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1       **Temperatures of Anvil Clouds and Radiative Tropopause in a Wide Array of Cloud-**  
2                               **Resolving Simulations**

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10 We present 123 cloud-resolving simulations to study how temperatures of anvil clouds and  
11 radiative tropopause (RT) change with surface warming. Our simulation results show that the RT  
12 warms at approximately the same rate as anvil clouds. This relationship persists across a variety  
13 of modeling choices, including surface temperature, greenhouse gas concentration, and the  
14 representation of radiative transfer. We further show that the shifting ozone profile associated with  
15 climate warming may give rise to a fixed RT temperature as well as a fixed anvil temperature. This  
16 result points to the importance of faithful treatment of ozone in simulating clouds and climate  
17 change; the robust anvil-RT relationship may also provide alternative ways to understand what  
18 controls anvil temperature.

## 19 **1. Introduction**

20 The tropical upper troposphere is home to extensive cirrus clouds detrained from thunderstorms,  
21 known as anvil clouds. As the surface warms, anvil clouds are robustly predicted to rise to greater  
22 altitudes so that their mean temperature increases less than that of the surface. This holds true in  
23 cloud-resolving models (CRMs) (Tompkins and Craig 1999; Kuang and Hartmann 2007; Harrop  
24 and Hartmann 2012; Khairoutdinov and Emanuel 2013; Narenpitak et al. 2017) and general  
25 circulation models (GCMs) (Zelinka and Hartmann 2010; Thompson et al. 2017), as well as  
26 observations (Zelinka and Hartmann 2011). Since anvil clouds' temperature changes little under  
27 surface warming, they will emit less longwave radiation to space than if they were to retain the  
28 same, warmer altitude. This yields a positive climate feedback when our reference assumption is  
29 that clouds would otherwise be fixed in altitude. For this reason, the most recent IPCC report  
30 expressed *high confidence* in a positive longwave cloud altitude feedback (Forster et al. 2021).

31 The Fixed Anvil Temperature (FAT) hypothesis is the most enduring explanation for the trend of  
32 high-cloud temperature with surface warming (Hartmann and Larson 2002). The FAT hypothesis  
33 claims that (1) upper tropospheric cloud amount is principally the result of the radiatively-driven  
34 horizontal convergence in clear skies, and (2) this convergence is physically constrained to occur  
35 at a fixed temperature where, for fixed relative humidity, the water vapor concentration becomes  
36 so small that it loses its ability to efficiently cool the atmosphere. Indeed, studies of CRMs, GCMs,  
37 and observations corroborate the first claim. The upper tropospheric maximum in convergence

38 covaries with the upper tropospheric maximum in cloud amount (Kuang and Hartmann 2007;  
39 Zelinka and Hartmann 2010; Bony et al. 2016; Seeley et al. 2019b; Zelinka and Hartmann 2011).  
40 However, models often contradict the second claim in FAT, showing that anvils and the location  
41 of maximum convergence may in fact warm appreciably, albeit slowly compared to the surface.  
42 For example, Kuang and Hartmann (Kuang and Hartmann 2007) showed in a CRM that the  
43 location of maximum cloud fraction to warm by 2 K when the surface warmed by 8 K, and the  
44 recent Radiative-Convective Equilibrium Model Intercomparison Project found an average of 4.4  
45 K of anvil warming over 10 K of surface warming (Wing et al. 2020). This slow but appreciable  
46 warming is sometimes known as a Proportionately Higher Anvil Temperature, or PHAT (Zelinka  
47 and Hartmann 2010). PHAT is usually found in models where the ozone profile is unrealistically  
48 fixed in pressure (Harrop and Hartmann 2012).

49 It is sometimes assumed that anvil clouds are linked to the radiative tropopause (RT), where  
50 radiative heating first goes to zero in the upper troposphere (see, e.g., Birner and Charlesworth  
51 2017; Kluft et al. 2019). The RT is the intersection of the radiative-convective equilibrium (RCE)  
52 temperature profile of the troposphere and the radiative or radiative-dynamical equilibrium profile  
53 of the stratosphere (Vallis et al. 2015; Hu and Vallis 2019). Since RT is the highest location where  
54 latent heating from convection balances radiative cooling in RCE, the RT is also known as the  
55 convective top (Thuburn and Craig 2002; Birner and Charlesworth 2017; Dacie et al. 2019).  
56 However, convective clouds in fact occur considerably above this point as they overshoot the level  
57 of neutral buoyancy (Kuang and Bretherton 2004; Hu et al. 2021). Tompkins and Craig (Tompkins  
58 and Craig 1999) found in a CRM that anvil temperature to increase with surface warming. They  
59 suggested this occurred because the RT temperature increases with warming due to their fixed  
60 ozone profile. In Kluft et al. (2019), RT is found to warm by about 0.5 K per 1 K of surface  
61 warming in a 1-D RCE model without clouds. Assuming a close relationship between RT and  
62 anvil, the authors suggested that their result supported a PHAT. Such an assumption appears to be  
63 a crude simplification of FAT/PHAT thinking, according to which a decline in radiative cooling  
64 with height below RT causes clear-sky convergence.

65 Since RT may be simulated by 1-D models without clouds, a robust anvil-RT relationship would  
66 simplify our understanding of anvil clouds. However, Seeley et al. (Seeley et al. 2019b) achieved  
67 a contrary result in “minimal recipe” CRM simulations which isolated the longwave effect of water

68 vapor by removing all other radiative constituents from the model. In their simulations the  
69 temperature of RT varied by less than 2 K despite 50 K of surface warming, yet the anvil warming  
70 was greater by an order of magnitude. They suggested there is a fixed (radiative) tropopause  
71 temperature (FiTT) with respect to surface warming, and RT temperature is unlikely to be related  
72 to the temperature of the anvil peak. That is, the top of the troposphere should be disentangled  
73 from the anvil location. However, Hartmann et al. (Hartmann et al. 2019) presented CRM  
74 simulations in which the anvil, the RT, and a sharp peak in the detrainment of cloud ice each  
75 occurred at a fixed temperature over 5 K of surface warming. They proposed that in convection-  
76 permitting RCE simulations the anvil is linked to the location of RT, as convective cooling from  
77 overshooting updrafts above the anvil must be compensated by radiative heating. Given this  
78 disagreement and the potential clarity provided by an anvil-RT relationship, it is worthwhile to  
79 investigate more thoroughly whether the location and temperature anvil clouds are in fact related  
80 to the location and temperature of RT.

81 Modeling choices about ozone are particularly important to the simulated anvil and RT  
82 temperatures. Many modeling studies of RCE often use an ozone profile which is unrealistically  
83 fixed in pressure, which can give rise to a PHAT (Tompkins and Craig 1999; Kuang and Hartmann  
84 2007; Zelinka and Hartmann 2010; Wing et al. 2020) as well as an increasing RT temperature  
85 (Dacie et al. 2019; Kluft et al. 2019). This occurs because the upper troposphere is lifted into a  
86 layer of stronger ozone heating. A real atmosphere may give rise to a FAT as climate warming  
87 lifts the ozone profile higher in the atmosphere. On this assumption, CRM studies of anvil  
88 temperature have modeled an atmosphere with zero ozone (Harrop and Hartmann 2012; Seeley et  
89 al. 2019b). In a similar vein, Nowack et al. (Nowack et al. 2015, 2018b) found that prescribing an  
90 ozone profile fixed in warming reduced upper tropospheric clouds in a GCM and reduced the  
91 positive cloud longwave feedback by about 0.1-0.2 W/m<sup>2</sup>/K as compared to simulations with  
92 interactive ozone. However, those two studies did not isolate the cloud altitude feedback, and to  
93 our knowledge it has yet to be explicitly verified whether the upward shift of ozone with warming  
94 equally offsets the PHAT behavior to give rise to an approximate FAT.

95 To test for an anvil-RT relationship, we conduct idealized experiments in a CRM systematically  
96 changing the radiation-relevant model settings. We ask: Do changes in model settings that change  
97 the simulated RT temperature cause similar changes in the anvil temperature? Are changes in the

98 RT temperature's *trend* with respect to surface warming associated with similar changes in the  
99 anvil temperature trend? In particular, we test the sensitivity of anvil and RT temperature to: (1)  
100 A wide range of surface temperatures (280 K to 315 K); (2) the amount of carbon dioxide; (3) the  
101 amount of insolation; (4) the shape, concentration, and location of the ozone profile; (5) the  
102 presence of a large-scale circulation and convective organization; and (6) the domain size.

## 103 **2. Simulations**

104 We use the 2D formulation of the System for Atmospheric Modeling (SAM), version 6.10  
105 (Khairoutdinov and Randall 2003). SAM is a cloud-permitting model using the anelastic equations  
106 for dynamics. 2D CRMs have long been used to study convection and clouds in the tropics (Held  
107 et al. 1993; Grabowski et al. 2000; Blossey et al. 2010; Yang 2018a,b; Seidel and Yang 2020). The  
108 horizontal resolution is 2 km. Radiation is parameterized using the Rapid Radiative Transfer  
109 Model for GCMs (RRTMG) (Mlawer et al. 1997). Cloud microphysics are parameterized using  
110 the SAM one-moment scheme. For the purposes of replicability and comparability, we borrowed  
111 many modeling parameters from the Radiative Convective Equilibrium Model Intercomparison  
112 Project (RCEMIP) protocol (Wing et al. 2018). The vertical grid is a modified version of the  
113 RCEMIP high-vertical-resolution grid, extended to allow for greater surface temperature. It  
114 consists of 160 levels, with a vertical resolution of 40m at the surface, 200m at altitudes between  
115 3 km and 25 km, and increasing to 500m above that. The model top is at 36 km. A sponge layer  
116 occupies the upper 30% of the model domain. The model stratosphere is allowed to equilibrate  
117 without any nudging of the thermodynamic profiles. To accommodate the computational cost of  
118 exploring a wide range of modeling conditions, as well as the long equilibration times required,  
119 our standard simulations use a small, 256 km domain. To test the relevance of convective  
120 organization, we use a larger 2048 km domain. Following RCEMIP, we use an idealized equatorial  
121 ozone profile and CH<sub>4</sub> and N<sub>2</sub>O concentrations of 1650 and 306 ppbv, respectively. Insolation is  
122 fixed at 409.6 W/m<sup>2</sup>. Unlike the RCEMIP protocol, we set CO<sub>2</sub> to its preindustrial value of 280  
123 ppmv. All other well-mixed greenhouse gases are set to zero.

124 The model is run over a sea surface with a prescribed temperature until the atmosphere  
125 approximately reaches radiative-convective equilibrium (RCE). RCE is an idealization of the  
126 tropical atmosphere which states that the latent heating from convection is balanced by radiative  
127 cooling in the free troposphere. Each simulation is integrated for 500 days, except for simulations

<b>Experiment</b>	<b>Domain</b>	<b>Ozone</b>	<b>Insolation</b>	<b>CO<sub>2</sub></b>
Standard	256 km	Standard	409.6 W/m <sup>2</sup>	280 ppm
Standard, no CO <sub>2</sub>	256 km	Standard	409.6 W/m <sup>2</sup>	0 ppm
Standard, 4xCO <sub>2</sub>	256 km	Standard	409.6 W/m <sup>2</sup>	1120 ppm
No Solar	256 km	Standard	0 W/m <sup>2</sup>	0 ppm
2x Solar	256 km	Standard	819.2 W/m <sup>2</sup>	0 ppm
H <sub>2</sub> O-only SW	256 km	Standard	409.6 W/m <sup>2</sup> (absorbed only by H <sub>2</sub> O)	0 ppm
O <sub>3</sub> -only SW	256 km	Standard	409.6 W/m <sup>2</sup> (absorbed only by O <sub>3</sub> )	0 ppm
O <sub>2</sub> -only SW	256 km	Standard	409.6 W/m <sup>2</sup> (absorbed only by O <sub>2</sub> )	0 ppm
Unif-O <sub>3</sub>	256 km	Uniform	409.6 W/m <sup>2</sup>	280 ppm
No O <sub>3</sub>	256 km	None	409.6 W/m <sup>2</sup>	280 ppm
Large	2048 km	Standard	409.6 W/m <sup>2</sup>	280 ppm
Large-Organized*	2048 km	Standard	409.6 W/m <sup>2</sup>	280 ppm
Standard-3D	80km x 80km	Standard	409.6 W/m <sup>2</sup>	280 ppm
Thompson*	256 km	Standard	409.6 W/m <sup>2</sup>	280 ppm
CAM Radiation*	256 km	Standard	409.6 W/m <sup>2</sup>	280 ppm

**Table 1. Summary of all idealized experiments conducted in this study.** Each experiment consists of 8 simulations with prescribed surface temperatures of 280 K, 285 K, 290 K, 295 K, 300 K, 305 K, 310 K, and 315 K. The Large-Organized experiment is conducted without homogenized radiation. The Thompson experiment uses Thompson microphysics rather than the SAM one-moment scheme. The CAM Radiation experiment is conducted using the CAM3 radiation scheme rather than RRTMG.

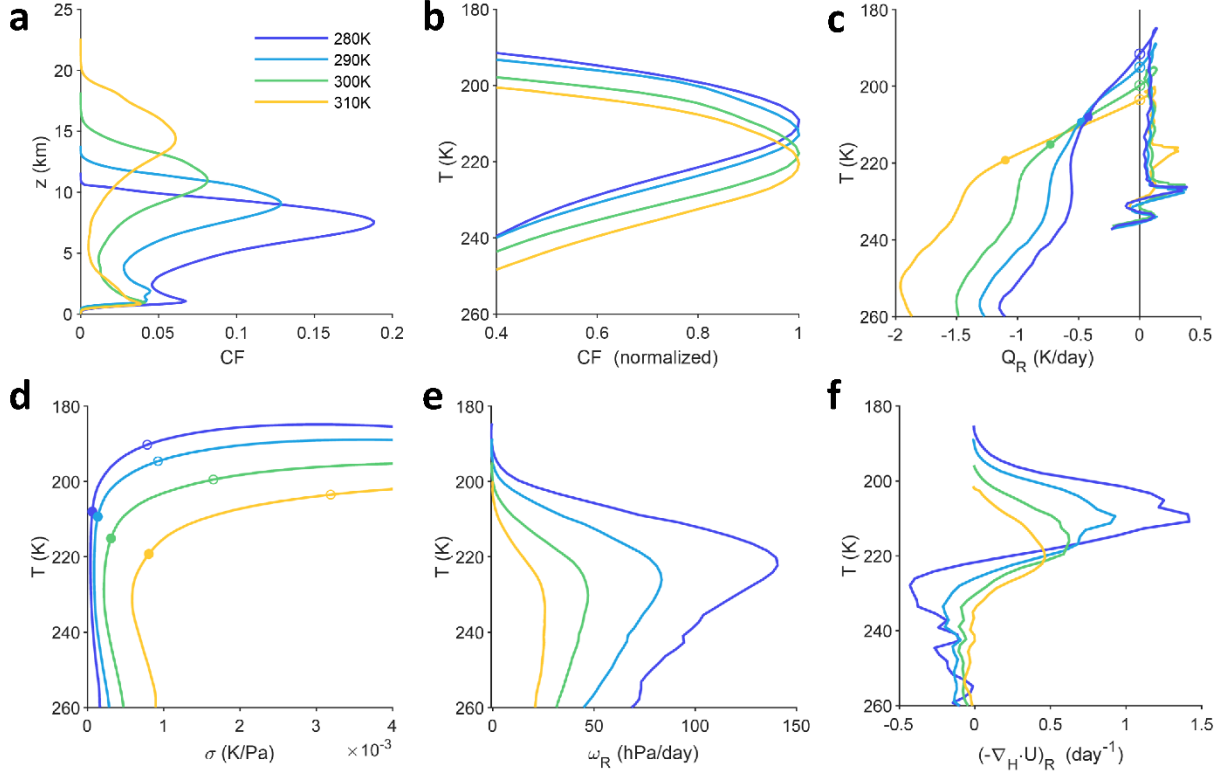
128 without ozone, which required 1000 days to equilibrate. The data reported are from the final 40%  
129 of the model integration. We identify cloudy grid cells as those whose condensates exceed either  
130  $1 \times 10^{-5} \text{ kg/kg}$  or 1% of the saturation specific humidity, whichever is smaller. This is consistent  
131 with the method of the RCEMIP protocol as well as SAM’s own diagnostic code. Even for small  
132 domains, SAM has a high propensity to undergo convective self-aggregation, in which convection  
133 spontaneously organizes into persistent moist and dry patches (Tompkins 2001; Bretherton et al.  
134 2005; Held et al. 1993). The spatial scale of self-aggregation depends on surface temperature  
135 (Yang 2018b), altering the climate state in ways independent of the physics at interest here. To  
136 prevent this, we horizontally homogenize radiation after computing each column, except in a set

137 of large-domain simulations testing the importance of organization. To verify that the choice of a  
138 2D modeling domain does not give substantially altered results, we performed 200-day 3D  
139 simulations in an 80 km x 80 km domain with a resolution of 1km. Due to the long equilibration  
140 times required, the 3D simulations were initialized using thermodynamic profiles from an  
141 otherwise identical 2D simulation. Since cloud microphysics are known to affect the properties of  
142 convection and convective clouds (Hu et al. 2021; Sokol and Hartmann 2022), we have performed  
143 one set of simulations with Thompson microphysics (Thompson et al. 2008). Each “experiment”  
144 in this study consists of eight simulations with prescribed sea-surface temperatures from 280 K to  
145 315 K. We present fifteen experiments in total, variously adjusting the CO<sub>2</sub> concentration, the  
146 insolation, and the ozone profile. These experiments are summarized in Table 1.

### 147 **3. Results**

148 As the climate warms, anvil clouds rise in altitude so that their temperature increases less than the  
149 air at any given level. Figure 1a shows profiles of cloud fraction from the Standard simulations  
150 (see Table 1). The cloud fraction profile has a two-peaked structure. Following the convention of  
151 other studies (Kuang and Hartmann 2007; Wing et al. 2020), we refer to upper-tropospheric peak  
152 in cloud fraction as the anvil. The anvil migrates upward as the surface warms. Figure 1b shows  
153 cloud fraction on a temperature coordinate and normalized by dividing by its local maximum  
154 value. The anvil temperature increases with warming.

155 We require a precise and general definition of “anvil temperature” appropriate for the wide range  
156 of surface temperature and physics perturbations in this study. Defining anvil to be the temperature  
157 where the cloud fraction reaches its maximum value (Kuang and Hartmann 2007; Seeley et al.  
158 2019b; Wing et al. 2020) proved inadequate for some of our experiments. The temperature of  
159 maximum cloud fraction may shift dramatically with warming due to a modest change in cloud  
160 profile shape, rather than a meaningful change in high-cloud temperature (Fig. S1). Using a cloud-  
161 mass-weighted temperature over the entire portion of the troposphere below a certain temperature  
162 (Zelinka and Hartmann 2010; Harrop and Hartmann 2012) is also not adequate for our  
163 experiments. Given the wide range of surface temperatures in our experiments, there is not a single  
164 temperature or pressure level consistently demarcating the “upper troposphere” from the “lower  
165 troposphere”. To avoid these shortcomings, we first identify the upper-tropospheric peak in cloud



**Figure 1. The Standard experiment.** (a) Profiles of cloud fraction from the Standard simulations. (b) Cloud fraction, normalized by its maximum value, and plotted against temperature. (c) All-sky radiative heating plotted against temperature. The open circles on the y-intercept indicate RT. The closed circles indicate the location of  $T_{Conv}$ . (d) Static stability profiles. The open circles indicate RT. The closed circles indicate  $T_{Conv}$ . (e) Radiatively driven subsidence. (f) Radiatively driven convergence.

166 fraction. Then we calculate a cloud-mass-weighted temperature over the locations where cloud  
 167 coverage of at least 80% of that maximum value:

$$T_{Anv} = \frac{\int_{p_{80\%,\uparrow}}^{p_{80\%,\downarrow}} T(p) \cdot CF(p) dp}{\int_{p_{80\%,\uparrow}}^{p_{80\%,\downarrow}} CF(p) dp} \quad (1)$$

168 where  $T$  is temperature,  $CF$  is cloud fraction, and  $p_{80\%,\uparrow}$  and  $p_{80\%,\downarrow}$  are the highest and lowest  
 169 pressure levels where the cloud fraction is at least 80% of its maximum value. This cutoff is  
 170 arbitrary choice, but in the supplemental material we show that Eq. (1) gives nearly the same  
 171 temperature as a strict “peak” definition except in a few cases where the shape of the cloud profile



172 changes abruptly with warming (Fig. S3). In those cases Eq. (1) retains monotonic behavior rather  
 173 than allowing an arbitrary jump in  $T_{Anv}$ . Therefore, this method is more appropriate for this study.  
 174 To reduce the imprecision introduced by a discrete model resolution, we linearly interpolate  $T(p)$   
 175 and  $CF(p)$  in pressure and calculate the integral in Eq. (1) numerically.

176 Figure 2 shows  $T_{Anv}$  for each experiment in this study. In the Standard simulations, anvil  
 177 temperature ( $T_{Anv}$ ) increases by 13.2 K while the surface temperature ( $T_s$ ) increases by 35 K, so  
 178 that  $\Delta T_{Anv}/\Delta T_s = 0.38$ . The anvil warms appreciably albeit more slowly than the surface, which  
 179 agrees with previous CRM and GCM studies. (Kuang and Hartmann 2007; Zelinka and Hartmann  
 180 2010; Harrop and Hartmann 2012; Khairoutdinov and Emanuel 2013). RCEMIP, whose protocol  
 181 forms the basis for our experimental design, showed an average anvil warming of  $\Delta T_{Anv}/\Delta T_s =$   
 182 0.44 (Wing et al. 2020).

183 As the climate warms, the RT becomes warmer as well. Figure 1c shows all-sky radiative heating  
 184 using temperature as a vertical coordinate. Considering the troposphere as the region of the  
 185 atmosphere in radiative-convective equilibrium, we identify radiative RT as the temperature at  
 186 which radiative heating changes sign. That is, RT is the y-intercept in Fig. 1c, marked with an open  
 187 circle for each simulation. The RT temperature for the Standard experiment is shown in Fig. 2a.  
 188 RT temperature ( $T_{RT}$ ) increases by 14.8 K over a 35 K increase in  $T_s$ , so that  $\Delta T_{RT}/\Delta T_s = 0.42$ .  
 189 This replicates recent studies of radiative-convective equilibrium in 1-D models without clouds.  
 190 Kluff et al. (2019) showed  $\Delta T_{RT}/\Delta T_s \approx 0.5$ , and they noted that the temperature increase of RT  
 191 (or “convective top”) resembled the slow temperature increase of anvil clouds. Dacie et al. (2019)  
 192 similarly showed  $\Delta T_{RT}/\Delta T_s \approx 0.4$ , though they defined radiative RT as the threshold where  
 193 convective heating (or radiative cooling) equals 0.2 K/day.

### 194 *3.1 Radiatively-Driven Convergence*

195 The cloud fraction profile is the result of sources and sinks of cloudy air: detrainment from the  
 196 convective core and evaporation or precipitation, respectively (Seeley et al. 2019a). We focus on  
 197 one component of the sources, due to the radiatively driven subsidence of air in clear skies (Kuang  
 198 and Hartmann 2007; Zelinka and Hartmann 2010):

$$\omega_R = -\frac{Q_R}{\sigma} \quad (2)$$

199 Here,  $\omega_R$  is a pressure velocity (Pa/day),  $Q_R$  is the radiative heating rate (K/day) and  $\sigma$  is the  
 200 static stability (K/Pa), given by:

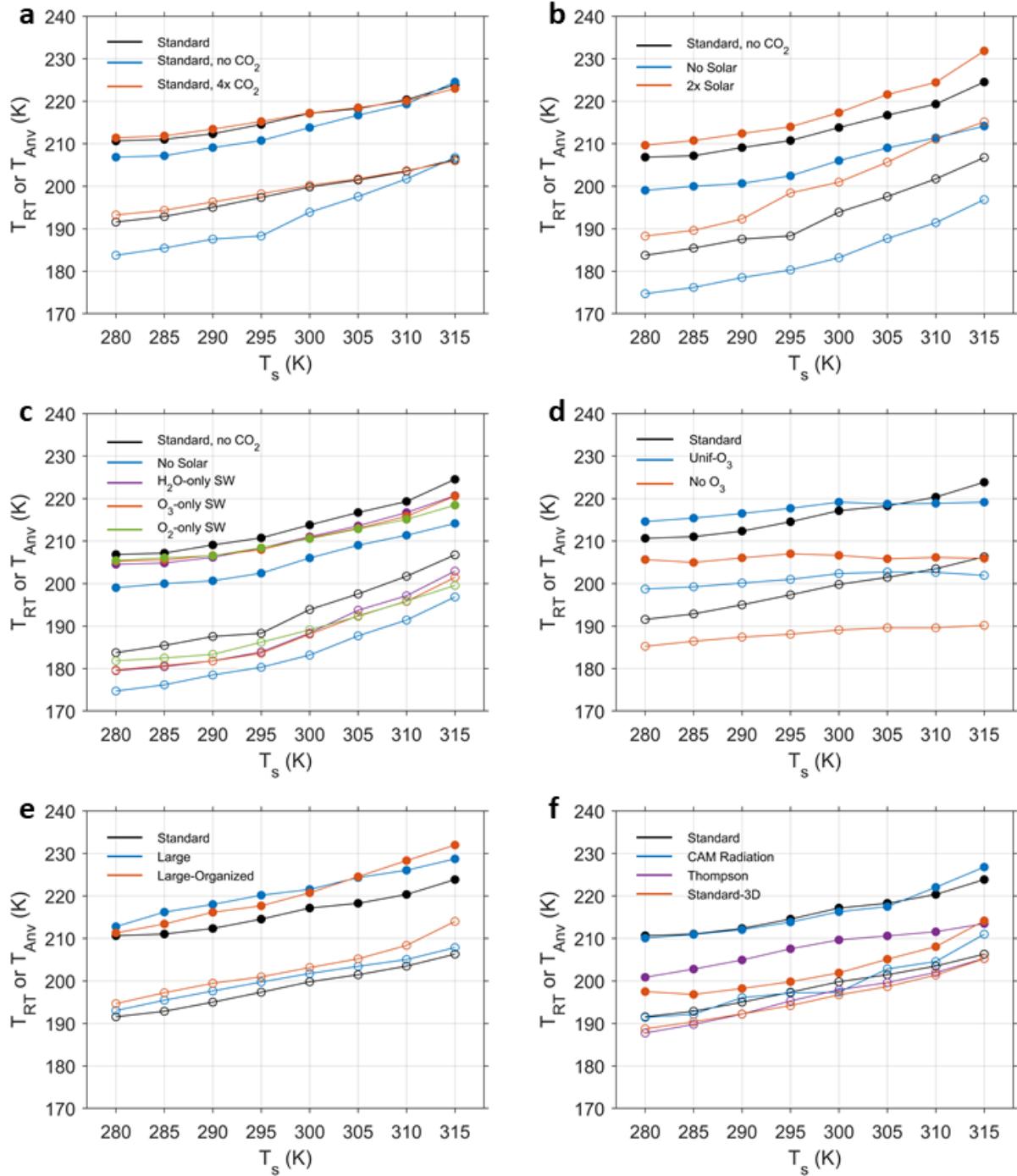
$$\sigma = \frac{\Gamma_d - \Gamma}{\rho g} \quad (3)$$

201 Where  $\Gamma$  is the lapse rate (K/m),  $\Gamma_d$  is the dry-adiabatic lapse rate,  $\rho$  is density, and  $g$  is the  
 202 acceleration due to gravity. The radiatively driven horizontal convergence of air in clear skies is  
 203 then given by:

$$(-\nabla_H \cdot \mathbf{U})_R = \partial \omega_R / \partial p \quad (4)$$

204 In the absence of mean ascent or subsidence over the domain,  $(-\nabla_H \cdot \mathbf{U})_R$  is balanced by  
 205 divergence out of the convective region at the same altitude. Past modeling studies found that the  
 206 peak upper-tropospheric cloud fraction tends to be located at or near the maximum in  $(-\nabla_H \cdot \mathbf{U})_R$   
 207 (Kuang and Hartmann 2007; Zelinka and Hartmann 2010; Seeley et al. 2019b).  $\mathbf{U}$  is a large-scale  
 208 velocity. The velocities associated with individual convective events are greater but in aggregate  
 209 would imply divergence from convective plumes at approximately the same level.

210 The radiative heating rate  $Q_R$  from the Standard experiment is shown in Fig. 1c. Since radiation is  
 211 horizontally homogenized in our simulations, we use domain-averaged values of  $Q_R$  in our  
 212 calculation. Figures 1d and 1e show  $\sigma$  and  $\omega_R$ , plotted against a temperature coordinate. The static  
 213 stability  $\sigma$  increases with height as the atmosphere transitions from a radiative-convective  
 214 equilibrium temperature profile below to a more stable radiative equilibrium profile above. This  
 215 transition to greater static stability is coincident with a steady decline in the magnitude of  $Q_R$   
 216 toward the RT. Therefore,  $\omega_R$  declines sharply with altitude at that level. The peak in radiative  
 217 convergence  $(-\nabla_H \cdot \mathbf{U})_R$  occurs there, as shown in Fig. 1f. The peak in  $(-\nabla_H \cdot \mathbf{U})_R$  moves to a  
 218 higher temperature as the surface temperature increases, much like the peak in cloud fraction in  
 219 Fig. 1b. Separately, the magnitude of  $(-\nabla_H \cdot \mathbf{U})_R$  declines due to increasing  $\sigma$ . This matches a  
 220 decline in anvil cloud extent seen in Fig. 1a, consistent with the “stability iris” hypothesis described  
 221 by Bony et al. (Bony et al. 2016).

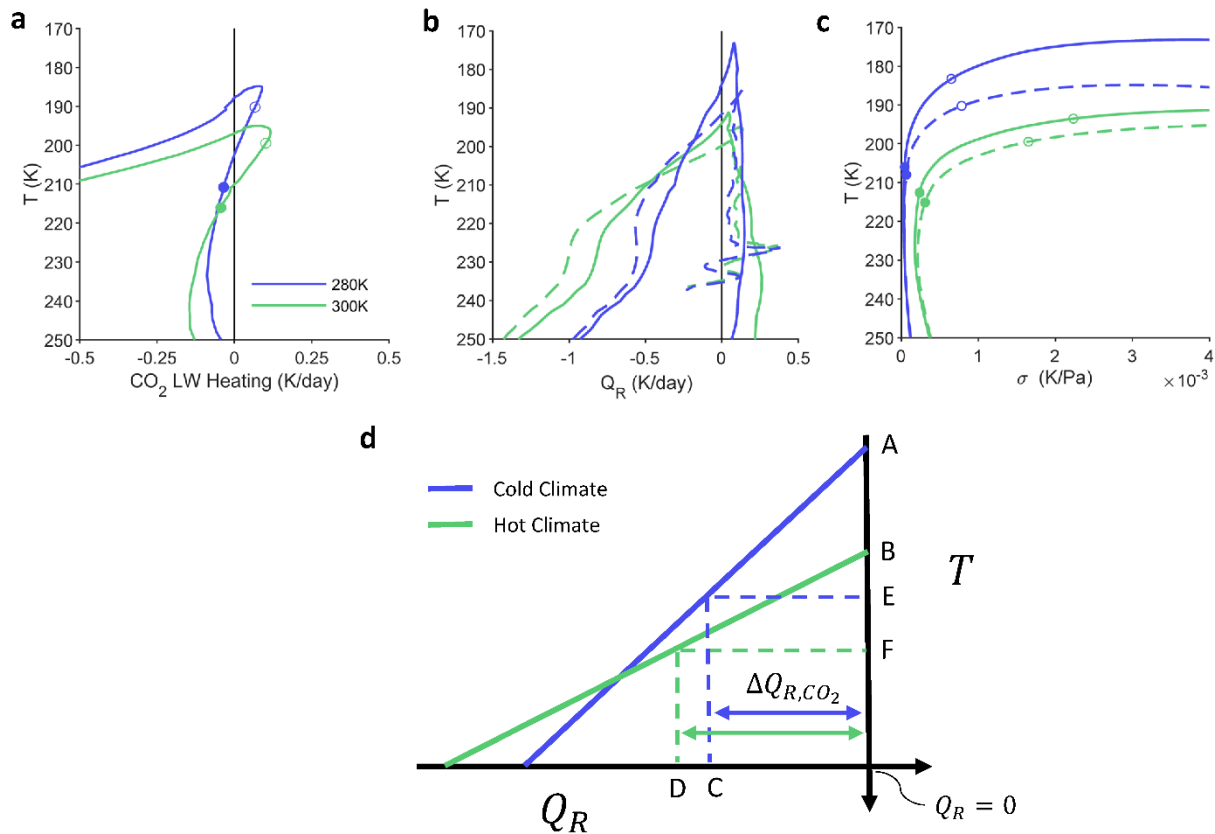


**Figure 2. Radiative tropopause and anvil temperatures.** RT temperature (open circles) and anvil temperature (closed circles) for each simulation used in this study. Black lines and marks indicate a simulation, also present in another panel, used as a baseline for comparison.

222 3.2 Sensitivity to CO<sub>2</sub>

223 We examine the relationship between the anvil and RT temperatures using a variety of modeling  
224 choices. We ask: do anvil temperature and RT temperature covary in response to a change of model  
225 parameters? We will focus on a sequence of experiments designed to elucidate the physical  
226 processes governing the anvil and RT. We begin by removing carbon dioxide from the Standard  
227 experiment. With CO<sub>2</sub> removed, RT and anvil become colder. The temperature increases more  
228 rapidly with warming ( $\Delta T_{RT}/\Delta T_s = 0.66$ ), as does the anvil temperature ( $\Delta T_{Anv}/\Delta T_s = 0.50$ ).  
229 Figure 3a shows the clear-sky CO<sub>2</sub> longwave heating rate from the Standard experiment. We obtain  
230 this from offline radiative transfer calculations with and without CO<sub>2</sub> in RRTMG, using the  
231 Standard experiment thermodynamic profiles. This calculation reasonably captures the differences  
232 in all-sky radiative heating between the Standard experiment and its no-CO<sub>2</sub> counterpart (Fig. 3b).  
233 CO<sub>2</sub> causes net heating around RT. This may be explained by the curvature of the temperature  
234 profile: near RT CO<sub>2</sub> is absorbing radiation from the warm troposphere below, while only emitting  
235 at its own, relatively cold temperature (Thuburn and Craig 2002). This additional heating results  
236 in a greater radiative equilibrium temperature and therefore a greater RT temperature. The anvil  
237 warming from CO<sub>2</sub> may be due to a shift in the static stability profile (Fig. 3c). RT marks the  
238 transition from the tropospheric RCE temperature profile below to the approximate radiative  
239 equilibrium profile above, which requires a sharp increase in static stability in the upper  
240 troposphere. Via eqs. (2) and (4), this helps to set the peak radiatively-driven convergence and  
241 anvil location, linking the RT to the anvil.

242 To understand the difference in RT *trend* with warming, we offer a schematic explanation in Fig.  
243 3d. The solid lines are the longwave heating rate for an atmosphere without CO<sub>2</sub> in the vicinity of  
244 RT, plotted against a temperature vertical coordinate. That is, we have zoomed in on the upper  
245 portion Fig. 3b. The magnitude of  $Q_R$  declines with decreasing temperature as the water vapor  
246 concentration becomes too small to efficiently cool the atmosphere, and its dependence on  
247 temperature is dominated by this mechanism (Hartmann and Larson 2002; Jeevanjee and  
248 Fueglistaler 2020). In an atmosphere without CO<sub>2</sub>, RT occurs at the intercept (e.g., point A). With  
249 CO<sub>2</sub>, RT occurs at a lower, warmer level where the water vapor cooling can offset CO<sub>2</sub> heating



**Figure 3. The role of CO<sub>2</sub>.** (a) The CO<sub>2</sub> clear-sky longwave heating rate in the Standard experiment, as obtained from offline calculations. The open circles indicate RT. The closed circles indicate  $T_{Conv}$ . (b) Radiative heating rate for the Standard experiment (dashed lines) and the Standard, no CO<sub>2</sub> experiment (solid lines). (c) Static stability for the Standard experiment (dashed lines) and the Standard, no CO<sub>2</sub> experiment (solid lines). (d) Conceptual picture of how CO<sub>2</sub> helps to set RT temperature. Points A and B denote the RT without CO<sub>2</sub>. Points C and D denote  $-\Delta Q_{R,CO_2}$ . Points E and F denote the RT with CO<sub>2</sub>.

250 (point E). As the climate warms, there are two competing factors at play: (1) the changing slope  
 251 of the  $T-Q_R$  curve, and (2) the changing magnitude of CO<sub>2</sub> heating near RT. The slope of the  $T$ -  
 252  $Q_R$  curve is declining due to the greater characteristic upper-tropospheric cooling rate at warmer  
 253 surface temperatures, as seen in Fig. 1c or 3c. This increase in cooling rate may be explained by  
 254 pressure effects on the transmission of radiation (Hartmann et al. 2022, preprint). The smaller slope  
 255 reduces the CO<sub>2</sub> effect on RT temperature. The CO<sub>2</sub> heating rate near RT is increasing with climate  
 256 warming, which would enhance the CO<sub>2</sub> effect on RT temperature (Fig. 3a). This effect partially

257 counters that of the declining slope of the  $T-Q_R$  curve. In our simulations, the declining  $T-Q_R$  slope  
258 dominates, so the RT temperature increases more slowly with  $\text{CO}_2$  than without.

### 259 *3.3 Sensitivity to solar insolation*

260 Solar radiation also has a substantial effect on anvil and RT temperatures. With  $\text{CO}_2$  still excluded,  
261 we also remove solar radiation from the model (Fig. 2b) and find that this cools both the RT and  
262 the anvil by about 10 K in all simulations. This is easily understood as the result of a colder  
263 stratospheric radiative equilibrium temperature, as  $\text{H}_2\text{O}$ ,  $\text{O}_3$ , and  $\text{O}_2$  are all responsible for  
264 shortwave heating there. Since RT is the intersection of the approximate radiative equilibrium  
265 profile above and the tropospheric RCE profile below, the colder radiative equilibrium temperature  
266 results in a colder RT. Figure 2b also shows that a doubling of solar radiation has an analogous  
267 warming effect on both RT and anvil. Curiously, for both No Solar and 2x Solar, the trends  
268  $\Delta T_{RT}/\Delta T_S$  and  $\Delta T_{Anv}/\Delta T_S$  are not especially sensitive to solar radiation. Since ozone heating is  
269 usually considered responsible for anvil warming, it might be surprising that this PHAT behavior  
270 persists in the absence of solar radiation. However, longwave heating by ozone is about as strong  
271 as its shortwave heating in the upper troposphere and tropopause layer (Thuburn and Craig 2002),  
272 so even in the absence of shortwave radiation there remains a substantial vertical gradient in ozone  
273 heating. Figure 2c shows three additional experiments,  $\text{H}_2\text{O}$ -only SW,  $\text{O}_3$ -only SW, and  $\text{O}_2$ -only  
274 SW, which selectively turn off all shortwave absorption except by  $\text{H}_2\text{O}$ ,  $\text{O}_3$ , and  $\text{O}_2$ , respectively.  
275 These show that shortwave heating from any one of these constituents alone is sufficient to produce  
276 much of the response to solar radiation.

### 277 *3.4 Sensitivity to $\text{O}_3$*

278 Our choices regarding ozone have a profound effect on the simulated trends of anvil and RT  
279 temperature. The RCEMIP ozone profile is based on the equatorial climatology so that it increases  
280 with height in the upper troposphere and lower stratosphere. Thus, when the surface warms, the  
281 troposphere is lifted into a region of greater ozone concentration. Beginning again from the  
282 Standard setup, we now manipulate ozone. In the Unif- $\text{O}_3$  experiment we remove ozone's vertical  
283 structure by prescribing a vertically uniform profile of the same column mass as in the Standard  
284 experiment. Indeed, the warming of the anvil as well as RT are greatly reduced compared to the  
285 Standard experiment, to  $\Delta T_{RT}/\Delta T_S = 0.09$  and  $\Delta T_{Anv}/\Delta T_S = 0.14$ , respectively.

286 The No-O<sub>3</sub> experiment achieved a similar result to Unif-O<sub>3</sub> (Fig. 4d), as  $\Delta T_{RT}/\Delta T_s = 0.14$  and  
287  $\Delta T_{Anv}/\Delta T_s = 0.00$ . The small change in anvil temperature replicates the findings of Harrop and  
288 Hartmann (Harrop and Hartmann 2012) in a similar setup. Seeley et al. (Seeley et al. 2019b), in  
289 their analogous “full complexity” simulations, found a more strictly fixed RT temperature as well  
290 as a nearly fixed anvil temperature for surface temperatures greater than freezing. That study used  
291 a different model and a small 3D domain, choices which may affect the RT temperature trend. At  
292 a tropical Earth-like surface temperature of 300K, the No-O<sub>3</sub> experiment shows a colder anvil and  
293 RT than the Standard experiment, whereas the Unif-O<sub>3</sub> experiment is a closer match since the  
294 ozone heating warms both the anvil and RT.

### 295 *3.5 Sensitivity to organization, domain geometry, and parameterizations*

296 Finally, we verify that our choice of a small 2D domain and lack of convective organization do  
297 not affect our earlier conclusions. Figure 2e shows the anvil and RT temperatures for the two large-  
298 domain experiments, as well as the Standard experiment. In one experiment the radiative heating  
299 is horizontally homogenized, preventing convective organization, and in the other radiation is  
300 interactive to allow organization. Compared to the standard, small-domain simulations presented  
301 in Fig. 1 and depicted by the black marks in Fig. 2e, the anvil temperature and RT temperature are  
302 both slightly warmer but display otherwise similar trends with warming. The warmer RT and anvil  
303 may be explained by the large-domain simulations having reduced upper-tropospheric relative  
304 humidity, moving the effective emission level to a lower, warmer location (Fig. S7a). This is  
305 analogous to the findings by Harrop & Hartmann (Harrop and Hartmann 2012), who found that  
306 artificially reducing the amount of upper tropospheric water vapor passed to the radiation scheme  
307 increased anvil temperature. Convective organization does not appear to affect anvil temperature’s  
308 trend with warming, consistent with previous studies (Wing et al. 2020; Harrop and Hartmann  
309 2012).

310 Figure 2f shows a series of simulations using a small 3D domain, as well as simulations using  
311 Thompson two-moment microphysics (Thompson et al. 2008). In either case, the anvil is  
312 considerably colder than in the Standard experiment, but the trend with climate warming is similar.  
313 The anvil-RT relationship remains robust. The colder anvils appear to be the result of greater upper  
314 tropospheric humidity in those experiments, which would move the emission level to a colder  
315 temperature (Fig. S7b). This may arise from, or be complementary to, cloud-radiative interactions

316 or differences between 2D and 3D convection. Another experiment using the CAM3 radiation  
 317 scheme (Collins et al. 2006) demonstrates that there is only small sensitivity to our choice of  
 318 radiation parameterization.

#### 319 **4. An Anvil-Radiative Tropopause Relationship**

320 Throughout our experiments, we find that the temperature of the cloud anvil is empirically related  
 321 to the temperature of RT. Figure 4a shows the anvil temperature plotted against the RT temperature  
 322 for each simulation we conducted. Anvil and RT always occur at different locations and  
 323 temperatures from one another, yet they appear closely related. If a simulation results in a warmer  
 324 RT, then it generally yields a warmer anvil. This behavior appears particularly robust when  
 325 comparing the temperature trends  $\Delta T_{trop}/\Delta T_s$  and  $\Delta T_{anv}/\Delta T_s$  for a single experimental  
 326 configuration (Fig. 5a). The anvil-RT relationship is robust over 120 simulations in a wide range  
 327 of model settings. This is our central result.

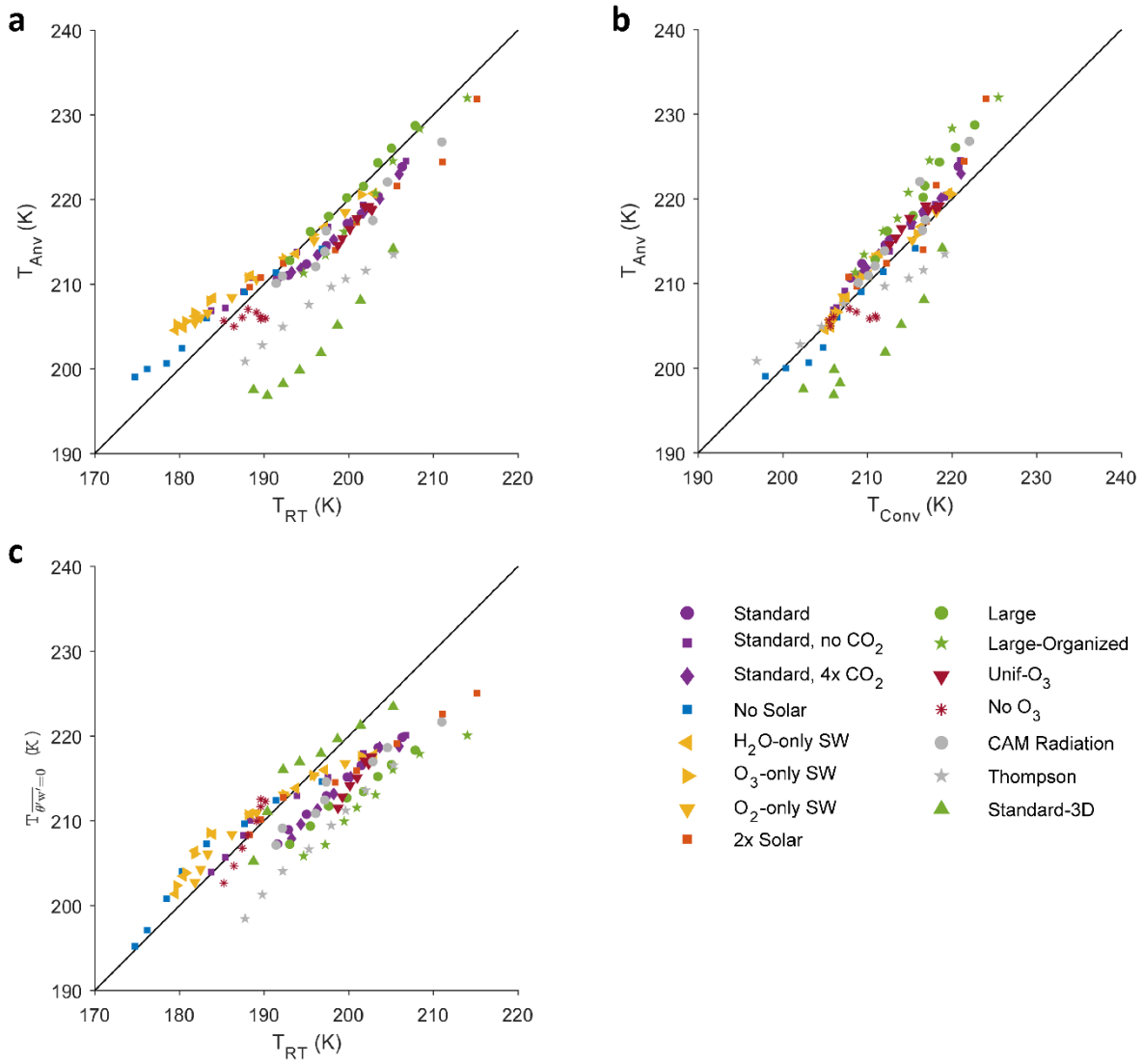
328 Insofar as the anvil location is set by the location of radiatively-driven convergence, we would  
 329 expect those locations to have similar temperatures. We define a convergence-weighted  
 330 temperature similarly to how we defined an anvil temperature before:

$$T_{Conv} = \frac{\int_{p_{80\%,\uparrow}}^{p_{80\%,\downarrow}} T(p) \cdot (-\nabla_H \cdot \mathbf{U})_R dp}{\int_{p_{80\%,\uparrow}}^{p_{80\%,\downarrow}} (-\nabla_H \cdot \mathbf{U})_R dp} \quad (5)$$

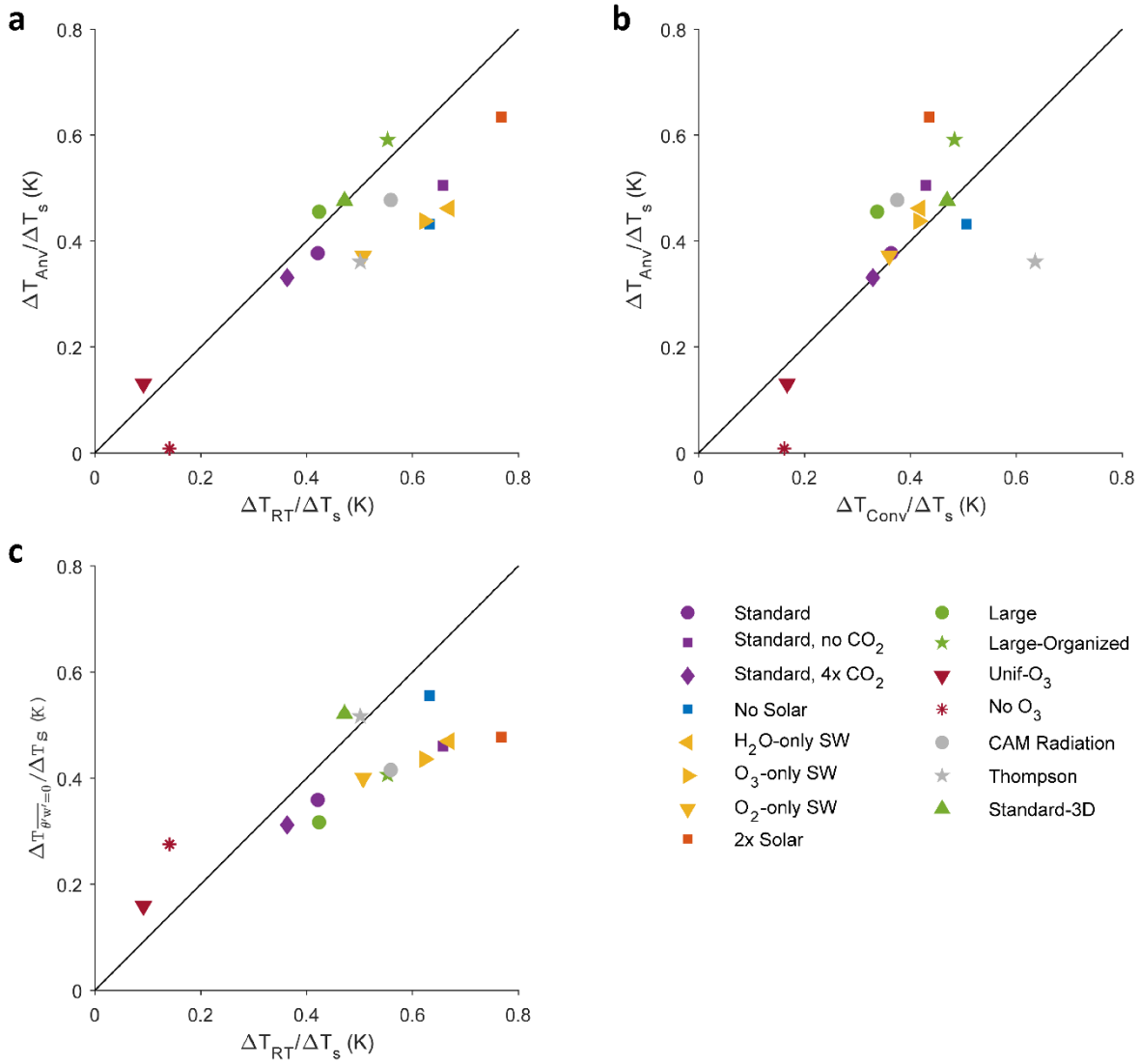
331 where  $p_{80\%,\uparrow}$  and  $p_{80\%,\downarrow}$  are the highest and lowest pressure levels where  $(-\nabla_H \cdot \mathbf{U})_R$  is at least  
 332 80% of its maximum value. Figure 4b shows the relationship between this convergence-weighted  
 333 temperature and anvil temperature. As found by previous studies of CRMs, GCMs, and  
 334 observations, the temperature of cloud anvils is well-predicted by the convergence temperature.

335 The empirical relationship between RT temperature, anvil temperature, and convergence  
 336 temperature suggests that anvil and RT arise from related physics. If convection is comprised of a  
 337 spectrum of plumes with varying entrainment rates (Arakawa and Schubert 1974), then the non-  
 338 dilute (non-entraining) plume reaches the greatest altitude. The level of neutral buoyancy for the  
 339 non-dilute plume occurs near RT, as convection would not be buoyant in the stable temperature  
 340 profile substantially above RT. It detrains there, setting the temperature as that of the moist adiabat.

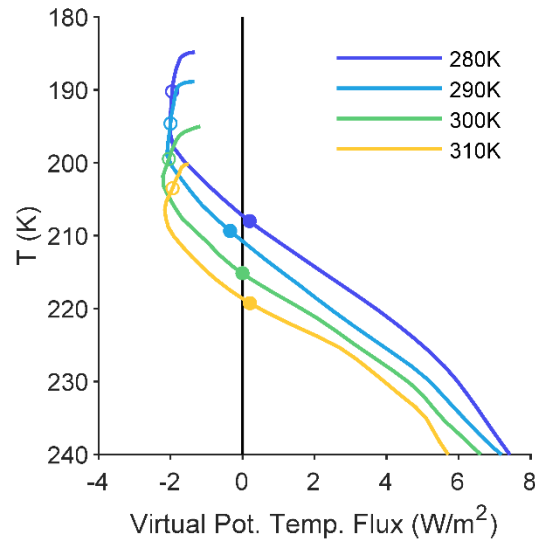




**Figure 4. Relationship between  $T_{RT}$  and  $T_{Anv}$ .** (A)  $T_{Anv}$  plotted against  $T_{RT}$  for each simulation in this study. (B)  $T_{Anv}$  plotted against  $T_{Conv}$  for each simulation in this study. (C)  $T_{w'_{\theta'_v=0}}$  plotted against  $T_{RT}$  for each simulation in this study. A one-to-one line is shown in black as an aid to the reader.



**Figure 5. Relationship between  $\Delta T_{RT}$  and  $\Delta T_{Anv}$ .** (A)  $\Delta T_{Anv}/\Delta T_s$  plotted against  $\Delta T_{RT}/\Delta T_s$  for each simulation in this study. (B)  $\Delta T_{Anv}/\Delta T_s$  plotted against  $\Delta T_{Conv}/\Delta T_s$  for each simulation in this study. (c)  $\Delta T_{w'\theta_v'=0}/\Delta T_s$  plotted against  $\Delta T_{RT}/\Delta T_s$  for each simulation in this study. A one-to-one line is shown in black as an aid to the reader.



**Figure 6. Virtual potential temperature flux in the Standard experiment.** The open circles indicate RT. The closed circles indicate  $T_{Conv}$ . Data are cut off at the cold point.

343 Below this level, dilute plumes are responsible for setting the temperature as colder than the moist  
 344 adiabat. See, for example Figs. 1a and 2f from Zhou & Xie (Zhou and Xie 2019), which show a  
 345 sharp increase in temperature relative to the moist adiabat at the top of the troposphere. This causes  
 346 static stability to increase with height below RT, as seen in our Fig. 1d. The static stability profile  
 347 then links RT to the level of convergence and anvil according to Eqs. (2) and (4).

348 This explanation resembles that of Hartmann et al. (Hartmann et al. 2019), who noted that due to  
 349 convective overshooting, the least entraining plumes inject relatively cold air above the level of  
 350 the anvil (see also, Kuang and Bretherton 2004). This causes a buoyancy flux divergence which  
 351 must be balanced by radiative heating, so RT appears there. Figure 6 shows a plot of virtual  
 352 potential temperature flux in our Standard experiment. It is expressed as an energy flux  $\rho c_p \overline{w' \theta'_v}$ .

353 Above the level of zero buoyancy flux, where  $\overline{w' \theta'_v} = 0$ , significant convective activity is present  
 354 due to overshooting. RT occurs above the minimum in virtual potential temperature flux, where  
 355 there is flux divergence. The temperature at the level of zero buoyancy flux is very close to  $T_{Conv}$ ,  
 356 indicating that convection tends to lose its buoyancy near the level of large-scale divergence from  
 357 convection. The temperature at the level of zero buoyancy flux increases with surface warming at  
 358 a rate comparable to both RT and anvil ( $\Delta T_{\overline{w' \theta'_v}=0} / \Delta T_s = 0.36$ ). Plots comparing the temperatures

359 at the level of zero buoyancy flux and at RT across all our simulations show that they indeed  
360 covary (Figs. 4c and 5c). This corroborates the explanation provided by Hartmann et al.

361 However, 1D radiative-convective models simulate a similar RT temperature and trend to that  
362 found in our Standard experiment when given the same RCEMIP radiation parameters (see Kluff  
363 et al. 2019, or the “hard convective adjustment” simulations in Dacie et al. 2019). The simplest  
364 such models do not simulate or parameterize overshooting convection and its associated negative  
365 buoyancy flux, and the level of neutral buoyancy is essentially set at RT. The fact that RT is well  
366 represented in these models suggests that RT is not caused or set by the reversal in buoyancy flux.  
367 Regardless of the particular explanation, when the modeled RT and anvil each remain at a nearly  
368 fixed temperature, as in our Unif-O<sub>3</sub> and No-O<sub>3</sub> experiments, this behavior likely arises in part  
369 from the FAT mechanism. That is, the Clausius-Clapeyron scaling of saturation vapor pressure  
370 causes H<sub>2</sub>O radiative cooling to decline near a fixed temperature (Hartmann and Larson 2002;  
371 Jeevanjee and Fueglistaler 2020).

## 372 **5. Tug of war: rising O<sub>3</sub> profiles vs. surface warming**

373 Our Standard simulations used an ozone profile which is fixed in pressure despite a warming  
374 surface. This is unrealistic. In the real tropical atmosphere, the ozone profile would evolve in  
375 response to deeper convective mixing of small tropospheric ozone concentrations. Additionally,  
376 upward transport of ozone may increase as stratospheric upwelling intensifies with surface  
377 warming (Lin et al. 2017). A fixed-in-pressure ozone profile will alter the equilibrium RT  
378 temperature, as ozone is the main absorber responsible for radiative heating there (Thuburn and  
379 Craig 2002). As shown in our simulations, surface warming leads to a warmer RT with a fixed O<sub>3</sub>  
380 profile. However, lifting the O<sub>3</sub> profile can lead to the local decline of ozone heating, which tends  
381 to reduce temperature. Therefore, there is a “tug of war” between the two effects to determine how  
382 RT temperature responds to climate warming in the real tropical atmosphere. We cannot predict  
383 the anvil or RT temperature trend with warming using a fixed ozone profile.

384 To investigate the role of ozone, past studies have artificially increased upper-tropospheric ozone,  
385 leading to greater anvil temperature (Kuang and Hartmann 2007) as well as greater RT temperature  
386 (Birner and Charlesworth 2017; Dacie et al. 2019). Other authors have simply removed ozone  
387 entirely (Jeevanjee and Romps 2018; Seeley et al. 2019b; Harrop and Hartmann 2012), as in our

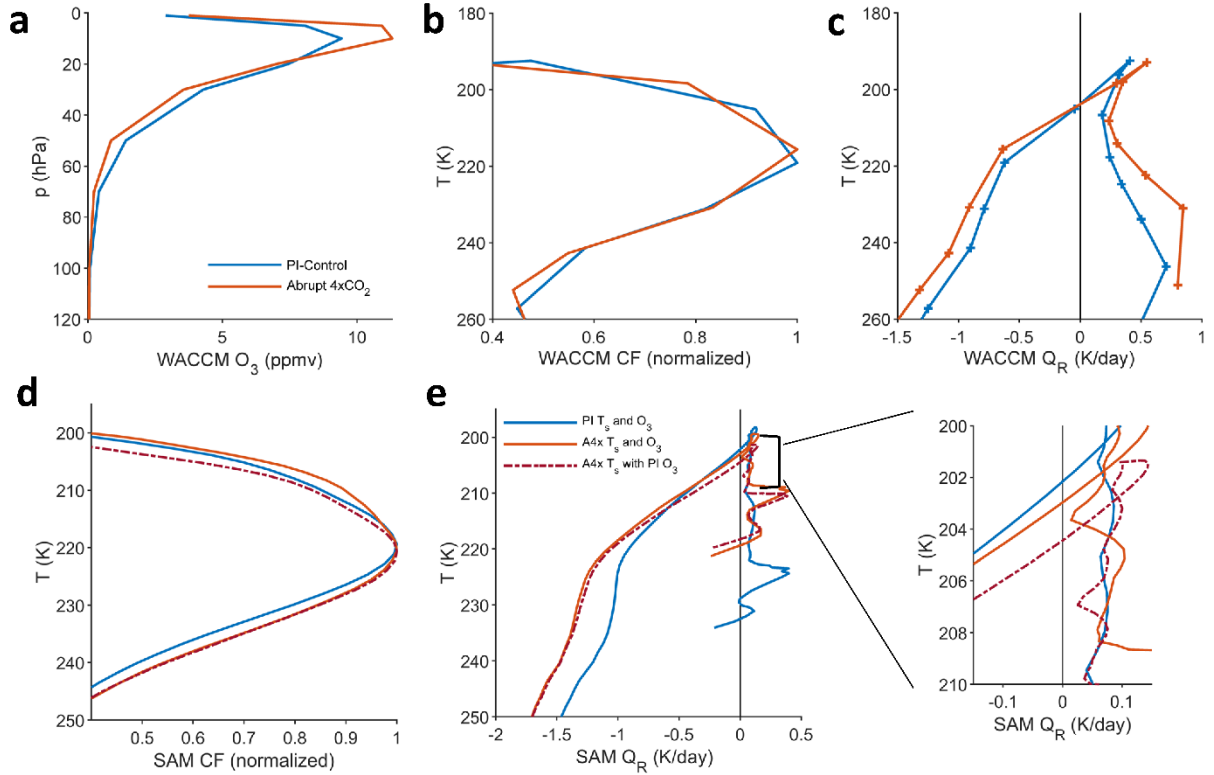
388 No O<sub>3</sub> experiment. However, those idealized treatments of the ozone profile cannot provide a  
389 quantitative estimate of how ozone influences the warming trend of anvil or RT. Does the rising  
390 troposphere or declining ozone concentration win the tug of war, or do they cancel one another?  
391 To answer that question, we shall prescribe ozone from the Whole Atmosphere Community  
392 Climate Model (CESM2-WACCM6), which employs coupled ozone chemistry (Gettelman et al.  
393 2019).

394 We use WACCM6 data from a pre-industrial control run in which the CO<sub>2</sub> concentration is fixed  
395 at 280 ppm (“piControl”), as well as a simulation of the response to an abrupt quadrupling of CO<sub>2</sub>  
396 concentration (“abrupt-4xCO<sub>2</sub>”) (Eyring et al. 2016; Danabasoglu 2019). Those two experiments  
397 are commonly used for estimating climate feedbacks, and the large forcing results in a large  
398 difference in surface temperature. For either simulation we average the final 50 years of data,  
399 within 10 degrees of the equator. In that region, tropical sea surface temperature increases from  
400 301.21 K at the end of the piControl simulation to 306.65 K at the end of the abrupt-4xCO<sub>2</sub>  
401 simulation. Figure 7a shows that as the climate warms, the ozone concentration decreases below  
402 the 20 hPa level and increases above. Figure 7b shows that the normalized cloud profiles are nearly  
403 the same in a temperature coordinate.<sup>1</sup> WACCM simulates a FAT in the deep tropics. Figure 7c  
404 shows that WACCM also simulates a FiTT in the deep tropics: RT temperature increases by only  
405 0.05 K. The coarse resolution and small surface temperature increment of the GCM output  
406 undercut the precision of this estimate, but it is nevertheless a striking result. The ozone profiles  
407 appear nearly the same in a temperature coordinate in the troposphere and tropopause layer (Fig.  
408 S8) due to nearly fixed tropospheric concentration and FiTT.

409 To what extent does the shifted ozone profile account for the apparent temperature-invariance of  
410 the WACCM radiative tropopause and anvil clouds? We modify our Standard formulation of 2D  
411 SAM. We conduct one simulation with the piControl surface temperature and ozone profile and a  
412 second simulation with the abrupt-4xCO<sub>2</sub> surface temperature and ozone profile. As a mechanism-  
413 denial experiment, we conduct a third simulation with the warmer abrupt-4xCO<sub>2</sub> surface  
414 temperature and the piControl ozone profile, which is shifted lower in altitude compared to the

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<sup>1</sup>  $T_{anv}$  as calculated from Eq. (1) decreases from 217.2 K to 216.6 K. However, due to the coarseness of the GCM output, the sign and magnitude of that change depend non-monotonically on what percentage threshold we consider as the “anvil” in that formula.



**Figure 7. CESM2-WACCM simulations and WACCM-informed SAM simulations.** (a) CESM2-WACCM ozone. (b) Cloud fraction plotted against a temperature coordinate. (c) Radiative heating plotted against temperature. (d) Normalized cloud fraction for the SAM simulations based on WACCM surface temperature and ozone. (e) Radiative heating for the SAM simulations based on WACCM surface temperature and ozone.

415 abrupt-4xCO2 ozone profile. Consistent with the GCM simulations, we increase CO<sub>2</sub> by four  
 416 times in both warming simulations.

417 Figure 7d shows the cloud fraction profiles of the WACCM-informed SAM simulations. With  
 418 ozone prescribed to match the surface temperature, the normalized cloud fraction profile is nearly  
 419 unchanged with respect to temperature.  $T_{Anv}$ , calculated according to Eq. (1). increases by less  
 420 than 0.1 K so that  $\Delta T_{Anv}/\Delta T_s = .01$ . When ozone is instead fixed,  $T_{anv}$  increases by 1.3 K so that  
 421  $\Delta T_{Anv}/\Delta T_s = .23$ . The difference in  $T_{Anv}$  between the two ozone treatments is mostly attributable  
 422 to greater cloud amount above the peak in the realistic-ozone scenario. The temperature at the peak  
 423 itself is nearly unchanged. Figure 7e shows the radiative heating profiles of all three simulations.  
 424 When ozone matches the surface temperature,  $T_{RT}$  increases by 0.8 K so that  $\Delta T_{RT}/\Delta T_s = .15$ .

425 When ozone is instead fixed,  $T_{RT}$  increases by 2.3 K so that  $\Delta T_{RT}/\Delta T_s = .42$ . The ozone-shifted  
426 results resemble the idealized No-O<sub>3</sub> experiment presented earlier. For both anvil and RT, the  
427 shifted ozone profile offsets most of the warming that would occur with fixed ozone. When ozone  
428 is realistically modeled as in WACCM, the effects of increasing surface temperature and a lifted  
429 ozone profile roughly cancel one another to produce a FiTT as well as a FAT. However, the ozone  
430 we prescribe does not reflect the ozone sources and sinks associated with deep convection in SAM,  
431 but rather those of a different model. Also, our simulations are also performed without a Brewer-  
432 Dobson circulation, though Kuang & Hartmann (Kuang and Hartmann 2007) found it had only a  
433 small effect on anvil temperature in an idealized CRM. In future studies it may also be worthwhile  
434 to investigate more than a single GCM's representation of ozone.

435 The difference in anvil warming between the fixed-ozone and lifted-ozone scenarios gives rise to  
436 a difference in top-of-atmosphere radiation in SAM. The cloud longwave radiative effect is 0.43  
437 W/m<sup>2</sup> more positive when we prescribe ozone to shift upward (or .31 W/m<sup>2</sup> net including  
438 shortwave.) This results in a stronger positive cloud longwave feedback by about 0.08 W/m<sup>2</sup>/K (or  
439 0.06 W/m<sup>2</sup>/K net including shortwave). This is smaller than the ozone-related cloud radiative effect  
440 of about 0.8 W/m<sup>2</sup> longwave feedback of 0.21 W/m<sup>2</sup>/K found in a GCM by Nowack et al. (Nowack  
441 et al. 2015), which may be due in part to the comparatively smaller SAM cloud fraction profile<sup>2</sup>.

## 442 6. Discussion

443 We have shown that the temperatures of cloud anvils and radiative tropopause (RT) strongly  
444 covary across a wide range of model settings and surface temperatures in a 2D cloud-resolving  
445 model. This affirms the intuition in FAT thinking that anvils occur near the top of the troposphere  
446 where the radiative cooling rate declines towards zero (Hartmann and Larson 2002). We have  
447 shown that the presence of CO<sub>2</sub> causes the anvil and RT temperatures to increase more slowly with  
448 surface warming than they otherwise would, and we have shown that solar radiation warms the  
449 RT and anvil. Both of these effects on RT temperature can be understood by considering the  
450 resulting change to the radiative equilibrium temperature there. Finally, we found that accounting

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<sup>2</sup> We are comparing the Nowack et al.'s B and C1 simulations. We estimated the cloud radiative effect using the Web Plot Digitizer (Rohatgi 2019) for their Fig. 2c and a comparable 5.44 K of surface warming.

451 for the shift in ozone profile with warming offsets the ozone-induced warming usually found in  
452 CRM studies, producing a nearly fixed RT temperature as well as a FAT.

453 Those results are significant in light of a recent contrary result. Seeley et al. (Seeley et al. 2019b)  
454 found that anvil temperature increased in spite of a fixed RT temperature in “minimal recipe” CRM  
455 simulations which isolated the longwave effect of water vapor from other gases present in Earth’s  
456 atmosphere. Their anvil and RT may have become decoupled because that modeling choice  
457 resulted in a greater distance between anvil and RT than would be found in more earthlike  
458 simulations. In our Standard simulations the distance between anvil and RT is 2-3 km, substantially  
459 less than the 5-10 km reported for the minimal recipe simulations in Seeley et al. The minimal-  
460 recipe anvil warming may be partly attributable to the exclusion of CO<sub>2</sub>, a choice we found to  
461 increase the temperature trend with warming (Fig. 2a). The Seeley et al. “full complexity”  
462 simulations, which contain CO<sub>2</sub>, show very little anvil warming for surface temperatures above  
463 freezing. Using the same model and a similar fixed-CO<sub>2</sub> setup, Romps (Romps 2020) found a near  
464 FAT for surface temperatures between 285 K and 315 K. Considering the results of those studies  
465 as well as the present study, the FAT prediction appears well-supported by the modeling evidence.  
466 Therefore, the contribution of Seeley et al. is principally conceptual: Although theory strongly  
467 suggests that the anvil is linked to a decline in H<sub>2</sub>O radiative cooling at a fixed temperature  
468 (Hartmann and Larson 2002; Jeevanjee and Fueglistaler 2020), other radiatively-active gases and  
469 physical processes help to shape the anvil temperature trend, or lack thereof.

470 Our WACCM-informed simulations showed that RT temperature is nearly fixed when the ozone  
471 profile is lifted with climate warming to match the surface temperature. In the CMIP6 *piControl*  
472 and abrupt-4xCO<sub>2</sub> experiments, used to estimate climate feedbacks and climate sensitivity, models  
473 without interactive ozone chemistry instead fix ozone at its pre-industrial concentrations (Eyring  
474 et al. 2016). For those models, our results suggests their RT and anvil may be biased towards  
475 warming. This would introduce a negative bias in cloud longwave feedback, similar to that found  
476 by Nowack et al. (Nowack et al. 2015, 2018b). Models’ representation of clouds may be improved  
477 if ozone can respond to the rising tropopause with climate change, as suggested in recent literature  
478 (Nowack et al. 2018a; Hardiman et al. 2019; Meraner et al. 2020). The continued development of  
479 models with interactive ozone chemistry, such as those documented by the Chemistry-Climate  
480 Model Initiative (CCMI), may also improve the simulation of clouds (Morgenstern et al. 2017).



481 Finally, we mention several caveats to this study. To afford the computational expense of  
482 conducting 123 five-hundred-day simulations, we use a small, two-dimensional domain. We  
483 prescribe no mean ascent or descent, whereas real tropical anvil clouds form in the context of mean  
484 ascent in both the troposphere and the stratosphere. We homogenize the radiation in all our  
485 experiments except for one, which may decouple any cloud-radiation feedback. Our analysis  
486 relates cloud amount to the radiatively driven convergence in clear skies. However, that is not a  
487 closed budget for cloud amount. Other factors are known to cause detrainment from the convective  
488 core, and cloud lifetime after detrainment depends on evaporation, microphysics, and within-cloud  
489 turbulence (Lilly 1988; Hartmann et al. 2018; Gasparini et al. 2019; Seeley et al. 2019a). The peak  
490 cloud amount itself also depends on microphysics as well as model resolution (Sokol and  
491 Hartmann 2022; Jeevanjee and Zhou 2022), and there is more work to be done to understand how  
492 cloud properties depend on these choices. As with other studies on this topic, we only consider the  
493 temperature of the cloud near its peak amount, not its effective radiating temperature, which may  
494 be different.

495 *Acknowledgements:*

496 This work was supported by a Packard Fellowship for Science and Engineering, and the France-  
497 Berkeley Fund. We acknowledge the World Climate Research Programme and its Working Group  
498 on Coupled Modelling, which coordinated and promoted CMIP6. We thank the Earth System Grid  
499 Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies  
500 who support CMIP6 and ESGF. Computational resources were provided by the Department of  
501 Energy's National Energy Research Scientific Computing Center (NERSC). SAM was provided  
502 by M. Khairoutdinov (<http://rossby.msrc.sunysb.edu/~marat/SAM.html>). The authors thank three  
503 reviewers for their helpful comments and suggestions.

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