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Key Points:
- A Fixed Anvil Temperature (FAT) does not result from temperature-dependent longwave radiative emission from water vapor
- Simulations of radiative-convective equilibrium without a FAT still have a Fixed Tropopause Temperature (FiTT)
- A FiTT does not imply a FAT because anvil clouds are not produced by enhanced detrainment below the tropopause

Supporting Information:
- Supporting Information S1

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FAT or FiTT: Are Anvil Clouds or the Tropopause Temperature Invariant?

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Abstract The Fixed Anvil Temperature (FAT) hypothesis proposes that upper tropospheric cloud fraction peaks at a special isotherm that is independent of surface temperature. It has been argued that a FAT should result from simple ingredients: Clausius-Clapeyron, longwave emission from water vapor, and tropospheric energy and mass balance. Here the first cloud-resolving simulations of radiative-convective equilibrium designed to contain only these basic ingredients are presented. This setup does not produce a FAT: the anvil temperature varies by about 40% of the surface temperature range. However, the tropopause temperature varies by only 4% of the surface temperature range, which supports the existence of a Fixed Tropopause Temperature (FiTT). In full-complexity radiative-convective equilibrium simulations, the spread in anvil temperature is smaller by about a factor of 2, but the tropopause temperature remains more invariant than the anvil temperature by an order of magnitude. In other words, our simulations have a FiTT, not a FAT.

Plain Language Summary Tropical anvil clouds play a large role in Earth's radiation balance, and their effect on anthropogenic global warming has been a point of contention. One popular school of thought is the Fixed Anvil Temperature (FAT) hypothesis, which argues that no matter how much the Earth warms, anvil clouds would continue to radiate to space at the same temperature. This behavior would amplify the warming caused by the addition of greenhouse gases to the atmosphere. In this paper, we show that the chain of logic underlying the FAT hypothesis—which attributes anvil cloud formation to a rapid decline of radiative cooling at the top of the troposphere—contains many weak and unsupported links. These weak links undermine the FAT hypothesis, which does not hold empirically in our simulations. However, the radiative tropopause does remain at a fixed temperature as the surface warms in our simulations. Therefore, we find evidence for a Fixed Tropopause Temperature (FiTT) rather than a FAT. There is currently no accepted theory for the tropopause temperature or why it appears to be independent of the surface temperature.

1. Introduction

The Fixed Anvil Temperature (FAT) hypothesis has become fairly well accepted (Boucher et al., 2013). The basic claim of the FAT hypothesis is simple: anvil clouds preferentially form at a special isotherm that is independent of the surface temperature (Hartmann & Larson, 2002). Since a fixed emission temperature for anvil clouds would tend to decouple the outgoing longwave radiation of convecting regions from the underlying surface temperature, a FAT would provide a positive feedback during global warming. Empirically, the longwave cloud feedback in global climate models (GCMs) is observed to be robustly positive, a finding for which a FAT is the most common explanation (Zelinka & Hartmann, 2010). Results from multiple cloud-resolving models (CRMs) have also appeared to support the existence of a FAT (Harrop & Hartmann, 2012; Khairoutdinov & Emanuel, 2013; Kuang & Hartmann, 2007; Singh & O'Gorman, 2015). Originally proposed as a constraint on tropical cloud-climate feedback, the FAT hypothesis has recently been extended from the tropics to the global atmosphere (Thompson et al., 2017).

The plausibility of the FAT hypothesis also derives, in part, from arguments that it should result from a few basic physical ingredients. These basic ingredients include Clausius-Clapeyron control of water vapor concentrations, longwave radiative emission from water vapor, the radiative-convective energy balance

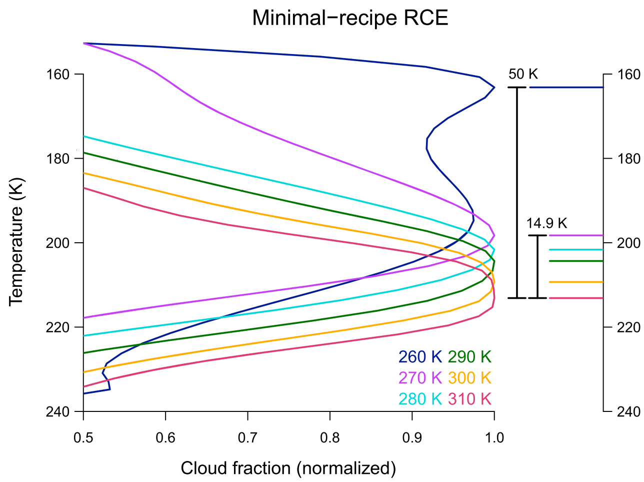

Figure 1. Cloud fraction profiles as a function of temperature for the minimal-recipe RCE simulations, which are forced only by longwave radiative cooling from water vapor and use a simplified microphysics scheme with no explicit temperature dependence. The profiles are normalized (i.e., divided by their maximum value) before plotting. Surface temperatures T_s between 260 K and 310 K are indicated by color. Horizontal lines mark the anvil temperatures.

of the tropical troposphere, and mass continuity between cloudy and clear skies. Since these basic ingredients should be present both in nature and in numerical models of the atmosphere, the FAT hypothesis has appeared to rest on a solid theoretical foundation, which has boosted confidence in its implications for contemporary climate change (Boucher et al., 2013; Zelinka & Hartmann, 2011).

The purpose of this paper is to take a step back and reevaluate the FAT hypothesis, as both an empirical result and a theoretical construct. The empirical half of this investigation is aided by the first cloud-resolving simulations of radiative-convective equilibrium (RCE) designed to contain only the basic ingredients emphasized by the literature. The cloud-resolving model used for these tests is DAM (Romps, 2008), which computes radiative transfer with Rapid Radiative Transfer Model (RRTM) (Clough et al., 2005; Iacono et al., 2008) and uses the Lin-Lord-Krueger microphysics scheme by default (Krueger et al., 1995; Lin et al., 1983; Lord et al., 1984). We refer to the simplified configuration of DAM—which is forced only by longwave radiative emission from water vapor—as the “minimal-recipe" setup (described in more detail in Text S1 in the supporting information). The use of a model that contains no inessential complexity with respect to the phenomenon of interest is the ideal framework for hypothesis testing and is a crucial step toward understanding the behavior of full-complexity models (Held, 2005; Jeevanjee et al., 2017).

For the reader interested in whether a FAT is produced by temperature-dependent longwave radiative emission from water vapor, Figure 1 is the key result. There we plot the cloud fraction profiles from the minimal-recipe RCE simulations as a function of temperature. With the anvil temperature defined as the temperature at which cloud fraction is maximum, we find that the anvil temperature varies by 50 K, or 100% of the 50-K range in simulated surface temperature. This very large anvil temperature spread is influenced by the coldest simulation, for which cloud fraction develops a second upper-tropospheric maximimum at a much colder temperature. The cause of this qualitatively different behavior in the 260-K simulation will be discussed in association with Figure 3. If we restrict our attention to the simulations with surface temperatures $T_s \geq 270$ K, the anvil temperature sensitivity is reduced to 37% of ΔT_s.

Whether Figure 1 should be taken as evidence of a fixed anvil temperature depends, of course, on the definition of “fixed". For $T_s \geq 270$ K, the changes in anvil temperature are smaller than, but of the same order of magnitude as, the changes in surface temperature: a 1-K increase in surface temperature causes about a 0.4-K increase in anvil temperature. We argue that it is not a useful approximation to consider some feature of the atmosphere as occurring at a “fixed" temperature if its temperature variations are of the same order of magnitude as the surface temperature variations; that is, the simple (albeit arbitrary) criterion we adopt is to say that feature x occuring at temperature T_x is fixed with respect to surface temperature if $\Delta T_x < 0.1 \times \Delta T_s$. By this criterion, the anvil temperature is not fixed in our minimal-recipe simulations. In the next section, we seek to explain these varying anvil temperatures by probing for weak links in the arguments for the FAT hypothesis.

2. How the FAT Hypothesis is Supposed to Work

Figure 2 enumerates the statements that are used to justify the FAT hypothesis. A chain of reasoning similar to the one depicted here can be found in most studies concerned with the FAT hypothesis (Eitzen et al., 2009; Harrop & Hartmann, 2012; Hartmann & Larson, 2002; Kuang & Hartmann, 2007; Kubar et al., 2007; Larson & Hartmann, 2003; Li et al., 2012; Thompson et al., 2017; Xu et al., 2007; Zelinka & Hartmann, 2010, 2011). The purpose of this section is to carefully step through this chain of reasoning—statement by statement—and determine if there are any weak links.

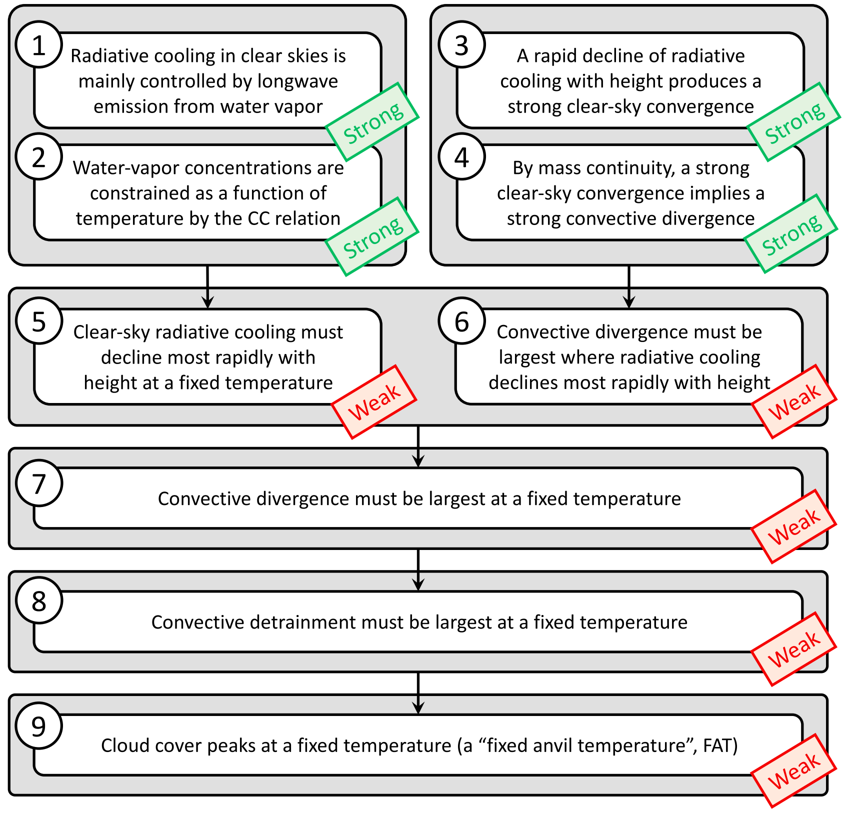

Figure 2. The chain of reasoning used to justify the FAT hypothesis. Statements for which we find strong support (theoretical and/or empirical) are marked "Strong," while those for which we find weak support or no support are marked "Weak." FAT = Fixed Anvil Temperature; CC = Clausius-Clapeyron.

Statement 1

Statement 1 says that the radiative cooling in clear skies is mainly controlled by longwave emission from water vapor. Indeed, observations and radiative transfer codes show that tropospheric longwave cooling rates from greenhouse gases such as carbon dioxide and ozone, as well as the shortwave heating rates from water vapor and these other gases, are smaller in magnitude than the longwave cooling from water vapor (Wallace & Hobbs, 2006). Therefore, statement 1 is a strong link.

Statement 2

Statement 2 says that water vapor concentrations are constrained as a function of temperature by the Clausius-Clapeyron relation. According to the Clausius-Clapeyron relation, the saturation vapor pressure p_v^* of water vapor declines quasi-exponentially as temperature drops. It is worth noting that the measure of water vapor concentration that is directly tied to longwave emissivity is not the vapor pressure, but the absorber density $\rho_v = \mathrm{RH} p_v^*/(R_v T)$. Although ρ_v depends on the relative humidity RH as well as the temperature T, it has recently been demonstrated (and justified by theory) that relative humidity is itself a nearly fixed function of temperature in RCE (Romps, 2014). To an excellent approximation, the mean water vapor density in an atmosphere in RCE is a fixed function of the local temperature. Therefore, statement 2 is a strong link.

Statement 3

Statement 3 says that a rapid decline of radiative cooling with height produces a strong clear-sky convergence. This statement is based on an approximate steady state energy budget for clear skies, which is typically written in a form equivalent to

$$M_e = -\frac{Q_e}{c_p\left(\Gamma_d - \Gamma\right)}, \tag{1}$$

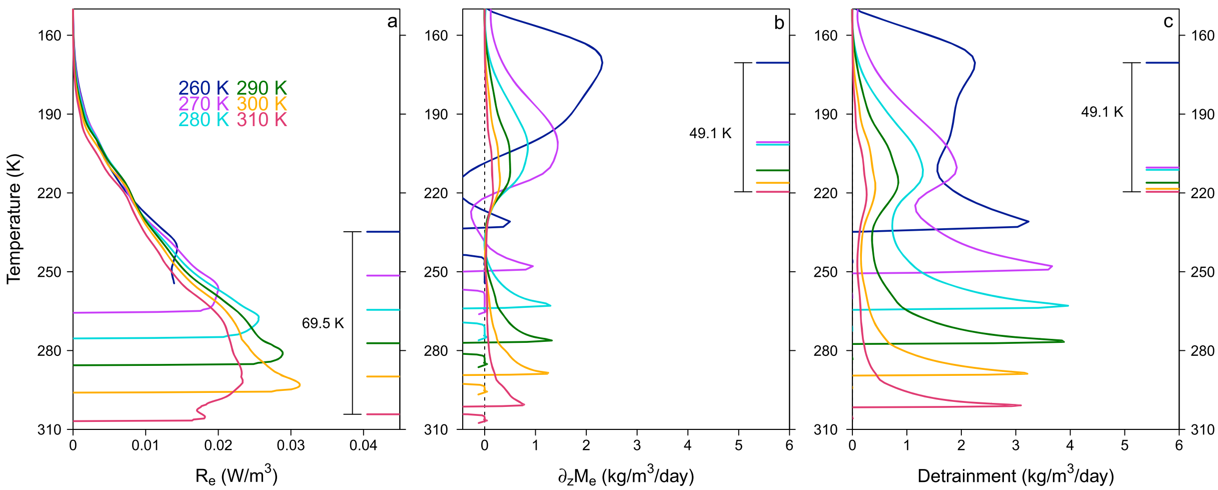

Figure 3. Profiles of (a) the clear-sky longwave radiative cooling rate, R_e; (b) convective divergence, $\partial_z M_e$; (c) convective detrainment, D. All profiles are from the "minimal-recipe" cloud-resolving simulations of RCE for sea surface temperature T_s in the range 260–310 K. In (a), the location of each simulation's most rapid decline of R_e with height is marked with a horizontal colored line. In (b) and (c), the horizontal colored lines mark the temperature of the upper tropospheric ($T \leq 230$ K) maximum from each simulation. The detrainment rates plotted in (c) are obtained from equation (2) in Text S2.

where M_e (kg/m^2/s) is the upward clear-sky mass flux (subscript e for "environment", value is negative), Q_e (W/m^3) is the clear-sky diabatic cooling rate (positive value for cooling), c_p (J/kg/K) is the heat capacity of air at constant pressure, Γ_d (K/m) is the dry-adiabatic lapse rate, and Γ is the actual lapse rate (Kuang & Hartmann, 2007; Minschwaner & Dessler, 2004). By mass continuity, the clear-sky horizontal convergence is equal to $\partial M_e/\partial z$. By equation (1), this is

$$\frac{\partial M_e}{\partial z} = -\frac{1}{c_p\left(\Gamma_d - \Gamma\right)}\frac{\partial Q_e}{\partial z} - \frac{Q_e}{c_p\left(\Gamma_d - \Gamma\right)^2}\frac{\partial \Gamma}{\partial z}. \quad (2)$$

If Γ did not vary with height and if Q_e were entirely due to radiation, then the clear-sky convergence would be proportional to $-\partial Q_e/\partial z$, that is, minus the decrease of radiative cooling with height. In reality, Γ does vary with height, and the proximity of Γ to Γ_d in the upper troposphere can make the static-stability factors in equation (2) quite important. And, Q_e is not entirely due to radiation; there is also a component due to evaporation of precipitation and detrained condensates. Nevertheless, if the decline of radiative cooling is sufficiently rapid (i.e., making $\partial Q_e/\partial z$ sufficiently negative), then that will generate a strong colocated convergence. Therefore, despite the caveats, statement 3 is a strong link.

Statement 4

Statement 4 says that a strong clear-sky convergence implies a strong convective divergence. This follows from mass conservation. If M_c (kg/m^2/s) is the upward convective mass flux (subscript c for "convection"), then, in the absence of any large-scale ascent or descent, $M_e = -M_c$. Then, the convective divergence ($-\partial M_c/\partial z$) is exactly equal to the clear-sky horizontal convergence ($\partial M_e/\partial z$). In the presence of large-scale ascent or descent, this equality is violated. But even in the presence of large-scale motions, a sufficiently strong clear-sky convergence still implies a strong convective divergence. Therefore, statement 4 is a strong link.

Statement 5

Statement 5 says that the clear-sky radiative cooling must decline most rapidly with height at a fixed temperature. The literature on the FAT hypothesis has argued that this follows logically from statements 1 and 2 (e.g., Hartmann et al., 2001), but this is not obvious. One can imagine a scenario in which statement 5 would follow from statements 1 and 2: If water vapor were a gray gas whose density were a fixed function of temperature, and if pressure-dependent collisional broadening did not exist, then the longwave emissivity of the atmosphere would be a fixed function of temperature. In that scenario, radiative cooling to space would be narrowly peaked around the altitude where the longwave optical depth (τ) equals one (Pierrehumbert, 2010). Since the absorber density is imagined to be fixed in temperature in this scenario, this peak in radiative cooling would also occur at a fixed temperature (as long as the temperature structure above the $\tau = 1$

level were also essentially fixed). Therefore, in this scenario, radiative cooling would decline with height most rapidly at a fixed temperature, which would occur on the cold side of the $\tau = 1$ level. This behavior of a gray atmosphere is confirmed in Figure S1.

Of course, it is well known that water vapor is not a gray gas: water vapor has a complex spectroscopy, with an absorption coefficient that varies by many orders of magnitude in the wavelengths of terrestrial emission (Pierrehumbert, 2010). Although the nongray spectroscopy of water vapor has been well known for decades, it seems that the implications of this physics for the FAT hypothesis have not been sufficiently appreciated. As a result of the complex spectroscopy of water vapor, there is no single $\tau = 1$ level that applies at all wavelengths; instead, the temperature at the $\tau = 1$ level depends strongly on the wavelength of light under consideration, with relatively cold emission temperatures corresponding to relatively optically thick wavelengths (Clough et al., 1992). Therefore, the principles of radiative transfer and Clausius-Clapeyron alone do not predict a rapid decline of radiative cooling at any particular temperature for a nongray atmosphere. Statement 5, then, is not an obvious logical consequence of statements 1 and 2.

Even if statement 5 does not follow logically from statements 1 and 2, could it still be empirically true? Let us denote the clear-sky radiative cooling rate as R_e (W/m^3, positive value for cooling) to distinguish it from the total diabatic cooling Q_e. In Figure 3a, we show R_e from the minimal-recipe simulations of RCE over surface temperatures ranging from 260 to 310 K. Plotted as a function of temperature, R_e shows a tendency to collapse to an approximately universal curve (Jeevanjee & Romps, 2018). However, we find no evidence for a particularly rapid decline of R_e with height at any particular temperature. This conclusion does not depend on the units one uses to plot the radiative cooling rate (i.e., W/m^3 versus K/day); see Text S3 and Figure S2 for a discussion of this point, including validation of RRTM results with the line-by-line radiative transfer model RFM (Dudhia, 2017). The horizontal lines in Figure 3a mark the temperatures where $\partial_z R_e$ is maximum, which occur in the lower troposphere of each simulation and vary by 69.5 K across the suite of simulations. In stark contrast to the narrowly peaked radiative cooling profiles generated by a gray radiation scheme, the radiative cooling from water vapor as computed by RRTM is spread out smoothly over the depth of the troposphere. Therefore, on both theoretical and empirical merit, statement 5 is a weak link.

Statement 6

Statement 6 says that convective divergence must be largest where radiative cooling declines most rapidly with height. Although the literature has argued that statement 6 follows directly from statements 3 and 4, this logic is not supported by equation (2). Note that statement 6 *would* follow from statements 3 and 4 if the lapse rate Γ were constant with height and if Q_e were entirely due to radiation. But, it is well known that neither of these conditions hold true for the tropical atmosphere. In Text S4, we use the right-hand side of equation (2) to decompose the clear-sky convergence into contributions from different factors. This analysis indicates that no single factor is solely responsible for the upper tropospheric peaks in convective divergence, but that the most important contributor is actually the minimum in static stability in the upper troposphere rather than a rapid decline in radiative cooling below the tropopause (Figures S3–S5).

Even though statement 6 is not a logical consequence of statements 3 and 4, it could still be an empirical fact. To test whether this is the case, we plot in Figure 3 the convective divergence from the minimal-recipe RCE simulations as a function of temperature. Comparing Figures 3a and 3b shows that the upper tropospheric ($T \leq 230$ K) peaks in convective divergence do not occur where R_e is declining especially rapidly with height. Therefore, statement 6 is a weak link.

Statement 7

Statement 7 says that convective divergence must be largest at a fixed temperature. This would be logically implied by statements 5 and 6 if those statements held true. However, since statements 5 and 6 were found to be weak links in the chain of reasoning, the logical support for statement 7 has been undermined.

Even if the logical antecedents of statement 7 do not hold true, could statement 7 still be an empirical fact? Figure 3b shows that the temperature of the upper tropospheric convective divergence peak varies by $\simeq 50$ K in the RCE simulations, which is just as large as the 50-K range in surface temperature. Therefore, statement 7 is a weak link.

Statement 8

Statement 8 says that convective detrainment must be largest at a fixed temperature. The literature argues that this follows from statement 7, which says that convective divergence must be largest at a fixed temperature. We have shown that statement 7 does not hold in our simulations, but even if it did, statement 8 would be a logical consequence only if convective detrainment D were proportional to convective divergence $\partial_z M_e$. However, it is well known that this is not the case: the standard bulk-plume equation relating these quantities is

$$\partial_z M_e = D - E, \tag{3}$$

where E is the entrainment rate and both E and D are nonnegative (Yanai et al., 1973). Therefore, $\partial M_e/\partial z$ simply places a lower bound on D, that is, $D \geq \partial M_e/\partial z$. Although we can expect significant detrainment where there is significant convective divergence, it is not necessarily true that this is where the largest detrainment is.

Empirically, is statement 8 true? Detrainment is notoriously hard to measure. Here we use a bulk-plume budget for a tracer that is conserved in cloudy air to estimate the detrainment rate in our simulations (Text S2; Romps & Kuang, 2010a, 2010b). The profiles of detrainment estimated by this method are plotted as a function of temperature in Figure 3c, which shows that the upper-tropospheric detrainment peaks occur at temperatures that vary by the full 50-K range in surface temperature. A significant fraction of that spread comes from the coldest simulation, whose upper-tropospheric detrainment peak occurs around the 170-K isotherm rather than between 210–220 K (as for the other simulations). We note that this upward shift of the detrainment peak is responsible for the uppermost cloud fraction peak in the 260-K simulation shown in Figure 1. It is not obvious why there should be such a large increase in upper tropospheric detrainment when the surface temperature drops from 270 K to 260 K, but it may have to do with how the troposphere approaches the dry-convective limit at very cold surface temperatures. It is well known that the character of the "convective" half of radiative-convective equilibrium is very different for dry and moist atmospheres, and the 260-K simulation may be exhibiting transitional behavior between these two regimes. Such behavior may be relevant to understanding the cloud-radiative effect in extremely cold climates—for example, "Snowball Earth" states (Abbot, 2014)—and deserves further study in follow-up work.

Even if the coldest simulation is excluded, however, the temperatures of the detrainment peaks vary by 23% of ΔT_s. Therefore, with or without the 260-K simulation, the detrainment peak does not occur at a fixed temperature across our suite of simulations, and statement 8 is a weak link.

Statement 9

Statement 9 says that the peak in cloud fraction occurs at a fixed temperature, that is, there is a "fixed anvil temperature." The literature argues that this follows from statement 8, which is the claim that convective detrainment must be largest at a fixed temperature. We have already shown that statement 8 does not hold in our simulations, but even if it were true, statement 9 would not be a logical consequence. That inference conflates the *source* of cloudy air (i.e., detrainment) with the *stock* of cloudy air (i.e., cloud fraction), when in reality cloud fraction is controlled by both its source and its sink. In fact, it has recently been demonstrated that the anvil cloud fraction peak in RCE is not caused by an anomalously large amount of detrainment, but by the anomalously slow rate of evaporation of cloudy air in the upper troposphere (Seeley et al., 2019). In general, since the rate of cloud decay can vary significantly with height, a peak in detrainment will not necessarily be collocated with a peak in cloud fraction. Therefore, statement 9 does not follow logically from statement 8.

3. Empirical Evidence for a FAT

We have already shown that the anvil temperature is not fixed in minimal-recipe simulations containing only the basic ingredients emphasized by the literature (Figure 1); so, if there is a FAT, it is not for the reasons that have been previously proposed. Could it be that the FAT hypothesis fares better in a more standard RCE configuration, due to other processes that have not been emphasized in the literature?

We tested this idea by adding back the inessential complexity that was stripped away for the minimal-recipe tests (Text S1). The cloud fraction profiles from these full-complexity simulations are shown in Figure 4. Compared to Figure 1, cloud fraction exhibits a much more obvious collapse in temperature coordinates,

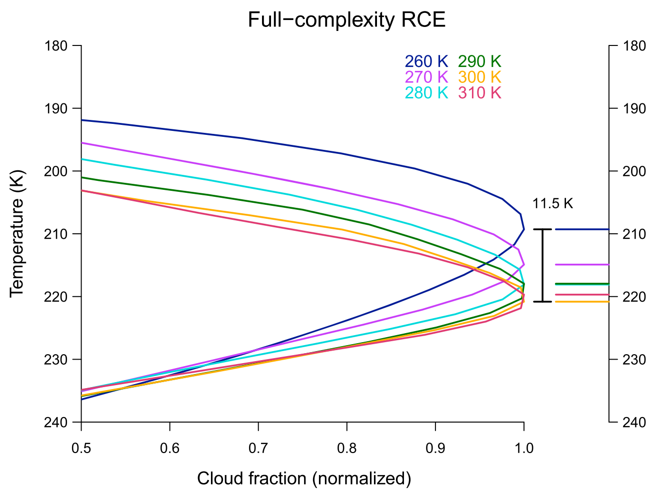

Figure 4. As in Figure 1, but for full-complexity RCE simulations. These simulations include shortwave radiative transfer, carbon dioxide, interactive cloud radiation, and temperature-dependent microphysics. RCE = radiative-convective equilibrium.

especially at warmer surface temperatures. Switching from the minimal-recipe to the full-complexity setup cuts the spread in anvil temperature by a bit less than half, from 37% to 23% of ΔT_s. Therefore, we can conclude that changes in anvil temperature are quite damped compared to changes in surface temperature in the full-complexity simulations. Further work is needed to determine whether it is temperature-dependent ice microphysics, interactive cloud radiation, shortwave absorption, or something else that pushes anvil cloud fraction toward a collapse in temperature coordinates in full-complexity simulations. However, our results have shown that a FAT is not produced by Clausius-Clapeyron control of longwave radiative cooling alone.

Although our results seem to contradict the general acceptance of the FAT hypothesis, they do not conflict with published numerical results. In the first paper on this topic, the FAT hypothesis was tested in simulations of RCE with parameterized convection (Hartmann & Larson, 2002). That study raised the surface temperature by 6 K and found that the temperature at the top of the tallest ice clouds varied by approximately 3 K, or 50% of ΔT_s. Subsequent results from CRMs found a 0.5 K change in T_a for a 2 K change in surface temperature (Kuang & Hartmann, 2007), a 1-K change in T_a for a 4-K change in surface temperature (Harrop & Hartmann, 2012), an 8-K change in T_a for a 15-K change in surface temperature (Khairoutdinov & Emanuel, 2013), and a 2-K change in T_a for a 4-K change in surface temperature (Thompson et al., 2017). The most compelling evidence for a FAT appeared in a paper that was not about FAT (Singh & O'Gorman, 2015); that study showed a 6-K change in T_a when the surface temperature was increased from 281 to 311 K, which is a slightly larger spread in T_a than we find in our full-complexity simulations over the same temperature range. These results in the literature have been used to support the existence of a FAT, although the reported anvil temperature sensitivities are in the range of 20–50% of ΔT_s and therefore fail our simple order-of-magnitude criterion. Our anvil temperature sensitivity of 23–37% of ΔT_s is in agreement with previous numerical results: the anvil temperature changes by less than the surface temperature, but it is not entirely fixed either. Note that the most important temperature for the radiative impact of high clouds is not that of the cloud fraction peak, but the average temperature at which the cloud optical depth equals 1 (looking down from space). Future analysis should quantify the difference between these two characteristic cloud temperatures.

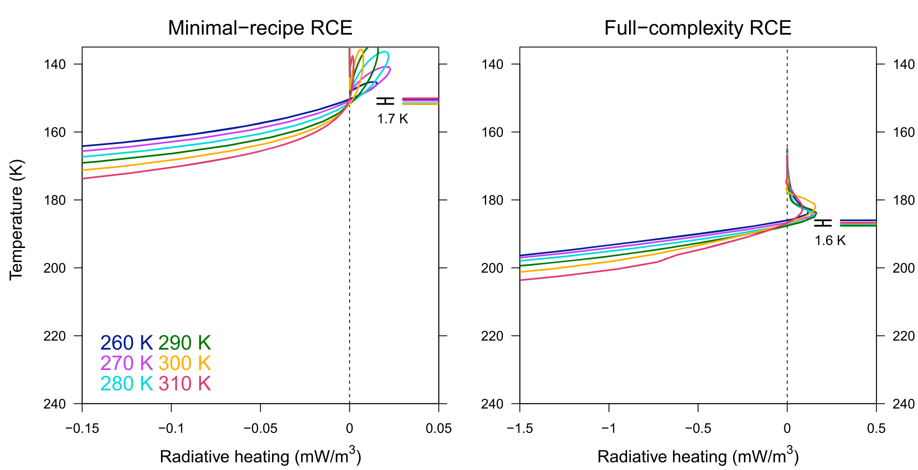

Figure 5. Clear-sky radiative heating rates as a function of temperature in (a) the minimal recipe and (b) the full-complexity RCE simulations. The radiative tropopause temperatures—where radiative cooling rates first go to zero—are marked with colored horizontal lines. RCE = radiative-convective equilibrium.

4. FiTT, not FAT

Although the anvil temperature is not fixed in our RCE simulations, we find that a different property of the atmosphere is remarkably invariant with respect to surface temperature. The temperature at the radiative tropopause—where clear-sky radiative cooling rates first go to zero—varies by only 1.7 K in our minimal-recipe setup (Figure 5). In the full-complexity simulations, the mean tropopause temperature is warmer by 35 K but also varies by only 1.6 K with respect to surface temperature. These tropopause temperature sensitivities are <4% of ΔT_s. In other words, we find strong evidence for a Fixed Tropopause Temperature (FiTT). This surface temperature invariance is most obvious when the tropopause is defined *radiatively*; if we use the common lapse rate definition of the tropopause (e.g., Fueglistaler et al., 2009), we find that the tropopause temperature varies by 11 K in the minimal-recipe simulations and by 5 K in the full-complexity simulations.

Taken all together, our results motivate a disentangling of two features of the atmosphere that are often lumped together: (1) the extensive cloud fraction produced by anvil clouds, and (2) the top of the troposphere. The basic idea that the top of the troposphere occurs at a fixed temperature is strongly supported by our results—as long as the top of the troposphere is identified by the radiative tropopause, rather than the anvil temperature. Since anvil clouds do not primarily result from enhanced detrainment below the tropopause (Seeley et al., 2019), the fact that the tropopause temperature is fixed does not imply that the anvil temperature is fixed. Indeed, the physical distance separating these two features is 5–10 km in our minimal-recipe simulations. Although the very tallest clouds (i.e., the zero crossing of the cloud fraction profile) must keep pace with the rising tropopause in order to maintain radiative-convective equilibrium, the *peak* in upper-tropospheric cloud fraction need not track with the rising tropopause.

If we understood why RCE in earthlike atmospheres has a FiTT, it would simplify the way we think about our atmosphere and those of other planets where water vapor is the dominant radiatively active gas. Unfortunately, we do not yet have this understanding: simple theories connecting the radiative properties of water vapor to climate change typically do not predict the tropopause temperature, but take it as a given (e.g., Ingram, 2010). Therefore, FiTT is currently only a modeling result from the single radiative-convective model used in this study (DAM). The reproducibility of FiTT in other radiative-convective models should be assessed, from the simplest 1-D models (e.g., Manabe & Strickler, 1964) to other cloud-resolving models; the latter will be facilitated by results from the upcoming RCEMIP (Wing et al., 2018). But, even if a model consensus is achieved, a satisfactory explanation for FiTT will require the development of a theory for the tropopause temperature in radiative-convective equilibrium.

Acknowledgments
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