

1     **Implementation and Exploration of Parameterizations of Large-Scale Dynamics in**  
2             **NCAR’s Single Column Atmosphere Model SCAM6**

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12    **Key Points:**

- 13       • We use three different methods to parameterize the large-scale dynamics in NCAR’s  
14       single column atmospheric model (SCAM6).
- 15       • As in the Global Atmospheric System Studies Intercomparison, we test SCAM6’s  
16       response to various boundary conditions and model parameters.
- 17       • Under all three methods, circulation strength is decreased when barriers to convection are  
18       reduced.

## 19 **Abstract**

20 A single column model with parameterized large-scale dynamics is used to better understand the  
21 response of steady-state tropical precipitation to relative sea surface temperature under various  
22 representations of radiation, convection, and circulation. The large-scale dynamics are  
23 parametrized via the weak temperature gradient (WTG), damped gravity wave (DGW), and  
24 spectral weak temperature gradient (Spectral WTG) method in NCAR's Single Column  
25 Atmosphere Model (SCAM6). Radiative cooling is either specified or interactive, and the  
26 convective parameterization is run using two different values of a parameter that controls the  
27 degree of convective inhibition. Results are interpreted in the context of the Global Atmospheric  
28 System Studies (GASS) Intercomparison (Daleu et al. 2016). Using the settings given in Daleu et  
29 al. (2016), SCAM6 under the WTG and DGW methods produces erratic results, suggestive of  
30 numerical instability. However, when key parameters are changed to weaken the strength with  
31 which the circulation acts to eliminate tropospheric temperature variations, SCAM6 performs  
32 comparably to single column models in the GASS Intercomparison. The Spectral WTG method  
33 is less sensitive to changes in convection and radiation than are the other two methods,  
34 performing at least qualitatively similarly across all configurations considered. Under all three  
35 methods, circulation strength, represented in 1D by grid-scale vertical velocity, is decreased  
36 when barriers to convection are reduced. This effect is most extreme under specified radiative  
37 cooling, and is shown to come from increased static stability in the column's reference radiative-  
38 convective equilibrium profile. This argument can be extended to interactive radiation cases as  
39 well, though perhaps less conclusively.

## 40 **Plain Language Summary**

41 Single column models, as the name suggests, only model the vertical dimension of the  
42 atmosphere. They are simpler than full-scale 3D global circulation models, but nonetheless play  
43 an important role in model development and in better understanding physical phenomena. We  
44 use NCAR's Single Column Atmosphere Model (SCAM6) to better understand tropical rainfall.  
45 In a single column model, the atmospheric wind coming from other locations (the large-scale  
46 circulation) must be either specified or approximated using a parameterization. We implement  
47 three different parameterizations of the large-scale circulation into SCAM6 and assess how  
48 SCAM6 responds to various changes while using these parameterizations. The Global  
49 Atmospheric System Studies (GASS) Intercomparison assessed the performance of various other  
50 single column models using parameterizations of the large-scale circulation; we fold SCAM6  
51 into this Intercomparison. We find that SCAM6 performs substantially differently to its peers  
52 under the settings used in the GASS Intercomparison, but more comparably to its peers when key  
53 circulation parameters are relaxed. Another notable finding is that, across all three  
54 parameterizations of large-scale dynamics, circulation strength decreases when we reduce  
55 SCAM6's barrier to convection.

## 56 **1 Introduction**

57 Single column models (SCMs) are one-dimensional (1D) models that only explicitly represent  
58 the vertical dimension of the atmosphere. While the column's full convective, radiative, and  
59 moist physics schemes are retained, the large-scale dynamics must be either specified or  
60 parameterized. While SCMs only represent a subset of the processes captured in full-scale 3D  
61 global circulation models (GCMs), they are part of model hierarchies which can play important

62 roles both in model development and in better understanding underlying physical phenomena  
63 (Held 2005).

64 Parameterizations of the large-scale dynamics are best developed in the context of the tropical  
65 atmosphere. Due to the smallness of the Coriolis parameter near the equator, tropical horizontal  
66 free-tropospheric pressure and density gradients are weak on climatic time scales (Charney  
67 1963). For some purposes, it can be assumed that large-scale dynamics will simply act to relax  
68 the column's temperature to a predefined profile representative of regions adjacent to the  
69 column, and by extension the tropics as a whole. This target profile is often modeled as a  
70 radiative convective equilibrium (RCE) solution over an appropriate sea surface temperature,  
71 representing either the tropical mean or the mean over regions of frequent deep convection  
72 (Sobel and Bretherton 2000, Sobel et al. 2002). In RCE, the large-scale vertical velocity is zero,  
73 meaning that radiative cooling balances convective heating at all pressure levels and column  
74 precipitation must equal column evaporation. Any given region within the tropics can sustain  
75 precipitation greater or less than the tropical mean by importing or exporting moisture via the  
76 large-scale circulation. Parametrizations of large-scale dynamics try to capture this process,  
77 including its dependence on both external parameters (e.g., local sea surface temperature) and  
78 internal ones (e.g., those that represent aspects of convective or radiative physics).

79 The goal of this paper is to test several parameterizations of large-scale dynamics in NCAR's  
80 Single Column Atmosphere Model, SCAM6 (Gettelman et al. 2019), the SCM version of  
81 NCAR's Community Earth System Model, CESM2.2.0 (Danabasoglu et al. 2020). SCAM6  
82 retains the full radiation, convection, and other physics schemes included in CESM2.2.0, but  
83 requires the large-scale circulation to be either specified or parameterized. We parameterize the  
84 circulation via the following methods: the weak temperature gradient (WTG) method (Raymond  
85 and Zeng 2005), damped gravity wave (DGW) method (Kuang 2008), and the spectral weak  
86 temperature gradient (Spectral WTG) method (Herman and Raymond 2014, Wang et al. 2016).

87 These parameterizations of large-scale dynamics have been implemented into various SCMs and  
88 cloud resolving models (CRMs). To date, the most comprehensive analysis of how the WTG and  
89 DGW methods perform across SCMs and CRMs is the Global Atmospheric Systems Study  
90 (GASS) WTG Intercomparison, which assessed the steady-state response of twelve models in  
91 precipitation, moisture, temperature, and circulation strength to changes in relative SST, i.e.,  
92 varying SST while holding the target tropospheric temperature profile fixed (Daleu et al. 2015,  
93 2016) using both WTG and DGW (but not Spectral WTG). One goal of this study is to fold  
94 NCAR's Single Column Atmospheric Model SCAM6 into the results of the GASS  
95 Intercomparison study by implementing the same parameterizations of large-scale dynamics into  
96 SCAM6 and replicating the conditions applied by Daleu et al. (2016). It will also assess how the  
97 Spectral WTG method compares to the WTG and DGW methods in SCAM6, and analyze how  
98 the circulation responds to changes to the radiative and convective scheme. Since SCAM6 is  
99 primarily a tool for model development (Gettelman et al. 2019), this study's idealized  
100 simulations may also serve to inform future development of CESM.

101 Under the conditions applied in the GASS Intercomparison study, the WTG and DGW methods  
102 produce erratic results, suggestive of numerical instability (see Results). Thus, we alter key  
103 parameters in the methods to improve performance and subsequently present four different  
104 configurations of the convection and radiation schemes in SCAM6: 1) specified radiation with

105 inhibited convection (RsCi), 2) specified radiation with uninhibited convection (RsCu), 3)  
 106 interactive radiation with inhibited convection (RiCi), 4) interactive radiation with uninhibited  
 107 convection (RiCu). Specifically in this study, idealized radiation refers to the radiative cooling  
 108 profile used in Daleu et al. (2016) and modeled radiation refers to the default radiation package  
 109 in SCAM6. Likewise, “inhibited” and “uninhibited” convection refer to different values of a  
 110 parameter in SCAM6’s deep convection scheme that controls the number of model levels over  
 111 which a rising parcel can experience negative buoyancy before deep convection is suppressed, a  
 112 parameter shown to have important effects in RCE simulations by Hu et al. (2022). We include  
 113 specified radiation cases for better comparison between SCAM6 and the SCMs in Daleu et al.  
 114 (2016), and we include interactive radiation cases for better assessment of the overall  
 115 performance of SCAM6 under parameterized large-scale dynamics and of the interaction  
 116 between its radiation and convection schemes.

117 This paper is organized as follows. The Methods section both describes the details of each  
 118 parameterization implemented into SCAM6 (WTG, DGW, and Spectral WTG) as well as  
 119 outlines the model set up and each of the four different configurations of the convection and  
 120 radiation schemes (RsCi, RsCu, RiCi, and RiCu). The Results section discusses the performance  
 121 of each parameterization under the conditions given in Daleu et al. (2016) and, once key  
 122 circulation parameters are relaxed, under each of four different radiative and convective  
 123 configurations. The Discussion section presents key takeaways regarding the relative  
 124 performance of each parameterization of large-scale dynamics under the configurations  
 125 considered and regarding important mechanistic feedbacks between the circulation, convection  
 126 and radiation schemes. Finally, the Conclusion section summarizes the study and assesses its  
 127 relevance to NCAR’s GCM CESM2.2.0 and to tropical precipitation more broadly.

## 128 **2 Methods**

### 129 **2.1 Parameterizations of Large-Scale Dynamics**

130 This study considers three parameterizations of large-scale dynamics: the weak temperature  
 131 gradient (WTG) method (Sobel and Bretherton 2000, Raymond and Zeng 2005), the damped  
 132 gravity wave (DGW) method (Kuang 2008, Kuang 2011), and the spectral weak temperature  
 133 gradient (Spectral WTG) method (Herman and Raymond 2014, Wang et al. 2016).

134 In the weak temperature gradient (WTG) method, we neglect the horizontal advection and time  
 135 dependent terms from the column’s temperature equation, and represent adiabatic warming or  
 136 cooling due to vertical motion by a Newtonian relaxation of the virtual potential temperature in  
 137 the column,  $\overline{\theta}_v$ , back to the target profile,  $\overline{\theta}_v^{ref}$ , on a time scale,  $\tau$ . The vertical velocity,  $\overline{\omega}$ , is  
 138 then diagnosed according to Raymond and Zeng 2005:

$$139 \quad \overline{\omega} \frac{\partial \overline{\theta}_v}{\partial p} = \frac{(\overline{\theta}_v - \overline{\theta}_v^{ref})}{\tau}$$

140 The WTG approximation breaks down in the boundary layer due to the effects of surface  
 141 turbulent fluxes of heat and momentum. The pressure vertical velocity ought to vanish at the  
 142 surface in steady state, so we linearly interpolate  $\overline{\omega}$  from its WTG value at 850 Pa to zero at the  
 143 surface, as is done in Daleu et al. (2016). In addition, to avoid numerical issues, we place a lower

144 limit of  $2e^{-4}$  K Pa<sup>-1</sup> on the absolute value of the static stability,  $\frac{\partial \bar{\theta}_v}{\partial p}$  (Raymond and Zeng 2005),  
 145 used in the calculation of  $\bar{\omega}$ .

146 The DGW method attempts to more explicitly capture the gravity wave dynamics that act to  
 147 relax the column back to the tropical mean. Using the 2D anelastic nonrotational momentum,  
 148 continuity, and hydrostatic equations, the DGW method applies a wave equation for  $\bar{\omega}$ . At each  
 149 time step, a single linear gravity wave of specified horizontal wave number,  $k$ , minimizes  
 150 deviations in virtual temperature,  $\bar{T}_v$ , from the target profile,  $\bar{T}_v^{ref}$  (Kuang 2008, Kuang 2011):

$$151 \quad \frac{\partial}{\partial p} \left( \epsilon \frac{\partial \bar{\omega}}{\partial p} \right) = \frac{k^2 R_D}{p^{ref}} \left( \bar{T}_v - \bar{T}_v^{ref} \right)$$

152 Here,  $R_D$  is the gas constant of dry air and  $\epsilon$  is the specified mechanical damping coefficient. We  
 153 exclude the time derivative on the left-hand side since we are primarily concerned with the  
 154 column's steady state response. We apply homogeneous boundary conditions for  $\bar{\omega}$  at the surface  
 155 and at a nominal upper boundary (100 hPa), and solve the wave equation at each time step using  
 156 a standard triangular matrix solver. As in Daleu et al. (2016), we set the horizontal wavenumber,  
 157  $k$ , to  $10^{-6}$  m<sup>-1</sup>, corresponding to a wavelength of about 6000 km.

158 The spectral WTG method also uses gravity wave dynamics to more accurately capture the large-  
 159 scale relaxation to the target temperature profile. Recognizing that gravity waves of different  
 160 wavelengths will travel at different speeds, the spectral WTG method damps each spectral  
 161 mode's temperature forcing proportionally to that mode's theoretical gravity wave speed  
 162 (Herman and Raymond 2014). Following Wang et al. (2016), who used a slightly different  
 163 approximation than Herman and Raymond (2014), we derive these spectral modes and their  
 164 corresponding theoretical wave speeds by constructing an equation for the vertical velocity,  
 165 again assuming a 2D non-rotating anelastic atmosphere. Homogeneous boundary conditions  
 166 enforce that the vertical velocity vanish at the surface and at the tropopause, and Boussinesq-like  
 167 assumptions eliminate any single derivatives in  $\bar{\omega}$ :

$$168 \quad (\rho \bar{\omega})_{zz} + \frac{N^2}{c^2} (\rho \bar{\omega}) = 0$$

169 Note that the vertical velocity,  $\bar{\omega}$ , is now in height, not pressure coordinates. For constant Brunt-  
 170 Vaisala frequency,  $N$ , each mode will be sinusoidal and its corresponding wave speed can be  
 171 diagnosed from its eigenvalue. We project the usual WTG forcing onto these modes, but the  
 172 damping time constant,  $\tau_n$ , of each  $n^{\text{th}}$  mode varies according to its wave speed,  $c_n$ . Since  $c_n$  is  
 173 inversely proportional to  $n$ , the gravest spectral mode is damped most quickly, while modes  
 174 associated with larger  $n$  are damped more slowly, yielding:

$$175 \quad \rho \bar{\omega} = \sum_{n=1}^{\infty} \frac{A_n}{n} \sin \left( \frac{n\pi z}{H} \right)$$

176

$$A_n = \frac{2}{H} \int_0^H \frac{(\overline{\theta}_v - \overline{\theta}_v^{ref})}{\left(\frac{\partial \overline{\theta}_v}{\partial z}\right) \tau_1} \sin\left(\frac{n\pi z}{H}\right) dz$$

177 Here,  $H$  is the specified height of the tropopause,  $A_n$  is the normalized projection of the WTG  
 178 forcing onto the spectral modes, and  $\tau_1$  is the damping time constant of the first, or gravest,  
 179 mode. Since modes of larger  $n$  will generally have smaller magnitude due to the linear scaling of  
 180  $\tau_n$  with  $n$ , we numerically implement the Spectral WTG method by considering only the first  
 181 twenty terms of the infinite series, with negligible truncation error (not shown). As with the  
 182 WTG method, we place a lower limit of  $2e^{-4}$  K Pa<sup>-1</sup> on the absolute value of the static stability,  
 183  $\frac{\partial \overline{\theta}_v}{\partial p}$ .

184

## 2.2 Model Configuration

185 The WTG, DGW, and Spectral WTG methods all require some choice of a reference tropical  
 186 temperature profile. Since circulation implies the horizontal advection of moisture (discussed in  
 187 more detail below), we must also determine a reference mean tropical moisture profile. To  
 188 replicate the setup used in Daleu et al. (2016), we calculate the reference temperature and  
 189 moisture profiles by running SCAM6 in RCE (i.e. imposing zero vertical velocity) for uniform  
 190 300K sea surface temperature (SST), a value intended to be representative of the tropical  
 191 average. Starting from a moist adiabatic temperature profile with uniform 70% relative humidity,  
 192 we run SCAM6 in RCE for 300 days and average over the final 100 days. In any runs that  
 193 explore different convection and radiation schemes, we also use these settings to generate  
 194 distinct RCE reference temperature and moisture profiles to ensure consistency between the  
 195 modeled column and the reference mean tropical state. In all cases, horizontal wind speed is set  
 196 to a vertically uniform value of 5 m s<sup>-1</sup>, a prescription which does not affect the dynamics of  
 197 convection, but plays an important role in computing surface fluxes (Daleu et al. 2015, 2016).  
 198 All RCE reference profiles assume 300K SST.

199 As in Daleu et al. (2016), this study assumes no horizontal advection of temperature, so that the  
 200 temperature ( $\overline{\theta}_v$ ) tendency can be written as:

$$201 \quad \left(\frac{\partial \overline{\theta}_v}{\partial t}\right)_{LS} = -\overline{\omega} \frac{\partial \overline{\theta}_v}{\partial p}$$

202 Moisture ( $\overline{q}_v$ ) is treated differently and instead is subject to a one-way ‘‘lateral entrainment’’  
 203 described by Raymond and Zeng (2005). In addition to vertical advection by  $\overline{\omega}$ , moisture is  
 204 horizontally advected into the column by local flow convergence, yet is not altered at levels of  
 205 local flow divergence:

$$206 \quad \left(\frac{\partial \overline{q}_v}{\partial t}\right)_{LS} = -\overline{\omega} \frac{\partial \overline{q}_v}{\partial p} + \max\left(\frac{\partial \overline{\omega}}{\partial p}, 0\right) (\overline{q}_v^{ref} - \overline{q}_v)$$

207 While some studies represent the horizontal advection of moisture differently (Sobel et al. 2007,  
 208 Sobel and Bellon 2009, Wang and Sobel 2012), Daleu et al. (2016) and many other studies

209 (Raymond and Sessions 2007, Sessions et al. 2010, Wang et al. 2013, Herman and Raymond  
210 2014) use this “lateral entrainment” of moisture.

211 Daleu et al. (2016) specifies an idealized radiative cooling profile to isolate interactions between  
212 convection and large-scale dynamics in each model. They prescribe a uniform  $1.5 \text{ K day}^{-1}$   
213 cooling rate below 200 hPa, relax the temperature above 100 hPa to 200 K, and linearly  
214 interpolate between these cooling rates between 100 hPa and 200 hPa:

$$215 \quad \left(\frac{\partial T}{\partial t}\right)_{RC} = \begin{cases} -1.5 & \text{if } \bar{p} \geq 200 \\ -1.5 \left(\frac{\bar{p} - 100}{100}\right) - \alpha_T \left(\frac{200 - \bar{p}}{100}\right) (\bar{T} - 200) & \text{if } 100 < \bar{p} < 200 \\ -\alpha_T (\bar{T} - 200) & \text{if } \bar{p} \leq 100 \end{cases}$$

216 They set the constant  $\alpha_T$  to  $1 \text{ day}^{-1}$ . For this study, we run cases using either the specified  
217 radiation above or the interactive radiation package in SCAM6, a streamlined version of the  
218 rapid radiative transfer method (RRTMG) that derives from a correlated k-distribution (Lacis et  
219 al. 1979). We refer to cases run using specified radiation with the label “Rs” and refer to cases  
220 run using RRTMG, or fully interactive radiation, with the label “Ri”.

221 SCAM6 uses a unified turbulence scheme, Cloud Layers Unified by Binormals (CLUBB), for  
222 shallow convection (Golaz et al. 2002) and the Zhang-McFarlane (ZM) scheme (Zhang and  
223 McFarlane 1995) for deep convection. The ZM scheme allows an ensemble of convective-scale  
224 updrafts, and associated saturated downdrafts, to occur whenever the lower troposphere is  
225 conditionally unstable and the updrafts have sufficient buoyancy to penetrate the stable layer.  
226 These updrafts act to consume convective available potential energy (CAPE) in the convective  
227 layer at a specified time scale (two hours).

228 One of the critical parameters in SCAM6’s version of the ZM scheme is *zmconv\_num\_cin*,  
229 renamed  $\delta_{CIN}$  for this study, which specifies the number of negative buoyancy levels that are  
230 allowed before the convective layer is capped and CAPE calculations are completed. This  
231 parameter determines the scheme’s ability to overcome some amount of convective inhibition  
232 (CIN), which in turn often determines the level of convective cloud top. The default value of  
233  $\delta_{CIN}$  for SCAM6 is one, which sets the lowest neutral-buoyancy level of a pilot entraining plume  
234 to be the convective cloud top. This choice tends to cause the model to underestimate tropical  
235 variability and convective cloud top in global simulations (Xie et al. 2018, Wang and Zhang  
236 2018) and produces a shallow-convection prevailing regime in an idealized RCE framework (Hu  
237 et al. 2022). The default value of  $\delta_{CIN}$  for SCAM6 is therefore being changed to three in future  
238 versions of CESM (personal communication). Thus, for this study we run cases using either  
239  $\delta_{CIN} = 1$ , referred to as inhibited convection (Ci), or  $\delta_{CIN} = 3$ , referred to as uninhibited  
240 convection (Cu).

241 Finally, each of the parameterizations of large-scale dynamics contain parameters that specify  
242 the strength of the circulation response to a given temperature anomaly. In the WTG and Spectral  
243 WTG methods,  $\tau$  and  $\tau_1$  set the time scale at which the column’s temperature and the gravest  
244 spectral mode of the column’s temperature, respectively, are relaxed back to the tropical mean.  
245 In the DGW method,  $\epsilon$  plays a similar role, setting the mechanical damping coefficient with  
246 which the gravity waves are damped, notwithstanding that its units are the inverse of those of  $\tau$ .

247 The specified horizontal wave number,  $k$ , also plays a significant role in setting the strength of  
 248 the circulation response, though this is left constant in the present study. Daleu et al. (2016) sets  
 249  $\tau$  to 3 hours and  $\epsilon$  to 1 day<sup>-1</sup>. These are typical values used in previous studies (Herman and  
 250 Raymond 2014, Daleu et al. 2012, Wang and Sobel 2011, Wang et al. 2013) and are chosen to  
 251 produce comparable circulation responses to the same free tropospheric temperature anomaly in  
 252 both methods. In the present study, we take the circulation parameter values given in Daleu et al.  
 253 (2016) as a starting point, and increase or decrease them to weaken or strengthen the circulation  
 254 response. The WTG and DGW methods in SCAM6 are led to erratic behavior, suggestive of  
 255 numerical instability, for the default values of  $\tau$  and  $\epsilon$  used in Daleu et al. (2016), perhaps due to  
 256 the ZM convection scheme. For  $\tau = 3$  hours, the WTG method yields vertical velocity and  
 257 convective heating profiles that oscillate wildly, and, for  $\epsilon = 1$  day<sup>-1</sup>, the DGW method both  
 258 crashes at 298K SST and yields unrealistic S-shaped vertical velocity profiles at other values of  
 259 SST (see Results). Thus, we increase  $\tau$  and  $\epsilon$  three- or five-fold from the Daleu et al. (2016)  
 260 values for most cases presented. While the Spectral WTG method tends to be robust even at  
 261 lower values of  $\tau_1$ , we match  $\tau_1$  to  $\tau$  in all cases considered.

262 We run all cases using parameterized large-scale dynamics for 400 days under constant SST  
 263 values of 298 K, 299 K, 300 K, 301 K, and 302 K. This range of SST values is comparable to the  
 264 range used in Daleu et al. (2016). We find the steady-state precipitation, evaporation, vertical  
 265 velocity, relative humidity, temperature anomaly, and convective and radiative heating rates by  
 266 averaging the final 100 days of the run. All runs presented in this study use twenty-minute time  
 267 steps and 32 pressure levels. Several cases were also run using sixty pressure levels, though we  
 268 observed no significant change in results under this increased vertical resolution. Some runs,  
 269 especially for lower values of  $\delta_{CIN}$ ,  $\tau$ , and  $\epsilon$ , demonstrate multiple quasi steady-state equilibria.  
 270 In all cases where we observe such behavior, we extend the run an additional 400 days to ensure  
 271 no sizable variations occur in the steady-state quantities considered. We leave further exploration  
 272 of such transient phenomena to future study. It is also worth mentioning that, in cases of  
 273 interactive radiation (Ri), there is a seasonal cycle of insolation equivalent to that seen at the  
 274 equator. However, when averaged over 365 days rather than 400 days, there is no significant  
 275 change in any output parameters.

## 276 **3 Results**

### 277 **3.1 Radiative-Convective Equilibrium**

278 To begin, we consider the reference RCE state for each model configuration. We present  
 279 quantities of interest from these RCE states in Table 1, which displays time-averaged  
 280 precipitation and evaporation, and Figure 1, which displays time-averaged temperature, relative  
 281 humidity, and radiative and convective heating profiles.

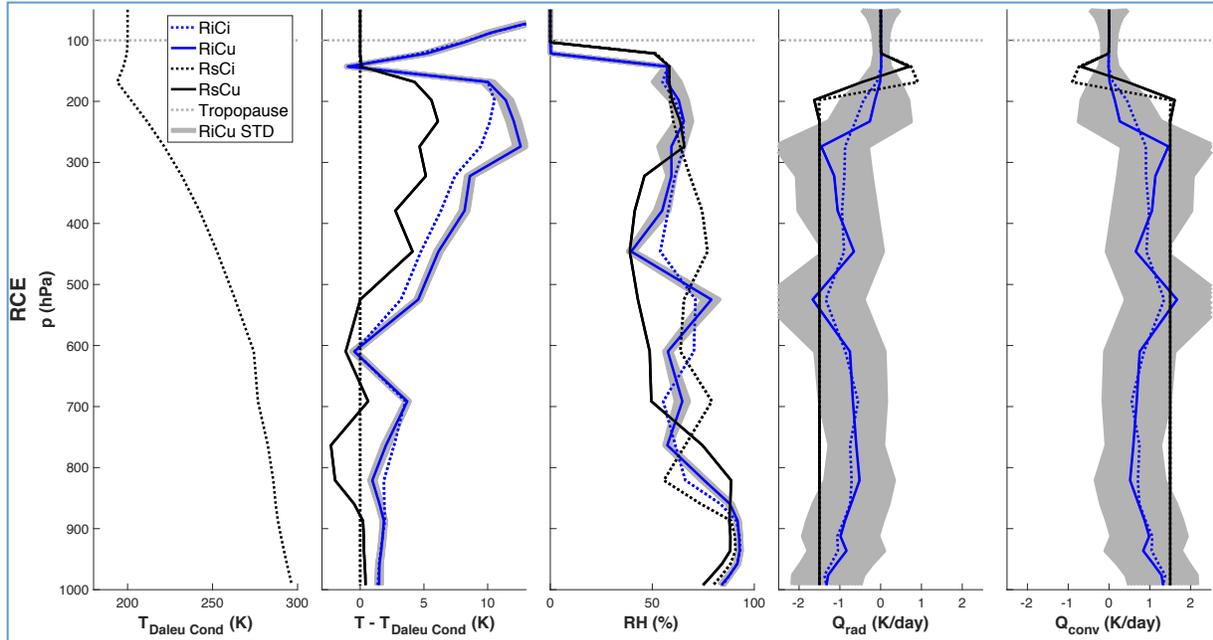
282 By design, the precipitation and evaporation in RCE are nearly identical (Table 1). The choice of  
 283 specified vs. interactive radiation scheme causes large differences in the time-averaged  
 284 precipitation and evaporation; this is unsurprising given that the idealized radiative cooling  
 285 profile in Daleu et al. (2016) implies a substantially larger vertically integrated cooling than the  
 286 interactive scheme computes under these conditions, and this integrated cooling must be  
 287 balanced by the sum of condensation heating and sensible surface heat flux in RCE. Differences  
 288 in convection affect precipitation not at all for the interactive radiation cases and only slightly for

289 the idealized radiation cases (less than 10%). Since we specify radiative cooling, and thus  
 290 convective heating, to be  $1.5 \text{ K day}^{-1}$  below 200 hPa in the idealized radiation configuration, the  
 291 changes appear to be primarily the result of relatively large upper tropospheric (above 200hPa)  
 292 temperature differences (Figure 1). Deep convection happens more easily when  $\delta_{CIN}$  is set to 3,  
 293 meaning the upper troposphere is substantially warmer in this case, yielding greater radiative  
 294 cooling, which is balanced with greater precipitation.

<b>Precipitation (Evaporation)</b>	Inhibited Convection (Ci)	Uninhibited Convection (Cu)
Interactive Radiation (Ri)	2.74 (2.72)	2.74 (2.74)
Specified Radiation (Rs)	4.29 (4.30)	4.57 (4.58)

295 **Table 1.** Precipitation and evaporation (mm/day) in RCE for each convective and radiative  
 296 setting considered. Ri indicates use of the default interactive radiation scheme in SCAM6, Rs  
 297 indicates use of specified radiative cooling, Ci indicates 1 level of CIN is tolerated in the  
 298 convection scheme, and Cu indicates 3 levels of CIN are tolerated in the convection scheme.

299 The far-left plot in Figure 1 shows the time-averaged RCE temperature profile in SCAM6 for the  
 300 radiative and convective conditions used in GASS (RsCi, black dotted line). The subsequent  
 301 plots in Figure 1 show (left to right) the deviation of each RCE temperature profile from RsCi,  
 302 the relative humidity profile, the radiative cooling profile, and the convective heating profile for  
 303 RsCi, RsCu, RiCi, and RiCu (black dotted line, black solid line, blue dotted line, and blue solid  
 304 line, respectively). All profiles are time-averaged. One standard deviation in time (gray shaded  
 305 area) is shown for RiCu; variances for other cases are similar in magnitude, save of course the  
 306 radiative cooling profile in Rs cases which is specified. On the whole, the idealized radiation  
 307 configuration yields a cooler troposphere than the interactive radiation case, likely because the  
 308 specified  $1.5 \text{ K day}^{-1}$  radiative cooling rate below 200 hPa is larger than what the interactive  
 309 radiation scheme predicts for nearly all pressure levels (Figure 1). Relative humidity (RH) is  
 310 computed with respect to liquid water and remains between 50% and 80% throughout the free  
 311 troposphere for all RCE cases except the specified radiation with uninhibited convection case  
 312 (RsCu), which shows substantially less moisture in the mid troposphere.



313

314 **Figure 1.** Column temperature, relative humidity, and convective and radiative heating in RCE  
 315 for each convective and radiative setting considered. Ri indicates use of the default interactive  
 316 radiation scheme in SCAM6, Rs indicates use of specified radiative cooling, Ci indicates 1 level  
 317 of CIN is tolerated in the convection scheme, and Cu indicates 3 levels of CIN are tolerated in  
 318 the convection scheme. The subscript “Daleu Cond” indicates use of all conditions given in  
 319 Daleu et al. 2015/2016, or RsCi. For reference, one standard deviation of model output over the  
 320 last 100 days is shown for the RiCu case. The tropopause (100 hPa) is shown in dashed grey.

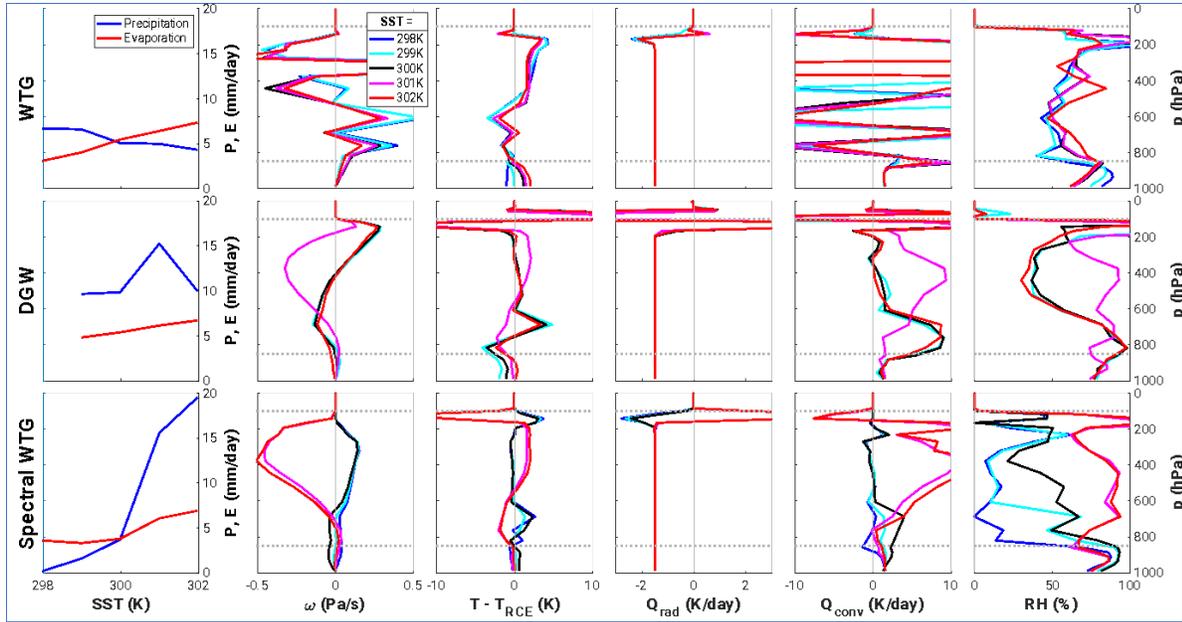
321

### 3.2 Parameterized Large-Scale Dynamics Under GASS Settings

322 We then simulate a column state in response to cooler and warmer SSTs than the reference 300K  
 323 RCE value (298K, 299K, 300K, 301K, and 302K), holding the above RCE temperature and  
 324 moisture profiles fixed as reference states for each of the parameterizations of large-scale  
 325 dynamics. We first consider the RsCi case as a way to directly compare SCAM6 with Daleu et  
 326 al. (2016). We also set the circulation parameters to the values given in Daleu et al. (2016), with  
 327  $\tau_1$  and  $\tau$  set to 3 hours and  $\epsilon$  set to  $1 \text{ day}^{-1}$ . Results are shown in Figure 2.

328 Under the WTG approximation, we expect a positive, monotonic relationship between SST and  
 329 precipitation (Sobel and Bretherton 2000). Lower-than-average SSTs should yield large-scale  
 330 descent that suppresses convection, dries out the free troposphere, and allows relatively little  
 331 precipitation. By contrast, higher SSTs should yield large-scale ascent that enhances convection,  
 332 moistens the free troposphere, and generates relatively heavy precipitation. In Figure 2, we check  
 333 this expectation by plotting precipitation (blue) and evaporation (red) as a function of SST.  
 334 While the Spectral WTG method performs as expected, the WTG and DGW methods not only do  
 335 not follow this expectation, but also demonstrate erratic behavior suggestive of numerical  
 336 instability. This is shown in the simulated profiles of vertical velocity, temperature deviation  
 337 from RCE, radiative cooling, convective heating, and relative humidity for each method at each  
 338 SST (Figure 2, colors scale from cool to warm). In the WTG method, both the vertical velocity  
 339 and convective heating oscillate wildly, with the substantial variations in SST showing little  
 340 effect on the solution. While the runs using the DGW method behave a bit less erratically, there

341 are clear numerical issues in the upper troposphere and again few if any interpretable results (this  
 342 result is robust across all rigid lid DGW simulations, even when the height of the rigid lid is  
 343 varied from 200 to 10 hPa). Additionally, the DGW method crashes at 298 K SST for this  
 344 configuration, so no data is shown for this run.



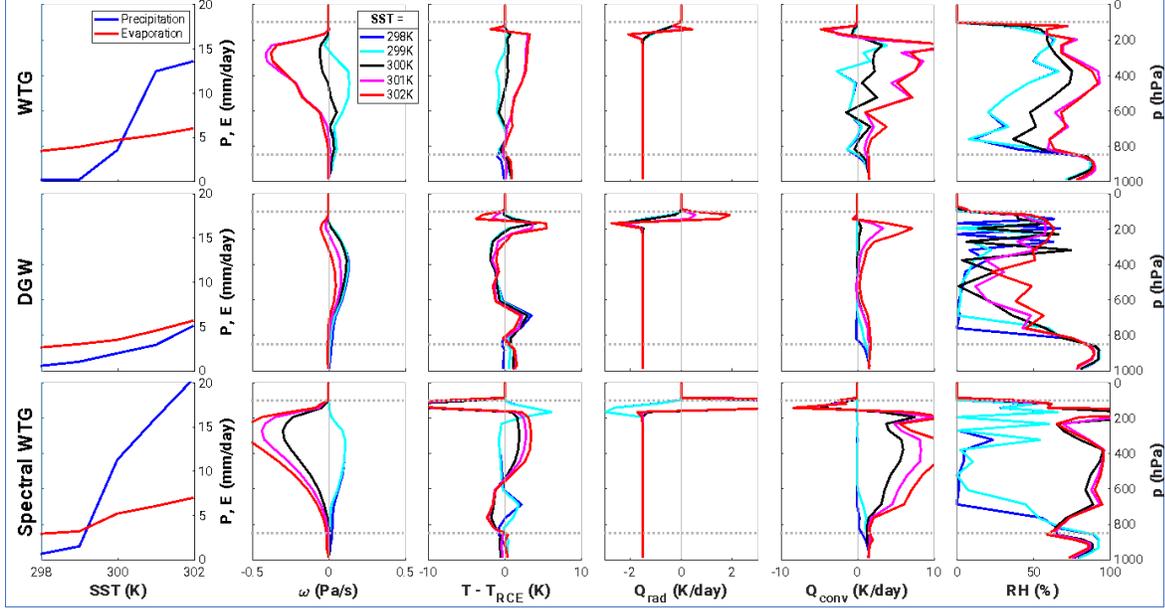
345

346 **Figure 2.** RsCi: Steady-state precipitation, evaporation, vertical velocity, temperature anomaly,  
 347 relative humidity, and convective and radiative heating in WTG, DGW, and Spectral WTG for  
 348  $\tau_1$  and  $\tau$  set to three hours and  $\epsilon$  set to one day<sup>-1</sup> using specified radiative cooling and tolerating  
 349 one level of CIN in the convection scheme. The tropopause and boundary layer height are shown  
 350 in dashed gray. Note that different scales are used for convective and radiative heating rates.

351

### 3.3 Parameterized Large-Scale Dynamics Under Relaxed Settings

352 If we increase the parameters used in Daleu et al. (2016) to weaken the strength of the circulation  
 353 response, the WTG and DGW methods perform more reasonably. This is shown in Figure 3,  
 354 which presents runs using three times the circulation parameters given in Daleu et al. (2016),  
 355 with  $\tau_1$  and  $\tau$  set to nine hours and  $\epsilon$  set to three days<sup>-1</sup>. Radiative and convective settings are left  
 356 unmodified (RsCi). Increasing  $\tau$ ,  $\tau_1$ , and  $\epsilon$  weakens the circulation response to a given  
 357 temperature perturbation from the tropical mean, which has the effect of smoothing the vertical  
 358 velocity profiles. The WTG method (top) behaves more consistently with expectations; low  
 359 SSTs yield gentle large-scale descent and light precipitation while high SSTs yield strong large-  
 360 scale ascent and heavy precipitation. Qualitatively, the WTG method performs similarly to the  
 361 Spectral WTG method for this configuration. However, the Spectral WTG method is able to  
 362 sustain larger magnitude large-scale ascent for higher SSTs, making its steady-state precipitation  
 363 for these runs substantially larger. The DGW method yields exceptionally dry conditions in this  
 364 configuration, where the expected deep convection and heavy precipitation for higher SST is not  
 365 observed. It is also worth noting that some grid-scale oscillation is observed for low SST runs in  
 366 the upper tropospheric relative humidity profiles of the DGW and Spectral WTG methods.



367

368 **Figure 3.** RsCi: Same as in Figure 2, but with  $\tau_1$  and  $\tau$  set to nine hours and  $\epsilon$  set to three days<sup>-1</sup>.

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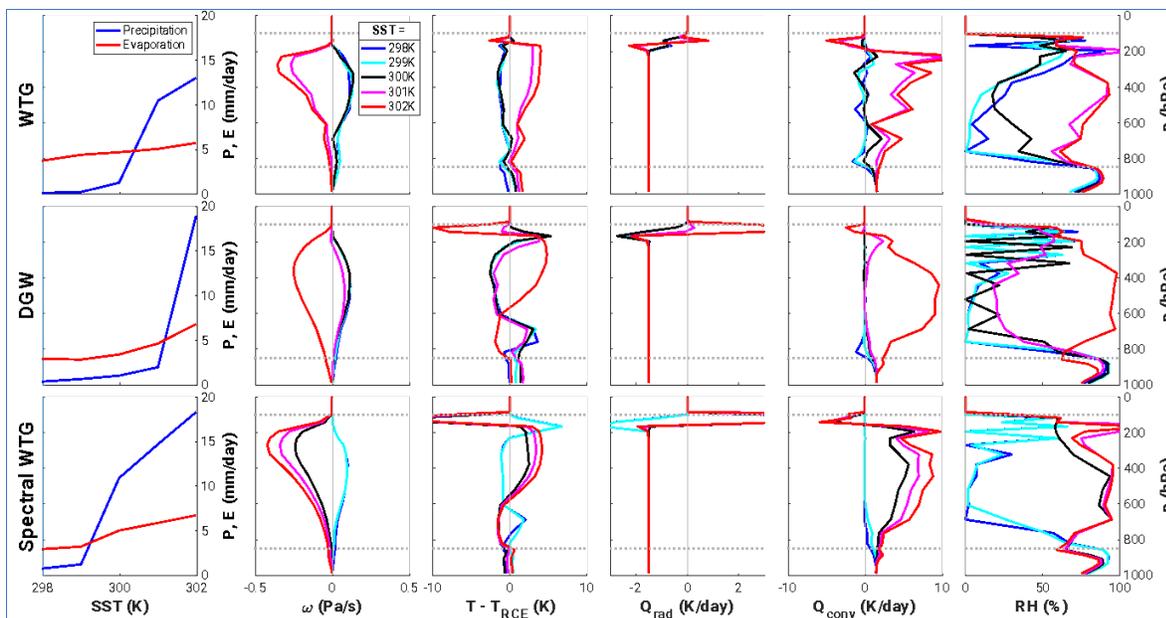
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If we increase the circulation parameters given in Daleu et al. (2016) even further to five times their original values (with  $\tau_1$  and  $\tau$  set to fifteen hours and  $\epsilon$  set to five days<sup>-1</sup>), again leaving radiative and convective settings unmodified, the DGW method begins to yield heavy precipitation for higher SST (Figure 4). Thus, for this configuration, all methods behave qualitatively similarly, following the broad theoretical expectation that low SST will yield large-scale descent and low precipitation while high SST will yield large-scale ascent and heavy precipitation. However, the SST at which heavy precipitation begins to occur varies substantially from method to method, with this transition occurring at 300 K SST for the Spectral WTG method, 301 K SST for the WTG method, and 302 K SST for the DGW method. In addition, vertical velocity profiles tend to be more top-heavy for the WTG method and Spectral WTG method than for the DGW method, a difference also observed in Daleu et al. (2016) and Romps (2012). By design, vertical velocity profiles are smoother for the Spectral WTG and DGW methods than for the WTG method, since the second order wave equation in the DGW method and the mode-dependent damping in the Spectral WTG method allow temperature perturbations in the column to produce non-local responses in  $\bar{\omega}$  (Herman and Raymond 2014, Wang et al. 2016, Kuang 2008). However, while these smoothing effects are observed in the convective heating profiles and the temperature deviation from RCE, they do not appear to smooth the column's relative humidity profile. This oscillatory structure of upper-tropospheric moisture is also observed in Hu et al. (2022), though this study focused on SCAM under RCE, not under parameterized large-scale dynamics. Nonetheless, the hypothesis posed in Hu et al. (2022) – that these oscillations in upper tropospheric moisture are caused by variations in convective height – is likely still relevant under parameterized large-scale dynamics at low SST.

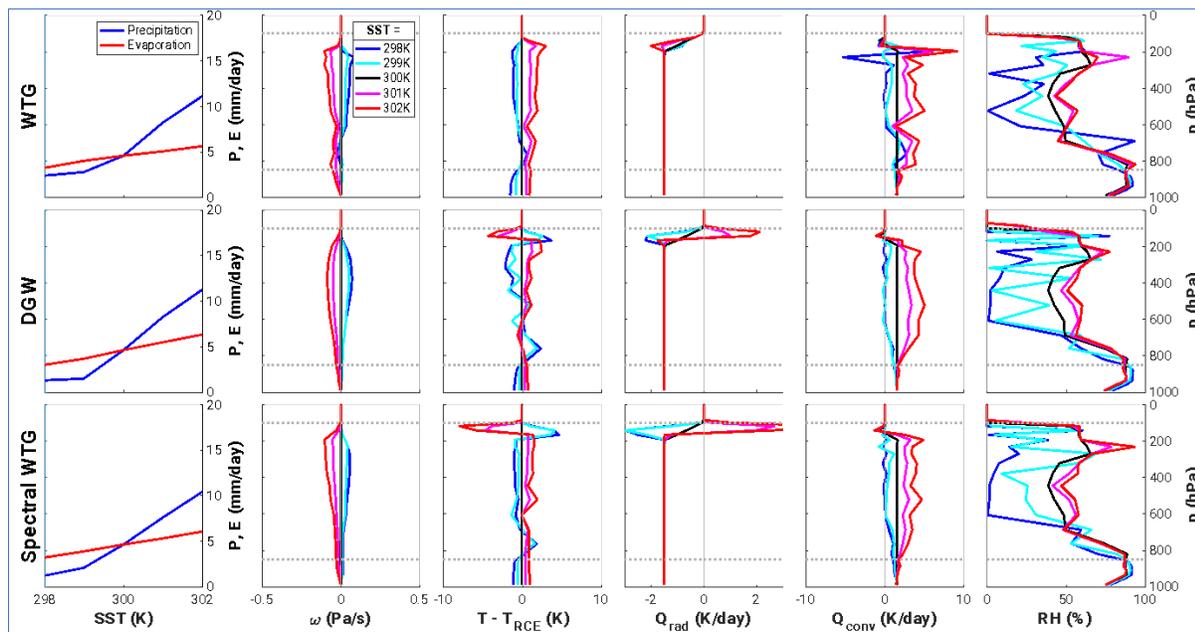


391  
 392 **Figure 4.** RsCi: Same as in Figures 2 and 3, but with  $\tau_1$  and  $\tau$  set to fifteen hours and  $\epsilon$  set to  
 393 five days<sup>-1</sup>.

394 The temperature deviation from the RCE reference profile tends to follow a similar structure  
 395 across all methods. Temperature deviations across the mid troposphere are of opposite sign as  
 396 the vertical velocity (in pressure coordinates, almost by design), with positive temperature  
 397 anomalies being associated with large-scale ascent and negative temperature anomalies being  
 398 associated with large-scale descent (Figure 4). However, in the upper and lower troposphere, we  
 399 observe the opposite relationship: large-scale ascent is associated with negative temperature  
 400 anomalies and large-scale descent is associated with positive temperature anomalies. In the upper  
 401 troposphere, this reversal in the sign of the temperature deviation is likely caused by the  
 402 inversion of the overall temperature profile. As shown in the RCE profiles (Figure 1), the  
 403 temperature and potential temperature reach a local minimum at around 200 hPa, meaning that  
 404 above this threshold large-scale ascent advects relatively low potential temperature air upward  
 405 and large-scale descent advects relatively high potential temperature air downward. It is worth  
 406 noting that the vertical velocity decays to zero at a lower altitude in the WTG method than in the  
 407 DGW or the Spectral WTG method (Figure 4), meaning the upper-tropospheric temperature  
 408 anomalies are also of smaller magnitude.

409 Next, we consider configurations with different radiative and convective settings, all using  
 410 circulation parameters with five times the value given in Daleu et al. (2016). While all radiative  
 411 and convective configurations were tested across a range of circulation parameters, all methods  
 412 either performed nearly identically or substantially more in line with expectation for these larger  
 413 values of circulation parameters (indicating weaker responses of the circulation to tropospheric  
 414 temperature deviations from the target profile). To begin, we consider RsCu, where the number  
 415 of tolerated negative buoyancy regions in the convective scheme ( $\delta_{CIN}$ ) is increased from one to  
 416 three, but the radiation is still specified (Figure 5). In this case, all methods perform remarkably  
 417 similarly to one another, transitioning from light to heavy precipitation at the same SST. Relative  
 418 humidity and vertical velocity profiles also look remarkably similar across methods. However, in  
 419 cases where deep convection does occur, convective ascent is generally weaker and the mid

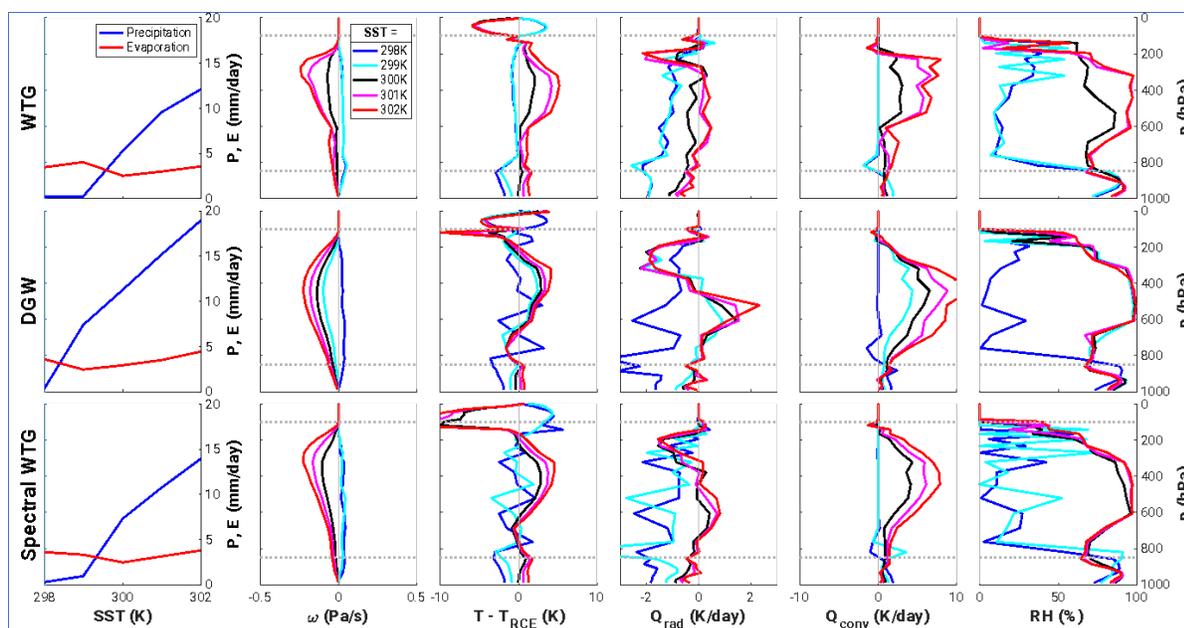
420 troposphere thus contains notably less moisture than it does for RsCi. These differences in the  
 421 magnitude of the vertical velocity likely stem more from differences in the RCE reference  
 422 profiles than from differences in the behavior of the convective scheme within the simulated  
 423 column. Under less-inhibited convection settings (Cu), the RCE profile is more statically stable  
 424 (Figure 1), meaning the free tropospheric temperature anomalies are smaller and the circulation  
 425 is weaker (see Discussion for details).



426  
 427 **Figure 5.** RsCu: Same as in Figure 4, but tolerating three levels of CIN in the convection  
 428 scheme.

429 Next, we consider configurations using SCAM6's default interactive radiation scheme  
 430 (RRTMG) rather than the idealized radiative cooling profile from Daleu et al. (2016). We present  
 431 results for RiCi (Figure 6) and RiCu (Figure 7). Runs with lower SST tend to yield greater  
 432 radiative cooling in the majority of the troposphere, primarily due to lower cloud fraction and  
 433 thus reduced shortwave heating (not shown). As with the idealized radiation cases, using  $\delta_{CIN} =$   
 434 3 tends to yield weaker convective ascent than using  $\delta_{CIN} = 1$ . However, this difference is  
 435 smaller when using interactive radiation than when using specified radiation.

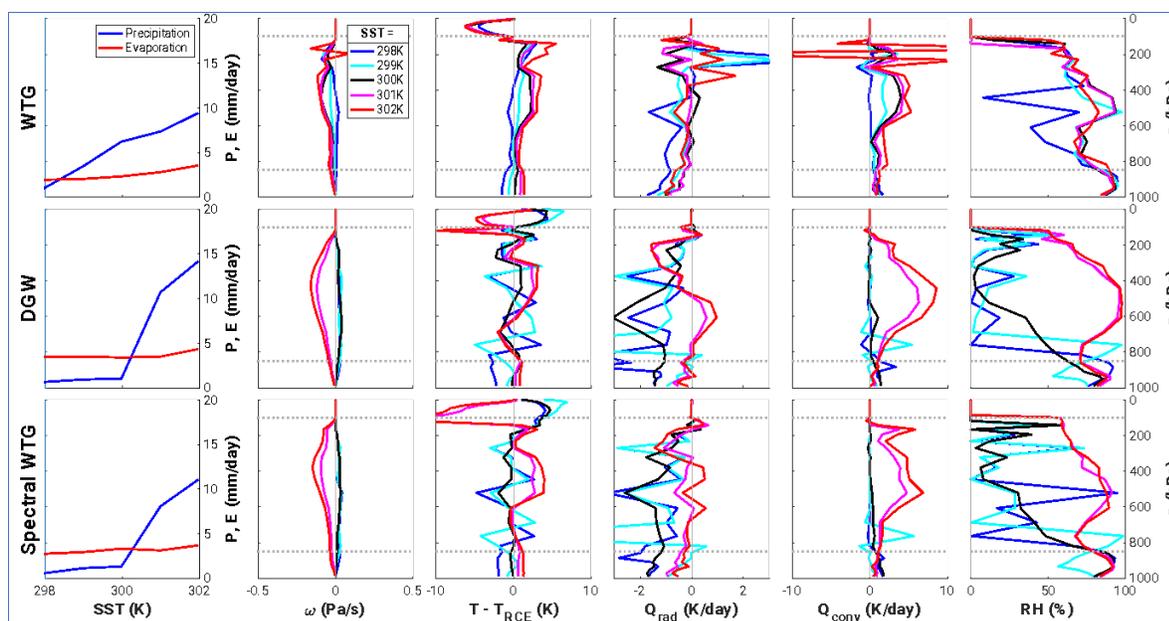
436 Sharp oscillations in convective heating suggest numerical issues in the 302 K SST run for the  
 437 WTG method in Figure 7 (RiCu). In fact, while nearly all cases using circulation parameters with  
 438 five times the value given in Daleu et al. (2016) performed reasonably, the WTG method  
 439 performed somewhat strangely under interactive radiation and uninhibited convection. The  
 440 expected monotonic relationship between SST and precipitation is apparent, but the method  
 441 tends to favor deep convection; even at the lowest SST, large-scale descent is weaker than in the  
 442 other methods, and correspondingly the troposphere does not as fully dry out.



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**Figure 6.** RiCi: Same as in Figure 4, but using interactive radiative cooling.



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**Figure 7.** RiCu: Same as in Figure 5, but using interactive radiative cooling.

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Finally, across configurations, there is significant variation in the “pickup” SST at which heavy precipitation begins to occur. Perhaps most notable in this regard is the DGW method: for RsCi (Figure 4) heavy precipitation begins to occur at an SST of 302 K, while for RiCi (Figure 6) this transition occurs at an SST of 299 K.

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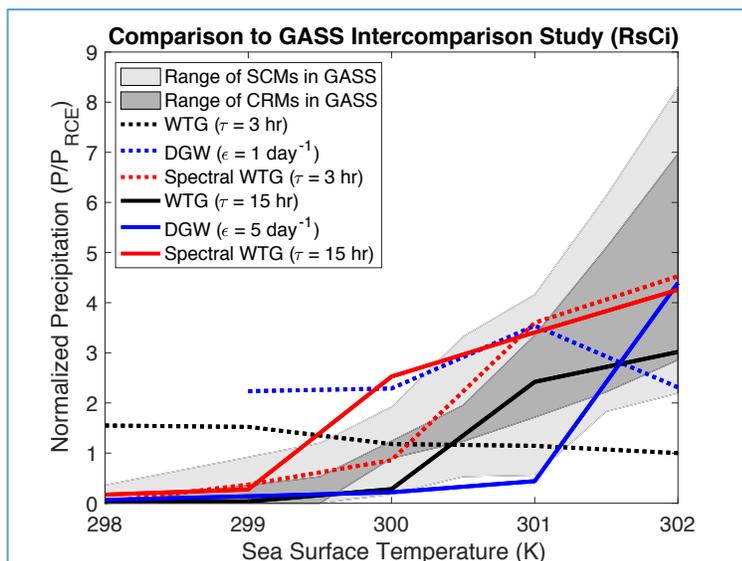
### 3.4 Comparison to GASS

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One of the main goals of this study is to compare the performance of SCAM6 under parameterized large-scale dynamics to those of the models in the GASS Intercomparison Study

454 (Daleu et al. 2016). Figure 8 compares precipitation vs SST curves for the WTG, DGW, and  
 455 Spectral WTG methods in SCAM6 (under idealized radiation and inhibited convection) to the  
 456 range of values seen in SCMs and CRMs in Figure 3 of Daleu et al. (2016). For circulation  
 457 parameters equal to those used in the GASS Intercomparison Study (dashed), the WTG and  
 458 DGW methods are numerically unstable in SCAM6 and thus show no clear relationship between  
 459 SST and precipitation. However, if key circulation parameters  $\tau$  and  $\epsilon$  are increased fivefold  
 460 fifteen hours and five day<sup>-1</sup> respectively (solid), the circulation response to a given free  
 461 tropospheric temperature anomaly decreases and solutions become reasonably numerically  
 462 resolved. These “relaxed” simulations produce the expected steep transition from light  
 463 precipitation at low SST to heavy precipitation at high SST, and the simulations are quite  
 464 comparable to the SCMs in Daleu et al. (2016).



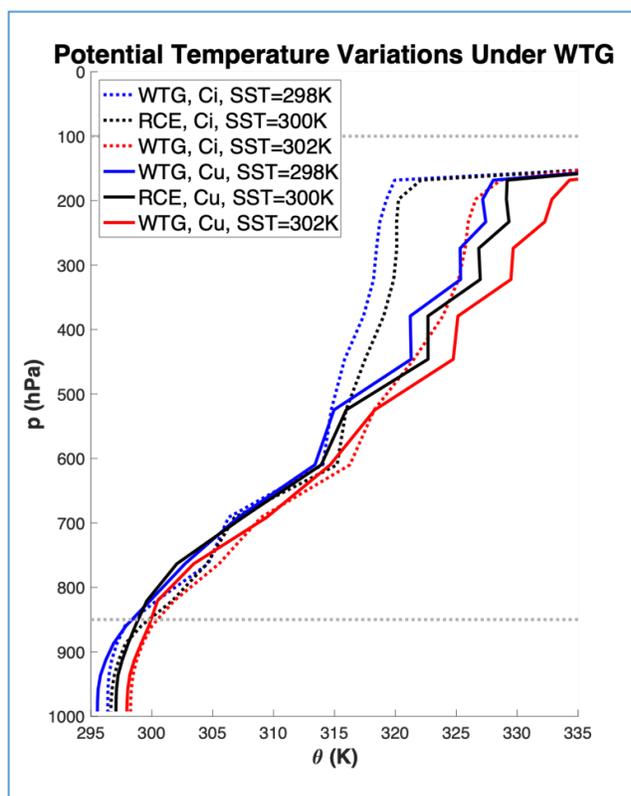
465  
 466 **Figure 8.** Normalized precipitation vs SST curves for the WTG, DGW, and Spectral WTG  
 467 methods in SCAM6 under specified radiation and inhibited convection. Curves are shown for  $\tau_1$   
 468 and  $\tau$  set to three hours and  $\epsilon$  set to one day<sup>-1</sup> (dashed) and for  $\tau_1$  and  $\tau$  set to fifteen hours and  $\epsilon$   
 469 set to five days<sup>-1</sup> (solid). They are compared to the range of values seen in SCMs (light shading)  
 470 and CRMs (dark shading) in Daleu et al. (2016).

### 471 3.5 Role of Static Stability Under Radiative-Convective Equilibrium

472 While each parameterization of large-scale dynamics performs slightly differently in a given  
 473 configuration, the overall strength of the large-scale circulation (i.e., the magnitude of the  
 474 vertical velocity profiles) remains roughly constant across all methods for given radiative and  
 475 convective settings, allowing us to focus on the effect of modifying the radiation and convection  
 476 schemes. Most notably in this regard, decreasing  $\delta_{CIN}$  ( $C_u \rightarrow C_i$ ) tends to increase the strength  
 477 of the circulation response, more so in the case of idealized radiation than in the case of  
 478 interactive radiation.

479 At least under idealized radiation, the increase in circulation strength when  $\delta_{CIN}$  is decreased can  
 480 be explained by variations in the static stability of the RCE temperature profile from one  
 481 configuration to another (Figure 9). In RCE under inhibited convection settings ( $C_i$ ,  $\delta_{CIN} = 1$ ),  
 482 deep convection cannot grow as easily nor consume as much available instability (Hu et al.

483 2022). This results in a less statically stable tropospheric temperature profile than that under  
 484 uninhibited convection settings (Cu,  $\delta_{CIN} = 3$ ). However, at high SST (302 K) under  
 485 parameterized large-scale dynamics, convection can grow deeply regardless of the convective  
 486 settings. In this case, the balance in the temperature equation is between the convective heating  
 487 and the vertical advection, since radiative cooling is much smaller than convective heating  
 488 (Figures 4-5). If we assume that the convection scheme roughly acts to relax the column's  
 489 temperature profile to an entraining moist adiabat set by the locally warm SST while the  
 490 circulation acts to drive the column's temperature towards the RCE reference profile, then the  
 491 steady-state solution in the column is effectively a time-averaged balance between these two  
 492 forcings. Thus, if the RCE profile is less statically stable under inhibited convection settings (Ci),  
 493 there will be a larger temperature difference between this RCE profile and the entraining moist  
 494 adiabat towards which the convection scheme is relaxing (Figure 9). This larger temperature  
 495 difference yields more large-scale ascent, more convection, and more steady-state precipitation.  
 496 In other words, inhibited convection settings (Ci) create a less statically stable RCE profile that  
 497 causes the circulation to introduce more CAPE into the column for a given circulation strength,  
 498 yielding more convection and in turn a stronger compensating circulation. In addition, lower  
 499 static stability in the column means that a larger vertical velocity is needed to create the same  
 500 temperature tendency. Thus, even at low SST where convection is nearly absent, decreasing  $\delta_{CIN}$   
 501 (Cu  $\rightarrow$  Ci) increases the strength of the circulation, though it is of opposite sign. In these cases,  
 502 the energetic balance is primarily between the radiation and the circulation, so a lower column  
 503 static stability under Ci yields a stronger downward large-scale vertical velocity (Figures 4-5)  
 504 even though the temperature deviation from RCE is similar (Figure 9).

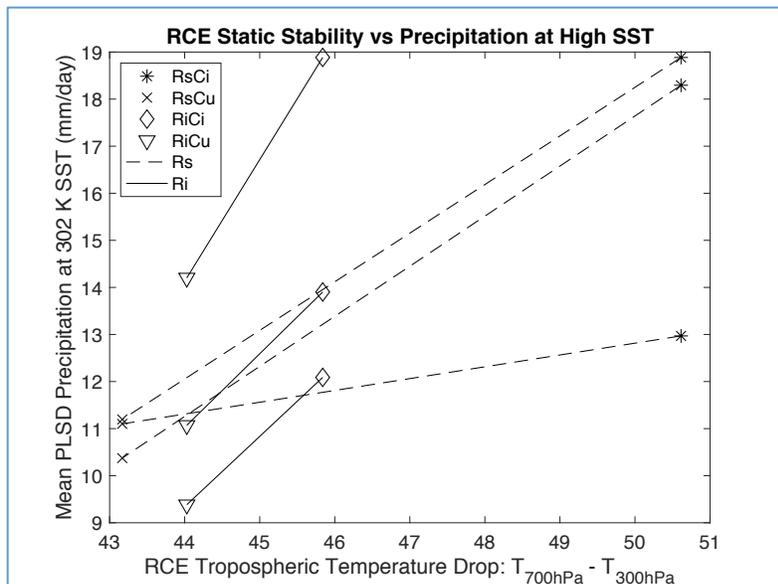


506 **Figure 9.** Time-averaged potential temperature profiles for RCE at 300 K SST (black), and  
 507 WTG at 298 K SST (blue) and 302 K SST (red) for  $\tau_1$  and  $\tau$  set to fifteen hours and  $\epsilon$  set to five  
 508 days<sup>-1</sup> using a specified radiative cooling profile and tolerating either one (dashed) or three  
 509 (solid) levels of CIN in the convection scheme.

510 We display this effect in Figure 9 for the WTG method; equivalent plots for the DGW and  
 511 Spectral WTG methods are qualitatively similar (not shown). Under WTG, the time-averaged  
 512 potential temperature profile at 302 K SST is much further from the RCE potential temperature  
 513 profile for inhibited convection ( $\delta_{CIN} = 1$ , red dotted profile) than for uninhibited convection  
 514 ( $\delta_{CIN} = 3$ , red solid profile). The RCE profile for CIN = 1 (black dotted) has substantially lower  
 515 static stability than that for  $\delta_{CIN} = 3$  (black solid), meaning there is a larger difference between  
 516 the temperature profile towards which the convection scheme roughly drives the model (an  
 517 entraining moist adiabat set by a 302 K fixed SST) and the RCE profile to which the circulation  
 518 relaxes. This increased competition between the circulation and the convection scheme yields  
 519 more steady-state precipitation and a stronger circulation response. At low SST, deep convection  
 520 largely stops, making the balance primarily between the radiation and the circulation. Under  
 521 specified radiation, radiative cooling is set to a constant 1.5 K day<sup>-1</sup> in the bulk of the  
 522 troposphere, so there are no changes in radiative effects that can cause different circulation  
 523 strength for different convection parameters. However, the reduced slope of time-averaged  
 524 potential temperature profile (static stability) means a larger vertical velocity is needed to create  
 525 the same temperature tendency. Thus, increasing the barrier to convection strengthens both large-  
 526 scale ascent and descent, but strengthens ascending motions more strongly.

527 How can we ensure the differences in circulation and precipitation described above are due to  
 528 differences in the RCE reference states and not to the effect of  $\delta_{CIN}$  on the convection directly?  
 529 At high SST (302K), the time-average top of convection is near the top of the tropopause for all  
 530 methods, regardless of the value of  $\delta_{CIN}$  (not shown). However, in RCE, the top of convection is  
 531 much lower for inhibited convection than for uninhibited convection. Since  $\delta_{CIN}$  affects the  
 532 convection scheme chiefly by setting the top of convection, this means that, at least in a time  
 533 average sense,  $\delta_{CIN}$  has a minimal effect on the column itself at high SST, and mostly affects the  
 534 column through its modification to the RCE reference profile. These results are in line with  
 535 findings from Hu et al. (2022).

536 We suggest that the above argument holds for interactive radiation cases as well. As in the  
 537 specified radiation cases, increasing  $\delta_{CIN}$  tends to increase the static stability of the reference  
 538 RCE profile and decrease the precipitation and strength of the circulation response at high SST,  
 539 but this effect is less extreme (Figure 10).



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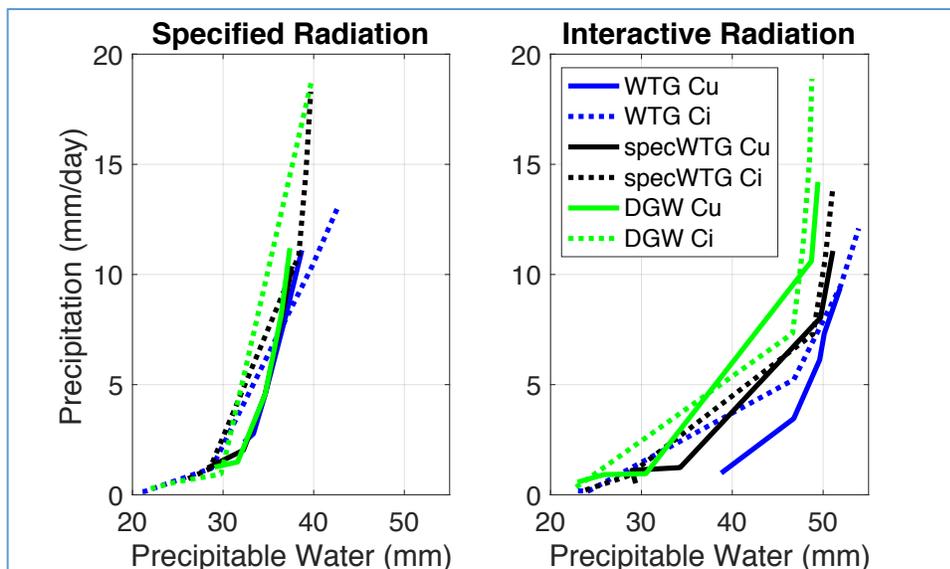
541 **Figure 10.** Mean precipitation at 302 K SST for all parameterized large-scale dynamics methods  
 542 vs tropospheric temperature change (from 300 hPa to 700 hPa) in RCE. Higher tropospheric  
 543 temperature change in RCE (at 300 K) indicates greater lapse rate and lower static stability in the  
 544 RCE reference profile, causing greater time-averaged precipitation under parameterized large-  
 545 scale dynamics at high SST (302 K). Lines, dashed and solid, indicate changes from Cu to Ci  
 546 across individual methods (WTG, DGW, Spectral WTG).

547 Figure 10 shows the relationship between a bulk measure of RCE static stability and the 302 K  
 548 SST precipitation under both idealized and modeled radiation. In both cases, precipitation at 302  
 549 K SST increases as the temperature drop from 700 to 300 hPa in the RCE reference state  
 550 increases, i.e., the static stability decreases. While the change in static stability in RCE under  
 551 interactive radiation is smaller than that under specified radiation, we observe the same  
 552 qualitative effect on precipitation at this high relative SST. Moreover, the top of convection is  
 553 again relatively independent of  $\delta_{CIN}$  at high SST (not shown) and convective heating likewise  
 554 dominates over radiative cooling, though the fact that radiation is interactive makes it more  
 555 difficult to exclude the possibility that differences in radiative effects in the column itself play a  
 556 role in setting the strength of the circulation response.

### 557 3.6 Relationship Between Humidity and Precipitation

558 Precipitation and column precipitable water vapor have been shown to be closely related in  
 559 observations (e.g., Bretherton et al. 2004; Neelin et al. 2022) and the relationship between the  
 560 two variables has been used as a diagnostic in prior modeling studies with parameterized large-  
 561 scale dynamics (e.g., Wang and Sobel 2011). In Figure 11 we present the relationship between  
 562 these variables under specified radiation (left panel) and interactive radiation (right panel).  
 563 Precipitable water is known to be highly correlated to precipitation, with precipitation typically  
 564 increasing steeply with precipitable water past a certain threshold. The WTG (blue), DGW  
 565 (green), and Spectral WTG (black) methods qualitatively follow such expectations under all  
 566 model configurations, though the methods can yield quantitatively different results depending on  
 567 the radiative and convective settings. Under idealized radiation, all methods collapse onto a  
 568 single curve for each convective setting. When convection is inhibited, precipitation spans a

569 larger range of values and begins increasing steeply at a lower threshold of precipitable water.  
 570 This is in line with our findings above, since we would expect a less statically stable RCE  
 571 reference profile to yield larger precipitation at a given precipitable water. Under modeled  
 572 radiation, the curves collapse substantially less overall, and separate more depending on the  
 573 parameterization of large-scale dynamics than on the choice of convective settings. The WTG  
 574 method yields the least precipitation at a given precipitable water, and the Spectral WTG method  
 575 yields the most. This is likely due to the introduction of radiative-convective feedback, though it  
 576 is unclear why each method interacts with the radiative scheme the specific way it does.



577  
 578 **Figure 11.** Precipitation vs precipitable water at all simulated SSTs for specified and interactive  
 579 radiation. Results for both inhibited (Ci) and uninhibited convection (Cu) settings are shown.

#### 580 4 Conclusions

581 This study has implemented various parameterizations of large-scale dynamics into NCAR's  
 582 single column atmospheric model SCAM6, with the purpose of both furthering development of  
 583 NCAR's Community Earth System Model and exploring the mechanisms that drive steady-state  
 584 tropical precipitation.

585 All the parameterizations of large-scale dynamics considered here act to relax the column  
 586 temperature towards a target profile, typically represented by a radiative-convective equilibrium  
 587 (RCE) solution. We implemented three parameterizations of large-scale dynamics into SCAM6:  
 588 the weak temperature gradient (WTG) method (Raymond and Zeng 2005), the damped gravity  
 589 wave (DGW) method (Kuang 2011), and the spectral weak temperature gradient (Spectral WTG)  
 590 method (Wang et al. 2016). These methods were run under the conditions used in the GASS  
 591 Intercomparison Study (Daleu et al. 2015, 2016) and, once circulation parameters  $\tau$  and  $\epsilon$  were  
 592 relaxed, under a variety of other convective and radiative settings: specified radiation with  
 593 inhibited convection (RsCi), specified radiation with uninhibited convection (RsCu), interactive  
 594 radiation with inhibited convection (RiCi), and interactive radiation with uninhibited convection  
 595 (RiCu). With the target tropospheric temperature profile held fixed based on the relevant RCE  
 596 solution (at 300 K SST), the underlying SST was varied, representing the effect of varying  
 597 relative SST (e.g., as a function of position).

598 The WTG and DGW methods lead to erratic behavior, with indications of numerical instability,  
599 in SCAM6 with the values of  $\tau$  and  $\epsilon$  used in the GASS Intercomparison Study (Daleu et al.  
600 2015, 2016). However, when these circulation parameters are increased fivefold, weakening the  
601 coupling between circulation and temperature, the WTG and DGW methods yield results  
602 qualitatively similar to those of Daleu et al. (2016), following the broad theoretical expectation  
603 that low SST will yield large-scale descent and low precipitation while high SST will yield large-  
604 scale ascent and heavy precipitation. As the radiation and convection schemes are modified, the  
605 WTG and DGW methods perform qualitatively similarly, but quantitatively differently,  
606 especially with regard to the SST at which the column transitions from low to high precipitation.  
607 The Spectral WTG method is more insensitive to changes in the circulation, radiation, and  
608 convection schemes, showing both greater numerical stability and a more consistent transition  
609 from light to heavy precipitation, always at the RCE SST or at an SST one K warmer.

610 For a given radiative and convective setting, all parameterizations of large-scale dynamics  
611 produce similar circulation strengths and precipitation levels to each other at very high and very  
612 low SST. However, across radiative and convective settings, circulation strength and  
613 precipitation level change substantially. Changing  $\delta_{CIN}$  from one (inhibited convection) to three  
614 (uninhibited convection) weakens the circulation and reduces precipitation at high SST. We  
615 demonstrate that this change is driven primarily by an increase in the static stability of the RCE  
616 reference profile.

617 Future study is needed to ascertain the relevance of these results to CESM model development  
618 and to steady state tropical precipitation more broadly. Next steps might include running CESM  
619 with inhibited ( $\delta_{CIN} = 1$ ) and uninhibited convection ( $\delta_{CIN} = 3$ ) to see if the GCM replicates the  
620 changes to circulation strength and precipitation at high SST that we observe in SCAM6.  
621 Furthermore, if these changes are replicated, what effect do they have on climatological features  
622 in the tropics such as the intertropical convergence zone (ITCZ) and the Walker circulation?  
623 Does the static stability of the tropical average change with radiative forcing and is this  
624 associated with a change in the relationship between SST and precipitation?

625 While it is difficult to extrapolate from the simulations presented in this study, we can reasonably  
626 speculate that decreasing the barrier to convection (using  $\delta_{CIN} = 3$  rather than  $\delta_{CIN} = 1$ ) in  
627 CESM's convection scheme will yield a more realistic representation of tropical convection.  
628 Tropical temperature profiles tend to be broadly moist adiabatic, but the SCAM6 simulations  
629 using inhibited convection show sizable upper tropospheric deviations from a moist adiabat  
630 (Figure 9) due to the fact that the convection scheme predicts a chronically low convective cloud  
631 top. Using uninhibited convection seems to alleviate this problem and could potentially prevent  
632 CESM from overestimating tropical circulation strength. This appears to be in line with findings  
633 from previous studies (Xie et al. 2018, Wang and Zhang 2018, Hu et al. 2022). However, these  
634 predictions are speculative and should be explored in future research.

635 Similarly, it is still an open question why SCAM6 requires more relaxed circulation parameters  
636 than the SCMs considered in Daleu et al. (2016) for the WTG and DGW methods in order to  
637 behave well. Given the centrality of the deep convection scheme in setting the column's  
638 circulation and precipitation, it may be that the Zhang-McFarlane scheme (which is not used by  
639 any of the other SCMs in Daleu et al.) is more prone to runaway feedbacks when paired with the  
640 WTG and DGW methods. In any case, our results suggest that the Spectral WTG method's  
641 insensitivity to changes in radiation, convection, and circulation make it better suited to use in  
642 SCAM6 and model development for CESM.

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649 **Open Research**

650 All presented data is available at <https://zenodo.org/record/7999372>.

651 **References**

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