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Aerosol-Cloud Interactions and the Intersection of Climate Forcing and Feedback

December 2025

Andrew Gettelman

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Abstract

The goal of this project has been to understand at the process level how the interaction of aerosols and cloud microphysics may alter the cloud response to climate change from the scale of turbulence to the global scale. Atmospheric aerosols (suspended particulates) have a unique role to play in the climate system. Anthropogenic aerosols may be an air pollution hazard and degrade human health. Their presence also results in the direct scattering or absorption of sunlight, with small net impacts on climate. But aerosols are also a key part of cloud formation, as the locations on which cloud droplets and ice crystals form. Understanding these Aerosol Cloud Interactions (ACI) is a critical uncertainty for climate models, including the Energy Exascale Earth System Model (E3SM), and affects how well models like E3SM can simulate the past and future. This work aims to understand cloud microphysics as well as the interaction of aerosol forcing and cloud feedback through improving our understanding of aerosol-cloud interactions (ACI) by looking at their uncertainty in critical environments at the process level. It will also contribute to the development of E3SM. Specific goals include: first, high level analysis of Perturbed Parameter Ensemble (PPE) simulations already available from the Community Earth System Model (CESM) and E3SM. Second, detailed analysis of recent changes to temperature and the role of aerosols.

Summary

Atmospheric aerosols (suspended particulates) have a unique role to play in the climate system. Aerosols are a key part of cloud formation, as the locations on which cloud droplets and ice crystals form. Anthropogenic increases in aerosols likely have increased cloud drop numbers, resulting in brighter clouds and longer lived and/or thicker clouds, cooling the climate system. But the magnitude of these Aerosol Cloud Interaction (ACI) affects is highly uncertain. Understanding the magnitude of ACI is a critical uncertainty for climate models, including the Energy Exascale Earth System Model (E3SM), and affects how well models like E3SM can simulate the past and future. In addition, the response of clouds to warming, called the cloud 'feedback' is the largest uncertainty in understanding the future evolution of climate change. This work will focus on understanding the interaction between aerosol forcing and cloud feedback, as well as then focusing on key process interactions that may control ACI. It will do so by analyzing existing model sensitivity experiments. Guided by these experiments, more targeted experiments to look at ACI processes will be conducted using high resolution models and contribute to development of those models, within E3SM and the community: representing DOE and E3SM at high level meetings on advanced modeling. Based on previous work, this proposal will focus particularly at high latitudes of both hemispheres using DOE collected data in cold cloud environments, which are particularly important for understanding forcing and feedback. The Southern Ocean is a nearly pristine and pre-industrial like environment, and is critical for understanding cloud feedbacks, while the Arctic is also undergoing some of the most rapid climate changes on the planet.

Acknowledgments

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Acronyms and Abbreviations

ACI	Aerosol Cloud Interactions
CCN	Cloud Condensation Nuclei
CERES	Clouds in the Earth Radiant Energy System
CESM	Community Earth System Model
CMIP	Coupled Model Intercomparison Project
DGW	Damped Gravity Wave
DOE	Department of Energy
E3SM	Energy Exascale Earth System Model
ECCO	Estimating the Circulation and Climate of the Ocean
ECMWF	European Center for Medium Range Weather Forecasts
ECS	Equilibrium Climate Sensitivity
ERF	Effective Radiative Forcing
GASS	Global Atmospheric System Studies
GCM	General Circulation Model
GMST	Global Mean Surface Temperature
GrIS	Greenland Ice Sheet
GWA	Global Warming per Activity
HEALPix	Hierarchical Equal Area isoLatitude Pixelation
IFS	Integrated Forecast System
IN	Ice Nuclei
JSC	Joint Scientific Committee
LWP	Liquid Water Path
MAC	Multi-sensor Advanced Climatology
MICRE	Macquarie Island Cloud and Radiation Experiment
MIT	Massachusetts Institute of Technology
MPAS	Model for Prediction Across Scales
PPE	Perturbed Parameter Ensemble
RF	Radiative Forcing
SCAM	Single Column Atmosphere Model
SIMA	System for Integrated Modeling of the Atmosphere
SO	Southern Ocean
SWFB	Shortwave Feedback
TCR	Transient Climate Response
UM	Unified Model
VR	Variable Resolution
WCRP	World Climate Research Program
WRF	Weather Research and Forecast
WTG	Weak Temperature Gradient

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1.0 Introduction

The goal of this project has been to understand at the process level how the interaction of aerosols and cloud microphysics may alter the cloud response to climate change from the scale of turbulence to the global scale.

Atmospheric aerosols (suspended particulates) have a unique role to play in the climate system. Anthropogenic aerosols may be an air pollution hazard and degrade human health. Their presence also results in the direct scattering or absorption of sunlight, with small net impacts on climate. But aerosols are also a key part of cloud formation, as the locations on which cloud droplets and ice crystals form. Anthropogenic increases in aerosols likely have increased cloud drop numbers, resulting in brighter clouds (Twomey, 1977) and longer lived and/or thicker clouds (Albrecht 1989). These Aerosol Cloud Interactions (ACI) effects are both cooling effects on the climate system, but are highly uncertain (Bellouin et al 2020). Understanding the magnitude of aerosol-cloud interactions is a critical uncertainty for climate models, including the Energy Exascale Earth System Model (E3SM), and affects how well models like E3SM can simulate the past and future (e.g. Ma et al 2022). In addition, the response of clouds to warming, called the cloud 'feedback' is the largest uncertainty in understanding the future evolution of climate change. This is because the effect of clouds on the current climate system (-20 Wm^{-2}) is 5 times the radiative effect of doubling carbon dioxide ($+4 \text{ Wm}^{-2}$), so small changes to clouds may significantly amplify or damp warming. Aerosols have been implicated in altering cloud feedbacks (Gettelman et al 2016), recently through changes to the ice nucleation process and ice phase (Gettelman et al 2019).

Much of the focus of understanding ACI has been focused on understanding the warm rain formation process and how it is represented in the bulk cloud microphysics schemes (e.g. Gettelman 2015, Ghan et al 2016). Theories have also been advanced that aerosol-cloud interactions are 'buffered' by turbulence (Stevens and Feingold, 2009; Ackerman et al 2000), and models seem to generally indicate very strong 'adjustments' to aerosols that may not be consistent with observations (Bellouin et al 2020). Bulk treatments of this buffering effect do not show much impact on ACI (Karset et al 2020). Recent work indicates that even a much more detailed treatment of rain formation derived from bin microphysics schemes does not alter aerosol-cloud interactions very much (Gettelman et al 2021). If this is the case, then perhaps the answer lies in representing turbulence more correctly in large scale models to try to address this uncertainty. It may also be that the sensitivity lies in cold clouds. Gettelman et al (2019) illustrated how the treatment of supercooled liquid may be important for cloud feedback in CESM2, following on earlier work from Tan et al (2016). Tan et al (2019) also highlighted the importance of these processes to Arctic climate change.

This work aims to understand cloud microphysics as well as the interaction of aerosol forcing and cloud feedback through improving our understanding of aerosol-cloud interactions (ACI) by looking at their uncertainty in critical environments at the process level. It will also contribute to the development of E3SM. Specific goals include: first, high level analysis of Perturbed Parameter Ensemble (PPE) simulations already available from the Community Earth System Model (CESM) and E3SM to examine cloud forcing and feedback. Second, a detailed look into non-CO2 climate impacts of aviation, mostly through contrails. Third, detailed analysis of recent changes to temperature and the role of aerosols. Finally, continued development of high-resolution global modeling in support of the Digital Earth Lighthouse Activity of the World Climate Research Program (WCRP).

2.0 Forcing and Feedback

Process studies with ACI included single column modeling work contributions in Cohen et al (2024). A single column model with parameterized large-scale (LS) dynamics was used to better understand the response of steady-state tropical precipitation to relative sea surface temperature under various representations of radiation, convection, and circulation. The large-scale dynamics are parameterized via the weak temperature gradient (WTG), damped gravity wave (DGW), and spectral weak temperature gradient (Spectral WTG) method in NCAR's Single Column Atmosphere Model (SCAM6). Radiative cooling is either specified or interactive, and the convective parameterization is run using two different values of a parameter that controls the degree of convective inhibition. Results are interpreted in the context of the Global Atmospheric System Studies -Weak Temperature Gradient (GASS-WTG) Intercomparison project. Using the same parameter settings and simulation configuration as in the GASS-WTG Intercomparison project, SCAM6 under the WTG and DGW methods produces erratic results, suggestive of numerical instability. However, when key parameters are changed to weaken the large-scale circulation's damping of tropospheric temperature variations, SCAM6 performs comparably to single column models in the GASS-WTG Intercomparison project. The Spectral WTG method is less sensitive to changes in convection and radiation than are the other two methods, performing qualitatively similarly across all configurations considered. Under all three methods, circulation strength, represented in 1D by grid-scale vertical velocity, is decreased when barriers to convection are reduced. This effect is most extreme under specified radiative cooling, and is shown to come from increased static stability in the column's reference radiative-convective equilibrium profile. This argument can be extended to interactive radiation cases as well, though perhaps less conclusively.

Also, a significant effort was more single column work on cloud microphysics in Gettelman et al 2024. Supercooled liquid clouds are common at higher latitudes (especially over the Southern Ocean) and are critical for constraining climate projections. We take advantage of the Macquarie Island Cloud and Radiation Experiment (MICRE) to perform an analysis of observed and simulated cloud processes over the Southern Ocean in a region and season dominated by supercooled liquid clouds. Using a single-column version of the European Centre for Medium Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS), we compare two different cloud microphysical schemes to ground-based observations of cloud, precipitation, and radiation over a 2.5-month period (1 January– 17 March 2017). Both schemes are able to reproduce aspects of the cloud and radiation observations during MICRE to within the uncertainty of the data when the thermodynamic profile is prescribed with relaxation. There are differences in water mass and representation of reflectivity between the schemes. A sensitivity study of the cloud microphysics schemes, one a bulk one-moment scheme and the other a two-moment scheme with prediction of mass and number, indicates that several key processes create differences between the schemes. Surface radiative fluxes and total water path are highly sensitive to the formation and fall speed of precipitation. The prediction of hydrometeor number with the two-moment scheme yields a better comparison with observed reflectivity and radiative fluxes, despite predicting higher liquid water contents than observed. With the two-moment scheme, we are also able to test the sensitivity of the results to the input of liquid cloud condensation nuclei (CCN) and ice nuclei (IN). The cloud properties and resulting radiative effects are found to be sensitive to the CCN and IN concentrations. More CCN and IN increase liquid and ice water paths, respectively. Thus, both the dynamic environment and aerosols, integrated through the cloud microphysics, are important for properly representing Southern Ocean cloud radiative effects.

Several other papers focused specifically on Forcing and Feedback. Gettelman et al 2024b used a Perturbed Parameter Ensemble (PPE) with the Community Atmosphere Model version 6 (CAM6) to better understand the sensitivity of aerosol forcing and cloud feedbacks to changes in model processes. Aerosol forcing through aerosol-cloud interactions is mostly negative (a cooling) due to shortwave radiation, while feedbacks are positive or negative in different regions due to contrasting longwave and shortwave effects. Both forcing and feedbacks are related to the mean climate state. Higher magnitude cloud radiative effects generally mean larger magnitude net negative forcing and larger magnitude net positive feedback. Aerosol forcing is broadly related to the susceptibility of clouds to drop number. Feedbacks also related to susceptibility, but to a lesser extent and in different regions to aerosol forcing. Aerosol forcing and cloud feedbacks are anti-correlated in the CAM6 PPE such that stronger negative forcing is associated with stronger positive feedbacks. Even the processes governing forcing and feedback sensitivity in the PPE are similar. These include the warm rain formation process, ice loss processes and deep convective intensity.

2.1 Aerosol Forcing

Continuing the work on aerosol forcing, Song et al (2024) looked at the Effective Radiative Forcing (ERF) due to warm clouds. Aerosol-cloud interactions (ACI) in warm clouds are the primary source of uncertainty in ERF during the historical period and, by extension, inferred climate sensitivity. The ERF due to ACI (ERF_{aci}) is composed of the radiative forcing due to changes in cloud microphysics and cloud adjustments to microphysics. Here, we examine the processes that drive ERF_{aci} using a perturbed parameter ensemble (PPE) hosted in CAM6. Observational constraints on the PPE result in substantial constraints in the response of cloud microphysics and macrophysics to anthropogenic aerosol, but only minimal constraint on ERF_{aci}. Examination of cloud and radiation processes in the PPE reveal buffering of ERF_{aci} by the interaction of precipitation efficiency and radiative susceptibility.

Zhou et al (2025) presented for the first time within the cloud physics context, the application of wavelet phase coherence analysis to disentangle counteracting physical processes associated with the lead-lag phase difference between cloud-proxy liquid water path (LWP) and aerosol-proxy cloud droplet number concentration (Nd) in an Eulerian framework using satellite-based observations and climate model outputs. This approach allows us to identify the causality and dominant adjustment timescales governing the correlation between LWP and Nd. Satellite observations indicate a more prevalent positive correlation between daytime LWP and Nd regardless of whether LWP leads or lags Nd. The positive cloud water response, associated with precipitation processes, typically occurs within 1 hr, while the negative response resulting from entrainment drying, usually takes 2–4 hr. CAM6 displays excessively rapid negative responses along with overly strong negative cloud water response and insufficient positive response, leading to a more negative correlation between LWP and Nd compared to observations.

In addition, Gettelman and Kahn (2025) argued in a perspective piece that aerosols, as part of the forcing of the earth system, are critical for understanding the current and near term evolution of extreme events.

2.2 Cloud Feedback

Duffy et al (2025) analyzed why the Community Earth System Model version 2 (CESM2) has a higher equilibrium climate sensitivity (ECS) than previous versions of CESM and many other

Coupled Model Intercomparison Project (CMIP) models. Relatedly, CESM2 simulates too-cold ice-age and too-hot warm paleoclimates. An inappropriate ice number limiter in the CESM2 microphysics scheme was discovered, and some simulations indicate that the high ECS may be partially attributable to this inappropriate limiter. In light of those findings, we seek to provide users of CESM2 guidance on the fitness of CESM2 for a variety of applications. We find that despite concerns about its climate sensitivity and simulations of past climates, the transient climate response (TCR) in CESM2 is moderate relative to the CMIP6 ensemble and robust across different versions of CESM. The changes made between CESM1 and CESM2 and the fixes to the microphysical issues of CESM2 have little impact on its simulated 20th and 21st century climates under SSP3-7.0. As a result, the simulated 20th and 21st century climates of CESM2 fall well within the range of the CMIP6 ensemble and agree well with observations over the historical record. However, hotter and colder paleoclimates simulated by CESM2 are inconsistent with paleoclimate evidence. A modified version of CESM2, PaleoCalibr CESM2, may be suitable for paleoclimate studies. Simulations past the end of the 21st century with default CESM2 and studies of microphysical processes in all GCMs should be analyzed with care.

Raghuraman et al (2024) took a different approach to look at the response of clouds to surface warming. The response of tropical high clouds to surface warming and their radiative feedbacks are uncertain. For example, it is uncertain whether their coverage will contract or expand in response to surface warming and whether such changes entail a stabilizing radiative feedback (iris feedback) or a neutral feedback. Global satellite observations with passive and active remote sensing capabilities over the last two decades can now be used to address such effects that were previously observationally limited. Using these observations, we show that the vertically averaged coverage exhibits no significant contraction or expansion. However, we find a reduction in coverage at the altitude where high clouds peak and are particularly radiatively-relevant. This results in a negative longwave (LW) feedback and a positive shortwave (SW) feedback which cancel to yield a near-zero high-cloud amount feedback, providing observational evidence against an iris feedback. Next, we find that tropical high clouds have risen but have also warmed, leading to a positive, but small, high-cloud altitude feedback dominated by the LW feedback. Finally, we find that high clouds have been thinning, leading to a near-zero high-cloud optical depth feedback from a cancellation between negative LW and positive SW feedbacks. Overall, high clouds lead the total tropical cloud feedback to be small due to the negative LW-positive SW feedback cancellations.

Focusing on extratropical cloud feedback, Werapitiya et al 2025 examined whether observations could help constrain cloud feedback. Constraining cloud feedback in global climate models (GCMs) using observations is important for establishing accurate predictions of future climate. Uncertainty in shortwave cloud feedback (SWFB) dominates uncertainty in total cloud feedback. Recent studies show a shift toward more positive extratropical SWFB in the latest generations of GCMs leading to the emergence of very high equilibrium climate sensitivity (ECS). In this study, we use precipitation efficiency and albedo susceptibility to constrain liquid water path (LWP) response to warming and SWFB in the Southern Ocean (SO; 50°–80°S). We analyze precipitation in extratropical cyclones (ECs) to learn about extratropical condensed water sink processes, combined with observations of clouds and moisture convergence, and use the analysis to better understand and constrain SWFB. We utilize a perturbed parameter ensemble (PPE) hosted in the Community Atmosphere Model, version 6 (CAM6), to provide a constraint on SWFB based on observations from Clouds and the Earth's Radiant Energy System (CERES) and Multisensor Advanced Climatology of LWP (MAC-LWP). We apply Gaussian process regression to emulate the model response to all parameters perturbed in the PPE. Confronting the emulator output with observations provides a new estimated response of Earth to global

warming. Our new estimates of SO LWP reduce the PPE range by 66%–72%, which results in a shortwave cloud radiative effect estimated range that is 27%–34% less than the PPE range. Observations suggest a more positive SO SWFB than the Community Earth System Model, version 2 (CESM2), and consequently do not reject the high climate sensitivity GCMs emerging from the Coupled Model Intercomparison Project phase 6 (CMIP6).

Zhu et al (2025) looked at the state dependence of cloud feedback. The state dependence of cloud feedback—its variation with the mean state climate—has been found in many paleoclimate and contemporary climate simulations. Previous results have shown inconsistencies in the sign, magnitude, and underlying mechanisms of state dependence. To address this, we utilize a perturbed parameter ensemble (PPE) approach with fixed sea surface temperature (SST) in the Community Atmosphere Model, version 6. Our suites of PPEs span a wide range of global mean surface temperatures (GMSTs), with spatially uniform SST perturbations of -4 , 0 , 4 , 8 , 12 , and 16 K from the preindustrial. The results reveal a nonmonotonic variation with GMSTs: Cloud feedback increases under both cooler and warmer-than-preindustrial conditions, with a rise of $\sim 0.1 \text{ W m}^{-2} \text{ K}^{-1}$ under a 4-K colder climate and $\sim 0.4 \text{ W m}^{-2} \text{ K}^{-1}$ under a 12-K warmer climate. This complexity arises from differing cloud feedback responses in high and low latitudes. In high latitudes, cloud feedback consistently rises with warming, likely driven by a moist adiabatic mechanism that influences cloud liquid water. The low-latitude feedback increases under both cooler and warmer conditions, likely influenced by changes in the lower-tropospheric stability. This stability shift is tied to nonlinearity in thermodynamic responses, particularly in the tropical latent heating, alongside potential state-dependent changes in tropical circulations. Under warmer-than-preindustrial conditions, the increase in cloud feedback with warming is negatively correlated with its preindustrial value. Our PPE approach takes the model parameter uncertainty into account and emphasizes the critical role of state dependence in understanding past and predicting future climates. **Significance Statement** This study focuses on how cloud feedback—one of the most uncertain aspects of climate change—varies as global temperatures rise. We found that the cloud feedback decreases at first with warming and then increases, showing significant variation. This complexity stems from nonlinear thermodynamics, such as the Clapeyron–Clausius relationship, which describes how temperature affects moisture in the atmosphere. Our results indicate that the cloud feedback depends on the level of global warming, which is a significant factor rooted in fundamental physics. Recognizing this dependence is important for studies that aim to interpret past climates and predict future climate changes.

3.0 Aviation – Climate Non-CO2 effects

A related part of this work focused on a small set of forcings: the non-CO2 forcing from commercial aircraft. This work was published in Nature as Prather et al (2025). Climate assessments of civil aviation have consistently quantified the dominant climate-forcing components: (1) CO2 emissions, (2) NOx (NO + NO2) emissions and (3) persistent contrails. All three components exert a positive Radiative Forcing (RF) and lead to climate warming of similar magnitudes. The aviation community is actively seeking to reduce its climate footprint through advanced engine technologies, more sustainable aviation fuel and optimal routing plans. These approaches usually involve a trade-off of CO2 against NOx or contrails (non-CO2), such as burning 1% more fuel to decrease contrail RF by 4%. Here, we show that a climate-trade-off risk curve derived from uncertainties in the RF components can give the probability that a specified trade-off ratio will produce a climate benefit. For each component, we calculate the integrated effective RF resulting from 1 year of flights: global warming per activity (GWA). The complementary cumulative probability distribution of the GWA(non-CO2) to GWA(CO2) ratio results in a climate-trade-off risk curve giving the likelihood of a positive climate outcome as a function of the trade-off-CO2 to trade-off-non-CO2 ratio, because the product, $GWA \times \text{trade-off}$, should be the same for both. We find a likely (67%) chance of climate mitigation on a 100-year time horizon for the above suggested ratio of 1:4, favoring proposed non-CO2 mitigation efforts with ratios smaller than this. A climate-trade-off risk curve derived from uncertainties in the radiative-forcing components indicates that focusing on reducing contrails or nitrogen oxide emissions is more effective than reducing CO2 emissions.

Zhang et al (2025) explored another aspect of aviation emissions. Estimates of aviation effective radiative forcing (ERF) indicate that contrail cirrus is currently its largest contributor, although with a substantial associated uncertainty of $\sim 70\%$. Here, we implement the contrail parameterisation developed for the Community Atmosphere Model (CAM) in the UK Met Office Unified Model (UM), allowing us to compare, for the first time, the impact of key features of the host climate model on contrail cirrus ERF. We find that differences in background humidity between the models result in the UM-simulated contrail fractions being 2 to 3 times larger than in CAM. Additionally, the models show contrasting responses in overall global cloud fraction, with contrails increasing the total cloud fraction in the UM and decreasing it in CAM. Differences in the complexity of the cloud microphysics schemes lead to significant differences in simulated changes to cloud ice water content due to aviation. After compensating for the unrealistically low contrail optical depth in the UM, we estimate the 2018 contrail cirrus ERF to be 40.8 mW m^{-2} in the UM, compared to 60.1 mW m^{-2} in CAM. These values highlight the substantial uncertainty in contrail cirrus ERF due to differences in microphysics and radiation schemes between the two models. We also find a factor-of-8 uncertainty in contrail cirrus ERF due to existing uncertainty in contrail cirrus optical depth. Future research should focus on better representing microphysical and radiative contrail characteristics in climate models and on improved observational constraints.

4.0 Recent Temperatures

This work comprised several papers, notably contributions to Forster et al 2023 on recent trends in temperatures and aerosols, and then a substantial paper on attribution of recent changes to emissions from ships as a potential contributor to recent planetary warming.

Gettelman et al 2024 examined the role of aerosols from shipping. Ships brighten low marine clouds from emissions of sulfur and aerosols, resulting in visible “ship tracks”. In 2020, new shipping regulations mandated an ~80% reduction in the allowed fuel sulfur content. Recent observations indicate that visible ship tracks have decreased. Model simulations indicate that since 2020 shipping regulations have induced a net radiative forcing of $+0.12 \text{ Wm}^{-2}$. Analysis of recent temperature anomalies indicates Northern Hemisphere surface temperature anomalies in 2022–2023 are correlated with observed cloud radiative forcing and the cloud radiative forcing is spatially correlated with the simulated radiative forcing from the 2020 shipping emission changes. These effects are projected to warm the planet in the next decade as well, contributing maybe 20% to overall global warming (Figure 1). Shipping emissions changes could be accelerating global warming. To better constrain these estimates, better access to ship position data and understanding of ship aerosol emissions are needed. Understanding the risks and benefits of emissions reductions and the difficulty in robust attribution highlights the large uncertainty in attributing proposed deliberate climate intervention.

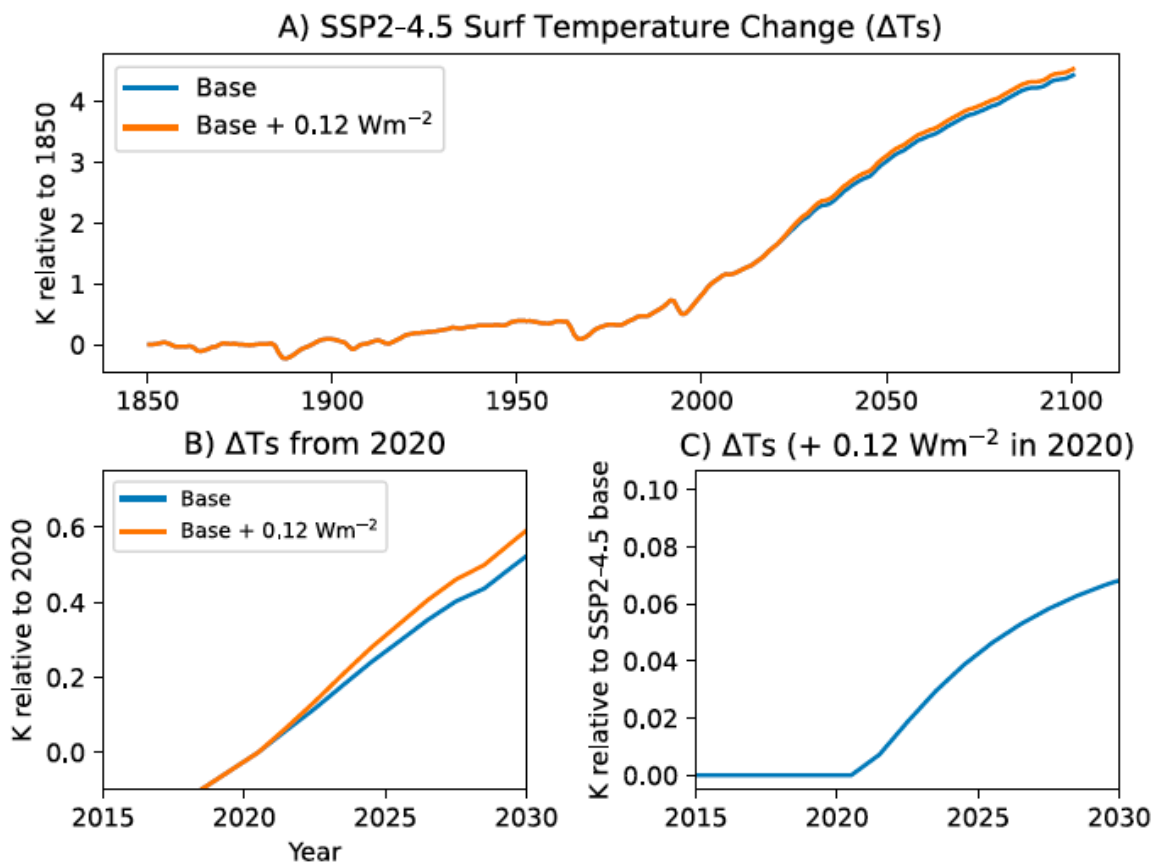


Figure 1: Energy balance model simulation results. (a) Surface Temperature relative to 1850 from the base simulation (blue) and base simulation $+0.15 \text{ Wm}^{-2}$ additional radiative

forcing (orange). (b) Temperatures for the two simulations over 2016–2030 as anomalies from 2020 (c) Temperature difference (perturbed—base) from 2016 to 2030.

Mauritsen et al 2025 was a related study that looked at observations of the recent energy imbalance at the top of the atmosphere, and found it to be increasing, with important implications for future warming. Global warming results from anthropogenic greenhouse gas emissions which upset the delicate balance between the incoming sunlight, and the reflected and emitted radiation from Earth. The imbalance leads to energy accumulation in the atmosphere, oceans and land, and melting of the cryosphere, resulting in increasing temperatures, rising sea levels, and more extreme weather around the globe. Despite the fundamental role of the energy imbalance in regulating the climate system, as known to humanity for more than two centuries, our capacity to observe it is rapidly deteriorating as satellites are being decommissioned.

5.0 High Resolution Model Development

Huang et al (2024) addressed storm resolving scales. Global climate models (GCMs) have advanced in many ways as computing power has allowed more complexity and finer resolutions. As GCMs reach storm-resolving scales, they need to be able to produce realistic precipitation intensity, duration, and frequency at fine scales with consideration of scale-aware parameterization. This study uses a state-of-the-art storm-resolving GCM with a non-hydrostatic dynamical core – the Model for Prediction Across Scales (MPAS), incorporated in the atmospheric component (Community Atmosphere Model, CAM) of the open-source Community Earth System Model (CESM), within the System for Integrated Modeling of the Atmosphere (SIMA) framework (referred to as SIMA-MPAS). At uniform coarse (here, at 120 km) grid resolution, the SIMA-MPAS configuration is comparable to the standard hydrostatic CESM (with a finite-volume (FV) dynamical core) with reasonable energy and mass conservation on climatological timescales. With the comparable energy and mass balance performance between CAM-FV (workhorse dynamical core) and SIMA-MPAS (newly developed dynamical core), it gives confidence in SIMA-MPAS's applications at a finer resolution. To evaluate this, we focus on how the SIMA-MPAS model performs when reaching a storm-resolving scale at 3 km. To do this efficiently, we compose a case study using a SIMA-MPAS variable-resolution configuration with a refined mesh of 3 km covering the western USA and 60 km over the rest of the globe. We evaluated the model performance using satellite and station-based gridded observations with comparison to a traditional regional climate model (WRF, the Weather Research and Forecasting model). Our results show realistic representations of precipitation over the refined complex terrains temporally and spatially. Along with much improved near-surface temperature, realistic topography, and land–air interactions, we also demonstrate significantly enhanced snowpack distributions. This work illustrates that the global SIMA-MPAS at storm-resolving resolution can produce much more realistic regional climate variability, fine-scale features, and extremes to advance both climate and weather studies. This next-generation storm-resolving model could ultimately bridge large-scale forcing constraints and better inform climate impacts and weather predictions across scales.

Yin et al (2025) also focused on high resolution variable resolution (VR) models. The simulation of ice sheet-climate interactions, such as surface mass balance fluxes, is sensitive to model grid resolution. The simulation of ice sheet-climate interactions, such as surface mass balance fluxes, is sensitive to model grid resolution. Here we simulate the multi-century evolution of the Greenland Ice Sheet (GrIS) and its interaction with the climate using the Community Earth System Model version 2.2 (CESM2.2) including an interactive GrIS component (the Community Ice Sheet Model v2.1 [CISM2.1]) under an idealized warming scenario (atmospheric CO₂ increases by 1%/yr until quadrupling the pre-industrial level and then is held fixed). A variable-resolution (VR) grid with 1/4° regional refinement over the broader Arctic and 1° resolution elsewhere is applied to the atmosphere and land components, and the results are compared with conventional 1° lat-lon grid simulations to investigate the impact of grid refinement. Compared with the 1° runs, the VR run features a slower rate of surface melt, especially over the western and northern GrIS, where the ice surface slopes gently toward the periphery. This

difference pattern originates primarily from higher snow albedo and, thus, weaker albedo feedback in the VR run. The VR grid better captures the CISM ice sheet topography by reducing elevation discrepancies between CAM and CISM and is, therefore, less reliant on the downscaling algorithm, which is known to underestimate albedo gradients. The sea level rise contribution from the GrIS in the VR run is 53 mm by year 150 and 831 mm by year 350, approximately 40% and 20% less than that of the 1° runs, respectively. Yin et al (2025) simulate the multi-century evolution of the Greenland Ice Sheet (GrIS) and its interaction with the climate using the Community Earth System Model version 2.2 (CESM2.2) including an interactive GrIS component (the Community Ice Sheet Model v2.1 [CISM2.1]) under an idealized warming scenario (atmospheric CO₂ increases by 1%/yr until quadrupling the pre-industrial level and then is held fixed). A variable-resolution (VR) grid with 1/4° regional refinement over the broader Arctic and 1° resolution elsewhere is applied to the atmosphere and land components, and the results are compared with conventional 1° lat-lon grid simulations to investigate the impact of grid refinement. Compared with the 1° runs, the VR run features a slower rate of surface melt, especially over the western and northern GrIS, where the ice surface slopes gently toward the periphery. This difference pattern originates primarily from higher snow albedo and, thus, weaker albedo feedback in the VR run. The VR grid better captures the CISM ice sheet topography by reducing elevation discrepancies between CAM and CISM and is, therefore, less reliant on the downscaling algorithm, which is known to underestimate albedo gradients. The sea level rise contribution from the GrIS in the VR run is 53 mm by year 150 and 831 mm by year 350, approximately 40% and 20% less than that of the 1° runs, respectively.

Over the period of this project, the PI continued to serve in a leadership role as co-chair of the World Climate Research Program (WCRP) Digital Earth Lighthouse Activity (<https://www.wcrp-climate.org/digital-earths>). The Digital Earths Lighthouse Activity will push the co-development of high-resolution Earth-system modeling and the exploitation of billions of observations with digital technologies from the convergence of novel High-Performance Computing (HPC), big data, and Artificial Intelligence (AI) methodologies. The overall objective of this activity is to carry out research activities that support the establishment of integrated interactive digital information systems that provide information on the past, present, and future of our planet. This will involve coordinating on-line virtual working groups, and attending the WCRP Joint Scientific Committee (JSC) meeting in May 2023 in Brussels, Belgium. This work will continue involvement of E3SM scientists at the highest levels. Coordination efforts will also contribute to E3SM development of high resolution models.

In 2024 and 2025 this project supported the development of a global hackathon for km-scale models. In May 2025 nearly 700 participants from all around the world coalesced at 10 regional nodes, and a few satellite nodes, to take part in a global hackathon of km-scale (horizontal grid spacing < 10 km) regional and global earth system models. Fantastic science is emerging from these efforts, ranging across novel model analysis, new ways of integrating with satellite data, and emulation with machine learning. New technologies were trialed that enable the community to work in new and complementary ways to democratize access to global information at a local scale from a set of the world's highest-resolution climate models. The hackathon demonstrated how exascale

data can be organized to be accessible to anyone. Fundamentally, the community could apply these techniques and technologies to move towards more participative models for co-production and delivery of climate information for climate scientists and citizens alike.



Figure 2: Schematic of the Hackathon technical stack.

The technical approach was unique, and illustrated in Figure 2. The first component is the data description for model output, and observational products, i.e., reanalyses (assimilated) and observations (mostly from satellite). The model output and observational products were converted from their native grids to a common equal-area grid. The Hierarchical Equal Area isoLatitude Pixelation (HEALPix) hierarchical grid (Górski et al., 2005) was originally developed to look at cosmic microwave background whole sky imagers on a spherical grid. A key feature of HEALPix is the ability to use hierarchical grids with different resolutions. Multi-resolution data stores might seem to compound the data storage problem, but a full HEALPix grid, with successive zoom levels associated with a four-fold finer data representation, requires considerably less storage than a single lat-lon grid at just the highest resolution (63% reduction from a full Gaussian or Lat-Lon Grid due to fewer grids towards the poles). Another feature is a data format that enables accessing variables, regions, and times that are desired, without loading any extra data. For example, for a user wanting to look at data over Europe with one variable, only that variable would be loaded over a small portion (2%) of the planet. Zarr is a cloud storage format that enables this. As illustrated in Figure 2, data could be local (on a traditional file system) or on a remote cloud storage device. Regardless of where data is stored, this method still enables reading of just the needed data (e.g. just data over Europe), reducing the need to transfer large amounts of data for any analysis.

Between the data storage and the user analysis software the hackathon used a common ‘catalog’ to organize the data, visually illustrated in Figure 3. The catalog has a descriptor of each data set, including metadata, how the data is organized (output frequency, zoom levels, etc.) as well as the actual locations of the Zarr store paths on a local system. Similar methods have been used by the Pangeo project for traditional GCM output. The catalog also contains descriptors of data stored on object storage in remote locations. The catalog is built for each node’s local data, and then combined with an ‘online’ catalog into a single file that can be accessed by a URL. Thus, the same catalog file is used at every node. The benefit of the catalog approach is that it removes from the user the burden of finding and referencing the different data needed for analysis, unifying data access through a relatively simple interface.

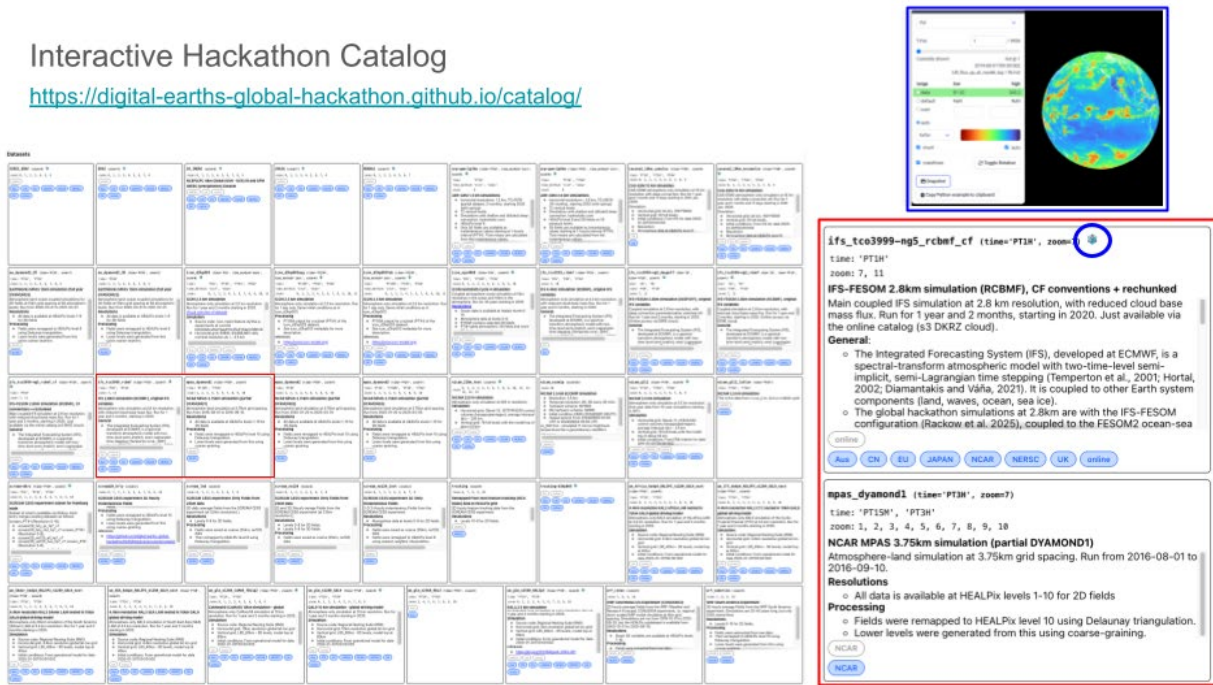


Figure 3: Illustration of the Hackathon catalog. Red box is blown up on the right, and clicking on the icon in purple launches an interactive viewer.

A user simply specifies which node they are at, and the catalog points to where their local data is, and where to find the online data on object storage. Any data within the catalog can be accessed by a reference (typically the model name). Ziemen et al. (in prep) describe the system and further describe a tool that collects all the catalog information onto a web page (displayed in Figure 3), from which the user can see the datasets, descriptors, metadata and which nodes have the data available locally (blue) and the originator of the data (white). The catalogues also enabled redundancy. Some data was found to be corrupted at one node, and another node had a 24 hour data center shutdown during the hackathon. In both cases it was possible to fall back on data that was available online from other nodes, and some of the nodes mostly worked with remote data.

Finally, there was the user platform for analysis. We developed a common platform by assuming all analysis was to be performed in Python, and providing a standard environment of the same set of Python packages. This environment can be described in a list of packages and installed with common tools on systems from laptops to supercomputers. We also used a common Integrated Development Environment (IDE): JupyterLab, but the workflow is compatible with other environments, and many participants used different IDEs (e.g., VSCode).

Beyond the hackathon, Gettelman et al (2025b) argued for a new way of using km-scale models to provide needed information for society. The climate is changing so rapidly that climatologies based on historical statistics cannot reliably capture the current risk of extreme weather events hazardous to society. Decision relevant projections of weather extreme probability over the next 10–15 years are needed to enable adaptation and resilience in the face of this evolving risk. Current weather forecasts/predictions and long-term climate projections for decades into the future are inadequate for providing this information to stakeholders that need it, targeting forecast horizons either too short or too far into the future. Gettelman et al 2025b argue that a new approach is needed: climate nowcasting. Climate nowcasting would focus on user-inspired extreme metrics over the next 10–15 year time frame, targeting specific impacts and locations down to a local scale, by engaging with stakeholders to understand their needs and provide information in a format relevant for decision making. Importantly, climate nowcasting will not consist of a single approach or data set, involving rather data fusion from different sources of information: simulations, observations and data driven methods, likely through different weights depending on the metric of interest. Predictions must be accompanied by serious engagement with stakeholders facing climate risks, and clearly present uncertainties and limitations of any prediction. Such a vision is very different from how typical climate or weather forecasts are applied today.

Stammer et al (2024) reported on a workshop on data assimilation for climate, that seeks new ways to bring observations together with climate and particularly high resolution climate models. A 3-day workshop took place from 12 to 14 June 2023, at the Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, focusing on data assimilation (DA) and machine learning (ML) in the context of Earth system reanalysis and climate model improvements. The workshop, organized 25 years after the inception of the Estimating the Circulation and Climate of the Ocean (ECCO), was an effort to lay out the roadmap for future development of DA in support of climate modeling and climate knowledge improvements, or “climate DA.”

6.0 References

- Cohen, S., A. Sobel, M. Biasutti, et al. 2024. "Implementation and Exploration of Parameterizations of Large-Scale Dynamics in NCAR's Single Column Atmosphere Model SCAM6." *Journal of Advances in Modeling Earth Systems* 16 (6): e2023MS003866. <https://doi.org/10.1029/2023MS003866>.
- Duffy, Margaret L., Isla Ruth Simpson, Brian Medeiros, et al. 2025. Is the High ECS in CESM2 Degrading Transient Climate Change Projections over the 21st Century? <https://www.authorea.com/doi/full/10.22541/essoar.173775739.93027483?commit=f70035379d508d59f13f2fd7f327c6254b3ff5db>.
- Forster, Piers M., Chris Smith, Tristram Walsh, et al. 2024. "Indicators of Global Climate Change 2023: Annual Update of Key Indicators of the State of the Climate System and Human Influence." *Earth System Science Data* 16 (6): 2625–58. <https://doi.org/10.5194/essd-16-2625-2024>.
- Gottelman, A., and H. Morrison. 2015. "Advanced Two-Moment Bulk Microphysics for Global Models. Part I: Off-Line Tests and Comparison with Other Schemes." *Journal of Climate* 28 (3): 1268–87. <https://doi.org/10.1175/JCLI-D-14-00102.1>.
- Gottelman, A. 2015. "Putting the Clouds Back in Aerosol–Cloud Interactions." *Atmos. Chem. Phys.* 15 (21): 12397–411. <https://doi.org/10.5194/acp-15-12397-2015>.
- Gottelman, A., L. Lin, B. Medeiros, and J. Olson. 2016. "Climate Feedback Variance and the Interaction of Aerosol Forcing and Feedbacks." *Journal of Climate* 29 (18): 6659–75. <https://doi.org/10.1175/JCLI-D-16-0151.1>.
- Gottelman, A., C. Hannay, J. T. Bacmeister, R. B. Neale, A. G. Pendergrass, G. Danabasoglu, J.-F. Lamarque, et al. 2019. "High Climate Sensitivity in the Community Earth System Model Version 2 (CESM2)." *Geophysical Research Letters* 46 (14): 8329–37. <https://doi.org/10.1029/2019GL083978>.
- Gottelman, A., D. J. Gagne, C.-C. Chen, M. W. Christensen, Z. J. Lebo, H. Morrison, and G. Gantos. 2021. "Machine Learning the Warm Rain Process." *Journal of Advances in Modeling Earth Systems* 13 (2): e2020MS002268. <https://doi.org/10.1029/2020MS002268>.
- Gottelman, Andrew, and Ralph Kahn. 2025. "Aerosols Are Critical for 'Nowcasting' Climate." *One Earth* 8 (4). <https://doi.org/10.1016/j.oneear.2025.101239>.
- Gottelman, Andrew, Claudia Tebaldi, and L Ruby Leung. 2025. "Climate Nowcasting." *Environmental Research: Climate* 4 (1): 013002. <https://doi.org/10.1088/2752-5295/adc327>.
- Gottelman, A., M. W. Christensen, M. S. Diamond, et al. 2024. "Has Reducing Ship Emissions Brought Forward Global Warming?" *Geophysical Research Letters* 51 (15): e2024GL109077. <https://doi.org/10.1029/2024GL109077>.
- Gottelman, Andrew, Richard Forbes, Roger Marchand, Chih-Chieh Chen, and Mark Fielding. 2024c. "The Impact of Cloud Microphysics and Ice Nucleation on Southern Ocean Clouds Assessed with Single-Column Modeling and Instrument Simulators." *Geoscientific Model Development* 17 (21): 8069–92. <https://doi.org/10.5194/gmd-17-8069-2024>.

Gettelman, A., T. Eidhammer, M. L. Duffy, D. T. McCoy, C. Song, and D. Watson-Parris. 2024b. “The Interaction Between Climate Forcing and Feedbacks.” *Journal of Geophysical Research: Atmospheres* 129 (18): e2024JD040857. <https://doi.org/10.1029/2024JD040857>.

Ghan, Steven, Minghuai Wang, Shipeng Zhang, Sylvaine Ferrachat, Andrew Gettelman, Jan Griesfeller, Zak Kipling, et al. 2016. “Challenges in Constraining Anthropogenic Aerosol Effects on Cloud Radiative Forcing Using Present-Day Spatiotemporal Variability.” *Proceedings of the National Academy of Sciences*, February, 201514036. <https://doi.org/10.1073/pnas.1514036113>.

Górski, K. M., E. Hivon, A. J. Banday, et al. 2005. “HEALPix: A Framework for High-Resolution Discretization and Fast Analysis of Data Distributed on the Sphere.” *The Astrophysical Journal* 622 (2): 759. <https://doi.org/10.1086/427976>.

Huang, Xingying, Andrew Gettelman, Brian Medeiros, and William C. Skamarock. 2024. “Examining Tropical Convection Features at Storm-Resolving Scales Over the Maritime Continent Region.” *Journal of Geophysical Research: Atmospheres* 129 (20): e2024JD040976. <https://doi.org/10.1029/2024JD040976>.

Ma, Po-Lun, Bryce E. Harrop, Vincent E. Larson, Richard B. Neale, Andrew Gettelman, Hugh Morrison, Hailong Wang, et al. 2022. “Better Calibration of Cloud Parameterizations and Subgrid Effects Increases the Fidelity of the E3SM Atmosphere Model Version 1.” *Geoscientific Model Development* 15 (7): 2881–2916. <https://doi.org/10.5194/gmd-15-2881-2022>.

Mauritsen, Thorsten, Yoko Tsushima, Benoit Meyssignac, et al. 2025. “Earth’s Energy Imbalance More Than Doubled in Recent Decades.” *AGU Advances* 6 (3): e2024AV001636. <https://doi.org/10.1029/2024AV001636>.

McFarquhar, Greg M., Chris Bretherton, Roger Marchand, Alain Protat, Paul J. DeMott, Simon P. Alexander, Greg C. Roberts, et al. 2020. “Observations of Clouds, Aerosols, Precipitation, and Surface Radiation over the Southern Ocean: An Overview of CAPRICORN, MARCUS, MICRE and SOCRATES.” *Bulletin of the American Meteorological Society* 1 (aop): 1–92. <https://doi.org/10.1175/BAMS-D-20-0132.1>.

Prather, Michael J., Andrew Gettelman, and Joyce E. Penner. 2025. “Trade-Offs in Aviation Impacts on Climate Favour Non-CO2 Mitigation.” *Nature*, July 2, 1–6. <https://doi.org/10.1038/s41586-025-09198-2>.

Raghuraman, Shiv Priyam, Brian Medeiros, and Andrew Gettelman. 2024. “Observational Quantification of Tropical High Cloud Changes and Feedbacks.” *Journal of Geophysical Research: Atmospheres* 129 (7): e2023JD039364. <https://doi.org/10.1029/2023JD039364>.

Shupe, Matthew D., Markus Rex, Byron Blomquist, P. Ola G. Persson, Julia Schmale, Taneil Uttal, Dietrich Althausen, et al. 2022. “Overview of the MOSAiC Expedition: Atmosphere.” *Elementa: Science of the Anthropocene* 10 (1): 00060. <https://doi.org/10.1525/elementa.2021.00060>.

Song, Ci, Daniel T. McCoy, Trude Eidhammer, et al. 2024. “Buffering of Aerosol-Cloud Adjustments by Coupling Between Radiative Susceptibility and Precipitation Efficiency.” *Geophysical Research Letters* 51 (11): e2024GL108663. <https://doi.org/10.1029/2024GL108663>.

Stammer, Detlef, Daniel E. Amrhein, Magdalena Alonso Balmaseda, et al. 2024. Earth System Reanalysis in Support of Climate Model Improvements. *Bulletin of the American Meteorological Society*. August 8. <https://doi.org/10.1175/BAMS-D-24-0110.1>.

Stevens, Bjorn, and Graham Feingold. 2009. “Untangling Aerosol Effects on Clouds and Precipitation in a Buffered System.” *Nature* 461 (7264): 607–13. <https://doi.org/10.1038/nature08281>.

Tan, Ivy, Trude Storelvmo, and Mark D. Zelinka. 2016. “Observational Constraints on Mixed-Phase Clouds Imply Higher Climate Sensitivity.” *Science* 352 (6282): 224–27. <https://doi.org/10.1126/science.aad5300>.

Tan, Ivy, and Trude Storelvmo. 2019. “Evidence of Strong Contributions From Mixed-Phase Clouds to Arctic Climate Change.” *Geophysical Research Letters* 46 (5): 2894–2902. <https://doi.org/10.1029/2018GL081871>.

Twomey, Sean. 1977. “The Influence of Pollution on the Shortwave Albedo of Clouds.” *Journal of the Atmospheric Sciences* 34 (7): 1149–52.

Werapitiya, Geethma, Daniel T. McCoy, Gregory S. Elsaesser, et al. 2025. Extratropical Cloud Feedback Constrained by Cloud Sources and Sinks in Cyclones. *Journal of Climate*. November 11. <https://doi.org/10.1175/JCLI-D-24-0607.1>.

Yin, Ziqi, Adam R. Herrington, Rajashree Tri Datta, Aneesh C. Subramanian, Jan T. M. Lenaerts, and Andrew Gettelman. 2025. “Improved Understanding of Multicentury Greenland Ice Sheet Response to Strong Warming in the Coupled CESM2-CISM2 With Regional Grid Refinement.” *Journal of Advances in Modeling Earth Systems* 17 (2): e2024MS004310. <https://doi.org/10.1029/2024MS004310>.

Zhang, Weiyu, Kwinten Van Weverberg, Cyril J. Morcrette, et al. 2025. “Impact of Host Climate Model on Contrail Cirrus Effective Radiative Forcing Estimates.” *Atmospheric Chemistry and Physics* 25 (1): 473–89. <https://doi.org/10.5194/acp-25-473-2025>.

Zhou, Xiaoli, David Painemal, Andrew Gettelman, and Graham Feingold. 2025. “Exploring Causal Relationships and Adjustment Timescales of Aerosol-Cloud Interactions in Geostationary Satellite Observations and CAM6 Using Wavelet Phase Coherence Analysis.” *Geophysical Research Letters* 52 (2): e2024GL111961. <https://doi.org/10.1029/2024GL111961>.

Zhu, Jiang, Bette L. Otto-Bliesner, Esther C. Brady, et al. 2025. “Investigating the State Dependence of Cloud Feedback Using a Suite of Perturbed Parameter Ensembles.” *Journal of Climate*. *Journal of Climate* 38 (16): 4063–81. <https://doi.org/10.1175/JCLI-D-24-0686>.

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