based detection scheme for virga events. It is a self-developed Python package (Witthuhn et al., 2022). The detection is based on a set of empirical thresholds, which are manually tuned on the EUREC^{4}A data set (Sect. 2) and summarized with their default values in Appendix A. This package provides a tool for detecting virga from profiles precipitation, virga and clouds from profile-by-profile observations of vertically-pointing cloud radar reflectivity and ceilometer observations of cloud base height (CBH), taking into account multilayer cloud situations. The radar data serve as a basis, as they define the temporal and vertical resolution for the *Virga-Sniffer*, which in the case of the EUREC^{4}A data set is 1.6–2.9 s and 22–42 m, respectively (see Sect. 2.1). The main result are Boolean masks, which mark clouds, virga and/or precipitation on the radar coordinates (range-gates and time-steps). It is highly configurable, modular and therefore usable for different measurement setups. In addition, virga detection can be refined by additionally considering radar mean Doppler velocity, LCL, and surface rain detection. Example cases presented in the following are based on the default settings of the *Virga-Sniffer* to process the EUREC^{4}A data set.

Fig. 2 caption:

The workflow of the *Virga-Sniffer* virga detection. Datasets are shown as polygons, applied methods as ellipses. The submodule *cbh_processing* is shown as square, listing implemented methods. Z_e and V_m refer to the radar variables reflectivity and mean Doppler velocity, respectively. The arrows showing the data flow within the *Virga-Sniffer*. the data is processed from the input dataset step by step, starting with (1) *CBH processing*, until stored in the output dataset. Flags to enable certain vira mask refinements are denoted in italics with their default setting.

5. *Figure 2. There seems to some parts of the flow missing, i.e. some arrows only lead to somewhere but don't start from anywhere, and there is a lonely ellipse "smoothing" that has no input put feeds into several polygons or ellipses. It also strikes me somewhat odd that from the orange box 2 Precip. & cloud detection there is no arrow leading to the polygons CBH and CTH in the Output dataset. Could the authors check that following the arrows in the figure one can indeed trace the data processing chain, and update the figure where needed.*

* The figure has been revised, including thicker arrows to connect the boxes.

6. *Figure 2, Orange box 3. There are some options shown in the figure, (e.g. mask_clutter=True, mask_vel=True). Are these default options, or the ones used for the EUREC4A data set? I kindly ask the authors to add this information in the figure caption.*

* The information has been added, see answer to comment #4.

7. *P. 7 L. 150-153. I find the introduction to this section confusing, and it is hard to keep track of the different configurable and non-configurable processing and in which order things are done. To make it easier to follow, I suggest changing the order so that the smoothing that is done as a first step, and which I gathered to be non-optional (however I'm not sure) would be introduced first. Following this, the optional, user-configurable modules could be introduced. Another option would be to first simply introduce the five modules, and in a separate paragraph explain how they are used.*

* To address this comment, the text of this section was revised and restructured as recommended. Please refer to the tracked-changes document to view the changes.

8. *P. 7 L. 152. "used settings and thresholds are..." could the authors specify where the settings and thresholds are used, as default values? For the EUREC4A data set?*

* Default settings are used for the EUREC4A dataset, which are user configurable and summarized in the Appendix. This particular line has changed as follows:

L152ff.:
In total five modules ~~(described below) are available~~are available. These modules are named *clean & sort*, *split*, ~~used settings and thresholds~~ *merge*, *add LCL* and *smooth*. Flags and thresholds used to control in the modules, and their default values, are summarized in ~~Sect.~~Appendix A.

9. *P. 7 L. 154-162. I cannot follow how this processing is done. What are CBH layers, and how is a data coverage threshold or a mean value for these calculated? As far as I understand, for each ceilometer profile a number of cloud base heights are detected, which I would expect to be related to different cloud layers, and thus I don't understand how e.g. a mean value would be calculated for a cloud layer for the one data point available. Is perhaps some kind of time window investigated? I also have trouble understanding the logic of the split and merge modules. Perhaps the authors could consider adding an illustrative figure to help the reader to follow their reasoning.*

* For clarification, we have added the following to the beginning of Sect. 3.1:

Sect. 3.1, 1st paragraph (L150ff.):
The ~~input CBH layer data is~~ ceilometer provides the input values of the CBH. Depending on the type of ceilometer and the underlying algorithm and the optical properties of the clouds, multilayer cloud situations can also be taken into account. In the *Virga-Sniffer* cloud layers are sorted within a processing interval, which depends on the given input data (here daily data). A cloud layer is identified in the *Virga-Sniffer* by its CBH, which on average differs from other layers over the processing interval by more than the set threshold of 500 m (*cbh_layer_thres*, see Sect. A). The term *layer* is used, if a variable is tied to a specific cloud layer, as the term CBH layer refers to the cloud-base height of one cloud layer. The CBH input data from the ceilometer must be pre-processed ~~before it is~~ to achieve a sorted CBH layer data set before it can be used for virga and cloud detection. As the *Virga-Sniffer* is designed to work on the radar data coordinates, the CBH input data, on a temporal resolution of 30 s, is interpolated to the temporal resolution of the radar (here: 1.6–2.9 s).

10. *P. 8 L. 163. Also here I don't understand how it is possible to have nan values for the lowest CBH layer, I would expect the lowest CBH to have the value given by the ceilometer for the first cloud base height, or clear sky conditions. Perhaps the clarification of the definition of a CBH layer makes also this more understandable.*

* In addition to the answer to comment #9, we added:

L154ff.:
clean & sort: ~~First, CBH layers with less valid~~ The valid data-points of each CBH layers are counted and compared to the number of data-points for the total processing interval. If the number is lower than the given threshold of 5 % are removed (*clean*). ~~Then, for~~ After the cleaning, the remaining layers ~~, the mean height of each layer is calculated. The CBH dataset is then re-indexed, by sorting the layers~~ are sorted in ascending order by ~~mean height~~ comparing their mean height over the processing interval (*sort*). .

11. *P. 8 L. 163-164. Is the running-median filter applied to the LCL data before or after replacing the lowest CBH balues with the LCL?*

* They are smoothed first, so we rearranged the two sentence accordingly.

12. *P. 7-8 L. 154-165 and Figure 2. The CPH preprocessing modules have different numbering in the figure and in the text (0-4 in the figure, 1-5 in the text). In the appendix (P. 22, L. 430) the 0-4 numbering seems to be in use. I suggest uniform notation to avoid confusion.*

* Yes, since Python logic starts at 0, the technical description was initially written on this basis. Now we start uniformly with 1 in the manuscript.

13. *P. 8. L. 165. What is done at this step? What is the parameter being smoothed? Clarification needed.*

* We have rephrased the sentence:

> **L165**:
>
> ~~The CBH layer data~~ Each layer of the CBH dataset is smoothed by applying a running-median filter with the window size of one minute.

14. *P. 9 L. 166-168. From this description I was not sure how to the EUREC4A data set was processed. To avoid ambiguity, perhaps the authors could here also give a list of the modules in order of at which the processing was done.*

* The text is rearranged and rephrased:

> **L166ff.**:
>
> ~~For the pre-processing of the EUREC⁴A RV *Meteor* CBH data~~As default, two iterations of the combination *split*, *merge*, *add LCL* are considered~~, followed by an additional smoothing step~~. The module *clean & sort* is applied in between each step to continuously filter outliers. ~~Note, that here additional data of LCL is required, which is calculated from surface observations of air pressure, temperature and humidity from the meteorological observation station on the RV *Meteor* using the method of~~ Romps (2017) ~~, which is build into the *Virga-Sniffer* package utilities~~After these two iterations, a last smoothing step is applied. As a final step, gaps smaller than ~~one minute~~ the threshold *cbh_fill_limit* of by one minute by default in the processed CBH data are filled by linear interpolation ~~to~~ by default (the filling method can be chosen with the option *cbh_fill_method*, see Appendix A). This step to fill gaps in the CBH layers is applied to increase the detection coverage, assuming negligible variability of CBH during ~~this time frame~~ a time frame controled by the *cbh_fill_limit* threshold. Larger gaps remain, as filling them might lead to non-physical results of CBH and false positive virga detection.

15. *P. 9 L. 171-172. Is the linear interpolation described here optional or not? Also, the interpolation is not mentioned in Fig. 2.*

* It is optional, as the maximum gap size filled by this interpolation can be set to zero. We have included the interpolation in the flowchart and rephrased the text, see answer to comment #14.

16. *Is the ceilometer CBH data brought to the same temporal and vertical resolution as the radar data? If not, how are differences in the temporal and vertical resolutions dealt with?*

* Yes, the CBH is interpolated to the radar resolution. We have added describing text, see answer to comment #9.

17. *P. 9 L. 182. Here the authors argue that a gap of 700 m, which is used as a threshold to detect precipitation associated with a cloud base height, is small enough to not mask out any lower cloud layer, however, later they show that it can*

happen and the authors discuss the difficulty on setting this threshold. I would find it appropriate to use less definitive language here, and perhaps write that the difficulty in setting this parameter is discussed later in Sect. 5.4.

* We have rephrased the text accordingly:

L182ff.:

Precipitation is detected at each range-gate of ~~valid radar reflectivity~~ the radar reflectivity mask iterating downward from CBH until a gap ~~(nan-value in radar reflectivity)~~ occurs, which is larger than the threshold *precip_max_gap* of 700 m per default (see Appendix A). This threshold is large by choice, to also capture precipitation which can be observed from fall streaks advected to the radar viewing volume by wind shear. At the same time, the threshold is still small enough to mask out any clutter ~~or unidentified clouds close to the surface~~ or a lower cloud layer ~~, respectively~~when the cloud layers are vertically well separated. Since the detection of clouds and precipitation with the *Virga-Sniffer* is carried out for individual profiles and no horizontal linking (in the temporal sense) of these profiles takes place, the handling of fall streaks is one of the most challenging aspects and is realized exclusively by the threshold value of the allowed gap size. The challenges associated with these thresholds (*cloud_max_gap* and *precip_max_gap*) are discussed in Sect. 3.5. In Appendix B2 the sensitivity of the two thresholds is analysed.

18. *P. 9 L. 188-190. Could the authors elaborate a bit more on this processing step. What are "intervening cloud layers"? How is the continuity of a cloud layer evaluated? How is the cloud layer selected that the virga or precipitation is associated to?*

* We have rephrased this paragraph:

L188ff.:

A special case occurs, when there are no gaps in radar reflectivity between some cloud base layers, which happens when precipitation originating from a higher cloud base falls into a lower ~~cloud. In this case, the intervening cloud layers are excluded. Therefore, the virga or precipitation events are connected and assigned to the highest continuous cloud base and associated cloud~~layer. In the default setting, the lowest CBH is retained and higher CBH layers are omitted from the processing because no distinction can be made between clouds and precipitations. The lowest CBH in such an event is therefore assigned to initialize precipitation and cloud detection. Note, the handling of this kind of events can be changed to assign the highest cloud base instead, by the configuration flag *cbh_connect2top* (see Appendix A).

19. *P. 9 L. 191-192. Unclear sentence, I do not understand which part of the sentence refers to the cloud top and what to the cloud base values. Perhaps splitting the sentence to first describe the smoothing applied for the cloud top values, followed by a sentence describing what this is similar to, would help with to make more understandable.*

* We have rephrased this sentence:

L191ff.:
The detected cloud-top values are smoothed as ~~cloud-base values are smoothed prior to the cloud-base processing~~a final step after the processing. The smoothing is applied in the same way as the cloud base by utilizing a rolling median filter of a one-minute window size per default (*cbh_smooth_window*).

20. *P. 9 L. 193-194. I don"t understand the meaning of the sentence "This mapping is used to separate the cloud and virga-mask into cloud layer components". What are "cloud layer components"?*

* We have rephrased this sentence:

L193ff.:
This mapping is used to separate the ~~cloud- and virga-mask into cloud layer components~~cloud, precipitation and virga masks for the cloud layers respectively, so that the masks can be narrowed down to individual cloud layers.

21. *P. 9 L. 195. Until here there has not been any differentiation between virga and precipitation, is the first step of assigning precipitation to virga to consider Ze at the lowest radar range gate? What about multi-layer situations? Could the authors elaborate how from the cloud and precipitation mask (shown as a circle in the orange box 2 in Fig. 2) the virga mask is derived for the first time? And where in the processing (as described in Fig. 2) does this take place? Since in the orange box 3, and Sect. 3.3. (according to the subsection heading), the virga mask is refined, it appears as there should be a virga mask set prior to the (optional) third step.*

* We have revised the flowchart and Sect. 3 to clearly differentiate between precipitation and virga. Section 3.2 was split into "Precipitation and cloud detection" and "Virga detection". Please see the attached tracked-changes document.

22. *P. 9 L. 195-198. Here the surface rain flag based on Ze threshold is presented as part of the standard processing in step 2 (since it is described in Sect. 3.2), although Fig. 2 suggest it is part of the optional virga detection refinement in the orange box 3. Could the authors clarify the optionality of this processing step and where in the processing flow, as described by Fig. 2, it takes place?*

* We agree, that the use of "optional" was misleading and have rephrased this part. All methods declared as optional in the submitted manuscript were optional to the user, but for virga detection one has to distinguish it from rain reaching the surface. The flowchart and section 3 were revised to clarify on this point, see also previous answers.

23. *Figure 3. This figure and the associated text are very nice and helpful for the reader to understand the details of the algorithm. Technically, the blue and pink values would also be valid Ze values, the authors could consider using another label for the green boxes. The authors should also check that the figure is readable for colorblind readers.*

* The colouring was changed to colour-blind friendly. The presentation has been adapted to ensure unambiguity.

24. *Figure 3. Are the range gates intended to correspond to certain range resolution (so that i.e. allowed gaps would correspond to specific thresholds), or is the figure merely illustrative? An additional note on the caption would avoid ambiguity.*

* We have added a note accordingly

> **Fig. 3 caption**:
>
> ~~Sketched representation of virga and cloud~~Illustration (not to scale) of cloud, precipitation and virga detection from radar reflectivity Z_e, surface rain flag and cloud base height data, corresponding to step 2 and 3 of Fig 2. In panel (a) the behaviour of the *Virga-Sniffer* in certain situations is shown in detail. Panel (b) shows the benefit and influence of different rain flags, as well as the threshold value of the allowed rain gaps (*precip_max_gap*).

25. *Figure 3. The figure clearly illustrates input and output parameters, however it is not clear to me to which part of the algorithm, as illustrated in Fig. 2, the processing illustrated by the Fig. 3 and associated text refers to? The entire orange box 2? Perhaps the authors could clarify which element of the processing chain the figure is illustrating.*

* We have added a note to the figure caption, see answer to comment #24.

26. *P. 10 L. 200. No mentioning of a minimum virga length to be required has been provided until here, and it is also not included in Fig. 2. I found the explanation on the next page in the next section for virga mask refinement. Could the authors clarify where this criteria is used (step 2 or 3 of the processing), and on the optionality of this criteria?*

* The text was revised to aid the description of the minimum range gate number. This particular sentence has been changed as follows:

> **L200ff.**:
>
> The gap (range-gate (rg) 7–8) is smaller than maximum allowed gap for virga (*precip_max_gap* = 700 m) to count rg 6 as virga, but rg 6 is filtered since the requirement of minimum ~~virga~~ length of 2 rg is not met~~.~~, which is a requirement of the virga mask refinement based on the threshold *minimum_rangegate_number* (see Sect. 3.3 and Appendix A)

27. *Related to the previous comment, for the reader it would be less confusing if any criteria used for Fig. 3 and its description on lines 200-208, would be described prior to the figure and the text appearing. I therefore suggest the authors move Fig. 3 and the associated text later in the manuscript, when all parts of the algorithm used have been introduced, or move the explanation of the minimum virga length to before L. 200.*

* As this figure is used to illustrate cloud, precipitation and virga detection described in Sect. 3.2 (and the new Sect.3.3), we keep it in place (We added it to Sect 3.3 in the tex-file, but latex automatic placement might be different in the manuscript in discussions and in print). Nevertheless, we added a reference to the section describing the *minimum_rangegate_number* threshold for clarity, see answer to comment #26.

28. *P. 10 L. 200. Could the authors either comment on rg 19 here, or remove this Ze valid value in the corresponding time step in the figure?*

   * We have moved the explanation from time-step 4 to time-step 3.

29. *P. 10 L. 206. In time-step 5 (and 6) there is no valid Ze value in the lowest range gate, so obviously the radar reflectivity threshold could not cause the surface rain flag to be set. Perhaps the authors could add a time step, or edit time-step 5, to have valid Ze-values to reach to lowest range gate, to illustrate the behavior in such a case?*

   * Thank you, this is an error made in the illustration. We have updated the figure accordingly.

30. *P. 11 L. 213-214. Is the Ze threshold at the lowest range gate an optional processing step, as suggested by Fig. 2, or is it always performed, as it appears from the text in Sect. 3.2?*

   * Section 3 was revised to clearly separate precipitation and virga detection, see previous answers, e.g. to comment #21.

31. *P. 11 L. 218. How does the Vm threshold of 0 ms-1 perform in convective situations? Figure A1 suggests that for Ze < 0 dBz, e.g. drizzle, Vm peaks very close to zero and values slightly above 0 ms-1 could be assumed to be drizzle observed in an updraft. Could the authors comment on the choice of this threshold in the context of convective situations, and have the authors evaluated the sensitivity of virga detection on this threshold?*

   * As the main goal is to identify precipitation/virga which contributes to precipitation evaporation, we chose to restrict the detection to falling droplets only. Anyway, a sensitivity study was conducted and is now added as Appendix B. It is shown, that setting this threshold for the mean Doppler velocity to 0.5 or even $1.0\,\mathrm{ms}^{-1}$ (updrafts) does not add significantly to the amount of identified data points.

32. *Does the movement of the platform have an influence in the use of Vm -based virga refinement and the used thresholds?*

   * The radar on the ship set up on a stabilizing platform to compensate for the ship movement and mitigate the influence of the horizontal wind on the retrieved mean Doppler velocity. In addition, the dataset was heave-corrected, as described in section 2.1. Please also see our detailed answer to minor comment 2 of reviewer 2 regarding the movement of the radar platform.

33. *Figure 4d. The contrast between the red and orange is quite poor, could the authors consider another choice of colors to aid the readability?*

   * The colours has been revised for this figure.

34. *In Fig. 4a and 4c there is a line around 300-400 that looks rather strange. Is this an artifact? Could the authors comment?*

   * Yes, this is an artefact from the radar reflectivity dataset, that we refer to as "clutter". These cases are omitted by the the "minimum rangegate number" threshold.

35. *Figure 4 Caption. The caption is missing the mentioning of the radar reflectivity factor shown in panels a, c, and e, which I understood to be the input for the Virga-Sniffer.*

* Yes, we added it to the figure caption.

> **Fig. 4 caption**:
>
> LIMRAD94 reflectivity factor Z_e (panels (a), (c), (e)) , and *Virga-Sniffer* output for different cloud situations during EUREC4A based on RV *Meteor* observations (panels (b), (d), (f)). The colorbar on the right side panels denote the maximumd number of cloud layers detected during the case study days (count starts at zero for the lowest layer). Panels (a) and (b) show stratocumulus with virga and a precipitation system, panels (c) and (d) altocumulus with virga, and panels (e) and (f) trade wind cumuli with virga. The dotted line labeled "filled cloud-base" refers to either LCL values which fill in gaps during the CBH pre-processing or CBH gaps which are filled by interpolation (see Sect. 3.1 and Appendix A).

36. *Figure 4. What is the filled cloud base in Fig. 4b, d, and f, shown with a dashed line? Is it denoting the interpolated values (L. 171)? How come is the lowest cloud layer continuous, is this from the LCL filling (L. 163)? Clarification from the authors to correctly interpret the figure would be appreciated.*

* We have added an explanation to the figure caption, see answer to comment #35.

37. *In the plots illustrating Virga-Sniffer results (Figs. 4, 5c), the green and blue are very hard to distinguish from each other, and I ask the authors to consider using colors with more contrast.*

* The colormapping has been revised.

38. *P. 15 L. 288. The authors mention here a smoothing at precipitation edges performed by the Virga-Sniffer algorithm. Could they please include a description of this procedure in the algorithm description?*

* This smoothing is not part of the Virga-Sniffer, rather the preparation of the Input data. We have rephrased this sentence:

> **L288ff.**:
>
> This can be attributed to smoothing of the input radar reflectivity and mean Doppler velocity values at precipitation edges used in the *Virga-Sniffer* algorithm.

Minor comments

39. *P. 1 L. 16, 18. There seems to be a slight mismatch between the values presented in the abstract and those in Table 3, where the fraction of clouds below the trade inversion producing virga is 51% and the fraction of virga produced by trade wind cumuli is 37%, in comparison to 50% and 36%, respectively, written in the abstract. Could the authors correct this, or clarify where the values corresponding to those in abstract are to be found in the manuscript?*

* This was a mistake and is now corrected.

40. *I believe the abstract as well as the conclusions should not make statements not supported by the results presented in the paper. The paper does not show the dependency of virga depth on liquid water path, only mentions that no dependency is found and the result is not shown. I recommend the authors either present the result, or remove the statement from the abstract. Furthermore, the paper does not provide any analysis on the cloud types producing virga, only relates virga to cloud height and depth. The attributions of certain virga features to cloud type are claims by the authors, not supported by any analysis in this study or references to the literature. Although these claims may be reasonable and supported by knowledge of the features of certain cloud types in the specific climate zone studied, I find it questionable to present these claims in the abstract and conclusions. I suggest that the sentence "The most important virga producing clouds were either anvils of convective cells or stratocumulus clouds." (P. 1 L. 17-18) be removed from the abstract, together with references to specific cloud type in the conclusions (P. 20 L. 372-373). Similarly, for the statement that virga detected by Virga-Sniffer that is classified by Cloudnet as 'aerosols and insects' occurs mostly at virga edges, the authors only show one case as evidence (Fig. 5). While I have no reason to doubt this result, the manuscript does not demonstrate that most cases are indeed like the one example shown, and I therefore suggest the authors consider if the statement should be included in the abstract (P. 1 L. 14-15) and in the conclusions (P. 19 L. 361-362).*

   * We acknowledge that in our initial manuscript version, the cloud classification was chosen to exclusive. We therefore now opted for a more general description. As suggested in Vial et al., 2019, we decided to now follow the cloud classification nomenclature of the broader trade cumulus community. Clouds with their base between 1 and 4km are now refered to as stratiform cloud layers or anvils of trade wind cumuli, as these are the dominant cloud types in these heights in the winter trades. Figure 1 shows a couple of other days with aerosols & insects (dark red pixels) at precipitation edges. Since we had a deep view inside all cases, and we checked all days of measurements during the field experiment, and we demonstrate a representative case, we can make conclusion and mention them in the abstract and conclusion sections.

41. *I kindly ask the authors to add a note in the abstract that the results for virga occurrence reported are for the winter (dry) season.*

   * Added note in abstract before referring to statistics and output.

L. 16.:
For the RV Meteor observations in the downstream winter trades during EUREC4A....

42. *P. 2 L. 32. "more numerous and smaller" ⟶ more numerous and smaller compared to?*

   * Changed "smaller" to "small"

43. *The introduction well motivates the relevancy of studying the evaporation of precipitation in the trades. However, observation-based techniques used to detect or evaluate evaporation in the literature are not described. I kindly ask the authors to add some background on the observational techniques used in previous studies, given that the papers main contribution is to improve on the observational methods available to study precipitation evaporation.*

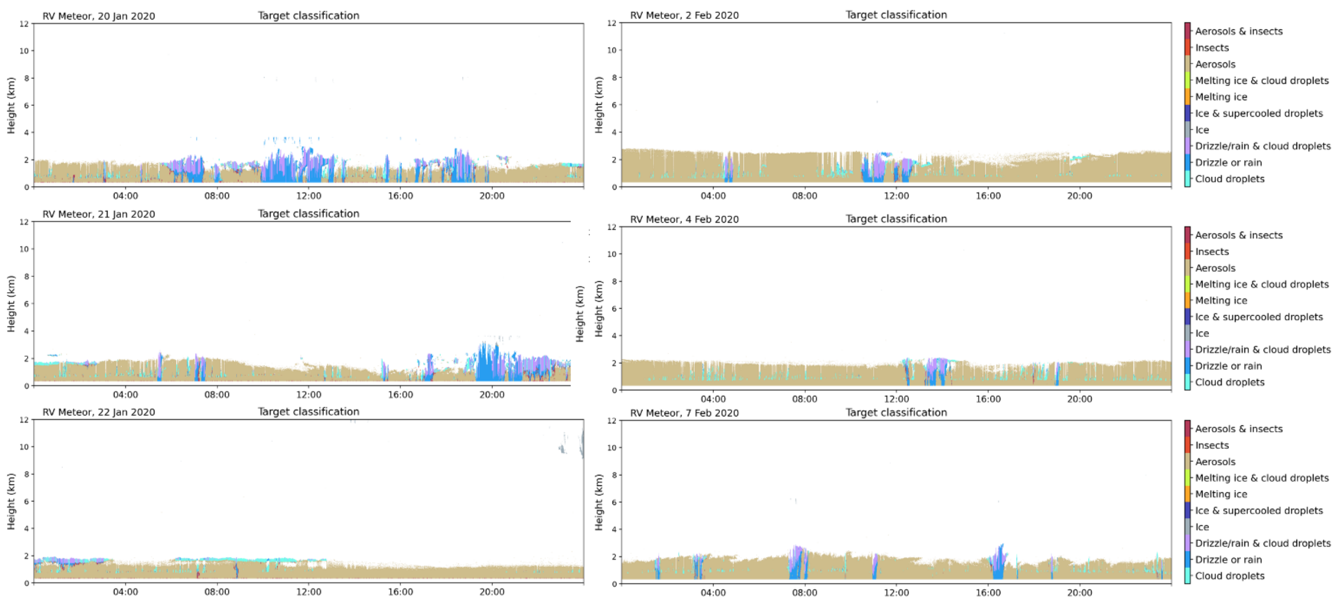

Figure 1. Cloudnet target classification for specific days showing that often insects are classified at virga edges.

* We agree and have added a short paragraph on previous radar-based precipitation evaporation studies in the introduction:

> **L88ff.**:
>
> However, also for ground-based radar observations overestimations of surface rain rate retrievals result when evaporation effects are neglected (Rosenfeld and Mintz, 1988; Li and Srivastava, 2001). While case studies of radar-based precipitation evaporation have e.g. been performed using observations with sophisticated Micro Rain Radar (MRR) and polarimetric X-band radar (Xie et al., 2016) or dual-frequency Doppler radar spectra (Tridon et al., 2017) we here aim to make use of widely available long-term single-frequency vertically-pointing millimetre Doppler cloud radar observations in combination with ceilometer measurements.

44. . *P. 4 L. 99-101. While I agree with the authors that evaluating the performance of the radar stabilization platform is a topic for a separate manuscript, it would be relevant to comment whether there is an impact on the virga detection presented in Section 4.*

* We expect no significant influence, as the experienced attitude angles were small. The effect of the observed attitude angles in combination with the observed horizontal winds on the mean Doppler velocity which is used for the virga mask refinement is detailed in the answer to comment #2 of reviewer #2. Also, the impact of the chosen mean Doppler velocity thresholds on the virga mask refinement is small, as shown in the sensitivity study in Appendix B. We added the following sentence in the manuscript after stating the mean and standard deviation of the attitude angles: L99: "These

small attitude angles do not affect the virga detection performance".

> **L97ff.**:
>
> ---
>
> Continuous attitude angle measurements by radar built-in motion sensors sampling at 0.5 Hz with an accuracy of 0.02° showed that ~~observed~~ absolute values of roll and pitch angles experienced by the radar generally were less than ~~0.09~~0.36 ± ~~0.49~~0.31° (mean ± standard deviation). These small attitude angles do not affect the virga detection performance.

45. *. P. 5 L. 104-105. Are there any references that could be provided for the radar data processing?*

   * Routines for radar data preprocessing are available within LARDA at https://zenodo.org/record/4721311. We added this reference in the manuscript.

46. *P. 5 L. 115 and 119. Integrated water vapor is not used in this study, and could be removed from the description of the data set.*

   * Indeed, we did not use IWV and thus removed it from the text.

47. *P. 1 L. 15, P. 5 L. 129, and elsewhere in the manuscript. CloudnetPy is sometimes referred to as CloudnetPy and sometimes Cloudnetpy, consistent naming should be used.*

   * Done.

48. *P. 7. L. 136-137. How much data was removed due to radar settings not being compatible for CloudnetPy? In Section 2.1 and Table 2 two chirp programs are described, are the measurements corresponding to these settings included in the analysis? If yes, what is the data that is excluded?*

   * Yes, the measurements performed using the radar settings listed in Table 2 are included in the analysis. Radar data that were not compatible to CloudnetPy input requirements, and which were thus excluded from the analysis, were the complete days of 27, 29, 30 and 31 January 2020. During these days, frequent switching between chirp programs (also other programs than the two listed in Table 2) in connection with software problems related to the instrument resulted in incoherent data, which could not be merged into CloudnetPy-compatible files. CloudnetPy requires daily files and problems arise when e.g. the range resolution of the radar is changed during a day.

> **L136ff.**:
>
> ---
>
> For the LIMRAD94 cloud radar, filtering of the data was performed to exclude periods when the chosen radar settings are not supported by ~~Cloudnetpy~~ CloudnetPy and would lead to erroneous results. Data is filtered at the complete days of 27, 29, 30 and 31 January 2020. During these days, frequent switching between chirp programs are performed for testing. Hourly profiles of pressure, temperature, and relative humidity from the European Centre for Medium-Range Weather ~~Forecast (ECMWF~~Forecasts Integrated Forecasting System (ECMWF-IFS) complemented the input to ~~Cloudnetpy~~CloudnetPy.

49. *P. 7 L. 138. Could the authors specify which model or reanalysis product from ECMWF was used?*

* Model data from the ECMWF Integrated Forecasting System (IFS) was used, we specified that in the manuscript now.

50. *P. 7 L. 152. Sect. A -> Appendix A.*

* Done.

51. *Some small editing is required for Table 1, specifically:*

    (a) *The table includes parameters not used in this study (spectral power, spectrum width), which I suggest the authors remove. Alternatively, the caption should be edited not to specify that the table includes "measured quantities used in this study".*

    (b) *For LIMHAT, the frequencies 22.23-31.4 GHz are missing.*

    (c) *It is not clear what the two different temporal resolution, vertical range and vertical resolution values given for the LIMRAD94 refer to. Comparing with Table 2 they seem to be associated with the two main chirp tables used during the campaign. I ask the authors to clarify this, as the table as it is currently presented might lead to misunderstanding that Ze and Vm have different temporal resolution and vertical range and resolution.*

    (d) *For the ceilometer, I believe that the cloud base height should also be given as a Measured/received quantity, especially as I understand from the description that the instruments internal retrieval is used and cloud base height is the parameter given as input to the Virga-Sniffer.*

    (e) *In the first row, I wonder if the authors would consider replacing received with retrieved in "Measured/received quantity", to reflect that some of the quantities (e.g. LWP) are retrieved from the measurements, and as I do not see the need to have both words 'measured' and 'received'.*

* We agree and changed the caption and the header of row 1 according to your suggestion We added:

> **Tab. 1 caption**:
>
> Specifications of instruments and measured quantities~~used in this study~~. For LIMRAD94, in the last three columns the upper values refer to the first chirp table used, the lower values refer to the second chirp table (see Table 2). The values in the last three rows refer to all the measured/received quantities of the respective data source.

* We also added the missing LIMHAT frequency and made clear what the different temporal resolutions refer to.

52. *Table 2 Caption. Parenthesis missing at the end.*

* Done.

53. *P. 13 L. 254-255. Could the authors clarify whether the recommended virga mask refinement using mean Doppler velocity was used in Fig. 5? Also, do the authors here mean the clutter filtering as described by Eq. 1, or the 0 ms-1 threshold criteria, or both?*

   * All refinements are used to process the casestudy in this article. The clutter filtering is done via Eq.1, the mean Doppler velocity threshold is used to ensure falling droplets. Please review the changes done to this paragraph and the description in section 3.3 in the track-changes document.

54. *P. 13 L. 268. Unfortunately I don't see where radar reflectivity is connecting through multiple ceilometer observed cloud layers around 5:00 UTC, could the authors perhaps indicate this more clearly in the figure?*

   * For clarity, the observed cloud base heights are added to the figure.

55. *P. 13 L. 270. Could the authors comment on why they decided on ignoring the lower CBH when cloud layers are connected by precipitation, instead of the higher one?*

   * We have reevaluated this strategy, and now changed this behaviour to retain the lowest CBH in order to avoid false positive detection of precipitation. See answer to comment #18.

56. *Figure 6. It is difficult to gain quantitative information of the inner ring. Could the authors add some ticks (for example every 10%?) to give guidance, or label the largest blocks, to provide the reader better understanding of the results?*

   * We labeled the largest blocks as suggested.

57. *Figure 6. It is not obvious from the figure legend how the individual Cloudnet target classes are grouped into the liquid-only and ice-containing groups. The authors could add more information in the caption or the labeling in the figure. The authors could also consider combining Figs. 6 and 7 to one figure with two panels, which would solve the problem, since Fig. 7 unambiguously shows which Cloudnet target classes are included in which grouping.*

   * We changed the label color in the legend to mark the grouping more clearly.

58. *Table 3. The text states that only clouds with CBH below 4 km are considered in the analysis. Could the authors also mention this in the table caption, in case it is valid for the table, to avoid any misunderstanding to what the percentages presented refer to.*

   * The table and the caption was now updated to avoid misunderstandings.

59. *Section 4.2.2-4.2.3. Is virga depth computed here as the geometrical depth from the lowest to highest bin of the bin, or are gaps ignored? Would the different way of calculating the virga depth have an impact on the results and their interpretation?*

* The virga depth without gaps is used to calculate this results. If gaps had been included, the maxima in the histogram around 0.7, 1.5 and 2 km are potentially more stretched towards larger virga dephts. Excluding gaps is chosen, as virga depths calculated in this way are closer related to the water content in the virga and thus precipitation evaporation. The paragraph describing different strategies to calculate virga depth has been moved to the end of section 3.4:

L234ff.:
For easy usability of the *Virga-Sniffer* results, the virga and cloud detection masks are stored in an output ~~dataset as boolean~~ data set as Boolean flags with the same dimensions (time, height) as the radar reflectivity input data. In addition, the processed cloud- and ~~virga base-~~ virga- base and top heights are stored, as well as some basic characteristics such as cloud depth and virga depth for each profile. When calculating virga depths, the maximum geometric extent is the difference between the initial values of the virga base and top heights. The output variable is called *virga_depth_maximum_extent* and contains the gaps allowed in the detection. Using this value to calculate volumetric features (e.g., LWP) can lead to errors because the liquid water content is then distributed within the gaps that do not physically contain water. Instead, the output variable *virga_depth* should be used for calculating LWP, as all virga gaps are subtracted in this variable.

60. *Figure 8. The smallest virga depth bin seems pronounced, do the authors have an explanation for this?*

* The physical explanation would be, that very shallow virga are detected the most. Likely because shallow clouds in the trades only produce very little precipitation, that fully evaporates rapidly.

61. *P. 17 L. 324. Figure 8 -> Figure 9.*

* Done.

62. *P. 17 L. 329-330. Could the authors elaborate on which basis they are making statements about specific cloud types based on CBH, perhaps by adding some references to the literature?*

* Please see the answer to your comment 40 concerning this question.

63. *The authors evaluate how cloud macrophysical properties, namely cloud base height, cloud depth and LWP relate to the virga depth. However, the sub-cloud relative humidity is quite relevant when considering the evaporation of rain. Could this provide some explanation why there are no strong relationships found in Sect. 4.2?*

* This is of course true, and outside of the content of this paper we did look at this. But because we wanted to focus on output obtained by the virga sniffer in this paper, we did not go into further detail.

64. *P. 19 L. 351-352. Similar to comment 40, I urge the authors to be careful to present results in the summary and conclusions section that were not actually shown in the paper. I suggest removing the statement about applying the Virga-Sniffer for RV Maria S. Merian measurements, because these are not shown.*

* We agree, that this statement is not required. We have removed any statement about the RV *Maria S. Merian* dataset.

65. *P. 19 L. 358. Here 30% of virga detected by the Virga-Sniffer for the EUREC4A data set is said to be classified by Cloudnet as ice-phase precipitation, but in Section 4.1. it is stated that 31% of virga pixels are classified as ice-containing (P. 15 L. 284). Could the authors explain the discrepancy?*

 * It was just confusion with numbers. Updated.

66. *P. 19 L. 363 – P. 20 L. 375. I don't see the purpose of the two one sentence paragraphs, and it seems to me that these two sentences could be merged to the following paragraph. However, I leave it to the discretion of the authors how they choose to present.*

 * Good point, we changed that.

67. *P. 20 L. 393. Are the default values given also the same as used for the processing the EUREC4A data set in this paper?*

 * Yes, the default setting is used to process the EUREC4A data set. We added a statement to the text, see answer to comment #2.

68. *P. 21 L. 424. Does this threshold correspond to the amount of valid data points required, as explained on P. 7 L. 154?*

 * Yes.

69. *P. 22 L. 426. Which preprocessing? Does this refer to the CBH preprocessing described in Sect. 3.1? Could the authors give a more clear reference*

 * We have added a proper reference.

70. *Figure A1. Colorbar is missing and should be added.*

 * A colorbar has been added to Fig. A1.

References

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