Author's response to:
RC#1 from anonymous referee #1
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Johanna Roschke[1], Jonas Witthuhn[1,2], Marcus Klingebiel[1], Moritz Haarig[2], Andreas Foth[1], Anton Kötsche[1], and Heike Kalesse-Los[1]

[1]Leipzig Institute for Meteorology (LIM), Leipzig University, Leipzig, Germany
[2]Leibniz Institute for Tropospheric Research (TROPOS), Leipzig, Germany

Correspondence: johanna.roschke@uni-leipzig.de

Dear Referee #1,

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

Johanna Roschke

Changes to the Manuscript:

We restructured the manuscript as suggested, moving the technical details of the Virga-Sniffer to a dedicated technical note in Roschke et al. (2024). This focuses the discussion on the introduced method and enhances clarity.

- Expanded the introduction with:
  - Importance of observing shallow cumulus convection and their macro- and microphysical properties.
  - Importance of sub-cloud evaporation in the trades.
  - Additional information about Cloudnet.
- Information in Sect. 2:
  - Added information about the Radar sensitivity and CFAD in Fig. 2
  - Included MWR and LWP processing in Sect. 2.3.
  - Improved Fig. 3 for better readability.
  - Moved Virga-Sniffer technical details (e.g., thresholds) to Sect. 2.4 of the technical note.
- Added information about the haze echo detection method in Sect. 3.1:
  - Added joint histograms for the radar reflectivity factor, mean Doppler velocity, and attenuated backscatter coefficient which show haze echo modes and explain the choice of parameters that determine the haze echo probability.
  - Added a table on how the choice of parameter influences combined haze echo probability.
  - Added Fig. 6 that illustrates the heuristic probability distributions for the radar reflectivity factor, mean Doppler velocity and attenuated backscatter coefficient.
- Cloud type classification in Sec. 3.2:
  - Clarified the reason of introducing cloud classification in Sect. 3.2.
  - Explained operational bounding box definition in Sect. 3.2.
- Restructured results in Sect. 4.3:
  - 4.3: Comparison to classifiers
  - 4.3.1: Comparison with the -50 dBZ threshold method
  - 4.3.2: Comparison with Virga-Sniffer
  - Added a case study (Fig. 11) that shows the comparison between different haze echo classifiers for a day where Drizzle or rain and haze echoes are detected simultaneously

  - Added a case study (Fig. 12) exemplary for a day of low haze echo occurrence where further differences in the proportion of detected haze echoes between the classifiers become evident
  - Added a long-term comparison of detected haze echo pixels for the classifiers (Fig.13)
  - Updated Sect. 4.4 (limitations) with conclusions on shallow and deep cumulus radar reflectivity.
  - Included Fig. 14 to illustrate a statistical comparison of radar reflectivities within shallow and deeper cumulus clouds for the case study presented in Fig. 11 and for the long-term period.
  - Virga-Sniffer long-term statistics can now be found in the appendix

- Appendix:
  - Virga-Sniffer configuration details can be found in the technical note.

Within the technical note for the Virga-Sniffer (Roschke et al., 2024), all datasets used in this study can be found. The technical note now contains the following information:

- description of configuration-specific thresholds that differ compared to the Virga-Sniffer configuration in Kalesse-Los et al. (2023).
- a section describing the CBH processing by the Virga-Sniffer, including a statistical comparison of CBH from the ceilometer internal cloud base detection algorithm and Cloudnet.
- an overview of different clutter-masks and velocity-masks and an explanation of how they influence virga and haze echo detection by the Virga-Sniffer.
- long-term statistical results by the Virga-Sniffer summarized in tables for different configurations
- analysis of object-based cloud classification statistics for the RV Meteor using the Virga-Sniffer configuration of Kalesse-Los et al. (2023)

Response to RC#1 of Anonymous Referee #1:

General comments

1. *GC1: The introduction summarizes that radar reflectivity thresholds are often used to exclude haze echoes from drizzle/rain occurrence analyses (L 71-73). The manuscript in its current state, however, does not clarify in what way the new haze category in Cloudnet improves or changes occurrence statistics compared to the Ze-threshold method (eg Klingebiel et al. (2019)). I would propose to add a comparison to the analysis Section (also see comment below).*

* We agree, that the manuscript in its current state lacks a comparison between the new haze echo classification method and the traditional radar reflectivity threshold method. To address this, we added a comparison in the results section.

Sect. 4.3.1 line 430.:
An analysis of the proportions of Cloudnet targets (including the new haze echo class) for all radar reflectivities below -50 dBZ for the period between 1 July 2021 to 1 July 2023 is shown in Fig. **??**. Fig. **??** a) shows that 12 % of all pixels with $Z_e <$ -50 dBZ are classified as "Liquid droplets", 25 % as "Drizzle or rain", 51 % as "Haze echoes" and 12 % as Insects and Aerosols. This means only about half of all targets that are filtered by the -50 dBZ-threshold are haze echoes. Applying a -50 dBZ-threshold-based method would lead to an underestimation of 6 % of all pixels classified as "Drizzle or rain" and an underestimation of 4 % of all pixels classified as "Liquid droplets". While this proportion seems rather small, it can influence precipitation statistics for specific case studies.

2. *GC2: The authors need to clarify where to find the data sets that they used for their analysis. Many datasets, especially those obtained during the EUREC4A period, are publically available with dois; were these data sets used?*

* We agree that data should be publicly available to enhance transparency and reproducibility in research. The BCO instrument data are available upon request from MPI Hamburg, while all datasets used in our study (including Cloudnet and Virga-Sniffer data) are publicly accessible in the technical note under zenodo in Roschke et al. (2024)

3. *GC3: Sec 3.1, L247 - 259: I am missing the reasons for the choice of μ, sigma, beta, and a justification for how they were optimized and set. The authors should clarify how sensitive the analyses are to these settings including the probability threshold of 60% (L261). How do users of the method need to adjust these settings for different maritime Cloudnet sites (or is it "plug and play"?)?*

* We agree that the current version of the manuscript misses the explanation for the choice of parameter values that defines the haze echo probability. We added a statistic and a sensitivity study to the respective section.

4. *GC4: I find the argumentation line of the analysis at times hard to follow. In order to be more convincing of the new method, I would propose to adapt the structure as follows:*

- *4 i) Apply method to BCO statistics and evaluate new approach by comparing to Virga-Sniffer and traditional -50dBZ threshold in order to highlight benefits of new classification scheme for haze detection; include an analysis of limitations using spectra/skewness (also see Specific comments below) and sensitivity to parameters (see comment above)*
- *4 ii) analyze driving factors of haze occurrences in water vapor or subsidence space (see comment below)*
- *(optional:) 4iii) make use of Cloudnet and Virga-Sniffer to analyze virga and precip statistics at BCO given the improved detection scheme excluding mis-labeled haze)*

* We agree that, due to the complexity of the haze echo classification method and of the Virga-Sniffer tool, the current manuscript structure could be clearer and more streamlined to effectively communicate the benefits of the new haze echo classification scheme. However, we note that radar Doppler spectra and skewness data were not available in the BCO dataset available to us, which limits our ability to perform a full analysis of these aspects as suggested. We have moved the detailed Virga-Sniffer results and configuration information to a supplementary Zenodo publication in Roschke et al. (2024). This allows us to streamline the manuscript and focus on the key findings.

5. *GC5: the main message of the paper should be clarified throughout the manuscript. Is the main scope of the manuscript to introduce a new Cloudnet classification scheme? Or, rather, to analyze rain and virga characteristics at BCO given an optimized detection method? The abstract and introduction rather focus on the novel Cloudnet method, while the main scope of the analysis Section seems to focus on BCO statistics.*

* We understand that the main message may seem split between the introduction of the new Cloudnet classification scheme and the comparisons of precipitation statistics. To clarify, this work has two goals: first, to introduce and evaluate the Cloudnet classification for haze echo and drizzle detection, and second, to use the improved Cloudnet target classification to provide valuable, long-term statistical insight into cloud and precipitation characteristics at BCO. Until now, long-term statistics of Cloudnet classification targets at the BCO are not published, so we believe that the inclusion of these statistics adds significant value and relevance to the manuscript.

Specific comments

- *L 21-26: The importance of evaporation and moistening processes in the sub-cloud layer for cloud and precipitation evolution should be highlighted here.*

* We added this information to the introduction.

> **Sect. 1 line 28.**:
>
> Precipitation from trade wind cumuli often occurs in the form of drizzle (Wu et al., 2017) ~~.~~ that often evaporates before reaching the ground Kalesse-Los et al. (2023). Precipitation evaporation influences the moisture and heat budgets of clouds themselves (Emanuel et al., 1994) as well as the subcloud environment via the formation of cold pools (Langhans and Romps, 2015).

– *L24: A reference should be added.*

* We added references to the repective line.

Sect. 1 line 28.:
Their spatial structure and evolution can be influenced by precipitation (Albrecht et al., 1995; Albrecht, 1993).

– *L177: To my knowledge, operation of the CORAL Radar and ceilometer continued at BCO after the EUREC4A campaign (http://bcoweb.mpimet.mpg.de/systems/data_availability/DeviceAvailability.html, last access July 2, 24)*

* Indeed, the CORAL radar and ceilometer continued measuring at the BCO after the EUREC4A campaign. However, we would like to clarify that no Liquid Water Path (LWP) data are available because the microwave radiometer only resumed operation in July 2021. Consequently, Cloudnet processing could not be performed due to the lack of continuous LWP data. We clarified this in the manuscript.

Sect. 2.3 line 188.:
~~Instruments were~~ The BCOHAT was not operating at the BCO after the EUREC^{4}A campaign in February 2020 until July ~~2021.~~ 2021, which is why Cloudnet data could not be retrieved.

– *L178: the authors should clarify why this data is not usable and why timestamps cannot be corrected in post-processing.*

* We agree that it's important to clarify why certain data were not usable. To date, five ceilometers have operated at the BCO between 2010 and 2020. Problems like dusty sensors or calibration factors are not reported in detail. This makes it challenging to process Cloudnet data for different ceilometers. Between 2011 and 2015, we encountered significant issues with the ceilometer data during Cloudnet processing due to random time jumps in the recorded timestamps. These time shifts can occur when the laser quality is low or when the radome is not clean. This makes the ceilometer system reboot itself, which in turn can lead to time stamp jumps. However, we do not know if this is the actual reason for these time jumps. The time shifts are not consistent or systematic, making it extremely difficult to identify a clear pattern for correction. Given the randomness of these timestamp jumps, it remains uncertain whether the timestamps are duplicated at actual true time steps or if the entire time axis is shifted forward or backward. This lack of clarity complicates efforts to adjust timestamps reliably in post-processing, as we cannot determine whether to correct timestamps into the future or the past. Importantly, these time jumps did not occur every day but sporadically, leading to gaps in the data. Moreover, a low laser quality makes it difficult to interpret the attenuated backscatter signal within our method. In conclusion, to maintain data integrity and avoid the potential influence of calibration differences across multiple ceilometers, we have chosen to focus our analysis on two years of data from after 2021, during which no time jumps were observed.

– *Sec 2.2.1 and Sec. 2.2.2; L 569: it remains unclear to me throughout the manuscript how MWR and MRR data impact the classification algorithm. Are they mandatory for the new classification class? The HATPRO in operation at the time* *of analysis is the BCOHAT instrument as specified in Schnitt et al, 2024, ESSD (doi.org/10.5194/essd-16-681-2024) (reference missing)*

* We acknowledge that the manuscript could clarify how these datasets influence the classification process and add information accordingly. Additionally, we appreciate your point regarding the HATPRO instrument. As a note, it is important to mention that in the metadata of the LWP files, the instrument source is listed as "RPG-HATPRO-G2" rather than BCOHAT. Moreover, the retrieval of the LWP for the MWR is provided by the RPG Radiometer Physics GmbH and was retrieved by a neural network.

Sect. 2.3 line 135-140.:

~~The scanning Radiometer Physics HATPRO radiometer (SUNHAT) has two receivers. It~~ The Humidity and temperature profiling radiometer (BCOHAT) measures seven brightness temperatures around the water vapor absorption band between 22 – 31 GHz and in the oxygen absorption complex between 51 – 58 GHz. Measurements around the water vapor absorption line are used to derive a column-integrated liquid water path (LWP) which is retrieved by a neural network provided by the RPG Radiometer physics GmbH. The vertical resolution is less than 40 m in the sub-cloud layer with a temporal resolution of 4 s. Data from the current microwave radiometer are available since April 2017 (Stevens et al., 2016).

– *Fig 3: I would suggest to add boxes in (a) which illustrate the zoomed areas in (b) and (c); and to maybe re-configure the plot such that (a) is largest on the left side, and (b) and (c) are smaller and connected to boxes in (a)*

* We appreciate your insight on how to improve the clarity and presentation of the figure. We improved the representation of the figure which can be found in Roschke et al. (2024)

– *Fig 4 : in order to highlight the added value of the new classification class compared to the conventional Ze threshold method (L70), I would propose to add a panel on the top to illustrate the measured radar reflectivity.*

* We understand the importance of highlighting the added value of the new classification class compared to the conventional Ze threshold method. We have added a comparison including a case studies to the result section. There the added value becomes more clear.

– *L205: arguments for why m and c were chosen this way should be added here. How sensitive is the clutter mask and resulting analysis and evaluation to these values? I suspect that the presented evaluation of the Cloudnet class with the Virga-Sniffer strongly depends on the values chosen here.*

* To provide clarity, we have moved the Virga-Sniffer configuration section, along with a more detailed sensitivity analysis regarding the clutter mask, to the Zenodo publication in Roschke et al. (2024). In the manuscript, we note that changing the clutter mask to $m = -55$ and $c = -38$ significantly reduces the proportion of identified virga by the Virga-Sniffer for classified haze echo pixels to 0 %. In this scenario, the proportion of haze echoes identified using our developed method, compared to the Virga-Sniffer, would increase to 89 %.

– *L205: do the authors refer to the sensitivity limit of the CORAL radar? If so, this limit should scale with range, and should be negative. If not, a clarification is needed here.*

* We agree that the sensitivity limit should scale with range. We added a joined histogram to the instrument section (also see comment of Rev2.). However, for the Virga-Sniffer clutter-mask, the minimum reflectivity is used to derive a linear function that filters clutter. We oriented our configurations to the original paper of the Virga-Sniffer, where the clutter-mask does not scale with range.

– *L232: a sentence should be added on how the insect detection scheme works and why it would be suitable for also detecting haze; this information should also be added to Sec 2.3. Why not including the Virga-Sniffer method to Cloudnet instead or in addition as it uses similar instruments? The advantages of the chosen method compared to the Virga-Sniffer should be highlighted.*

* We appreciate your suggestion for clarification. The method we employ for insect detection is indeed similar to the approach used in Cloudnet. Insects are classified by combining heuristic probabilities derived from various radar parameters, along with additional variables such as temperature. However, it is important to note that the insect detection method is novel and still requires validation, as highlighted in the Cloudnetpy code. While the Virga-Sniffer is highly configurable, it operates as an independent tool and is not part of the Cloudnet framework. The advantages of our approach include its integration within the Cloudnet target classification scheme, allowing for reconfigurability to marine Cloudnet sites and their specific instrumentation. Additionally, our haze echo detection method incorporates the ceilometer, which is primarily used in the Virga-Sniffer for cloud base height identification. This added instrument enhances our ability to detect haze echoes more effectively. We will ensure to add a brief explanation of how the insect detection scheme operates and its suitability for haze detection in Section 3 of the manuscript.

> **Sect. 3 line 229-234.**:
>
> This section gives an overview of the method that was developed to discriminate between sea salt aerosols and "Drizzle or rain" in Cloudnet. The method is similar to the approach for insect detection in Cloudnet~~, which ensures~~ . Insects are classified by combining the heuristic probabilities derived from various radar parameters and additional variables such as temperature. As highlighted in the CloudnetPy code, insect detection is novel and still needs to be validated. The advantage of using a similar approach is, that it can be easily implemented within the Cloudnet target classification scheme and that it is configurable for marine Cloudnet sites and their particular instrumentation.

– *L290: doubles L261.*

* Thank you for your observation regarding the duplicated sentence in Line 290. We have removed the redundant sentence.

– *L 311: more explanation is needed for why it would be important and interesting to split the analysis in the two cloud classes; this should be stated already in the introduction as well.*

* We added an explanation to the following section. Also see answer to Rev.2.

Sect. 3.2 line 314-317.:

Existing statistics on clouds an precipitation over Barbados focus on warm clouds and trade wind cumuli (Kalesse-Los et al., 2023; Nuijens et al., 2014; Acquistapace et al., 2019; Schulz et al., 2021). In order to compare our statistics with existing literature and to investigate precipitation properties of warm clouds and haze echo occurrence an object-based cloud classifier was developed.

– *Sec 4.1: Rather than splitting the analysis into dry and wet season statistics for each year, an occurrence analysis could be performed in subsidence or water vapor space for both years to exclude for example skewing wet intrusions in the dry season from the statistics. The EUREC4A period could be used to analyze driving factors in more detail, such as cloud organization type, cloud type, wind direction, wind speed, and to include the impact of Saharan dust events on haze occurrence (which is mentioned in L403 but not shown).*

* Thank you for your thoughtful suggestions regarding the analysis in Section 4.1. We appreciate your perspective on performing an occurrence analysis in subsidence or water vapor space for both years. Our analysis is oriented towards established statistics, such as those from Stevens et al. (2016); Nuijens et al. (2014) and Nuijens et al. (2015), which focus specifically on dry and wet season statistics. We recognize the significance of analyzing driving factors like cloud organization type, wind direction, and the impact of Saharan dust events on haze occurrence. However, it's important to note that the primary focus of this study is to introduce a haze echo classification method in Cloudnet and its validation, while further statistics on driving factors could be interesting for future studies.

– *Sec 4.3: The authors should clarify why they are comparing BCO and the Meteor observations; I am confused - did the authors also run Cloudnet based on the Meteor? If so, additional input is needed in Sec 2 and the introduction. Maybe the authors rather use the comparison to optimize the application of the Virga-Sniffer to BCO measurements in which case the text needs to be clarified to underline this.*

* Thank you for highlighting the need for clarification regarding the comparison between BCO and RV Meteor observations in Section 4.3. We conducted the Virga-Sniffer comparison during the EUREC^{4}A campaign to evaluate the configuration differences between measurements from the RV *Meteor* and BCO during the same period. This approach allows us to explore how measurement variations arise due to differing instruments, particularly radar wavelength and ensures consistency by examining a common period. While this is partially noted in Line 407, we have now expanded this explanation to clearly state that the goal was not to run Cloudnet specifically on the RV *Meteor* but rather to assess the implications of using different instrument configurations on virga and haze echo detection during an overlapping observation period.

Appendix 1 line 572-577.:

This comparison contextualizes the long-term virga statistics at the BCO by aligning them with the published results of Kalesse-Los et al. (2023). By comparing data from both platforms during the same time period, we aim to highlight differences due to instrument variations and provide a more comprehensive understanding of the statistics across different observation environments.

– *L425 and Fig 9: The text should comment on the large occurrence of 'Unclassified' aboard the Meteor compared to the BCO; and should summarize why the difference between object- and profile-based statistics is particularly profound for the trade wind cumulus class in panel (b) compared to the warm clouds class in panel (a) (which is hinted at in L434, and extensively analysed in Appendix C, but should be summarized here)*

* The category "unclassified" in this context represents time steps where clouds are observed but are not precipitating. We updated the figure legend and clarified this in the text.

– *Sec 4.3.2 As I understand the analysis presented here, the Virga-Sniffer is applied to BCO measurements and occurrence statistics of virga, precipitation and clouds are analysed. I am not sure how this Section relates to the title of the manuscript, as the Cloudnet haze method is not included in this Section (also see GC 4 and 5)*

* Thank you for your feedback regarding Section 4.3.2 and its relation to the title of the manuscript. We agree that the analysis presented in this section, which focuses on the application of the Virga-Sniffer to BCO measurements and the occurrence statistics of virga, precipitation, and clouds, may not align directly with the main focus of the paper on the Cloudnet haze classification method. Consequently, we included a comparison of our method to other classifiers such as the Virga-Sniffer and the -50 dBZ threshold method. Virga-Sniffer-related statistics can now be found in the appendix or the zenodo technical note of Roschke et al. (2024)

– *L476: it should be clarified if Virga-Sniffer results are shown, or Cloudnet classification results; also see comment above*

* See comment above.

– *L502: Spectra and higher moments are available at MPI for the analyzed period and should be used in the analysis to strengthen the proposed method, or, at least, to quantify the limitations more thoroughly. Could the classification scheme be adapted to include skewness as an additional proxy for detecting haze?*

* Thank you for your suggestion to incorporate spectra and higher moments, particularly skewness, as additional proxies for detecting haze. We understand that these metrics could potentially strengthen the proposed method. However, as noted in the manuscript, neither spectral data nor skewness was available in the input files accessible to us for the analyzed period. Skewness could indeed be added as an additional input parameter in future analyses if this data becomes available. Incorporating a skewness probability into the combined haze echo probability, could enhance the robustness of the classification scheme.

Technical Corrections

– *Fig 2: All colors seem to be related to 24h data coverage; the colorbar should be adjusted to enhance the Figure's message.*

– *Fig 8: Legend should be adjusted to distinguish solid and dashed line without reading the caption.*

– *Fig 9 caption: last sentence should be moved to main body text.*

– *Figs 7-10: description of colors shown in legends need to be added to the captions.*

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