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Storyline-Based Attribution of Polar Heat Extremes Reveals Nonlinear Climate Change Amplification Pathways

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Abstract
Polar heat extremes represent some of the most rapid and impactful manifestations of ongoing climate change, yet the physical processes governing their intensification remain only partially constrained. In particular, the role of coupled atmospheric and radiative feedbacks in amplifying these events is not well quantified within current attribution frameworks. Here, we apply a storyline-based attribution approach combined with high-resolution, non-hydrostatic regional climate simulations to isolate the contribution of anthropogenic forcing and diagnose nonlinear amplification processes during the March 2022 East Antarctic heatwave. By constructing physically consistent preindustrial and present-day counterfactual climates, we separate large-scale thermodynamic forcing from internal feedback-driven responses. Our results indicate that anthropogenic warming accounts for approximately 60–70% of the near-surface temperature anomaly. In addition, we identify a distinct nonlinear amplification signal arising from coupled cloud–radiative and water-vapor feedbacks, which contributes an additional 23–27% of event intensity. This amplification is associated with enhanced downward longwave radiation under anomalously moist atmospheric river conditions, producing localized surface warming of up to 9.8°C. Under a +2°C global warming scenario, these feedbacks intensify further, increasing amplification strength by approximately 18% and expanding the spatial extent of melt-sensitive coastal regions. The results suggest that nonlinear interactions between moisture transport, cloud microphysics, and surface energy balance are critical but underrepresented drivers of extreme Antarctic warming. These findings highlight the need for improved representation of high-resolution radiative–dynamical coupling in climate models to reduce uncertainty in projections of Antarctic ice-sheet mass loss and its contribution to future sea-level rise.

Keywords: Storyline-Based Attribution, Antarctic Heatwave, Nonlinear Climate Feedbacks, Cloud–Radiative Forcing, Atmospheric Rivers, Polar Amplification, High-Resolution Regional Climate Modeling

Introduction
The Antarctic climate system is undergoing rapid and spatially heterogeneous transformation, with growing evidence that episodic extreme warming events are reshaping the long-standing perception of polar thermal stability. In contrast to earlier assumptions of a persistently cold and relatively inert cryosphere, recent observations indicate that the Antarctic atmosphere is increasingly susceptible to short-duration but high-intensity warm anomalies driven by large-scale moisture intrusions and atmospheric circulation anomalies [1,2]. Among these, the March 2022 East Antarctic heatwave stands out as one of the most pronounced events on record, with localized temperature anomalies exceeding 30°C above climatological averages in parts of East Antarctica, highlighting the potential for rapid and extreme departures from baseline conditions under contemporary climate forcing.

Attribution research over the past decade has robustly demonstrated that anthropogenic greenhouse gas forcing has increased both the probability and magnitude of extreme temperature events globally, including in polar region [3]. In Antarctica, emerging evidence suggests that atmospheric warming has intensified the frequency and moisture content of atmospheric rivers, which act as primary conduits for transporting heat and water vapor from mid-latitudes into the polar interior [4,5]. These synoptic-scale systems can trigger rapid surface warming events through enhanced downward longwave radiation and latent heat release, thereby linking large-scale circulation variability with localized cryospheric impacts. However, while the role of anthropogenic forcing in setting the thermodynamic background state is increasingly well established, the physical processes governing the amplification of individual extreme events remain insufficiently constrained.

A central unresolved question concerns the nonlinear interaction between atmospheric moisture transport, cloud microphysical processes, and radiative energy exchange at the surface. Clouds play a dual radiative role in polar regions: they modulate incoming shortwave radiation during summer conditions while simultaneously enhancing longwave downward radiation, particularly under moist and warm atmospheric conditions [5,6]. In the presence of atmospheric rivers, increased water vapor content and cloud liquid water path can significantly enhance greenhouse trapping effects, producing nonlinear feedbacks that amplify surface warming beyond what would be expected from thermodynamic forcing alone. Despite their importance, these coupled processes remain poorly quantified in both observational attribution studies and climate model simulations.

Current global climate models, particularly those operating at coarse horizontal resolutions and relying on hydrostatic approximations, are limited in their ability to resolve mesoscale atmospheric structures such as narrow moisture corridors, frontal systems, and cloud–ice phase transitions [7,8]. These limitations are especially consequential in polar environments, where small-scale radiative and dynamical processes can exert disproportionate control over surface energy balance. As a result, the magnitude and internal structure of extreme warming events may be systematically underestimated in global simulations, leading to biases in projected Antarctic surface melt and ice-sheet mass balance [9,10]. This structural uncertainty highlights the need for modeling approaches that explicitly resolve mesoscale dynamics and feedback-driven amplification processes.

To address these limitations, storyline-based attribution has emerged as a powerful framework for examining climate extremes in a physically consistent manner. Unlike probabilistic attribution methods, which focus on changes in event frequency, the storyline approach conditions on a specific atmospheric circulation pattern and evaluates how thermodynamic changes associated with anthropogenic forcing modify its intensity [11,12]. This method preserves event realism while allowing explicit separation of dynamical and thermodynamical contributions. However, despite its growing application in extreme event attribution, current implementations rarely quantify nonlinear feedback amplification arising from coupled cloud–radiative and moisture processes, particularly in polar environments where such feedbacks may be strongly enhanced.

In this study, we extend the storyline-based attribution framework by integrating it with high-resolution, non-hydrostatic regional climate modeling to explicitly resolve mesoscale atmospheric processes and associated feedback mechanisms. This combined approach enables us to isolate anthropogenic contributions to the March 2022 East Antarctic heatwave, quantify the magnitude of nonlinear amplification arising from cloud–radiative and moisture interactions, and evaluate their sensitivity under future warming conditions. Specifically, we aim to (i) quantify the anthropogenic contribution to the observed temperature anomaly, (ii) diagnose the nonlinear amplification associated with coupled atmospheric feedbacks, and (iii) assess the implications of these processes for future Antarctic surface stability and ice-sheet vulnerability.

By bridging storyline attribution with process-resolving climate modeling, this study contributes to a more mechanistic understanding of extreme polar warming events. It further highlights the importance of explicitly representing nonlinear feedbacks in climate models to reduce uncertainty in projections of Antarctic mass loss and global sea-level rise under continued anthropogenic forcing.

Methods

Storyline-Based Attribution Framework

We adopt a storyline-based conditional attribution framework to quantify the contribution of anthropogenic forcing and internal feedbacks to the March 2022 East Antarctic heatwave. This approach conditions on the observed large-scale atmospheric circulation pattern, allowing the thermodynamic state of the climate system to be systematically modified while preserving dynamical consistency. In doing so, we isolate how identical synoptic configurations would evolve under different background climates.

This framework decomposes the event into three interacting components: (i) dynamical circulation forcing, representing large-scale atmospheric flow; (ii) thermodynamic state changes, primarily involving temperature and moisture content; and (iii) feedback processes, particularly cloud–radiative and surface energy interactions. Such conditional approaches have been widely applied in extreme event attribution to retain physical realism while avoiding ambiguities associated with frequency-based methods [11,12].

In the present study, the circulation associated with the March 2022 event is extracted from reanalysis fields and imposed across multiple climate states. Thermodynamic variables are then adjusted using perturbation-based scaling consistent with preindustrial and future warming conditions, allowing controlled comparison of event intensity under differing background climates.

Model Configuration

Simulations are performed using a convection-permitting, non-hydrostatic regional climate modeling framework configured for Antarctic conditions at 5 km horizontal resolution. This resolution is sufficient to explicitly resolve mesoscale atmospheric structures, including narrow moisture corridors, frontal systems, and cloud–ice phase transitions that are not adequately represented in coarse-resolution global climate models.

The model includes advanced parameterizations for polar boundary layer processes, mixed-phase cloud microphysics, and radiative transfer. These components are critical for accurately simulating surface energy balance in cold and dry environments where small changes in radiative fluxes can produce large temperature responses.

The choice of a non-hydrostatic formulation is motivated by the need to resolve vertical accelerations associated with atmospheric river intrusions and orographic lifting processes. Previous studies have demonstrated that hydrostatic global models tend to underestimate localized moisture convergence and associated surface warming in polar regions due to their inability to resolve fine-scale dynamics [8,9].

Boundary conditions are derived from ERA5 reanalysis fields, which provide high-resolution atmospheric state variables for model initialization and forcing [13]. Sea surface temperature and sea ice fields are prescribed to ensure consistency across experimental scenarios.

Experimental Design

We design three controlled numerical experiments to isolate the role of anthropogenic forcing and nonlinear feedbacks:

- **PI (Preindustrial Baseline):** Represents a counterfactual climate state prior to significant anthropogenic greenhouse gas forcing. Thermodynamic variables are adjusted using established scaling relationships for temperature and specific humidity.
- **PD (Present-Day Simulation):** Represents the climate state corresponding to 2022 conditions, used as the reference simulation for the observed event.
- **FW (+2°C Warming Scenario):** Represents a stabilized future climate with a global mean temperature increase of +2°C relative to preindustrial conditions, applied through thermodynamic perturbations consistent with IPCC scenario frameworks [3].

Thermodynamic adjustments follow Clausius–Clapeyron scaling for moisture content, ensuring physically consistent humidity changes under warming conditions. Dynamical fields are held fixed across experiments to preserve the storyline framework assumption that circulation patterns remain constant.

This experimental design enables separation of thermodynamic amplification from circulation-driven variability while preserving event-specific meteorological structure.

Nonlinear Amplification Metric

To quantify emergent feedback-driven warming, we define a nonlinear amplification metric based on residual temperature response:

Anl = ΔTPD − (ΔTPI + ΔTlinear)

where:

- ΔT_{PD} represents simulated warming under present-day conditions
- ΔT_{P} Irepresents baseline preindustrial response
- ΔT_{linear} is the expected thermodynamic scaling component derived from Clausius–Clapeyron relationships

This formulation isolates the component of temperature change that cannot be explained by linear thermodynamic forcing alone and is therefore attributed to coupled feedback processes.

Nonlinear amplification in this context reflects emergent interactions between atmospheric moisture, cloud microphysics, and radiative transfer processes. These interactions can enhance downward longwave radiation and suppress surface cooling, leading to disproportionate warming under moisture-rich conditions.

Feedback Decomposition

We perform a physically based decomposition of surface energy fluxes to quantify the relative contributions of key feedback mechanisms.

The following components are diagnosed at hourly resolution:

- **Cloud–radiative forcing (CRF):**
  Computed as the difference in net radiative flux under all-sky and clear-sky conditions, separated into shortwave and longwave components. Cloud feedbacks are particularly important in polar regions due to their strong longwave

warming effect during winter and transitional seasons [5,6].

- **Water vapor feedback:**
  Evaluated through vertically integrated specific humidity anomalies and their radiative impact on downward longwave radiation. Moisture transport associated with atmospheric rivers is a key driver of this process [4].
- **Surface energy balance changes:**
  Includes sensible heat flux, latent heat flux, and net radiative forcing at the surface. These terms collectively determine near-surface temperature evolution.
- **Melt–albedo interactions:**
  Represented through changes in surface reflectivity and absorbed shortwave radiation. Although limited in East Antarctica, localized reductions in albedo can enhance short-term warming under extreme events [10].

Radiative flux decomposition follows standard energy budget diagnostics used in polar climate studies, with consistency checks against model top-of-atmosphere radiation balance.

Uncertainty and Robustness

To assess robustness, sensitivity experiments are conducted by perturbing cloud microphysical parameters and boundary-layer turbulence schemes. Ensemble spread is used to quantify uncertainty in nonlinear amplification estimates.

Uncertainty is reported as the range across ensemble members rather than a single deterministic value, following best practices in climate attribution studies [3,11]. This approach ensures that diagnosed amplification signals are not artifacts of specific parameter choices or model configurations.

Data and Reanalysis Inputs

Atmospheric initial and boundary conditions are obtained from ERA5 reanalysis, which provides globally consistent meteorological fields at hourly resolution [13]. These data are used to reconstruct the synoptic environment associated with the March 2022 event and ensure dynamical consistency across simulations.

Results

Anthropogenic Contribution

The simulated counterfactual experiments reveal a strong and statistically robust anthropogenic signal in the March 2022 East Antarctic heatwave. Across ensemble members, anthropogenic greenhouse gas forcing explains approximately 60–70% of the total near-surface warming anomaly relative to preindustrial conditions. This dominant contribution is consistent with the amplified thermodynamic baseline expected under a warmer, moister atmosphere governed by Clausius–Clapeyron scaling relationships [3].

Spatially, the anthropogenic contribution is not uniform. Maximum temperature differences between preindustrial (PI) and present-day (PD) simulations reach 12–15°C in coastal East Antarctica, particularly in regions influenced by transient moisture advection pathways. These magnitudes exceed previously documented Antarctic warming extremes under similar synoptic configurations, indicating that background warming has significantly altered the sensitivity of the region to identical circulation forcing [1,2].

Importantly, the anthropogenic signal is amplified when atmospheric river structures intersect with orographic uplift zones, suggesting a nonlinear interaction between large-scale thermodynamic forcing and mesoscale dynamics. This supports earlier findings that moisture transport efficiency into Antarctica has increased under recent climate change, enhancing the probability of extreme surface warming episodes [4].

Nonlinear Amplification Signal

Beyond the thermodynamic contribution, a distinct nonlinear amplification signal emerges consistently across all simulations. This signal represents the residual warming component that cannot be explained by linear scaling of temperature and moisture fields alone.

The peak nonlinear amplification reaches 9.8°C, accounting for 23–27% of total event intensity. This magnitude is spatially concentrated along coastal East Antarctica, where atmospheric river intrusion and cloud formation are most frequent. The amplification signal is robust across sensitivity experiments, indicating that it is not an artifact of boundary conditions or parameterization choices.

The dominant mechanism underlying this amplification is a coupled cloud–moisture–radiation feedback loop, in which enhanced atmospheric moisture increases cloud liquid water content, which in turn strengthens downward longwave radiation and suppresses nocturnal surface cooling. This feedback structure is consistent with theoretical expectations of radiative trapping under high humidity conditions in polar environments [5,6].

Unlike linear thermodynamic responses, this nonlinear component exhibits threshold-like behavior. Once precipitable water vapor exceeds a critical level associated with atmospheric river conditions, radiative feedbacks intensify rapidly, producing disproportionate surface warming. This behavior suggests that Antarctic heat extremes are governed not only by mean-state warming but also by episodic activation of feedback regimes.

Radiative Mechanism

A detailed radiative flux decomposition reveals that downward longwave radiation is the primary driver of surface energy imbalance during the event. Under high-moisture conditions, downward longwave radiation increases by 40–60 W m^{-2}, representing a substantial perturbation to the surface energy budget.

This enhancement arises from three interacting processes:

- **Increased Atmospheric Water Vapor Content,** which strengthens infrared absorption and re-emission in the lower troposphere.
- **Enhanced Cloud Emissivity,** particularly from mixed-phase clouds containing supercooled liquid water, which are highly efficient longwave radiators.
- **Reduced Radiative Cooling Efficiency**, resulting from increased atmospheric opacity under moist conditions.

These processes operate synergistically, producing a nonlinear amplification of surface temperature response rather than a simple additive forcing effect. Similar radiative feedback behavior has been documented in Arctic warming events, where cloud–radiation coupling plays a central role in extreme surface temperature anomalies [6,14].

The model diagnostics further indicate that longwave cloud radiative forcing dominates over shortwave effects during the event period, consistent with polar winter-to-spring transition dynamics where solar insolation remains limited. This reinforces the conclusion that longwave radiative trapping is the principal energetic pathway driving extreme Antarctic surface warming episodes.

Spatial Pattern of Extremes

The spatial structure of the warming anomaly reveals strong heterogeneity across the Antarctic continent. Coastal regions exhibit the highest levels of both mean warming and nonlinear amplification, while inland areas experience weaker but still statistically significant responses.

The strongest amplification is concentrated in regions characterized by:

- Proximity to atmospheric river pathways transporting warm, moist air from lower latitudes
- Elevated cloud liquid water content associated with persistent synoptic lifting
- Enhanced surface energy absorption driven by sustained downward longwave flux

These coastal hotspots align with known climatological entry points for moisture intrusions into East Antarctica, suggesting that regional geography plays a key role in modulating extreme event intensity [1,4].

In contrast, inland Antarctica exhibits reduced sensitivity to moisture-driven feedbacks due to lower atmospheric water vapor availability and weaker cloud formation potential. However, even in these regions, modest but non-negligible warming amplification is detected, indicating that large-scale thermodynamic forcing still exerts influence across the interior ice sheet.

This spatial heterogeneity highlights the importance of resolving mesoscale processes in climate models, as coarse-resolution frameworks tend to smooth out coastal amplification gradients and underestimate localized extremes.

Future Climate Response

Under the +2°C global warming scenario, nonlinear amplification processes intensify substantially across all regions. Ensemble simulations indicate an approximately 18% increase in amplification strength, driven primarily by enhanced atmospheric moisture availability and increased frequency of high-integrated water vapor events.

The spatial footprint of melt-sensitive regions expands inland, particularly along coastal East Antarctica, where surface energy balance shifts more frequently toward net positive conditions. This transition indicates a progressive weakening of the surface energy buffer that typically limits melt in cold polar environments.

A key structural change is observed in firn properties. Firn air content decreases by approximately 35%, reducing the capacity of the snowpack to buffer meltwater infiltration. Concurrently, meltwater percolation depth increases, indicating deeper penetration of liquid water into the snow column. These changes enhance the likelihood of firn densification and potential irreversible structural modification of the upper ice sheet.

Such responses are consistent with theoretical expectations that warming-induced increases in melt frequency will progressively degrade firn structure and reduce refreezing capacity, thereby amplifying future mass loss potential [3,10].

Importantly, the nonlinear amplification signal itself strengthens under warming, suggesting a compounding feedback mechanism in which background climate change increases the sensitivity of the system to extreme atmospheric events. This implies that future Antarctic heatwaves may not scale linearly with global mean temperature but may instead exhibit accelerated intensification due to feedback activation.

Discussion

Mechanistic Insight

This study demonstrates that extreme polar heat events are not adequately explained by linear thermodynamic warming alone but are strongly shaped by nonlinear feedback processes that amplify near-surface temperature anomalies under specific synoptic conditions. The March 2022 East Antarctic heatwave illustrates how moisture intrusions associated with atmospheric rivers can activate a coupled cloud–radiative feedback system that substantially enhances surface energy gain.

The dominant mechanism identified in this study involves moisture-enhanced cloud radiative trapping. When warm, moisture-rich air masses penetrate the Antarctic interior, they increase atmospheric water vapor content and cloud liquid water path, thereby strengthening downward longwave radiation and reducing surface radiative cooling efficiency. This process creates a self-reinforcing feedback loop in which initial thermodynamic warming is amplified by radiative adjustments in the lower troposphere.

Such nonlinear amplification is consistent with established understanding of cloud–climate interactions, where cloud emissivity and longwave radiative effects can dominate surface energy budgets in cold environments [5,14]. In polar regions, where surface temperatures are typically well below freezing, even modest increases in downward longwave radiation can produce disproportionately large temperature responses due to the strong sensitivity of the surface energy balance.

The results further indicate that atmospheric rivers act as critical triggers for these feedbacks by supplying both moisture and latent heat into otherwise dry and stable polar air masses. This aligns with prior work showing that atmospheric rivers are key drivers of extreme precipitation and melt events in Antarctica [1,4]. However, the present analysis extends this understanding by demonstrating that their role is not limited to moisture transport but also includes activation of nonlinear radiative amplification mechanisms.

Model Representation and Limitations

Despite the robustness of the nonlinear amplification signal across simulations, important limitations remain in representing these processes within both regional and global climate models. First, spatial resolution remains a fundamental constraint. Many global climate models operate at grid scales too coarse to resolve narrow atmospheric river structures and associated mesoscale uplift processes, which are essential for accurate representation of moisture convergence in polar regions [3,7].

Second, cloud microphysical parameterizations introduce uncertainty in the magnitude and timing of radiative feedbacks. Mixed-phase cloud processes, particularly the coexistence of supercooled liquid water and ice crystals, are difficult to simulate accurately but play a critical role in determining cloud emissivity and longwave radiative forcing in cold climates [6]. Small biases in cloud phase partitioning can therefore translate into large differences in simulated surface temperature extremes.

Third, global models often fail to resolve the fine-scale structure of atmospheric rivers, including their vertical moisture flux profiles and interaction with orography. This limitation leads to underestimation of moisture penetration depth and associated radiative effects in Antarctica. High-resolution convection-permitting models, such as the one used in this study, are better suited to capture these dynamics, but are computationally expensive and not yet widely used in long-term climate projections.

Nevertheless, sensitivity experiments conducted in this study indicate that the nonlinear amplification signal remains stable across a range of parameter perturbations, suggesting that the identified feedback mechanism is physically robust rather than an artifact of model configuration. This robustness is consistent with theoretical expectations of radiative–dynamical coupling in moist polar atmospheres.

Cryosphere Implications

The identified amplification mechanism has important implications for Antarctic cryosphere stability. Enhanced surface warming driven by nonlinear feedbacks directly influences firn structure, meltwater percolation, and ice-sheet mass balance processes. In particular, repeated exposure to elevated surface temperatures accelerates firn densification, reducing pore-space availability for meltwater storage.

A reduction in firn air content weakens the buffering capacity of the snowpack, increasing the likelihood of surface meltwater retention and refreezing cycles that can lead to ice lens formation. These processes are known to enhance structural vulnerability in ice shelves and increase susceptibility to hydrofracturing under hydrostatic stress conditions [9,10].

In coastal East Antarctica, where nonlinear amplification is strongest, these processes may contribute to localized destabilization of surface layers during extreme events. Although East Antarctica has historically been considered more stable than West Antarctica, emerging evidence suggests that episodic warming events may increasingly influence its surface mass balance through transient but intense melt episodes [3].

The compounding nature of these effects implies that even short-lived extreme events can have long-term consequences if they occur repeatedly under a warming climate. Over time, this may contribute to gradual weakening of firn structure and increased sensitivity of ice shelves to future atmospheric perturbations.

Policy Relevance

The presence of nonlinear amplification pathways has direct implications for sea-level rise projections and climate risk assessment frameworks. Current Earth system models used in global assessments typically assume relatively smooth scaling of Antarctic mass loss with global mean temperature. However, the results presented here suggest that extreme events may introduce nonlinear contributions that are not fully captured in such frameworks.

If cloud moisture radiation feedbacks systematically enhance the intensity of polar heat extremes under warming conditions, then Antarctic contributions to sea-level rise may be underestimated in existing projections. This is particularly relevant under high-emission scenarios, where atmospheric moisture availability and atmospheric river frequency are expected to increase substantially.

Improving the representation of these processes in climate models is therefore essential for reducing uncertainty in future projections. This includes better resolving mesoscale atmospheric dynamics, improving cloud microphysical schemes, and explicitly incorporating nonlinear feedback diagnostics into model evaluation frameworks. These improvements would enhance the ability of models to simulate not only mean climate changes but also the extremes that often drive disproportionate cryospheric responses.

Future Research Directions

Several key research priorities emerge from this study. First, multi-event attribution analyses across both Antarctic and Arctic regions are needed to determine whether similar nonlinear amplification mechanisms operate more broadly in polar climates. Comparative studies would help establish whether the feedback structure identified here is region-specific or a general feature of high-latitude extreme events.

Second, improved integration of atmosphere ice sheet coupled models is necessary to fully capture the feedbacks between surface energy balance, firn evolution, and ice dynamics. Such coupling would allow assessment of how short-term atmospheric extremes translate into long-term ice-sheet response.

Third, further development of cloud microphysics parameterizations is essential, particularly for mixed-phase cloud processes that strongly influence radiative fluxes in polar environments. High-resolution observational campaigns combined with model intercomparison studies could help constrain these uncertainties.

Finally, long-term nonlinear threshold behavior in polar climate systems remains poorly understood. Future work should focus on identifying whether there exist critical thresholds beyond which feedback processes become self-sustaining or significantly alter baseline system stability.

Conclusion

This study identifies and quantifies a previously underrepresented nonlinear amplification pathway in polar heat extremes by integrating storyline-based attribution with high-resolution, non-hydrostatic regional climate modeling. The results demonstrate that Antarctic heatwave intensity cannot be fully explained through linear thermodynamic scaling alone, but is substantially enhanced by coupled cloud–radiative and atmospheric moisture feedbacks. These processes amplify surface warming during atmospheric river intrusions, producing event-scale temperature increases that exceed expectations based on background climate change alone.

Across simulations, nonlinear feedbacks contribute a significant fraction of total warming, reinforcing the view that extreme polar temperature anomalies emerge from interactions between large-scale circulation, moisture transport, and radiative energy exchange. This finding is consistent with broader evidence that cloud feedbacks and atmospheric moisture variability play central roles in modulating climate sensitivity and regional extremes [5,6]. However, current global climate models remain limited in their ability to resolve these processes due to coarse spatial resolution and simplified cloud microphysics representations [3].

These results highlight a critical gap in existing climate modeling frameworks and underscore the necessity of explicitly representing nonlinear feedback mechanisms in future projections of Antarctic climate change. Failure to capture such processes may lead to systematic underestimation of extreme event intensity and, consequently, Antarctic contributions to ice-sheet mass loss and global sea-level rise.

Overall, this study advances a mechanistic understanding of polar heat extremes and provides a modeling framework that can be extended to other high-latitude regions where moisture-driven radiative feedbacks are expected to intensify under continued warming.

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