Linearity of the climate system response to raising and lowering West Antarctic and coastal Antarctic topography

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ABSTRACT: A hierarchy of general circulation models (GCMs) is used to investigate the linearity of the response of the climate system to changes in Antarctic topography. Experiments were conducted with a GCM with either a slab-ocean or fixed SSTs and sea ice, in which the West Antarctic ice sheet (WAIS) and coastal Antarctic topography was either lowered or raised in an idealized way. Additional experiments were conducted with a fully-coupled GCM with topographic perturbations based on an ice-sheet model in which the WAIS collapses. The response over the continent is the same in all model configurations and is mostly linear. In contrast, the response has substantial non-linear elements over the Southern Ocean that depend on the model configuration due to feedbacks with sea ice, ocean, and clouds. The atmosphere warms near the surface over much of the Southern Ocean and cools in the stratosphere over Antarctica, whether topography is raised or lowered. When topography is lowered, the Southern Ocean surface warming is due to strengthened southward atmospheric heat transport and associated enhanced storminess over the WAIS and the high latitudes of the Southern Ocean. When topography is raised, Southern Ocean warming is more limited, and associated with circulation anomalies. The response in the fully-coupled experiments is generally consistent with the more idealized experiments, but the full-depth ocean warms throughout the water column whether topography is raised or lowered. These results indicate that ice sheet-climate system feedbacks differ depending on whether the Antarctic ice sheet is gaining or losing mass.

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SIGNIFICANCE STATEMENT: Throughout Earth's history, the Antarctic ice sheet was at times taller or shorter than it is today. The purpose of this study is to investigate how the atmosphere, sea ice, and ocean around Antarctica respond to changes in ice sheet height. We find that the response to lowering the ice sheet is not the opposite of the response to raising it, and that in either case the ocean surface near the continent warms. When the ice sheet is raised, the ocean warming is related to circulation changes; when the ice sheet is lowered, the ocean warming is from an increase in southward atmospheric heat transport. These results are important for understanding how the ice sheet height and local climate evolve together through time.

1. Introduction

The Antarctic ice sheet has undergone dramatic changes in volume over the last few million years, driven by changes in orbital parameters and greenhouse gas concentrations (Scherer 1991; Lisiecki and Raymo 2005; Naish et al. 2009). During some interglacial periods, the West Antarctic ice sheet (WAIS) may have lost much volume rapidly, or perhaps entirely collapsed, in response to ocean warming, coupled with the the marine ice sheet instability (Weertman 1974; Mercer 1978; Schoof 2007) and possibly other mechanisms such as ice-cliff failure (Pollard et al. 2015). During such a collapse, substantial ice mass loss begins at the continental margins, since these regions are both warmer and closer to the ocean, and proceeds into the interior.

The height of the WAIS is of interest because it influences sea level and climate, which can feedback on the ice sheet height. Understanding the climate response is useful for identifying locations and types of proxies that might inform us about the ice sheet's height in the past (e.g., Steig et al. 2015). The effect of Antarctic topography on climate has been investigated with general circulation models (GCMs) in a number of studies (e.g., Mechoso 1980, 1981; Parish et al. 1994; Simmonds and Law 1995; Ogura and Abe-Ouchi 2001; Holden et al. 2010; Otto-Bliesner et al. 2013; Justino et al. 2014; Steig et al. 2015; Singh et al. 2016; Holloway et al. 2016; Dütsch et al. 2023).

Most studies have focused on the impact of lowering the Antarctic continent. All find warming over most regions where topography had been lowered, as would be expected from simple lapse-rate effects. Most studies also find an increased top-of-atmosphere cooling, and increased southward energy transport by the atmosphere towards Antarctica. However, most such studies have used

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highly idealized Antarctic topographic changes. For example, Singh et al. (2016) lowered the entire Antarctic continent to 10% of its present-day elevation in a GCM with coupled atmosphere, ocean, sea ice and land surface components and found substantial warming at high southern latitudes and slight cooling elsewhere. They attributed these temperature changes to increased southward energy transport in both the atmosphere and ocean. They also found a significant increase in the circumpolar westerlies. Holloway et al. (2016) lowered the WAIS (only), and conducted experiments in which the elevation was set to a uniform 200 m (a reduction of about 90%) or removed entirely and replaced with ocean; the latter experiment was also conducted by Otto-Bliesner et al. (2013). In these cases, there is no significant change in the circumpolar westerlies, though the meridional energy transport changes are similar (though smaller in magnitude) to those in Singh et al. (2016). Steig et al. (2015) and Dütsch et al. (2023) prescribed more realistic ice sheet topographic perturbations compared to previous work, based on an ice sheet model simulation of WAIS collapse (Pollard and DeConto 2009). The major finding is that a cyclonic circulation anomaly forms over the lowered topography – owing to first-order conservation of angular momentum. This atmospheric circulation anomaly causes some areas to warm and others to cool; the latter occurs even in areas (particularly the Ross Sea and Marie Byrd Land) where elevations are lower. These results show that the climate response to Antarctic ice sheet topographic changes – both locally and at the large scale – is sensitive to the magnitude of ice sheet loss and to the configuration of that loss.

Recently Tewari et al. (2021) investigated the response to both raising and lowering Antarctic topography in a series of idealized perturbations with an atmospheric GCM subject to prescribed unperturbed sea surface temperature and sea ice boundary conditions. They scaled the Antarctic topography by an amount ranging from 0 to 200% of its present-day elevation in 25% increments. In addition to assessing the tropospheric temperature and circulation changes, they examined the precipitation response over the ice sheet and shelves. They found that lowering Antarctica on average caused warming and increased precipitation over the Antarctic continent. Temperatures remain sufficiently cold to increase snow accumulation and therefore damp the topographic perturbation. They concluded that the response is the opposite when topography is raised.

In this paper, we are interested in illuminating the processes responsible for the climate response to physically-plausible, spatially non-uniform changes in Antarctic ice sheet topography. We

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examine the climate system response to both lowering and raising Antarctic topography, with most of the topography changes occurring in West Antarctica and around the continental margins, consistent with Antarctic ice-sheet dynamics. These model experiments contrast with the majority of previous studies that have focused only on the response to lowering the ice sheet, despite the evidence that the Antarctic ice sheet may have been higher than its present elevation for most of the last million years (e.g., Pollard and DeConto 2009). In particular, we test the linearity of the climate system response to raising or lowering Antarctic topography, in part motivated by the results of White et al. (2017). They found that increasing the elevation of Northern Hemisphere mountain ranges above ~2000 m elevation had little impact on the atmospheric circulation response, in contrast to the large response to lowering below this elevation threshold. We first conduct Antarctic topography change experiments in scenarios with an idealized and exaggerated WAIS collapse-type topography change. Our topographic perturbations are primarily near the coast of Antarctica, since this is where topography is most variable (e.g., Pollard and DeConto 2009). We use three GCM configurations: an atmospheric GCM (AGCM) with prescribed sea surface temperature (SST) and sea ice conditions, an AGCM coupled to slab-ocean and sea ice components, and a fully-coupled GCM. In the first two configurations, the topography changes are more idealized, while for the fully-coupled GCM we use a WAIS collapse scenario taken from an ice sheet model. We evaluate the linearity of the climate system response in the fully-coupled GCM by both raising and lowering the topography by the same amount, and examine the influence of feedbacks associated with sea ice, ocean and clouds.

2. Methods

The majority of our work employed the Community Climate System Model version 4 (CCSM4, Gent et al. 2011) in a series of experiments with its atmosphere coupled to ocean models of increasing complexity: (1) prescribed SST and sea ice conditions, (2) a slab-ocean with interactive sea ice, and (3) an ocean general circulation model with interactive sea ice. When fully-coupled, CCSM4 includes the Community Atmosphere Model version 4 (CAM4, Neale et al. 2010), the Parallel Ocean Program version 2 (POP2, Smith et al. 2010), the Community Land Model version 4 (CLM4, Oleson et al. 2010) and the Community Ice Code version 4 (CICE4, Hunke et al. 2010). CAM4 solves the primitive equations assuming hydrostatic balance in a finite-volume atmospheric

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dynamical core. The atmosphere and land components were run at nominally 1 degree horizontal resolution. CAM4 was run with 26 vertical layers in the atmosphere using a hybrid-sigma vertical coordinate, which is terrain-following near the surface and transitions smoothly to constant pressure levels in the upper atmosphere. In the slab-ocean and fully-coupled integrations, the ocean and sea ice were run at 0.9×1.25 degree horizontal resolution.

To verify that a more recent AGCM with improved representation of cloud physics produces the same results as those with CCSM4, we repeated the slab-ocean experiments with the Community Earth System Model version 2 (CESM2, Danabasoglu et al. 2020) with the Community Atmosphere Model version 6 (CAM6), which has been shown to have a much smaller bias in cloud fraction over the Southern Ocean due to improved cloud physics parameterizations (Kay et al. 2016). As in the CCSM4 experiments, CESM2 was run at 0.9×1.25 degree horizontal resolution.

Topography was changed in the various model configurations by specifying the surface geopotential in the atmosphere model component. We did not alter the surface type or albedo of the regions where the surface geopotential was changed.

Because simulations with prescribed SST or a slab ocean isolate processes by limiting physical interactions, we chose to employ idealized topographic scenarios in experiments with these configurations. We specified topography perturbations that are a simple function of the present-day topography, designed to vary the most near the low-elevation regions around the Antarctic coast and in West Antarctica. These regions are expected to change the most in a warmer climate (e.g., Pollard et al. 2015). Hence, the topographic perturbations Δh are only non-zero in regions where the present-day elevation is less than 2200 m, which approximately delineates the high East Antarctic plateau. The surface elevation, h, is scaled by a constant fraction f of the present-day elevation (e.g., $f = 0.9$) and then weighted by a parabolic weighting function $w(h)$ with zero-crossings at 0 m and 2200 m elevation and a maximum value of 1 at $h = 1100$m elevation, so that elevation changes are continuous at the boundaries of the altered regions. Thus, the change in elevation is given by:

$$\Delta h = f h w(h), \tag{1}$$

where f is positive when topography is raised and negative when topography is lowered. The specific values employed for f are summarized in the table in Figure 1 and the elevation anomalies are shown in Figure 2.

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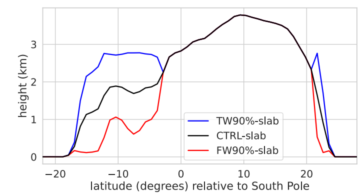
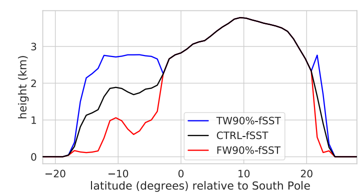
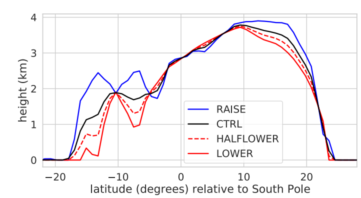
Model	Experiment Name	Description	Transect	Key Feedbacks
Slab	CTRL-slab/CESM2-CTRL-slab	CESM2/CCSM4 with slab ocean control		Cloud, sea ice fraction/thickness, temperature, albedo, and mixed-layer SST
	FW90%-slab/CESM2-FW90%-slab	Topography below 2200m reduced by 90%		
	TW90%-slab/CESM2-TW90%-slab	Topography below 2200m increased by 90%		
fSST	CTRL-fSST	CCSM4 with fixed SST and sea ice fraction and thickness control		Cloud, sea ice temperature, albedo
	FW90%-fSST	Topography below 2200m reduced by 90%		
	TW90%-fSST	Topography below 2200m increased by 90%		
CPL	CTRL	CCSM4 fully-coupled control		Cloud, sea ice fraction/thickness, temperature, albedo, mixed-layer SST, and ocean circulation
	LOWER	"WAIS collapse" topography from the Pollard and DeConto (2009) ice sheet model		
	HALFLOWER	As for LOWER but scale by half		
	RAISE	As for LOWER but scale by −1		

FIG. 1. Experiment descriptions with topography transects through 90°E/W. Simulations are by default with CCSM4 unless specifically noted with CESM2.

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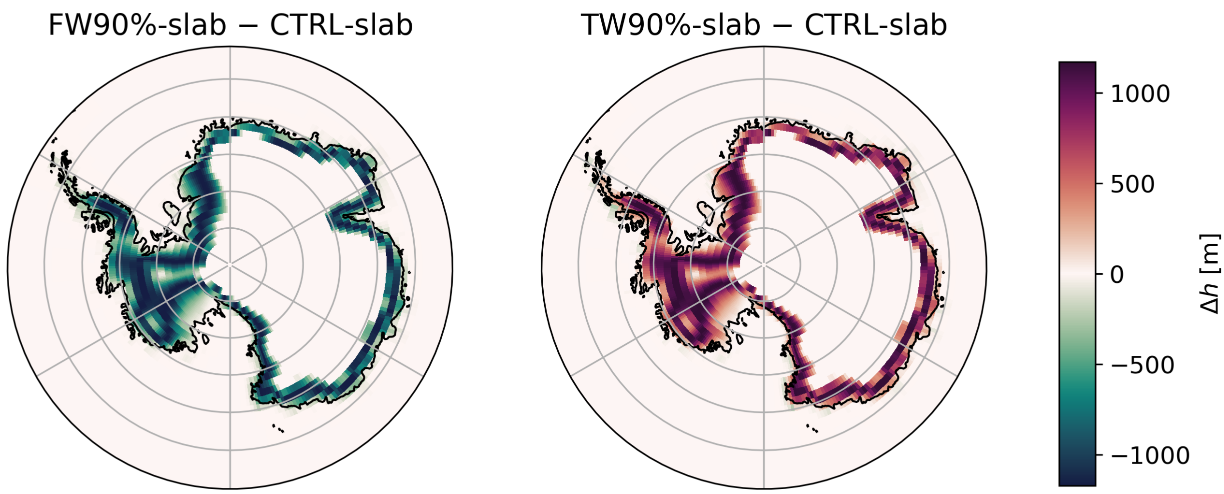

FIG. 2. Elevation change relative to the present-day topography for the slab-ocean and fixed SST topography change experiments. Experiments with slab and fixed-SST configurations employ present-day or perturbed topography input files that are the same in both CCSM4 and CESM2.

a. Slab-ocean experiments

The purpose of the experiments with an AGCM coupled to a slab ocean and interactive sea ice is to examine the atmospheric response when the sea surface and sea ice are allowed to interact, without the additional complexity and computational expense of a fully-coupled dynamic ocean. In the slab ocean configuration, the ocean heat transport is prescribed as an annually-periodic surface heat flux convergence, commonly referred to as a "q-flux".

We conducted a set of three experiments with the slab-ocean configurations of CCSM4 and CESM2, a control with no topography changes and two experiments where the topography was raised or lowered by up to 90% (corresponding to $f = \pm 0.9$) of its present-day elevation. We refer to the control as CTRL-slab, the experiment where topography was lowered by up to 90% as FW90%-slab (FW = "Flat WAIS"), and that where it was raised by up to 90% is referred to as TW90%-slab (TW = "'Tall WAIS"). The topography changes relative to the present day are shown in Figure 2. Experiment with CCSM4 were run for 90 years and experiments with CESM2 (denoted by the prefix "CESM2" in the experiment names) were run for 75 years. Results are presented as the difference between each experiment and the control averaged over the last 30 years of each integration for CCSM4 and the last 20 years for CESM2.

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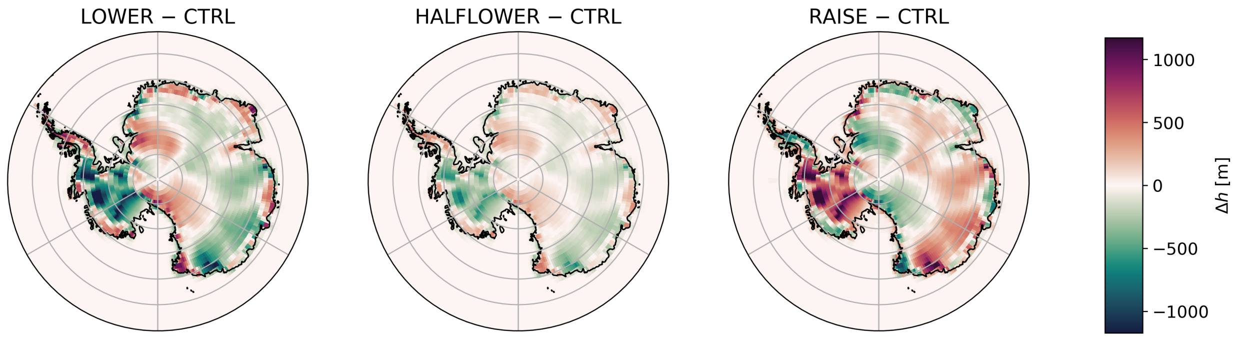

FIG. 3. Surface elevation change relative to the default CCSM4 present-day topography for the three fully-coupled experiments.

b. Fixed SST experiments

The purpose of the experiments with fixed SSTs and sea ice is to isolate the response of the atmosphere without feedback from the sea surface temperature and sea ice fraction and thickness. The surface temperature and snow depth on sea ice are prognostic variables in this model configuration. We conducted the same set of three experiments with the fixed-SST configuration of CCSM4 as with the slab-ocean configuration. In all three experiments we used the SSTs and sea ice fraction climatology from the last 30 years of the 90-year slab-ocean experiment with present-day topography (CTRL-slab). The first experiment, henceforth referred to as CTRL-fSST, was run with present-day topography, while the FW90%-fSST and TW90%-fSST experiments were run with topography lowered or raised by up to 90% ($f = \pm 0.9$) respectively.

c. Fully-coupled experiments

In the final set of model experiments, we investigate the response to a more realistic spatial distribution of topography changes than the idealized experiments before, and include the coupled response of a full dynamic ocean, the importance of which was highlighted by Justino et al. (2014) and Singh et al. (2016). We conducted four experiments with CCSM4 with fully-coupled dynamical atmosphere, land, ocean and sea ice model components. The first is a control with no changes to Antarctic topography, henceforth referred to as CTRL. In the second, which we refer to as LOWER, we used Antarctic ice sheet topography from 700,000 years before present (700 ka) from the ice sheet model of Pollard and DeConto (2009), regridded to the CCSM4 $0.9 \times 1.25°$ grid, following

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the experiments in Steig et al. (2015). At that time (in the ice-sheet model), the West Antarctic Ice Sheet had mostly "collapsed", and had lost a large fraction of its volume. In the third experiment, henceforth referred to as HALFLOWER, the Antarctic ice sheet surface elevation was lowered by half the difference between the LOWER experiment and the default CCSM4 topography. Finally we conducted an experiment in which the negative of the difference between the LOWER and the CCSM4 default topography was added to the present-day topography, referred to as RAISE. All four experiments were branched from the same point in time in a pre-industrial control run that used modern Antarctic topography. Each experiment was continued for 300 years after branching.

The surface elevation anomalies for each experiment are shown in Figure 3. For the LOWER experiment, the largest reductions in elevation are in West Antarctica, with other regions of lowered elevation near the coast in East Antarctica. There are some (unrealistic) local regions of slightly increased elevation due to differences between the CCSM4 "present-day" topography and the present-day topography in the ice sheet model of Pollard and DeConto (2009).

3. Results

a. Idealized topography change experiments

In this section we discuss the response of the climate system to Antarctic topography perturbations in the fixed-SST and slab-ocean model configurations where the topography perturbations are idealized. These results are a first step in identifying the physical mechanisms responsible for the climate system response in the absence of the complicated topography changes in a fully-coupled model that will be discussed later.

1) Atmospheric Temperature, Precipitation, and Sea Ice Response

We find widespread warming over Antarctica in the 2-m temperature response to our idealized topography lowering perturbations in the slab ocean and fixed-SST experiments (Figure 4), consistent with lapse-rate effects and previous studies that have investigated the climate response to lowered Antarctic topography (see, e.g., Steig et al. 2015; Singh et al. 2016; Tewari et al. 2021; Dütsch et al. 2023). The near-surface warming is greatest in a swath near the coast, in the vicinity of where we have prescribed the topographic perturbations (see Figure 2). The exception to near-surface warming occurs in a narrow band even closer to the coast of WAIS that Singh et al. (2016) showed

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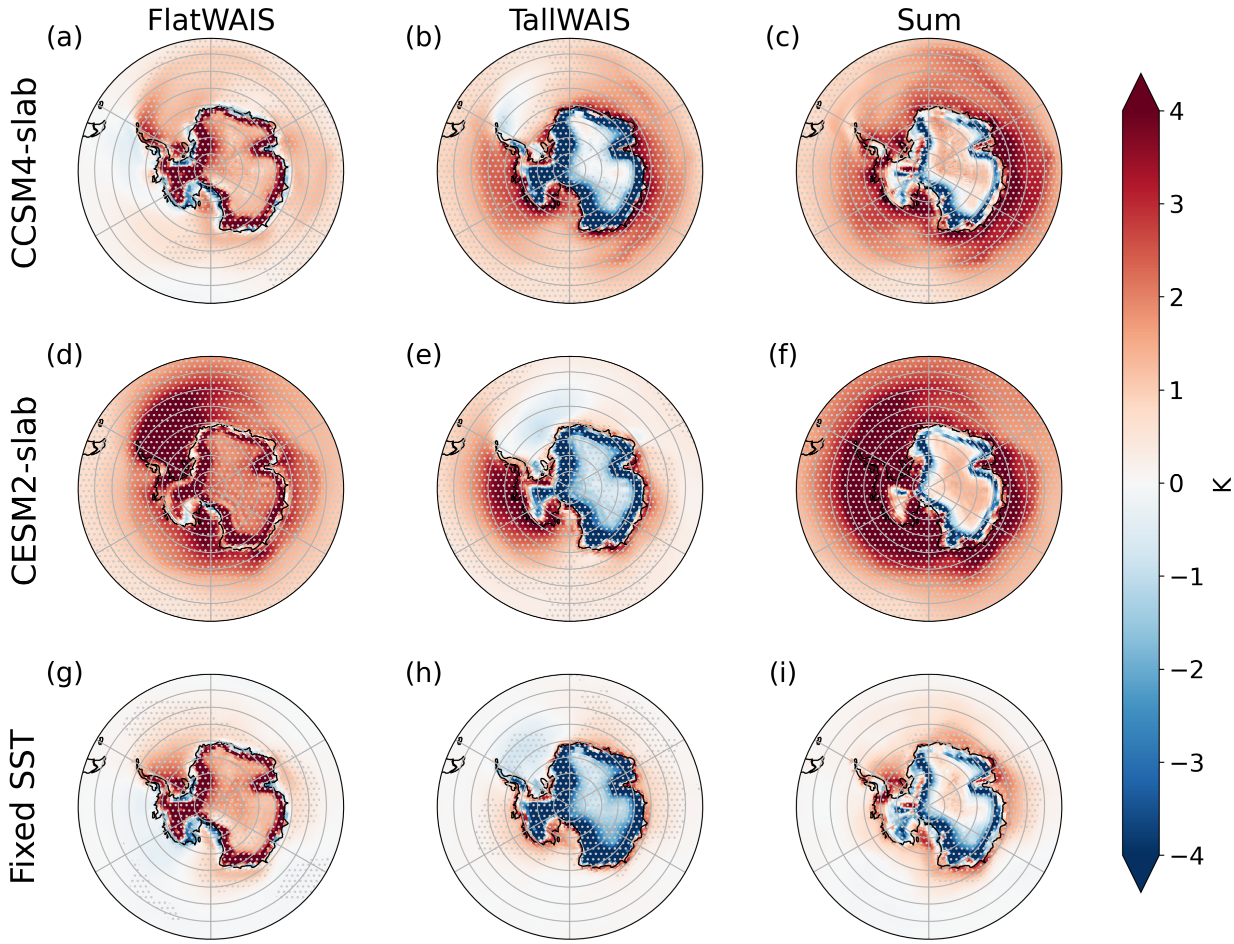

FIG. 4. Annual-mean 2 m air temperature response for the slab-ocean CCSM4 (a-c), slab-ocean CESM2(d-f) and fixed-SST (g-i) model configurations. Each is the anomaly between the experiment with up to 90% topography change and a control run with no topography change. The right-hand column shows the sum of the left two columns for each model configuration. Values close to zero indicate that the response is approximately linear with respect to Antarctic topography change. Stippling denotes where the anomalies are significant at the 95% confidence level using a 2-tailed Student t-test.

was the result of weakened downslope katabatic winds. Steig et al. (2015) associated such cooling along the east edge of the Ross Ice Shelf with anomalous cold air advection from the south. When topography is raised by the same amount, the 2-m temperature response over the continent has a similar structure, that is almost exactly the opposite, but the swath of maximum cooling near the coast is much broader. On the whole, the 2-m temperature response to topographic perturbations is relatively linear over Antarctica.

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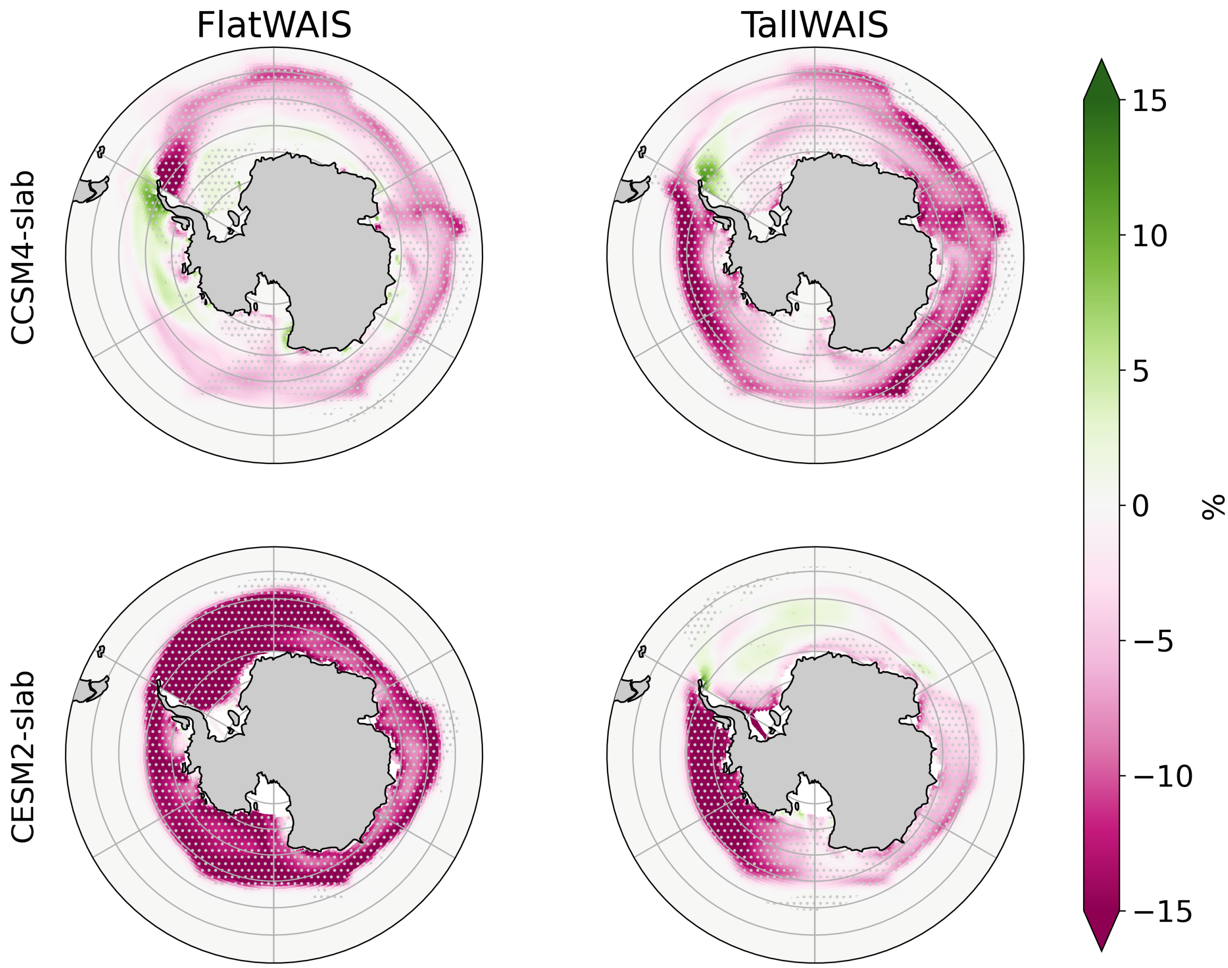

FIG. 5. Annual-mean sea ice concentration response for the slab-ocean model experiments in CCSM4 (a-b) and CESM2 (c-d). Anomalies are between experiments with up to 90% topography change and a control run with no topography change averaged over the last 30 years of 90-year integrations. Stippling denotes where anomalies are significant at the 95% confidence level, based on a 2-tailed Student t-test.

In contrast, the 2-m air temperature response is strongly non-linear offshore of Antarctica (Figure 4), especially in the slab-ocean configuration, with warming by up to ~4 K over the Southern Ocean regardless of whether topography is raised or lowered. Consistent with the off-shore near-surface warming, the annual-mean sea ice concentration in the Southern Ocean in the slab-ocean experiments decreases whether topography is raised or lowered (Figure 5). The offshore warming is larger in the CESM2 simulations than in the CCSM4 simulations, indicating that atmospheric physics influences the climate feedbacks that control the magnitude of the response.

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The 2-m temperature anomalies offshore in the fixed-SST experiments are limited to where the sea ice occurs and are weaker than in the slab-ocean experiments due to an absence of feedbacks related to SST, sea ice concentration, or sea ice thickness (Figure 4g-i). Because sea ice in the fixed-SST experiments is fixed in concentration and thickness, surface warming over sea ice can be caused only by changes to the surface fluxes. The much larger offshore warming in the slab-ocean experiments indicates that the warming is amplified by SST and sea ice feedbacks, possibly including a sea ice dynamical response to surface wind anomalies.

In the annual zonal-mean response (Figure 6d-f), the non-linear near-surface warming offshore extends into the lower troposphere and the stratosphere cools, regardless of whether topography is raised or lowered. The vertical temperature structure of the anomaly reveals the consequence of raising or lowering topography at the edge of the dome-shaped Antarctic continent where the surface slope gradients are largely confined to the margin. By raising the topography, we have steepened the gradient and narrowed the region of strong slope gradient. In contrast, when the topography is lowered, the region of steep gradients expands. Adiabatic warming/cooling occurs at different heights, according to how the topography is changed. Specifically, when topography is raised, adiabatic cooling occurs mostly from 500–750 hPa, while when topography is lowered, adiabatic warming occurs mostly from 750–1000 hPa. Therefore, by construction, these topographic perturbations cause a non-linear response in the lower troposphere at the continent's edge directly from the adiabatic effects of raising/lowering the surface and from the katabatic winds by changing the slope gradient.

The zonal-mean temperature response in the fixed-SST experiments (Figure 6g-i) over the continent and near shore of the Southern Ocean is similar to the slab-ocean experiments, indicating that the non-linear response need not involve SST changes or sea ice concentration or thickness changes. However, the weak atmospheric temperature response over the Southern Ocean in the fixed-SST experiments compared to the slab-ocean experiments suggests that caution should be taken in drawing conclusions about the response away from the continent in fixed-SST experiments.

The precipitation response to our idealized topography perturbations mostly echoes the temperature response over Antarctica, with increased precipitation where there is surface warming and vice versa. The precipitation response over the continent is mostly linear, and in agreement with that of Tewari et al. (2021). Like Singh et al. (2016) and Tewari et al. (2021), we see the precipitation

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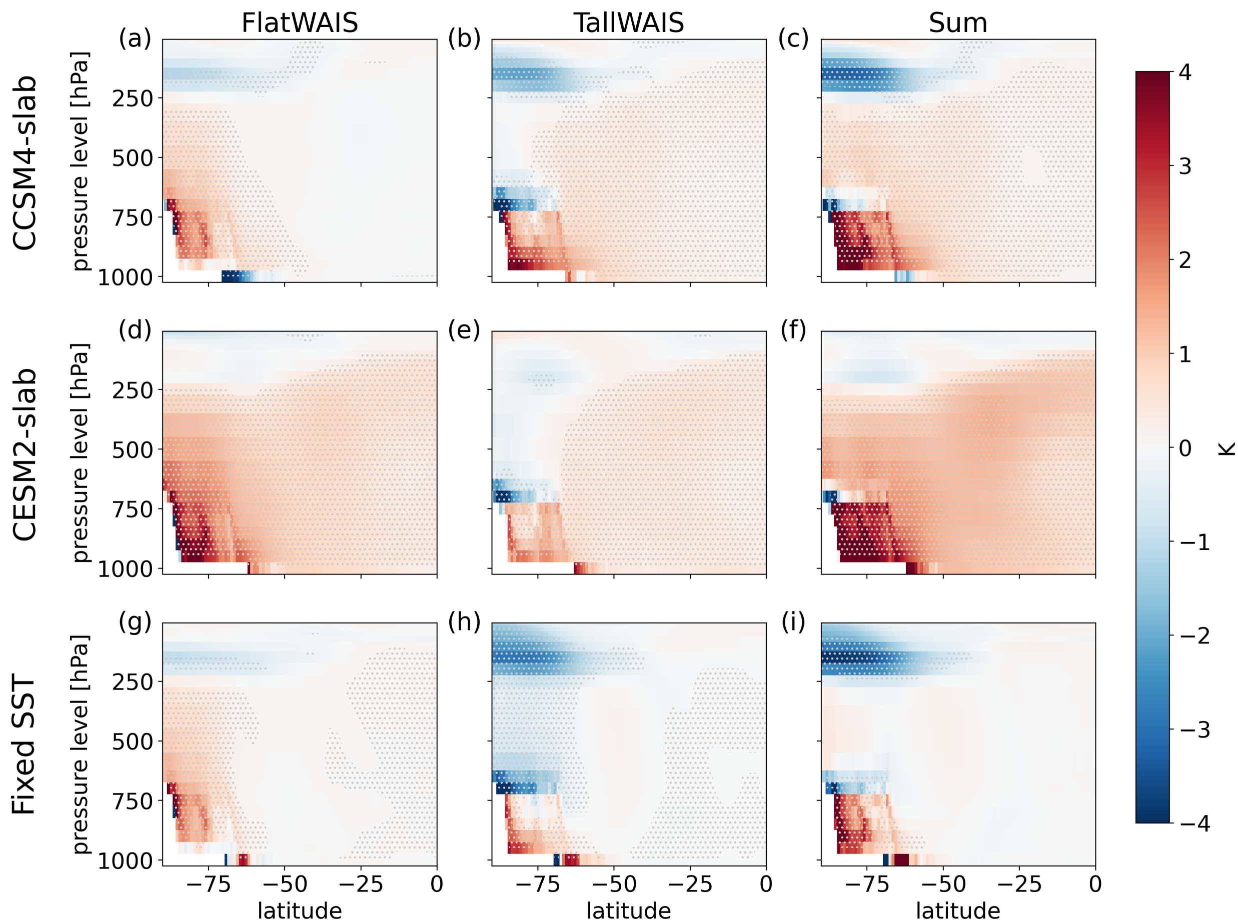

FIG. 6. As in Figure 4 except for annual-mean zonal-mean temperature.

response changes sign just offshore of the Antarctic Peninsula and stretching to the west around West Antarctica. There is a similar but much weaker sign change in the precipitation anomalies just offshore of East Antarctica in our simulations. Further offshore by ~500 km, the response is weak and dissimilar among our model configurations. Tewari et al. (2021) make the point that precipitation, which is nearly always snowfall over Antarctica, acts as a negative feedback on ice sheet height perturbations.

These results suggest that the 2-m temperature and precipitation response over the continent is relatively insensitive to whether the model is configured with fixed-SST and sea ice or a slab ocean. The *sign* of the response is not sensitive to whether the topography is changed predominantly near the coast or over the plateau. However, the *magnitude* of the response, though mostly linear, does

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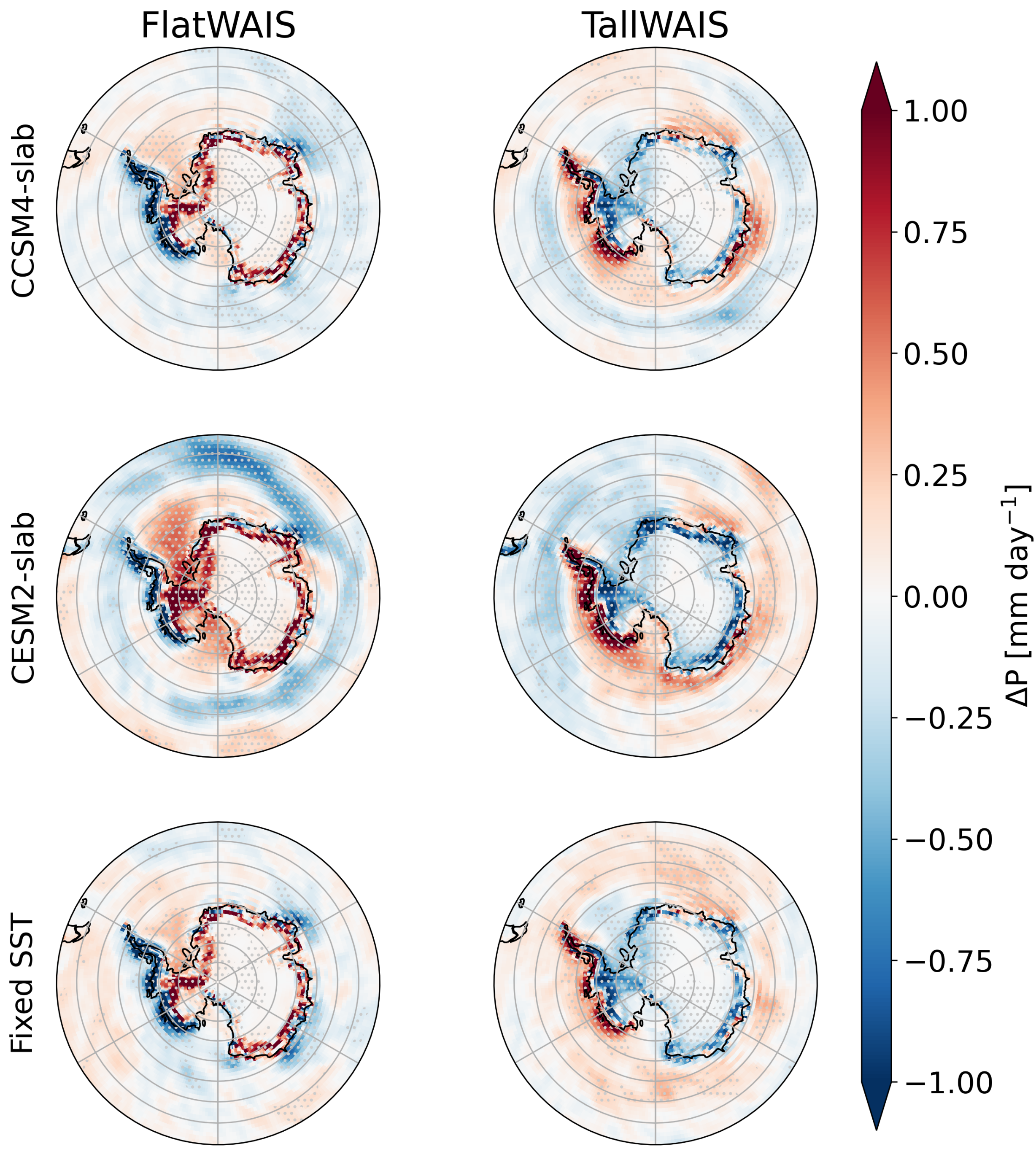

FIG. 7. As in Figure 4 except for annual-mean precipitation.

depend on the location of the topographic perturbation. The atmospheric temperature response offshore is non-linear, where non-linearities are amplified by feedbacks.

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In summary, the topographic perturbations cause a non-linear response that can be partially explained by changes to the slope of ice sheet near the edge. Next we delve deeper into the dynamical response.

2) Circulation Response

As mentioned in the previous section, Steig et al. (2015) attributed a portion of the surface cooling in response to their WAIS collapse scenario to circulation changes. Specifically, they identified an anomalous surface cyclonic circulation centered over the WAIS that causes substantial changes in the pattern of cold and warm air advection, altering the surface temperature response of the WAIS and the surrounding waters of the Southern Ocean beyond the simple adiabatic response to topographic changes. We find a similar anomalous cyclonic circulation in our integrations with the WAIS lowered, and the opposite circulation when the WAIS is raised (Figure 8). Overall, the large-scale annual-mean circulation anomalies at 850 hPa are fairly linear in response to raising and lowering topography, and remarkably similar across the model configurations with our idealized topographic perturbations. Fairly consistent and linear circulation anomalies in the Weddell and Ross Seas can be seen at all levels in Figure 8. Elsewhere the circulation anomalies are generally weaker, less linear, and more variable across the levels and model configurations. We interpret the large-scale annual-mean circulation anomalies in our simulations as contributing to the overall linearity of the temperature response over Antarctica and not inconsistent with the non-linear temperature response over the Southern Ocean.

3) Energy Transport Response and Storminess

To further investigate contributions to the temperature and sea ice response over Antarctica and the Southern Ocean, we next examine the atmospheric energy transport response to Antarctic topography change in Figure 9 for the fixed-SST and slab-ocean model configurations. South of 55° S, southward energy transport increases when topography is lowered and decreases when it is raised, by approximately the same magnitude in the slab ocean and fixed-SST model configurations. A consequence of the atmospheric energy transport response to Antarctic topography change is to dynamically enhance the magnitude of the adiabatic warming and cooling in the lower troposphere. This enhancement is roughly linear with respect to topography change.

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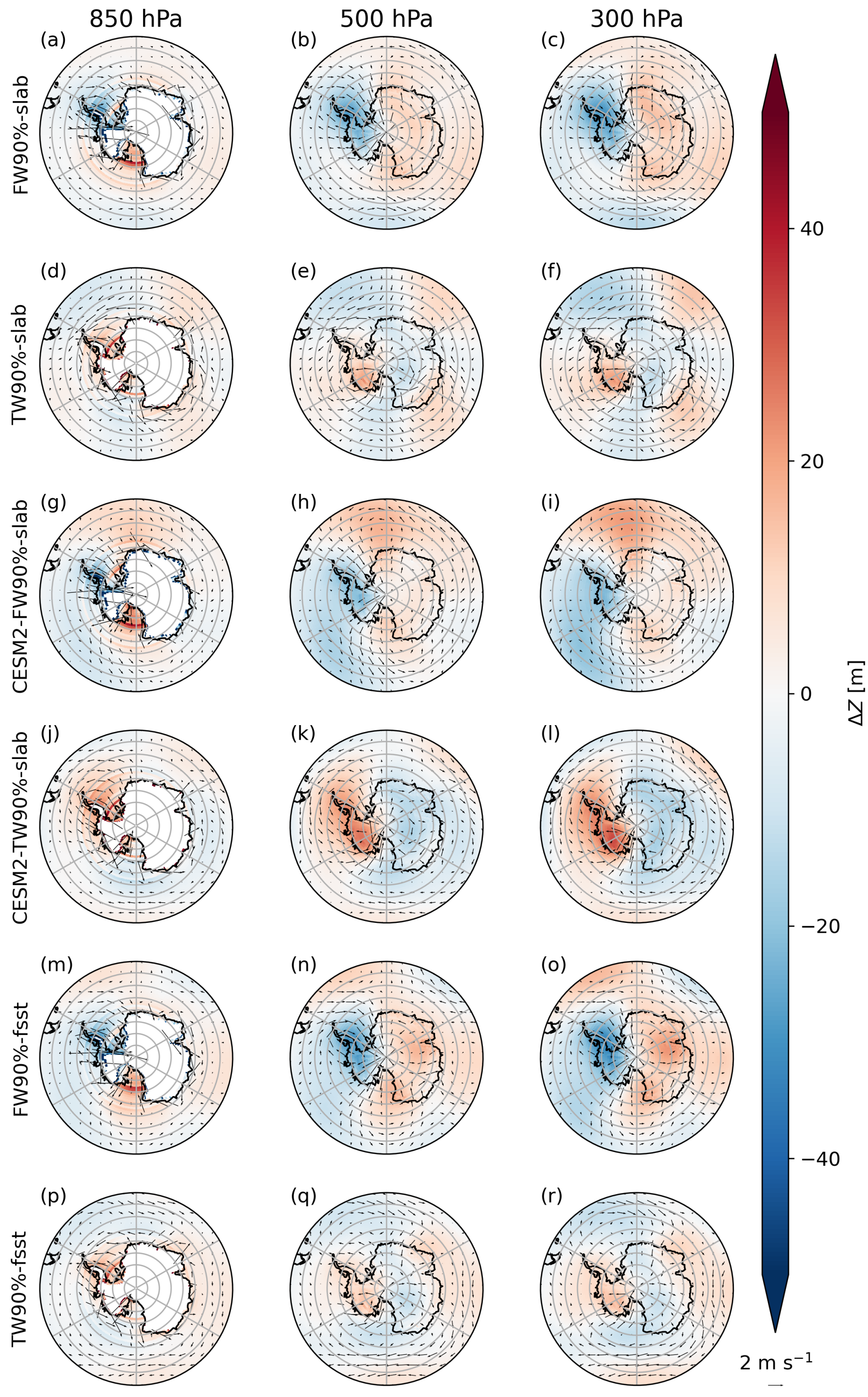

FIG. 8. Wind and eddy geopotential height response for experiments with up to 90% topography change in the CCSM4 slab-ocean, CESM2 slab-ocean and fixed-SST model configurations. "Eddy geopotential" means that the zonal-mean has been removed from the geopotential height.

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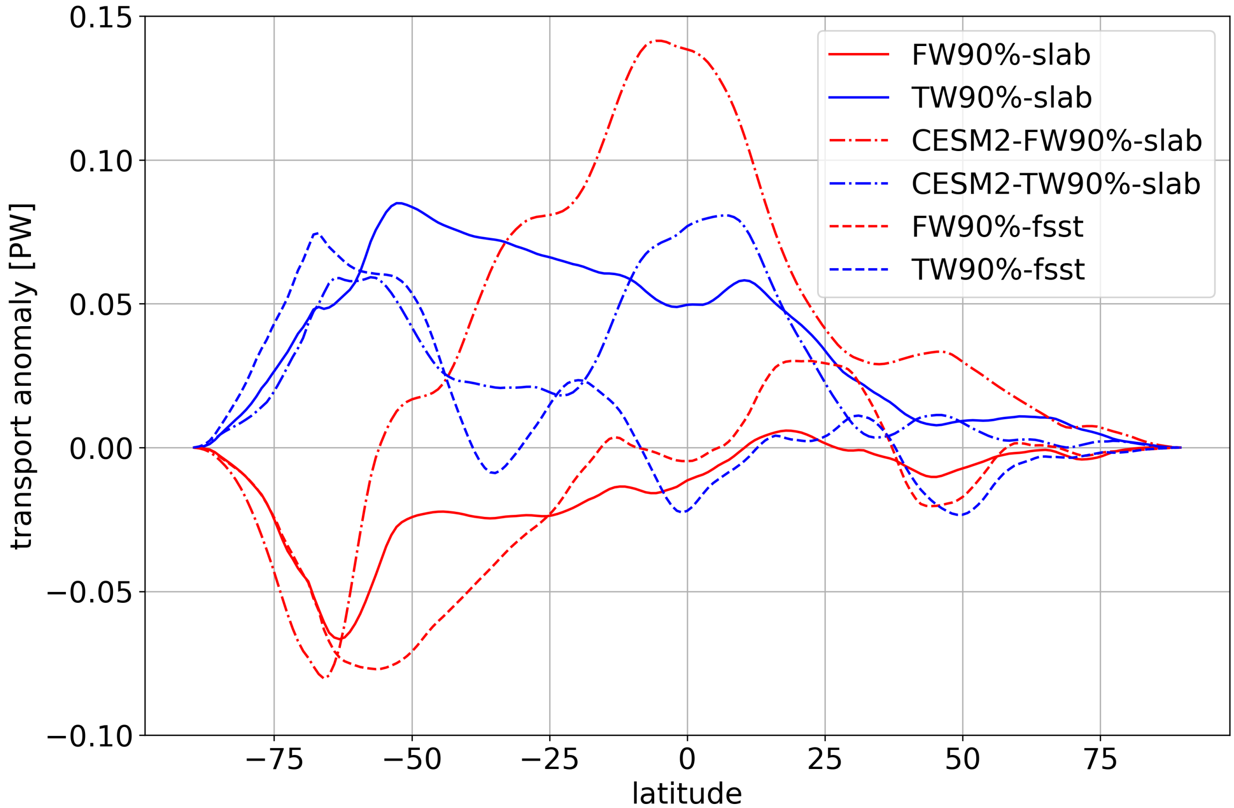

FIG. 9. Annual-mean atmospheric energy transport response for the fixed-SST and slab-ocean model configurations. Each is the anomaly between the experiment with up to 90% topography change and a control run with no topography change. Positive values denote anomalous northward transport.

Because these simulations have reached steady state at the point of our analysis, the annual-mean atmospheric energy transport across a latitude circle (such as 55° S) must balance the top-of-atmosphere (TOA) annual-mean spatial-average net radiative flux south of the latitude circle assuming that the surface is in energy balance in the annual mean. In agreement with most previous studies, lowering Antarctic topography results in an increase in TOA net radiative flux south of 55° S (see, e.g., Singh et al. 2016, and references therein). We find the opposite occurs when raising Antarctic topography. Thus, as expected, the atmospheric energy transport near Antarctica responds linearly to Antarctic topographic changes, as shown in Figure 9.

The remote response of the atmospheric energy transport response north of 55° S is less consistent among our simulations. The remote response is a consequence of teleconnections and feedbacks, which are limited in the fixed-SST simulations, and depend in our slab-ocean simulations on

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parameterization differences between CAM4 and CAM6. Cloud feedbacks are known to be quite different between these model versions, motivating us to examine the cloud response (see next section). Singh et al. (2016) determined that south of ~20° N the atmospheric energy transport response to flattening Antarctica is composed of substantial contributions of southward dry static static transport anomalies and mostly northward latent heat transport anomalies. They found that the magnitude of dry static energy transport anomalies nearly always dominates over latent heat transport anomalies, therefore the net atmospheric energy transport anomaly is southward south of ~20° N. Our simulations with CCSM4 are in agreement with those of Singh et al. (2016) (who also used CCSM4) in the net, but the dry static energy and latent heat transport anomalies in the tropics are much smaller in magnitude, consistent with weak and insignificant precipitation changes in the tropics and subtropics. In contrast, our simulations with CESM2 with lowered topography respond differently in the tropics and subtropics, with latent heat transport anomalies overwhelmingly dominant, suggesting a substantial southward shift in the Hadley circulation but without the global cooling that Singh et al. (2016) found. The CESM2 lowered topography simulation also has a shift in precipitation in the tropics, consistent with the shift in Hadley circulation.

The atmospheric energy transport response over the Southern Ocean in Figure 9 is not as would be expected purely from changes to the local meridional temperature gradient, but rather reflects a shift of the midlatitude storm track in response to Antarctic topography changes. Many previous studies have investigated the dynamics of the storm-track response to lowering Antarctic topography and found that the jet stream shifts south with enhanced storm activity over the continent and enhanced southward transient eddy heat transport (e.g., Mechoso 1980, 1981; Parish and Bromwich 2007; Quintanar and Mechoso 1995; Ogura and Abe-Ouchi 2001; Walsh et al. 2000; Singh et al. 2016; Patterson et al. 2020). The linearity of the atmospheric energy transport response that we find suggests the changes to the storm track are also linear.

We compute a simple metric for the "storminess", which we define as the standard deviation of daily sea-level pressure, where the sea-level pressure data is first filtered with a high-pass 6th order Butterworth filter with a cutoff at a period of 10 days, for all seasons in each grid cell (Figure 10). We find that storminess increases when topography is lowered, especially over the Antarctic Peninsula and Weddell Sea region, associated with increased eddy heat flux convergence in regions where storminess increases, consistent with many previous studies (e.g., Singh et al.

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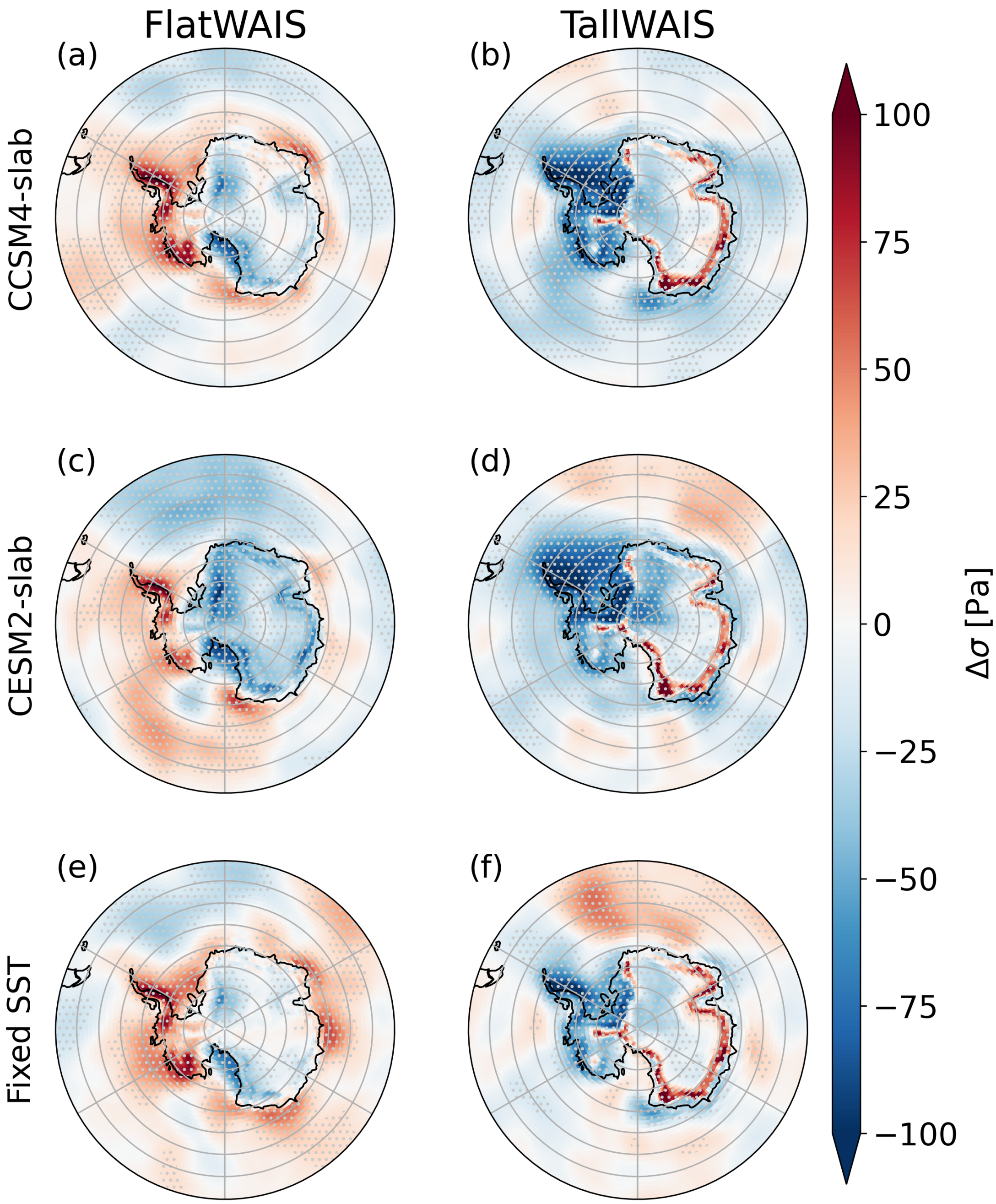

FIG. 10. The standard deviation of daily sea-level pressure, filtered with a high-pass 6th order Butterworth filter with a cutoff at a period of 10 days, for the slab-ocean CCSM4 (a-b), slab-ocean CESM2(c-d) and fixed-SST (e-f) model configurations. Each is the difference between the experiment with up to 90% topography change and a control run with no topography change. Stippling denotes where the variance differs between the experiment and the control at the 95% confidence level using an F-test.

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2016; Patterson et al. 2020). Storminess decreases over the Antarctic Peninsula and Weddell Sea when topography is raised, resulting in less transport of heat into the interior of the continent. The response of storminess with respect to Antarctic topography change is consistent with the energy transport response.

4) Cloud Response

We next present the seasonal high cloud fraction response to Antarctic topography changes (Figure 11) since they can feed back on the temperature response through their influence on atmospheric heating rates and surface and TOA radiative fluxes. The low and middle cloud response is not shown because it was found to be far less substantial and influential, though generally of the same sign. In simulations with the CCSM4 slab ocean and fixed SSTs, we see an increase in high cloud fraction when topography is raised that is roughly co-located with the near-surface warming in the same simulations, particularly in the winter and spring. This increase in winter-spring cloud fraction increases the downwelling longwave radiation toward the surface, which amplifies the warming. There are other locations where the cloud-temperature anomalies are of the opposite sign, such as over the Weddell Sea and parts of the WAIS when topography is lowered and over much of the Antarctic continent when topography is raised.

We also examine the high cloud response in the CESM2 slab-ocean model configuration (Figure 11i-p). Clouds in CESM2 respond in a more complex way than in the CCSM4 experiments. There are regions with agreement and disagreement between the two model versions in winter and spring. CESM2 clouds respond more strongly in summer and autumn than in CCSM4. The response across seasons is fairly similar. These cloud anomalies indicate that the cloud-surface temperature connection is inconsistent across the domain and between models.

b. Realistic Topography Simulations

To investigate the response to more realistic topographic perturbations and coupled feedbacks, we run CCSM4 with its AGCM coupled to a full-depth, dynamic ocean model and Antarctic ice sheet topography from the ice sheet model of Pollard and DeConto (2009), following the earlier work of Steig et al. (2015). Here, we focus on the non-linear aspects of the simulation and where

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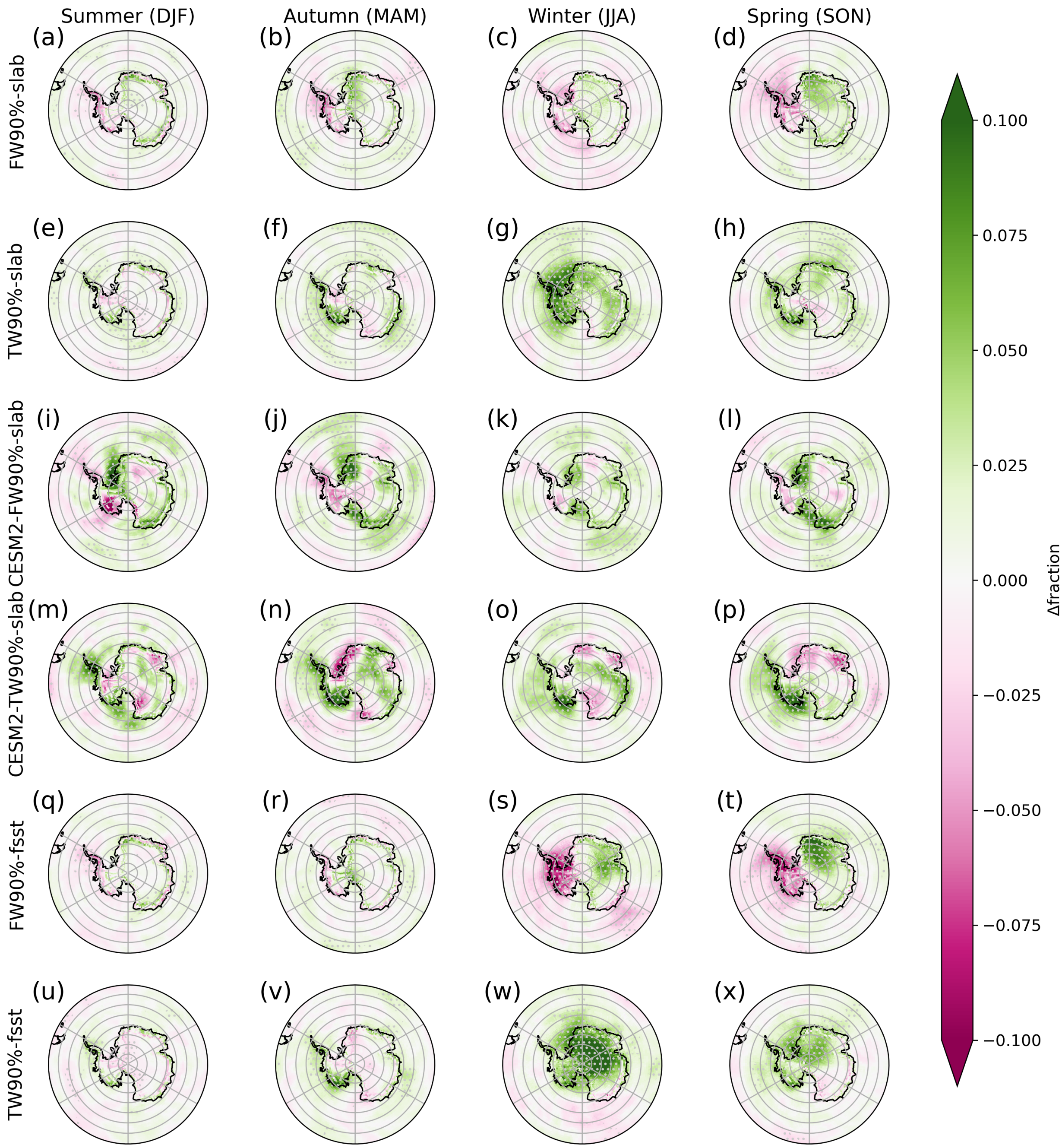

FIG. 11. High cloud fraction response by season for the slab-ocean and fixed-SST model configurations. Each is the difference between the experiment with up to 90% topography change and a control run of the model with no topography change. FW denotes FlatWAIS, and TW denotes TallWAIS. Stippling denotes where the anomalies are significant at the 95% confidence level using a 2-tailed Student t-test.

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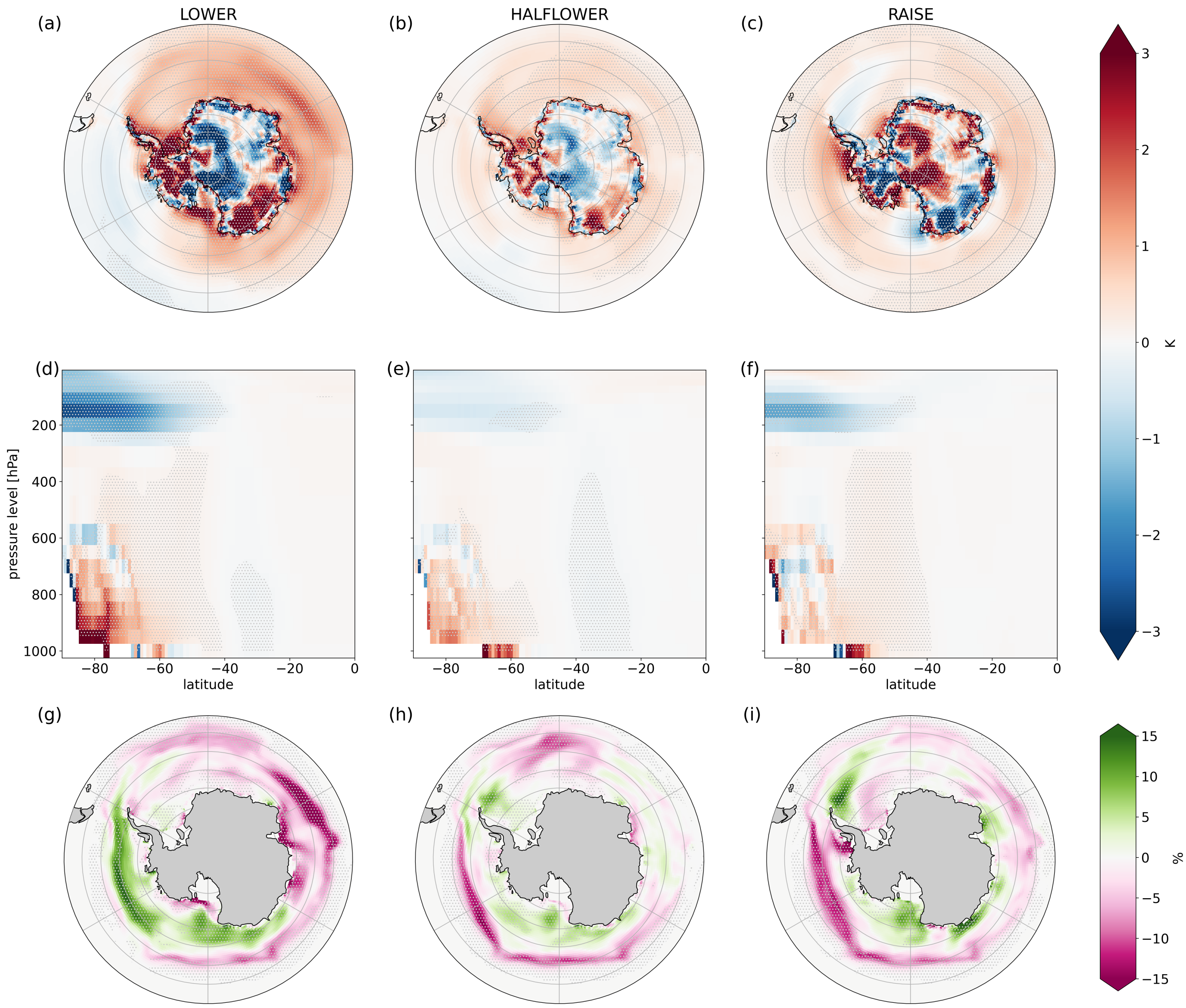

FIG. 12. Annual-mean 2 m air temperature (a-c), zonal-mean temperature (d-f), and sea ice concentration (g-i) responses to Antarctic topography change for each of the fully-coupled simulations. Each is the difference between the experiment and a control run with no topography change averaged over the last 50 years of 300 year integrations. Stippling denotes where the anomalies are significant at the 95% confidence level using a 2-tailed Student t-test.

coupled feedbacks with the full-depth, dynamical ocean lead to different results from those with a slab-ocean.

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1) Atmospheric Temperature and Sea Ice Response

As in the more idealized model configurations presented in the previous sections, there is a non-linear annual-mean 2-m temperature response to Antarctic topography change with more realistic ice-sheet topography perturbations in a fully-coupled model (Figure 12a-c). While the 2-m temperature response appears more complicated over the continent due to the differences between the present-day topography standard in CCSM4 and that in the ice-sheet model of Pollard and DeConto (2009), at the large scale it is clear that the surface near the continent warms whether topography is raised or lowered. In contrast to the idealized experiments, the off-shore warming is stronger in the case where topography is lowered, but the overall response is weaker in the fully-coupled experiments (but still non-linear).

We also see similar vertical structure in the temperature response to that seen in the more idealized model configurations, with the annual-mean warming extending up into the troposphere and cooling in the stratosphere in all experiments (Figure 12d-f). The annual-mean 2-m air temperature increase over the ocean is also associated primarily with annual-mean sea ice loss in all fully-coupled experiments (Figure 12), as in the slab-ocean model configuration, although as with the temperature response, there is more ice loss in the LOWER experiment than in the RAISE experiment.

The response to a smaller topography change (comparing LOWER to HALFLOWER) is approximately linear, with about half the temperature response in HALFLOWER than in LOWER. This suggests that the non-linear behavior we observe reflects a fundamental difference in the physics of the response to raising Antarctic topography than that for lowering topography, relative to the current topography.

2) Ocean Temperature Response

With the addition of a full-depth, dynamic ocean, the near-surface atmospheric warming extends down throughout the entire water column within 300 years of integration (Figure 13). The northward propagation of the warming signal is consistent with anomalous northward ocean heat transport in Figure 14. Thus, changes in Antarctic topography in our simulations have a non-linear impact on the ocean that extends far from the continent through oceanic transport.

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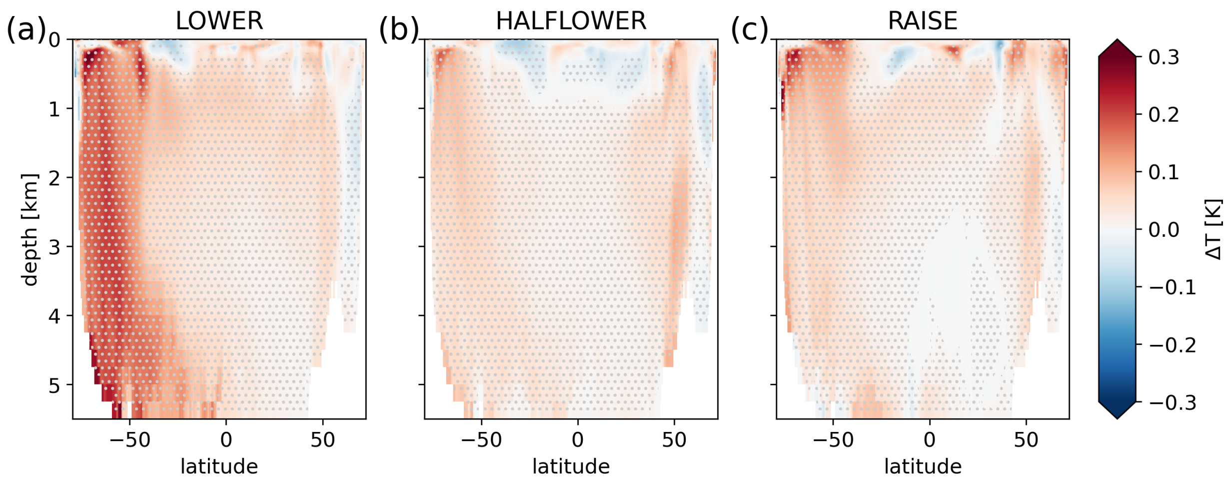

FIG. 13. Annual-mean, zonal-mean ocean temperature response for each of the fully-coupled experiments. Each is the difference between the experiment and a control run with no topography change averaged over the last 50 years of 300 year integrations. Stippling denotes where the anomalies are significant at the 95% confidence level using a 2-tailed Student t-test.

3) Energy Transport Response

The annual-mean energy transport response is more complicated than that in the idealized model configurations, due to the presence of the full-depth, dynamic ocean (see Figure 14 compared to Figure 9). In all fully-coupled experiments, there is anomalous southward atmospheric heat transport and anomalous northward ocean heat transport. In contrast to the idealized model configurations, here the energy transport response is non-linear, though the atmospheric response is relatively weak, with the total energy transport response being dominated by the ocean.

The northward atmospheric energy transport anomaly at high southern latitudes is in noteworthy contrast to other latitudes in all cases in Figure 14. It is especially surprising when topography is lowered since it is opposite to the response at these latitudes when topography is lowered in the slab ocean and fixed-SST experiments.

The anomalous northward atmospheric heat transport in our simulations occurs with little change to the global overturning circulation but a weakening of the Southern Ocean overturning cell, in contrast to the weaker global overturning and stronger Southern Ocean cells found by Singh et al. (2016) when they flattened all of Antarctica in CCSM4. In addition, Singh et al. (2016) only found near-surface warming in the Weddell Sea surface, while we see widespread near-surface warming

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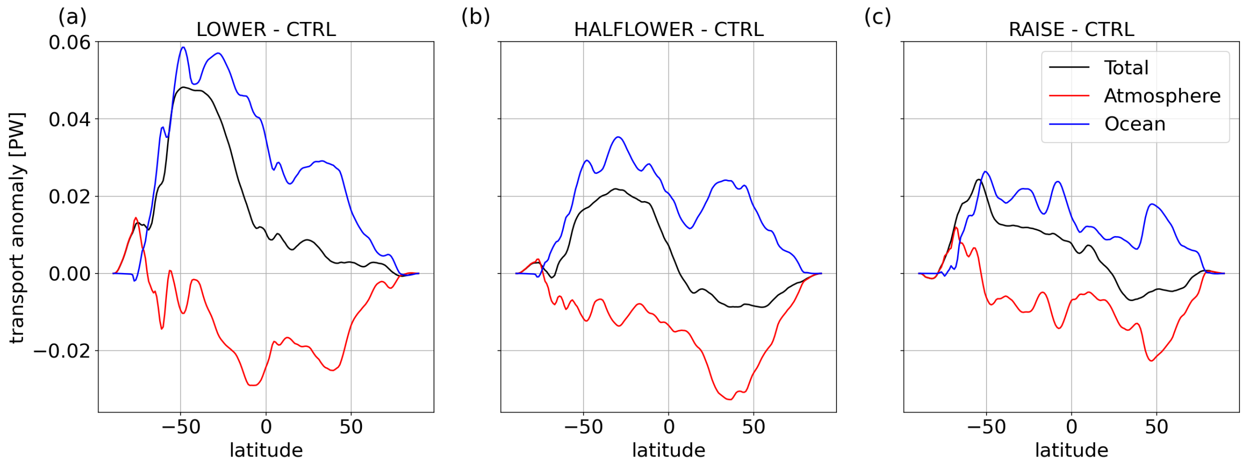

Fig. 14. Annual-mean energy transport response for each of the fully-coupled simulations. Each is the difference between the experiment and a control run with no topography change, averaged over the last 50 years of 300 year integrations. Positive values denote anomalous northward transport.

across the Southern Ocean. Because we use the same model version as Singh et al., but with different topographic perturbations, our contrasting results demonstrate that the way topography is perturbed strongly influences the response of the ocean.

The atmosphere and ocean energy transport response in our simulations is generally strongest in the LOWER experiment, and weakest in the RAISE experiment. Further, the atmospheric energy transport response to lowering topography is similar north of ~ 55° S across all model configurations (fixed-SST and slab-ocean versus fully-coupled, and CCSM4 versus CESM2 with slab-ocean) and most different when topography is raised, suggesting that not only does raising topography drive a fundamentally different physical response than lowering it, but the response to raising depends on the details of how the topography is perturbed and how feedbacks are modeled. We leave further exploration of the ocean response to future work; see also Justino et al. (2014), Steig et al. (2015) and Singh et al. (2016).

4) Cloud Response

The cloud response in the fully-coupled experiments shares some features with that in the more idealized model configurations. There is an increase in winter-spring high cloud fraction in both the LOWER and RAISE experiments, suggesting cloud changes contribute to the surface warming in both experiments. That the cloud response is stronger in the LOWER experiment is consistent

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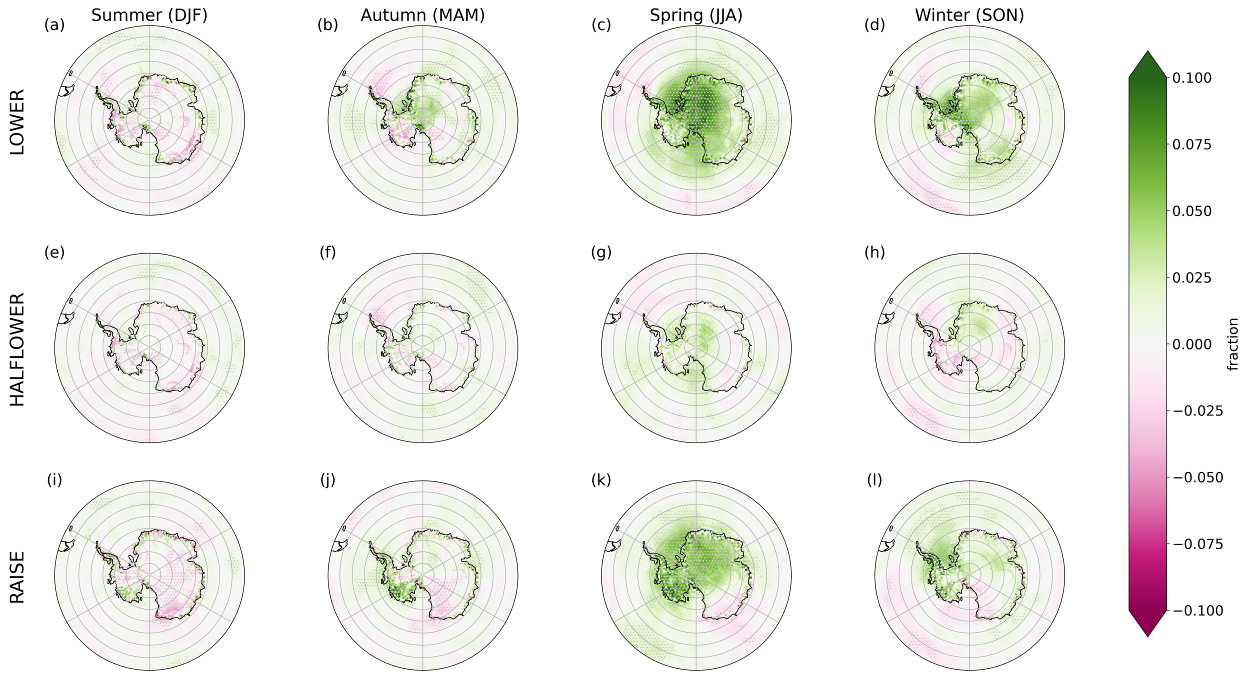

FIG. 15. Seasonal high cloud fraction response for each of the fully-coupled experiments. Each is the difference between the experiment and a control run with no Antarctic topography change averaged over the last 50 years of 300 year integrations. Stippling denotes where the anomalies are significant at the 95% confidence level using a 2-tailed Student t-test.

with the stronger warming in all seasons. These results suggest that the warming when topography is lowered is amplified by a combination of anomalous southward atmospheric heat transport and increased wintertime cloud fraction, which is then amplified by the feedbacks involving sea ice concentration and thickness and SST. The warming when topography is raised is mostly amplified by the cloud response, with a weaker role for atmospheric energy transport.

4. Discussion

We have presented results of raising and lowering topography on Antarctica, focused on the WAIS and coastal Antarctica. We find that the 2-m temperature and precipitation response on the continent is on the whole quite linear, with exceptions at the edge where linear topographic perturbations shift the location of sharp topographic gradients. Topographic gradients drive katabatic winds, which shift in position and are altered in strength by our topographic perturbations. Further, raising topography at the edge of a dome the size of Antarctica results in adiabatic cooling at elevations

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of ~500-750 hPa, while lowering topography causes adiabatic warming at elevations below ~750 hPa.

We find changes in circulation induced by topographic perturbations influence the temperature response over the WAIS, as previously shown by Steig et al. (2015). Lowering topography induces a cyclonic circulation anomaly over West Antarctica, which advects warmer air from lower latitudes into the Weddell Sea and onto the Antarctic Peninsula, corresponding to the greater warming seen in that region. Conversely, raising topography induces an anti-cyclonic circulation anomaly over West Antarctica, which advects warmer air into the Amundsen/Bellingshausen Sea region and onto the bordering region of Antarctica. Thus, circulation changes contribute to the linearity of the response on the continent and the Southern Ocean region surrounding West Antarctica.

Atmospheric and oceanic temperature and sea ice in the Southern Ocean away from West Antarctica exhibit a non-linear response, where raising Antarctic topography does not produce the opposite response to lowering it. In general the response to raising topography is either of the same sign as the response to lowering topography, or the response is negligible. Near-surface warming off the coast of Antarctica is present in all model configurations, whether topography is raised or lowered. The warming response is strongest in the slab-ocean and fully-coupled model configurations, where the ocean and sea ice are able to respond to the atmosphere. The presence of this warming response in the fixed-SST experiments, although weak, indicates that neither SST changes nor sea ice motion or mass changes are necessary, and instead a purely atmospheric and sea ice surface flux response is sufficient.

The non-linear temperature and sea ice response with respect to Antarctic topography change is present in both CCSM4 and CESM2 used in this study, as well as in the study of Tewari et al. (2021), who raised and lowered Antarctic topography by simply scaling the present day elevation in the Community Atmosphere Model version 5 (CAM5) with prescribed SSTs and sea ice fraction. CAM6, the atmosphere model component used in CESM2, has a substantially different cloud microphysics scheme than either CAM4 or CAM5 (Gettelman and Morrison 2014; Gettelman et al. 2014). That the same non-linear temperature response is seen in all three model configurations with differing physics and topography changes strengthens our findings.

We find a role for changes in high cloud fraction in contributing to the non-linear temperature response in some regions. In all experiments where topography was raised, we generally find an

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increase in high cloud fraction in winter and spring. We examined the response of the moisture convergence and vertical motion around Antarctica (not shown) and found no non-linear response with respect to Antarctic topography change. This suggests that the cloud changes are due to the coupled response of temperature, tropospheric stability and clouds. In winter, there is no sunlight in Antarctica, so the radiative impact of clouds reflecting incoming shortwave radiation is unimportant. Instead, the increased downwelling longwave radiation due to increased high cloud fraction dominates, resulting in surface warming. Changes in downwelling longwave radiation and surface temperature are tightly coupled (Vargas Zeppetello et al. 2019), and so cause and effect are not possible to disentangle without more detailed process modeling.

When SSTs, sea ice concentration and thickness are allowed to respond in the slab-ocean model configuration, the surface warming and cloud increases become more pronounced. The circulation and cloud changes that contribute to the non-linear temperature response are present in all experiments, and are then amplified by sea ice and surface temperature feedbacks. Thus, while the near-surface warming near the Antarctic continent when topography is lowered can be explained by an increase in southward atmospheric heat transport by transient eddies, the pattern of warming when topography is raised appears to be a consequence of shifting the influence of katabatic winds further offshore and with an increase in high cloud fraction over some parts of the Southern Ocean.

With the addition of a fully-coupled dynamic ocean, the atmospheric heat transport becomes highly non-linear with respect to Antarctic topography change due to the non-linear ocean heat transport response. Whether topography is lowered or raised, there is anomalous southward atmospheric heat transport over the Southern Ocean. There is also an increase in high cloud fraction whether topography is lowered or raised. Thus, it appears that the warming in the fully-coupled model configuration is due to a complex combination of the elevation where adiabatic warming or cooling occurs, katabatic winds shifts, non-linear atmospheric heat transport and feedbacks with clouds, sea ice and ocean dynamics.

In the model configurations where the sea ice is interactive, the near-surface warming over the ocean coincides spatially with sea ice loss in both the slab-ocean and fully-coupled model configurations (Figures 5 and 12g-i). The weak surface warming present in the fixed-SST experiments suggests that the SST and sea-ice fraction and thickness amplifies the surface warming when they are active, resulting in the much stronger warming in the slab-ocean configuration. In all

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fully-coupled experiments, the warming extends to the full depth of the water column (Figure 13), indicating that the non-linearity of the atmospheric response to Antarctic topography change is responsible for the non-linear ocean response. The results for the lowered ice sheet are consistent with the experiments of Justino et al. (2014) and Steig et al. (2015).

The sea ice and ocean response seen in the fully-coupled integrations in this study have important implications for ice-sheet climate system feedbacks. In an ice sheet mass-loss scenario, the ocean warms near Antarctica owing to anomalous winds, which may enhance ice shelf melt from warm Circumpolar Deep Water, acting as a positive feedback, and accelerating ice sheet mass loss (e.g., Jacobs et al. 1996; Thoma et al. 2008; Steig et al. 2012; Jenkins et al. 2016; Holland et al. 2019). If the ice sheet is experiencing mass gain, on the other hand, our simulations indicate the ocean also warms near Antarctica, which may counteract ice sheet mass gain, thus providing a negative feedback. These topography-forced responses are not represented in most current Earth system model configurations due to the lack of coupled ice-sheet models. Our experiments consider only ice-sheet topography change, and do not include the climate forcing that would have led to that change. Furthermore, our experiments do not consider the impact of ice-sheet melting on the ocean circulation, which could amplify or damp these effects (see e.g., Bintanja et al. 2015; Pauling et al. 2017). Additional experiments with varying climate forcing, meltwater, and simulations with fully-interactive ice sheets, will be important for evaluating the importance of these feedbacks in determining the climate response to past and future forcing.

We have shown, through the use of a hierarchy of general circulation models, aspects of the response of the climate system to changes in the topography of West Antarctica and the continental margins that are linear and aspects that are non-linear. While the near-surface temperature and precipitation response over the Antarctic continent is quite linear with respect to Antarctic topography change, the temperature response in the middle and upper troposphere and lower stratosphere, as well as the surface and deep ocean response away from the Antarctic continent, is not. Stratospheric cooling at high southern latitudes and near-surface warming over the Southern Ocean and associated sea ice loss occurs whether West Antarctic ice sheet topography is raised or lowered. Warming extends throughout the Southern Ocean water column by the end of the simulations, which has important implications for ice sheet-climate system feedbacks that cannot currently be simulated by most Earth system models.

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Data availability statement. Model output and code to reproduce the simulations from this paper are available from the authors on request.

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