Evaluating simulated convective clouds during Arctic cold-air outbreaks: A model intercomparison study based on COMBLE

Timothy W. Juliano[1], Florian Tornow[2], Ann M. Fridlind[2], Andrew S. Ackerman[2], Bart Geerts[3], Branko Kosović[1], Mikhail Ovchinnikov[4], Peng Wu[4], Lulin Xue[1]

[1]National Center for Atmospheric Research (NCAR)
[2]NASA Goddard Institute for Space Studies (GISS)
[3]University of Wyoming
[4]Pacific Northwest National Laboratory (PNNL)

Correspondence: Timothy W. Juliano (tjuliano@ucar.edu)

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1. Motivation

Throughout the Arctic's winter and spring months, the large-scale meteorological forcing fosters so-called cold-air outbreaks (CAOs). During CAOs, large swaths of relatively cold air advect off an ice sheet or landform and pass over the much warmer open ocean. In response to the strong air-sea temperature contrast, some of the most intense surface heat fluxes on Earth develop (Aemisegger et al. 2018) to form a convective boundary layer (CBL). Under CAO conditions, the CBL deepens with downwind fetch, oftentimes reaching several kilometers. As can be seen in satellite imagery, intricate cloud structures accompany the CBL evolution, typically beginning as rolls near the ice edge before transitioning to cells at some distance downwind.

Despite the frequent occurrence of Arctic CAOs, many numerical weather prediction (NWP) models have difficulty representing various aspects of the mixed-phase cloud (MPC) system (e.g., Forbes and Ahlgrimm 2014; Field et al. 2017). A main NWP modeling inadequacy relates to mesoscale cloud organization. For instance, the CBL is relatively shallow (~100s of meters to ~1 kilometer) near the ice edge where roll structures are present. Due to the small atmospheric scales of motion that are relevant in this region, a large-eddy simulation (LES) approach is required to properly resolve the structure sizes whereas even relatively high-resolution mesoscale NWP simulations with horizontal grid cell spacing, Δx approaching 1 kilometer will not properly resolve roll structures (e.g., Tomassini et al. 2017). Moreover, the downwind transition from roll to cell structures occurs likely in response to multiple overlapping factors (e.g., aerosol loading, precipitation intensity, CBL depth, wind shear, and air-sea temperature contrast), with recent studies pointing to the importance of both liquid-phase precipitation and ice processes (e.g., Eirund et al. 2019; Tornow et al. 2021). Thus, morphological transitions may occur at different downwind locations depending upon a model’s representation of aerosol and cloud physics, as well as CBL dynamics.

Another important topic that remains a challenge for NWP models in the CAO regime is cloud microphysics and the connection with CBL structure and turbulence. For example, the partitioning between liquid and ice phases is a continued challenge for NWP models, in part because of the correlation between strong updrafts, intense turbulence, and liquid water production (e.g., Geerts et al. 2022). As a general rule of thumb, resolved vertical motion scales with Δx, and so when Δx is insufficiently small, strong, localized up- and downdrafts are left unsimulated. This may lead to NWPs producing an insufficient amount of liquid water in CAOs. Accurate representation of ice processes, such as primary and secondary ice formation, and the ice properties that are shaped by the process efficiencies, such as riming versus vapor growth (e.g., Morrison et al. 2020), are also profound challenges facing models. Ultimately, each of the aforementioned model inadequacies influence basic macrophysical cloud properties such as cloud fraction, liquid water path (LWP), ice water path (IWP), and precipitation rates, and therefore affect surface energy exchanges and the radiation budget.

Earth system models (ESMs) face similar challenges simulating CAO conditions at extratropical latitudes in both northern and southern hemispheres (e.g., Tselioudis et al. 2022). As for NWP, focusing on basic CAO process realism against observations as a function of atmospheric thermodynamic and aerosol states offers one pathway forward to evaluate and improve ESM physics. Efforts to identify differences in ESM physics that are most responsible for differing predicted equilibrium climate sensitivity (ECS) values have pinpointed differing shallow cloud responses to warming as a key driver of ECS range, including both warm and mixed-phase clouds such as CAOs (e.g., Zelinka et al., 2020). McCoy et al. (2020) also showed that precipitation processes at mid and high latitudes, and specifically the rate at which moisture is depleted by precipitation processes, is critical to determine extratropical cloud feedbacks, which may be the dominant determinant of the ECS spread in CMIP6 models (Zelinka et al., 2020). McCoy et al. (2020) and Mülmenstädt et al. (2020) advocate testing the parameterization of mixed-phase and aerosol-modulated processes impacting precipitation as a key avenue for reducing uncertainty in predicted extratropical shortwave cloud feedbacks and ECS. Owing to the knowledge gaps remaining in basic physical processes, such as primary and secondary ice formation as one prominent example (cf. Morrison et al., 2020), a strong observational foundation is needed to focus on process realism.

During the Arctic winter and spring of 2019-2020, the Cold-Air Outbreaks in the Marine Boundary Layer Experiment (COMBLE; Geerts et al. 2022) deployed the U.S. DOE

Atmospheric Radiation Measurement (ARM) Mobile Facility (AMF) #1 at a coastal site in Andenes, Norway (70°N) in addition to instruments on Bear Island (75°N). These two locations around the Norwegian Sea collected data from 1 Dec 2019 through 31 May 2020, with a main goal to measure the spatiotemporal evolution of convective MPC structures, including mesoscale organization, LWP and IWP, and turbulence properties. The campaign was largely successful: nearly 20% of campaign hours experienced CAO conditions at Andenes, Norway, including several strong events. While a wide range of CAO intensities was observed during COMBLE, here we propose to focus on the 13 March 2020 case due to the distinct cloud structures, alignment of air mass trajectories between Andenes (Wu and Ovchinnikov 2019) and upwind aerosol measurements at Svalbard, and broad data availability. With respect to the clouds, both convective roll and cell structures were observed, with a gradual transition in morphology occurring in the alongwind (north to south) direction. These cloud structures were also relatively long-lived, as they persisted over the course of approximately two days.

2. A potential GASS project

This white paper proposes a potential GASS project focused on evaluating the capability of LES and ESM single column model (SCM) simulations to reproduce the Lagrangian evolution (see Section 2.2) of Arctic convective MPC features under CAO conditions. Model domains will follow the CBL along the ~1000 km distance from cloud-free conditions at sea ice edge to the Adenes site at the coast of Norway. The overall goals are to understand fundamental CBL and cloud properties, as well as explore which factors control mesoscale cloud organization and macrophysical cloud properties in simulations under the observed conditions.

We propose to examine these topics using a two-pronged approach. First, we aim to examine how well different LES (and similarly SCM) frameworks agree with one another and with observations using a simplified aerosol treatment (i.e., diagnosed cloud droplet number and ice number concentrations). This task will set a baseline to understand the spread in LES and SCM models during intense CAO conditions when using a Lagrangian approach, including optional sensitivity tests to probe model responses to a reasonably large spread in thermodynamic forcing factors such as horizontal wind speed, initial atmospheric stability, and sea surface temperature. The second part of the study will introduce an observational-based aerosol specification suitable for predicting droplet number concentration and primary ice formation, and will include optional sensitivity tests to probe model response to prognostic versus diagnostic aerosol treatments, perturbations to the aerosol specification, and liquid precipitation or ice microphysical processes including secondary ice production. Aerosol initial and boundary conditions will be informed by analysis of upwind aerosol measurements obtained at the Zeppelin station on Svalbard, aerosol and ice nucleating particle measurements at Adenes, and two aerosol reanalyses. This two-pronged activity will elucidate physical relationships between model forcing or physics options and the resultant cloud structures and properties within a Lagrangian framework. In addition to evaluating models against observations, the consistency (or lack thereof) in response to these sensitivities between models will be examined.

2.1 Potential research themes

There is a wide breadth of potential research themes associated with the CAO regime and its representation in models, including those listed below. It is anticipated that discussions with participants will shape the highest priorities for focus areas and sensitivity tests.

a) Mesoscale cloud organization
    i) Widening/broadening of convective roll/cell structures
    ii) Transition from convective rolls to cells
    iii) Evolution from closed to open cells
    iv) Impact on cloud fraction, albedo, and radiative fluxes
b) Boundary layer structure and turbulence
    i) First-order characteristics: CBL depth/growth rate, cloud-top temperature, LWP/IWP partitioning
    ii) Linking dynamics/turbulence to condensate production
    iii) Relative importance of surface forcing vs. cloud top cooling as the system evolves (do we see surface decoupling during cellular regime?)
c) Model sensitivities
    i) Initial and boundary conditions and forcings
        1) Initial stability and wind speed profile
        2) Momentum, heat, and moisture roughness length formulations
        3) Sea surface temperature
        4) Marginal ice zone
    ii) Aerosol-cloud interactions
        1) Prognostic aerosol treatment for droplet and ice formation
        2) Sea spray
        3) Secondary ice production
        4) Liquid and ice precipitation processes

2.2 General modeling approach

Most Arctic cloud intercomparison studies have relied on an Eulerian approach to elucidate model spread as well as important physical relationships linking aerosols, clouds, and turbulence, and most have been focused only on LES models (e.g., Fridlind and Ackerman, 2018). As this is the first model intercomparison study based on COMBLE observations, we propose to solicit community interest using Lagrangian LES and SCM frameworks, motivated by the added value of the Lagrangian approach for studying Arctic air mass transformations (e.g., Pithan et al., 2018) and the SCM "fingerprint" of parent ESM physics performance as a model evaluation and development tool (Neggers, 2015).

The Lagrangian approach is motivated by the fact that CAOs are characterized by strong boundary layer wind speeds (commonly 10-30 m/s). As a result, air masses may cover distances of *O*(1000 km) over the course of a day or so. To capture the evolution of a swiftly drifting CAO air mass and remain computationally efficient, simulations will represent a Lagrangian domain of *O*(10-100 km), intended to be large enough to yield results that are relatively insensitive to increasing domain size and to be representative of a typical climate model grid cell.

Whereas the de Roode et al. (2019) CAO intercomparison focused on the complexities of representing mesoscale structure through the gray zone, here we propose to focus on the role of aerosol and cloud microphysical processes in evolving mesoscale cloud structure in well-resolved LES. Moreover, we aim to understand the capability of today's SCMs, with operational physics packages, to reproduce basic cloud system properties and radiative fluxes. This would be the first CAO model intercomparison since Klein et al. (2009) to include both LES and SCM models, and the first to include a modal aerosol specification suitable as a basis for predicting both droplet and ice formation as in ESMs. It is expected that future modeling exercises drawing on COMBLE data could also utilize additional modeling frameworks (e.g., cloud permitting models and general circulation models) to explore other salient questions about the Arctic cloud environment, and we expect that there may be an opportunity to perform a similar intercomparison in the future while focusing on COMBLE.

2.3 Model evaluation approach

We propose to perform a range of observation-model evaluations that will take place as part of a model intercomparison exercise for the 13 March 2020 COMBLE CAO case. We plan that the ARM user facility will act as a centralized body to host LES and SCM specification files, as well as model outputs from intercomparison participants in an effort to simplify the evaluation process. In this context, we have been in communication with ARM program managers, who have expressed interest in supporting the proposed research activities. To this end, we have submitted a computational request for use of the ARM Cumulus cluster, which will provide computational power for forward simulation from model outputs and allow for a relatively straightforward interrogation of the ARM observations to better understand LES/SCM representation of Arctic MPCs observed during COMBLE. Moreover, we hope that such an effort will entice a wide range of researchers – and thus modeling platforms – to engage with ARM data sets. It is hoped that use of ARM resources to archive LES/SCM model results, alongside constraining observations and scripts used to compare simulations with observations, will also serve as the most efficient transition to a lasting archive for future model users and developers. To the extent that this workflow serves as a successful intercomparison strategy, it may serve as a blueprint for others to follow in the future.

For the intercomparison study, we will use ARM data from the COMBLE field project. Specifically, we will use radiosonde and surface met data in addition to radar and lidar measurements for comparison with forward-simulated quantities from model outputs using the EMC^2 package for LES and SCM (Silber et al. 2022) and CR-SIM (Oue et al. 2020). We will also utilize retrievals of cloud boundaries, water contents, precipitation rates, and turbulence quantities; LWP and IWP time series; surface cloud condensation nuclei (CCN) and ice nucleating particle (INP) measurements (in collaboration with relevant mentors and PIs). Sounding measurements from Ny-Alesund will be used to examine conditions upwind of Andenes, and reanalysis data will be used for the Lagrangian trajectory calculations, which will provide estimates of the atmospheric state along estimated trajectories. Both upwind (Svalbard) and downwind (Andenes) aerosol analyses, used to inform the LES/SCM model setup, are being led by University of California, San Diego and Colorado State University.

Several research groups have already conducted COMBLE observational analyses, including the University of Wyoming and the State University of New York at Stony Brook (SBU). Collectively, these two groups have looked at a mix of raw data and retrievals, with particular interest in reflectivity, Doppler velocity, and ice water content from the Ka-band ARM Zenith Radar (KAZR), LWP from the microwave radiometer (MWR), and cloud base height from the ceilometer. SBU has performed two different retrievals on the KAZR data: one for vertical air motion and one for eddy dissipation rate (EDR), and they've analyzed updraft structures (both strength and size), hydrometeor fraction, LWP distributions and its relationship with the updrafts, and EDR with respect to height. The work by SBU is to be submitted to *Atmos. Chem. Phys.* by the end of July.

Collocated satellite measurements will be used for evaluation earlier in the simulation before the Lagrangian domain reaches Andenes to provide regional context. Using such data will enable a more complete picture of the model performance. For instance, we want to ensure that any model results that agree with the observations further downstream at Andenes (approximately 18 hours after the simulation start time) occur for the correct reasons and that the good agreement did not happen by chance. We have already identified all available satellite overpasses covering our region of interest. Retrievals are available from MODIS Aqua and Terra (1 km resolution), in addition to VIIRS [NOAA-20 (JPSS-1) and SUOMI-NPP; 750 m resolution] at several times during the cloud evolution. Thus, we propose to compare model output to satellite using a "snapshot in time" approach, as well as a potential time series approach using domain-averaged quantities.

Satellite measurements, including cloud top height and temperature, cloud water path (CWP), optical thickness, effective radius, and phase, will complement the comprehensive observations available downwind at Andenes. In general, we acknowledge that satellite retrievals in MPC conditions are challenging, and as a result we are currently assessing which of the aforementioned cloud properties are most appropriate to use for the model intercomparison. Nonetheless, PNNL has already analyzed MODIS measurements during COMBLE CAOs. For instance, cloud size distributions have been obtained from visible channel reflectance images using an object segmentation method (Wu and Ovchinnikov, 2022). The roll-to-cell transition region is identified from the homogeneity of MODIS retrieved CWP. The co-evolution of cloud morphology and environment is also investigated using MODIS observations and ERA5 meteorology. Roll breakup is found to be accompanied by a local minimum in wind shear and local maxima in cloud size and marine CAO index. The mean cloud horizontal aspect ratio has weak fetch dependency and is around 2 in roll, transition, and cell regimes. Further investigation into extraction of LWP from satellite retrievals will be led by NASA GISS. We anticipate that the statistical results can be used to evaluate cloud morphologies and their relationships with environmental parameters in models.

2.4 Expected results

Here we very briefly offer a few topical predictions about expected model skill based on previous studies, without delving into what cannot be known without actually conducting the intercomparison and observational evaluation (e.g., re connections between physical process research and model physics development/evaluation efforts).

First, we expect that ice-free LES simulations could be largely in line with one another in terms of mixed-layer depth and LWP as in de Roode et al. (2019). Such agreement could be somewhat degraded relative to that study, though, if surface flux parameters are not specified. Since this exercise is intended as a broad test of both LES and SCM models, it is valuable to test surface flux schemes, but a sensitivity test could be made with specified fluxes such as used in the Klein et al. (2009) specification for LES and SCMs. Even if LWP is in relatively good agreement, however, we expect that both initial roll features and fully developed cellular convection could be substantially different across LES results; evaluation methods devised to measure agreement with observations will be well suited to establish such morphological differences across LES also for (unrealistic) liquid-only simulations.

Second, even for liquid-only simulations, we expect that SCMs will produce diverse behavior as in Klein et al. (2009). Since preliminary LES of this case study are not strongly sensitive to cloud top cooling, we expect that will primarily be an indication of stratiform, convective, and unified turbulence scheme performance, which is likely relevant to parent ESM performance in the CAO regime. Comparing SCMs to multiple LES could offer a stronger benchmark for SCM development than single-LES approaches that most ESM groups use, especially where mesoscale features could be sensitive to precipitation processes and subgrid scale schemes, etc.

Third, we expect that including ice will introduce significant divergence across both LES and SCMs owing to severe uncertainties in how to represent both ice processes and properties. Rather than avoiding a model intercomparison for lack of understanding, it is intended that this observation-constrained case can offer some degree of benchmark for model performance in the face of such uncertainties. While acknowledging that it is not likely that this work can resolve process-level and modeling scheme approach uncertainties in secondary ice formation, for instance, it can offer some guidance on the relative importance of such uncertainties to agreement with basic observational constraints such as LWP and albedo.

Finally, we expect that constraining models will be a formidable challenge from the observational perspective. Establishing reliable uncertainties in ground-based and satellite remote sensing products under unique CAO conditions will be important yet challenging.

3. Timelines, participants, and publication plan

This white paper covers several topics specific to mesoscale organization and macrophysics properties of convectic Arctic CAO clouds observed during COMBLE. We anticipate that these observation-model intercomparison efforts will span multiple years since there are different sub-topics of interest involving multiple research groups. To start, we propose an initial intercomparison study focused on one or two research themes selected from those outlined above. This study is expected to take approximately one year with model forcing information provided to participating groups by the leading research groups (see Section 6). Considerable coordination has already taken place between observationalists and modelers across several groups to narrow the research scope by scrutinizing the best CAO cases from COMBLE, evaluating available observations, and conducting preliminary LES. Nonetheless, we continue to advance the study foci, and detailed timelines will be determined through future iterations among participating groups. Any interested observational or modeling groups are welcome to participate in the study by contributing observational data, model results, and/or analyses.

We anticipate that results will be summarized in at least two papers in peer-reviewed journals. Submitted model results will also be made available on a rolling basis with permission from submitting groups for follow-on studies to help motivate more extensive observational analyses and modeling approaches. Inspired by previous Pan-GASS efforts, we plan to have a meeting at an upcoming conference/meeting where most participants would be available to discuss a more detailed plan and some preliminary results. The targeted conferences/meetings could be the upcoming ARM/ASR PI, AMS, AGU, EGU, or GEWEX/GASS sponsored meetings. This will be further discussed among the groups who are interested in participating in the project.

4. Coordination with other projects

The model intercomparison efforts conducted up until the writing of this document have spawned as a result of collaboration between national laboratory and academic researchers working on Arctic cloud projects funded by DOE and NASA. There have been coordinated efforts between both observationalists and modelers to ensure a robust model evaluation process.

Looking further ahead, we anticipate coordinating activities with the 19th International Commission on Clouds and Precipitation (ICCP) Conference, to be held in Jeju, South Korea in 2024, as well as the next International Cloud Modeling Workshop (ICMW). A recent summary of the 10th ICMW may be found in Xue et al. (2022). It is our hope that the COMBLE intercomparison case outlined in this proposal may be further explored during these international collaborations.

5. Potential participants and institutes

Contributors who have already expressed an interest in providing observational products, conducting numerical simulations, and/or guiding analyses are listed in this section. There will be room for any number of additional such participants with observational, modeling, or analysis expertise via the open source and community code approach on the ARM computing cluster.

5.1 Observational groups

1. University of Wyoming (lead: Bart Geerts; confirmed)

2. Pennsylvania State University (lead: Israel Silber; confirmed)
3. SBU (lead: Pavlos Kollias; confirmed)
4. University of California, San Diego (lead: Lynn Russell; confirmed)
5. Colorado State University (lead: Paul DeMott; confirmed)
6. PNNL (lead: Mikhail Ovchinnikov; confirmed)
7. NASA GISS (lead: Greg Elsaesser; confirmed)
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5.2 LES/SCM models and groups

1. WRF (NCAR; confirmed)
2. CCPP-SCM (NCAR; confirmed)
3. SAM (PNNL; confirmed)
4. DHARMA (NASA GISS; confirmed)
5. GISS ModelE (NASA GISS; confirmed)
6. DALES (University of Cologne/TU Delft; confirmed)
7. AOSCM (Stockholm University/Chalmers Technical University; confirmed)
8. MIMICA (Stockholm University/Chalmers Technical University; confirmed)
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6. Leadership

Organizers: Timothy W. Juliano (NCAR; tjuliano@ucar.edu), Florian Tornow (NASA GISS; florian.tornow@nasa.gov), and Ann Fridlind (NASA GISS; ann.fridlind@nasa.gov)

7. References

Aemisegger, F. and L. Papritz, 2018: A Climatology of Strong Large-Scale Ocean Evaporation Events. Part I: Identification, Global Distribution, and Associated Climate Conditions. J. Climate, 31, 7287–7312, doi:10.1175/JCLI-D-17-0591.1.

de Roode, S.R., et al., 2019: Turbulent transport in the gray zone: A large eddy model intercomparison study of the CONSTRAIN cold air outbreak case. Journal of Advances in Modeling Earth Systems, 11. doi:10.1029/2018MS001443.

Eirund, G. K., Lohmann, U., and Possner, A., 2019: Cloud ice processes enhance spatial scales of organization in Arctic stratocumulus. Geophysical Research Letters, 46(23), 14109-14117.

Field, P. R., et al., 2017: Exploring the convective grey zone with regional simulations of a cold air outbreak. Quarterly Journal of the Royal Meteorological Society, 143.707, 2537-2555.

Forbes, R. M. and M. Ahlgrimm, 2014: On the Representation of High-Latitude Boundary Layer Mixed-Phase Cloud in the ECMWF Global Model, Monthly Weather Review, 142(9), 3425-3445.

Fridlind, A. M., and A. S. Ackerman, 2018: Simulations of Arctic Mixed-Phase Boundary Layer Clouds: Advances in Understanding and Outstanding Questions. In Mixed Phase Clouds, Ed. C. Andronache, 153-183. doi:10.1016/B978-0-12-810549-8.00007-6.

Geerts, B., et al., 2022: The COMBLE Campaign: A Study of Marine Boundary Layer Clouds in Arctic Cold-Air Outbreaks. Bulletin of the American Meteorological Society, 103(5), E1371-E1389.

Klein, S.A., et al., 2009: Intercomparison of model simulations of mixed-phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment. I: single-layer cloud. Quart. J. R. Meteorol. Soc, 135, 979–1002, doi:10.1002/qj.416.

McCoy, D.T., P. Field, A. Bodas-Salcedo, G.S. Elsaesser, and M.D. Zelinka, 2020: A regime-oriented approach to observationally constraining extratropical shortwave cloud feedbacks, J. Clim., 33, 9967–9983.

Morrison, H., et al., 2020: Confronting the challenge of modeling cloud and precipitation microphysics. J. Adv. Model. Earth Syst., 12, no. 8, e2019MS001689, doi:10.1029/2019MS001689.

Mülmenstädt, J., et al., 2020: Reducing the aerosol forcing uncertainty using observational constraints on warm rain processes. Sci. Adv. 6, doi: 10.1126/sciadv.aaz6433.

Neggers, R. A. J. (2015), Attributing the behavior of low-level clouds in large-scale models to subgrid-scale parameterizations, J. Adv. Model. Earth Syst., 7, doi:10.1002/2015MS000503.

Oue, M., Tatarevic, A., Kollias, P., Wang, D., Yu, K., and Vogelmann, A. M.: The Cloud-resolving model Radar SIMulator (CR-SIM) Version 3.3: description and applications of a virtual observatory, Geosci. Model Dev., 13, 1975–1998, https://doi.org/10.5194/gmd-13-1975-2020, 2020.

Pithan, F., Svensson, G., Caballero, R., Chechin, D., Cronin, T.W., Ekman, A.M., Neggers, R., Shupe, M.D., Solomon, A., Tjernström, M. and Wendisch, M., 2018: Role of air-mass transformations in exchange between the Arctic and mid-latitudes, Nature Geosci., 11, 805–812.

Silber, I., R.C. Jackson, A.M. Fridlind, A.S. Ackerman, S. Collis, J. Verlinde, and J. Ding, 2022: The Earth Model Column Collaboratory (EMC2) v1.1: An open-source ground-based lidar and radar instrument simulator and subcolumn generator for large-scale models. Geosci. Model Dev., 15, no. 2, 901-927, doi:10.5194/gmd-15-901-2022.

Tomassini, L., et al., 2017: The “Grey Zone” cold air outbreak global model intercomparison: A cross evaluation using large‐eddy simulations. Journal of Advances in Modeling Earth Systems, 9(1), 39-64.

Tornow, F., A. S. Ackerman, and A. M. Fridlind, 2021: Preconditioning of overcast-to-broken cloud transitions by riming in marine cold air outbreaks. Atmospheric Chemistry and Physics, 21(15), 12049-12067.

Tselioudis, G., et al., 2021: Evaluation of clouds, radiation, and precipitation in CMIP6 models using global weather states derived from ISCCP-H cloud property data. Journal of Climate, 34(17), 7311-7324.

Wu, P. and M. Ovchinnikov, 2019: Air mass back trajectories during cold-air outbreaks (CAOs) at Andenes and Bear Island, Norway. United States. doi: 10.5439/1843763.

Wu, P., and M. Ovchinnikov, 2022: Cloud Morphology Evolution in Arctic Cold-Air Outbreak: Two Cases During COMBLE Period. Journal of Geophysical Research: Atmospheres 127, e2021JD035966, doi:10.1029/2021JD035966.

Xue, L., et al., 2022: Progress and Challenges in Modeling Dynamics–Microphysics Interactions: From the Pi Chamber to Monsoon Convection, Bulletin of the American Meteorological Society, 103(5), E1413-E1420.

Zelinka, M.D., Myers, T.A., McCoy, D.T., Po‐Chedley, S., Caldwell, P.M., Ceppi, P., Klein, S.A. and Taylor, K.E., 2020: Causes of higher climate sensitivity in CMIP6 models. Geophysical Research Letters, 47, e2019GL085782, doi:10.1029/2019GL085782.