



## Abstract

Shifts in Southern Ocean (SO, 40–85°S) shortwave (SW) cloud feedback ( $SW_{FB}$ ) towards more positive values are the dominant contributor to higher effective climate sensitivity (ECS) in Coupled Model Intercomparison Project phase 6 (CMIP6) models. The positive shift in  $SW_{FB}$  in CMIP6 global climate model (GCMs) can be traced back to the greater reduction in low cloud cover and the weaker cloud liquid water response to warming in the SO. To evaluate how realistic the CMIP6 cloud response is, we connect the SO  $SW_{FB}$  to changes in column-integrated liquid water mass (LWP) and the susceptibility of albedo to LWP in 50 CMIP5 and CMIP6 GCMs. In turn, we predict the responses of SO LWP to warming using a cloud-controlling factor (CCF) model. The combination of the CCF model and radiative susceptibility explains about 50 % of the variance in the GCM-simulated  $SW_{FB}$  in the SO. Observations of SW radiation fluxes, LWP, and reanalysis of CCFs are used to constrain the SO  $SW_{FB}$ . This yields a constrained response of SO LWP to warming of  $2.89 - 4.41 \text{ g m}^{-2} \text{ K}^{-1}$ , relative to the total GCM range of  $-0.48 - 9.33 \text{ g m}^{-2} \text{ K}^{-1}$ . The susceptibility of albedo to LWP is constrained to be  $0.41 - 0.86 (\text{kg m}^{-2})^{-1}$ , relative to the GCM range of  $0.23 - 3.62 (\text{kg m}^{-2})^{-1}$ , where albedo is unitless. The overall constraint on the contribution of SO  $SW_{FB}$  to global cloud feedback is  $-0.19 - 0.05 \text{ Wm}^{-2}\text{K}^{-1}$ , relative to GCM range of  $-0.28 - 0.27 \text{ Wm}^{-2}\text{K}^{-1}$ . In summary, observations suggest a moderate negative to weak positive SO  $SW_{FB}$ .

## Plain Language Summary

Clouds over the Southern Ocean (SO, 40–85°S) efficiently reflect sunlight back to space and cool the planet. Previous studies suggest that SO clouds become optically thicker and thus more strongly cool the planet in response to global warming—a compensating feedback (i.e., a negative shortwave cloud feedback ( $SW_{FB}$ )). The SO  $SW_{FB}$  in the latest generation of global climate models (GCMs) participating in the Coupled Model Intercomparison Project phase 6 (CMIP6) has shifted towards more positive values, leading to the larger predicted temperature responses to greenhouse gas increases by these GCMs. In this study, we examine if this more positive  $SW_{FB}$  is consistent with observations. We connect the effect of SO clouds on reflected sunlight to the predicted response of cloud liquid content to global warming. Satellite observations of reflected sunlight, cloud liquid, and reanalysis of atmospheric state are applied to constrain the SO  $SW_{FB}$ . The results suggest that SO cloud liquid will increase with warming around the average of GCM predictions. Satellite records suggest that the sensitivity of reflected sunlight to cloud liquid is weak compared to GCMs. In combination, these two constraints suggest a moderately negative SO  $SW_{FB}$ .

## 1 Introduction

Shortwave cloud feedback ( $SW_{FB}$ ) is the largest uncertainty in net climate feedback, and by extension, effective climate sensitivity (ECS) (Zelinka et al., 2020; Sherwood et al., 2020). This uncertainty can be attributed to the difficulties in representing subgrid-scale cloud processes in the global climate models (GCMs) (Sherwood et al., 2014; Zhao, 2014; Storelvmo et al., 2015; Webb et al., 2015; McCoy et al., 2016). Although there is a large intermodel spread in the sign and magnitude of  $SW_{FB}$ , some robust features emerged from previous generations of GCMs. For example, positive  $SW_{FB}$  in subtropics due to decreased cloud coverage and negative  $SW_{FB}$  in extratropics due to increased cloud optical depth (Zelinka et al., 2012; Ceppi, McCoy, & Hartmann, 2016).

Zelinka et al. (2020) shows that GCMs participating in the Coupled Model Intercomparison Project phase 6 (CMIP6) report positive shifts in extratropical  $SW_{FB}$  poleward of 30° relative to previous generations of GCMs. This results in an increase in ECS

63 in CMIP6 GCMs. Zelinka et al. (2020) demonstrates the positive shift in extratropical  
 64  $SW_{FB}$  is driven by the stronger reduction of low cloud cover and weaker increase of in-  
 65 cloud liquid water content in extratropics in response to warming in CMIP6 GCMs. This  
 66 corresponds to a more positive cloud amount feedback and less negative cloud optical  
 67 depth feedback, respectively. In this study, observations are used to constrain extratrop-  
 68 ical  $SW_{FB}$  and evaluate whether the more positive  $SW_{FB}$  in the Southern Ocean re-  
 69 gion (SO, defined as  $40\text{--}85^\circ S$ ) in CMIP6 GCMs are consistent with observed variabil-  
 70 ity.

71 Examining the response of cloud liquid water content to warming is an idealized  
 72 way to constrain extratropical  $SW_{FB}$ . The column-integrated liquid water mass (i.e.,  
 73 Liquid Water Path, hereafter LWP) is proportional to the cloud optical depth in an over-  
 74 cast region. Increased in-cloud LWP increases the amount of reflected shortwave (SW)  
 75 radiation more than it reduces the outgoing longwave (LW) radiation, leading to a neg-  
 76 ative cloud optical depth feedback (Paltridge, 1980). In this study, LWP is defined as  
 77 the liquid water mass averaged over cloudy and clear-sky pixels. It incorporates infor-  
 78 mation about cloud fraction (CF) coverage into this variable as well as in-cloud LWP  
 79 ( $LWP \approx CF \cdot LWP_{in-cloud}$ ).

80 Across GCMs, SO LWP increases in response to increased surface temperature. Fig  
 81 1a shows that the changes in LWP scaled by changes in global-mean surface air temper-  
 82 ature (GMT) in the quadrupling  $CO_2$  (*abrupt4xCO<sub>2</sub>*) simulations of GCMs are anti-correlated  
 83 with model extratropical  $SW_{FB}$ . The response of LWP to warming also reproduces the  
 84 dipole pattern of  $SW_{FB}$  in the SO. Our analysis will focus on constraining SO  $SW_{FB}$   
 85 by constraining the changes in LWP with warming in  $40 - 85^\circ S$ .

86 Many potential mechanisms can explain the increase of extratropical LWP with warm-  
 87 ing, as shown by Fig 1b (Terai et al., 2019). For example, the phase changes of suscep-  
 88 tible ice to liquid in the mixed-phased cloud region and the resultant suppression of pre-  
 89 cipitation (Senior & Mitchell, 1993; McCoy et al., 2014a; Ceppi, Hartmann, & Webb, 2016;  
 90 Tan et al., 2016, 2019); the strongly increased moist adiabat at high latitudes (Betts &  
 91 Harshvardhan, 1987); and increases in cloud liquid water content driven by enhanced ex-  
 92 tratropical moisture convergence (McCoy, Field, Bodas-Salcedo, et al., 2020; McCoy et  
 93 al., 2022). In this study, we focus our analysis on how changes in extratropical moisture  
 94 convergence contribute to SO  $SW_{FB}$ . As shown in Held and Soden (2006), column-integrated  
 95 water vapor increases with warming following Clausius-Clapeyron scaling (C-C) (glob-  
 96 ally averaged rate about  $7\%/K$ ). Two direct consequences of increased lower-tropospheric  
 97 humidity are increased horizontal transport of water vapor and enhanced patterns of mois-  
 98 ture convergence and divergence. The latter change also satisfies the C-C scaling, albeit  
 99 with some adjustments in its spatial pattern such as the poleward expansion of subtrop-  
 100 ical drying (Siler et al., 2018; Bonan et al., 2023). Local precipitation and evaporation  
 101 in the extratropics increase with warming but at a slower rate than C-C scaling owing  
 102 to the energetic constraints (Allen & Ingram, 2002; Lorenz & DeWeaver, 2007; Stephens  
 103 & Ellis, 2008; K. Trenberth, 2011). Thus, the convergence of moisture exceeds local evap-  
 104 oration and increases the extratropical moisture supply (K. E. Trenberth, 1998). Because  
 105 the conversion of water vapor to precipitation happens in clouds, increases in both source  
 106 and sink of clouds should guarantee an increase in extratropical cloudiness (McCoy et  
 107 al., 2022). The negative  $SW_{FB}$  owing to increased liquid cloud condensates is most no-  
 108 table in the region where moisture convergence is increasing with warming, which tends  
 109 to be poleward of  $50^\circ S$  in the SO (Fig 1a and Fig S1). Here, we will investigate if changes  
 110 in moisture flux can predict the SO LWP response to warming and in turn, how this af-  
 111 fects the SO  $SW_{FB}$ . Spaceborne observations and reanalysis are used to constrain the  
 112 SO  $SW_{FB}$ . We provide an outline of how we do this below.

113  $SW_{FB}$  is the change in upwelling shortwave (SW) radiation fluxes ( $SW_{\uparrow}$ ) at the  
 114 top of atmosphere (TOA) due to adjustment of cloud properties and scaled by changes  
 115 in GMT. Because downwelling SW radiation flux ( $SW_{\downarrow}$ ) is a function of season and lat-

116 itude, the local  $SW_{FB}$  should be proportional to the cloud-induced change in SW albedo  
 117 ( $\alpha = SW_{\uparrow}/SW_{\downarrow}$ ) scaled by GMT ( $\partial\alpha_C/\partial GMT$ ) for a given time and latitude. In turn,  
 118 the change in  $\alpha$  can be expressed as the product of the susceptibility of  $\alpha$  to liquid ( $\partial\alpha/\partial LWP$ )  
 119 and the response of cloud liquid to warming ( $dLWP/dGMT$ )

$$120 \quad SW_{FB} \propto \frac{\partial\alpha_C}{\partial GMT} \sim \frac{\partial\alpha}{\partial LWP} \cdot \frac{dLWP}{dGMT} \quad (1)$$

121 The change in  $\alpha$  caused by ice is ignored for two reasons: First, the response of cloud  
 122 ice is much smaller than response of liquid to global warming (McCoy et al., 2022), with  
 123 a median ratio of changes in LWP to ice water path across GCMs of 8 (McCoy et al.,  
 124 2016). Second, the reflectivity of SW radiation per unit mass of ice is typically less than  
 125 that of liquid, owing to the smaller average size of liquid droplets (Liou, 2002; McCoy  
 126 et al., 2014b). In Section 3.3 we evaluate the predictive ability of the right-hand side of  
 127 Equation 1 in GCMs neglecting ice.

128 We constrain the SO  $SW_{FB}$  by providing constraints on each term on the right-  
 129 hand side of Equation 1. Methods for computing the right-hand side of Equation 1 are  
 130 discussed in section 2. LWP response to global warming is predicted using meteorolog-  
 131 ical variability, discussed in detail in section 2.1 and 2.2. The method for estimating the  
 132 radiative susceptibility is presented in section 2.3. Sections 2.4 and 2.5 describe how to  
 133 compute these two terms from GCM data and observations, respectively. Section 3.1 pro-  
 134 vides observational constraints on the GCM LWP responses. Section 3.2 analyzes the  
 135 opposing roles of radiative susceptibility and LWP response in setting the SO  $SW_{FB}$ .  
 136 Section 3.3 produces a constraint on the SO  $SW_{FB}$  by splitting the LWP constraint into  
 137 latitude bands consistent with regions of persistent drying and moistening. Conclusions  
 138 are presented in section 4 with suggestions for future work.

## 139 2 Data and Methodology

### 140 2.1 Cloud-controlling Factor Analysis

141 In this study, we examine the linear relationships between large-scale environmen-  
 142 tal factors and clouds. The large-scale environmental factors that control local cloud pro-  
 143 cesses are referred to as cloud-controlling factors (CCFs, Stevens and Brenguier (2009)).  
 144 CCF analysis is based on the idea that response of local cloud properties to global warm-  
 145 ing can be expressed by a first-order Taylor expansion in CCFs ( $X_i$ ) (Klein et al., 2017).  
 146 CCF analysis allows us to use observations to constrain the response of LWP to to global  
 147 mean temperature (GMT) (Qu et al., 2015). Following Qu et al. (2015), we predict the  
 148 response of LWP to GMT as follows:

$$149 \quad \frac{\Delta LWP}{\Delta GMT} = \sum \frac{\partial LWP}{\partial X_i} \frac{\Delta X_i}{\Delta GMT} + Res \quad (2)$$

$$X_i = T_s, P - E, LTS, \omega_{500}$$

150 The LWP response GMT is decomposed into the LWP response to CCFs and a resid-  
 151 ual term. LWP response to GMT induced by each CCF is a product of the sensitivity  
 152 of LWP to CCF ( $\partial LWP/\partial X_i$ ) and the response of CCFs to changes in GMT ( $\Delta X_i/\Delta GMT$ ).  
 153 We constrain the LWP response to GMT by replacing the  $\partial LWP/\partial X_i$  derived from GCMs  
 154 with the observed sensitivities and estimating  $\Delta X_i/\Delta GMT$  from GCMs' quadrupling  
 155  $CO_2$  simulations. The constraint assumes that the sensitivities derived from present cli-  
 156 mate are applicable to predict future cloud change. This assumption requires an invari-  
 157 ant relationship between local cloud properties and CCFs across any time scale greater  
 158 than 2-3 days, which is the time scale that the boundary layer and its clouds can re-adjust  
 159 to CCF changes (Schubert et al., 1979; Bretherton, 1993). This is referred to as "time-

scale invariance” (Klein et al., 2017). We evaluate the time-scale invariance of our relationships between CCFs and LWP with an out-of-sample test from the observational record and an out-of-sample test from the GCM simulations. In section 3.1.1, we show that the observed sensitivities of LWP to CCFs derived from 2012–2016 monthly-mean data are able to predict the annual mean LWP change in the SO back to the early 1990s. For GCMs, section 3.1.2 shows the sensitivities computed using monthly preindustrial control (*piControl*) simulations are able to predict the long-term variation of LWP in 150 years of abrupt CO<sub>2</sub> quadrupling (*abrupt4xCO<sub>2</sub>*) simulations.

The CCFs considered in this study are surface skin temperature ( $T_s$ ), precipitation minus evaporation ( $P-E$ ), lower tropospheric stability ( $LTS$ ) (Klein & Hartmann, 1993), and 500 mb subsidence ( $\omega_{500}$ ). These factors are consistent with McCoy, Field, Bodas-Salcedo, et al. (2020) and McCoy et al. (2022). Because GCMs do not output moisture convergence as a variable, we use  $P-E$  as a proxy. These terms differ by the change in moisture storage over time (see Fig 1 in Seager and Henderson (2013)). Fig S2 shows  $P-E$  is close to moisture convergence in the 40–85°S region for ERA-5 reanalysis if we averaged the variables over a large spatial scale (5° x 5°). Seager and Henderson (2013) also states that the discrepancy between these two terms should be smaller in GCMs than in reanalysis because of the absence of an analysis increment in GCMs. For the above reasons, we average LWP and CCFs data into 5° x 5° gridboxes in the SO to make  $P-E$  a reasonable approximation of moisture convergence. In this study, the LWP response is predicted on each 5° x 5° gridbox in the SO.

The moisture convergence is consistently positive across GCMs in the SO region in *picontrol* simulations (gray lines in Fig S1). In *abrupt4xCO<sub>2</sub>* simulations moisture convergence reduces in 40–50°S region and enhances in 50–85°S region (colored lines in Fig S1). This implies a poleward expansion of subtropical drying under global warming (Siler et al., 2018; Bonan et al., 2023) and is consistent with 50°S acting as the demarcation between the positive  $SW_{FB}$  (negative  $\Delta LWP/\Delta GMT$ ) region and negative  $SW_{FB}$  (positive  $\Delta LWP/\Delta GMT$ ) region (Fig 1a) in GCMs driven by changes in moisture convergence. Following the regimes of persistent drying and moistening, SO LWP response and  $SW_{FB}$  are constrained in 40–50°S and 50–85°S regions in section 3.1.2 and 3.3.

## 2.2 Temperature Partitioning of Southern Ocean Clouds

CCF analysis has been used to predict the response of boundary layer cloud to warming in the tropics and subtropics (Qu et al., 2015; Zhai et al., 2015; Myers & Norris, 2016; Brient & Schneider, 2016; McCoy et al., 2017; Myers et al., 2021; Wall et al., 2022). The extratropical region presents a unique set of challenges in predicting the boundary layer cloud response to warming with a single set of linear relationships as in Equation 2. In the SO region, surface temperature varies from 210 K in the austral winter over the sea ice to around 290 K in the summer near 40°S. The temperature of clouds over the ocean and sea ice varies along with the surface temperature. The wide temperature range in the SO results in a combination of mixed-phase and liquid-only boundary layer clouds. The formation and removal processes governing these cloud types are very different. The initial nucleation and growth processes happen at different rates in mixed-phase ( $T < 0^\circ C$ ) and liquid-only ( $T > 0^\circ C$ ) clouds (Jeffery & Austin, 1997; Koop et al., 2000; Schaller & Fukuta, 1979; Mossop, 1985; Lamb & Verlinde, 2011). Precipitation efficiency is higher in mixed-phase clouds than in liquid-only clouds due to the rapid growth of ice crystals at the expense of liquid drops (Wegener-Bergeron-Findeisen (WBF) process) (Storelmo & Tan, 2015). The higher precipitation efficiency of mixed-phase clouds results in the majority of mid-latitude precipitation events originating as snow (Field & Heymsfield, 2015).

210 Previous studies suggest that mixed-phase and liquid-only clouds respond differ-  
 211 ently to global warming. Gordon and Klein (2014) shows that low cloud optical depth  
 212 increases with warming for cold clouds and decreases with warming for warm clouds in  
 213 GCMs. This behavior is also found by in-situ observations (Terai et al., 2019). These  
 214 studies state that the increase of cold cloud optical depth is due to the increased cloud  
 215 water content, while the decrease of warm cloud optical depth is owing to reduced cloud  
 216 physical thickness. In addition to these mechanisms, analysis of GCMs has suggested that  
 217 phase changes in mixed-phase clouds in response to warming are important to the ac-  
 218 curate representations of  $SW_{FB}$  and ECS (Tan et al., 2016; Bjordal et al., 2020).

219 Because of the strongly differing cloud physics and response behaviors of warm and  
 220 cold clouds, we treat them separately by splitting our analysis into two CCF models. We  
 221 characterize cold and warm clouds in the SO by  $T_s$ . Each  $5^\circ \times 5^\circ$  gridbox in  $40-85^\circ S$   
 222 is counted as the cold (warm) regime if the  $T_s$  of this gridbox is lower than (larger or  
 223 equal to) a threshold  $T_s$  ( $TR_{T_s}$ ). This results in two CCF models split over  $TR_{T_s}$ :

$$\begin{aligned}
 \frac{\Delta LWP}{\Delta GMT}|_{Cold} &= \sum_{T_s < TR_{T_s}} \left( \frac{\partial LWP}{\partial X_i}|_{Cold} \cdot \frac{\Delta X_i}{\Delta GMT}|_{Cold} \right) + Res_1 \\
 \frac{\Delta LWP}{\Delta GMT}|_{Warm} &= \sum_{T_s \geq TR_{T_s}} \left( \frac{\partial LWP}{\partial X_i}|_{Warm} \cdot \frac{\Delta X_i}{\Delta GMT}|_{Warm} \right) + Res_2
 \end{aligned}
 \tag{3}$$

225 For each GCM,  $TR_{T_s}$  is the temperature that maximizes the explained variance  
 226 of GCM LWP by Equation 3. We iterate through potential values of  $TR_{T_s}$  from 210 K  
 227 to 290 K. For each potential  $TR_{T_s}$ , the  $r^2$  of Equation 3 trained by *piControl* simu-  
 228 lations is computed. Fig 2 shows the  $r^2$  for each GCM as a function of potential  $TR_{T_s}$  in  
 229 *piControl* simulations. The  $TR_{T_s}$  for most GCMs is around 270 K, which generally sep-  
 230 arates the clouds over sea ice from the warm open ocean. This is consistent with other  
 231 studies showing minimal supercooled liquid fraction in GCMs when cloud temperature  
 232 is lower than 255 K (Komurcu et al., 2014). If we assume a typical lapse rate of  $6.5K/km$   
 233 and cloud height of 2–3 km in the extratropical environment, this is consistent with  
 234 a surface temperature of 270 K. The  $TR_{T_s}$  and resultant regime-specific  $\partial LWP/\partial X_i$   
 235 derived from *piControl* simulations are used to partition the regimes and predict the LWP  
 236 response to warming in *abrupt4xCO2* simulations. Fig S3 shows that the  $TR_{T_s}$  trained  
 237 by *abrupt4xCO2* simulations are qualitatively the same as the mean-state values.

238 Because microwave radiometers do not retrieve LWP over sea ice (Elsaesser et al.,  
 239 2017), it is hard to do the same cold-warm partitioning in observations. The lack of high-  
 240 latitude LWP data in the SO limits the possible range of  $TR_{T_s}$  derived from observa-  
 241 tions, and they do not significantly improve predictions as in GCMs shown in Fig 2. For  
 242 this reason, the observed SO is only treated as a single regime. In section 3.1.1, we eval-  
 243 uate whether our prediction of observed LWP is degraded by only using the single regime  
 244 CCF model Equation 2.

### 245 2.3 Radiative Susceptibility

246 In Equation 1, the response of LWP to GMT is connected to its SW radiative ef-  
 247 fect through a radiative susceptibility term ( $\partial\alpha/\partial LWP$ ). This term describes how a change  
 248 in LWP affects  $\alpha$  while keeping other factors fixed. Following McCoy et al. (2022), the  
 249 radiative susceptibility is estimated by training the multi-linear regression model:

$$\alpha = c_1 * LWP + c_2 * \alpha_{clear-sky} + c_3;
 \tag{4}$$

where  $c_1$  is  $\partial\alpha/\partial LWP$ .  $\alpha$  is a function of clear-sky albedo ( $\alpha_{cs}$ ) and LWP, which is in turn affected by cloud areal extent (Bender et al., 2017) and cloud optical depth (Gordon & Klein, 2014). To reduce the effects introduced by the seasonal cycle of solar zenith angle (SZA), we only train Equation 4 on January data, during which time the SZA is smallest and the effect of cloud properties on  $\alpha$  is most pronounced (see Fig 2 in McCoy et al. (2018) for the relationships between  $\alpha$ , cloud fraction, and SZA). The effects of high  $\alpha_{cs}$  is excluded in our analysis by threshold ( $TR_{\alpha_{cs}}$ ). We test a series of  $TR_{\alpha_{cs}}$  in section 3.2 to estimate whether  $c_1$  is sensitive to this threshold. Removing high  $\alpha_{cs}$  removes data over sea ice from the models, making this calculation analogous to the observations where retrievals are not available over sea ice. The regression model is trained on data from the SO region at the native spatial resolution of each GCM and of observations.

## 2.4 Global Climate Models

We compute the LWP response to GMT of GCMs by using monthly-mean output from the mean-state (*piControl*) and the quadrupling  $CO_2$  (*abrupt4xCO2*) simulations from 50 GCMs participating in CMIP5 (20) and CMIP6 (30). GCMs used in this study are listed in Table S1.

Radiative susceptibility ( $\partial\alpha/\partial LWP$ ) is computed using *piControl*. The CCF model (Equation 3) is trained on *piControl* output to calculate regime-specific sensitivities of LWP to CCFs ( $\partial LWP/\partial X_i$ ). Changes in CCFs scaled by GMT ( $\Delta X_i/\Delta GMT$ ) are computed as the differences between the *piControl* average and the 121 - 140 year mean of *abrupt4xCO2* simulations following Myers et al. (2021). Following Equation 3, these terms are combined to predict  $\Delta LWP/\Delta GMT$ . The time-scale invariance of Equation 3 is evaluated by comparing  $\Delta LWP/\Delta GMT$  predicted from Equation 3 to  $\Delta LWP/\Delta GMT$  calculated from GCM output.

LWP is the column-integrated liquid water mass, computed by using *clwvi* (total condensed water path for liquid and ice) minus *clivi* (ice water path). Monthly-mean LWP for GCM is averaged over the cloudy and cloud-free portion of the model gridbox, which is consistent with the microwave LWP retrieval used in this study (section 2.5). The following variables are used for CCFs ( $X_i$ ): *ts* for surface temperature; *pr* and *hfls* for precipitation and evaporation; *ta* at 700 mb, *ps*, and *ts* for lower tropospheric stability and *wap* at 500 mb for subsidence. The radiative susceptibilities ( $\partial\alpha/\partial LWP$ ) of GCMs are computed by regressing the SW albedo ( $\alpha = rsut/rsdt$ ) on clear-sky albedo ( $\alpha_{cs} = rsutcs/rsdt$ ) and LWP.

## 2.5 Observations

Observations of monthly-mean cloud LWP are provided by the Multisensor Advanced Climatology of Liquid Water Path (MAC-LWP) data set (Elsaesser et al., 2017; O'Dell et al., 2008). MAC-LWP synthesizes microwave LWP observations from multiple satellites. Cloud LWP is the liquid water mass within an atmospheric column excluding precipitating liquid. The monthly-mean LWP is averaged over the cloudy and cloud-free scenes of each  $1^\circ \times 1^\circ$  gridbox. Microwave observations of LWP are only available over the open ocean. Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) reanalysis (Gelaro et al., 2017) is used to describe CCFs. MAC-LWP LWP and MERRA-2 CCFs from 1992 to 2016 are used to conduct the out-of-sample test in section 3.1.1 and provide constraints on GCM LWP responses in section 3.1.2. LWP and CCFs are binned into the same  $5^\circ \times 5^\circ$  averages used in the analysis of GCM output.

A missing data threshold of 50% is used in each  $5^\circ \times 5^\circ$  gridbox. Fig 3 compares the fraction of gridboxes with sufficient data to the fraction of warm regime gridboxes for 50 GCMs. The distribution of observations in SO is qualitatively close to the warm

regime of GCMs. Since most of the GCMs group all open water into one regime ( $TR_{T_s} \approx 270\text{ K}$ ), the observed SO becomes an approximation to the GCM warm regimes. Because of this, a CCF model with only one regime (Equation 2) is used to predict the historical record of LWP in section 3.1.1. The derived  $\partial LWP/\partial X_i$  from observations is used to constrain the warm regime LWP response to GMT in GCMs. The propagation of the constraint range from the warm regime to the entire SO is discussed in section 3.1.2.

Equation 4 is used to calculate  $\partial\alpha/\partial LWP$  from monthly-mean TOA shortwave fluxes from the Clouds and the Earth’s Radiant Energy System (CERES) EBAF-TOA data (Ed 4.1) (Loeb et al., 2018; Wielicki et al., 1996) combined with LWP from MAC-LWP. Observations from 2003 to 2016 are used. This period is set by the availability of CERES and MAC-LWP data.

### 3 Results

#### 3.1 Prediction of LWP

To constrain  $SW_{FB}$  using Equation 1, we need to constrain the response of SO LWP to warming. To do this, we need to evaluate whether the sensitivity of LWP to CCFs is time-scale invariant (Klein et al., 2017). We examine time-scale invariance using two out-of-sample tests. First, we evaluate whether the regression model in Equation 2 trained on a short period of observations can predict past variations of LWP. This is shown in section 3.1.1. Second, we evaluate whether the regression model in Equation 3 trained on the mean-state climate from GCMs can predict the LWP response to a quadrupling in CO<sub>2</sub>. This is discussed in section 3.1.2. Following these tests, we use observations to constrain the spread of GCM LWP responses to GMT in *abrupt4xCO<sub>2</sub>* simulations in section 3.1.2 and discuss the contribution of CCFs to LWP response to GMT in section 3.1.3.

##### 3.1.1 Historical Trends in LWP

We split the observations of LWP and reanalysis of CCFs from 1992 to 2016 into a training period (2012 - 2016) and a validation period (1992 - 2011). We train the sensitivities of LWP to CCFs ( $\partial LWP/\partial X_i$ ) using monthly-mean observational data in the training period and use them to predict the annual variation of LWP in the validation period. Fig 4a shows the decadal trend in SO LWP from MAC-LWP observation and the prediction of Equation 2. MAC-LWP shows a positive trend of LWP in the past two decades, consistent with Manaster et al. (2017). The predicted LWP by Equation 2 broadly reproduces the positive trend of LWP during this period from 1996 until 2012. Before 1996, the predicted LWP trend appears to reverse. This may be because the meteorological predictors used in the regression model are reliant on the observations being ingested in MERRA-2. Many fewer observations of precipitation are available before the mid-1990s (Gelaro et al., 2017). The lack of observational input to reanalysis may lead to the disagreement between the Equation 2 predicted LWP and observations in the early 1990s. The ability of Equation 2 to predict decadal-scale trends in LWP in an out-of-sample test supports the time scale invariance of  $\partial LWP/\partial X_i$  derived from observations. Our choice of training and validation period does not substantially affect the ability of the CCF model to predict LWP (Fig S4).

Fig 4b shows the decomposition of LWP response into contributions from individual CCFs. The positive trend in SO LWP can be largely explained by the changes in  $P-E$ . Increases in surface temperature explain only a small fraction of the LWP trend. Stability and large-scale subsidence have negligible effects on the SO LWP on a decadal scale. Increased  $P-E$  is related to the increased moisture content in the extratropical atmosphere. This result suggests the important role of hydrological response to the observed LWP increase in the SO for the past two decades.

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### 3.1.2 Predicting LWP response to CO2 Quadrupling

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Following our evaluation of whether Equation 2 can predict the observed decadal variability of LWP, we evaluate whether Equation 3 trained on mean-state (*piControl*) output can predict the response of LWP to CO2 quadrupling (*abrupt4xCO2*). Fig 5 shows the predicted LWP change scaled by GMT change ( $\Delta LWP/\Delta GMT$ ) between the *piControl* average and the 121 - 140 years mean of *abrupt4xCO2* simulations. The 50 GCMs shown are from CMIP5 and CMIP6 and are listed in Table S1. LWP response to GMT is shown separated into three different latitude bands: 40–85°S (Fig 5ab); 40–50°S (Fig 5cd); and 50 – 85°S (Fig 5ef). The 40 – 50°S and 50 – 85°S correspond to the regions of drying and moistening in response to warming (Fig S1). As discussed in section 2.5, observational constraint from MAC-LWP is only available in the warm regime. Latitudinal-averaged  $\Delta LWP/\Delta GMT$  in the warm regime is shown in Fig 5ace. Latitudinal-averaged  $\Delta LWP/\Delta GMT$  for both regimes is shown in Fig 5bdf.

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Equation 3 explains 70% of the variance in 40–85°S  $\Delta LWP/\Delta GMT$  across GCMs (Fig 5b). The best fit line between the CCF model predictions and the actual GCM output is close to 1-1 line. This result supports the time-scale invariant relationships between LWP and CCFs in Equation 3. The explained variance in  $\Delta LWP/\Delta GMT$  by Equation 3 is 59% averaged over 40–50°S (Fig 5d). This decrease in explained variance may be related to the hydrological response in this region. While moisture convergence is positive in 40–50°S in the mean-state climate, this pattern becomes less robust at the end of *abrupt4xCO2* simulations with some GCMs displaying drying and some displaying moistening (Fig S1). In the 50–85°S latitude band, explained variance in  $\Delta LWP/\Delta GMT$  is 86% (Fig 5f).

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To provide observational constraints on  $\Delta LWP/\Delta GMT$  in these three latitude bands, we need to evaluate the amount of constraint provided by the warm component of Equation 3 because observations are only available in this regime. Fig 5ace display the constraint range of warm regime  $\Delta LWP/\Delta GMT$  in each latitude band as red shading on the x-axis. These constraints are obtained by replacing the GCM  $\partial LWP/\partial X_i$  in the warm regime with  $\partial LWP/\partial X_i$  computed from observations in section 3.1.1. The warm regime explains a large fraction of variance in  $\Delta LWP/\Delta GMT$  across GCMs for all latitude bands (see  $r^2$  in Fig 5ace). The variance in  $\Delta LWP/\Delta GMT$  averaged over 40–85°S explained by the warm regime is high ( $r^2 = 0.88$ , Fig 5a). Only the warm regime exists in the 40 – 50°S region and  $r^2 = 1$  (Fig 5c). The explained variance in  $\Delta LWP/\Delta GMT$  is still relatively high in the 50 – 85°S region ( $r^2 = 0.67$ , Fig 5e).

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We propagate the observational constraint from the warm regime to latitudinal-averaged  $\Delta LWP/\Delta GMT$ . This is done using the linear relationships in Fig 5ace. Uncertainty in the fit is estimated by Jackknife resampling (Tukey, 1958). We intersect the shaded region on the x-axis of Fig 5ace with the best fit line and uncertainty to propagate our constraint from the warm regime to the sum of warm and cold regimes in each latitude band. In Fig 5bdf, the constraints from the y-axis of 5ace are shown as the brown shading on the x-axis. The fit lines in Fig 5bdf are used to propagate the constraints on the CCF model predictions to the GCM LWP response. These constraints are used in section 3.3 to constrain  $SW_{FB}$ .

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### 3.1.3 CCF Contributions to LWP Response to CO2 Quadrupling

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In this section we show the sensitivities of LWP to CCFs ( $\partial LWP/\partial X_i$ ) and each CCFs contribution to the response of LWP to warming ( $\Delta LWP/\Delta GMT$ ). Values of  $\partial LWP/\partial X_i$  for each GCM is shown in Fig 6a. The change in each CCF between *picontrol* and *abrupt4xCO2* simulations is shown in Fig 6b. Following Equation 3, the product of these two terms is the contribution of each CCF to  $\Delta LWP/\Delta GMT$  (Fig 6c). Cold and warm regime values are shown in each subplot separately. Observed  $\partial LWP/\partial X_i$  are displayed for the warm regime (Fig 6a).

400 The dependence of LWP on CCFs across GCMs and observations is broadly con-  
 401 sistent with previous studies (Fig 6a). The dependence of LWP on  $T_s$  is positive across  
 402 all the GCMs for the cold regime but with less agreement in the sign for the warm regime.  
 403 This is consistent with previous studies suggesting cold cloud optical depth will increase  
 404 with temperature (Gordon & Klein, 2014; Terai et al., 2019), mostly due to the increased  
 405 cloud water content (Betts & Harshvardhan, 1987). Terai et al. (2019) suggests that the  
 406 cloud optical depth for warm clouds may decrease or stay constant with increasing tem-  
 407 perature owing to the reduced cloud adiabaticity. The dependence of LWP on  $P - E$  is  
 408 positive for warm and cold regimes, which is consistent with previous literature (McCoy  
 409 et al., 2019; McCoy, Field, Gordon, et al., 2020). The dependence of LWP on  $LTS$  is mostly  
 410 positive in the warm regime of GCMs, while the sensitivity of LWP to  $\omega_{500}$  is small. This  
 411 is consistent with previous work on boundary layer cloudiness (Zelinka et al., 2018; My-  
 412 yers & Norris, 2015, 2013). The observed sensitivities of LWP to  $T_s$  and  $P - E$  are pos-  
 413 itive and much larger than the  $LTS$  and  $\omega_{500}$  sensitivities.

414 Both  $T_s$  and  $P - E$  increase with warming in warm and cold regimes (Fig 6b).  $LTS$   
 415 increases with warming in the warm regime but decreases in the cold regime. This ro-  
 416 bust pattern may be related to the poleward shift of the Hadley cell (stabilizing the warm  
 417 regime lower troposphere) and the poleward shift of the Southern Hemisphere storm track  
 418 (destabilizing the cold regime lower troposphere) simulated by GCMs (Barnes & Polvani,  
 419 2013; Bender et al., 2012). The change in large-scale subsidence is relatively small com-  
 420 pared with other CCFs.

421 Combining  $\partial LWP / \partial X_i$  and the response of CCF to warming ( $\Delta X_i / \Delta GMT$ ) al-  
 422 lows us to apportion  $\Delta LWP / \Delta GMT$  among CCFs (Fig 6c). In the warm regime, GCMs  
 423 have roughly equivalent contributions due to surface temperature, moisture convergence,  
 424 and stability. In the cold regime, moisture convergence and surface temperature changes  
 425 contribute the most.

426 Among the GCMs surveyed here (Table S1), the second Community Earth System  
 427 Model (CESM2, Danabasoglu et al. (2020)) and its variants (CESM2-FV2, CESM2-WACCM,  
 428 CESM2-WACCM-FV2, and E3SM-1-0) in CMIP6 predict a decrease in LWP after the  
 429 first 15 years in *abrupt4xCO<sub>2</sub>* simulations (Bjordal et al., 2020; McCoy et al., 2022). This  
 430 is shown in Fig 1b where these models display a non-monotonic response of LWP to GMT.  
 431 These models also report the most positive extratropical  $SW_{FB}$  (Fig 1a) and the high-  
 432 est ECS among GCMs (Table S1). We single out CESM2 in Fig 6. The prediction of CESM2  
 433 LWP response to warming by the CCF model is not as accurate as other GCMs (Fig S5).  
 434 However, it is substantially improved from McCoy et al. (2022) (CESM2 is much closer  
 435 to the 1-1 line in Fig 5b compared to Fig 2 in McCoy et al. (2022)). While more work  
 436 is needed to more accurately predict CESM2 LWP response to warming using a CCF  
 437 model, the near-zero change in LWP from *piControl* to the end of the *abrupt4xCO<sub>2</sub>* sim-  
 438 ulations in the warm regime is captured by the CCF model (Fig 6c and Fig S5). Fig 6  
 439 suggests that the  $LTS$ -induced increase in LWP in the warm regime is offset by decreases  
 440 related to  $T_s$ . CESM2 displays the lowest sensitivity of warm regime LWP to  $P - E$  and  
 441 the  $P - E$  contribution to LWP response is small. Observational constraint suggests that  
 442 CESM2 overestimates the  $LTS$  sensitivity and underestimates the  $P - E$  sensitivity in  
 443 the warm regime. The dependence of LWP to  $T_s$  in the warm regime is negative in CESM2  
 444 but is positive from observations (Fig 6a). Because of the positive changes in  $T_s$ ,  $P -$   
 445  $E$ , and  $LTS$  in response to warming in the warm regime (Fig 6b), the overall effect is the  
 446 near-zero response of LWP in CESM2 in the *abrupt4xCO<sub>2</sub>* simulation.

### 447 3.2 Radiative Susceptibility

448 Following Equation 1,  $SW_{FB}$  is proportional to the product of changes in LWP and  
 449 the sensitivity of albedo to the changes in LWP. The radiative susceptibility ( $\partial\alpha/\partial LWP$ )  
 450 is computed for each GCM and from observations. Across GCMs,  $\partial\alpha/\partial LWP$  varies by

451 nearly a factor of seven. One emergent behavior in GCMs is an inverse relationship be-  
 452 tween  $\partial\alpha/\partial LWP$  and mean-state LWP (Fig 7). This is consistent with previous stud-  
 453 ies (McCoy et al., 2022).  $\alpha$  and cloud fraction (areal coverage of clouds) are approximately  
 454 linearly related (Bender et al., 2017). However, the effect of  $LWP_{in-cloud}$  on albedo sat-  
 455 urates at high  $LWP_{in-cloud}$  (Lacis & Hansen, 1974). The SO mean-state LWP is a func-  
 456 tion of cloud fraction and  $LWP_{in-cloud}$ . A GCM that simulates high mean-state LWP  
 457 would have fewer clear-sky pixels that could be filled in the warmed climate and is closer  
 458 to radiative saturation. As LWP increases with warming, additional liquid affects  $\alpha$  less  
 459 efficiently by only increasing the in-cloud liquid rather than increasing cloud coverage.

460 Observed radiative susceptibility trained on CERES and MAC-LWP is also shown  
 461 in Fig 7. One potential source of uncertainty in estimating  $\partial\alpha/\partial LWP$  is the clear-sky  
 462  $\alpha$  threshold ( $TR_{\alpha_{cs}}$ ) applied in Equation 4. We show this uncertainty in the  $SW_{FB}$  con-  
 463 straint by examining a range of observed  $\partial\alpha/\partial LWP$  computed using  $TR_{\alpha_{cs}}$  from 0.11  
 464 to 0.30. The  $\partial\alpha/\partial LWP$  derived from observations is on the low end of the GCM dis-  
 465 tribution even accounting for this uncertainty in observations and GCMs. This result  
 466 suggest that the too-bright and too-homogeneous bias of tropical clouds in CMIP6 GCMs  
 467 may also exist in the simulation of extratropical clouds (Konsta et al., 2022).

468 The sensitivity of LWP to moisture convergence ( $\partial LWP/\partial P - E$ ) positively cor-  
 469 relates with mean-state LWP in both cold and warm regime (Fig 7). This relationship  
 470 can be explained in the context of sources and sinks of cloud liquid content (McCoy et  
 471 al., 2022). Source and sink rates of clouds can be written as:

$$472 \begin{aligned} K_{source} &= e_{source} \cdot r_{water\ vapor} \\ K_{sink} &= e_{sink} \cdot r_{LWP} \end{aligned} \quad (5)$$

473 the product of a bulk efficiency of sources ( $e_{source}$ ) and sinks ( $e_{sink}$ ) of cloud liquid with  
 474 their respective reservoir terms. The reservoir that liquid draw from is water vapor ( $r_{water\ vapor}$ )  
 475 and the reservoir of the sink of liquid in this model is cloud liquid itself ( $r_{LWP}$ ). In the  
 476 mean-state climate, sources and sinks are balanced ( $K_{source} = K_{sink}$ ) and

$$477 \frac{e_{source}}{e_{sink}} = \frac{r_{LWP}}{r_{water\ vapor}}. \quad (6)$$

478 Following this model, mean-state LWP is proportional to the relative strength of source  
 479 and sink efficiencies (i.e.,  $e_{source}/e_{sink}$ ). If we assume the same water vapor ( $r_{water\ vapor}$ )  
 480 in the mean-state climate in GCMs, the diversity in model mean-state LWP can be traced  
 481 back to the subgrid-scale parameterization of cloud source and sink processes. We note  
 482 that the similar water vapor amount is only an assumption as free-running models with-  
 483 out a fixed SST will result in slightly different mean-state water vapor paths (Jiang et  
 484 al., 2012). In this simple model, the sensitivity of LWP to moisture convergence ( $\partial LWP/\partial P - E$ )  
 485 trained using GCM mean-state climate may act as a proxy of this relative strength of  
 486 source to sink efficiencies ( $e_{source}/e_{sink} \propto \partial LWP/\partial P - E$ ).

487 The steady-state framework presented above may help us understand why  $\partial LWP/\partial P - E$   
 488 in the cold regime is consistently larger than the value in the warm regime (Fig 7). In  
 489 this framework, it is because of a stronger source efficiency for cold regime clouds due  
 490 to the larger moist adiabat (Betts & Harshvardhan, 1987), even though the sink efficiency  
 491 for cold regime clouds is likely to be larger as well (Field & Heymsfield, 2015).

492 How does this steady-state framework inform us about the diversity in the response  
 493 of LWP to warming? The moisture content ( $r_{water\ vapor}$ ) in extratropics increases with  
 494 GMT. If we assume the relative strength of source to sink efficiency ( $e_{source}/e_{sink}$ ) is fixed  
 495 under climate change, a model with larger mean-state sensitivity of LWP to  $P-E$  would  
 496 lead to a larger increase in LWP. The warm regime  $\partial LWP/\partial P - E$  and  $\Delta LWP/\Delta GMT$   
 497 covary across GCMs (Fig S6) with a correlation of  $r = 0.78$ .

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### 3.3 Constraints on Southern Ocean SW Cloud Feedback

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In the proceeding section, we examine the response of SO LWP to GMT predicted by CCFs and the response of  $\alpha$  to LWP in order to predict  $SW_{FB}$  (Equation 1). Based on the observational constraints on  $\Delta LWP/\Delta GMT$  in Fig 5 and the observational constraint on  $\partial\alpha/\partial LWP$  in Fig 7, we provide constraints on  $SW_{FB}$  in Fig 8. Equation 1 explains 53 % and 52 % of the variance in GCM  $SW_{FB}$  averaged over 40 – 50°S and 50–85°S regions, respectively (Fig 8). Observational constraints on the right-hand side of Equation 1 predict the contributions to global mean  $SW_{FB}$  from 40–50°S and 50–85°S regions to be  $-0.04-0.06 W m^{-2} K^{-1}$  and  $-0.15-0.01 W m^{-2} K^{-1}$ . The latter range is consistent with the 50–85°S constraint range ( $-0.10-0.0 W m^{-2} K^{-1}$ ) reported by McCoy et al. (2022). These ranges are calculated by taking the shaded y-ranges in Fig 8 and scaling them by the ratio of the area in the latitude band to global area. The uncertainties in 40 – 50°S and 50 – 85°S  $SW_{FB}$  constraints are calculated by combining uncertainties in the observational constraint on  $\Delta LWP/\Delta GMT$  (see section 3.1.2 for details of uncertainty propagation) and uncertainties in  $\partial\alpha/\partial LWP$  (the observational uncertainty owing to  $\alpha_{cs}$  threshold). The constraint on 40–50°S is tighter than 50 – 85°S because observational constraint on  $\Delta LWP/\Delta GMT$  is only available in the warm regime and the 40 – 50°S region is entirely warm regime.

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We combine our constraints on  $SW_{FB}$  in the 40 – 50°S and 50 – 85°S latitude bands to compute the constraint on 40 – 85°S  $SW_{FB}$ . The distributions of 40 – 50°S and 50 – 85°S  $SW_{FB}$  located in the constraint ranges on the x-axis of Fig 8 are normally distributed. We take the sum of the area-weighted latitudinal constraints in 40–50°S and 50–85°S and propagate their standard errors to estimate 40–85°S  $SW_{FB}$ . The contribution of the SO (40–85°S) to the global mean  $SW_{FB}$  is constrained as  $-0.19-0.05 W m^{-2} K^{-1}$  at 95% confidence interval (Fig 9). This range is a bit wider than the range reported by McCoy et al. (2022), but we have added a new constraint from 40–50°S latitude band and taken into account the uncertainty owing to different  $\alpha_{cs}$  thresholds.

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## 4 Conclusions

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In this work, we built a Cloud Controlling Factor (CCF) regression model to predict the response of the Southern Ocean (SO, 40 – 85°S) LWP. The CCFs considered in the regression model were surface temperature ( $T_s$ ), precipitation minus evaporation ( $P-E$ , approximately the moisture convergence), lower tropospheric stability ( $LTS$ ), and 500 mb subsidence ( $\omega_{500}$ ). Warm and cold clouds are regulated by very different microphysical processes and have different responses to warming. To allow the CCF regression model to adapt to this, we partitioned the SO into cold and warm regimes. This new method increases the robustness of the CCF model prediction compared to previous work (McCoy et al., 2022). We used two out-of-sample tests to evaluate the predictive ability of our CCF regression model: the ability of our CCF model trained on observations to replicate the observed decadal trend in SO LWP (section 3.1.1, Fig 4) and the ability of our CCF model trained on the mean-state output of GCMs to predict their response to  $CO_2$  quadrupling (section 3.1.2, Fig 5). Using the CCF regression model trained on observations combined with the GCM simulated changes in CCFs in response to  $CO_2$  quadrupling, we were able to provide an observational constraint on the change in LWP in response to GMT ( $\Delta LWP/\Delta GMT$ ) of  $2.89 - 4.41 gm^{-2} K^{-1}$  (Fig 5b).

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Ultimately, the quantity we care about in relation to Earth’s radiation budget is not cloudiness, but radiative flux. We define a radiative susceptibility metric ( $\partial\alpha/\partial LWP$ ) that we can use to scale our constrained LWP response. We computed  $\partial\alpha/\partial LWP$  from satellite observations and GCM output. The observational constraint suggest that most of the GCMs overestimate  $\partial\alpha/\partial LWP$  (Fig 7), which is consistent with recent studies

548 of tropical clouds (Konsta et al., 2022). Satellite observations estimate  $\partial\alpha/\partial LWP$  to be  
 549  $0.41 - 0.86 (kg m^{-2})^{-1}$ .

550 GCMs with higher mean-state LWP tend to have lower  $\partial\alpha/\partial LWP$  (Fig 7). This  
 551 can be connected to the sensitivity of LWP to moisture convergence ( $\partial LWP/\partial P - E$ ).  
 552 GCMs with higher  $\partial LWP/\partial P - E$  simulate higher mean-state LWP. These GCMs will  
 553 tend to predict a larger LWP response ( $\Delta LWP/\Delta GMT$ ) but have a lower  $\partial\alpha/\partial LWP$   
 554 due to radiative saturation. This results in compensation between the LWP response to  
 555 warming and the radiative susceptibility.

556 The product of  $\partial\alpha/\partial LWP$  and  $\Delta LWP/\Delta GMT$  predicts roughly 50 % of the vari-  
 557 ance in SO  $SW_{FB}$  across 50 CMIP5 and CMIP6 GCMs (Fig 8). Observational constraints  
 558 on  $\Delta LWP/\Delta GMT$  and  $\partial\alpha/\partial LWP$  produce a constrained range on SO  $SW_{FB}$  of  $-0.19$   
 559 to  $0.05 Wm^{-2}K^{-1}$  (95% confidence interval) (Fig 9), which suggest a moderate nega-  
 560 tive to weak positive SO  $SW_{FB}$ . This is consistent with previous work, but expands the  
 561 constraint region to the entire SO as opposed to just constraining the region where GCMs  
 562 consistently moisten (McCoy et al., 2022).

563 Our analysis suggests some directions of future studies seeking to constrain the ex-  
 564 tratropical  $SW_{FB}$ :

- 565 1. Our analysis identified increased moisture convergence into the SO as a key driver  
 566 of increased LWP. This mechanism ultimately links the global circulation and hy-  
 567 drological cycle to the extratropical  $SW_{FB}$ . To better understand this linkage, it  
 568 would be useful to understand how Hadley cell expansion and transient eddies (i.e.  
 569 atmospheric rivers) contribute to long-term variability of the SO moisture bud-  
 570 get.
- 571 2. Due to the lack of microwave observations of LWP over sea ice, we cannot pro-  
 572 vide an observations-constrained CCF model for the cold regime. In this study,  
 573 the GCM relationship between the warm regime LWP response and the response  
 574 averaged over the latitude band is used to fill the gap. Ground-based LWP ob-  
 575 servations in high latitude SO, such as those taken during the Atmospheric Ra-  
 576 diation Measurement (ARM) West Antarctic Radiation Experiment (AWARE, Lubin  
 577 et al. (2020)), may be able to provide an observational constraint on the cold regime  
 578 LWP response.
- 579 3. We found that  $\partial\alpha/\partial LWP$  varied dramatically across GCMs and strongly mod-  
 580 ulated the effect of changes in LWP on radiation. We also found that observations  
 581 suggested that GCMs tended to have a  $\partial\alpha/\partial LWP$  that was too large. One pos-  
 582 sibility is that this is due to clouds that are too uniform and radiatively efficient  
 583 (Konsta et al., 2022; Nam et al., 2012). Determining the origin of this behavior  
 584 might be helpful in identifying a potential source of GCM bias in  $SW_{FB}$ .

## 585 5 Open Research

586 GCM output used in this study are available from Earth System Grid Federation  
 587 (ESGF) [esgf-node.llnl.gov](https://esgf-node.llnl.gov). MAC-LWP and MERRA-2 reanalysis data are available from  
 588 the Goddard Earth Sciences Data and Information Services Center at [disc.gsfc.nasa.gov](https://disc.gsfc.nasa.gov).  
 589 CERES data is available from [ceres.larc.nasa.gov](https://ceres.larc.nasa.gov).

## 590 Acknowledgments

591 The efforts of CT, DTM, and GSE are supported under NASA-PMMST Grant #80NSSC22K0599.  
 592 GSE acknowledges additional support from the NASA Modeling, Analysis and Predic-  
 593 tion Program and APAM GISS Co-Op #80NSSC18M0133.

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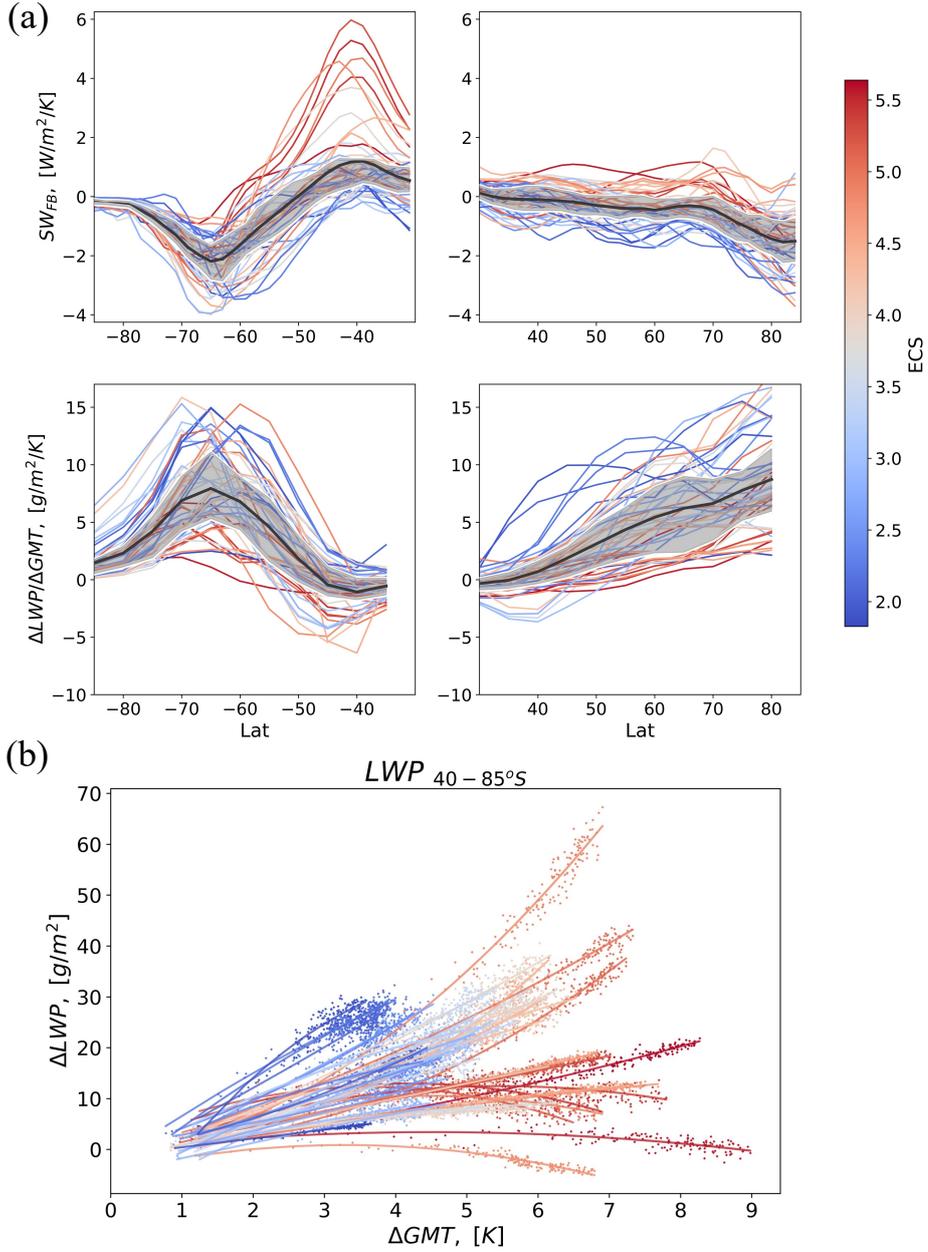
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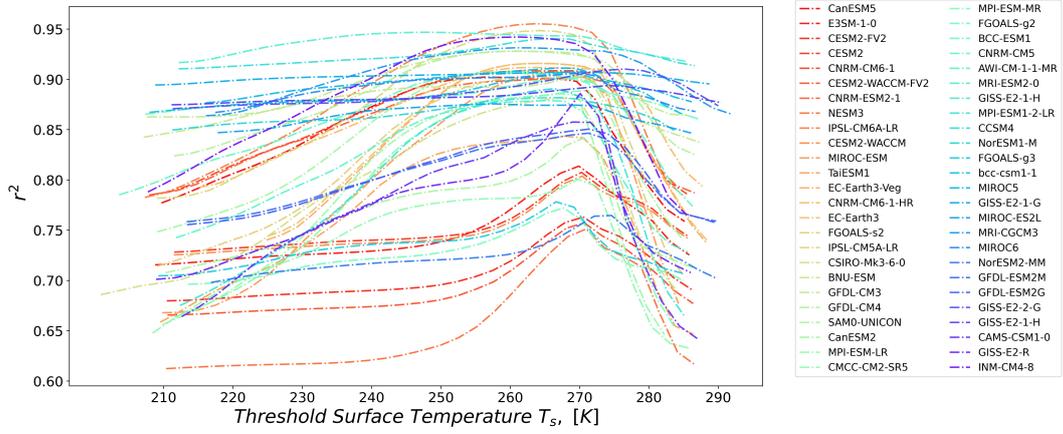
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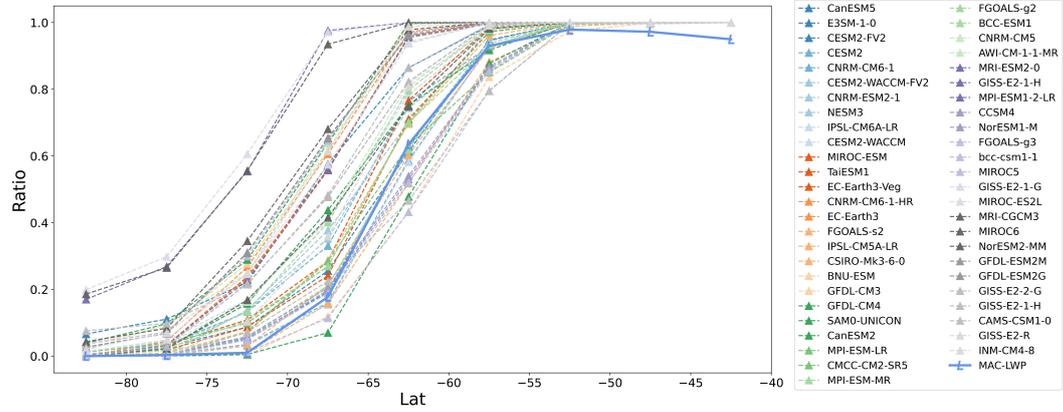
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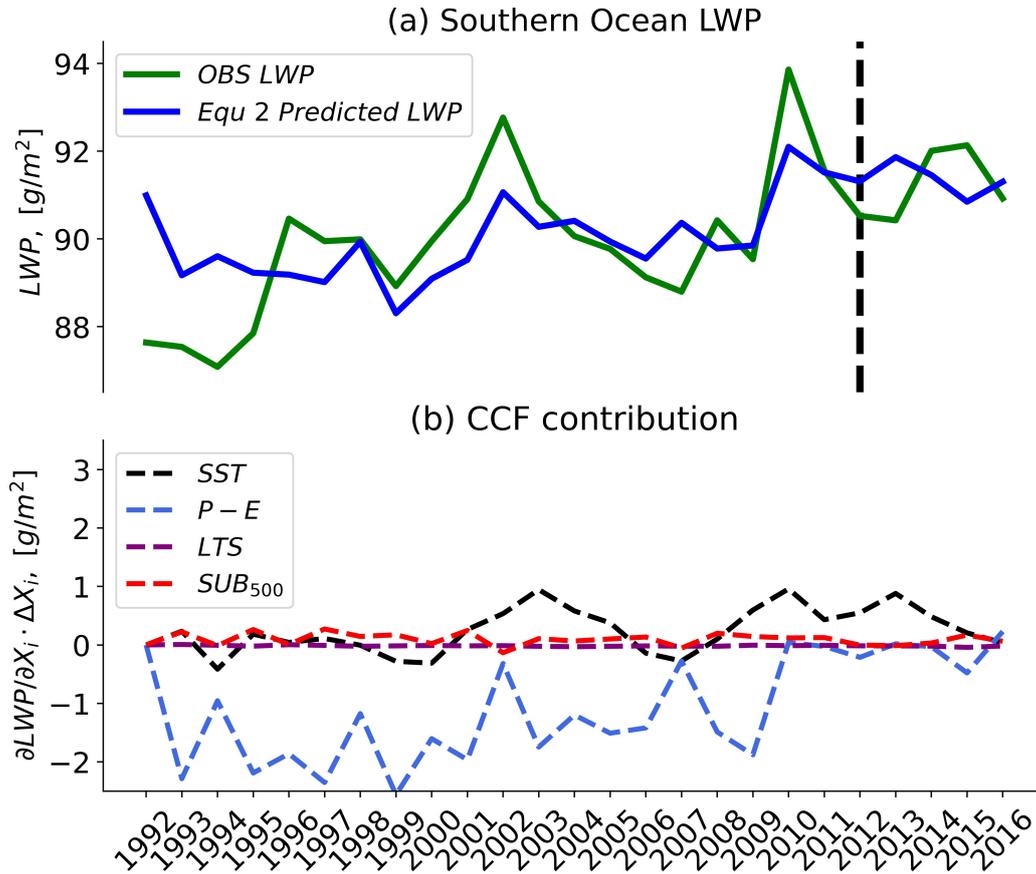
**Figure 1.** (a) Extratropical  $SW_{FB}$  (top) and the response of LWP to global-mean air temperature (GMT) ( $\Delta LWP/\Delta GMT$ ) calculated as the difference *piControl* and years 121 - 140 from the *abrupt4xCO<sub>2</sub>* simulation. (b) Annual-mean anomalies in LWP relative to *piControl* averaged over 40 - 85°S versus anomalies in GMT in the first 150 years of *abrupt4xCO<sub>2</sub>* simulations. The thick black lines in subplot (a) are the multi-model mean, and the shaded regions correspond to the 25th-75th percentiles of quantities. Lines in subplot (b) are the second-order polynomial fits of the annual LWP responses. SW cloud feedback and effective climate sensitivity (ECS) data are derived from Zelinka et al. (2020). Fifty CMIP5 and CMIP6 GCMs are shown (Table S1). Lines for each GCM in (a) and (b) are colored by the ECS for that specific GCM.



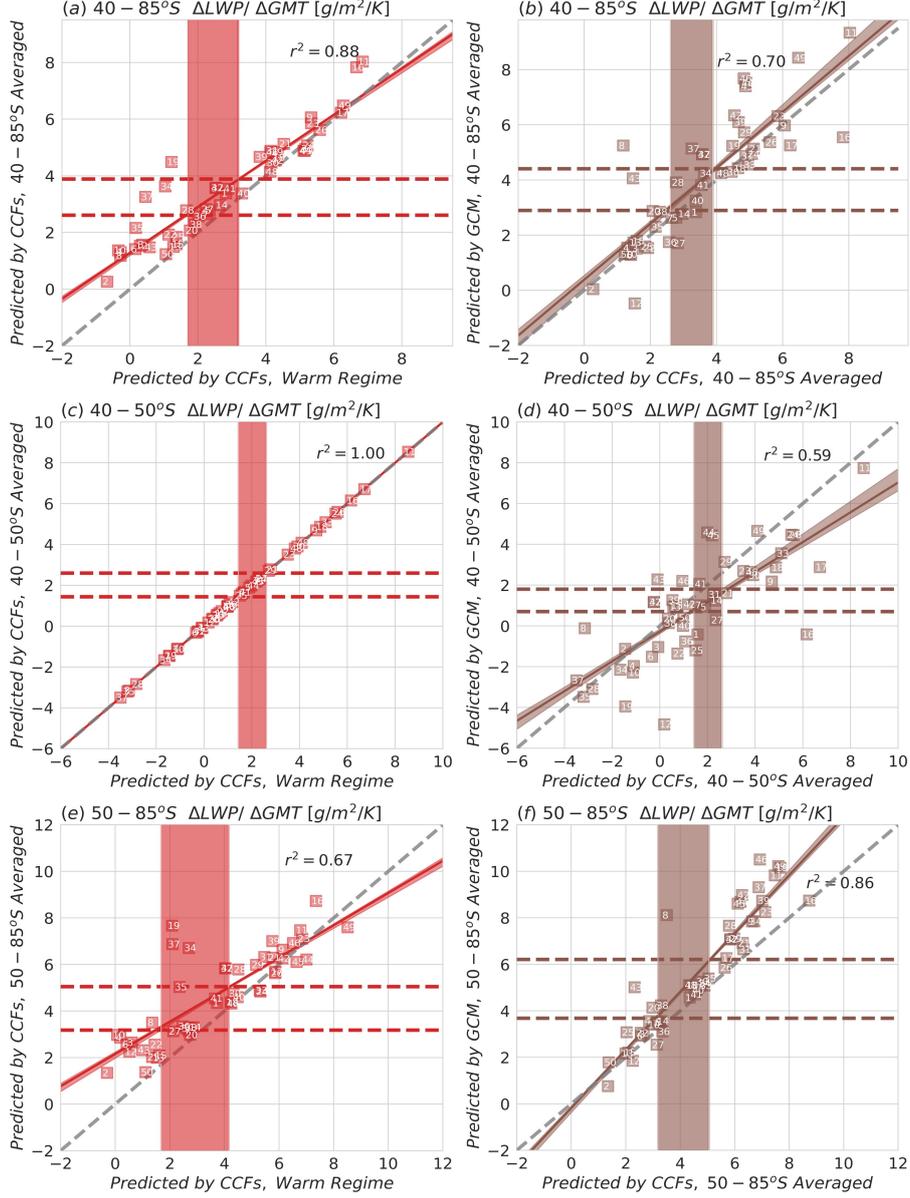
**Figure 2.** The  $r^2$  between the LWP predicted by Equation 3 and GCM output in *piControl* simulations as a function of potential threshold surface temperature ( $TR_{T_s}$ ) used to partition the cold and warm regimes in Equation 3.  $TR_{T_s}$  is selected to maximize  $r^2$ .



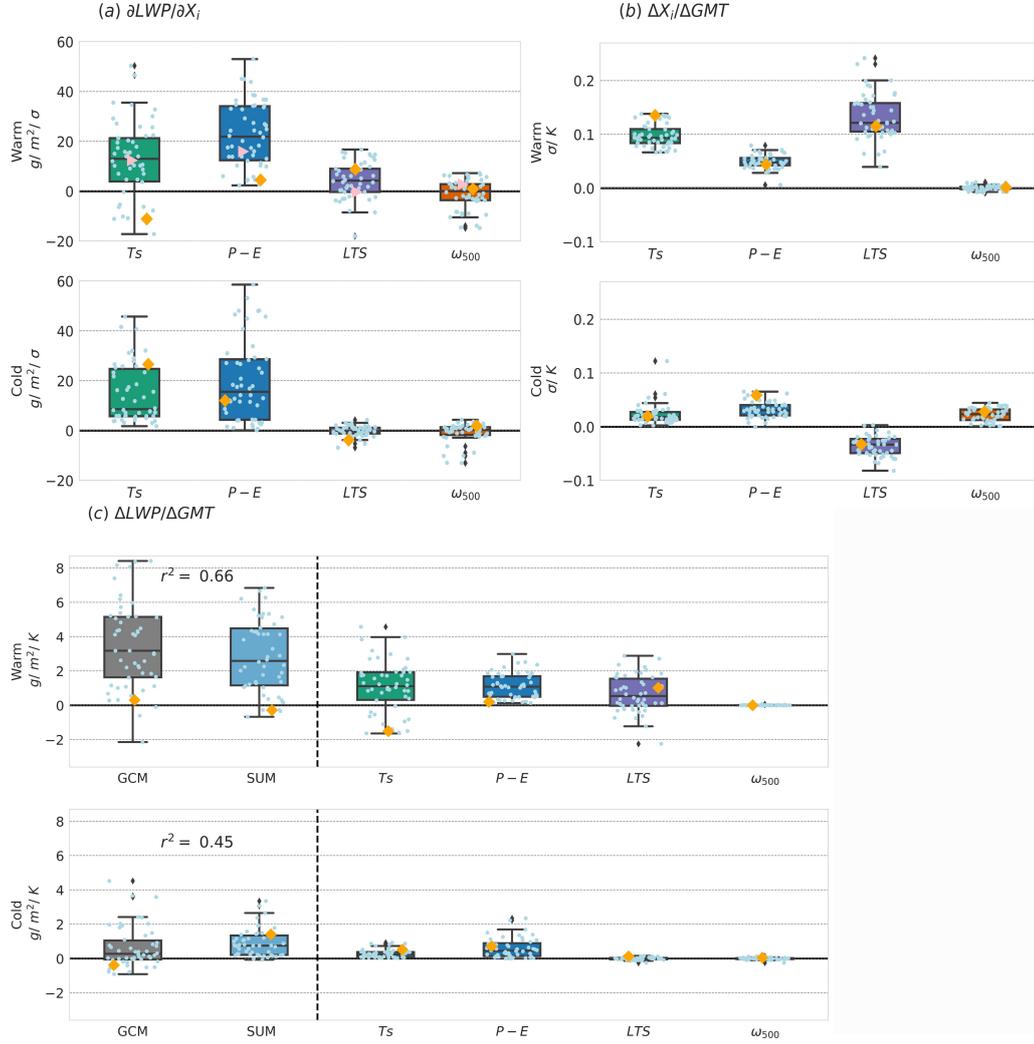
**Figure 3.** Latitudinal distribution of the ratio of gridboxes that are classified as warm regime to the total number of gridboxes for GCMs (dashed lines) and the ratio of gridboxes with more than 50% coverage in microwave retrievals to the total number of gridboxes for MAC-LWP observations (solid line).



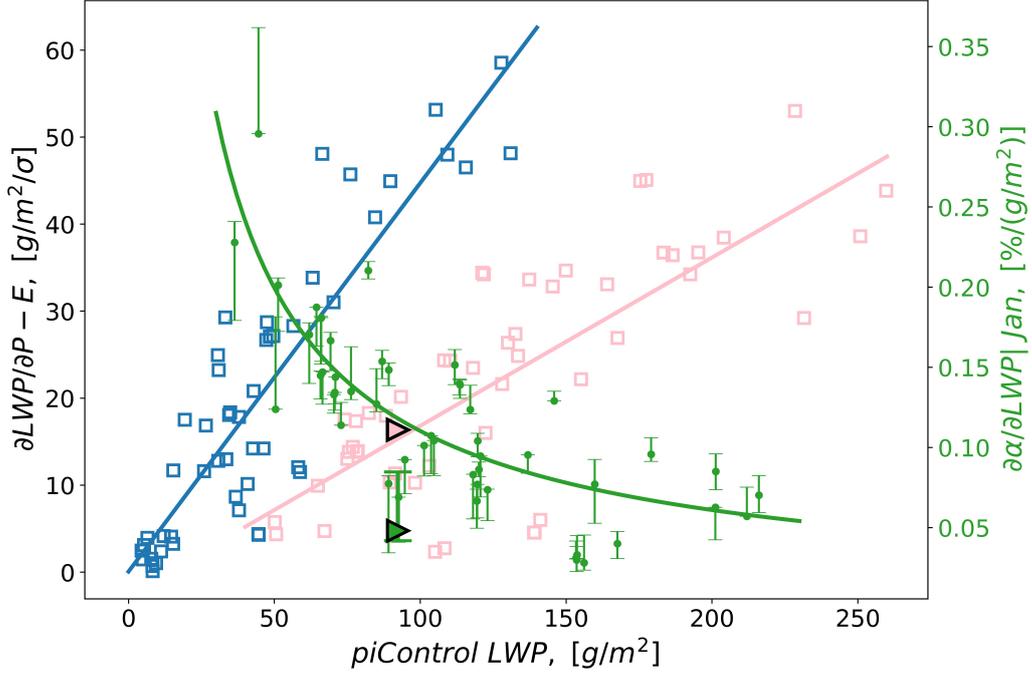
**Figure 4.** (a) Observed Southern Ocean annual-mean LWP from MAC-LWP (green) and LWP predicted by the CCF model (Equation 2; blue) from 1992 to 2016. The CCF model is trained on data from 2012 to 2016 (right side of the dashed line) and is used to predict LWP back to 1992. (b) The decomposition of annual mean LWP anomalies into individual CCF contributions by Equation 2.



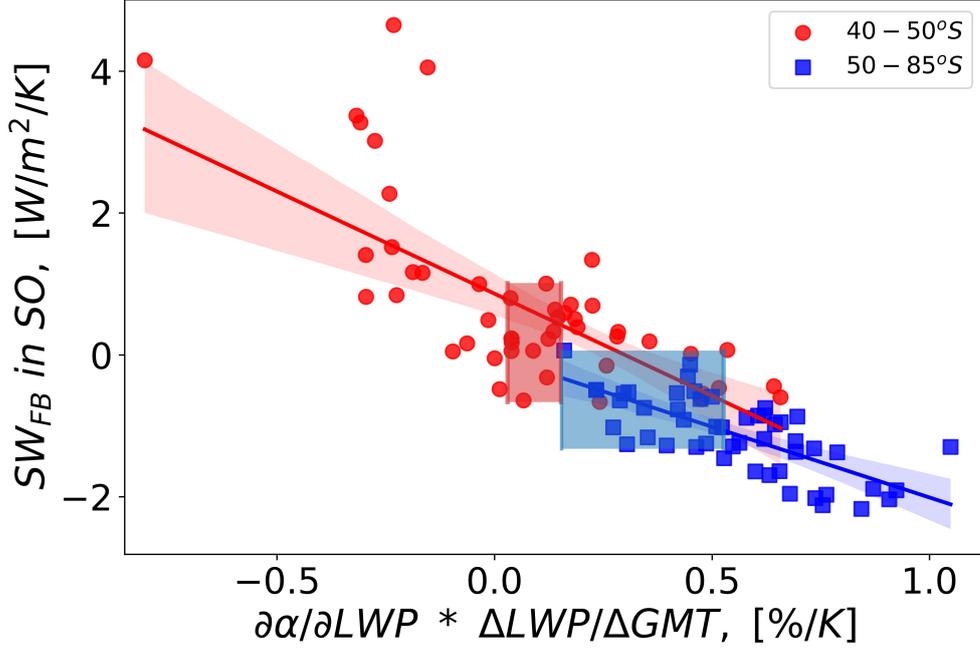
**Figure 5.** Predictions of the GCM-simulated  $\Delta LWP/\Delta GMT$  by (Equation 3).  $\Delta LWP/\Delta GMT$  is shown averaged over (a,b) 40 – 85°S, (c,d) 40 – 50°S, and (e,f): 50 – 85°S. (a,c,e) Predicted  $\Delta LWP/\Delta GMT$  from Equation 3 versus  $\Delta LWP/\Delta GMT$  in only the warm regime. (b,d,f)  $\Delta LWP/\Delta GMT$  simulated by GCMs versus  $\Delta LWP/\Delta GMT$  predicted by Equation 3 for all regimes. 1-1 lines are shown using dashed gray lines and best fit are shown as solid red and brown lines with their uncertainties estimated by Jackknife resampling. Observational constraints (red shading) are shown in (a,c,e). This constraint is propagated from the warm regime  $\Delta LWP/\Delta GMT$  to the latitudinal-averaged  $\Delta LWP/\Delta GMT$  by taking the intersection between the red shading and the fit line with its uncertainty (red dashed lines). Constraints on latitudinal-averaged  $\Delta LWP/\Delta GMT$  are then shown using brown shading in (b,d,f). This is combined with the uncertainty in the CCF model prediction by using the best fit line between GCM and CCF model predictions to yield an observational constraint on GCM-simulated  $\Delta LWP/\Delta GMT$ . Explained variance ( $r^2$ ) are shown within each subplot. GCMs are denoted with the number listed in Table S1.



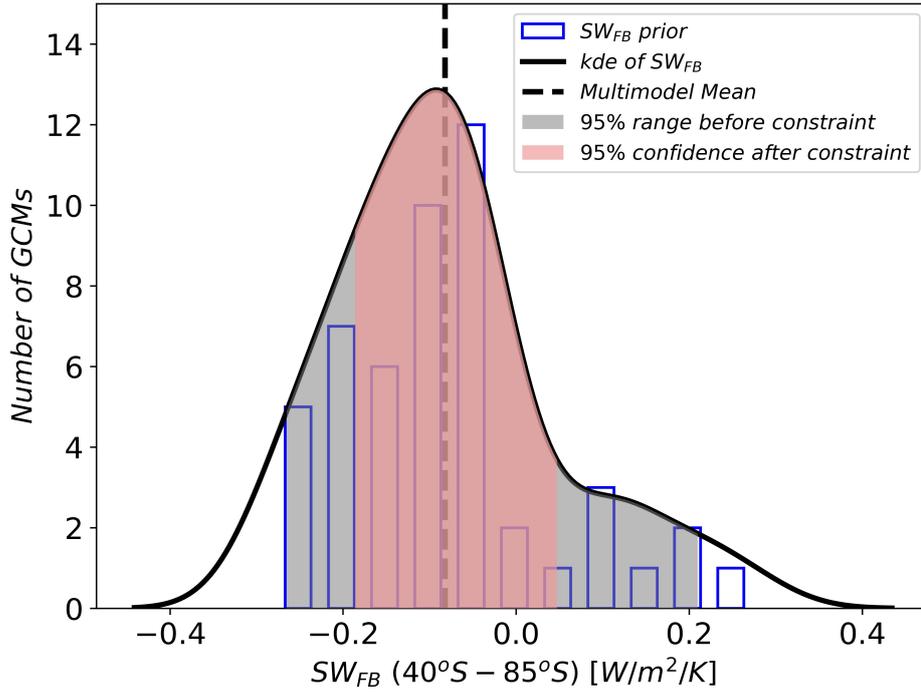
**Figure 6.** The contribution of each term in Equation 3 for  $40 - 85^\circ S$  averaged LWP response to GMT for warm and cold regimes: (a) Sensitivities of LWP to CCFs in GCMs (observational sensitivities are shown as pink triangle markers in the warm regime); (b) Changes in each CCF per degree GMT change; (c) LWP changes due to individual CCFs (the product of (a) with (b)), their sum (light blue box), and the GCM response (gray box). The  $r^2$  between Equation 3 predicted LWP response to GMT and the GCM output in each regime is noted. CCFs are normalized by their spatio-temporal standard deviations of each regime in the mean-state climate. CESM2 values are denoted by orange diamonds, all other GCMs are denoted by light blue dots.



**Figure 7.** The sensitivity of LWP to moisture convergence ( $\partial LWP/\partial P - E$ , left axis) in the warm (red) and cold (blue) regimes and the radiative susceptibility ( $\partial\alpha/\partial LWP$ , right axis) as a function of mean-state (*piControl*) LWP. Observational  $\partial LWP/\partial P - E$  and  $\partial\alpha/\partial LWP$  are shown by the pink and green triangles (observational  $\partial LWP/\partial P - E$  is comparable to the warm regime  $\partial LWP/\partial P - E$  of GCMs for reason discussed in section 2.2 and 2.5). The linear fit between  $\partial LWP/\partial P - E$  in each regime and *piControl* LWP and the power law fit between  $\partial\alpha/\partial LWP$  and *piControl* LWP are shown.  $\partial\alpha/\partial LWP$  for  $TR_{\alpha_{cs}}$  be 0.15 is shown with marker and uncertainty from varying  $TR_{\alpha_{cs}}$  from 0.11 to 0.30 is shown as the error bar.



**Figure 8.** GCM SW cloud feedback ( $SW_{FB}$ ) from Zelinka et al. (2020) as a function of  $SW_{FB}$  predicted by Equation 1 for 40 – 50°S (red) and 50 – 85°S (blue) latitude bands. Observational constraints on 40 – 50°S and 50 – 85°S  $\Delta LWP/\Delta GMT$  are from Figure 5 (d) and (f) and the observational constrain on  $\partial\alpha/\partial LWP$  is shown in Figure 7. The combination of these constraints yields constraints on 40 – 50°S and 50 – 85°S  $SW_{FB}$  shown as shaded regions along the x-axis. The linear fit between  $SW_{FB}$  and prediction from Equation 1 are shown with their 95% confidence interval. Constraints on 40 – 50°S and 50 – 85°S  $SW_{FB}$  are the extents of the y-coordinate of models within the shaded regions.



**Figure 9.** The contribution of Southern Ocean ( $40 - 85^{\circ}S$ )  $SW_{FB}$  to the global mean cloud feedback.  $SW_{FB}$  for 50 CMIP5 and CMIP6 GCMs listed in Table S1 is shown as a blue histogram black kernel density estimate. A dashed black line denotes the multimodel mean  $SW_{FB}$ . Gray shading shows the 95% range of the model  $SW_{FB}$  before constraint. Red shading shows the 95% confidence interval of the Southern Ocean  $SW_{FB}$  by combining the  $40 - 50^{\circ}S$  and  $50 - 85^{\circ}S$   $SW_{FB}$  constraints (Figure 8). Observational constraint suggests a moderate negative to weak positive Southern Ocean  $SW_{FB}$ .