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Limited climate response to extreme Arctic mixed-phase cloud thinning

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Cloud-based climate interventions seek to reduce climate change impacts by altering Earth's radiation budget through targeted cloud modifications. Mixed-phase regime cloud thinning (MCT) is a recently proposed intervention that aims to reduce cloud longwave trapping by seeding mixed-phase regime clouds with ice-nucleating particles, thereby promoting liquid-to-ice conversion and cloud thinning. Although the microphysical basis of MCT is well known, its large-scale climatic potential is poorly known. Here we address this question by evaluating the climatic response to removing all target clouds for MCT in the wintertime Arctic in a climate model. We find that, even under this intentionally extreme scenario, the response remains both localized to the Arctic Ocean and limited in magnitude, producing $-0.47 \pm 0.08^{\circ}\text{C}$ of Arctic annual-mean cooling and 0.23 ± 0.04 million km^2 of annual-mean sea ice expansion. This offsets 4.3% of Arctic warming and 3.5% of sea ice loss under doubled CO_2 , or approximately 18% and 13%, respectively, relative to observed changes over the past four decades. These findings suggest limited large-scale climatic leverage of MCT but potential value for locally targeted applications, particularly near susceptible marginal ice zones.

Introduction

The deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change (1), known as climate intervention or climate engineering, generally encompasses carbon dioxide removal and Earth radiation management (ERM). ERM seeks to reduce Earth's positive energy imbalance by either decreasing incoming solar radiation or increasing outgoing infrared radiation, thereby alleviating global warming.

Polar regions have attracted growing interest for ERM because they are experiencing some of the most rapid climate change on Earth, with profound environmental transformation threatening ecosystems and human societies and including six of the fifteen policy-relevant future climate tipping elements (2, 3). In addition, unlike global ERM strategies, polar-focused approaches may offer unique advantages by exploiting distinctive features of the polar climate system. For instance, the low polar tropopause may facilitate high-latitude stratospheric aerosol injection (SAI) (4, 5), the strong ice–albedo feedback motivates surface albedo modification (6–8), and the widespread low-level clouds have inspired cold cloud-based interventions such as marine cloud brightening (MCB) (9) and mixed-phase regime cloud thinning (MCT) (10). Among these polar-focused interventions, MCT is a relatively recent proposal and remains one of the least explored, particularly regarding its potential to counteract Arctic warming and sea-ice loss at large scales (11).

In theory, MCT aims to reduce cloud longwave trapping by seeding ice-nucleating particles (e.g., natural dust or silver iodide) into the liquid-containing subset of mixed-phase regime clouds (MPRCs; -39 to 0°C), thereby promoting liquid-to-ice conversion through the Wegener–Bergeron–Findeisen (WBF) process (10, 12). The resulting ice crystals subsequently grow into precipitation-sized particles, enhancing precipitation and reducing cloud optical thickness, ultimately leading to cloud thinning or even dissipation. The physical basis of MCT is well established. Laboratory studies (13), weather-modification applications (14), and natural analogues (15) all demonstrate that glaciogenic seeding can efficiently promote liquid-to-ice conversion in supercooled clouds, suggesting the physical plausibility of the MCT approach. However, whether such microphysical changes can translate into meaningful climatic responses at large scales remains unknown. Existing studies have primarily focused on cloud micro-physical, macro-physical, and radiative responses (10, 12, 16), with only one study (10) estimating the large-scale climatic impacts of intentional MCT in one model, despite

the growing interest in this proposal (11).

Unlike other cloud-based intervention strategies, such as MCB and also cirrus cloud thinning (CCT), which can in principle be deployed over broad regions to influence the global climate (9, 17–19), MCT is inherently limited in both space (high latitudes) and season (winter). MPRCs occur most frequently at high latitudes (20) and exert a longwave-dominated warming effect primarily during winter (Supplementary Fig. S1). These limitations naturally raise a fundamental question: can such a geographically and seasonally constrained intervention produce a climatically meaningful response? More broadly, evaluating the feasibility of a climate intervention strategy requires asking not only whether it can be implemented, but also whether it possesses sufficient leverage to produce a meaningful climate response.

Here we address this question for Arctic MCT using a state-of-the-art climate model. Rather than focusing on a typical MCT implementation, we construct an intentionally extreme scenario that does not consider all real-world constraints on cloud modification. Although not intended to represent a realistic deployment, this framework provides a plausible upper limit of the climatic potential of Arctic MCT. More broadly, this methodology establishes a general framework for evaluating the theoretical maximum cooling of climate intervention strategies.

Results

Mixed-phase regime clouds and longwave radiative forcing under extreme MCT

The abundance and liquid water content of Arctic low-level MPRCs, the primary target of MCT, provide the foundation for its climatic potential. We focus on the polar winter (November–February), when low-level clouds exert a net longwave warming effect at both the surface and the top of the atmosphere (Supplementary Fig. S1; see Methods), such that thinning these clouds produces a cooling perturbation (10). Wintertime low clouds are widespread across the study domain (non-land areas north of 60°N), with a mean coverage of 75% and peak occurrence exceeding 90% over the open ocean near the ice edge (Fig. 1a). In contrast, their liquid water content exhibits much stronger spatial variability (Fig. 1b), averaging nearly four times larger over the open ocean (114 g m⁻²) than over sea ice (30 g m⁻²), despite only modest differences in cloud occurrence (84% versus

71%). This pronounced sea ice–open ocean contrast suggests a substantially greater potential for MCT-induced longwave radiative perturbations over the open ocean, particularly the North Atlantic sub-Arctic. Here, cloud properties in CESM2 are broadly consistent with satellite observations, particularly the wintertime frequency of supercooled liquid-containing clouds relevant to this study (21–23).

Ice-nucleating particle seeding of liquid-containing MPRCs can reduce cloud optical thickness through liquid-to-ice conversion while leaving cloud cover largely intact (*thinning*). If the subsequent ice crystals continue to grow and precipitate until the cloud condensate is removed, the clouds may instead dissipate completely (*thinned out*). To test the maximum climate response achievable by MCT within our model, we consider an intentionally extreme scenario (*maxMCT*), in which all wintertime low-level liquid-containing MPRCs north of 60°N (see Methods) are assumed to be completely thinned out. This design ignores essentially all practical and microphysical constraints on cloud modification, including aerosol delivery, seeding efficiency, and incomplete cloud dissipation. Complete cloud removal generates a strong instantaneous surface longwave cooling (Fig. 1c) that closely mirrors the distribution of cloud liquid water (Fig. 1b), with a nearly threefold larger forcing over the open ocean (-39 W m^{-2}) than over sea ice (-14 W m^{-2}). Here and throughout, longwave forcing refers to the instantaneous radiative perturbation diagnosed from radiative transfer calculations with and without complete cloud removal (see Methods).

In contrast to the surface, the longwave forcing at the TOA exhibits a pronounced dipole pattern (Fig. 1d), with strong cooling over the open ocean (approximately -11 W m^{-2}) but weak warming over the ice-covered Arctic ($+0.76 \text{ W m}^{-2}$). This contrast arises from fundamental differences in boundary-layer cloud structure and thermodynamics (Fig. S2). Over the open ocean, low clouds are typically elevated above the surface and remain colder than the underlying ocean because the lower troposphere follows a near-moist-adiabatic temperature profile (Fig. S2b). Removing these clouds therefore increases outgoing longwave radiation by exposing the warmer surface, producing TOA cooling. In contrast, over sea ice, low clouds are often embedded within persistent surface-based temperature inversions (Fig. S2a), making the clouds warmer than the underlying ice surface. Complete cloud removal therefore reduces outgoing longwave radiation by exposing the colder surface, resulting in weak TOA warming. This seemingly counterintuitive wintertime cooling effect of Arctic low clouds over sea ice—and the corresponding warming following their

removal—is consistent with satellite observations (24).

Having established the intentionally extreme *maxMCT* scenario, we next consider a more realistically constrained scenario (*maxMCTocean*), in which only wintertime low-level liquid-containing MPRCs over the open ocean are completely thinned out. This experiment is motivated by two considerations. First, open-ocean cloud seeding is likely to be both more logistically feasible and more radiatively effective because wintertime low-level clouds there contain substantially more liquid water than those over sea ice, and the warmer ocean surface can lose more longwave radiation to space when clouds are removed (Fig. 1b). Consequently, similar longwave forcing can be achieved while perturbing a much smaller region. Second, excluding sea-ice regions avoids the weak TOA warming associated with complete cloud removal over persistent surface-based temperature inversions (Fig. 1d), thereby reducing the potential for unintended climatic consequences. As expected, *maxMCTocean* produces strong longwave cooling over the open ocean, with magnitudes comparable to those in *maxMCT*, while producing essentially no radiative perturbation over the ice-covered Arctic (Fig. 1c,d).

The diagnosed longwave radiative perturbation remains remarkably stable throughout the 150-year simulations when averaged annually (Fig. S3a). Within the perturbation period, the forcing exhibits a distinct intra-seasonal evolution, peaking in November and weakening progressively through February at both the surface and TOA (Fig. S3b). Cloud thinning produces distinct longwave heating perturbation vertical profiles over sea ice and open ocean (Fig. S3c). Over sea ice, cloud thinning generates warming throughout most of the lower troposphere, with a bottom-heavy structure consistent with the typically low cloud bases and limited liquid water content (25). Over open ocean, it induces near-surface below-cloud longwave cooling that transitions to warming aloft, peaking near the climatological low-cloud layer (800–900 hPa). This pattern largely reflects the classic longwave heating profile of optically thick low clouds (26): clouds normally warm the surface and below-cloud atmosphere through downward longwave emission while cooling the cloud layer, particularly near cloud top, through stronger upward than downward longwave radiation.

The stability of the longwave forcing is consistent with compensating cloud and thermodynamic adjustments. Over sea ice, reductions in cloud liquid water tend to weaken the longwave perturbation but are largely offset by lower-tropospheric warming and strengthened surface-based temperature inversions (Fig. S4a,b,e–h). Over the open ocean, increased near-surface cloud liquid is similarly

compensated by cooling of the lower atmosphere. Meanwhile, changes in Arctic low-cloud amount resulting from the imposed radiative perturbations remain modest (less than 6%), suggesting that feedbacks in cloud fraction play only a minimal role in the long-term evolution of the imposed radiative perturbation (Fig. S4c,d).

Limited climatic response to extreme MCT

Under the intentionally extreme *maxMCT* scenario, the climatic response remains limited despite the large radiative perturbation, particularly at the surface (Fig. 2). The annual-mean surface air temperature response is almost entirely confined to the Arctic Ocean, with little cooling over surrounding land areas except for weak signals ($< 0.5^{\circ}\text{C}$) across northwestern Europe and northeastern North America. Spatially, the strongest annual-mean cooling is concentrated along the marginal ice zone in the North Atlantic sub-Arctic, where abundant liquid-containing MPRCs generate the largest longwave radiative perturbations at both the surface and TOA (Fig. 1c,d). Temporally, the largest cooling response occurs during winter (Fig. 2a inset; Fig. S5), with a wintertime Arctic (non-land) mean cooling of $-1.78 \pm 0.14^{\circ}\text{C}$. Cooling during the other seasons is substantially weaker. At the global scale, the annual-mean temperature response remains undetectable.

Sea ice expansion occurs primarily within three regions (Fig. 2e). The largest increase in ice concentration occurs along the North Atlantic sub-Arctic marginal ice zone (annual mean $\sim 5\%$), corresponding to the region of strongest cooling, and persists throughout the year with the strongest enhancement during winter (Fig. S6a). The remaining two regions exhibit even smaller responses (typically 1–3%), including the Arctic peripheral seas over the shallow continental shelves during late summer and autumn and Hudson Bay and Baffin Bay during early winter (Fig. S6a).

The more realistically constrained *maxMCTocean* scenario produces an even more geographically confined climatic response, with cooling largely restricted to the North Atlantic sub-Arctic open ocean (Fig. 2). In contrast to *maxMCT*, where the strongest cooling occurs primarily over the ice-covered side of the marginal ice zone, the cooling maximum in *maxMCTocean* shifts to the adjacent open-ocean side of the sea ice edge (Fig. 1b,d) and persists throughout the year, with the strongest response during winter (Fig. S5). Compared with *maxMCT*, the weak remote cooling signal extends farther into the Northern Hemisphere midlatitudes, while remaining small in mag-

168 nitude. The overall sea ice expansion is similar between the two scenarios (Fig. S7). Reduced ice
169 growth in the East Siberian Sea is largely compensated by enhanced growth in Hudson Bay, Baffin
170 Bay, and regions adjacent to the North Atlantic hotspot of liquid-containing MPRCs.

171 **Limited ability of Arctic MCT to offset greenhouse warming**

172 To assess the ability of MCT to offset greenhouse warming in the Arctic we compare the climatic
173 responses with an equilibrium doubled- CO_2 simulation (Fig. 3). In the CESM-SOM configuration,
174 the equilibrium climate sensitivity is 5.3°C (Fig. 3), comparable to that of the fully coupled
175 CESM2 (27), with Arctic warming amplified by a factor of 2–3 relative to the global mean
176 and strongest during winter (Fig. 3). Against this greenhouse warming benchmark, the warming
177 offset achieved by *maxMCT* remains below 10% across all four temperature metrics, reaching a
178 maximum of 10% only under the most favorable metric (Arctic winter non-land) and less than 1%
179 for the global annual mean (Fig. 3). The more realistically constrained *maxMCTocean* produces
180 consistently smaller offsets, with a maximum of only about 4%. We obtain similar results for sea
181 ice, where the simulated sea ice expansion under both scenarios remains nearly indiscernible from
182 the greenhouse-driven sea ice loss, whether evaluated using annual mean, September minimum, or
183 March maximum sea ice extent.

184 Comparing the simulated response with observed Arctic warming over the past four decades
185 ($+2.60^\circ\text{C}$; Fig. S8a) leads to a similar conclusion. The intentionally extreme *maxMCT* scenario
186 produces $-0.47 \pm 0.08^\circ\text{C}$ of Arctic annual-mean cooling, offsetting approximately 18% of the
187 observed warming, equivalent to roughly 7–8 years of warming at the observed rate. Similarly, the
188 simulated annual-mean sea ice growth offsets about 13% of the observed sea ice loss (Fig. S8b). The
189 more realistically constrained *maxMCTocean* yields slightly smaller offsets for both temperature
190 and sea ice.

191 Together, these comparisons demonstrate that the ability of MCT to offset greenhouse-driven
192 warming and Arctic sea ice loss remains limited, even under an intentionally extreme scenario.
193 Since such a deployment is itself unlikely to be physically or practically achievable owing to
194 logistical, technological, economic, and microphysical constraints, realistic implementations would
195 be expected to produce even smaller climatic responses. These findings therefore motivate a re-

evaluation of the role of MCT, including whether its greatest potential lies in targeted regional applications, where modest but spatially and seasonally localized cooling and sea ice growth may still prove beneficial (see Discussion).

Conclusion and Discussion

This study examines the potential of mixed-phase regime cloud thinning and asks the fundamental question: What is the maximum climatic response that MCT could achieve under an intentionally extreme cloud-thinning scenario? The answer is unexpectedly modest. Even in this highly idealized experiment, the resulting cooling and sea ice expansion remain modest and largely confined to the Arctic, indicating limited potential to counteract large-scale greenhouse-driven Arctic climate change while leaving open the possibility of more targeted regional applications. More broadly, our findings suggest that physically plausible cloud modifications do not necessarily translate into meaningful climatic responses, reframing the evaluation of climate interventions by emphasizing the need to first establish their maximum achievable climatic response.

The unexpectedly limited climatic response found here raises two important questions for future research. First, because this study is based on a single climate model, a coordinated multi-model assessment is needed to determine the robustness of these findings and establish a more reliable estimate of the maximum climatic potential of MCT. Second, if this limited response proves robust across models, the next challenge will be to understand the physical processes that constrain the achievable cooling. Possible mechanisms include the limited spatial coverage of Arctic MPRCs, the finite radiative perturbation that can be generated, and the relatively low efficacy of wintertime forcing (28).

To date, (10), which first introduced the MCT concept, remains the only study to explicitly examine its climatic potential. Using the ECHAM–HAM climate model coupled to a mixed-layer ocean (29), they simulated MCT by artificially increasing the droplet freezing rate within MPRCs and reported an annual cooling of $-1.03 \pm 0.56^\circ\text{C}$ over a selected Arctic North Atlantic sector (60°N – 90°N , 30°W – 90°E), where the response is relatively strong. Over the same region, our *maxMCT* and *maxMCTocean* experiments produce annual cooling of $-0.80 \pm 0.13^\circ\text{C}$ and $-0.85 \pm 0.11^\circ\text{C}$, respectively. Several factors may contribute to the quantitative differences between the two studies,

including differences in equilibrium climate sensitivity (2.5 K in ECHAM–HAM versus 5.3 K in CESM2), the representation of mixed-phase clouds, which are relatively rare in ECHAM–HAM despite being central to the MCT mechanism (30), and the experimental design and background climate state. Together, these differences further underscore the need for a coordinated multi-model assessment to establish a more robust estimate of the maximum climatic potential of MCT.

Beyond MCT, the idealized framework developed here provides a general approach for estimating the maximum climatic potential of cloud-based interventions and beyond. By deliberately removing real-world constraints on the intervention, similar experiments could be designed for other strategies to evaluate their maximum climatic potential. For example, analogous experiments could examine the maximum potential of cirrus cloud thinning through complete thinning of target cirrus clouds, or marine cloud brightening through idealized increases in cloud albedo to 100%.

The intentionally idealized framework adopted here also introduces several limitations that warrant future investigation. First, owing to computational constraints, we employ a slab ocean model coupled to an interactive sea ice model, which provides an efficient framework for isolating the climatic response to extreme MCT. A fully coupled ocean model could potentially modify the equilibrium response through changes in meridional ocean heat transport, which would likely increase as the Arctic cools and partially offset the imposed cooling (31, 32). Second, our experiments are conducted under pre-industrial forcings. In a warmer future Arctic, increased liquid-containing clouds (21, 23) and greater exposure of the relatively warm ocean surface could potentially strengthen the radiative perturbation, while the continued decline of sea ice may reduce the potential for additional sea ice recovery and alter the overall climatic response. Finally, to clearly isolate the climatic response to MCT, we consider the cloud perturbation in the absence of anthropogenic greenhouse warming. Future work should investigate the combined effects of extreme MCT and greenhouse forcing, where a different cloud state and sea ice background may introduce nonlinear interactions, likely of secondary importance.

Several physically relevant processes also warrant further investigation. First, the present experiments do not explicitly account for snowfall associated with MCT, which could provide additional cooling and sea ice growth by freshening and stabilizing the upper ocean, thereby suppressing ocean–atmosphere heat exchange (33). Second, our idealized implementation represents extreme MCT by modifying the radiative properties of the targeted clouds rather than explicitly simulat-

ing the aerosol–cloud microphysical processes responsible for cloud thinning. Such an approach inevitably alters cloud-top radiative cooling, one of the key processes for maintaining Arctic MPRCs (34). Nevertheless, the simulated cloud response indicates that the cloud system remains relatively resilient to the imposed perturbation, with reduced liquid water over sea ice and increased liquid water over open ocean, while overall cloud amount changes only modestly, suggesting that Arctic low clouds are well buffered against even this extreme perturbation.

Finally, the intentionally idealized framework adopted here is designed to isolate the climatic response to extreme MCT. Accordingly, we do not address the practical implementation or technological feasibility of MCT, including the generation and delivery of cloud-seeding aerosols at the required scale, nor do we explicitly represent the detailed aerosol–cloud microphysical processes involved. In addition, the broader ethical, political, and governance questions surrounding cloud-based climate intervention are beyond the scope of this study and warrant careful interdisciplinary consideration.

Methods

CESM2 climate model setup

To isolate the climatic response to extreme mixed-phase regime cloud thinning (MCT), we perform equilibrium climate simulations using the Community Earth System Model version 2 (CESM2; production release 2.2.2) (27) configured with a slab ocean model (SOM) (35) and a dynamic sea ice model (36).

The atmosphere component is the low-top Community Atmosphere Model version 6 (CAM6), configured with 32 vertical levels, a model top near 40 km, the finite-volume dynamical core, and a horizontal resolution of $0.9^\circ \times 1.25^\circ$. The land component is the Community Land Model version 5 (CLM5), while the sea ice component is the Community Ice CodE version 5 (CICE5), using the displaced Greenland-pole 1° grid and a salinity-dependent freezing temperature. Of particular relevance to this study are the cloud microphysics and radiative transfer parameterizations. Cloud microphysics are represented using the Morrison–Gettelman version 2 (MG2) scheme (37), which explicitly simulates mixed-phase ice nucleation as a function of both temperature and aerosols. Radiative transfer is calculated using the Rapid Radiative Transfer Model for GCMs (RRTMG) (38).

The version of RRTMG used here neglects longwave scattering, a process that future radiative transfer schemes may explicitly incorporate to improve simulations of polar cloud radiative effects, particularly for wintertime ice clouds (39).

The slab ocean model represents the upper ocean as a motionless, vertically well-mixed layer while allowing fully interactive sea ice. Ocean boundary conditions, including the monthly climatological ocean heat flux convergence (Q-flux) that accounts for unresolved processes such as advection and vertical mixing, are derived from a long pre-industrial equilibrium CESM2 simulation (35, 40). The slab depth is prescribed as the spatially varying but time-invariant climatological mixed-layer depth, with a global mean of approximately 45 m. The mixed-layer temperature evolves freely in response to surface energy fluxes while remaining fully coupled to the CICE5 sea ice model. Particularly, sea ice moves in this configuration and uses fixed ocean currents for bottom drag (35). This framework efficiently isolates the equilibrium climatic response to the imposed cloud perturbations while retaining the essential coupled interactions among the atmosphere, sea ice, and upper ocean (40, 41).

Experimental design

All simulations are conducted under pre-industrial atmospheric composition and radiative forcings. The control experiment (*CTL*) is configured consistently with the long pre-industrial fully coupled CESM2 simulation used to derive the prescribed Q-flux for the slab ocean model. The *CTL* simulation is integrated for 150 years to establish the reference climate. All perturbation experiments are initialized from the same initial conditions as the *CTL* and differ only in the imposed cloud or greenhouse forcing.

The *maxMCT* experiment represents an intentionally idealized extreme scenario in which all liquid-containing low-level clouds meeting the prescribed selection criteria are assumed to undergo complete glaciation and subsequent removal during the polar winter. Target clouds (Table 1) are identified using three criteria: (1) cloud-top pressure exceeding 635 hPa (approximately 3.5 km climatological height), (2) the presence of cloud liquid water, and (3) occurrence north of 60°N during nighttime conditions (solar zenith angle $> 90^\circ$) between November and February, when low clouds produce a net longwave warming of the Arctic surface (Fig. S1). Here, no explicit temperature criterion is applied. Clouds colder than -38°C are implicitly excluded by the liquid-

containing criterion, whereas liquid-containing clouds warmer than 0°C account for less than 0.1% of the selected grid points in our simulations.

A second experiment (*maxMCTocean*) applies the identical cloud perturbation but only over Arctic open ocean (sea ice concentration < 50%). This configuration is motivated by two major considerations. First, Arctic MPRCs occur most frequently over open water, particularly along the North Atlantic sea ice margin (20, 42), where they provide the greatest potential for generating longwave radiative perturbations per unit area while also offering a more accessible and logistically practical deployment target. Second, previous work has shown that low clouds over sea ice often produce warming at the top of the atmosphere due to persistent surface-based temperature inversions (24). Although thinning these clouds can still cool the surface, their TOA warming reduces the overall climatic benefit, making them less favorable targets for cloud thinning.

The cloud perturbation is imposed directly within the RRTMG radiative transfer calculations by setting the cloud fraction and the cloud optical depths associated with both liquid and ice to zero for all selected clouds. Consequently, the targeted clouds become radiatively invisible while remaining dynamically and microphysically active within the model. This implementation represents the limiting assumption that complete glaciation of supercooled liquid water ultimately causes the collapse of the entire liquid-containing cloud deck, thereby approximating the theoretical maximum MCT scenario within the model.

The *CTL*, *maxMCT*, and *maxMCTocean* simulations are each integrated for 150 years. Because the climatic response to MCT is relatively weak compared with internal climate variability, long integrations are required to obtain robust equilibrium responses. Unless otherwise noted, all analyses use monthly output from the final 100 years of each simulation.

To provide a benchmark for greenhouse-driven climate change, an additional experiment with doubled atmospheric CO₂ concentration is performed using the same CESM2–SOM configuration. Because the imposed radiative forcing is substantially larger than in the MCT experiments, this simulation is integrated for 60 years, with the final 20 years used to characterize the equilibrium response.

338 **“Unperturbed-sky” radiative computation**

339 To quantify the radiative perturbation imposed by extreme MCT, we introduce an additional diag-
340 nostic radiative transfer calculation that we refer to as the “unperturbed-sky” computation. In the
341 standard CAM6 radiation scheme, the radiative transfer model is called twice at every time step:
342 once using the simulated clouds to compute the all-sky radiative fluxes that interact with the climate
343 model, and once assuming cloud-free conditions to diagnose clear-sky radiative fluxes. In the MCT
344 experiments, the all-sky calculation uses the perturbed cloud field, in which all targeted clouds are
345 made radiatively invisible by setting their cloud fraction and cloud optical depths to zero within the
346 radiative transfer calculations. The clear-sky calculation remains unchanged and is retained solely
347 as a diagnostic.

348 We modify the model by introducing a third call to the radiative transfer scheme using the
349 unperturbed simulated cloud field which omits the MCT perturbation. This additional calculation
350 produces unperturbed-sky radiative diagnostics, including longwave radiative fluxes at the top of
351 the atmosphere and the surface, as well as the vertical profile of the longwave radiative heating
352 rates. These fields are archived for diagnostic purposes only and do not affect the model evolution.

353 The instantaneous radiative perturbation imposed by the cloud thinning is then diagnosed as
354 the difference between the model’s all-sky radiative calculation (with the cloud perturbation) and
355 the corresponding unperturbed-sky calculation (without the cloud perturbation). This approach
356 provides a diagnosis of the imposed radiative perturbation while avoiding contamination from
357 subsequent changes in meteorology or other feedback processes.

Table 1: Design of the extreme MCT scenario. The extreme scenario is defined by the cloud selection criteria, spatial domain, seasonal and solar conditions, and the method used for diagnosing the radiative perturbation.

Parameter	Choice
Cloud type	Low-level clouds ($CTP \geq 635$ hPa; ~ 3.5 km)
Cloud phase	Liquid-containing clouds ($\tau_{liq} > 0$)
Season	NDJF
Solar condition	Nighttime only ($SZA > 90^\circ$)
Domain (<i>maxMCT</i>)	North of 60°N and non-land
Domain (<i>maxMCTocean</i>)	North of 60°N and non-land and open ocean
Forcing diagnosis	Third-call radiation calculation

Note: CTP, cloud-top pressure; τ_{liq} , cloud liquid optical depth; SZA, solar zenith angle; NDJF, November–February.

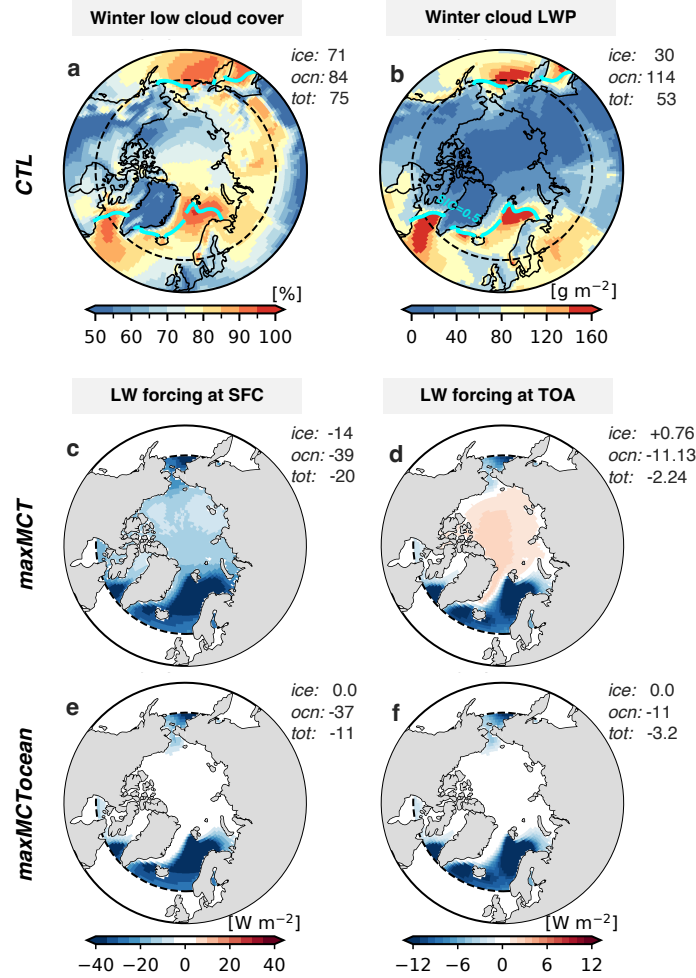


Figure 1: Liquid-containing mixed-phase regime clouds and the resultant longwave radiative forcing under extreme MCT scenarios in CESM2. **a,b,** Climatological (150-year mean) low-cloud cover and column-integrated liquid water path (LWP) simulated by CESM-SOM. For clarity, the maps are displayed over the region north of 50°N , although the study domain is the non-land areas north of 60°N (black dashed outline). Solid cyan contours denote the sea-ice edge (SIC 0.5). Here, low-cloud cover is the default model diagnostic, defined as cloud cover below 700 hPa using the maximum-random overlap assumption. **c,d,** Instantaneous longwave (LW) radiative forcing at the surface (SFC) and top of the atmosphere (TOA) following the hypothetical removal of all target liquid-containing low-level clouds over the entire study domain (*maxMCT*). Here, LW forcing is defined as the instantaneous change in net LW radiation at the surface and TOA, diagnosed from a third radiation call as the difference between computations with and without cloud removal (see Methods). **e,f,** As in (**c,d**), but from cloud removal only over the open-ocean domain (*maxMCTocean*). Numbers in the upper-right corner of each panel show the area-weighted means over the sea-ice ($\text{SIC} \geq 0.5$), open-ocean ($\text{SIC} < 0.5$), and full study domains.

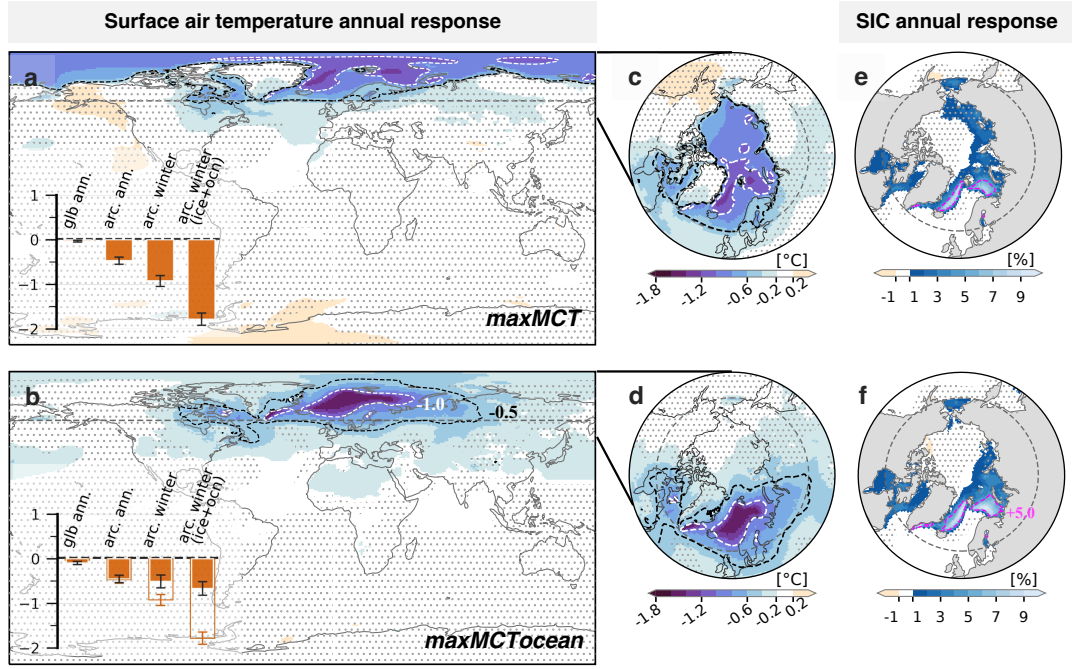


Figure 2: Limited surface air temperature and sea ice response under extreme MCT. **a,b,** Global distribution of the annual-mean surface air temperature response under the *maxMCT* and *maxMCTocean* scenarios. Insets show the global annual mean, Arctic annual mean, Arctic winter mean (NDJF), and Arctic winter mean over the non-land region. Error bars denote ± 1 standard error of the mean (SEM) from the effective sample size. Unfilled bars in **b** reproduce the *maxMCT* responses shown in **a** for comparison. Gray dashed lines mark 60°N . White and black dashed contours indicate the -1.0 K and -0.5 K cooling contours, respectively. Dotted stippling denotes differences that are not statistically significant ($p > 0.05$). **c,d,** As in **a,b**, but shown over the Arctic in a north polar projection. **e,f,** As in **c,d**, but for the annual-mean sea ice concentration response. Magenta dashed contours indicate a 5% increase in sea ice concentration.

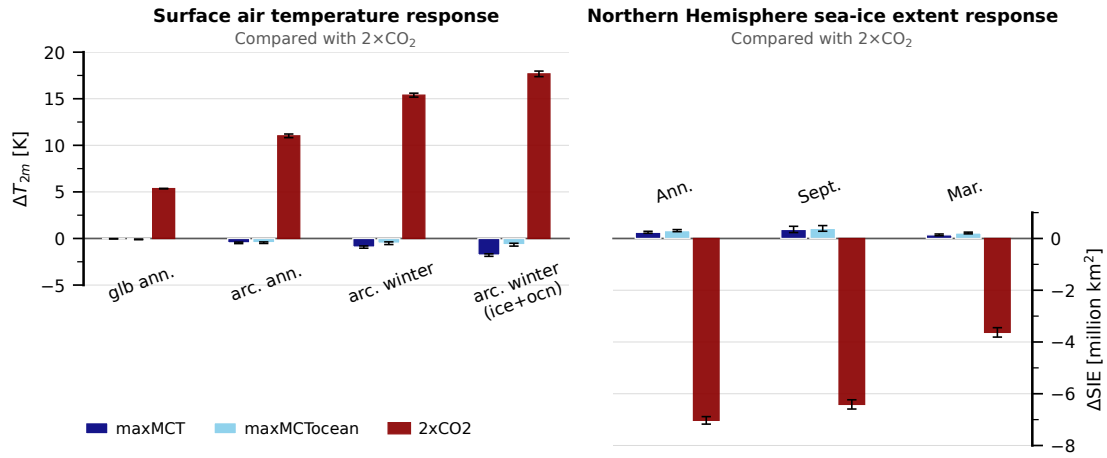


Figure 3: Limited offset of surface warming and sea ice loss by extreme MCT. Surface air temperature (T_{2m}) and Northern Hemisphere sea ice extent (SIE) responses under the extreme MCT scenarios, *maxMCT* and *maxMCTocean*, shown relative to the response under doubled CO_2 . Temperature metrics include the global annual mean, Arctic annual mean, Arctic winter mean (NDJF), and Arctic winter mean over the non-land region. Sea-ice metrics include the annual mean, September mean, and March mean. Error bars denote ± 1 standard error of the mean (SEM), computed using the effective sample size to account for temporal autocorrelation.

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Data and materials availability: All data and code needed to evaluate and reproduce the results in the paper are present in the paper and/or the Supplementary Materials. Source code of CESM2.2.2 model (27) is publicly available at https://www.cesm.ucar.edu/models/cesm2/release_download.html. The monthly ERA5 reanalysis data (43) are publicly available at <https://gdex.ucar.edu/datasets/d633001/>. The NSIDC sea ice dataset is publicly available at <https://noaadata.apps.nsidc.org/NOAA/G02135/>.

Supplementary materials

Figs. S1 to S8

480 **Supplementary Materials for**

481 **Limited climate response to extreme Arctic mixed-phase cloud**
482 **thinning**

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485 **This PDF file includes:**

486 Figures S1 to S8

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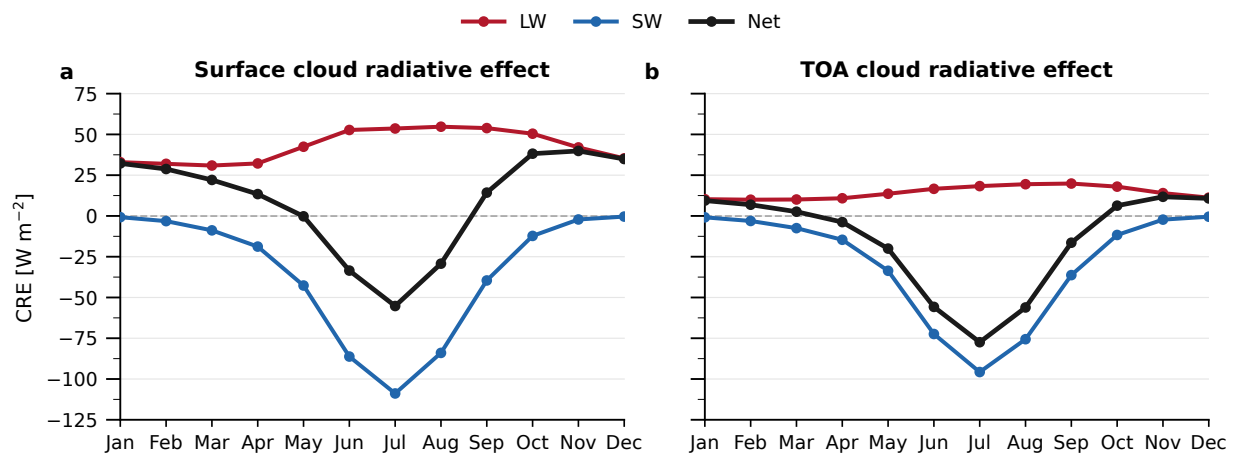


Figure S1: Seasonal cycle of Arctic cloud radiative effects. **a**, Monthly climatological Arctic-mean cloud radiative effect (CRE) in CESM2 at the surface, averaged over all grid cells north of 60°N in the control climate. Net CRE (black) is decomposed into its longwave (LW; red) and shortwave (SW; blue) components. **b**, As in **a**, but for CRE at the top of the atmosphere (TOA).

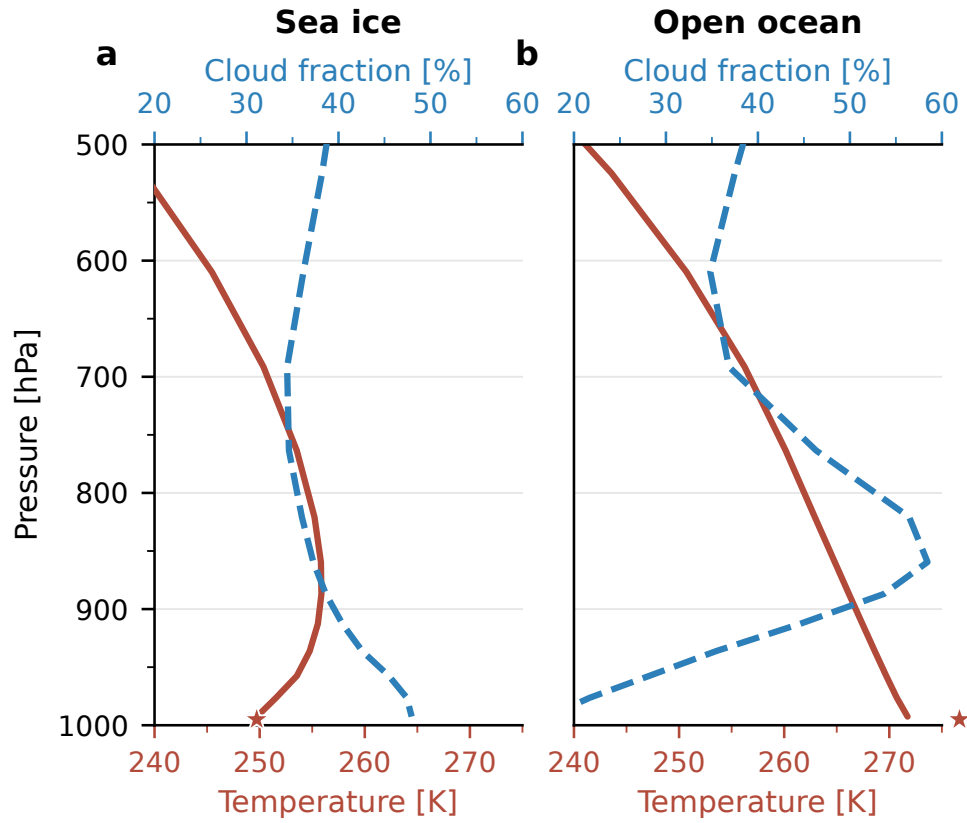


Figure S2: Contrasting temperature and cloud vertical structures over Arctic sea ice and open ocean. a, Winter (NDJF) climatological temperature (red) and cloud fraction (blue) profiles averaged over sea-ice-covered regions north of 60°N in the control simulation. The red star marks the domain-mean surface temperature. **b,** As in **a**, but averaged over the open-ocean region.

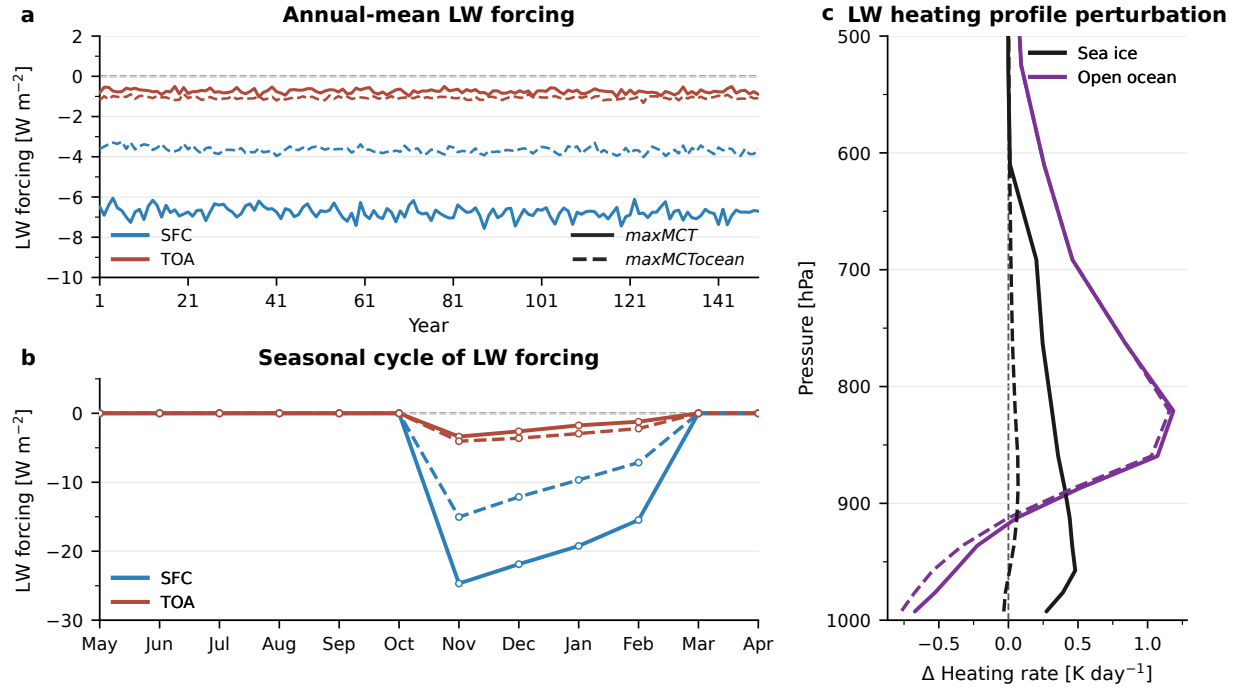


Figure S3: Temporal and vertical characteristics of the instantaneous LW radiative perturbation

a, Annual-mean instantaneous LW radiative forcing (perturbations) at the surface (SFC; blue) and top of the atmosphere (TOA; red) under the *maxMCT* (solid) and *maxMCTocean* (dashed) scenarios over the 150-year simulation. Values are averaged over the cloud-perturbation domain (non-land areas north of 60°N) and diagnosed as the difference between cloud-perturbed and cloud-unperturbed radiation calculations (see Methods). **b**, Seasonal cycle of the instantaneous LW radiative perturbation. Perturbations are zero from March to October because cloud removal is applied only during winter (NDJF). Months are reordered to center the seasonal cycle on winter. **c**, Winter-mean vertical profile of the instantaneous LW heating-rate perturbation following cloud removal over sea-ice-covered (black) and open-ocean (purple) regions.

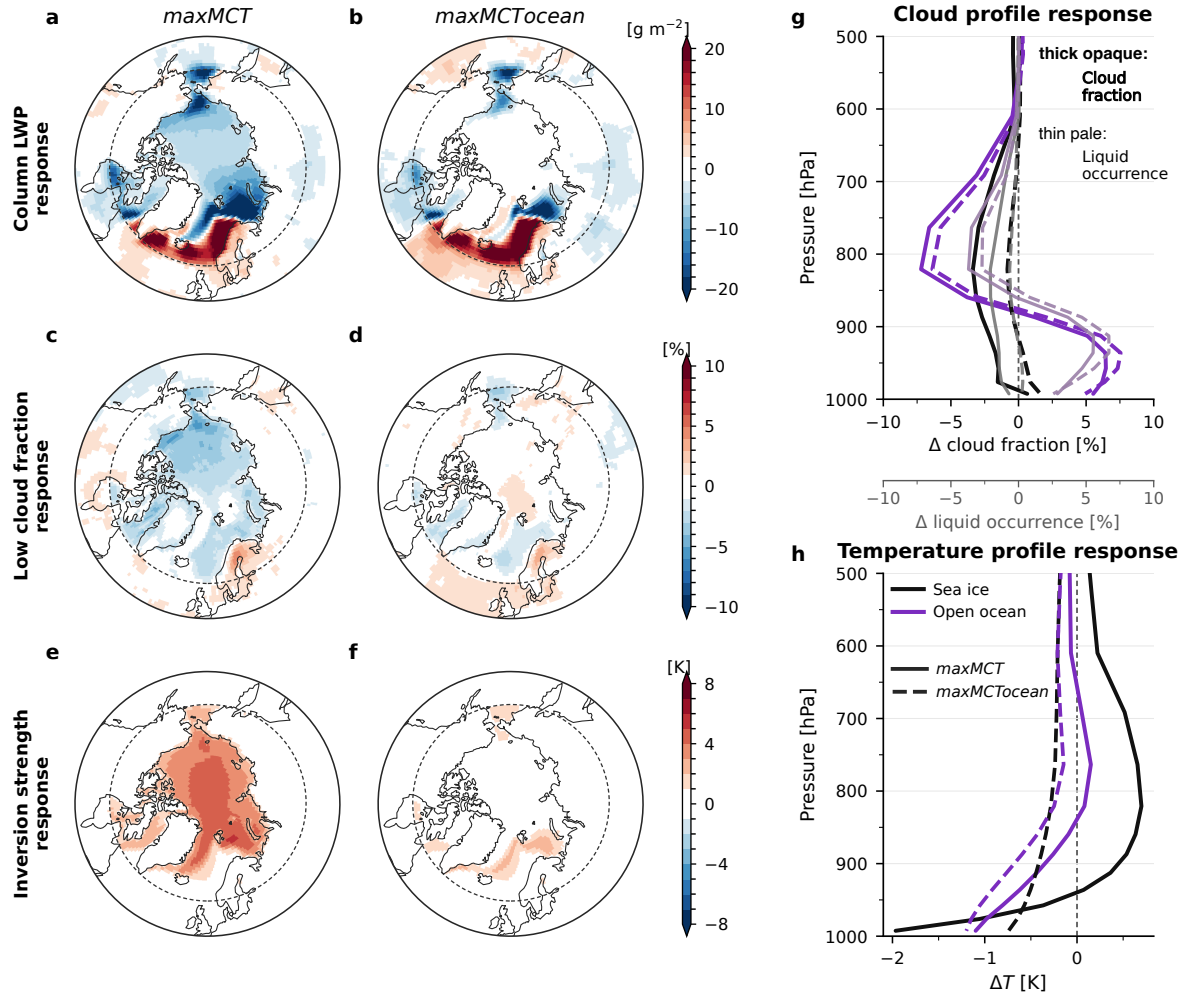


Figure S4: Cloud and thermodynamic structure responses to cloud “removal” under the extreme MCT scenarios a,c,e, Spatial responses of column-integrated liquid water path (LWP; a), low cloud fraction (c), and surface-based temperature inversion strength (a) during winter under the *maxMCT* scenario over the 150-year simulation. Inversion strength is defined as the air temperature at 850 hPa minus the surface temperature. Unless otherwise noted, dashed circles mark the 60°N latitude, and Arctic maps are shown to 50°N for clarity. **b,d,f,** As in **a,c,e**, but for the *maxMCTocean* scenario. **g,** Winter-mean responses of the vertical profiles of total cloud fraction (thick opaque lines) and the occurrence frequency of liquid-containing clouds (thin pale lines). Black and purple denote averages over sea-ice-covered and open-ocean regions, respectively. Solid and dashed lines represent the *maxMCT* and *maxMCTocean* scenarios, respectively. **h,** As in **g**, but for the winter-mean temperature profile response.

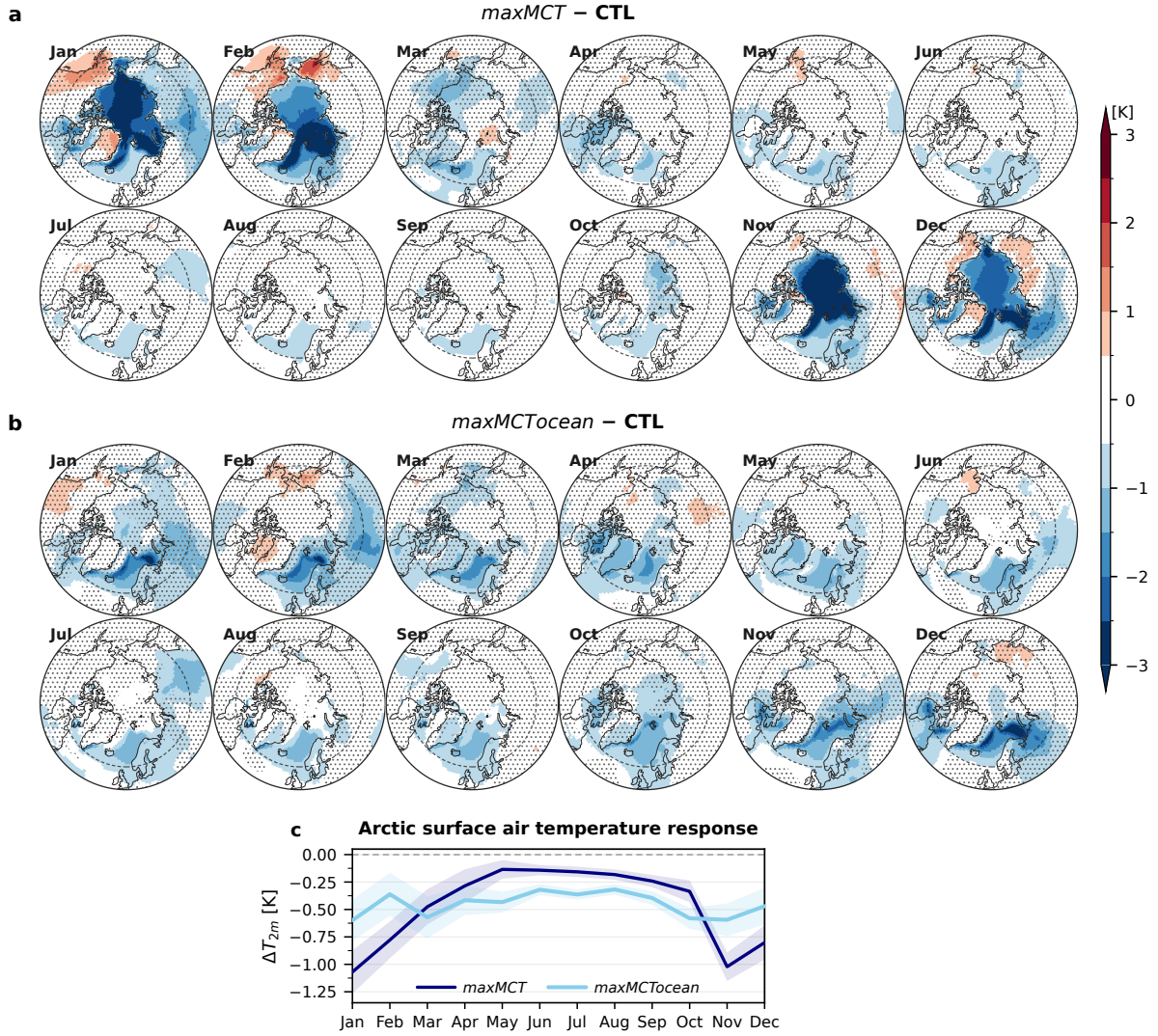


Figure S5: Seasonal evolution of the surface air temperature response to extreme MCT. a, Monthly surface air temperature response under the *maxMCT* scenario. Dots indicate responses that are not statistically significant ($p > 0.05$; two-sided Student's t -test using the effective sample size to account for temporal autocorrelation). **b,** As in **a**, but for the *maxMCTocean* scenario. **c,** Seasonal cycle of the Arctic-mean surface air temperature response, averaged over all grid cells north of 60°N , under the *maxMCT* (navy) and *maxMCTocean* (blue) scenarios. Shading denotes ± 1 standard error of the mean (SEM).

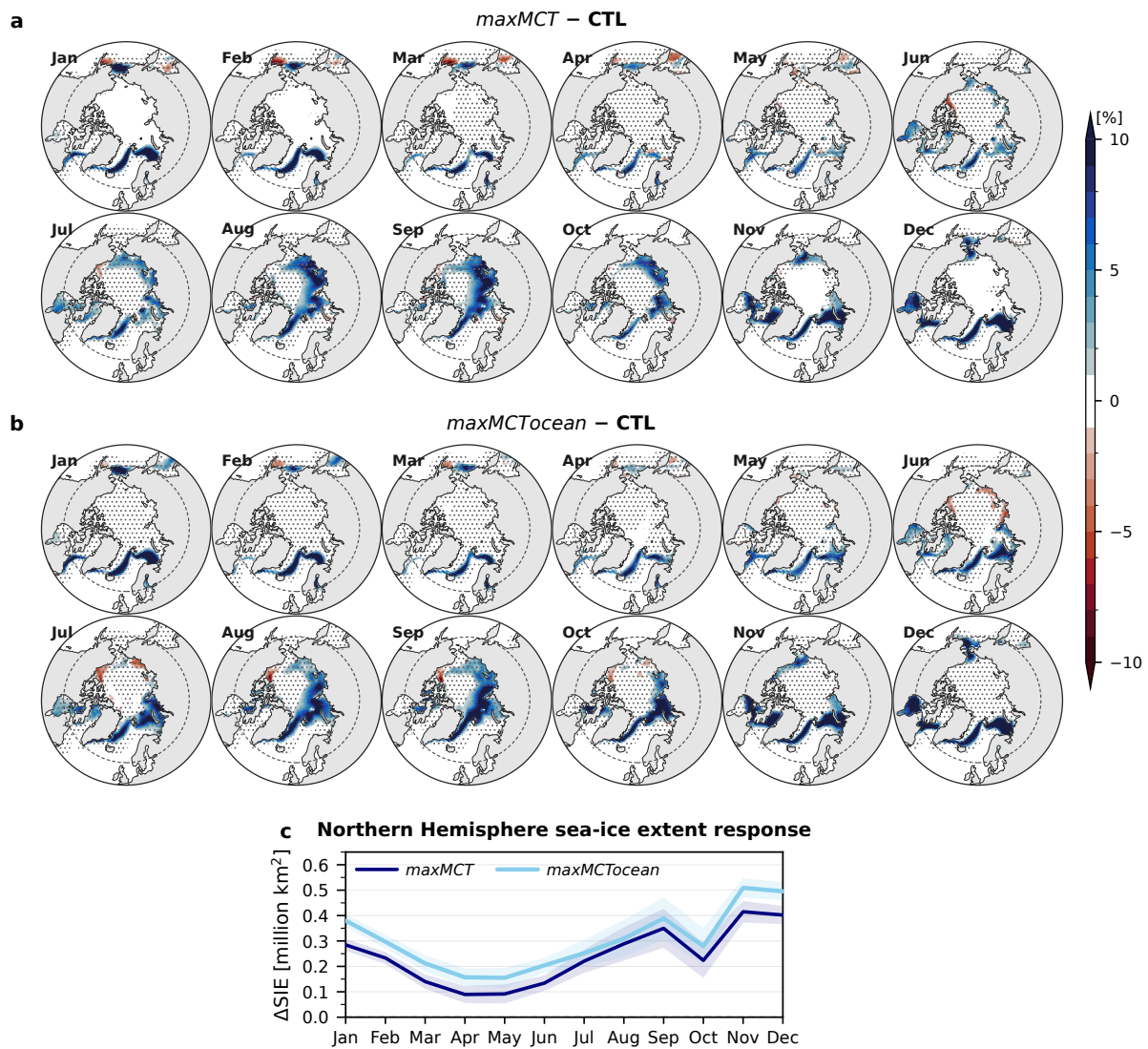


Figure S6: Seasonal evolution of the sea ice concentration response to extreme MCT. a–c, As in Figure S5, but for the sea ice concentration response.

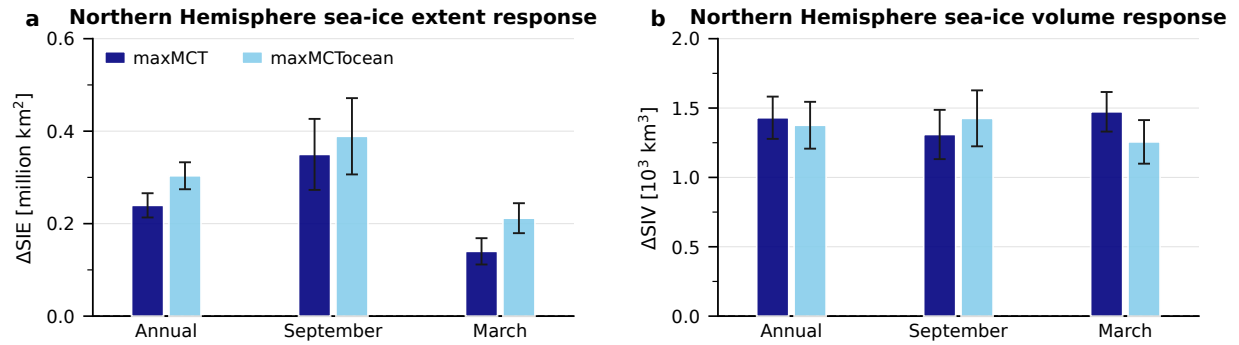


Figure S7: Northern Hemisphere sea-ice extent and volume response under extreme MCT.

a, Northern Hemisphere sea-ice extent (SIE) response for the annual mean, September minimum, and March maximum under the *maxMCT* (navy) and *maxMCTocean* (blue) scenarios. Error bars denote ± 1 standard error of the mean (SEM), computed using the effective sample size to account for temporal autocorrelation. **b**, As in **a**, but for sea-ice volume (SIV).

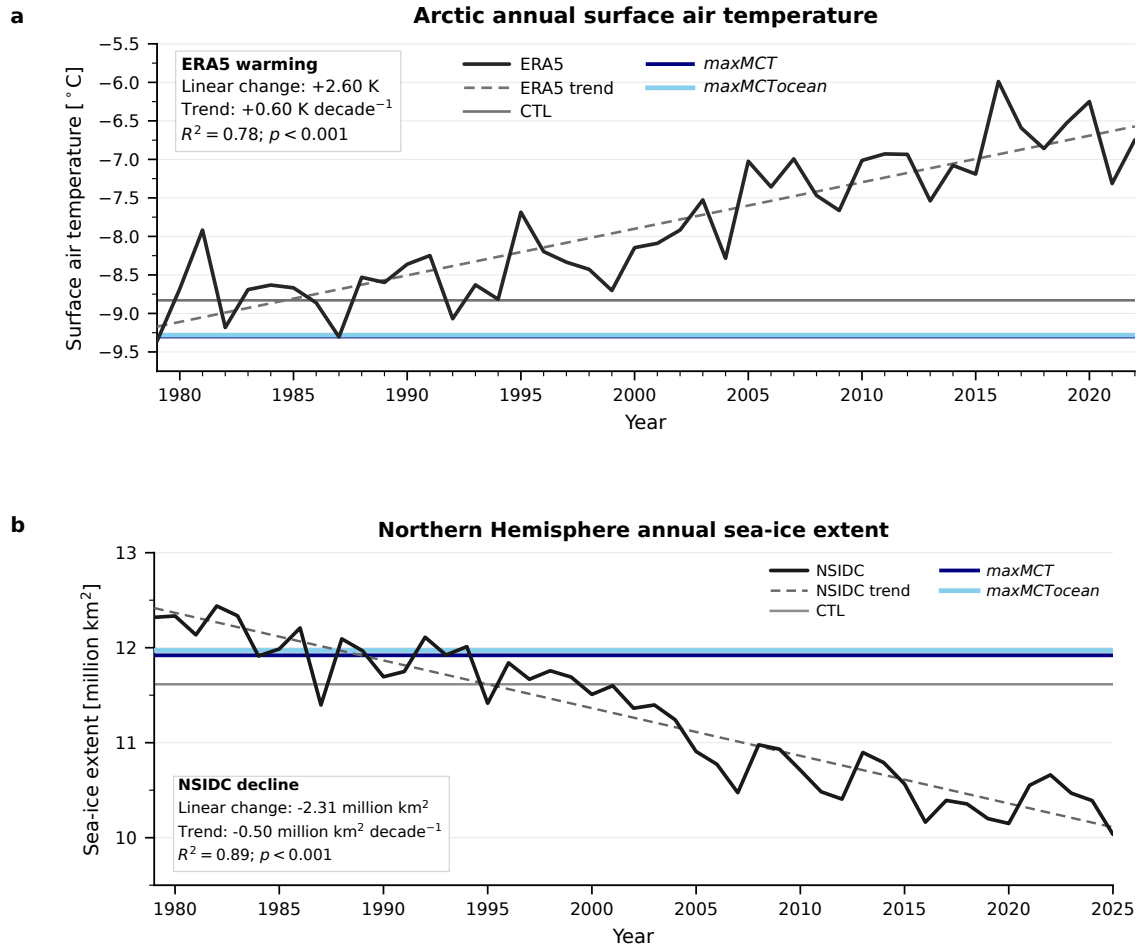


Figure S8: Extreme MCT response relative to recent Arctic climate change over the satellite era. a, Observed Arctic annual-mean surface air temperature from the ERA5 reanalysis (1979–2022; black). The gray dashed line shows the linear trend. Horizontal lines denote the climatological Arctic annual-mean surface air temperature from the control simulation (gray) and under the *maxMCT* (navy) and *maxMCTocean* (blue) scenarios. **b,** As in **a**, but for annual Northern Hemisphere sea-ice extent from the NSIDC Sea Ice Index (1979–2025).