Reviewer comments to authors of "Surface-based observation of cold-air outbreak clouds during the COMBLE field campaign."

In this paper, the authors characterized low-level cumulus clouds during the Cold-air Outbreak (CAO) in Marine Boundary Layer Experiment (COMBLE) using ground-based observations. They investigated 13 COMBLE cases of low-level convective clouds and found a general understanding of cloud dynamical properties (e.g., vertical air motion and eddy dissipation rate) related to thermodynamical quantities (e.g., liquid water path). Last, the authors presented the presence of secondary ice production in one available case (31 December 2019). The characteristics of these low convective clouds are important to improve model parameterizations, and response to a changing climate. This scientific information will be very useful to many scientific and stakeholder communities.

Thank you to Reviewer #1 for providing valuable feedback. It is much appreciated, and it improved our paper!

I have three serious concerns about the manuscript, in addition to specific questions and comments listed as below:

Comment 1: The thresholds in this study are somewhat arbitrary and the lack of background. The review needs to understand why the authors choose those thresholds. This is important because the results should be changed in how the authors selected the thresholds. I strongly recommend that the authors should add an exact explanation (or specific background) in choosing the below thresholds.

Response: This is a very good general comment. Our group has extensive experience in the application of cloud radar observations for cloud and precipitation microphysics, and we hope that our explanations will provide sufficient information to the reviewer and to the readers of the manuscript. One challenge in our analysis is that CAOs have not been previously observed by an ARM-like observing facility for such an extensive period, and to a certain extent, we had to come up with some criteria/thresholds that are based on the available observations.

Comment 1a: In Line 119, why did the authors choose those 13 cases?

Response: In the recently published BAMS article that describes the COMBLE field experiment (The COMBLE Campaign: A Study of Marine Boundary Layer Clouds in Arctic Cold-Air Outbreaks, Bulletin of the AMS, Geerts et al. 2022, doi:10.1175/BAMS-D-21-0044.1), a total of 39 CAO cases were identified based on the boundary layer thermodynamic structure. We decided to focus on 13 of them using the following criteria: The selected cases were long-lived (several hours, while many of the identified cases in the BAMS article were very short-lived), and the cloud field morphology was relatively simple (i.e., avoid cases with extensive upper-level cloud presence that interacted with the underlying cumulus field that was the primary focus of our study).

Comment 1b: In Line 120, why are the prefrontal and frontal clouds neglected?

Response: We wanted to focus on the convective cumulus that develop from the strong surface heat fluxes in the cold air outbreak system. Any period with just prefrontal/frontal clouds does not fall into the regime we want to study, and any period with both prefrontal/frontal clouds and convective cumulus may have competing effects or be too complex.

Comment 1c: In Lines 135-143, the LWP threshold of 0.25 - I cannot find a strong relationship between KAZR observation and LWP > 0.25 kg m^{-2}. Also, the frequencies are too small when you choose LWP < 0.25 kg m^{-2} as a low LWP period in Figure 7. Please add the percentage of LWP data as the author mentioned in Line 307–308.

Response: Another excellent comment. The strong relationship that we are referring to is that of upward motions (positive KAZR Doppler velocities) and LWP values from the MWR. This correlation is easy to see when perusing time series data like those illustrated in Fig. 2b. In Figure 7, we tried to illustrate this relationship, but the original version of Figure 7 does not capture this relationship. Thus, we have revised one of the panels of Figure 7, and we now show the relationship between the LWP measurements from the MWR and the maximum observed KAZR Doppler velocity in the column.

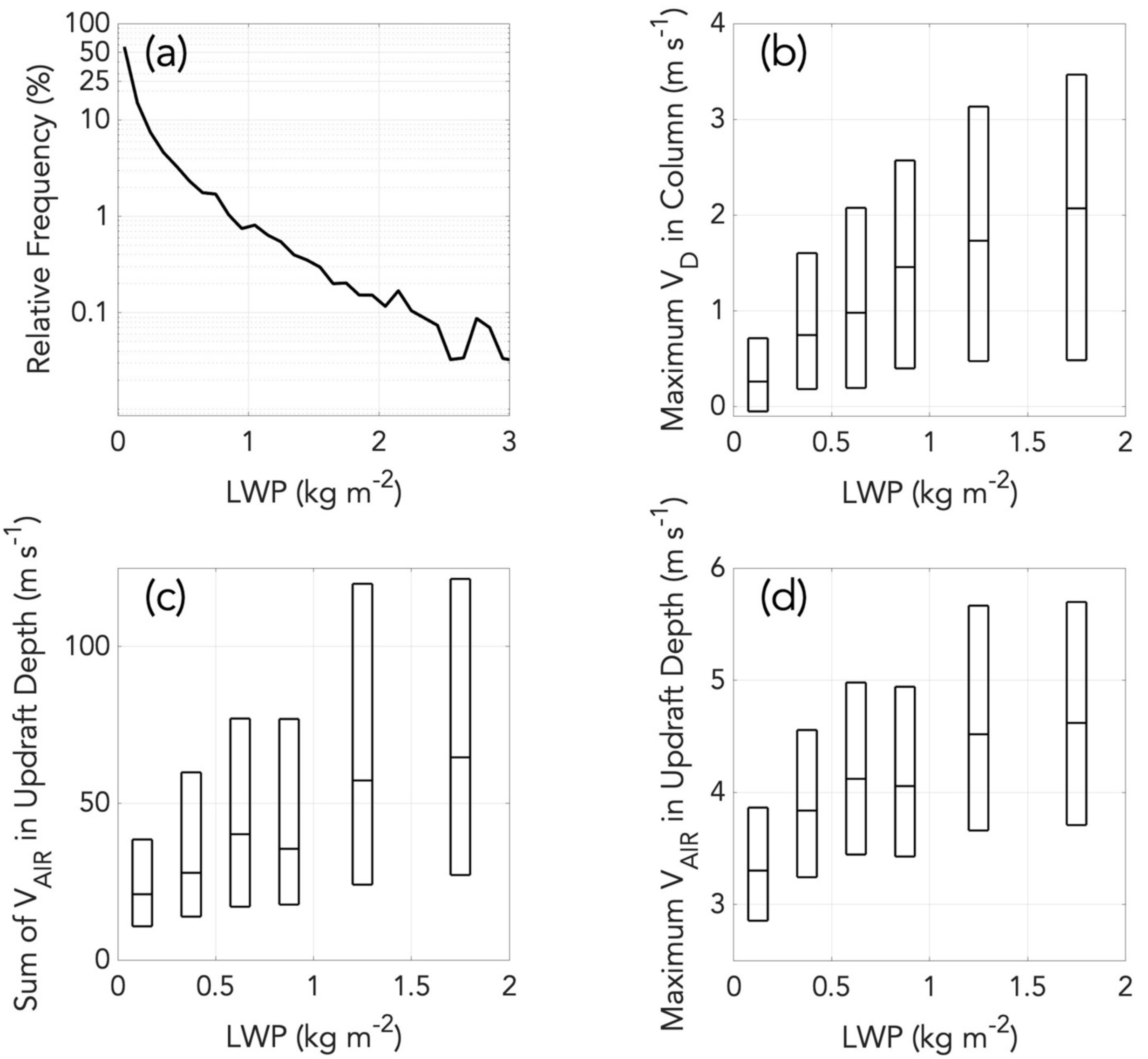


Figure 7. For all 13 COMBLE cases, (a) the relative frequency of liquid water path (LWP) in bins of width 0.1 kg m^{-2}, (b) the median, 25th, and 75th percentile of the maximum Doppler velocity (V_D) in the atmospheric column for each LWP bin of width 0.25 kg m^{-2} or 0.5 kg m^{-2}, (c) the median, 25th, and 75th percentile of the sum of vertical air velocity (V_{AIR}) in the updraft depth for each LWP bin of width 0.25 or 0.5 kg m^{-2}, and (d) the median, 25th, and 75th percentile of the maximum V_{AIR} in the updraft depth for each LWP bin of width 0.25 or 0.5 kg m^{-2}.

<u>**Comment 1d**</u>: In Line 268, with regards to the horizontal resolution of 250 m and 1 km, why did the authors choose the resolution of 250 m? Also, the reviewer does not convince the data conversion from time-height to horizontal distance-height. Since the KAZR is a vertically pointing radar, this data is unable to explain (or represent) the horizontal distribution associated with the model resolution.

Response: As part of the COMBLE CAOs investigation, a model intercomparison study is underway. The simulations are being set up with sub-kilometer grid spacing (250-500 m), while other regional model runs will be conducted at kilometer-scale resolution. Thus, our aim was to adapt our study to provide them useful information. At resolutions better than 250 m, our results closely resembled the original KAZR measurements too closely.

Comment 1e: In Line 277, with regards to the three categories of updraft depths (1 km and 2 km), the results should be changed when the authors choose different categories.

Response: We did not use literature to create these groups. We categorized the data in a way that gave 3 subgroups of nearly equal size. We will make note of this. We were also limited by the data itself, where cloud tops peaked at 5 km or less. This limited the amount of depth classes we could choose. Finally, we chose thresholds that were easily reproducible with models.

Change: The observed updraft structures are classified into three categories of nearly equal size based on their vertical extent: those with depths less than 1 km (Fig. 5a)…

Comment 1f: In Line 323, with regards to the cloud thickness types (CTH of 3.5 km and 4.5 km), I cannot find any results and references as to why the authors choose the CTH of 3.5 km and 4.5 km to categorize the cloud thickness.

Response: We did not use literature to create these groups. We categorized the data in a way that gave 3 subgroups of nearly equal size. We will make note of this. Similarly to Comment 1e, we chose thresholds that were easily reproducible with models.

Change: The dataset is further classified into three CAO cloud thicknesses types by splitting it into 3 samples of nearly equal size: cloud top heights (CTHs) less than 3.5 km…

Comment 2: Overall, the author presented the results without detailed physical interpretation. I don't want to point them out here. Please add a more detailed physical interpretation in the result section.

Response: The reviewer is correct; we decided to describe our results and avoid physical interpretation. There are couple of reasons for this. First, we did not want to overreach by adding physical interpretation based on incomplete data/information. For example, we do know that CAOs occur under strong air-sea interaction and flux conditions, but these surface conditions are not available in COMBLE. In addition, our observations are limited to profiling, and the role of mesoscale organization will be examined using modeling in follow-up studies. Finally, our analysis identified and quantified CAO cumulus dynamics for the first time, and we feel that a detailed description of our dynamical retrievals is sufficient. We are currently working on calibrating the KAZR observations and developing a hydrometeor classification that along with a complete analysis of the secondary ice production climatology in these cloud systems will form the basis of a follow-up study that will be more integrated and will contain more physical interpretation.

Comment 3: The reviewer suggests adding more research background in the introduction.

Comment 3a: Please review the previous studies using the COMBLE field campaign.

Response: To our knowledge, only one scientific paper has been published using the COMBLE field campaign.

Change: Here, analysis of surface-based observations from the Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) field campaign are presented. Initial work has been done using satellite data on two COMBLE cases (Wu and Ovchinnikov, 2022), and this study will focus also focus on measurements taken during the campaign. Using profiling Doppler cloud radar…

Citations Added:
Wu, P., and Ovchinnikov, M.: Cloud Morphology Evolution in Arctic Cold-Air Outbreak: Two Cases During COMBLE Period, Journal of Geophysical Research: Atmospheres, 127, https://doi.org/10.1029/2021JD035966, 2022.

Comment 3b: There are some recent field campaigns the authors mentioned in Lines 64–71. What are the differences compared to previous field campaigns?

Response: Thank you for this comment. We need to be more precise with our wording.

Change: Early observational analyses of CAOs have focused on aircraft and sounding data from various field campaigns around the globe (Lau and Lau, 1984; Hein and Brown, 1988; Chou and Ferguson, 1991; Brümmer, 1996; Brümmer, 1997; Brümmer, 1999; Renfrew and Moore, 1999). Recently, work has been done on data from the ACTIVATE (Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment) and ACCACIA (Aerosol-Cloud Coupling And Climate Interactions in the Arctic) field campaigns that managed to capture some CAO events (Young et al., 2016; Seethala et al., 2021; Turnow et al., 2021), although studying CAOs was not the main goal of the study. The MPACE (Mixed-Phase Arctic Cloud Experiment) field campaign also provided opportunity for ground-based observations of CAO events in Alaska (Shupe et al., 2008). However, there are other regions in the Northern Hemisphere where ground-based observations of CAOs are lacking. Despite the importance of CAO clouds, high resolution dynamical and microphysical observations, especially from surface-based remote sensing facilities in the regions of Greenland and the Norwegian Sea where models exhibit large inconsistencies, are not available (Pithan et al., 2014; Tomassini et al., 2017).

Comment 3c: Previous field campaigns (i.e., ACTIVATE) collected the observational data for the high-resolution dynamic and microphysical observations.

Response: This is correct. However, to our knowledge, the ACTIVATE campaign did not sample CAOs, at least with the characteristics that we observed during COMBLE in the Norwegian Sea in the Arctic.

Minor comments:

Comment 4: In Lines 139-140, please add the figure if the authors want to explain the relationship.

Response: We have added this to Figure 7. See above in response to Comment 1c.

Comment 5: In Line 150, what is the "$V_{SED,BE}$"?

Response: BE stands for Best Estimate. We will make note of this.

Change: The median Doppler velocity is our best estimate (BE) of the $V_{SED,BE}$ for the radar…

Comment 6: In Line 170, I do not find how authors can calculate the uncertainty (below 0.1 m s^{-1}).

Response: The uncertainty of the KAZR Doppler velocity measurement can be estimated using well-established relationships (Doviak and Zrnic, 1984).

$$var(V_d) = \frac{\lambda \cdot PRF^2}{2 \cdot M}\left[\frac{\sigma_{vn}}{4\sqrt{\pi}} + 2 \cdot (\sigma_{vn})^2 \cdot \frac{N}{S} + \frac{1}{12}\left(\frac{N}{S}\right)^2\right]$$

where σ_{vn} is the normalized spectrum width

$$\sigma_{vn} = \frac{\sigma_v}{2 \cdot V_{Nyquist}}$$

and N/S is the ratio of noise to signal (linear units), $V_{Nyquist}$ is the Nyquist velocity of the radar and σ_v is the spectrum width. For typical COMBLE values of $\sigma_v = 0.3$ ms^{-1}, $V_N = 10.75$ ms^{-1}, M = 10000, and N/S = 0.1, the standard deviation of the KAZR Doppler velocity is 0.15 ms^{-1}. We will include this formula in the paper, and we will replace 0.1 with 0.15 ms^{-1}.

Change: …has negligible uncertainty (below 0.15 m s^{-1}). The uncertainty of the …

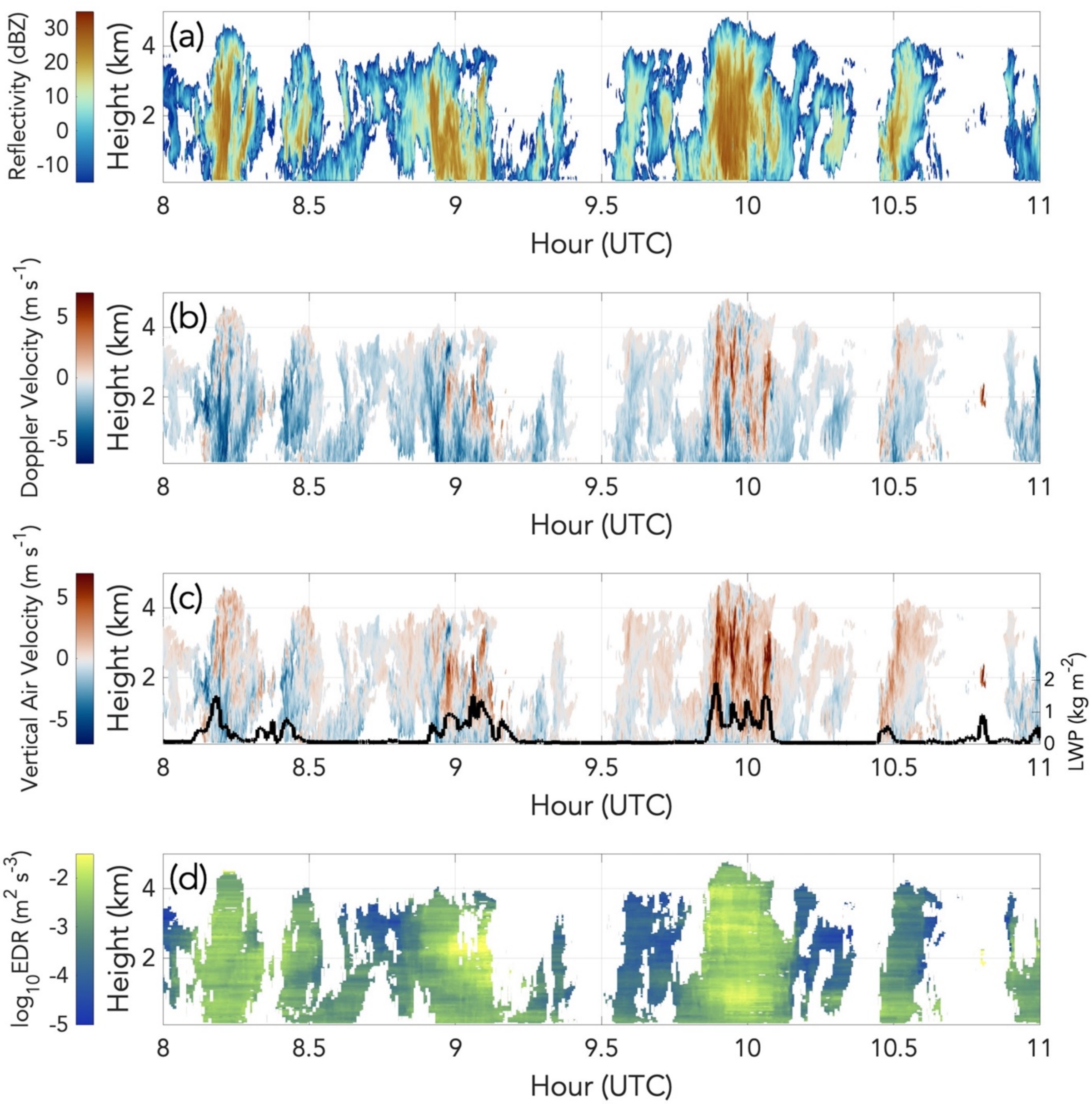
Comment 7: In Line 190, what are the intervals for the sonde observations? I assume the authors collected the sonde data every 6 hours, then interpolated 2 sec. Can this interpolated data (2 sec) compare with KAZR? The reviewer thinks that this interpolated data for horizontal winds cannot correlate with updrafts derived from KAZR due to large time differences. Can you estimate the uncertainty of eddy dissipation rates? If so, please add the uncertainties.

Response: ARM's INTERPSONDE data product provides high time-resolution profiles of atmospheric state variables like temperature and relative humidity and is widely used and cited. We do not create the interpolated sounding grid on our own and instead use this.

Comment 8: In Line 241, please add a local time.

Response: This comment made us aware of an incorrect x-axis in Figure 2; the hour variable is in UTC. We will change the label to UTC, and we will make note of the time in both UTC and local time (UTC+1) in Line 241.

Change: In particular, the cumulus cloud detected around 10 UTC/11 LT exhibits four…



Comment 9: In Line 245, there are peaks of LWP (> 0.25 kg m^{-2}) around 8.3–8.5 hours and ~10.8 hours in Figure 2c. What is the reason for those peaks?

Response: The peaks coincide with an active cumulus passing over AMF1. These peaks are the response of the microwave radiometer to the microwave emissions of liquid, here specifically supercooled liquid. These regions of supercooled liquid are coincident with the updrafts. We posit that other KAZR echoes that pass without peaks in LWP are dissipating cumulus that have reached glaciation.

Comment 10: In Line 251, remove “.”.

Response: We accept this change.

Comment 11: In Line 287, I do not think 10^{-1} m^2 s^{-3} is correct, because there is no frequency between $log_{10}(-1.7)$ to $log_{10}(-1.5)$. Please recheck this value.

Response: You are right; 10^{-1} m^2 s^{-3} is not correct. It should be 10^{-2} m^2 s^{-3}. Thank you!

Change: The highest EDR values (10^{-3} m^2 s^{-3} – 10^{-2} m^2 s^{-3}) are observed near the surface.

Comment 12: In Line 288, what is “the strong surface forcing”? Does it mean “surface sensible heat flux”?

Response: Yes, we mean “strong surface sensible heat flux”. We will change our wording.

Change: This is consistent with strong surface sensible heat fluxes that characterize CAO cloud systems.

Comment 13: In Line 290, please add reference about “above a value of 10^{-3} m^2 s^{-3}”.

Comment 14: In Line 291, please add a correct explanation for “strong turbulence”.

Response: We will make changes to address Comments 13 and 14 at the same time.

Change: Two modes appear, one where the EDR steadily decreases with height and another where EDR stays constant with height. Overall, the strongest turbulence in the distribution is concentrated in the lowest 2 km between values of 10^{-3} and 10^{-2} m^2 s^{-3}. The two stratiform EDR profiles shown in Borque et al. (2016) do not share these characteristics. One does not have as a deep a layer as shown here, and the other has values hovering around 10^4 m^2 s^{-3}, one order of magnitude less than shown here.

Comment 15: In Lines 300-301, does it correct? How can the authors argue the correlation (or relationship) with $R^2 = 0.121, 0.153$?

Response: In the new Figure 7, we do not include correlations anymore. See the response to Comment 1c.

Comment 16: In Line 299, suggest removing “physical”.

Response: We accept this change.

Comment 17: In Line 318, please add the meaning of the normalized height at 1 or 0. I assume normalized height at 1 would be cloud top height, right?

Response: We will add an explanation.

Change: The distribution of the hourly-estimated hydrometeor fraction as a function of normalized cloud height, where 0 represents cloud base and 1 represents cloud top, is shown in Fig. 8a.

Comment 18: In Line 378, suggest changing "modeling".

Response: We accept this change.