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Projected Antarctic Land Warming and Uncertainty Driven by Atmospheric Heat Transport

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Key Points:

- Meridional Atmospheric heat transport (AHT), particularly latent energy (LE) transport, serves as the primary driver of Antarctic land warming
- LE transport delivers heat to Antarctic land surface, boosting moisture and amplifying the regional water vapor feedback
- The uncertainty in Antarctic land warming projections is closely linked to variations in the strength of AHT

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract A significant warming is projected in Antarctic climate change under high CO_2 forcing, involving complex interactions between ocean and land surfaces. While previous studies have emphasized the seasonal mechanism driving Antarctic ocean surface warming, the processes governing land surface warming remain less explored. Here we show that, under abrupt quadrupled CO_2 forcing, Antarctic land surface experiences uniform warming throughout the year, primarily driven by poleward atmospheric heat transport, with latent energy transport playing a dominant role. This moisture-related transport not only delivers energy but also amplifies the water vapor feedback, significantly contributing to the warming. Our findings suggest that the discrepancies in representing these atmospheric processes across models, contribute substantially to the uncertainties in Antarctic land surface warming projections. The result emphasizes the need for improved understanding of the atmospheric dynamics in polar regions to reduce model uncertainties under future climate scenarios.

Plain Language Summary To project the surface warming of Antarctic under high-emission scenarios, we utilize the pre-industrial and abrupt quadrupled CO_2 (abrupt-4 × CO_2) experiments from 18 Coupled Model Intercomparison Project Phase 6 models. The surface temperature response is analyzed using the climate feedback-response analysis method. Our research highlights significant warming differences between the ocean and land surfaces: the ocean surface exhibits strong winter warming and weak summer warming attributable to the seasonal energy transfer mechanism; in contrast, land surface warming is relatively weak and more uniform throughout the year, primarily driven by poleward atmospheric heat transport (AHT), with latent energy (LE) transport playing a central role in both energy delivery and the amplification of water vapor (WV) feedback. The inter-model spread in land warming is closely tied to the variations in the strength of AHT, particularly the transport of LE, which influences regional WV content. Understanding these mechanisms is crucial for advancing future climate changes in the Antarctic region.

1. Introduction

Polar amplification, in which polar regions warm faster than the global average (Holland & Bitz, 2003; Manabe & Stouffer, 1980; Stuecker et al., 2018), has been studied extensively for the Arctic, where observed warming is two to four times greater than the global mean (Pithan & Mauritsen, 2014; Rantanen et al., 2022; Serreze et al., 2009). This enhanced warming, known as Arctic Amplification, is driven by well-understood processes, including sea ice decline, albedo feedback, lapse-rate feedback, and dynamic interactions between oceans and the atmosphere (Boeke et al., 2021; Dai et al., 2019; Hahn et al., 2022; Pithan & Mauritsen, 2014; Previdi et al., 2021; Taylor et al., 2022). Unlike the Arctic, where lapse rate feedback contributes strongly to surface warming by enhancing the vertical temperature gradient (Pithan & Mauritsen, 2014), the Antarctic lapse rate feedback behaves differently due to the continent's high elevation and unique atmospheric stratification. Previous studies have shown that the steep topography of Antarctica can suppress wintertime surface warming by stabilizing the lower troposphere, leading to a weaker lapse rate feedback compared to the Arctic (Hahn et al., 2020). This hemispheric asymmetry in lapse rate feedback is a key factor in the differences between Arctic and Antarctic warming responses. In contrast, Antarctic Amplification has been less prominent in both observations and climate simulations (Marshall et al., 2014; Salzmann, 2017; Wang et al., 2021), with significant uncertainties surrounding the mechanisms that drive Antarctic warming, particularly over land surface (Jones et al., 2019; Ludescher et al., 2016; Turner et al., 2005).

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The complexity of the Antarctic climate system, characterized by unique land-sea distribution and high elevation, has challenged full understanding of its response to rising CO_2 levels (Turner & Overland, 2009). Although Arctic Amplification is currently the most dominant phenomenon, model simulations suggest that, with sufficient external forcing and extended response time, Antarctic Amplification could reach an extremely high level and reverse the level of Arctic Amplification (Sadai et al., 2020; Siegert et al., 2020). This potential shift underscores the importance of investigating the processes driving the Antarctic warming. While previous studies have identified sea ice-ocean interactions and seasonal energy transfer mechanisms as key contributors to Antarctic Amplification, these processes are primarily associated with ocean surface warming (Boeke & Taylor, 2018; Hahn et al., 2022; Zhang et al., 2023). In contrast, Antarctic land warming has received less attention, although it has been attributed to the high elevation of the Antarctic Plateau. Moreover, significant inter-model spread in the projections of Antarctic land warming persists, due likely to the uncertainties in how different models represent atmospheric processes (Dai, 2024; Ludescher et al., 2016; Xin et al., 2023).

In this study, we focus on the role of atmospheric heat transport, particularly the poleward transport of LE, in driving Antarctic land warming under abrupt quadrupled CO_2 forcing. While previous studies have highlighted the importance of atmospheric dynamics in polar warming (Alexeev & Jackson, 2013; Cai, 2005), few have quantified how these processes contribute specifically to Antarctic land warming. Additionally, the contribution of WV feedback to this warming, and its role in amplifying temperature change, remain insufficiently understood in the Antarctic context.

Here, we particularly address the above knowledge gap by investigating the mechanisms for Antarctic land warming and analyzing the inter-model uncertainty and associated physical processes. By examining how LE transport influences the WV feedback and Antarctic land surface warming, we provide a new insight into the key drivers of Antarctic land warming under future climate scenarios. Our findings highlight the need for improved representation of AHT in climate models to reduce the uncertainties in projections of climate change over the Antarctic land.

2. Data and Methods

2.1. Data

The monthly climate data from the abrupt quadrupled CO_2 (abrupt-4 × CO_2) and pre-industrial experiments of Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016) are utilized in this study. Table S1 in Supporting Information S1 lists the 18 CMIP6 climate models and their details. We analyze the climate response to CO_2 increase by comparing the mean of the last 20 years from the 150-year abrupt-4 × CO_2 experiments with the mean of the last 50 years from the pre-industrial experiments.

2.2. Climate Feedback-Response Analysis Method

Climate feedback-response analysis method (CFRAM) is employed to decompose the simulated surface warming into partial temperature changes (PTCs) attributed to external forcing (CO_2 increase) and individual feedback processes (Lu & Cai, 2009a). Further details about this method are provided in Text S1 in Supporting Information S1. The feedbacks include radiative feedbacks composed of albedo (AL), WV, cloud shortwave (CLDS), and cloud longwave effect (CLDL), as well as non-radiative feedbacks, which involve atmospheric horizontal large-scale circulation and vertical convection (ATM), ocean circulation and heat storage (OCH), surface sensible and latent heat fluxes (SH + LH), namely,

$$\Delta \mathbf{T} = \Delta \mathbf{T}^{CO_2} + \Delta \mathbf{T}^{AL} + \Delta \mathbf{T}^{WV} + \Delta \mathbf{T}^{CLDS} + \Delta \mathbf{T}^{CLDL} + \Delta \mathbf{T}^{ATM} + \Delta \mathbf{T}^{OCH} + \Delta \mathbf{T}^{SH+LH} \quad (1)$$

The inter-model spread is defined as the difference between the simulation of each individual model and the multi-model ensemble (MME) mean.

2.3. Meridional Atmospheric Heat Transport

As indicated by previous studies (Donohoe et al., 2020; Fajber et al., 2023), annual-mean meridional AHT (AHT) at a given latitude (φ) can be estimated by integrating the heat flux of the atmospheric column (Q_{atm}) from the South Pole to latitude φ under the assumption of no energy storage in the atmosphere:

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$$\mathrm{AHT}(\varphi) = 10^{-15} \cdot 2\pi R^2 \int_{-\frac{\pi}{2}}^{\varphi} \cos(\varphi') \cdot Q_{\mathrm{atm}}(\varphi')\,\mathrm{d}\varphi' \tag{2}$$

where R is the Earth's radius, and φ' denotes the latitude at which the integration is performed. Q_{atm} ($=Q_{TOA} - Q_{sfc}$) represents the difference between the net heat flux at the top of the atmosphere and that on the surface. In the analysis of long-term climatological states, kinetic energy transport is typically neglected. AHT is often approximated as moist-static energy transport, which consists of LE and dry-static energy (DSE) transport (Caballero & Langen, 2005). Similarly, LE transport can be inferred from the moisture imbalance with no moisture storage:

$$\mathrm{LE}(\varphi) = 10^{-15} \cdot 2\pi R^2 \int_{-\frac{\pi}{2}}^{\varphi} \cos(\varphi') \cdot (E(\varphi') - P(\varphi')) \cdot L_{\mathrm{vap}}\mathrm{d}\varphi' \tag{3}$$

where E is evaporation, P is precipitation, and L_{vap} is the latent heat of vapourization constant for water. Dry-static energy transport is then recognized as the residual between AHT and LE. In abrupt-4 $\times$ CO_2 simulations, the equations include additional terms for energy or moisture storage in the atmosphere. However, our focus is on the quasi-equilibrium state here, where these storage terms become negligible as the system has largely stabilized.

3. Results

3.1. Dominant Role of AHT in Antarctic Land Warming

In this section, we focus on the mechanisms driving the seasonally uniform Antarctic land warming under the abrupt quadrupled CO_2 (abrupt-4 $\times$ CO_2) scenario, with particular emphasis on the contribution of AHT. Figure 1 illustrates the surface warming across the Antarctic for the annual, winter (JJA), and summer (DJF) means. The oceans exhibit stronger warming than the land, especially during winter (Figures 1b–1d), showing an apparent winter amplification. This feature is attributed to sea ice decline and the well-documented seasonal energy transfer mechanism (SETM; Zhang et al., 2023). During summer, sea ice retreat allows oceans to absorb more solar radiation, with heat stored and subsequently released during winter, amplifying the warming during the colder months. This SETM is clearly reflected in the partial temperature changes (PTCs) over the oceans, derived using the Climate Feedback-Response Analysis Method (CFRAM; Lu & Cai, 2009a), as shown in Figure 2 (bottom panel).

In contrast, Antarctic land warming is more uniform throughout the year. The CFRAM-derived PTCs quantitatively reveal that the primary contributor to this warming is atmospheric dynamic term (PTC_ATM, top panel in Figure 2). This term includes both horizontal energy redistribution via large-scale advection and vertical energy exchange through convective systems (Cai, 2005, 2006; Lu & Cai, 2010). Atmospheric heat transport plays an important role in the atmospheric term and amplifies polar warming by redistributing energy from lower latitude to polar region (Taylor et al., 2013). Following this dominant AHT-driven amplification, contributions from quadrupled CO_2 forcing and WV feedback, further intensifies the warming. These processes combine to make AHT a critical driver of Antarctic land surface warming under abrupt 4 $\times$ CO_2 forcing.

3.2. Latent Energy Transport and Its Contribution to Water Vapor Feedback

In the preceding section, we examine the seasonal variations in Antarctic land warming. The results demonstrate that AHT plays a crucial role in Antarctic land warming, consistent with its well-established role as a vital component of the global climate system (Alexeev & Jackson, 2013; Cai, 2005; Yoshimori et al., 2017). However, the seasonality of Antarctic land warming and associated temperature changes driven by AHT are relative weak. To gain a deeper understanding of the long-term energy balance, we now shift our focus to annual mean quantities. In this context, we decompose the total AHT into LE transport and dry-static energy (DSE) transport to explore the relative contributions of wet and dry processes, as well as their connection to WV feedback.

LE represents the energy associated with WV. Its transport, calculated as the product of WV content and the latent heat of vapourization, is linked to phase changes through its role in balancing the energy exchange during evaporation and condensation processes (Graversen & Burtu, 2016), while DSE is related to temperature

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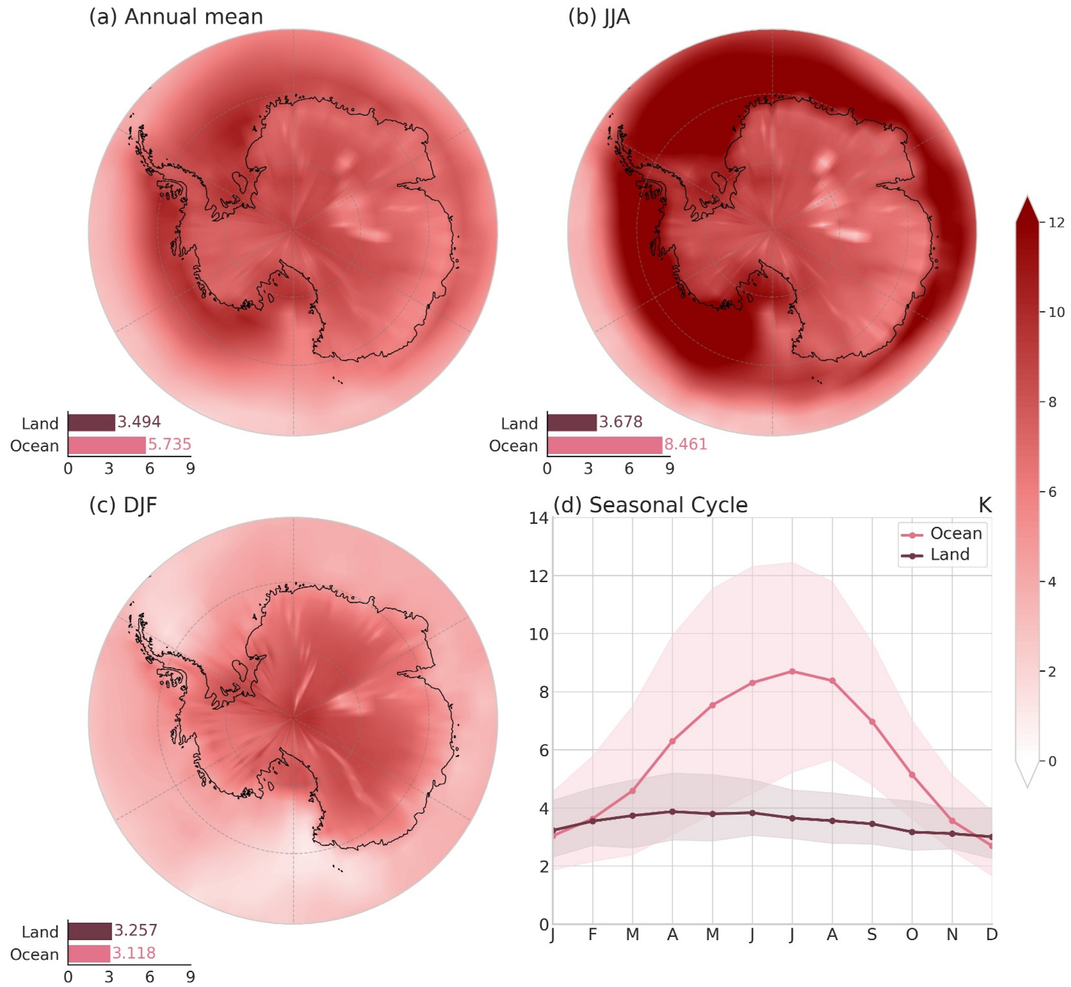

Figure 1. Spatial distribution and season cycle of Antarctic surface warming under quadrupled CO_2 forcing. (a–c) Antarctic surface temperature response (K) of the annual, winter (JJA), and summer (DJF) means. The warming values of land and ocean surfaces are indicated at the lower left of each panel. (d) Is the seasonal cycle of warming for the ocean (red) and land (brown) surfaces, with shading representing the 25th to 75th percentiles across 18 models.

distribution and large-scale atmospheric dynamics (Langen & Alexeev, 2007). We analyze the transports of AHT, LE, and DSE before and after quadrupled CO_2 forcing, and assess the resulting anomalies (Figure 3).

Climatologically, AHT transports energy from the equator toward the South Pole, driven by the uneven latitudinal distribution of solar radiation (Figures 3a and 3d). As seen in previous studies, the peak southward transport occurs around 40°S (Armour et al., 2019; Fajber et al., 2023; Trenberth & Caron, 2001). The transport of DSE remains consistently poleward (Figures 3c and 3f). In the tropics, LE transport is dominated by the Hadley Circulation (Trenberth & Stepaniak, 2003), moving heat toward the equator (Figures 3b and 3e). Outside the tropics, eddy activity facilitates a poleward LE transport (Yang et al., 2015).

Under quadrupled CO_2 forcing, AHT shows a poleward transport anomaly into the Antarctic around 60°S (Figure 3g). Although this MME anomaly (around 0.12 PW) is relatively small, its impact on regional climate variation can still be significant. For comparison, a 0.5 PW change in energy transport for Earth's surface north of 40°N corresponds to an atmospheric radiative forcing of 9 W/m^2, far exceeding the radiative flux anomaly caused by CO_2 doubling (Wunsch, 2005). However, as the poleward transport weakens toward the Antarctic, it decreases to approximately 0.04 PW at 70°S, primarily due to the predominance of radiative cooling (Trenberth & Stepaniak, 2003). Given the limited heat capacity of the ice sheet, this relatively weak AHT leads to a pronounced warming response over the continent. In the latitude band between 60°S and 70°S, while the atmospheric energy retention is 0.08 PW (i.e., 0.12 PW minus 0.04 PW), oceanic processes play a dominant role, with the atmospheric

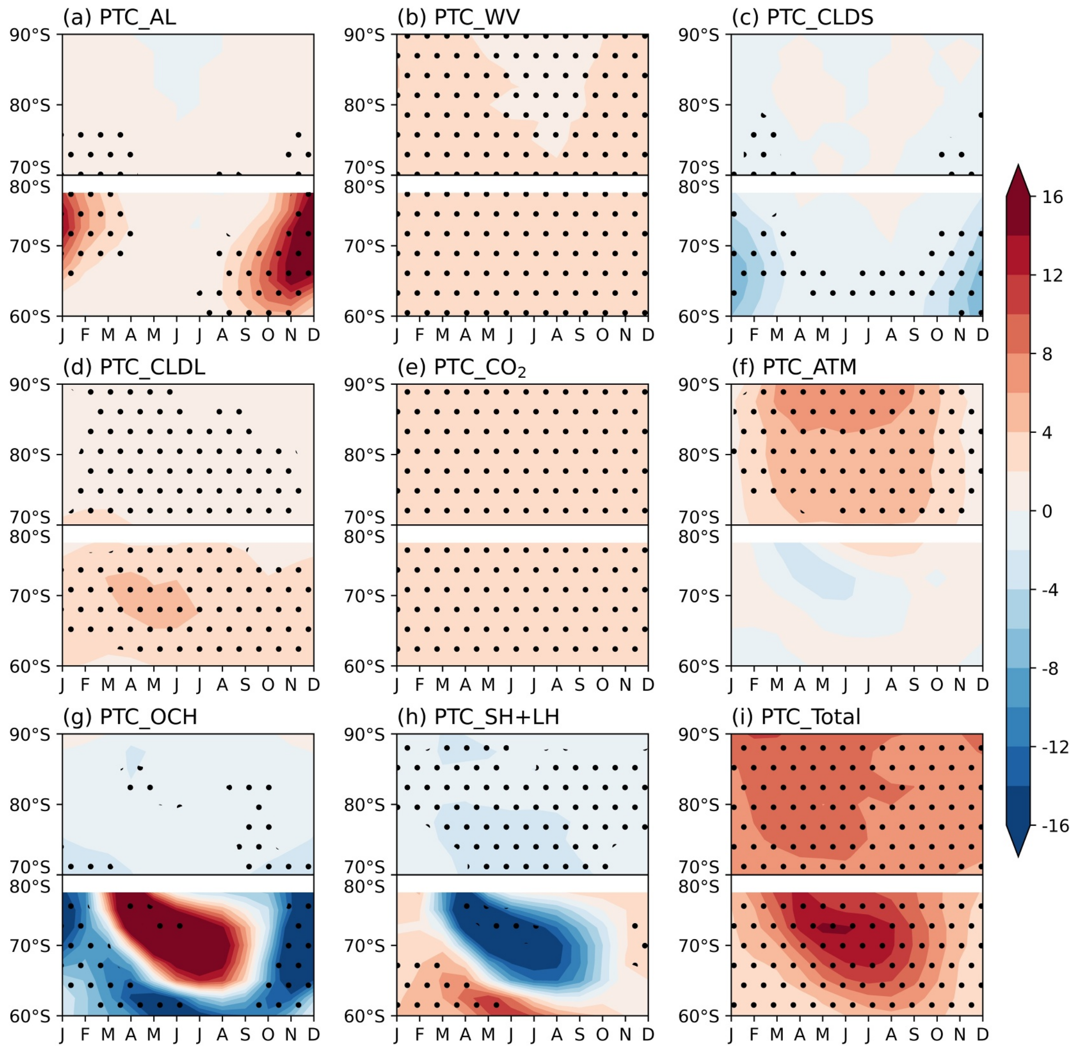

Figure 2. Seasonal cycles of zonal-mean total and partial temperature changes (PTCs) due to individual processes over land (top panel) and ocean (bottom panel) surfaces. (a–h) PTCs (K) caused by the changes in panels (a) surface albedo, (b) water vapor, (c) cloud shortwave effect, (d) cloud longwave effect, (e) quadrupled CO_2 concentration, (f) atmospheric horizontal large-scale circulation and vertical convection, (g) ocean circulation and heat storage, and (h) surface sensible and latent heat fluxes. (i) Total surface warming, representing the sum of the PTCs from (a) to (h). Black dots indicate the regions where the changes are statistically significant at the 95% confidence level.

influences being comparatively minor. These factors collectively explain why, despite the relatively small magnitude of AHT at 70°S, it induces a more significant warming response over the Antarctic continent, while the warming effect over the Antarctic ocean surface is comparatively weaker (Figure 2f). As polar amplification reduces the meridional temperature gradient, DSE transport into the Antarctic decreases (Figure 3i; Hwang et al., 2011). However, increasing specific humidity in tropical regions strengthens the humidity gradient, thereby enhancing the poleward moisture transport in a warming climate (Figure 3h; Graversen & Burtu, 2016). The intensified LE transport surpasses the reduction in DSE transport, leading to a net increase in AHT and positive PTC_ATM over the Antarctic.

The strong correlation between Antarctic-averaged land PTC_ATM and both AHT and LE transport anomalies entering the Antarctic land surface at 70°S (Figures 4a and 4b) further validates the dominant role of LE transport. Correlation coefficients of 0.85 for AHT and 0.87 for LE both pass the 99% confidence level of significance test. In contrast, DSE transport does not show a significant correlation with PTC_ATM (Figure 4c). This feature confirms that the increase in AHT toward the Antarctic is primarily driven by enhanced LE transport. In addition

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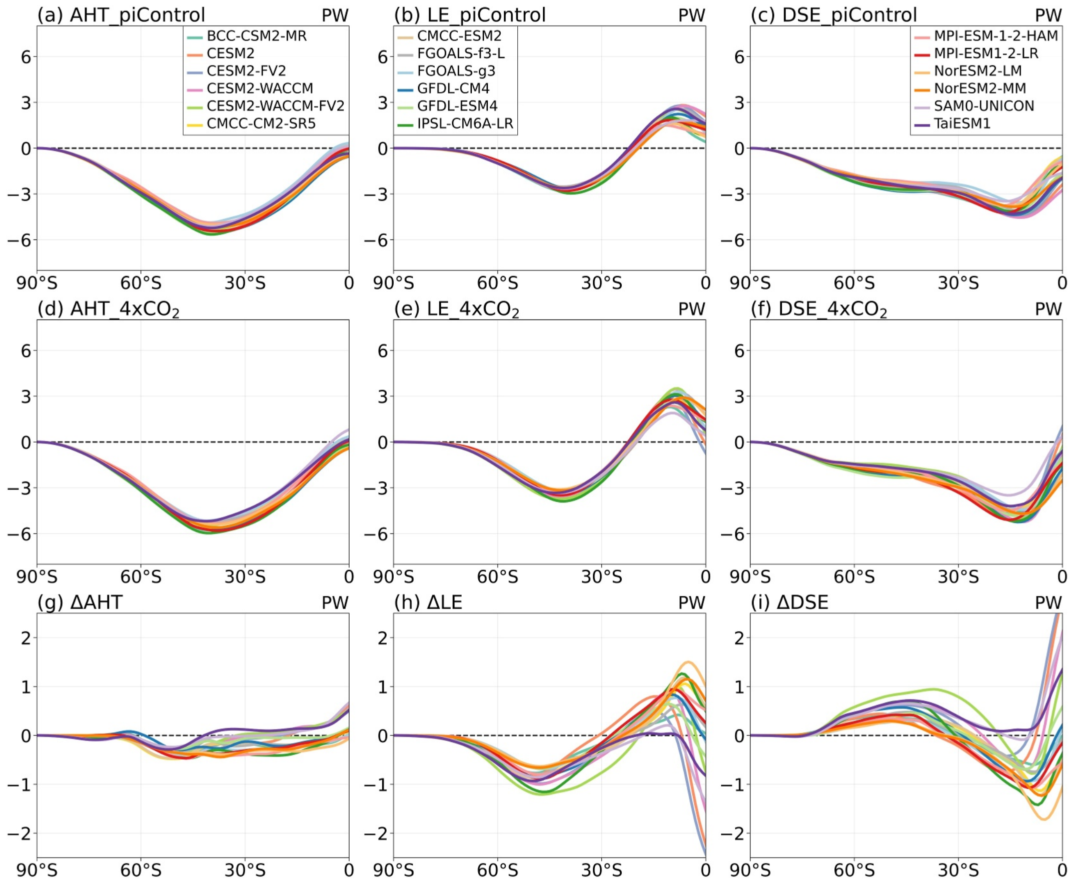

Figure 3. Annual-mean meridional atmospheric heat (AHT), latent energy (LE), and dry-static energy (DSE) transport in the Southern Hemisphere. (a–c) AHT, LE, and DSE transports (in petawatts, PW) in the piControl experiment across 18 climate models. (d–f) Corresponding transports in the abrupt $4 \times CO_2$ experiments. (g–i) Anomalies between the abrupt $4 \times CO_2$ and piControl experiments, where positive values indicate northward heat transport.

to delivering energy to the land surface, LE transport increases regional WV content, amplifying the WV feedback (Figures 4d and 4e).

In conclusion, enhanced poleward transport of LE plays a dominant role in Antarctic land surface warming by directly transporting energy and intensifying the WV feedback. The relationship between LE transport and WV feedback underscores the importance of accurately representing these processes in climate models to better project future Antarctic climate dynamics.

3.3. Drivers of Inter-Model Spread in Antarctic Land Warming Projections

As shown in Figure 1d, the inter-model spread in Antarctic land warming remains relatively uniform throughout the year, in contrast to the ocean surface warming, where larger variability is observed. This difference suggests that the mechanisms driving Antarctic land and ocean warmings are distinct, and the sources of inter-model spreads for ocean and land surface warmings also differ from each other.

Figure S1 in Supporting Information S1 depicts the relationship between the uncertainties of total and PTCs over the Antarctic land surface, with the ocean surface counterpart in Figure S2 in Supporting Information S1. Under CO_2 forcing, rising temperatures enhance atmospheric WV levels, amplifying the greenhouse effect and forming a positive feedback loop that strengthens surface warming (Dessler et al., 2008). Therefore, the inter-model spread induced by WV feedback correlates strongly with that in total warming over both ocean and land surfaces (Figures S1b and S2b in Supporting Information S1). For the Antarctic land surface, there is a significant correlation between the inter-model spread in PTC_ATM and the overall warming ($r = 0.96$, $p < 0.01$; Figure S1f in Supporting Information S1). This atmospheric dynamic term is closely linked to AHT, particularly the

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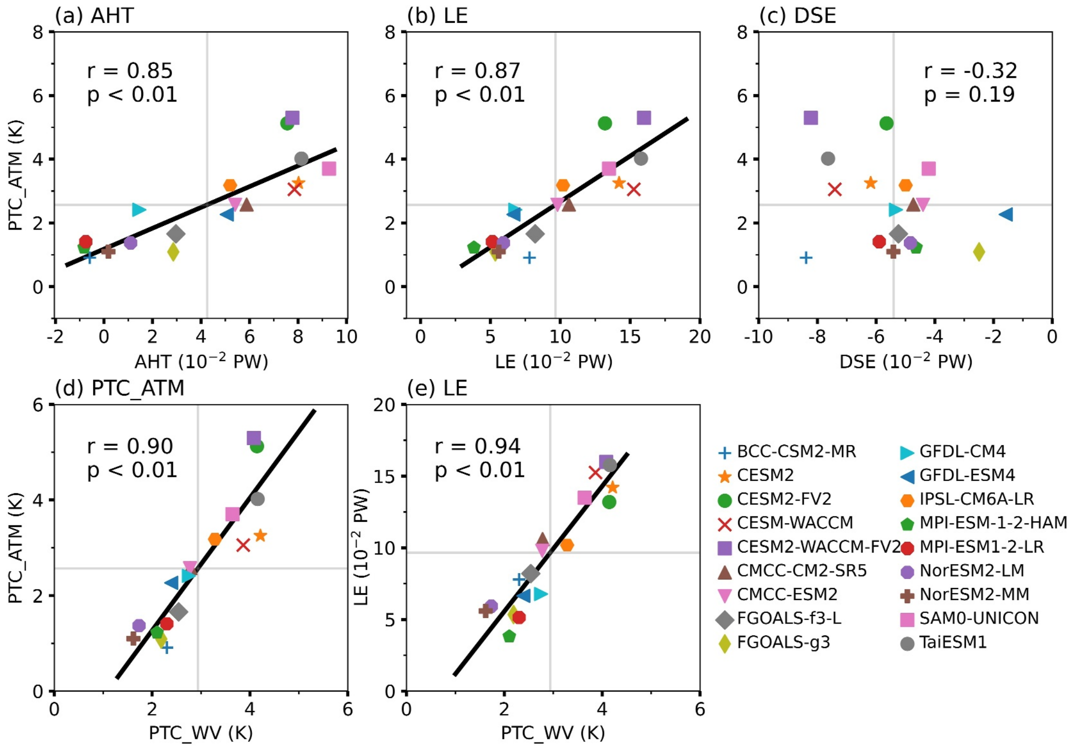

Figure 4. Relationship between partial temperature changes due to meridional heat transport and water vapor (WV) feedback. (a) Atmospheric heat transport anomalies, (b) latent energy (LE) transport anomalies, and (c) dry-static energy transport anomalies entering the Antarctic land surface at 70°S (*x*-axis, in 10^{-2} PW) plotted against the land surface temperature changes caused by atmospheric horizontal large-scale circulation and vertical convection from climate feedback-response analysis method (CFRAM) for the region 70°S–90°S (*y*-axis, in K). (d) Land surface temperature changes caused by atmospheric processes from CFRAM, and (e) LE transport anomalies (*y*-axis) plotted against the surface temperature changes caused by WV feedback (*x*-axis). All variables represent annual means. The correlation coefficients (r) and p-values (p) are noted in the panels. Positive values on the *x*-axis indicate southward heat transport anomalies. The gray vertical and horizontal lines represent the mean values of the data on *x*-axis and *y*-axis, respectively.

transport of LE. Variability in the strength of AHT, and especially LE transport, is therefore inferred to be a key driver of the inter-model spread in land surface warming. This finding emphasizes the critical role of LE transport in shaping model projections for Antarctic land warming. Other feedback mechanisms, such as cloud longwave feedback and surface albedo feedback, exhibit a comparatively weaker correlation with total land surface warming (Figures S1a and S1d in Supporting Information S1). The PTCs due to direct CO_2 forcing and the cloud shortwave effect are relatively uniformly represented across models, resulting in minimal inter-model spread (Figures S1c and S1e in Supporting Information S1).

Over the ocean surface, the inter-model spread in surface warming is primarily governed by the strengths of WV feedback and seasonal energy transfer mechanism (SETM)—findings consistent with previous studies (Po-Chedley et al., 2018), amplified by model discrepancies in representing surface albedo feedback and ocean heat exchange processes (Figures S2a and S2g in Supporting Information S1), while partially offset by reduced inter-model spread in sensible and latent heat flux (Figure S2h in Supporting Information S1).

In summary, the inter-model spread in Antarctic land surface warming is primarily driven by the variations in the strength of AHT, particularly the transport of LE, and its contribution to WV feedback. Model variability lies in the representation of atmospheric dynamics, particularly LE transport, which governs the extent of Antarctic land warming under CO_2 forcing.

4. Conclusions and Discussions

While the mechanisms governing the ocean surface warming in the Antarctic—such as the SETM and winter warming amplification—have been well-documented in previous studies (Feldl & Merlis, 2021; Lu & Cai, 2009b),

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the current research emphasizes the distinct mechanisms responsible for seasonally uniform Antarctic land surface warming. The quantitative analysis based on the CFRAM provides a clear understanding of the relative contributions of feedback processes to Antarctic land surface warming and its associated uncertainty under abrupt quadrupled CO_2 forcing.

Our findings indicate that poleward AHT, particularly the transport of LE, plays a dominant role in Antarctic land warming. The moisture-related transport enhances WV feedback, which significantly amplifies surface warming. This mechanism, combined with the direct contribution from CO_2 forcing, drives the relatively uniform warming observed over the Antarctic land surface throughout the year. Additionally, the inter-model spread in poleward AHT, especially in LE transport, emerges as the primary driver of the inter-model spread in Antarctic land warming projections.

These results have important implications for understanding climate change and improving climate model projections for the Antarctic. The key challenge lies in how models simulate atmospheric circulations and the associated AHT. Previous studies have identified atmospheric circulation as a source of uncertainty in regional climate change projections, such as the circulation over the North Atlantic and precipitation in monsoon regions (Shepherd, 2014; Xie et al., 2015). Our findings highlight that improving the representation of atmospheric circulation is also crucial for reducing the uncertainty in future Antarctic climate projections. By addressing these challenging issues, we can better predict the impact of climate change on the Antarctic and provide more reliable guidance for global climate assessments.

Data Availability Statement

The CMIP6 model outputs used in this study can be downloaded from the CMIP6 data archive (https://esgf-node.llnl.gov/search/cmip6/). These data are listed in Table S1 of Supporting Information S1.

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