Supplement to: Evolution of cloud-top radiative cooling and entrainment during Arctic cold air outbreaks

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This Supplement provides details of the cloud-property retrievals, cloud-profile reconstruction, radiative-transfer simulations, and uncertainty assessment.

S1 Cloud optical thickness and effective radius from specMACS

Two-dimensional (2D) fields of τ and r_{eff} are retrieved from upward specMACS radiance fields (Weber et al., 2024b) using an extended approach based on Nakajima and King (1990), Ruiz-Donoso et al. (2020), and Klingebiel et al. (2023). It applies a multi-dimensional look-up table (LUT) generated with the library for Radiative transfer (`libRadtran`, version 2.0.4, Mayer and Kylling, 2005; Emde et al., 2016) and Discrete Ordinate Radiative Transfer Solver (DISORT, Stamnes et al., 2000) using 16 streams and plane-parallel cloud geometry. Molecular absorption is parameterized with the Representative Wavelengths Absorption Parameterization (REPTRAN, Gasteiger et al., 2014). A subarctic summer standard atmosphere (Anderson et al., 1986), constrained by collocated dropsonde temperature and humidity profiles (George et al., 2024), is used as atmospheric background. Approximate CTHs are derived from a combination of WALES observations (Wirth et al., 2009; Wirth and Groß, 2024) and dropsonde information and are used to constrain the cloud geometry in the radiative-transfer calculations.

Cloud optical properties are calculated assuming liquid-water clouds. This assumption is supported by the predominantly liquid-water cloud-top phase indicated by the specMACS polarization measurements (Weber et al., 2024a,c). To identify regions in which the liquid-water assumption may not be appropriate, an independent shortwave-infrared phase-suspect screening is applied. Inspired by the spectral-slope approach of Ehrlich et al. (2008), the screening combines normalized slope, contrast, and curvature-like spectral features from several wavelength windows between 1550 nm and 1710 nm. Conservative thresholds for each feature are derived from the liquid-dominated reference population as the 99th percentile of the absolute deviation from its median. Pixels are classified as phase-suspect when at least two independent spectral features exceed their respective thresholds, provided that at least three features are valid. This classification is used as a quality-control criterion rather than as a quantitative cloud-phase retrieval. Therefore, phase-suspect pixels are interpreted as exhibiting spectral signatures inconsistent with the liquid-water reference population and potentially indicative of ice-containing or mixed-phase cloud-top conditions.

Ice is nevertheless known to occur below the predominantly liquid cloud tops (Weber et al., 2026). Such vertically structured mixed-phase conditions cannot be identified completely from cloud-top remote sensing and are not represented explicitly in the present retrieval and radiative-transfer framework. Therefore, residual effects of ice below the liquid-dominated cloud top may contribute additional uncertainty to the retrieved cloud properties and derived radiative

diagnostics. The LUT spans τ = 0.5–128 and r_{eff} = 4–24 µm. Ocean-surface reflection is represented using the Cox–Munk bidirectional reflectance distribution function (Cox and Munk, 1954a,b) with a wind speed of 5 m s^{-1} derived from dropsonde observations (George et al., 2024). Aerosol effects are represented by a maritime clean aerosol model (Hess et al., 1998), and the solar irradiance spectrum follows Gueymard (2018).

Radiances are simulated at 1250 nm and 1600 nm and used in a classical bispectral Nakajima–King retrieval. The retrieval is performed directly in the two-dimensional radiance space defined by the absolute radiances I_{1250} and I_{1600}. Instrument-specific spectral response functions with a full width at half maximum of 8 nm are applied (Ewald et al., 2016). The LUT further accounts for viewing zenith angle and relative azimuth angle. The solar zenith angle and corresponding solar geometry are prescribed separately for each flight leg using a representative time derived from the corresponding observation period.

Retrieved values of τ and r_{eff} are obtained by minimizing the weighted squared differences between the measured radiances and the corresponding LUT radiances at 1250 nm and 1600 nm. Relative weights corresponding to 5 % of the measured radiance in each channel are used to scale the radiance differences in the retrieval metric. These weights define the relative distance metric of the retrieval and are not interpreted as radiometric measurement uncertainties. The radiometric measurement uncertainties used for the uncertainty propagation are specified separately in Sect. S4. For each pixel, the LUT radiances are first interpolated to the corresponding viewing geometry, and the best-fitting combination of τ and r_{eff} is identified on the discrete LUT grid. The solution is subsequently refined by local interpolation within the τ–r_{eff} grid surrounding the best-fitting LUT point.

The retrieved fields are subjected to an additional quality-control procedure before being used in the subsequent analysis. Pixels for which the measured radiances cannot be represented sufficiently well by the liquid-water, plane-parallel LUT are rejected based on the retrieval residuals and the available support within the LUT. Additional screening identifies retrievals affected by saturation at the upper τ boundary and pixels classified as phase-suspect by the independent spectral screening described above. Phase-suspect pixels account for 3 %, 2 %, 9 %, and 11 % of the originally identified cloudy pixels in Legs 4, 3, 2, and 1, respectively. Thus, the fraction of cloudy pixels exhibiting phase-suspect spectral signatures increases towards the downstream cloud regimes, particularly in Legs 2 and 1. These signatures may be associated with ice-containing or mixed-phase cloud-top conditions but are not interpreted as a definitive cloud-phase classification.

Among the remaining pixels, retrievals that remain inconsistent with the one-dimensional plane-parallel LUT after application of the quality-control criteria account for 19.9 %, 15.6 %, 8.9 %, and 14.4 % of the originally identified cloudy pixels in Legs 4, 3, 2, and 1, respectively. Such inconsistencies may arise, among other causes, from three-dimensional cloud-radiative effects, particularly near heterogeneous cloud boundaries, but are not interpreted as a direct quantitative measure of three-dimensional effects. Saturation at the upper τ boundary constitutes an additional limitation, particularly in Legs 2 and 1.

After all quality-control criteria are applied, 67.7 %, 66.2 %, 58.9 %, and 54.7 % of the originally identified cloudy pixels remain available for the quantitative retrieval-based analysis in Legs 4, 3, 2, and 1, respectively. The resulting quality-controlled retrieval mask is propagated to the subsequently derived radiative quantities.

S2 Cloud-top height retrieval from VELOX with WALES-based adjustment

Two-dimensional fields of CTH are derived from VELOX T_{B} observations (Schäfer et al., 2023) using a forward-model-based retrieval. A LUT relating CTH to T_{B} is constructed with `libRadtran` (Mayer and Kylling, 2005; Emde et al., 2016). Radiative-transfer calculations cover 7.7–12 µm,

consistent with the VELOX spectral sensitivity (Schäfer et al., 2022), and use DISORT (Stamnes et al., 2000) together with REPTRAN (Gasteiger et al., 2014) for gaseous absorption.

Clouds are represented as vertically homogeneous liquid-water layers with a fixed geometric thickness of 0.2 km and $\tau = 10^6$, effectively approximating blackbody emitters in the thermal–infrared. The geometric thickness is not expected to influence the simulated T_B for such optically opaque clouds, but provides a well-defined cloud layer in the radiative-transfer calculations. A thickness of 0.2 km is chosen to keep the cloud base above the surface even for the lowest simulated CTH of 0.3 km. Simulations are performed for CTH values between 0.3 km and 3.0 km with a vertical spacing of 0.05 km and for viewing zenith angles between 0° and 30° in 5° increments using collocated dropsonde temperature and humidity profiles (George et al., 2024).

Although ice may be present within the observed cloud layers, the cloud-top layer relevant for the thermal-infrared CTH retrieval is assumed to be liquid dominated, consistent with the cloud-phase assessment described above. For optically thick liquid-water cloud tops, thermal-infrared emissivity is expected to be close to unity, such that the simulated T_B is primarily controlled by cloud-top temperature. For optically thinner clouds, thermal emission from the comparatively warm ocean surface may contribute to the observed T_B. For the observed temperature contrast between the ocean surface and cloud tops, emissivities of 0.95–0.99 correspond to T_B biases of approximately 0.1–1.5 K, whereas lower emissivities may lead to larger deviations.

For each observation, measured T_B is matched to the LUT to infer CTH from the monotonic relationship between cloud-top temperature and altitude. Retrieved CTH values are subsequently adjusted using collocated nadir lidar observations from WALES (Wirth et al., 2009; Wirth and Groß, 2024; Ehrlich et al., 2024). The resulting corrections are typically about 200–300 m and reduce systematic biases associated with atmospheric stratification, effective cloud emissivity, and temperature inversions while preserving the continuous horizontal sampling provided by VELOX. Uncertainties in cloud emissivity can affect the retrieved CTH, particularly for optically thin clouds. They may also influence the spatial differences in CTH analyzed here.

S3 Cloud profiles and derived diagnostics

Retrieved CTH, τ, and r_{eff} are used to construct simplified one-dimensional cloud profiles for radiative-transfer simulations. Valid cloudy pixels are grouped into classes using CTH bins of 100 m at lower cloud-top altitudes and coarser bins at higher altitudes, six logarithmically spaced τ bins between 1 and 100, and seven r_{eff} bins between 4 and 24 μm. For each class containing at least 50 pixels, the median CTH, τ, and r_{eff} values are used to define a representative cloud state.

The resulting profiles are constrained by the retrieved bulk cloud properties but do not represent direct retrievals of the vertical cloud structure. Cloud base is fixed at 0.3 km, consistent with the observed thermodynamic structure from the dropsonde profiles (see the dropsonde profiles in Fig. 2 of the main manuscript), while cloud top is prescribed by the retrieved CTH. Each cloud profile is represented by 41 equally spaced vertical grid points between cloud base and cloud top, resulting in a vertical grid spacing that varies with cloud thickness. This resolution was found to be sufficient, with negligible changes in the radiative cooling diagnostics when using a finer vertical grid. The LWC increases linearly with height following an idealized adiabatic-like profile. The r_{eff} profile is prescribed to increase linearly from cloud base to cloud top, consistent with the expected vertical increase in droplet size in adiabatically developing liquid-water clouds (Brenguier et al., 2000). The cloud-base value is set to 60 % of the retrieved cloud-top r_{eff}, motivated by median in situ profiles of non-precipitating marine stratocumulus reported by Buggee and Pilewskie (2025). The LWC profile is subsequently scaled such that the vertically integrated extinction reproduces the retrieved τ. Thus, the retrieved CTH, τ, and cloud-top r_{eff} constrain the geometric extent, integrated optical thickness, and upper-boundary effective radius of each idealized cloud profile, respectively.

Broadband radiative-transfer simulations are performed with `libRadtran` (Mayer and Kylling, 2005; Emde et al., 2016) and DISORT (Stamnes et al., 2000). Solar (0.3–4 µm) and terrestrial (4–100 µm) radiative fluxes are calculated separately using atmospheric profiles constrained by collocated dropsonde observations (George et al., 2024). Radiative fluxes are computed on a vertically refined grid with 10 m resolution within the cloud and 50 m resolution above and below the cloud layer. Radiative heating-rate profiles (ζ) are subsequently derived from the simulated net-flux divergence according to the definition of the radiative potential-temperature tendency in the main manuscript.

Following the definitions in Sect. 2.3 of the main manuscript, the simulated heating-rate profiles are used to derive $\zeta_{20\,\mathrm{m}}$, z_c, and ω_e^*. The framework does not explicitly account for mechanical forcing, wind shear, large-scale subsidence, or detailed cloud-internal microphysical variability. Therefore, the analysis focuses primarily on relative regime-dependent changes and radiative–dynamical coupling rather than on absolute entrainment rates or exact cloud-internal structure.

S4 Uncertainty assessment

The uncertainty analysis propagates measurement and retrieval uncertainties through the complete diagnostic chain from the retrieved cloud properties to the radiative quantities and the radiatively derived entrainment velocity ω_e^*. Uncertainties in cloud optical thickness τ and cloud-droplet effective radius r_eff are derived locally from the retrieval lookup table by propagating independent radiometric uncertainties of 3 % in the 1250 nm and 1600 nm specMACS channels through the corresponding retrieval Jacobian. This results in median relative uncertainties in τ of 12.2 %, 13.5 %, 15.3 %, and 16.6 % for Legs 1–4, respectively, while the corresponding median absolute uncertainties in r_eff are 2.50 µm, 2.18 µm, 2.00 µm, and 2.27 µm. An uncertainty of $\sigma_\mathrm{CTH} = 130\,\mathrm{m}$ is adopted for CTH.

The propagation of these uncertainties into the cloud-top cooling rate $\zeta_{20\,\mathrm{m}}$ and cooling-centroid depth z_c is evaluated with the same radiative-transfer configuration used for the quantitative analysis. Because a full perturbation of every radiative-transfer bin would be computationally prohibitive, 24 representative support bins are selected for each flight leg in the three-dimensional parameter space spanned by CTH, $\log(\tau)$, and r_eff. For each support bin, six perturbation cases are evaluated by independently perturbing τ, r_eff, and CTH by their respective positive and negative uncertainties. Local derivatives of $\zeta_{20\,\mathrm{m}}$ and z_c with respect to the three retrieved cloud properties are calculated from these paired perturbations and interpolated to all radiative-transfer bins using inverse-distance weighting in standardized parameter space. The resulting input contributions are combined in quadrature, assuming independent uncertainties in τ, r_eff, and CTH. All reported aggregate uncertainty statistics are weighted by the number of retrieval pixels represented by each radiative-transfer bin.

The resulting median relative uncertainties in $\zeta_{20\,\mathrm{m}}$ range from 12.4 % to 17.5 % among the four flight legs, while the median absolute uncertainties in z_c range from approximately 9 m to 13 m. The uncertainty propagation indicates that τ and CTH provide the dominant contributions to the radiative uncertainty, whereas the contribution from r_eff is generally smaller. Leave-one-out tests are used to assess the robustness of the support-bin interpolation. Although local deviations occur, particularly where individual sensitivities are small, the tests support the use of the sparse interpolation for estimating the pixel-weighted aggregate uncertainty.

For ω_e^*, the uncertainties in $\zeta_{20\,\mathrm{m}}$ and z_c are not treated as independent because both quantities respond to the same perturbations in the retrieved cloud properties. For each input quantity $x \in \{\tau, r_\mathrm{eff}, \mathrm{CTH}\}$, the corresponding first-order sensitivity is therefore evaluated as

$$\frac{\partial \omega_\mathrm{e}^*}{\partial x} = -\frac{1}{3600 \cdot \Delta\theta_\mathrm{inv}} \left(z_\mathrm{c} \frac{\partial \zeta_{20\,\mathrm{m}}}{\partial x} + \zeta_{20\,\mathrm{m}} \frac{\partial z_\mathrm{c}}{\partial x} \right). \tag{S1}$$

Table S1: Summary of the uncertainty assessment for the radiatively derived entrainment velocity ω_e^*. The radiative/retrieval contribution represents the pixel-weighted median relative uncertainty obtained by propagating the uncertainties in τ, r_{eff}, and CTH while retaining the coupled response of $\zeta_{20\,\mathrm{m}}$ and z_c. The $\Delta\theta_{\mathrm{inv}}$ contribution is derived independently from the RD41 temperature and pressure uncertainties. Representative absolute uncertainties are obtained by applying the combined relative uncertainty to the corresponding leg-wise median ω_e^*.

Leg	Median ω_e^* ($\mathrm{mm\,s^{-1}}$)	Radiative/retrieval (%)	$\Delta\theta_{\mathrm{inv}}$ (%)	Combined (%)	Representative $\sigma_{\omega_e^*}$ ($\mathrm{mm\,s^{-1}}$)
Leg 4	15.8	7.40	4.46	8.64	1.36
Leg 3	19.0	11.45	4.53	12.32	2.34
Leg 2	23.4	10.06	5.05	11.26	2.63
Leg 1	24.7	10.21	5.80	11.74	2.90

This formulation retains the common response of the cooling magnitude and cooling-centroid depth to perturbations in the retrieved cloud properties. The resulting pixel-weighted median radiative/retrieval contribution to the relative uncertainty in ω_e^* ranges from 7.4 % to 11.5 % among the four flight legs.

The uncertainty in the inversion potential-temperature jump $\Delta\theta_{\mathrm{inv}}$ is estimated separately from the representative RD41 dropsonde profiles. Temperature and pressure are perturbed in a Monte Carlo calculation using uncertainties of 0.20 K and 0.50 hPa, respectively, and $\Delta\theta_{\mathrm{inv}}$ is recalculated using the same procedure as for the nominal profiles. The resulting relative uncertainties in $\Delta\theta_{\mathrm{inv}}$ are 4.46 %, 4.53 %, 5.05 %, and 5.80 % for Legs 4–1, respectively. These estimates quantify the uncertainty associated with the dropsonde measurements, but not the representativeness of a single inversion strength for an entire flight leg. Unresolved along-leg variations in $\Delta\theta_{\mathrm{inv}}$ may introduce additional uncertainty that cannot be quantified from the available thermodynamic observations. Assuming independence between the radiative/retrieval uncertainty and the dropsonde thermodynamic uncertainty, these contributions are combined in quadrature:

$$\left(\frac{\sigma_{\omega_e^*}}{\omega_e^*}\right)^2 = \left(\frac{\sigma_{\omega_e^*,\mathrm{rad}}}{\omega_e^*}\right)^2 + \left(\frac{\sigma_{\Delta\theta}}{\Delta\theta_{\mathrm{inv}}}\right)^2. \tag{S2}$$

The resulting combined median relative uncertainties range from 8.6 % to 12.3 % (Table S1). Applied to the leg-wise median ω_e^* values, these correspond to representative absolute uncertainties of approximately 1.4–2.9 $\mathrm{mm\,s^{-1}}$. The uncertainties are therefore substantially smaller than the full upstream-to-downstream difference in median ω_e^*, whereas differences between neighbouring flight legs should still be interpreted with appropriate caution.

Additional structural uncertainty arises from assumptions in the radiative-transfer representation that are not included in the propagated measurement and retrieval uncertainties above. The simulations employ one-dimensional, plane-parallel cloud profiles and therefore do not explicitly represent horizontal radiative transfer or unresolved three-dimensional cloud heterogeneity. Pixels exhibiting pronounced inconsistencies with the plane-parallel retrieval assumptions are removed by the retrieval quality control, reducing but not eliminating the potential influence of such effects on the retained dataset. The simulations further prescribe liquid-water-only cloud profiles with idealized vertical distributions of LWC and r_{eff}. Cloud-top pixels exhibiting phase-suspect signatures are excluded from the quantitative analysis. However, ice below an apparently liquid-dominated cloud top cannot be identified completely from the available cloud-top remote sensing. Residual mixed-phase structure and precipitation may therefore locally modify the radiative-transfer response. These effects represent structural model uncertainty and are not included in the numerical uncertainty ranges reported in Table S1. Likewise, the assumption of a leg-wise constant $\Delta\theta_{\mathrm{inv}}$ introduces a separate thermodynamic representativeness uncertainty that is not captured by the propagated uncertainty estimates.

Uncertainty in CTH may additionally be affected by assumptions concerning thermal-infrared cloud emissivity, particularly for optically thin clouds where radiation from below the cloud can contribute to the observed T_B. The adopted CTH uncertainty of 130 m is based on the evaluated performance of the CTH retrieval, while the statistical adjustment using collocated WALES cloud-top detections reduces systematic differences in the retrieved CTH.

Therefore, $\zeta_{20\,m}$, z_c, and ω_e^* should be interpreted as physically consistent diagnostic quantities rather than as direct observations of cloud-top entrainment rates. The propagated measurement, retrieval, and thermodynamic uncertainties do not alter the pronounced difference between the upstream and downstream ends of the sampled sequence, but structural radiative-transfer uncertainty and the limited thermodynamic sampling remain additional constraints on the quantitative interpretation. Accordingly, the analysis emphasizes the systematic downstream evolution of the radiatively derived entrainment velocity, its substantial spatial variability within each cloud regime, and the regime-dependent associations between ω_e^* and the observed cloud properties.

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