Using Satellite and ARM Observations to Evaluate Cold Air Outbreak Cloud Transitions in E3SM Global Storm-Resolving Simulations

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Abstract

This study evaluates the performance of a global storm-resolving model (GSRM), the Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM). We analyze marine boundary layer clouds in a cold air outbreak over the Norwegian Sea in a 40-day simulation, and compare them to observations from satellite and a field campaign of the Atmospheric Radiation Measurement program (ARM). SCREAM qualitatively captures the cold air outbreak cloud transition in terms of the boundary layer growth, cloud mesoscale structure, and phase partitioning. SCREAM also correctly locates the greatest ice and liquid in the mesoscale updraft. However, the study finds that SCREAM might underestimate cloud supercooled liquid water in the cumulus cloud regime.

This study showcases the promise of employing high-resolution and high-frequency observations under similar large-scale conditions for evaluating GSRMs. This approach can help identify model features for future process-level studies before allocating extra resources for a time-matched model intercomparison of a specific case.
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\textbf{Key Points:}

- The Simple Cloud-Resolving E3SM Atmosphere Model (SCREAMv0), at a resolution of 3 km, simulated three distinctive cloud regimes in cold air outbreaks with credible mesoscale structures.
- SCREAMv0 qualitatively captures the transition of the cloud phase partitioning based on high-resolution observations.
- Observations selected based on large-scale conditions can be important references for global storm-resolving model evaluation.

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This study showcases the promise of employing high-resolution and high-frequency observations under similar large-scale conditions for evaluating GSRMs. This approach can help identify model features for future process-level studies before allocating extra resources for a time-matched model intercomparison of a specific case.

Plain Language Summary

Cold air outbreaks occur when cold, dry air moves over warmer ocean regions, forming extensive boundary layer clouds. However, current climate models struggle to accurately represent these clouds due to their complex nature. This study examines the performance of the global storm-resolving model, the Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM), in simulating marine boundary layer clouds during cold air outbreaks over the Norwegian Sea. This study compares the SCREAM simulated clouds during a cold air outbreak event to observations under similar large-scale conditions from satellites and ground-based measurements collected during a field campaign of the Atmospheric Radiation Measurement program. The results indicate that SCREAM successfully simulates three distinct cloud patterns during cold air outbreaks with credible mesoscale structures. Yet, it tends to underestimate supercooled liquid water and consequently, the cloud liquid water fraction, especially in cumulus clouds. The study suggests that using high-resolution observations under similar large-scale conditions can effectively evaluate global storm-resolving models. This approach helps identify areas for improvement without requiring expensive global storm-resolving model simulation designed for specific cases.

1 Introduction

Marine cold-air outbreaks (MCAO) are characterized by the advection of cold and dry air masses over much warmer ocean (Pithan et al., 2018). Intense MCAOs often originate in polar regions and generate extensive boundary layer clouds (Papritz & Spen-gler, 2017). The MCAO cloud micro/macro-physical transition and mesoscale variability can lead to marked changes in the cloud radiative effects (Field et al., 2014). Yet, current climate models and numerical weather prediction models poorly capture MCAO clouds and clouds in the postfrontal cold sector in general (e.g., Field et al., 2017; Forbes & Alhigrimm, 2014; Naud et al., 2019), because the operating scales of shallow convection and the related mixed-phase cloud processes are much finer than the model effective resolution.

Recent advances in computing have enabled the development of global storm-resolving models (GSRMs) with kilometer-scale grid spacing as an invaluable and feasible complement to traditional climate models (e.g., Satoh et al., 2019; Stevens et al., 2019; Neumann et al., 2019). At this frontier, the U.S. Department of Energy (DOE) Energy Exascale Earth System Model (E3SM) project released its GSRM, the Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM) version 0 (v0), at 3.25 km resolution (Caldwell et al., 2021). The great advantage of GSRMs is the explicit representations...
of mesoscale variabilities, such as the cloud transition in MCAOs. However, even kilometer-scale models still struggle to represent detailed MCAO cloud macrophysics, due to the sub-grid-scale parameterized turbulence and microphysical processes and their tight interactions with the resolved-scale dynamics and physics that cannot be parameterized independently (e.g., Field et al., 2014, 2017).

The field campaign called Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) was held by the US DOE Atmospheric Radiation Measurement (ARM) program in 2020 over the northern Atlantic Ocean (Geerts et al., 2022). ARM ground-based observations during COMBLE, along with pixel-level satellite retrievals, provide valuable fine-scale observations for evaluating the resolved mesoscale variations and sub-grid cloud-scale processes in GSRMs. However, a direct time-matched comparison is impossible because, without data assimilation nor nudging to reanalysis, atmospheric large-scale states in global free runs naturally drift apart from observations after 5 days (Ma et al., 2014). Therefore, this study explores an alternative strategy by performing comparisons between clouds in SCREAM and those observed under similar large-scale conditions. The goal of this paper is to establish a qualitative diagnosis of general model biases in cloud processes during MCAOs with similar large-scale features. Thus, this work sets an exploratory stage for model bias identification, and provides guidance for the future in-depth process-oriented model sensitivity studies to trace model error sources and improve SCREAM performance.

The paper is organized as follows. The SCREAMv0 40-day global simulation and COMBLE observations are briefly described in section 2. Section 3 evaluates model performance on cloud mesoscale variability and phase partitioning. The final section presents discussion and conclusions.

2 Model simulation and observations

2.1 SCREAMv0 simulation

This study analyzes the SCREAMv0 40-day global simulation at 3.25 km grid spacing with prescribed SST and sea ice between 20 January and 1 March 2020 (Caldwell et al., 2021). This simulation produced ~ 4.5 TB output data per simulated day, which are regridded to 0.05° lat–lon grids. SCREAMv0 adopts Simplified Higher Order Closure (SHOC; P. Bogenschutz & Krueger, 2013) as the turbulence scheme and the Predicted Particle Properties (P3; Morrison & Milbrandt, 2015) as the cloud microphysics scheme. P3 uses one single category for ice, in which the ice water variables, such as water path (IWP) and mixing ratio (q_i), include both cloud and precipitating ice (snow and graupel). The model liquid water path (LWP) here also includes rain water path to be more consistent with the definition of model IWP and ARM LWP retrievals. For further model details, please refer to Supporting Information.

2.2 Observational data

The ARM Mobile Facility (AMF1) of COMBLE was deployed at a coastal site near Andenes in northern Scandinavia (69°N, 16°E) between 1 December 2019 and 31 May 2020 (Geerts et al., 2022). The Active Remotely-Sensed Cloud Locations (ARSCl) product (Kollias et al., 2007) is used for the cloud structure analysis and the hourly total cloud fraction (Xie et al., 2010). To quantify the cloud phase partition, the cloud liquid water fraction is defined as the ratio of LWP to (LWP+IWP), in which LWP measurements are from microwave radiometer (Cadeddu et al., 2013) and IWP retrievals are based on cloud radar and lidar data (Deng et al., 2022). Furthermore, cloud top temperatures are calculated using the observed cloud top heights and 6-hourly radiosonde soundings (Holdridge, 2020; Hu, Lebo, et al., 2023). To minimize uncertainties in such calculation, we only in-
clude data within a one-hour window of the radiosonde launching time for evaluating the relationship between cloud top temperature and cloud liquid fraction.

Since COMBLE AMF1 was located (Fig. 1a) more than 1000 km away from the sea-ice edge, it only observed the downstream cumulus regime during MCAOs. To capture the cloud transition over the open ocean (Fig. 2), we use satellite data from Moderate Resolution Imaging Spectroradiometer (MODIS), CloudSat, and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). The pixel-level cloud retrievals are available with similar spatial resolutions as in SCREAMv0, which include cloud top temperature, cloud masks, cloud top phase, whole cloud phase, and the vertical profiles of radar reflectivity (Sassen et al., 2008; Marchand et al., 2008). There are five satellite paths capturing the cloud transition during the selected MCAO days in the COMBLE region (Fig. S5).

### 2.3 Selection of MCAO cases for model-observation comparison

To compare SCREAMv0 clouds with observations, we identify MCAO events using an MCAO index ($M$), where $M$ represents the difference between the surface skin and 800 hPa potential temperature ($M = \theta_s - \theta_{800\text{hPa}}$). MCAO events are characterized by a positive $M$ index in the COMBLE region (1°W-17°E, 63°N-80°N) and prevailing northwesterly surface winds around the Norwegian coast (Fletcher et al., 2016; Geerts et al., 2022).

In the 40-day SCREAMv0 global simulation, the most intense simulated MCAO event in the COMBLE region occurs from Day 33 to Day 36 and peaks on Day 34 (Fig. S1). Daily-mean maps (Fig. 1) of surface conditions on Day 34 confirm that a low pressure system just passed north of the Norwegian coast with the majority of the Norwegian Sea experiencing strong northwesterly surface wind. Along the large-scale flow from the Arctic sea-ice edge to the Norwegian coast, the $M$ index exceeds 5 K with a peak value of $\sim 10$ K. The lowest model level wind speed exceeds 10 ms$^{-1}$ and even reaches 16 ms$^{-1}$. As a result, the daily-mean sensible heat flux is higher than 450 W m$^{-2}$ right off the sea-ice edge and gradually reduces to $\sim 100$ W m$^{-2}$ near the Norwegian coast, whereas the latent heat flux is higher than 150 W m$^{-2}$ with a maximum region of $\sim 250$ W m$^{-2}$ north of the Norwegian coast. These maps all indicate a typical large-scale environment of intense MCAOs (Geerts et al., 2022; Pithan et al., 2018).

Because the SCREAMv0 simulation is a free run without constraining the large-scale circulations towards observations, the large-scale atmospheric conditions on Day 34 have drifted away from the observed states matching the simulated period. To address this temporal mismatch, we selected observational cases with the similar large-scale conditions as those on Day 34. Such selection is based on the combined root-mean-square error (RMSE) and Pearson correlation coefficient of daily-mean sea-level pressure, 2-m air temperature, 700-hPa geopotential height, and 500-hPa geopotential height between the SCREAMv0 Day 34 and ERA5 data in February and March, 2020 (Fig. S2a). The large-scale condition on 28 March 2020 (Fig. S3) is found to be the closest match to that on Day 34 (Fig. 1). In addition, the magnitude and distribution of the $M$ index across the Norwegian Sea shown in Fig. 1b is very similar to that on 28 March 2020 (Fig. S3a and Fig. 2 in Geerts et al., 2022). Therefore, to examine the general behavior of cloud regime transition, cloud observations from 28 March 2020 (Fig. 2) are used as the observational reference to compare with the instantaneous cloud fields on Day 34 (Fig. 3).

Meanwhile, in the SCREAMv0 simulation the large-scale conditions on Day 33 show the highest similarity to those on Day 34 (Fig. S2b, Fig. S4). In observations, MCAOs on March 19, 20, 27, and 29 all bear similarities to the conditions on March 28, 2020 (Fig. S2a). In the following, observations from March 19, 20, 27, 28 and 29 are used to evaluate the statistical features of the detailed cloud phase partitions, and their interaction with dynamics on Day 33 and 34 (Fig. 4-5).
3 Results

3.1 Cloud morphology transition

The large-scale cloud field associated with intense MCAO events usually consists of three different regimes. Clouds offshore of the sea-ice edge are overcast BL clouds embedded with fine-scale cloud rolls. As the large-scale air mass moves southward to the open ocean, the clouds grow deeper and become more distinctive cloud streets with plenty of supercooled cloud liquid (Tornow et al., 2021). Over the downstream region near the coast, the clouds transition to less organized open-cellular clouds, and eventually ice-dominated cumulus clouds that may be 4-5 km deep (e.g., McCoy et al., 2017; Lloyd et al., 2018; Geerts et al., 2022; Wu & Ovchinnikov, 2022).

The MCAO on 28 March 2020 (Fig. 1f) is a typical example of such cloud transition. The snapshot of the simulated SWCRE on Day 34 at 1200UTC (12-13 local standard time (LST)) demonstrates that SCREAMv0 is capable of generating all three regimes: overcast shallow BL cloud deck, cloud streets and scattered cumulus clouds (Fig. 1c). The vertical cross-section along the red dashed line in Fig. 3a covers the regime transition, whose mesoscale cloud structure is demonstrated with model instantaneous cloud variables (Fig. 3).

In the upstream overcast BL cloud region (e.g., north of 75°N in Fig. 1c, and the first 500 km of the vertical cross-section in Fig. 3), while many km-scale models often tend to underestimate cloud fraction and the related cloud radiative forcing (Field et al., 2017), SCREAMv0 faithfully reproduces a homogeneous overcast stratocumulus cloud deck (Fig. 1c), although lacking fine-scale cloud roll structures when compared with the MODIS reflectance (Fig. 1f). The simulated planetary boundary layer (PBL) originates below 1 km and gradually grows to near 2 km in depth (Fig. 3c), consistent with the observed clouds in the same regime (Fig. 2b). The cloud top temperature, defined as the model air temperature at the top of the cloud layer, is \(\sim -20 \text{--} -25^\circ C\) (Fig. 3b,d). A thin supercooled liquid cloud layer exists at the top of the PBL with ice-phase hydrometeors falling out of the cloud layer (Fig. 3c). The solid cloud layer is maintained by subgrid PBL turbulent processes, given the weak model-resolved vertical velocity \((\lesssim \pm 0.5 Pa/s\) in Fig. 3e). All these imply that SHOC (P. Bogenschutz & Krueger, 2013) effectively represents the PBL turbulence and BL clouds generated in strong offshore flows with significant sensible heat flux and lower-troposphere instability (Field et al., 2014).

Between \(\sim 550 \text{--} 700 \) km of the vertical cross-section, the cloud streets emerge in SCREAMv0 as the PBL deepens to above 2km and the resolved updrafts and downdrafts intensify \((\geq \pm 3.5 Pa/s \sim \pm 0.3 m/s\) Fig. 3e,f). Within this regime, the supercooled liquid cloud layer breaks up with reduced peak cloud water content (Fig. 3c,d) and the ice underneath intensifies and collocates with the resolved updrafts (Fig. 3e,f). The daily-mean cloud structures also show a cloud top deepening with decreasing supercooled liquid clouds (Fig. 1g). While clouds extend higher, cloud top temperatures remain similar to those of the overcast cloud regime due to the continuous warming of the PBL by the surface sensible and latent heat. The model vertical cross-sections, both along and across the clouds streets (Fig. 3e,f), reveal organized secondary circulations, which consist of a strong updraft within each convective cloud cell and compensating subsidence between cells (Gryschka & Rausch, 2005; Brüninger, 1999). These convective cells align with wind direction to form cloud streets, while the strong subsidence between streets cause the clouds to break up. Compared with the upstream overcast clouds off the sea-ice edge, more individual cloud cells appear along the CloudSat orbit indicating the scale of the observed convective clouds is increased (Fig. 2b). The simulated cloud streets (Fig. 1c,f) are wider (15-50 km) compared to observed streets (5-10 km). This difference may be attributed to the typical aspect ratio of roll convection in MCAOs ranging from 2 to 10 (e.g., Brüninger, 1999; Yang & Geerts, 2006). Given SCREAMv0’s effective resolu-
tion (~15 km, Caldwell et al., 2021), a convective mixed layer depth of approximately 2 km is required for distinct rolls to form.

Surface sensible heat flux decreases and latent heat flux increases along the northwest-to-southeast flow towards the Scandinavian coast (Fig. 1d,e). This leads to the breakup of organized cloud streets and their transition into scattered cumulus clouds with similar spatial sizes but clearer edges compared to observed cumulus clouds in the MODIS reflectance (Fig. 1c,f). These simulated cumulus clouds, deeper than the upstream cloud streets, are primarily composed of ice (Fig. 3a,b). At the end of the cross-section, the simulated cloud-top height is ~3 km, and the cloud top temperatures exhibit clear fluctuations, occasionally dropping as low as -30°C (Fig. 3b,c).

The SCREAMv0 daily mean cloud-top height, estimated from daily mean $q_i$ and $q_c$, is slightly lower than the median value of hourly ARM cloud top heights (Fig. 1g) in the region. Additionally, the SCREAM0 daily-mean cloud cover (~0.85–0.9, depicted as the black line in Fig. 1h) is close to the range of the ARM hourly cloud cover (~0.82–1). The simulated daily mean IWP aligns with the observed median value, whereas the simulated daily mean LWP is significantly lower than the 25 percentile of ARM hourly LWPs (Fig. 1i). Consistently, the daily mean simulated cloud liquid water fraction in this area is ~0.07 (Fig. 1i), notably lower than the observed variability range of 0.23 to 0.48 based on hourly data (Fig. 1i). Furthermore, an uncertainty analysis considering observational uncertainties (supporting information for details) in ARM IWP and LWP suggests that daily mean cloud liquid water fraction likely ranges between 0.12 and 0.45, which is also higher than the simulated value.

### 3.2 Cloud phase partition

The observed COMBLE MCAOs undergo a distinct cloud phase transition (Fig. 2). In the upstream overcast cloud deck region, satellite lidar-based retrievals identify the cloud top phase as supercooled liquid and the combined lidar-radar retrievals further confirm the whole cloud layer to be mixed-phase, similar to the findings in the Arctic of a supercooled layer at the top of stratocumulus clouds with continuous ice particles below the liquid cloud base (Jackson et al., 2012; Klein et al., 2009; Verlinde et al., 2007). In the downstream cloud streets and cumulus regimes (Fig. 1g,h), both the satellite cloud-top and whole-cloud phase retrievals indicate more dominance of cloud ice (Fig. 2), which is also supported by the ground-based ARM observation (Fig. 1h,i).

The SCREAMv0 simulated MCAO clouds reproduce a similar transition from the upstream mixed-phase clouds with a supercooled liquid layer near the cloud top to the downstream ice-dominated cumulus (Fig. 1h,i and Fig. 3a). In terms of IWP and LWP, SCREAMv0 clouds are dominated by ice, particularly for cloud streets and scattered cumulus (Fig. 1h,i and Fig. 3a). The modeled cumulus top heights are lower with warmer cloud-top temperatures than the observed (Fig. 1g and Fig. 5g). Even so, the SCREAMv0 LWP is much lower, e.g., below the 25th percentile of ARM LWPs (Fig. 1i). This leads to cloud liquid water fraction lower than the 25th percentile of ARM data (Fig. 1h). To further assess the SCREAMv0 cloud phase partition and its relationship to dynamics and temperature, we focus on two relationships between: 1) model-resolved updraft and cloud IWP and LWP respectively, 2) cloud liquid water fraction and cloud-top temperature. As aforementioned, these analyses adopt 3-hourly instantaneous model outputs of SCREAMv0 Day 33 and 34, and observations of five selected days for statistical robustness.

On the dynamic impact, Fig. 4 presents the joint probability distribution function (PDF) between the peak model-resolved vertical velocity below cloud tops and IWP and LWP respectively for BL clouds. The peak model-resolved vertical velocity represents the maximum absolute vertical velocity value beneath the cloud top, specifically at the highest level where $q_i + q_c \geq 1e^{-4} g/kg$. This peak model-resolved vertical velocity cor-
responds to in-cloud updrafts and downdrafts (Fig. 3e,f) associated with the secondary flow of roll and cell convection (Brümmer, 1999; Yang & Geerts, 2006). The cloud streets with high IWP and LWP values (e.g., top 10% and 1% percentile) were found to be mainly collocated with updrafts (Fig. 4e,f). Although grid-boxes with high cloud liquid water fraction mainly locate around cloud edges in cloud streets and cumulus regimes (Fig. 3a), a very small portion ($\leq 0.01$ Joint-PDF value) of high IWPs ($\geq 200 g/m^2$) in the cumulus cloud regime is found in downdrafts (Fig. 4g), likely around the edges of deeper cumulus clouds (Fig. 3a, b, c). Previous observational studies using ground-based data found strong correlations between vertical velocity and both IWP and LWP in Arctic mixed-phase stratiform clouds (Shupe et al., 2008) and between the cloud liquid water and updrafts in COMBLE MCAO cumulus clouds (Mages et al., 2023). Air-borne flight data indicate no evidence of cloud ice collocating with strong updrafts in the Southern Ocean cumulus clouds (Hu, Geerts, et al., 2023). Therefore, further process-oriented modeling studies and more observational evidence are needed to fully understand the strong correlations between updrafts and IWP/LWP found in SCREAMv0.

On the temperature impact, Fig. 5 presents the joint-PDFs between cloud liquid water fraction and cloud-top temperature in the three cloud regimes shown in Fig. 4a, b. To compare model and observation, we further assume correspondences between the phase identification and the value of cloud liquid water fraction: ice for less than 0.1, liquid for greater than 0.9, and mixed-phase for between 0.1 and 0.9. Compared with observations, the SCREAMv0 PDFs show less frequent liquid-phase clouds across all regimes, especially those with cloud-top temperature $\leq -15^\circ C$. In cloud streets and scattered cumulus regimes with cloud-top temperature $\leq -25^\circ C$, there are a notable portion of mixed-phase clouds in both satellite and ARM observations (Fig. 5c and g). However, SCREAMv0 indicates shows all ice-phase clouds (Fig. 5f), despite the limited presence of SCREAM-modeled clouds with cloud-top temperatures of $\leq -25^\circ C$, primarily due to insufficient cloud depth. The cloud-top phase partitioning from satellite retrievals and the model estimates (Fig. S6) also suggests that cloud-top supercooled water is underestimated in SCREAMv0 for cloud-top temperature $\leq -15^\circ C$. Since the ice initiation and production processes are primarily temperature dependent in model microphysics schemes (e.g., Field et al., 2014; Morrison & Milbrandt, 2015; Hu, Geerts, et al., 2023), more in-depth sensitivity tests are needed to understand such discrepancies.

It is worth noting that the assumed SCREAM cloud phase partitioning mentioned above is considered rudimentary and arbitrary. Consequently, it may not effectively capture the subtle sensitivity of various satellite cloud phase retrieval algorithms to cloud microphysics (D. Zhang et al., 2010). Ideally, more realistic satellite simulators should be employed (e.g., Y. Zhang et al., 2019), but they are not available in this SCREAMv0 simulation.

### 4 Summary

This study evaluates the performance of a global storm resolving model, SCREAMv0, in representing the transition of cloud morphology, and cloud phase partitioning during MCAO events against both satellite and ground-based observations collected in the North Atlantic during the ARM COMBLE field campaign.

On MCAO cloud morphology, SCREAMv0 captures the cloud mesoscale variability: solid stratiform clouds off sea-ice edge, cloud streets over open oceans and scattered cumulus clouds near the Norwegian coast. Accompanying the cloud transition, SCREAMv0 captures the deepening of PBL and intensification of circulations that support cloud streets. However, when compared to observations, SCREAMv0 falls short in reproducing roll cloud structures near the sea-ice edge, and it exhibits much larger horizontal spacing between cloud streets $\sim 500 km$ downstream. This discrepancy is partly due to SCREAMv0’s effective resolution and should improve with higher model resolution.
Using samples from multiple observed and modeled MCAO days, we found that SCREAMv0 underestimates the cloud liquid water fraction in regimes of cloud streets and scattered cumulus, even with much warmer cloud-top temperatures than the observed. In addition, the high values of cloud IWP and LWP positively correlate with the resolved-scale updrafts in SCREAMv0, indicating that cloud ice and liquid condensates are mainly generated in the mesoscale updrafts for the cloud streets and scatter cumulus regimes. Based on joint PDFs between cloud liquid water fraction and cloud-top temperature, SCREAMv0 underestimates the occurrence of supercooled clouds for cloud-top temperatures ranging from $-15$ to $-30^\circ$C when compared with both satellite and ARM data. Such temperature range is much higher than the typical temperature needed for homogeneous freezing ($\leq -38^\circ$C). One possibility is that the SCREAMv0 treatment of the Wegener–Bergeron–Findeisen (WBF) process in mixed-phase clouds might be too efficient, e.g., the assumed maximum vertical overlap between liquid and ice for WBF might unrealistically enhance the liquid-to-ice transition (Caldwell et al., 2021). Another possibility is that the prescribed aerosols in SCREAMv0 might provide overabundant Ice Nuclei (IN) without sufficient depletion processes. As a result, when air masses are carried by model-resolved updrafts to height levels close to condensation, there are sufficient IN and water for cloud ice to grow and induce other processes for further ice-phase growth within and below the cloud layer (Hu, Geerts, et al., 2023; Shupe et al., 2008). Testing these hypothesis is a target for future work.

Due to the limited 40-day SCREAMv0 global run, our analysis is based on two days of a simulated MCAO event and five observed MCAO days with similar large-scale conditions. Meanwhile, satellite cloud phase retrievals and the ARM ground-based cloud ice retrieval are challenging for heterogeneous mixed-phase clouds, with considerable uncertainties to be better quantified (Marchant et al., 2020; Ahn et al., 2018; Hu, Geerts, et al., 2023; Deng et al., 2022). A future comprehensive analysis using more MCAO cases, improved retrievals and model satellite simulators could help reduce sampling biases. In addition, we will investigate the impacts of prescribed aerosols and simplified mixed-phase cloud microphysics in SCREAMv0 using the Doubly Periodic configuration of SCREAM (DP-SCREAM) (P. A. Bogenschutz et al., 2023) and Regionally Refined Model configuration of SCREAM (RRM-SCREAM) that simulates a portion of the globe at the kilometer-resolution and leaves the remaining area at coarse-resolution for computational efficiency. Hopefully such process-level sensitivity study against high quality observations will help improve SCREAM in detailed representations of the MCAO mixed-phased cloud transition.
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Open Research

The SCREAMv0 output used in this study is publicly available as part of the DYAMOND2 intercomparison as described at https://www.esiwace.eu/services/dyamond. The code base for this global SCREAMv0 simulation is available at https://github.com/E3SM-Project/scream/releases/tag/SCREAMv0.

All the ARM and satellite data downloaded for this study are archived and available online through the NERSC Science Gateways https://portal.nersc.gov/project/mp193/zxzheng/COMBLE/. For the original data source, all ARM observational data sets used in this study are publicly available from the ARM data archive site (https://adc.arm.gov/discovery/#/results/iopShortName::amf2019comble/datastream::anxarmbeatmM1.c1/datastream::anxarmbecldradM1.c1/datastream::anxarsclkazr1kolliasM1.c0). MODIS MOD06_L2 cloud product are publicly available from (https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD06_L2, DOI:10.5067/MODIS/MOD06_L2.061). CloudSat products can be ordered from the CloudSat Data Processing center (https://www.cloudsat.cira.colostate.edu/order/). To download CloudSat data, a new user must first create an account by filling out the signup form (https://www.cloudsat.cira.colostate.edu/accounts/signup/).

ERA5 hourly data on single levels and pressure levels are downloaded from Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Hersbach, Bell, Berrisford, Biavati, et al., 2023; Hersbach, Bell, Berrisford, P., et al., 2023).
**Figure 1.** SCREAMv0 MCAO event on Day 34: daily-mean map of (a) sea level pressure (hPa) and (b) MCAO index (K); (c) snapshot of shortwave cloud radiative effect (W m⁻²) with near surface wind at 1200UTC (12-13LST); daily-mean map of surface (d) latent heat flux (W m⁻²), and (e) sensible heat flux (W m⁻²) with near surface wind field over the COMBLE region. (f) MODIS reflectance with ERA5 near surface wind (vectors, ms⁻¹) on 28 March 2020 around 1100UTC. On (c) and (f), the red lines are 100-km reference lines and the cyan dashed line is a 300-km reference line. The location of the ARM AMF1 site is marked as a red dot on (a) and (b). The vertical cross section of daily-mean (g) cloud ice condensate (shaded, g kg⁻¹), cloud liquid condensate (contours, g kg⁻¹) within the band of green dashed lines on (b), and plotted as a function of fetch from the Arctic ice edge. The variability range of the ARM observed hourly cloud top height on 28 March 2020 is shown as navy box-whiskers. (h) Daily-mean low-level cloud cover and cloud liquid water fraction (CLF), along with the variability range of the ARM hourly cloud liquid water fraction (green box-whiskers). (i) Daily-mean IWP (orange dashed) and LWP (navy) (gm⁻²) within the green dashed band in (b), along with the variability range of the ARM observed hourly IWP (orange box-whisker) and LWP (blue box-whisker). Box and whiskers show 25th, median, 75th, 5th, and 95th percentile of the hourly observational data.
Figure 2. (a) MODIS reflectance during the MCAO event on March 28, 2020. The orange-blue-orange line from Greenland to Norway indicates the path of CALIOP and CloudSat measurements shown in (b) and (c). (b) Vertical cloud structure across the cloud field during the MCAO event sampled by CALIOP and CloudSat, including CloudSat radar reflectivity (shaded), CALIOP lidar cloud top height (gray solid line), sea surface temperature (ECMWF-AUX, black), and CALIOP cloud top temperature retrieval (magenta dots). The orange-blue-orange line, along with corresponding letters, represents the path and locations in (a). (c) CALIOP cloud top phase retrieval (blue dots) and satellite lidar-radar combined whole cloud phase retrieval (black dots). Note that CALIOP cloud top phase retrievals are shifted by -0.3 km for clarity.
Figure 3. Snapshot of the SCREAMv0 simulated (a) cloud liquid water fraction and (b) cloud top temperature over the COMBRE region on Day 34 at 1200UTC (12-13LST). The vertical cross section of (c) cloud ice condensate (shaded), cloud liquid condensate (contours), and cloud top temperature (magenta symbols) and (e) resolved omega vertical velocity (shaded) and cloud ice condensate (contours) along the cloud street marked as the red dash line in (a-b). (d) and (f) represent the same as (c) and (e) but across the cloud stress (cyan dashed line in a-b and Fig. 1c,f). The start and end of the cloud street, determined by the shortwave cloud radiative effect, are marked by red squares on (c) and (e). The y-axis in (c-f) is the geopotential height estimated from surface pressure, temperature and humidity.
Figure 4. Snapshot of SCREAMv0 (a) IWP and (b) LWP on Day 34 at 1200UTC. Joint-PDF of the 3-hourly instantaneous model-resolved updraft and (left) IWP and (right) LWP during Day 33 and Day 34 over three areas as shown in (a-b). (c-d) Joint PDF for the overcast BL clouds within the green box in (a-b). (e-f) Joint PDF for the cloud streets within the blue box in (a-b). (g-h) Joint PDF for the scattered cumulus clouds within the orange box in (a-b).
Figure 5. Joint-PDFs of the satellite lidar-radar combined cloud phase retrievals vs. cloud top temperature from 19, 20, 27, 28, 29 March 2020 for (a) overcast cloud regime, (b) transition regime corresponding to the modeled cloud street region, and (c) scattered cumulus cloud regime as shown in Fig. 2 and Fig. S5. Joint-PDFs of the SCREAMv0 cloud liquid water fraction vs. cloud top temperature on Day 33-34 at 0900UTC and 1200UTC for the (d) overcast region, (e) cloud street region, and (f) scattered cumuli region as shown in Fig. 4(a). (g) Joint-PDF of observed cloud liquid water fraction vs. cloud top temperature at the ARM AMF1 site on 19, 20, 27, 28, 29 March 2020.
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Using Satellite and ARM Observations to Evaluate Cold Air Outbreak Cloud Transitions in E3SM Global Storm-Resolving Simulations

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Key Points:

- The Simple Cloud-Resolving E3SM Atmosphere Model (SCREAMv0), at a resolution of 3 km, simulated three distinctive cloud regimes in cold air outbreaks with credible mesoscale structures.
- SCREAMv0 qualitatively captures the transition of the cloud phase partitioning based on high-resolution observations.
- Observations selected based on large-scale conditions can be important references for global storm-resolving model evaluation.

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Abstract

This study evaluates the performance of a global storm-resolving model (GSRM), the Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM). We analyze marine boundary layer clouds in a cold air outbreak over the Norwegian Sea in a 40-day simulation, and compare them to observations from satellite and a field campaign of the Atmospheric Radiation Measurement program (ARM). SCREAM qualitatively captures the cold air outbreak cloud transition in terms of the boundary layer growth, cloud mesoscale structure, and phase partitioning. SCREAM also correctly locates the greatest ice and liquid in the mesoscale updraft. However, the study finds that SCREAM might underestimate cloud supercooled liquid water in the cumulus cloud regime.

This study showcases the promise of employing high-resolution and high-frequency observations under similar large-scale conditions for evaluating GSRMs. This approach can help identify model features for future process-level studies before allocating extra resources for a time-matched model intercomparison of a specific case.

Plain Language Summary

Cold air outbreaks occur when cold, dry air moves over warmer ocean regions, forming extensive boundary layer clouds. However, current climate models struggle to accurately represent these clouds due to their complex nature. This study examines the performance of the global storm-resolving model, the Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM), in simulating marine boundary layer clouds during cold air outbreaks over the Norwegian Sea. This study compares the SCREAM simulated clouds during a cold air outbreak event to observations under similar large-scale conditions from satellites and ground-based measurements collected during a field campaign of the Atmospheric Radiation Measurement program. The results indicate that SCREAM successfully simulates three distinct cloud patterns during cold air outbreaks with credible mesoscale structures. Yet, it tends to underestimate supercooled liquid water and consequently, the cloud liquid water fraction, especially in cumulus clouds. The study suggests that using high-resolution observations under similar large-scale conditions can effectively evaluate global storm-resolving models. This approach helps identify areas for improvement without requiring expensive global storm-resolving model simulation designed for specific cases.

1 Introduction

Marine cold-air outbreaks (MCAO) are characterized by the advection of cold and dry air masses over much warmer ocean (Pithan et al., 2018). Intense MCAOs often originate in polar regions and generate extensive boundary layer clouds (Papritz & Spengler, 2017). The MCAO cloud micro/macro-physical transition and mesoscale variability can lead to marked changes in the cloud radiative effects (Field et al., 2014). Yet, current climate models and numerical weather prediction models poorly capture MCAO clouds and clouds in the postfrontal cold sector in general (e.g., Field et al., 2017; Forbes & Ahlgrimm, 2014; Naud et al., 2019), because the operating scales of shallow convection and the related mixed-phase cloud processes are much finer than the model effective resolution.

Recent advances in computing have enabled the development of global storm-resolving models (GSRMs) with kilometer-scale grid spacing as an invaluable and feasible complement to traditional climate models (e.g., Satoh et al., 2019; Stevens et al., 2019; Neumann et al., 2019). At this frontier, the U.S. Department of Energy (DOE) Energy Exascale Earth System Model (E3SM) project released its GSRM, the Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM) version 0 (v0), at 3.25 km resolution (Caldwell et al., 2021). The great advantage of GSRMs is the explicit representations
of mesoscale variabilities, such as the cloud transition in MCAOs. However, even kilometer-scale models still struggle to represent detailed MCAO cloud macrophysics, due to the sub-grid-scale parameterized turbulence and microphysical processes and their tight interactions with the resolved-scale dynamics and physics that cannot be parameterized independently (e.g., Field et al., 2014, 2017).

The field campaign called Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE) was held by the US DOE Atmospheric Radiation Measurement (ARM) program in 2020 over the northern Atlantic Ocean (Geerts et al., 2022). ARM ground-based observations during COMBLE, along with pixel-level satellite retrievals, provide valuable fine-scale observations for evaluating the resolved mesoscale variations and sub-grid cloud-scale processes in GSRMs. However, a direct time-matched comparison is impossible because, without data assimilation nor nudging to reanalysis, atmospheric large-scale states in global free runs naturally drift apart from observations after 5 days (Ma et al., 2014). Therefore, this study explores an alternative strategy by performing comparisons between clouds in SCREAM and those observed under similar large-scale conditions. The goal of this paper is to establish a qualitative diagnosis of general model biases in cloud processes during MCAOs with similar large-scale features. Thus, this work sets an exploratory stage for model bias identification, and provides guidance for the future in-depth process-oriented model sensitivity studies to trace model error sources and improve SCREAM performance.

The paper is organized as follows. The SCREAMv0 40-day global simulation and COMBLE observations are briefly described in section 2. Section 3 evaluates model performance on cloud mesoscale variability and phase partitioning. The final section presents discussion and conclusions.

2 Model simulation and observations

2.1 SCREAMv0 simulation

This study analyzes the SCREAMv0 40-day global simulation at 3.25 km grid spacing with prescribed SST and sea ice between 20 January and 1 March 2020 (Caldwell et al., 2021). This simulation produced ~ 4.5 TB output data per simulated day, which are regridded to 0.05° lat–lon grids. SCREAMv0 adopts Simplified Higher Order Closure (SHOC; P. Bogenschutz & Krueger, 2013) as the turbulence scheme and the Predicted Particle Properties (P3; Morrison & Milbrandt, 2015) as the cloud microphysics scheme. P3 uses one single category for ice, in which the ice water variables, such as water path (IWP) and mixing ratio ($q_i$), include both cloud and precipitating ice (snow and graupel). The model liquid water path (LWP) here also includes rain water path to be more consistent with the definition of model IWP and ARM LWP retrievals. For further model details, please refer to Supporting Information.

2.2 Observational data

The ARM Mobile Facility (AMF1) of COMBLE was deployed at a coastal site near Andenes in northern Scandinavia (69°N, 16°E) between 1 December 2019 and 31 May 2020 (Geerts et al., 2022). The Active Remotely-Sensed Cloud Locations (ARSLC) product (Kollias et al., 2007) is used for the cloud structure analysis and the hourly total cloud fraction (Xie et al., 2010). To quantify the cloud phase partition, the cloud liquid water fraction is defined as the ratio of LWP to (LWP+IWP), in which LWP measurements are from microwave radiometer (Cadeddu et al., 2013) and IWP retrievals are based on cloud radar and lidar data (Deng et al., 2022). Furthermore, cloud top temperatures are calculated using the observed cloud top heights and 6-hourly radiosonde soundings (Holdridge, 2020; Hu, Lebo, et al., 2023). To minimize uncertainties in such calculation, we only in-
clude data within a one-hour window of the radiosonde launching time for evaluating the relationship between cloud top temperature and cloud liquid fraction.

Since COMBLE AMF1 was located (Fig. 1a) more than 1000 km away from the sea-ice edge, it only observed the downstream cumulus regime during MCAOs. To capture the cloud transition over the open ocean (Fig. 2), we use satellite data from Moderate Resolution Imaging Spectroradiometer (MODIS), CloudSat, and Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO). The pixel-level cloud retrievals are available with similar spatial resolutions as in SCREAMv0, which include cloud top temperature, cloud masks, cloud top phase, whole cloud phase, and the vertical profiles of radar reflectivity (Sassen et al., 2008; Marchand et al., 2008). There are five satellite paths capturing the cloud transition during the selected MCAO days in the COMBLE region (Fig. S5).

2.3 Selection of MCAO cases for model-observation comparison

To compare SCREAMv0 clouds with observations, we identify MCAO events using an MCAO index (M), where M represents the difference between the surface skin and 800 hPa potential temperature (M = θ_s − θ_{800 hPa}). MCAO events are characterized by a positive M index in the COMBLE region (16°W-17°E, 63°N-80°N) and prevailing northwesterly surface winds around the Norwegian coast (Fletcher et al., 2016; Geerts et al., 2022).

In the 40-day SCREAMv0 global simulation, the most intense simulated MCAO event in the COMBLE region occurs from Day 33 to Day 36 and peaks on Day 34 (Fig. S1). Daily-mean maps (Fig. 1) of surface conditions on Day 34 confirm that a low pressure system just passed north of the Norwegian coast with the majority of the Norwegian Sea experiencing strong northwesterly surface wind. Along the large-scale flow from the Arctic sea-ice edge to the Norwegian coast, the M index exceeds 5 K with a peak value of ~10 K. The lowest model level wind speed exceeds 10 m s\(^{-1}\) and even reaches 16 m s\(^{-1}\). As a result, the daily-mean sensible heat flux is higher than 450 W m\(^{-2}\) right off the sea-ice edge and gradually reduces to ~100 W m\(^{-2}\) near the Norwegian coast, whereas the latent heat flux is higher than 150 W m\(^{-2}\) with a maximum region of ~250 W m\(^{-2}\) north of the Norwegian coast. These maps all indicate a typical large-scale environment of intense MCAOs (Geerts et al., 2022; Pithan et al., 2018).

Because the SCREAMv0 simulation is a free run without constraining the large-scale circulations towards observations, the large-scale atmospheric conditions on Day 34 have drifted away from the observed states matching the simulated period. To address this temporal mismatch, we selected observational cases with the similar large-scale conditions as those on Day 34. Such selection is based on the combined root-mean-square error (RMSE) and Pearson correlation coefficient of daily-mean sea-level pressure, 2-m air temperature, 700-hPa geopotential height, and 500-hPa geopotential height between the SCREAMv0 Day 34 and ERA5 data in February and March, 2020 (Fig. S2a). The large-scale condition on 28 March 2020 (Fig. S3) is found to be the closest match to that on Day 34 (Fig. 1). In addition, the magnitude and distribution of the M index across the Norwegian Sea shown in Fig. 1b is very similar to that on 28 March 2020 (Fig. S3a and Fig. 2 in Geerts et al., 2022). Therefore, to examine the general behavior of cloud regime transition, cloud observations from 28 March 2020 (Fig. 2) are used as the observational reference to compare with the instantaneous cloud fields on Day 34 (Fig. 3).

Meanwhile, in the SCREAMv0 simulation the large-scale conditions on Day 33 show the highest similarity to those on Day 34 (Fig. S2b, Fig. S4). In observations, MCAOs on March 19, 20, 27, and 29 all bear similarities to the conditions on March 28, 2020 (Fig. S2a). In the following, observations from March 19, 20, 27, 28 and 29 are used to evaluate the statistical features of the detailed cloud phase partitions, and their interaction with dynamics on Day 33 and 34 (Fig. 4-5).
3 Results

3.1 Cloud morphology transition

The large-scale cloud field associated with intense MCAO events usually consists of three different regimes. Clouds offshore of the sea-ice edge are overcast BL clouds embedded with fine-scale cloud rolls. As the large-scale air mass moves southward to the open ocean, the clouds grow deeper and become more distinctive cloud streets with plenty of supercooled cloud liquid (Tornow et al., 2021). Over the downstream region near the coast, the clouds transition to less organized open-cellular clouds, and eventually ice-dominated cumulus clouds that may be 4-5 km deep (e.g., McCoy et al., 2017; Lloyd et al., 2018; Geerts et al., 2022; Wu & Ovchinnikov, 2022).

The MCAO on 28 March 2020 (Fig. 1f) is a typical example of such cloud transition. The snapshot of the simulated SWCRE on Day 34 at 1200UTC [12-13 local standard time (LST)] demonstrates that SCREAMv0 is capable of generating all three regimes: overcast shallow BL cloud deck, cloud streets and scattered cumulus clouds (Fig. 1c). The vertical cross-section along the red dashed line in Fig. 3a covers the regime transition, whose mesoscale cloud structure is demonstrated with model instantaneous cloud variables (Fig. 3).

In the upstream overcast BL cloud region (e.g., north of 75°N in Fig. 1c, and the first 500 km of the vertical cross-section in Fig. 3), while many km-scale models often tend to underestimate cloud fraction and the related cloud radiative forcing (Field et al., 2017), SCREAMv0 faithfully reproduces a homogeneous overcast stratocumulus cloud deck (Fig. 1c), although lacking fine-scale cloud roll structures when compared with the MODIS reflectance (Fig. 1f). The simulated planetary boundary layer (PBL) originates below 1 km and gradually grows to near 2 km in depth (Fig. 3c), consistent with the observed clouds in the same regime (Fig. 2b). The cloud top temperature, defined as the model air temperature at the top of the cloud layer, is \(-20\) to \(-25°C\) (Fig. 3b,d). A thin supercooled liquid cloud layer exists at the top of the PBL with ice-phase hydrometeors falling out of the cloud layer (Fig. 3c). The solid cloud layer is maintained by sub-grid PBL turbulent processes, given the weak model-resolved vertical velocity (\(>\pm 0.5\) Pa/s in Fig. 3e,c). All these imply that SHOC (P. Bogenschutz & Krueger, 2013) effectively represents the PBL turbulence and BL clouds generated in strong offshore flows with significant sensible heat flux and lower-troposphere instability (Field et al., 2014).

Between \(\sim 550 - 700\) km of the vertical cross-section, the cloud streets emerge in SCREAMv0 as the PBL deepens to above 2km and the resolved updrafts and downdrafts intensify (\(>\pm 3.5\) Pa/s \(\sim \pm 0.3 \text{m/s}\) Fig. 3e,f). Within this regime, the supercooled liquid cloud layer breaks up with reduced peak cloud water content (Fig. 3c,d) and the ice underneath intensifies and collocates with the resolved updrafts (Fig. 3e,f). The daily-mean cloud structures also show a cloud top deepening with decreasing supercooled liquid clouds (Fig. 1g). While clouds extend higher, cloud top temperatures remain similar to those of the overcast cloud regime due to the continuous warming of the PBL by the surface sensible and latent heat. The model vertical cross-sections, both along and across the clouds streets (Fig. 3c,f), reveal organized secondary circulations, which consist of a strong updraft within each convective cloud cell and compensating subsidence between cells (Gryschka & Rausch, 2005; Brümmer, 1999). These convective cells adjust with wind direction to form cloud streets, while the strong subsidence between streets cause the clouds to break up. Compared with the upstream overcast clouds off the sea-ice edge, more individual cloud cells appear along the CloudSat orbit indicating the scale of the observed convective clouds is increased (Fig. 2b). The simulated cloud streets (Fig. 1c,f) are wider (15-50 km) compared to observed streets (5-10 km). This difference may be attributed to the typical aspect ratio of roll convection in MCAOs ranging from 2 to 10 (e.g., Brümmer, 1999; Yang & Geerts, 2006). Given SCREAMv0’s effective resolu-
tion (∼15 km, Caldwell et al., 2021), a convective mixed layer depth of approximately 2 km is required for distinct rolls to form.

Surface sensible heat flux decreases and latent heat flux increases along the northwest-to-southeast flow towards the Scandinavian coast (Fig. 1d,e). This leads to the breakup of organized cloud streets and their transition into scattered cumulus clouds with similar spatial sizes but clearer edges compared to observed cumulus clouds in the MODIS reflectance (Fig. 1c,f). These simulated cumulus clouds, deeper than the upstream cloud streets, are primarily composed of ice (Fig. 3a,b). At the end of the cross-section, the simulated cloud-top height is ∼3 km, and the cloud top temperatures exhibit clear fluctuations, occasionally dropping as low as −30°C (Fig. 3b,c).

The SCREAMv0 daily mean cloud-top height, estimated from daily mean $q_i$ and $q_c$, is slightly lower than the median value of hourly ARM cloud top heights (Fig. 1g) in the region. Additionally, the SCREAM0 daily-mean cloud cover (∼0.85–0.9, depicted as the black line in Fig. 1h) is close to the range of the ARM hourly cloud cover (∼0.82–1). The simulated daily mean IWP aligns with the observed median value, whereas the simulated daily mean LWP is significantly lower than the 25 percentile of ARM hourly LWPs (Fig. 1i). Consistently, the daily mean simulated cloud liquid water fraction in this area is ∼0.07 (Fig. 1h), notably lower than the observed variability range of 0.23 to 0.48 based on hourly data (Fig. 1i). Furthermore, an uncertainty analysis considering observational uncertainties (supporting information for details) in ARM IWP and LWP suggests that daily mean cloud liquid water fraction likely ranges between 0.12 and 0.45, which is also higher than the simulated value.

3.2 Cloud phase partition

The observed COMBLE MCAOs undergo a distinct cloud phase transition (Fig. 2). In the upstream overcast cloud deck region, satellite lidar-based retrievals identify the cloud top phase as supercooled liquid and the combined lidar-radar retrievals further confirm the whole cloud layer to be mixed-phase, similar to the findings in the Arctic of a supercooled layer at the top of stratocumulus clouds with continuous ice particles below the liquid cloud base (Jackson et al., 2012; Klein et al., 2009; Verlinde et al., 2007). In the downstream cloud streets and cumulus regimes (Fig. 1g,h), both the satellite cloud-top and whole-cloud phase retrievals indicate more dominance of cloud ice (Fig. 2), which is also supported by the ground-based ARM observation (Fig. 1h,i).

The SCREAMv0 simulated MCAO clouds reproduce a similar transition from the upstream mixed-phase clouds with a supercooled liquid layer near the cloud top to the downstream ice-dominated cumulus (Fig. 1h,i and Fig. 3a). In terms of IWP and LWP, SCREAMv0 clouds are dominated by ice, particularly for cloud streets and scattered cumulus (Fig. 1h,i and Fig. 3a). The modeled cumulus top heights are lower with warmer cloud-top temperatures than the observed (Fig. 1g and Fig. 5g). Even so, the SCREAMv0 LWP is much lower, e.g., below the 25th percentile of ARM LWPs (Fig. 1i). This leads to cloud liquid water fraction lower than the 25th percentile of ARM data (Fig. 1h). To further assess the SCREAMv0 cloud phase partition and its relationship to dynamics and temperature, we focus on two relationships between: 1) model-resolved updraft and cloud IWP and LWP respectively, 2) cloud liquid water fraction and cloud-top temperature. As aforementioned, these analyses adopt 3-hourly instantaneous model outputs of SCREAMv0 Day 33 and 34, and observations of five selected days for statistical robustness.

On the dynamic impact, Fig. 4 presents the joint probability distribution function (PDF) between the peak model-resolved vertical velocity below cloud tops and IWP and LWP respectively for BL clouds. The peak model-resolved vertical velocity represents the maximum absolute vertical velocity value beneath the cloud top, specifically at the highest level where $q_i+q_c \geq 1 \times 10^{-4} g/kg$. This peak model-resolved vertical velocity cor-
responds to in-cloud updrafts and downdrafts (Fig. 3e,f) associated with the secondary flow of roll and cell convection (Brümmer, 1999; Yang & Geerts, 2006). The cloud streets with high IWP and LWP values (e.g., top 10% and 1% percentile) were found to be mainly collocated with updrafts (Fig. 4e,f). Although grid-boxes with high cloud liquid water fraction mainly locate around cloud edges in cloud streets and cumulus regimes (Fig. 3a), a very small portion (≤ 0.01 Joint-PDF value) of high IWPs (≥ 200 g/m²) in the cumulus cloud regime is found in downdrafts (Fig. 4g), likely around the edges of deeper cumulus clouds (Fig. 3a,b,e). Previous observational studies using ground-based data found strong correlations between vertical velocity and both IWP and LWP in Arctic mixed-phase stratiform clouds (Shupe et al., 2008) and between the cloud liquid water and updrafts in COMBLE MCAO cumulus clouds (Mages et al., 2023). Air-borne flight data indicate no evidence of cloud ice collocating with strong updrafts in the Southern Ocean cumulus clouds (Hu, Geerts, et al., 2023). Therefore, further process-oriented modeling studies and more observational evidence are needed to fully understand the strong correlations between updrafts and IWP/LWP found in SCREAMv0.

On the temperature impact, Fig. 5 presents the joint-PDFs between cloud liquid water fraction and cloud-top temperature in the three cloud regimes shown in Fig. 4a,b. To compare model and observation, we further assume correspondences between the phase identification and the value of cloud liquid water fraction: ice for less than 0.1, liquid for greater than 0.9, and mixed-phase for between 0.1 and 0.9. Compared with observations, the SCREAMv0 PDFs show less frequent liquid-phase clouds across all regimes, especially those with cloud-top temperature ≤ −15°C. In cloud streets and scattered cumulus regimes with cloud-top temperature ≤ −25°C, there are a notable portion of mixed-phase clouds in both satellite and ARM observations (Fig. 5 c and g). However, SCREAMv0 indicates shows all ice-phase clouds (Fig. 5 f), despite the limited presence of SCREAM-modeled clouds with cloud-top temperatures of ≤ −25°C, primarily due to insufficient cloud depth. The cloud-top phase partitioning from satellite retrievals and the model estimates (Fig. 6) also suggests that cloud-top supercooled water is underestimated in SCREAMv0 for cloud-top temperature ≤ −15°C. Since the ice initiation and production processes are primarily temperature dependent in model microphysics schemes (e.g., Field et al., 2014; Morrison & Milbrandt, 2015; Hu, Geerts, et al., 2023), more in-depth sensitivity tests are needed to understand such discrepancies.

It is worth noting that the assumed SCREAM cloud phase partitioning mentioned above is considered rudimentary and arbitrary. Consequently, it may not effectively capture the subtle sensitivity of various satellite cloud phase retrieval algorithms to cloud microphysics (D. Zhang et al., 2010). Ideally, more realistic satellite simulators should be employed (e.g., Y. Zhang et al., 2019), but they are not available in this SCREAMv0 simulation.

4 Summary

This study evaluates the performance of a global storm resolving model, SCREAMv0, in representing the transition of cloud morphology, and cloud phase partitioning during MCAO events against both satellite and ground-based observations collected in the North Atlantic during the ARM COMBLE field campaign.

On MCAO cloud morphology, SCREAMv0 captures the cloud mesoscale variability: solid stratiform clouds off sea-ice edge, cloud streets over open oceans and scattered cumulus clouds near the Norwegian coast. Accompanying the cloud transition, SCREAMv0 captures the deepening of PBL and intensification of circulations that support cloud streets. However, when compared to observations, SCREAMv0 falls short in reproducing roll cloud structures near the sea-ice edge, and it exhibits much larger horizontal spacing between cloud streets ~ 500 km downstream. This discrepancy is partly due to SCREAMv0’s effective resolution and should improve with higher model resolution.
Using samples from multiple observed and modeled MCAO days, we found that SCREAMv0 underestimates the cloud liquid water fraction in regimes of cloud streets and scattered cumulus, even with much warmer cloud-top temperatures than the observed. In addition, the high values of cloud IWP and LWP positively correlate with the resolved-scale updrafts in SCREAMv0, indicating that cloud ice and liquid condensates are mainly generated in the mesoscale updrafts for the cloud streets and scatter cumulus regimes. Based on joint PDFs between cloud liquid water fraction and cloud-top temperature, SCREAMv0 underestimates the occurrence of supercooled clouds for cloud-top temperatures ranging from $-15$ to $-30^\circ C$ when compared with both satellite and ARM data. Such temperature range is much higher than the typical temperature needed for homogeneous freezing ($\leq -38^\circ C$). One possibility is that the SCREAMv0 treatment of the Wegener–Bergeron–Findeisen (WBF) process in mixed-phase clouds might be too efficient, e.g., the assumed maximum vertical overlap between liquid and ice for WBF might unrealistically enhance the liquid-to-ice transition (Caldwell et al., 2021). Another possibility is that the prescribed aerosols in SCREAMv0 might provide overabundant Ice Nuclei (IN) without sufficient depletion processes. As a result, when air masses are carried by model-resolved updrafts to height levels close to condensation, there are sufficient IN and water for cloud ice to grow and induce other processes for further ice-phase growth within and below the cloud layer (Hu, Geerts, et al., 2023; Shupe et al., 2008). Testing these hypothesis is a target for future work.

Due to the limited 40-day SCREAMv0 global run, our analysis is based on two days of a simulated MCAO event and five observed MCAO days with similar large-scale conditions. Meanwhile, satellite cloud phase retrievals and the ARM ground-based cloud ice retrieval are challenging for heterogeneous mixed-phase clouds, with considerable uncertainties to be better quantified (Marchant et al., 2020; Ahn et al., 2018; Hu, Geerts, et al., 2023; Deng et al., 2022). A future comprehensive analysis using more MCAO cases, improved retrievals and model satellite simulators could help reduce sampling biases. In addition, we will investigate the impacts of prescribed aerosols and simplified mixed-phase cloud microphysics in SCREAMv0 using the Doubly Periodic configuration of SCREAM (DP-SCREAM) (P. A. Bogenschutz et al., 2023) and Regionally Refined Model configuration of SCREAM (RRM-SCREAM) that simulates a portion of the globe at the kilometer-resolution and leaves the remaining area at coarse-resolution for computational efficiency. Hopefully such process-level sensitivity study against high quality observations will help improve SCREAM in detailed representations of the MCAO mixed-phased cloud transition.
Acknowledgments

We would like to express our gratitude to the ARM Data Facility and the COMBLE team for providing field campaign observation data, as well as the E3SM and SCREAM development team for supplying the global SCREAMv0 simulation output. Our thanks also go to the MODIS, CALIPSO, and CloudSat cloud product teams for making their data publicly available. Special appreciation is extended to Dr. Matthew Lebsock for his invaluable assistance with CloudSat data products. This work was funded by the Atmospheric System Research program of the U.S. Department of Energy under the project 'Tying in High-Resolution E3SM with ARM Data (THREAD)'. Most of the analyses were conducted using computing resources from the National Energy Research Scientific Computing Center (NERSC). This work was performed under the auspices of the U.S. Department of Energy by LLNL under contract DE-AC52-07NA27344. LLNL-JRNL-856632. The Pacific Northwest National Laboratory (PNNL) is operated for DOE by the Battelle Memorial Institute under contract no. DE-AC05-76RLO1830. B. Geerts is supported by DOE Atmospheric System Research (ASR) Grants DE-SC0018927 and DE-SC0021151. M. Deng’s work was partially supported by the Office of Biological and Environmental Research in the Department of Energy, Office of Science, through the United States Department of Energy Contract No. DE-SC0012704 to Brookhaven National Laboratory. Z. Zhang’s work is partly supported by the Atmospheric System Research grant (DE-SC0020057). C. R. Terai and P. Caldwell’s efforts were supported as part of the Energy Exascale Earth System Model (E3SM) project, funded by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research.

Open Research

The SCREAMv0 output used in this study is publicly available as part of the DYAMOND2 intercomparison as described at https://www.esiwace.eu/services/dyamond. The code base for this global SCREAMv0 simulation is available at https://github.com/E3SM-Project/scream/releases/tag/SCREAMv0.

All the ARM and satellite data downloaded for this study are archived and available online through the NERSC Science Gateways https://portal.nersc.gov/project/mp193/xzheng/COMBLE/. For the original data source, all ARM observational data sets used in this study are publicly available from the ARM data archive site (https://adc.arm.gov/discovery/#/results/iopShortName::amf2019comble/datastream::anxarmbeatmM1.c1/datastream::anxarmbecldradM1.c1/datastream::anxarsclkazr1kolliasM1.c0).

CloudSat products can be ordered from the CloudSat Data Processing center (https://www.cloudsat.cira.colostate.edu/order/). To download CloudSat data, a new user must first create an account by filling out the signup form (https://www.cloudsat.cira.colostate.edu/accounts/signup/).

ERA5 hourly data on single levels and pressure levels are downloaded from Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Hersbach, Bell, Berrisford, Biavati, et al., 2023; Hersbach, Bell, Berrisford, P., et al., 2023).
Figure 1. SCREAMv0 MCAO event on Day 34: daily-mean map of (a) sea level pressure (hPa) and (b) MCAO index (K); (c) snapshot of shortwave cloud radiative effect (W m⁻²) with near surface wind at 1200UTC (12-13LST); daily-mean map of surface (d) latent heat flux (W m⁻²), and (e) sensible heat flux (W m⁻²) with near surface wind field over the COMBLE region. (f) MODIS reflectance with ERA5 near surface wind (vectors, m s⁻¹) on 28 March 2020 around 1100UTC. On (c) and (f), the red lines are 100-km reference lines and the cyan dashed line is a 300-km reference line. The location of the ARM AMF1 site is marked as a red dot on (a) and (b). The vertical cross section of daily-mean (g) cloud ice condensate (shaded, g kg⁻¹), cloud liquid condensate (contours, g kg⁻¹) within the band of green dashed lines on (b), and plotted as a function of fetch from the Arctic ice edge. The variability range of the ARM observed hourly cloud top height on 28 March 2020 is shown as navy box-whiskers. (h) Daily-mean low-level cloud cover and cloud liquid water fraction (CLF), along with the variability range of the ARM hourly cloud liquid water fraction (green box-whiskers). (i) Daily-mean IWP (orange dashed) and LWP (navy) (gm⁻²) within the green dashed band in (b), along with the variability range of the ARM observed hourly IWP (orange box-whisker) and LWP (blue box-whisker). Box and whiskers show 25th, median, 75th, 5th, and 95th percentile of the hourly observational data.
**Figure 2.** (a) MODIS reflectance during the MCAO event on March 28, 2020. The orange-blue-orange line from Greenland to Norway indicates the path of CALIOP and CloudSat measurements shown in (b) and (c). (b) Vertical cloud structure across the cloud field during the MCAO event sampled by CALIOP and CloudSat, including CloudSat radar reflectivity (shaded), CALIOP lidar cloud top height (gray solid line), sea surface temperature (ECMWF-AUX, black), and CALIOP cloud top temperature retrieval (magenta dots). The orange-blue-orange line, along with corresponding letters, represents the path and locations in (a). (c) CALIOP cloud top phase retrieval (blue dots) and satellite lidar-radar combined whole cloud phase retrieval (black dots). Note that CALIOP cloud top phase retrievals are shifted by -0.3 km for clarity.
Figure 3. Snapshot of the SCREAMv0 simulated (a) cloud liquid water fraction and (b) cloud top temperature over the COMBLE region on Day 34 at 1200UTC (12-13LST). The vertical cross section of (c) cloud ice condensate (shaded), cloud liquid condensate (contours), and cloud top temperature (magenta symbols) and (d) resolved omega vertical velocity (shaded) and cloud ice condensate (contours) along the cloud street marked as the red dash line in (a-b). (e) and (f) represent the same as (c) and (e) but across the cloud stress (cyan dashed line in a-b and Fig. 1c,f). The start and end of the cloud street, determined by the shortwave cloud radiative effect, are marked by red squares on (c) and (e). The y-axis in (c-f) is the geopotential height estimated from surface pressure, temperature and humidity.
Figure 4. Snapshot of SCREAMv0 (a) IWP and (b) LWP on Day 34 at 1200UTC. Joint-PDF of the 3-hourly instantaneous model-resolved updraft and (left) IWP and (right) LWP during Day 33 and Day 34 over three areas as shown in (a-b). (c-d) Joint PDF for the overcast BL clouds within the green box in (a-b). (e-f) Joint PDF for the cloud streets within the blue box in (a-b). (g-h) Joint PDF for the scattered cumulus clouds within the orange box in (a-b).
Figure 5. Joint-PDFs of the satellite lidar-radar combined cloud phase retrievals vs. cloud top temperature from 19, 20, 27, 28, 29 March 2020 for (a) overcast cloud regime, (b) transition regime corresponding to the modeled cloud street region, and (c) scattered cumulus cloud regime as shown in Fig. 2 and Fig. S5. Joint-PDFs of the SCREAMv0 cloud liquid water fraction vs. cloud top temperature on Day 33-34 at 0900UTC and 1200UTC for the (d) overcast region, (e) cloud street region, and (f) scattered cumuli region as shown in Fig. 4(a). (g) Joint-PDF of observed cloud liquid water fraction vs. cloud top temperature at the ARM AMF1 site on 19, 20, 27, 28, 29 March 2020.
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ing, and cloud data products. *Journal of Atmospheric and Oceanic Technology*, 24(7), 1199 - 1214. Retrieved from https://journals.ametsoc.org/view/journals/atot/24/7/jtech2033_1.xml doi: https://doi.org/10.1175/JTECH2033.1


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Supporting Information for "Using Satellite and ARM Ground-based Observations to Evaluate Cold Air Outbreak Cloud Transitions in E3SM Global Storm-Resolving Simulations"

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SCREAMv0 simulation

SCREAMv0 uses a nonhydrostatic dynamical core with $1024 \times 1024$ spectral elements on a cubed sphere geometry, which is equivalent to a $3.25 km$ grid spacing. The physical parameterizations for the atmosphere model run on a grid spacing of $\sim 6 km$. SCREAMv0 has 128 layer vertical grid with a model top at $40 km$. The vertical resolution below $800 hPa$ is $< 150 m$ and the representative grid spacing in the boundary layer is $\sim 50 m$. The land model in SCREAMv0 runs on a $0.25 ^\circ$ grid, while the sea surface temperature (SST) and sea ice are prescribed on the ocean grid in the high-resolution configuration of E3SMv1. The radiation scheme is the RTE+RRTMGP radiative transfer package (Pincus et al., 2019). Without interactive aerosol scheme, SCREAMv0 prescribes aerosols
with the interpolated monthly output from an E3SMv1 simulation. Although the main time step is 75 second, different model components might use different timesteps (see Caldwell et al., 2021 Table 1. for the list of model time steps for this simulation). Following the protocol for the second GCPM intercomparison called DYnamics of the Atmospheric general circulation Modeled On Nonhydrostatic Domains (DYAMOND2, https://www.esiwace.eu/services/dyamond/winter), this global SCREAMv0 simulation was run for 40 days with prescribed SST and sea ice for the boreal winter period between 20 January 2020 and 1 March 2020. Besides the model improvements in the global precipitation, tropical and extratropical storms, coastal stratocumulus clouds and cold-air outbreaks, this simulation reveals remaining model deficiencies in SCREAMv0, such as the double-ITCZ bias, too strong surface wind speed, and surface temperature bias at high latitudes, etc (Caldwell et al., 2021). Specifically, this simulation underestimates the frequency of MCAOs in the Nordic Seas, likely due to an overly warm Greenland. Fig. S1 indicates that there are two simulated MCAO events over the COMBLE region with northerly prevailing surface winds near the ARM AMF1 site (Day 2- Day 3, Day 33- Day 36). This study focuses on Day 34 when the MCAO event is the most intense in terms of MCAO index. To select the observed MCAO event similar to Day 34, we remap sea-level pressure, 2-m air temperature, 700-hPa geopotential height, and 500-hPa geopotential height from both SCREAMv0 model and the European Center for Medium Range Weather Forecasting (ECMWF) ERA-5 reanalysis data (Hersbach et al., 2020) to the same 256x512 latitude-longitude grids, and then generate the daily-mean meteorological conditions to calculate the Pearson correlation coefficient and root-mean-square error.
The calculated RMSEs are normalized for each variable to be between zero and one. Lastly, we average the Pearson correlation coefficient and normalized RMSE for all estimated variables. Fig. S2a shows the average Pearson correlation coefficient and normalized RMSE between the SCREAMv0 Day 34 and ERA5 data for each day between February and March 2020, while Fig. S2b shows the average Pearson correlation coefficient and normalized RMSE between the SCREAMv0 Day 34 and all SCREAMv0 days over the COMBLE region.

**ARM COMBLE observations**

The DOE’s ARM Mobile Facility (AMF1) was on a coastal site near Andenes in northern Scandinavia during the COMBLE field campaign. COMBLE obtained a total of 34 days of CAO conditions at the AMF1 site during the 6-month COMBLE campaign. (Geerts et al., 2022). This study analyzed cloud observations on 19, 20, 27, 28, 29 March 2020, with a focus on the MCAO day on 28 March 2020. Here we only briefly describe the measurements used in the cloud top and cloud phase evaluation.

The observed cloud LWP is derived from a standard two-channel microwave radiometer (Cadeddu et al., 2013). The MWR receives microwave radiation from the sky at 23.8 GHz and 31.4 GHz. These two frequencies allow simultaneous determination of water vapor and liquid water burdens along a selected path. Cloud liquid in the atmosphere emits in a continuum that increases with frequency, dominating the 31.4 GHz observation, whereas water vapor dominates the 23.8 GHz channel. The water vapor and liquid water signals can, therefore, be separated by observing at these two frequencies. The LWP is from the ARM data stream - anxmwrlosM1.b1. The LWP uncertainty is 20 - 30 gm$^{-2}$.
The observed cloud IWP is a column-integrated value from retrieved cloud ice water content (IWC) based on Ka-band (35 GHz) ARM zenith radars (KAZR)’s radar reflectivity and Doppler velocity. Briefly speaking, the underlining assumption of the radar only IWP retrieval is that KAZR mainly observes backscattering signal from large ice particles. An ice habit sensitivity study shows that the retrieved IWC with aggregate ice particle habit agrees the best with the in-situ measurement, especially in ice or ice-dominated mixed-phase clouds with a correlation coefficient of 0.91 and a bias of close to 0. For mixed-phase clouds with ice fraction ratio less than 0.8, the correlation coefficient reduces to 0.76, and the retrieved mean IWC is larger than in-situ IWC by a factor of 2. This larger difference between the retrieved IWC and in-situ IWC for mixed-phase clouds with a lower ice fraction ratio is found to be related to the uncertainty of in-situ measurements, the large cloud heterogeneity, and the retrieval assumption uncertainty. More details of the retrieval techniques and uncertainties can be found in (Deng & Mace, 2006; Deng et al., 2022). The cloud liquid water fraction is quantified as the ratio of LWP to (LWP+IWP). A 2-minute running average is applied to the LWP and IWP data before computing the cloud liquid fraction in order to be more comparable to SCREAM’s cloud liquid fraction which is computed using 3.5 km grid-box average LWP and IWP.

The observed cloud top height is the top height of the first hydrometeor layer above the surface based on combined radar and micropulse lidar observations as recorded in the ARM Active Remotely-Sensed Cloud Locations (ARSCL) product. The cloud top height data have a temporal resolution of 4 s. There were four radiosondes per day around 05:30,
11:30, 17:30, and 23:30 UTC during COMBLE. The vertical resolution of the temperature soundings used to estimate the cloud top temperature is 45 m. The cloud top temperature is estimated based on the observed cloud top height and 6-hourly radiosonde soundings. To minimize the uncertainty in the estimated cloud top temperature from the uncertainty in cloud top height, we only include data within a one-hour window of the radiosonde launching time and times with multi-layer clouds are excluded.

**Satellite retrievals**

MODIS, CloudSat, and CALIPSO sampled this region around 10:00-11:00 UTC (12:00 local time) during the selected observational days (Fig. S5). Besides using MODIS 250-m reflectance to demonstrate the cloud fields, we analyzed the cloud phase partitioning with CloudSat and CALIPSO level 2 pixel-level productions. The CloudSat radar reflectivity (2B-GEOPROF, Marchand, Mace, Ackerman, & Stephens, 2008) and Lidar cloud top height (2B-CLDCLASS-LIDAR, Sassen, Wang, & Liu, 2008) provide the cloud vertical structures across the three cloud regimes (Fig. 2b and Fig. S5). The CALIPSO data product is the Level-2 1-km Cloud Layer, Version 4-20 data product (https://catalog.data.gov/dataset/calipso-lidar-level-2-1-km-cloud-layer-v4-21-ec525). The cloud phase information from CALIPSO Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) (CAL-LID-L2-01kmCLay) captures the cloud phase near the cloud top. Therefore, the 1-km CALIOP cloud top temperature and phase information can be used to estimate the cloud-top phase partitioning as a function of cloud top temperature (Fig. S6a-c).
The cloud phase retrieval (2B-CLDCLASS-LIDAR) based on CloudSat cloud profiling radar and CALIPSO lidar measurements represents the cloud phase of the whole cloud layer as liquid, ice and mixed phase cloud containing a combination of ice and liquid (Sassen et al., 2008). We use the whole cloud layer phase retrieval and the collocated CALIOP cloud top temperature to estimate the whole cloud phase partitioning as a function of cloud top temperature for different cloud regimes (Fig. 5a-c).

Previous studies (e.g., Bruno et al., 2021; Marchant et al., 2020; Hong & Di Girolamo, 2020; Ahn et al., 2018) found that different cloud phase retrieval products, such as MODIS, CloudSat-CALIPSO combined product, and a merged radar-lidar product (DARDAR, Delanoë & Hogan, 2010), can have significant differences, especially in the high-latitude mixed-phase clouds. Overall, cloud phase retrievals for single cloud layers are more accurate than those for multiple cloud layers (McErlich et al., 2021).
## Table S1. ARM observations, satellite retrievals and ERA-5 reanalyses

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Figure S1. (top) Time series of MCAO index for the region of (5°E-17°E, 67°N-78°N). (bottom) Time series of the lowest-model-level U and V winds for the region of (13°E-16°E, 68°N-72°N), where is close to the ARM AMF1 site during the COMBLE field campaign.
Figure S2. Scatter plot of Pearson correlation coefficient and normalized root-mean-square error calculated for daily-mean 700hPa Geopotential Height, 500hPa Geopotential Height, sea level pressure, and 2-meter temperature between (a) SCREAMv0 Day 34 and ERA5 reanalysis for each day between 01 February and 31 March, 2020 and (b) SCREAMv0 Day 34 and all SCREAMv0 days over the COMBLE region (1°W-17°E,63°N-80°N). Crosses on (a) denotes 19, 20, 27, 28, 29 March 2020, while the black cross marks SCREAMv0 Day 34 and the white cross marks SCREAMv0 Day 33 on (b).
Figure S3. Daily-mean maps of (a) Sea-level pressure, (b) MCAO index, (c) 500-hPa Geopotential height, (d) surface latent heat flux, (e) surface sensible heat flux, (f) 700-hPa Geopotential height, and (g) 2-m temperature from ERA5 reanalysis on 28 March 2020.
Figure S4. SCREAMv0 MCAO event on Day 33: daily-mean map of (a) sea level pressure (hPa) and (b) MCAO index (K); (c) snapshot of shortwave cloud radiative effect (Wm$^{-2}$) with near surface wind at 1200UTC (12-13LST); daily-mean map of surface (d) latent heat flux (Wm$^{-2}$), and (e) sensible heat flux (Wm$^{-2}$) with near surface wind field over the COMBLE region. The location of the ARM AMF1 site is marked as a red dot on (a) and (b). The vertical cross section of daily-mean (f) cloud ice condensate (shaded, gkg$^{-1}$), cloud liquid condensate (contours, gkg$^{-1}$) within the band of green dashed lines on (b). (g) Daily-mean low-level cloud cover and cloud liquid water fraction (CLF). (h) Daily-mean IWP (orange dashed) and LWP (navy) (gm$^{-2}$) within the green dashed band in (b).
Figure S5. Similar to Fig. 3 except for additional days sharing similar large-scale conditions with SCREAMv0 Day 34, including 19, 20, 27, 29 March 2020. For each day: (Top) MODIS reflectance during MCAO events. The red-blue-red line from Greenland to Norway indicates the path of CALIOP and CloudSat measurements shown in the bottom panel. (Bottom) The vertical cloud structure across the cloud field during the MCAO event sampled by CALIOP and CloudSat. The color contour in the figure corresponds to CloudSat radar reflectivity, the yellow and solid black line correspond to the cloud top height and SST, respectively. The horizontal blue and black dots represent the CALIOP cloud top phase retrieval and the whole cloud phase retrieval, respectively. Note that they are shifted by -0.3 for clarity. The magenta dots represent the CALIOP cloud top temperature retrieval. The white crosses mark the beginning and end points of the blue track line shown on the overpass in the top plot.
Figure S6. Joint-PDFs of the CALIPO cloud top phase retrievals vs. cloud top temperature for the (a) overcast cloud regime, (b) transition regime, and (c) scattered cumulus cloud regime as shown in Fig. S5. Joint-PDFs of the SCREAMv0 cloud-top liquid water fraction calculated with $q_c/(q_l + q_c)$ at the cloud top level vs. cloud top temperature for the (d) overcast region, (e) cloud street region, and (f) scattered cumuli region as shown in Fig. 4a.
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