

Axisymmetric Hadley Cell theory with a fixed tropopause temperature rather than heightSPENCER A. HILL *[†]*Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, and Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles*

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Axisymmetric Hadley cell theory has traditionally assumed that the tropopause height (H_t) is uniform and unchanged from its radiative-convective equilibrium (RCE) value by the cells' emergence. Recent studies suggest that the tropopause temperature (T_t), not height, is nearly invariant in RCE, which would require appreciable meridional variations in H_t . Here, we derive modified expressions of axisymmetric theory by assuming a fixed T_t and compare the results to their fixed- H_t counterparts. If T_t and the depth-averaged lapse rate are meridionally uniform, then at each latitude H_t varies linearly with the local surface temperature, altering the diagnosed gradient-balanced zonal wind at the tropopause appreciably (up to tens of m s^{-1}) but the minimal Hadley cell extent predicted by Hide's theorem only weakly ($\lesssim 1^\circ$) under standard annual-mean and solsticial forcings. A uniform T_t alters the thermal field required to generate an angular-momentum-conserving Hadley circulation, but these changes and the resulting changes to the equal-area model solutions for the cell edges again are modest ($< 10\%$). In numerical simulations of latitude-by-latitude RCE under annual-mean forcing using a single-column model, assuming a uniform T_t is reasonably accurate up to the mid-latitudes, and the Hide's theorem metrics are again qualitatively insensitive to the tropopause definition. However imperfectly axisymmetric theory portrays the Hadley cells in Earth's macroturbulent atmosphere, evidently its treatment of the tropopause is not an important error source.

1. Introduction

Absent any large-scale circulation, local radiative-convective equilibrium (RCE) would necessarily prevail at each latitude: the large-scale meridional and vertical velocities vanishing, the lapse rate nearly adiabatic from the surface to the tropopause, and the interplay between local radiative forcing and convection generating equilibrium temperature and zonal wind fields in gradient balance. Provided zonal flow is weak at the surface, the tropopause height then controls the maximum magnitude of the zonal wind within the troposphere at each latitude. Via Hide's theorem, the resulting absolute angular momentum and absolute vorticity fields determine the emergence (Hide 1969; Schneider 1977; Plumb and Hou 1992)

and minimal extent (Held and Hou 1980; Hill et al. 2019) of the Hadley cells in axisymmetric and zonally varying (Emanuel 1995) atmospheres.

The original expressions of Hide's theorem and of the angular momentum conserving (AMC) model of the Hadley cells (Schneider 1977; Held and Hou 1980) were derived in a dry, Boussinesq framework in which the tropopause height, H_t , is assumed uniform in latitude and, if a Hadley circulation emerges, to be unaltered from its RCE value. This includes the equal-area model for the cell edge locations that combines the AMC assumption with assumptions of continuity in depth-averaged potential temperature and energy conservation within each cell (Held and Hou 1980; Schneider 1987; Lindzen and Hou 1988). In the adaptation of axisymmetric theory to moist atmospheres obeying convective quasi-equilibrium (CQE; Emanuel et al. 1994; Emanuel 1995), the tropopause height — which appears in temperature coordinates as the difference between the surface and tropopause temperatures, $T_s - T_t$ — is not assumed uniform in the expression

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of Hide’s theorem (Eq. 10 of Emanuel 1995) but is in deriving the AMC, or “critical,” subcloud equivalent potential temperature field (Eq. 11 of Emanuel 1995).

That assuming a fixed tropopause height may be problematic can be seen from the hypsometric equation applied at each latitude over the local depth of the troposphere: $H_t = (R_d/g)\hat{T} \ln(p_s/p_t)$, where R_d is the atmospheric gas constant, g is gravity, and \hat{T} is temperature averaged in log-pressure from the surface with pressure p_s to the tropopause with pressure p_t . Neglecting surface pressure variations, a given value of H_t will occur at larger p_t values in warmer columns compared to cooler columns — opposite to both simulations of latitude-by-latitude RCE to be presented below and to observations¹, wherein the tropopause pressure is lowest (and height is highest) in the warmest columns (e.g. Held 1982; Hu and Vallis 2019).

Recent work based on RCE simulations in a doubly periodic, cloud-resolving model suggests that the tropopause temperature, T_t , rather than height, is nearly climate-state invariant averaged over the domain (Seeley et al. 2019b), refining (Seeley et al. 2019a) previous arguments that cloud anvils form at a climate-state-invariant temperature both in the tropics (Hartmann and Larson 2002) and extratropics (Thompson et al. 2017, 2018).² The tropopause temperature is also invariant in simple, single-column theoretical models for the tropopause height that assume grey radiative transfer and an optically thin stratosphere (e.g. Vallis et al. 2015; Hu and Vallis 2019). And a fixed T_t is effectively assumed (via an isothermal, 200-K stratosphere) in widely used Newtonian cooling profiles including the canonical Held and Suarez (1994) forcing and that of the Schneider (2004) idealized, dry GCM used in many recent studies of the Hadley cells (e.g. Walker and Schneider 2005, 2006; Schneider and Bordoni 2008; Hill et al. 2019).

Absent compensating lapse rate variations, a fixed tropopause temperature would cause H_t to vary with surface temperature: given a lapse rate $\Gamma \equiv \partial_z T$ vertically averaged (in z coordinates) from the surface to the tropopause, $\hat{\Gamma}$, the tropopause height must satisfy

$$H_t = \frac{T_s - T_t}{\hat{\Gamma}}. \quad (1)$$

If T_t and $\hat{\Gamma}$ are fixed, H_t varies linearly with T_s — rising on Earth, for example, by approximately 1 km per 10 K of surface warming in dry-adiabatic columns or per ~ 6.5 K in moist-adiabatic columns. Insofar as $\hat{\Gamma}$ and T_t are meridionally uniform, (1) applied at each latitude immediately

resolves the aforementioned problem arising from a uniform tropopause height: $T_s - T_t$, and therefore H_t , must increase with T_s .

While the original, fixed- H_t theories have been remarkably successful for Hadley cells on Earth and other planetary bodies at the conceptual to qualitative levels, it remains possible that (and, to our knowledge, unexamined whether) appreciable quantitative or even qualitative changes to their results emerge when meridional variations in H_t are accounted for. Fang and Tung (1994) compare analytical Hadley cell solutions attained with a fixed H_t with or without the tropopause temperature assumed fixed in their linear, viscous model, but this viscous regime is inappropriate for Earth’s nearly inviscid free troposphere. Zalucha et al. (2010) incorporate meridional variations in surface height into the equal-area model, motivated by the mean downward surface slope from the south pole to the low latitudes on Mars (Richardson and Wilson 2002).

At the same time, Singh (2019) demonstrates that $T_s - T_t$, not T_t , is nearly meridionally uniform in a GCM simulation of latitude-by-latitude RCE [his Figure 5(b)]. So it remains necessary to assess the validity of a fixed T_t in simulations of latitude-by-latitude RCE, and — to solidify the link between simulation and theory — how usefully simple semi-analytical approximations and the analytical forcing profiles underlying classical dry, Boussinesq, axisymmetric theory (Held and Hou 1980; Lindzen and Hou 1988) can approximate those moist, numerically simulated RCE solutions.³

These considerations motivate the present study. We begin by demonstrating that, based on (1) and provided T_t and $\hat{\Gamma}$ are meridionally uniform, meridional tropopause height variations can indeed be large in the latitude-by-latitude RCE state generated under both annual-mean and more solstice-like forcings (Section 2). We then derive a fixed- T_t solution for the gradient-balanced zonal wind at the tropopause in these RCE states, compare it to its fixed- H_t counterpart (Section 3), and investigate the resulting influences on the three conditions (Adam and Paldor 2010; Hill et al. 2019) of Hide’s theorem for the emergence and minimal extent of the Hadley circulation (Section 4). In a similar progression, we then derive fixed- T_t forms of the AMC (i.e. “critical”) depth-averaged potential temperature distribution (Section 5) and explore the resulting impacts on the equal-area model (Section 6). We then generate numerical, annual-mean, latitude-by-latitude RCE solutions via single-column model simulations to assess whether a meridionally uniform T_t is plausible, how sensitive the gradient wind at the tropopause and the Hide’s theorem metrics are to the tropopause definition, and how

¹The observed tropopause structure reflects, in addition to these radiative-convective influences, dynamical and radiative influences induced by the large-scale circulation, making this comparison with pure RCE imperfect.

²Specifically, in doubly periodic, fixed-SST, cloud-resolving-model simulations with uniform, prescribed sea surface temperatures varied from 260 to 310 K, the domain-mean tropopause temperature varies by $\lesssim 5$ K (Seeley et al. 2019b).

³Singh (2019) also demonstrates that $T_s - T_t$ at the cross-equatorial Hadley cell edge is nearly climate-state invariant across dynamically equilibrated simulations with a wide range of planetary rotation rates (his Figure 9).

accurately the numerical results can be captured by simple analytical and semi-analytical approximations (Section 7).

As fully summarized in Section 8, we find overall that the results of axisymmetric theory are qualitatively insensitive to how the tropopause is treated. This should add to the community’s confidence in the original axisymmetric theories (within those parameter regimes in which they are justifiable in the first place), one of several implications we discuss in Section 9.

2. Effect of a fixed T_t on the tropopause height in latitude-by-latitude RCE

Figure 1 shows H_t diagnosed using (1) assuming $T_t = 200$ K, a meridionally and vertically uniform lapse rate of $\Gamma = \Gamma_d$ with $\Gamma_d = g/c_p$ the dry adiabatic lapse rate, and a vertically averaged potential temperature distribution $\hat{\theta} \equiv (1/H_t) \int_0^{H_t} \theta dz$ given by the canonical vertically averaged forcing of Lindzen and Hou (1988):

$$\frac{\hat{\theta}_{\text{rce}}}{\theta_0} = 1 + \frac{\Delta_h}{3} [1 - 3(\sin \varphi - \sin \varphi_m)^2]. \quad (2)$$

In (2), $\hat{\theta}_{\text{rce}}$ maximizes at the latitude φ_m , which we set to either 0, 6, or 23.5°N, Δ_h is an imposed fractional planetary-scale temperature contrast set to 1/6, and the Boussinesq reference potential temperature θ_0 is set to 290 K.

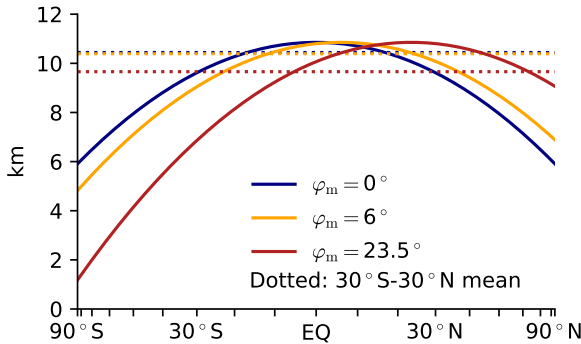


FIG. 1. (Solid curves) Tropopause height in the RCE state given by (2) with the forcing maximum latitude value, φ_m , according to the legend, assuming a uniform tropopause temperature of 200 K and a dry adiabatic lapse rate. (Dotted lines) Fixed-height tropopause to which we compare the fixed-temperature results, defined as the tropical-mean (30°S-30°N, area-weighted average) value of the solid curve with the corresponding color. Note that the horizontal-axis spacing is linear in the sine of latitude here and in all subsequent figures unless otherwise noted in the corresponding caption.

In the annual-mean case of $\varphi_m = 0^\circ$, the RCE tropopause height is ~ 11 km at the equator and decreases to ~ 9 km at $\pm 30^\circ$ and ~ 6 km at the poles. As the forcing maximum latitude is moved into the Northern Hemisphere, by construction the tropopause height at φ_m remains ~ 11 km, but the tropopause drops to successively

lower values in the southern, winter hemisphere. The $\varphi_m = 23.5^\circ$ case reveals the over-simplicity of this expression sufficiently far from the forcing maximum, with H_t dropping below 2 km at the poles; for φ_m sufficiently farther poleward (not shown), T_s drops below T_t near the winter pole, yielding the fallacious prediction of a vanishing or negative tropopause height.

Restricting to low- to mid-latitudes where the results are more reasonable and of more relevance to the Hadley cells, H_t varies meridionally by up to ~ 5 km, i.e. by $\sim 40\%$ — variations sufficiently large to motivate examining their influence on the corresponding gradient-balanced zonal wind field at the tropopause.

3. Effect of a fixed T_t on the gradient-balanced zonal wind at the tropopause

When integrated in height from the surface to the tropopause and assuming negligible surface zonal wind, gradient balance in a Boussinesq atmosphere may be written

$$2\Omega \sin \varphi u_t + \frac{\tan \varphi}{a} u_t^2 = -\frac{g}{a\theta_0} \int_0^{H_t(\varphi)} \frac{\partial \theta}{\partial \varphi} dz, \quad (3)$$

where Ω is planetary rotation rate, φ is latitude, u_t is zonal wind at the tropopause, a is planetary radius, and θ is the perturbation potential temperature.⁴

In the presence of nonzero $\partial_\varphi H_t$, (3) can still be solved as standard for u_t provided that the stratification is dry-adiabatic. Otherwise, θ and $\partial_\varphi \theta$ are not generally uniform in height, and applying the Leibniz integral rule generates an additional term. For the quantities of interest regarding axisymmetric Hadley cell theory, the presence of this term complicates all subsequent derivations without adding physical insight. Similarly, in the moist, CQE system, though by construction the stratification is moist adiabatic and this extra term therefore absent, the presence of moisture complicates the derivations in ways that do not add physical insight as regards our present focus. Moreover, the influence of a fixed T_t on the fields of interest is similar in all three cases (Boussinesq dry-adiabatic, Boussinesq non-dry-adiabatic, and CQE; not shown). Accordingly, in the main text we focus on the dry adiabatic case, relegating derivations and results for the dry-stably

⁴The perturbation potential temperature is in hydrostatic balance with a perturbation pressure field, p' , according to $\partial_z \Phi = g\theta/\theta_0$, where $\Phi = p'/\rho_0$ and ρ_0 is the reference density [note that Hill et al. (2019) incorrectly refer to Φ as “geopotential”]. Lindzen and Hou (1988) and Held and Hou (1980) define $\hat{\theta}_{\text{rce}}$ [in (2)] as the RCE *full* depth-averaged potential temperature; elsewhere those authors use θ and $\hat{\theta}$ to refer either to the full or perturbation (i.e. the full potential temperature minus θ_0) potential temperature depending on the context. This casualness is not problematic in those studies or the present one, because all potential temperature fields only appear as derivatives or differences for which the use of full or perturbation quantities is irrelevant. As such, henceforth we refer without confusion to θ as simply potential temperature and $\hat{\theta}$ as simply depth-averaged potential temperature.

stratified Boussinesq case to Appendix A and for the CQE case to Appendix B.

Restricting then to the general Boussinesq, dry-adiabatic case in the presence of meridional H_t variations, solving (3) yields

$$u_t = \Omega \cos \varphi \left[\sqrt{1 - \frac{1}{\cos \varphi \sin \varphi} \frac{g H_t}{\Omega^2 a^2 \theta_0} \frac{\partial \hat{\theta}}{\partial \varphi}} - 1 \right]. \quad (4)$$

Applied to each latitude of the hypothetical RCE state and using (1), this becomes an expression for the RCE gradient-balanced zonal wind at the tropopause, $u_{t,\text{rce}}$,

$$u_{t,\text{rce}} = \Omega \cos \varphi \left[\sqrt{1 - \frac{1}{\cos \varphi \sin \varphi} \frac{c_p (T_s - T_t)}{\Omega^2 a^2 \theta_0} \frac{\partial T_s}{\partial \varphi}} - 1 \right], \quad (5)$$

which in fact holds whether or not T_t is assumed uniform.

Comparing fixed- H_t and fixed- T_t results of (5) requires choosing values for each version's fixed parameters. In all that follows, for the fixed- T_t value we use 200 K, and for the fixed- H_t value we use the tropical-mean (30°S - 30°N , area-weighted) value of H_t , denoted \bar{H}_t , taken from the corresponding fixed- T_t calculation (cf. dotted lines in Figure 1). This subjective choice was made to avoid artificially inflating the seeming influence of a fixed T_t within the latitudes of relevance to the Hadley cells. Corresponding to this \bar{H}_t value and the given T_t and $\hat{\Gamma}$ values is a characteristic surface temperature $\bar{T}_s = T_t + \hat{\Gamma} \bar{H}_t$. The fixed- T_t calculation of $u_{t,\text{rce}}$ then differs from its fixed- H_t counterpart at any latitude whose surface temperature differs from that tropical-mean value: where $T_s > \bar{T}_s$, the magnitude of the diagnosed u_t increases, and where $T_s < \bar{T}_s$, the magnitude of the diagnosed u_t decreases relative to the fixed-height calculation. Results are qualitatively insensitive to reasonable variations to this averaging domain (not shown).

Figure 2(a) shows $u_{t,\text{rce}}$ diagnosed using (4) with either T_t fixed to 200 K or H_t fixed as just described for φ_m equal to 0, 6, or 23.5°N . In the annual-mean-like case ($\varphi_m = 0^\circ$), the tropopause's maximum height at the equator and its monotonic decrease toward either pole makes the fixed- T_t -calculated $u_{t,\text{rce}}$ more westerly than its fixed- H_t counterpart from the equator to $\sim 15^\circ\text{S/N}$, but only by $\lesssim 3 \text{ m s}^{-1}$. Poleward thereof, the tropopause height is lower than its tropical-mean value, and this reduces $u_{t,\text{rce}}$ compared to the fixed- H_t formulation by up to 5 m s^{-1} .

For the solstice-like cases ($\varphi_m = 6, 23.5^\circ$), the relatively deep tropopause near φ_m slightly increases the magnitudes of both the easterlies on its equatorward side within the summer hemisphere and the westerlies on its poleward side. In the winter hemisphere, the westerlies are weakened more appreciably — up to $\sim 20 \text{ m s}^{-1}$ in the mid-latitudes and by $\sim 10 \text{ m s}^{-1}$ in the subtropics for $\varphi_m = 23.5^\circ$ — due to a comparatively low tropopause height locally.

4. Effect of a fixed T_t on the minimal Hadley cell extent based on Hide's theorem

Given $u_{t,\text{rce}}$, any isolated extremum in the corresponding absolute angular momentum field, $M_{t,\text{rce}} = a \cos \varphi (\Omega a \cos \varphi + u_{t,\text{rce}})$, or (nearly equivalently) any sign change within either hemisphere in the corresponding absolute vorticity field, $\eta_{t,\text{rce}} = -(a^2 \cos \varphi)^{-1} \partial_\varphi M_{t,\text{rce}} = f - a^{-1} \partial_\varphi u_{t,\text{rce}}$, is unattainable in a steady, axisymmetric atmosphere (Hide 1969; Schneider 1977; Plumb and Hou 1992). Therefore, a Hadley cell must emerge if the RCE state exhibits any of $M_{t,\text{rce}} > \Omega a^2$, $M_{t,\text{rce}} < 0$, or $f \eta_{t,\text{rce}} < 0$ at any latitude (Ωa^2 and 0 being the extremal planetary values of angular momentum, at the equator and either pole, respectively), and at the very least the resulting circulation must span all latitudes meeting any of these three conditions of Hide's theorem (Hill et al. 2019). For annual-mean-like forcing, only the $M_{t,\text{rce}} > \Omega a^2$ condition is typically met; for solstice-like forcing, typically the $M_{t,\text{rce}} > \Omega a^2$ condition is met over some appreciable range of the winter hemisphere, the $M_{t,\text{rce}} < 0$ condition is met in a narrow range near the equator in the summer hemisphere (though under exotic forcings it can extend to the summer pole, cf. Hill et al. 2019), and the $f \eta_{t,\text{rce}} < 0$ condition is met over some appreciable range poleward thereof, making where $\eta_{t,\text{rce}} = 0$ in the summer hemisphere a lower bound on how far the Hadley circulation extends into the summer hemisphere.

Directly at the equator, these three conditions serve purely as Hadley cell *emergence* indicators and are unaffected by meridional variations in H_t : an equatorial $\hat{\theta}_{\text{rce}}$ maximum still yields equatorial westerlies and thus $M_{t,\text{rce}} > \Omega a^2$ locally, and a nonzero cross-equatorial $\hat{\theta}_{\text{rce}}$ gradient still cannot be balanced. But as indicators of minimal cell *extent* away from the equator, the $M_{t,\text{rce}} > \Omega a^2$, $M_{t,\text{rce}} < 0$, and $f \eta_{t,\text{rce}} < 0$ extents are all in principle altered by the tropopause treatment.

Figure 2(b) shows $M_{t,\text{rce}}$ computed for the same $\varphi_m = 0, 6, 23.5^\circ$ cases discussed above, with either H_t or T_t fixed, and Table 1 shows the maximal poleward extent of each Hide's theorem metric. For $\varphi_m = 0^\circ$ and $\varphi_m = 6^\circ$, the $M_{t,\text{rce}} > \Omega a^2$ extent is essentially unchanged by the fixed- T_t formulation. For $\varphi_m = 23.5^\circ$, the summer hemisphere westerlies are far enough poleward (where the planetary angular momentum values are lower) that neither the fixed- H_t nor fixed- T_t calculations of $M_{t,\text{rce}}$ exceed Ωa^2 in the summer hemisphere. In the winter hemisphere the $M_{t,\text{rce}} > \Omega a^2$ extent contracts equatorward by a more appreciable 1.2° .

Figure 2(c) shows the corresponding calculations of $\eta_{t,\text{rce}}$, and Table 1 shows the $\eta_{t,\text{rce}} = 0$ locations for the off-equatorial forcing maximum cases [cf. Hill et al. (2019), the $M_{t,\text{rce}} < 0$ and $f \eta_{t,\text{rce}} < 0$ conditions are never met in the $\varphi_m = 0$ case]. For $\varphi_m = 6^\circ$, westerlies occurring

TABLE 1. Metrics of Hadley cell extent from Hide’s theorem, the angular-momentum-conserving model, and the equal-area model (in degrees latitude) and, for the equal-area model, the predicted depth-averaged potential temperature at the ascent latitude ($\hat{\theta}_a$; in Kelvin) computed using either the traditional, fixed-height equations or the new, fixed-temperature equations. Also shown in parentheses next to each forcing maximum latitude value is \bar{H}_t , i.e. the value (in km) used for the fixed- H_t calculations, namely the tropopause height averaged over 30°S–30°N given that forcing and assuming a fixed T_t .

φ_m (\bar{H}_t)	0° (10.4 km)		6° (10.4 km)		23.5° (9.7 km)	
Metric	Fixed H_t	Fixed T_t	Fixed H_t	Fixed T_t	Fixed H_t	Fixed T_t
$M_{t,rce} > \Omega a^2$, summer	15.5°	15.5°	10.0°	10.6°	—	—
$M_{t,rce} > \Omega a^2$, winter	-15.5°	-15.5°	-17.6°	-17.4°	-20.9°	-19.7°
$M_{t,rce} < 0$	—	—	0.8°	0.8°	2.9°	3.1°
$f\eta_{t,rce} < 0$	—	—	9.0°	9.1°	14.3°	14.8°
$u_{t,rce} = u_{amc}$, summer	15.5°	15.5°	22.3°	22.5°	35.4°	34.8°
$u_{t,rce} = u_{amc}$, winter	-15.5°	-15.5°	-24.7°	-24.3°	-38.7°	-36.7°
Equal area φ_s	19.5°	18.7°	24.1°	24.4°	35.9°	35.3°
Equal area φ_w	-19.5°	-18.7°	-32.7°	-32.5°	-51.1°	-48.7°
Equal area φ_a	0°	0°	18.1°	18.2°	34.5°	33.8°
Equal area $\hat{\theta}_a$	305.2 K	305.2 K	303.4 K	303.3 K	304.7 K	304.8 K

just poleward of φ_m are sufficiently strong as to generate a local $M_{t,rce}$ maximum poleward of φ_m that slightly exceeds the local planetary angular momentum value with either tropopause treatment, and this maximum is nearly unchanged (9.0° vs. 9.1°) when the fixed- T_t assumption is introduced. For $\varphi_m = 23.5^\circ$, the local $M_{t,rce}$ maximum is generated equatorward of φ_m at a value less than the local planetary angular momentum value, driven by strong east-erlies, and this moves from 14.3° to 14.8° when a fixed T_t is assumed.

What explains this qualitative insensitivity of the Hide’s theorem metrics to the tropopause meridional structure? For the $\varphi_m = 0^\circ$ case, $u_{t,rce}$ is only altered by up to $\sim 3 \text{ m s}^{-1}$, making the insensitivity unsurprising. But even if the differences were larger in magnitude, the $M_{t,rce} = \Omega a^2$ point occurs within a few degrees latitude of where the fixed- T_t tropopause height goes from being greater-than to less-than its tropical-mean value \bar{H}_t used in the fixed- H_t calculations (cf. Figure 1). So $u_{t,rce}$, and in turn $M_{t,rce}$, is only modestly affected in the region of relevance. A similar phenomenon occurs for the $\eta_{t,rce} = 0$ metric in the off-equator forcing cases. By construction, $u_{t,rce} = 0$ at φ_m regardless of the tropopause structure, and at least for the cases examined the $\eta_{t,rce} = 0$ point is not far removed from φ_m . The effects of the tropopause treatment on $u_{t,rce}$, and in turn $M_{t,rce}$ and $\eta_{t,rce}$, in the vicinity are accordingly modest. In contrast, for $\varphi_m = 23.5^\circ$, the winter hemisphere $M_{t,rce} = \Omega a^2$ point occurs where the fixed- T_t tropopause height differs more appreciably from its tropical mean, yielding a nontrivial difference between the fixed height vs. temperature calculations.

We reiterate that all comparisons between fixed- T_t and fixed- H_t calculations depend on the H_t value chosen for the fixed- H_t calculations and that this choice is somewhat arbitrary. Nevertheless, as noted above, we deem the tropical-mean value from the fixed- T_t solutions, i.e. \bar{H}_t , to

be a reasonable choice — neither values much higher or much lower than \bar{H}_t seem justifiable.

5. Effect of a fixed T_t on the angular momentum conserving model

Assuming that any of the three Hide’s theorem conditions is met at any latitude (as can nearly always be expected, cf. Schneider 2006; Hill et al. 2019), the latitude-by-latitude RCE state cannot be sustained, and a Hadley circulation must emerge. Provided that drag is strong in the boundary layer but viscosity is small and eddy-induced stresses weak in the free troposphere, air parcels ascending out of the boundary layer will conserve the local planetary angular momentum value as they circulate within the free troposphere. If this ascent is concentrated into a narrow convergence zone at the latitude φ_a and vertical momentum advection is negligible (Shell and Held 2004; Adam and Paldor 2009), the Hadley cell will then exhibit the AMC zonal wind profile

$$u_{amc} = \Omega a \cos \varphi \left(\frac{\cos^2 \varphi_a}{\cos^2 \varphi} - 1 \right) \quad (6)$$

and a corresponding gradient-balanced AMC thermal field $\hat{\theta}_{amc}$ given by — if H_t is uniform —

$$\frac{\hat{\theta}_{amc}(\varphi) - \hat{\theta}_a}{\theta_0} = -\frac{\Omega^2 a^2}{2gH_t} \frac{(\cos^2 \varphi_a - \cos^2 \varphi)^2}{\cos^2 \varphi}, \quad (7)$$

where $\hat{\theta}_a$ is the value of $\hat{\theta}_{amc}$ at φ_a (Held and Hou 1980; Lindzen and Hou 1988). At minimum, the resulting AMC Hadley circulation must span all latitudes where $u_{amc} < u_{t,rce}$; otherwise a local extremum in $M_{t,rce}$ would still exist at the cell edge in violation of Hide’s theorem (Held and Hou 1980). Typically, this $u_{amc} < u_{t,rce}$ expanse is broader than the minimal extent directly set by Hide’s theorem.

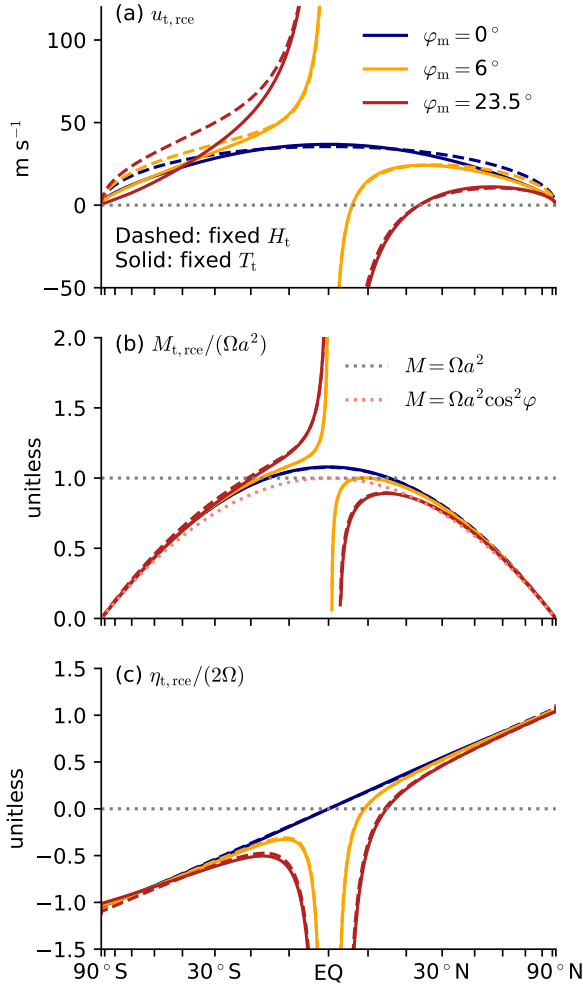


FIG. 2. At the local tropopause, (a) zonal wind in m s^{-1} , (b) absolute angular momentum normalized by the equatorial planetary angular momentum, and (c) absolute vorticity normalized by 2Ω , in the RCE state given by (2) with the forcing maximum latitude φ_m value according to the legend in (a), with either the tropopause (dashed) height or (solid) temperature assumed constant. The fixed-height calculations use the 30°S – 30°N average tropopause height listed in Table 1 from the corresponding fixed-temperature calculation (all of which set $T_t = 200\text{ K}$). Overlaid in (b) are (dotted grey) the equatorial planetary angular momentum and (dotted pink) the local planetary angular momentum. Overlaid in (c) is (dotted grey) the $\eta = 0$ curve, which would correspond to uniform angular momentum, e.g. the dotted grey curve in (b).

In the previous sections relating to the hypothetical RCE state, the RCE thermal field was taken as given, and the task at hand was to determine how tropopause height variations alter the zonal wind field. For the AMC model, we consider the converse: the AMC wind u_{amc} varies only with latitude, not height, in thin-shell atmospheres (e.g. Fang and Tung 1996), and it is the column-averaged temperature field in gradient balance with u_{amc} , $\hat{\theta}_{\text{amc}}$, that may be altered by a fixed T_t . Strictly speaking, the original

fixed- T_t argument (Seeley et al. 2019b) applies to RCE, not to the tropopause in the presence of a large-scale circulation. Nevertheless, in analogy to the assumption by Held and Hou (1980) of a uniform value of H_t within the AMC Hadley cells equal to its RCE value, we assume uniform values of T_t and $\hat{\Gamma}$ within the AMC Hadley cells equal to their RCE values.

Combining (1), (3), and (6) yields

$$\frac{\partial \hat{\theta}}{\partial \varphi} = \frac{\theta_0 \Omega^2 a^2}{c_p (T_s - T_t)} \left(\frac{\sin \varphi}{\cos^3 \varphi} \cos^4 \varphi_a - \cos \varphi \sin \varphi \right).$$

Bringing the $T_s - T_t$ term to the opposite side, using $\hat{\theta} = T_s$ (recall that the stratification has been assumed dry adiabatic), and using the chain rule yields

$$\frac{1}{2} \frac{\partial \hat{\theta}^2}{\partial \varphi} - T_t \frac{\partial \hat{\theta}}{\partial \varphi} = \frac{\theta_0 \Omega^2 a^2}{c_p} \left(\frac{\sin \varphi}{\cos^3 \varphi} \cos^4 \varphi_a - \cos \varphi \sin \varphi \right).$$

Integrating this expression in latitude and then applying the quadratic formula yields the AMC depth-averaged potential temperature for a fixed T_t and dry adiabatic lapse rate:

$$\hat{\theta}_{\text{amc}}(\varphi) = T_t + \sqrt{(\hat{\theta}_a - T_t)^2 - \frac{\theta_0 \Omega^2 a^2}{c_p} \frac{(\cos^2 \varphi_a - \cos^2 \varphi)^2}{\cos^2 \varphi}}. \quad (8)$$

Figure 3 shows the RCE and AMC tropopause height and column-integrated potential temperature, with either fixed- H_t or fixed- T_t assumed, for each of the $\varphi_m = 0, 6, 23.5^\circ$ RCE cases discussed in previous sections. For each AMC solution, φ_a is determined from the equal-area model discussed in the next section. As was the case for the RCE state, a fixed T_t and lapse rate forces H_t to have the same meridional structure as T_s , including the equatorial minimum for $\varphi_a \neq 0$. In the $\varphi_a = 0$ case, this leads to a very flat tropopause height in low latitudes but a sharp shoulder poleward thereof — H_t decreases by $< 0.5\text{ km}$ from the equator to 15°N and by $\sim 2.5\text{ km}$ over the subsequent 15° . For $\varphi_m \neq 0$, this sharp shoulder emerges poleward of φ_a in the summer hemisphere and $-\varphi_a$ in the winter hemisphere, occurring farther toward the mid-latitudes as φ_m is increased.

These shoulders in H_t , in turn, sharpen the corresponding shoulders of $\hat{\theta}_{\text{amc}}$. But ultimately this effect is modest (a few Kelvin), and within the core of the Hadley cells the changes to $\hat{\theta}_{\text{amc}}$ are smaller still. The fixed- T_t $\hat{\theta}_{\text{amc}}$ is undefined at values colder than T_t , since this would imply a vanishing tropopause height.

Table 1 lists the locations of the $u_{\text{amc}} = u_{t,\text{rce}}$ points controlling the minimal AMC Hadley cell extent for each φ_m value ($u_{t,\text{rce}}$ profiles are shown in Figure 2(a); u_{amc} profiles are not shown). Recall that φ_m determines $u_{t,\text{rce}}$ and, via the equal-area model, φ_a , and φ_a in turn determines u_{amc} , meaning that going from a fixed H_t to a fixed T_t can

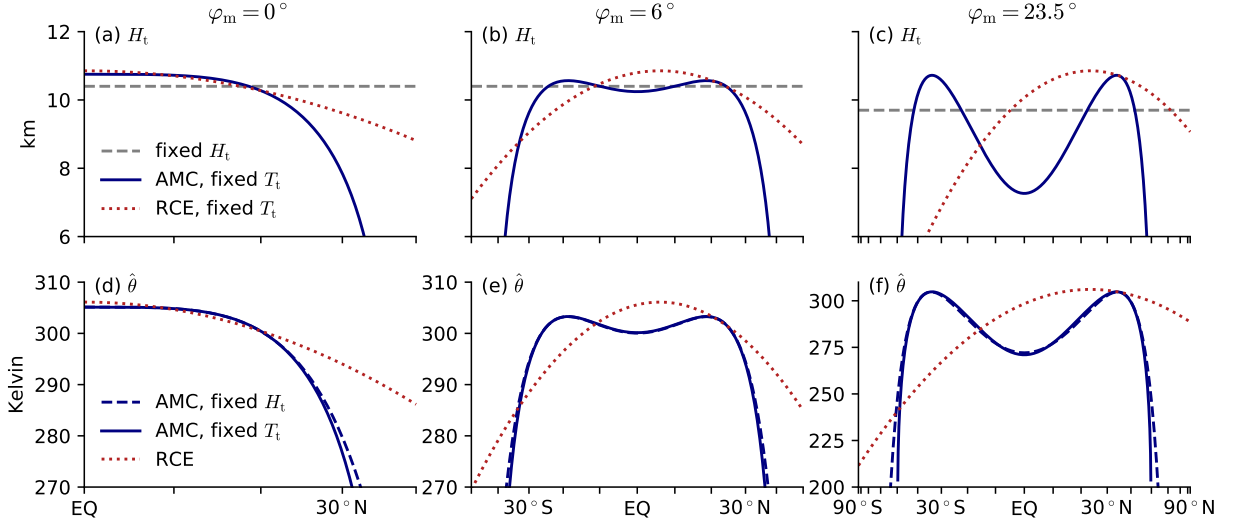


FIG. 3. (top row) Tropopause height and (bottom row) vertically averaged potential temperature corresponding to the RCE state given by (2), with the forcing maximum latitude φ_m set to (columns, left to right) 0, 6, or 23.5° , or to the angular momentum conserving (AMC) model, with the ascent latitudes used for the AMC solutions computed using the equal-area model applied to the given RCE potential temperature profile (listed in Table 1), and with either the tropopause (dashed) height or (solid) temperature assumed fixed. Note differing horizontal axis ranges in each column and differing vertical axis ranges across panels in the bottom row.

directly alter $u_{t,\text{rce}}$ and, through modifying φ_a , indirectly alter u_{amc} . Under annual-mean forcing, $\varphi_a = \varphi_m = 0$ regardless of the tropopause treatment, and the $u_{\text{amc}} = u_{t,\text{rce}}$ latitudes are essentially unchanged going from a fixed H_t to a fixed T_t . For $\varphi_m = 6^\circ$, the equal-area-predicted φ_a is altered by only 0.1° by the tropopause treatment. The summer-hemisphere $u_{\text{amc}} = u_{t,\text{rce}}$ point is moved slightly poleward by a fixed T_t (by 0.2°), but its winter-hemisphere counterpart contracts equatorward by slightly more, 0.4° . For $\varphi_m = 23.5^\circ$, the equal-area-predicted φ_a is more sensitive to the tropopause treatment, being 34.5 vs. 33.8° for a fixed height or temperature, respectively. This and the alterations to $u_{t,\text{rce}}$ cause the summer-hemisphere $u_{t,\text{rce}} = u_{\text{amc}}$ point to contract from 35.4 to 34.8° and the corresponding winter-hemisphere point to contract from -38.7 to -36.7° .

6. Effect of a fixed T_t on the equal-area model

The equal-area model assumes that the Hadley cells conserve⁵ angular momentum, that column-averaged temperature is continuous at all cell edges (which requires the Hadley cell temperatures to equal the RCE temperatures at the circulation's outer edges), and that the cells conserve energy in the sense that the potential temperature

integrated over the extent of each cell is the same as it was over that extent in the RCE state (Held and Hou 1980; Lindzen and Hou 1988). It predicts, given only the knowledge of the RCE potential temperature distribution, the locations of all three Hadley cell edges (the two poleward edges and φ_a) and $\hat{\theta}_a$.

Figure 4 shows the equal-area model solutions for the three cell edges for φ_m varied from 0.1 up to 23.5° , with the AMC temperature fields constructed either using (7) (in all cases with $\bar{H}_t = 10$ km) or (8) (with $T_t = 200$ K), and with all other parameters Earth-like. And Table 1 lists these values and the corresponding $\hat{\theta}_a$ solutions for the $\varphi_m = 0, 6, 23.5^\circ$ cases. Because going from fixed- H_t to fixed- T_t tends to sharpen the subtropical shoulder in $\hat{\theta}_{\text{amc}}$, the equal-area solutions for the cell poleward edges typically move equatorward, the more so the farther poleward φ_m is and more so in the winter hemisphere than summer hemisphere (cf. Table 1, for $\varphi_m = 6^\circ$ the summer hemisphere edge actually moves slightly poleward). And φ_a moves either very weakly ($\varphi_m = 6^\circ$) or modestly equatorward ($\varphi_m = 23.5^\circ$). Though the three predicted cell edges all move equatorward when comparing fixed H_t to fixed T_t calculations (for sufficiently large φ_m), the equal-area predicted Hadley cell extents are still appreciably larger than observed and simulated solstitial Hadley cell extents for Earth (Hill et al. 2019).

Also overlaid in Figure 4 are the $\eta_{t,\text{rce}} = 0$ locations assuming either fixed- H_t or fixed- T_t in Figure 4. As φ_m moves poleward and the overall predicted Hadley circulation grows, $\eta_{t,\text{rce}} = 0$ falls equatorward of φ_m and becomes

⁵In the “strict” sense as in the preceding section, wherein the entire free-tropospheric expanse of the Hadley circulation possesses a single value of angular momentum. The term “angular-momentum-conserving” is sometimes used in a weaker sense in reference to states in which Hadley cell streamlines and angular momentum contours are (approximately) coincident but the angular momentum nevertheless varies appreciably across the cells in the free troposphere.

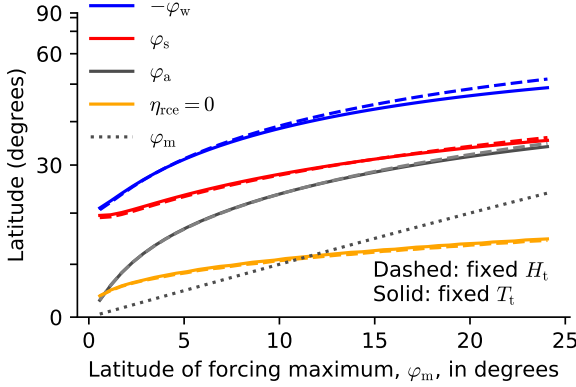


FIG. 4. Equal-area model solutions for the latitude of the poleward edges of the winter (φ_w ; flipped in sign for easier visual comparison with the other metrics) and summer (φ_s) Hadley cells and their shared edge (φ_a), for φ_m ranging from 0.5 to 23.5°, with θ_{ame} derived with either the tropopause (dashed) height or (solid) temperature assumed constant. (Orange curves) latitude in the summer hemisphere where $\eta_{\text{lrce}} = 0$. Note that both the horizontal- and vertical-axis spacing are linear in sine of latitude.

increasingly separated from φ_a (Hill et al. 2019), and this is insensitive to the tropopause treatment.

7. Numerically simulated and analytically approximated latitude-by-latitude RCE

The previous sections indicate that the results of nearly inviscid, axisymmetric Hadley cell theory are largely insensitive to how the tropopause height varies with latitude, at least under the given analytical profiles of the RCE thermal state. In principle, however, the tropopause treatment could be more influential when a more realistic latitude-by-latitude RCE state is considered. And, as described in the Introduction, the accuracy of the fixed- T_t assumption as applied on a latitude-by-latitude basis requires additional consideration. This section addresses those concerns.

a. Model and simulations description

We use the single-column model provided by the `climlab` package (Rose 2018) for the Python programming language. Convection is represented by simple convective adjustment (Manabe and Wetherald 1967) to a specified lapse rate that we set to 0.65 times the dry adiabatic. Radiative transfer calculations use the RRTMG model (Mlawer et al. 1997) assuming clear-sky conditions and a uniform surface albedo of 0.3. Relative humidity is prescribed, using the profile of Manabe and Wetherald (1967) (see their Eq. 2), which decreases in height from a surface value of 0.77 but is uniform horizontally and in time. The

surface is a mixed layer ocean of 1 meter depth.⁶ There are no surface turbulent fluxes; instead convective adjustment adjusts both atmospheric and surface temperatures, with the surface timescale dependent on the mixed-layer depth. This setup is very similar to the single-column model used by Dacie et al. (2019) in their study of the tropical tropopause layer.

Simulations are performed with time-invariant insolation representing present-day, annual-mean insolation sampled at latitude values separated by 1°, from 89.5°S to 89.5°N. Each is run for 3000 days, with averages taken over the last 2200 days, wherein a steady state has been reached (Cronin and Emanuel 2013). Each column has 100 evenly spaced pressure levels from the surface to 0 hPa. We emphasize that each latitude is its own single-column simulation with no communication across latitudes. The latitude value for each simulation is used to specify the insolation only; the single-column model does not account for rotational effects and is thus agnostic to the local Coriolis parameter.

From the equilibrated temperature profiles in each column, the tropopause is computed using several different metrics: the World Meteorological Organization definition of the lowest point at which the lapse rate reaches 2 K km⁻¹ (WMO 1957); the “cold point tropopause”, i.e. the coldest point in each column; and, c.f. Schneider and Walker (2006), the location where the vertical curvature in temperature, i.e. $\partial_{zz}T$, maximizes. A fixed-height tropopause definition is also computed using a value of 14 km, a value chosen by eye to be similar within the Tropics to the other tropopause definitions (results are insensitive to reasonable modifications of this value; not shown). On similarly ad-hoc grounds, we select the 214 K isotherm as the fixed-temperature tropopause; values closer to the 200 K used in the preceding analytical work yields too deep a tropopause in the Tropics compared to the other definitions (not shown).

To remove the distracting influence of gridpoint noise, we apply a 1-2-1 smoothing filter in latitude to the temperature field. Because the insolation and other boundary conditions are symmetric about the equator, we average the model output at each latitude across the northern and southern hemispheres after applying the smoothing but before computing the various tropopause definitions or the gradient wind.

b. Results

Figure 5 shows the simulated equilibrium temperature distribution as a function of latitude and pressure with the tropopause indicators overlaid. All become colder overall going from the Equator to the poles. Unlike all

⁶ A smaller mixed layer depth would lead to faster equilibration times, but at smaller depths instabilities can arise in highly insolated columns that cause the model to crash.

the other tropopause definitions, the pressure level of the fixed-height tropopause is highest in the tropics. All others generally become colder and sit at higher pressures moving poleward and are oriented with the curvature-based value below the WMO value, both of which sit somewhere below the cold point (Hu and Vallis 2019).

Qualitatively, the fixed- T_t assumption is largely borne out, in the sense that the given isotherm remains in the vicinity of the other, more conventional tropopause definitions from the equator to mid-latitudes. And the other tropopause definitions all occur at temperatures within 210–220 K within 30°S–30°N. At the same time, the fixed- T_t definition has the sharpest meridional drop of all, with near the highest values of all the definitions at the Equator, dropping to the lowest in the mid-latitudes, and then further dropping precipitously, nearly to the surface, at the poles.

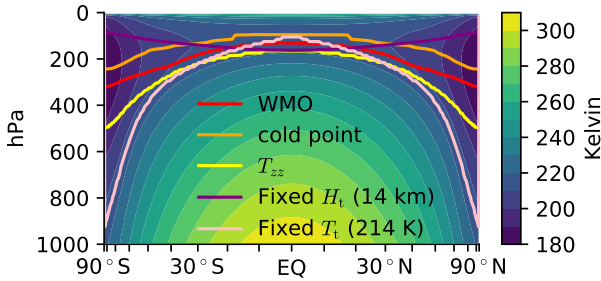


FIG. 5. (Filled contours) temperature in the single-column model simulations of latitude-by-latitude RCE with values as indicated in the colorbar. The overlaid thick contours are various definitions of the tropopause, with colors corresponding to the legend.

Solid curves in Figure 6 show $u_{t,rce}$ as a function of latitude diagnosed at each of these tropopause definitions, computed using the expression for gradient balance in pressure coordinates. Assuming negligible surface wind, this is

$$u(p, \varphi) = \Omega a \cos \varphi \left(\sqrt{1 - \frac{1}{\cos \varphi \sin \varphi} \frac{R_d}{\Omega^2 a^2} \ln \left(\frac{p_0}{p} \right)} \frac{\partial \hat{T}}{\partial \varphi} - \hat{T} \right)$$

where \hat{T} is the log-pressure-weighted average temperature from the surface pressure (set always to $p_0 = 1000$ hPa) to the given pressure p .⁷

All share a common overall structure, maximizing near the equator and decreasing mostly monotonically poleward. Depending on the tropopause definition, the diagnosed $u_{t,rce}$ value differs by as much ~ 15 m s⁻¹ at some low latitudes (and by more still at higher latitudes, but

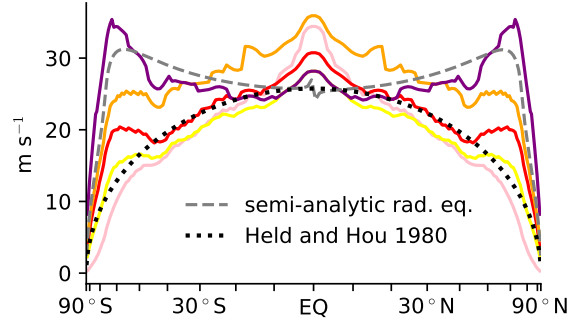


FIG. 6. (solid curves) $u_{t,rce}$ computed using the temperature structure from the single-column model simulations of latitude-by-latitude RCE shown in Figure 5, assuming negligible surface wind, and using various definitions of the tropopause as indicated by the legend in Figure 5. (dashed grey) semi-analytical, radiative-equilibrium solution for surface temperature described in the main text, a tropopause height of 10 km, and a lapse rate of $\Gamma = \gamma T_d$ with $\gamma = 0.65$ (small local maxima and minima straddling the equator are finite-differencing artifacts). (dotted black) the $u_{t,rce}$ distribution from Held and Hou (1980) (in its original, fixed- H_t form) using $\Delta_h = 1/8$ and $H_t = 10$ km.

those are of less relevance to the Hadley cells). However, in the subtropics where the $M_{t,rce} > \Omega a^2$ condition becomes no longer satisfied, the $u_{t,rce}$ (and in turn $M_{t,rce}$) differences across definitions are more modest: the $M_{t,rce} = \Omega a^2$ point lies between 12.5 and 13.5° for all of them except for the cold-point-based value, which is slightly farther poleward at 14.8° (not shown).

c. Non-numerical approximations to simulation results

We now consider two approximations to this simulated latitude-by-latitude RCE state that do not require running a numerical model. The first, which is purely analytic, is simply the original $\hat{\theta}_{rce}$ profile of Held and Hou (1980) — i.e. that in gradient balance with (2) for $\varphi_m = 0$ — and the corresponding gradient-balanced zonal wind at the tropopause (see Eq. 5 of Held and Hou 1980). To best fit the simulated latitudinal profile of depth-averaged temperature, we set Δ_h to 1/8 [smaller than the 1/3 and 1/6 values used by Held and Hou (1980) and Lindzen and Hou (1988), respectively]. In computing $u_{t,rce}$, we retain the original $H_{t,rce} = 10$ km value of Held and Hou (1980).⁸

The second, which is semi-analytical, applies the well-known planetary energy balance (i.e. radiative equilibrium) model with a one-layer greenhouse at each latitude. Given the local top-of-atmosphere insolation S and albedo

⁷Symbolically, $\hat{T} \equiv (\int_{\ln p}^{\ln p_0} T d \ln p) / \ln(p_0/p)$, a slight deviation from the previous notation in which hatted quantities corresponded to vertical averages (using the appropriate vertical coordinate) from the surface all the way to the tropopause.

⁸These parameter values result in a thermal Rossby number, $R \equiv g H_{t,rce} \Delta_h / (\Omega^2 a^2)$, of ~ 0.06 , much lower than the original thermal Rossby number value from Held and Hou (1980) of ~ 0.15 . If the latter is used, the resulting $u_{t,rce}$ values are too large over most of the domain, in particular being roughly 2–3 times as large as the simulated values at low latitudes (not shown).

α , this yields a surface temperature of

$$T_s = 2^{1/4} \left[\frac{S(1-\alpha)}{\sigma} \right]^{1/4},$$

where σ is the Stefan-Boltzmann constant. The corresponding $u_{t,rce}$ field is then computed as follows. First, given T_s and $\Gamma = \gamma\Gamma_d$ and neglecting any difference between surface pressure and the reference pressure appearing in the potential temperature (i.e. assuming $p_s = p_0$), it follows that $\theta(z) = T_s^{1/\gamma}(T_s - \gamma\Gamma_d z)^{1-1/\gamma}$, and therefore

$$\hat{\theta} = \frac{\gamma}{2\gamma-1} \frac{T_s^{1/\gamma}}{T_s - T_t} \left(T_s^{2-1/\gamma} - T_t^{2-1/\gamma} \right). \quad (9)$$

Using (9) at each latitude with $\gamma = 0.65$ and the simple radiative-equilibrium-predicted T_s , we compute the corresponding $\hat{\theta}$ distribution. We then compute $u_{t,rce}$ using (5) setting $\theta_0 = 290$ K and, to be consistent with the Held and Hou (1980) approximation, $H_{t,rce} = 10$ km.

Figure 7 shows, as deviations from their global average, the latitudinal distributions of troposphere-averaged temperature from the simulations (assuming a uniform tropopause pressure of 150 hPa) and potential temperature from the two approximations. Both approximations capture the overall meridional structure from the simulations, though with a steeper drop off toward the poles, particularly for the radiative equilibrium solution.

The $u_{t,rce}$ fields computed using these two approximations are overlaid in Figure 6. The $u_{t,rce}$ values predicted by both approximations (and as a result the corresponding $M_{t,rce}$ values; not shown) fall within the range of the various diagnosed values at most latitudes, most importantly in the aforementioned 12.5-15.0°N range where the $M_{t,rce} = \Omega a^2$ point occurs.

These results suggests that, for the sake of the Hadley cells at the level of accuracy presently considered, the properties of the latitude-by-latitude RCE state that acts as the “forcing” driving the Hadley cells can be interrogated without integrating a numerical model. Most usefully, they are captured adequately by the well-known analytical forcing from Held and Hou (1980) (with Δ_h modified from 1/3 to 1/8).

8. Summary

Studies of axisymmetric Hadley cell theory — namely, those using Hide’s theorem, the angular-momentum-conserving (AMC) model, and the equal-area model — have traditionally assumed that the tropopause height is uniform in latitude in the absence of an overturning circulation, i.e. in latitude-by-latitude radiative-convective equilibrium (RCE), and is unchanged by the emergence of the Hadley circulation. But recent work (Seeley et al. 2019b) suggests that the tropopause temperature is more nearly invariant than the tropopause height in RCE, at least

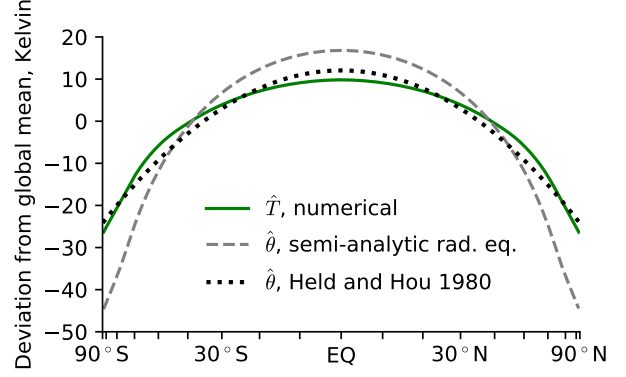


FIG. 7. (solid green) Temperature (in Kelvin) from the single-column-model simulations averaged in pressure from the surface to the local tropopause (defined as occurring at a fixed pressure, 150 hPa, at all latitudes) and potential temperature from (dashed gray) the semi-analytical, radiative-equilibrium approximation and (dotted black) the original Held and Hou (1980) analytical expression for annual-mean forcing, both averaged from the surface to a specified tropopause height of 10 km. All three are presented as deviations from their respective global mean, since it is their meridional structure that influences $u_{t,rce}$.

on a domain-mean basis. Insofar as the tropopause temperature and vertically averaged lapse rate do not vary meridionally, the tropopause height varies linearly with surface temperature, and the resulting meridional variations in tropopause height alter the gradient-balanced zonal wind at the tropopause that figures centrally in Hide’s theorem, the AMC model, and the equal-area model. We re-derive these axisymmetric theories assuming that the tropopause temperature is constant in latitude and across climate states. We then examine the tropopause temperature and Hadley cell metrics in numerical simulations of annual-mean, latitude-by-latitude RCE using a single-column model.

If the tropopause temperature is uniform, under standard annual-mean and solsticial Newtonian cooling reference temperature profiles (Lindzen and Hou 1988) the RCE tropopause height can vary in latitude by $\sim 40\%$ across the Tropics, being deepest where surface temperature is largest. Compared to the case if the tropopause height were uniform in latitude, the resulting gradient-balanced zonal wind at the tropopause can differ by up to tens of m s^{-1} , but over most of the domain the differences are a few m s^{-1} or less, particularly in the subtropics. Differences between fixed-height and fixed-temperature calculations are largest in the winter hemisphere for solsticial forcing and increase as the forcing maximum is moved toward the summer pole.

As such, the resulting absolute angular momentum and absolute vorticity fields, and with them the range of supercritical forcing based on the conditions of Hide’s theorem, are weakly modified, by $\lesssim 1^\circ$. This is both because of the modest magnitudes of the changes to $u_{t,rce}$ and also be-

cause the Hide’s theorem criteria typically stop being met in the subtropics precisely where the fixed-temperature tropopause height approaches its tropical-mean value that seems the most appropriate value to use for fixed-height calculations. In other words, where the values of $u_{t,\text{rce}}$ matter most for Hide’s theorem, they are least sensitive to the tropopause treatment.

The angular-momentum-conserving (AMC) zonal wind, u_{amc} , is determined by the ascent latitude ϕ_a and is a function of latitude but not height (in thin-shell atmospheres like Earth’s). It is thus unaltered by the tropopause treatment, but tropopause height variations consistent with a fixed T_t engender changes in the “critical” temperature field in gradient balance with that u_{amc} field. Specifically, a sharp subtropical shoulder in H_t causes $\hat{\theta}_{\text{amc}}$ to also have a sharper shoulder than does the fixed- H_t calculation. When plugged into the equal-area model, this results in a trivial to modest equatorward contraction of the overall predicted Hadley circulation extent. Qualitatively similar results for both the RCE and AMC quantities are found whether a dry or moist adiabat is assumed in the Boussinesq framework or if the CQE framework is used (Appendixes A and B).

The tropopause temperature is reasonably uniform in latitude across the Tropics in single-column model simulations sampling the full latitudinal range of Earth’s annual-mean insolation. As was the case for the results using analytically specified RCE potential temperature profiles, the diagnosed $u_{t,\text{rce}}$ field and with it the minimal Hadley cell extent from Hide’s theorem is only modestly sensitive to the tropopause definition. Moreover, the simulated temperature fields and corresponding diagnosed $u_{t,\text{rce}}$ fields are, given the purposes, adequately approximated by both a semi-analytical approximation based on latitude-by-latitude radiative equilibrium and (with one parameter value modified from its standard value) the fully analytical forcing profile of Held and Hou (1980).

9. Discussion

We have assumed identical lapse rates and tropopause temperatures in RCE and in the presence of a large-scale overturning circulation. However, the Hadley cells must generate some positive static stability (dry in a dry atmosphere, moist in a moist atmosphere) that is not present in a true state of RCE in order to effect any net meridional energy transport and thus alter the depth-averaged temperature fields (Caballero et al. 2008). While this increased static stability going from RCE to the dynamically equilibrated state would not appear to alter the influence of the fixed- T_t assumption, it could in principle alter the equal-area solutions: at low latitudes, $\hat{\theta}$ will have increased overall, likely leading to a smaller meridional extent that conserves the $\hat{\theta}$ integral from the RCE state.

For moist atmospheres, some meridional variation in the vertically averaged lapse rate is likely over the extent of the Hadley cells, as can be seen from two largely independent lines of argument. First, cf. Held (2000), convection will be deepest where insolation and surface temperatures are highest, which combined with the weak temperature gradient (WTG) constraint at low latitudes (e.g. Sobel et al. 2001) sets the lapse rate remotely also. The resulting static stability suppresses convection in columns with lower insolation and surface temperature, ultimately producing an inversion at the boundary layer top. Second, cf. Emanuel (1995), if a significant fraction of a parcel’s moisture is rained out in the ascending branch, then the parcel will be forced to warm dry adiabatically over most of its return to the surface in the descending branch, setting up a different lapse rate between the two branches and leading to a de-coupling between the boundary layer and the free troposphere in the descending branch.

In the real tropics, a physically unambiguous tropopause level is not generally found; instead, the level where clear-sky radiative heating vanishes occurs below where the WMO lapse-rate definition is met, which in turn sits below the cold point tropopause. The behavior of this tropical tropopause layer involves a rich interplay among radiative, dynamical (incorporating both the tropospheric circulations and the stratospheric Brewer-Dobson circulation), chemical, and thermodynamic processes (Fueglistaler et al. 2009). This makes temperature-based tropopause definitions less capable of demarcating the boundary between the dynamically active troposphere and (by comparison) dynamically quiescent stratosphere (Hu and Vallis 2019).

Moreover, in principle the depth of the Hadley circulation could separate from any of these other metrics. But one can argue that it should be closely related to the dynamical boundary between the troposphere and stratosphere: insofar as the majority of deep convection that penetrates to the tropopause occurs within the ITCZ as part of the zonal-mean Hadley cells, then the height of the Hadley circulation will indeed be the same height as the tropopause.

In response to mean surface warming, the temperature at which these metrics occur can rise non-trivially in GCMs (e.g. Vallis et al. 2015; Lin et al. 2016; Hu and Vallis 2019), in contrast to the RCE results in cloud resolving models, which are more climate-state invariant (Seely et al. 2019b). Singh (2019) find the surface-tropopause temperature drop to be nearly invariant within the tropics in their idealized aquaplanet GCM featuring grey radiative transfer. Meanwhile, from Fig. 7 of Hu and Vallis (2019), one can infer that, in CMIP5 models in the first century of a standard CO_2 doubling simulation (with CO_2 increased by 1% per year until the initial value is doubled, in year 70), this surface-tropopause temperature difference increases markedly in high latitudes (where the surface

warms strongly and the tropopause weakly) but least of all in the Tropics (where, compared to higher latitudes, the surface warming is more moderate and tropopause warming more appreciable). Thus, to first order for the sake of the Hadley cells, a uniform $T_s - T_t$ value is reasonable, helping to explain that assumption's utility in the CQE framework.

The meridional structure of H_t in the fixed- T_t AMC solution for an on-equatorial forcing maximum bears resemblance to the real-world, annual-mean structure at sufficiently low latitudes (see e.g. Fig. 1a of Hu and Vallis 2019), being quite flat over the deep tropics but with a sharp shoulder in the subtropics (though, of course, with the real world shoulder then tapering off towards a more linear and gentle decrease in height moving farther poleward). This shoulder occurs farther poleward in observations (near $\sim 30^\circ$) than in the fixed- T_t AMC solution (closer to $\sim 20^\circ$). The poleward flanks of the annual-mean and equinoctial cells are known to be very strongly influenced by baroclinic eddy processes, and the AMC model is arguably inappropriate there, meaning that this similarity may not have much physical relevance for Earth. However, the fixed- T_t AMC shoulder may be of relevance to slower-rotating, smaller, or less strongly insulated planetary bodies (more formally, those with larger thermal Rossby numbers), since in such atmospheres baroclinicity is less important and axisymmetric processes more important. More generally, it is possible that sufficiently strong forcing or in planetary atmospheres sufficiently removed in parameter space from Earth's atmosphere, tropopause variations could make more of an impact than in the solutions we have presented for Earth under conventional forcings.

But for Earth's Hadley cells, these analytical results suggest that — notwithstanding concerns regarding the relevance of axisymmetric theory to Earth's macroturbulent, strongly eddying atmosphere (e.g. Schneider 2006) — the axisymmetric theory itself is quite insensitive to meridional tropopause variations. This should bolster (however modestly) our confidence in classical, dry, Boussinesq, nearly inviscid axisymmetric theory's utility: whatever its imperfections, assuming a fixed tropopause height is not an important one.

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APPENDIX A

Fixed- T_t , non-dry-adiabatic derivations and results in the Boussinesq system

In this Appendix, we reproduce the relevant Boussinesq derivations from the main text but without the assumption of dry adiabatic stratification. We continue to assume a uniform lapse rate, but it now takes the form $\Gamma = \gamma\Gamma_d$, with $\gamma < 1$ representing dry-stable stratification.

Evaluating the integral on the right-hand side of (3) then requires the Leibniz integral rule, yielding

$$\int_0^{H_t(\varphi)} \frac{\partial \theta}{\partial \varphi} dz = H_t \frac{\partial \hat{\theta}}{\partial \varphi} - (\theta_t - \hat{\theta}) \frac{\partial H_t}{\partial \varphi} \quad (\text{A1})$$

where θ_t is potential temperature at the tropopause. After using (A1) in (3), the derivation for u_t proceeds as standard (i.e. by using the quadratic formula to solve for u_t), resulting in

$$u_t = \Omega a \cos \varphi \left[\sqrt{1 - \frac{1}{\cos \varphi \sin \varphi} \frac{g}{\Omega^2 a^2 \theta_0} \left(H_t \frac{\partial \hat{\theta}}{\partial \varphi} - (\theta_t - \hat{\theta}) \frac{\partial H_t}{\partial \varphi} \right)} - 1 \right] \quad (\text{A2})$$

If $\gamma < 1$, then $\theta_t > \hat{\theta}$. Moreover, we expect the meridional gradients of $\hat{\theta}$ and H_t to have the same sign: the warmer the troposphere, the deeper the tropopause. Under these conditions, meridional tropopause height variations always act to reduce the magnitude of u_t compared to if H_t had the same value locally and no meridional gradient.

Even given a $\hat{\theta}_{\text{rce}}$ field, (A2) is not a closed expression unless T_s is known, which requires numerically solving (9) for T_s . One could instead take the distribution of T_s as fixed and use it to solve for $\hat{\theta}$, but then the $\hat{\theta}_{\text{rce}}$ profile is no longer identical between the fixed- H_t and fixed- T_t cases, complicating the interpretation of any differences in the Hadley cell metrics between them.

The presence of the $(\theta_t - \hat{\theta}) \partial_\varphi H_t$ term in the gradient balanced $u_{t,\text{rce}}$ for $\gamma < 1$ makes a compact analytical solution for the fixed- T_t $\hat{\theta}_{\text{amc}}$ field unattainable.

We conclude this Appendix by comparing the fixed lapse rate, $\Gamma = \gamma\Gamma_d$ formulation to the original vertical structure in θ_{rce} chosen by Held and Hou (1980) and Lindzen and Hou (1988). The latter is $\theta_{\text{rce}}(z)/\theta_0 = \dots + \Delta_v(z/H_t - 1/2)$, where $\Delta_v = 1/8$ is an imposed fractional potential temperature increase from the surface to the tropopause. Assuming $p_s = p(z=0) = p_0$, this implies a lapse rate of

$$\frac{dT}{dz} = \frac{\theta_0 \Delta_v}{H_t} - \Gamma_d \left[1 + \frac{R_d}{c_p} \ln \left(\frac{p_0}{p} \right) \right].$$

Using parameter values from Lindzen and Hou (1988), this yields effective γ values ranging from roughly 0.7 to 0.9, with the lapse rate decreasing vertically upward and

poleward away from the forcing maximum (not shown). All else equal, vertically averaged lapse rates with $\gamma \approx 0.65$ would require $\Delta_v \approx 1/4$ (not shown).

APPENDIX B

Fixed- T_t derivations and results in the CQE system

a. Gradient balance

The CQE derivation of gradient balance proceeds identically whether or not T_t is taken as fixed. Following Emanuel (1995), gradient balance in a CQE atmosphere may be expressed as

$$\left. \frac{\partial T}{\partial p} \right|_{s^*} \frac{\partial s_b}{\partial \varphi} = \frac{1}{a^2} \frac{\sin \varphi}{\cos^2 \varphi} \frac{\partial M^2}{\partial p}, \quad (\text{B1})$$

where s^* is the saturation moist entropy and $s_b = c_p \ln \theta_{eb}$ the subcloud moist entropy with θ_{eb} the subcloud equivalent potential temperature. The core assumption of (strict) CQE is that $s^*(p) \equiv s_b$ at each latitude: convection is sufficiently frequent and vigorous as to make the time-mean stratification exactly moist adiabatic, with the time-mean saturation moist entropy at each height equal to the time-mean moist entropy of the subcloud air transported into the free troposphere by the convection. Integrating from the surface where $u \approx 0$ and thus $M \approx \Omega a^2 \cos^2 \varphi$ to the tropopause yields

$$(T_s - T_t) \frac{\partial s_b}{\partial \varphi} = \frac{1}{a^2} \frac{\sin \varphi}{\cos^2 \varphi} (M^2 - \Omega^2 a^4 \cos^4 \varphi). \quad (\text{B2})$$

Using the definitions of s_b and M , solving for $u_{t,\text{rce}}$ yields

$$u_{t,\text{rce}} = \Omega a \cos \varphi \left[\sqrt{1 - \frac{1}{\cos \varphi \sin \varphi} \frac{c_p (T_s - T_t)}{\Omega^2 a^2 \theta_{eb}} \frac{\partial \theta_{eb}}{\partial \varphi}} - 1 \right]. \quad (\text{B3})$$

b. Critical subcloud equivalent potential temperature field

If $T_s - T_t$ is fixed, the CQE θ_{eb} distribution in gradient balance with u_{amc} is, cf. Eq. 11 of Emanuel (1995),

$$\theta_{eb} = \theta_{eb,a} \exp \left[-\frac{\Omega^2 a^2}{2c_p (T_s - T_t)} \frac{(\cos^2 \varphi_a - \cos^2 \varphi)^2}{\cos^2 \varphi} \right], \quad (\text{B4})$$

where $\theta_{eb,a}$ is the value of θ_{eb} at φ_a .

Unlike for the gradient balance derivation, T_s must be specified in deriving the fixed- T_t AMC θ_{eb} . On the one hand, the inclusion of moisture in the expression for θ_e acts to make it larger than T_s . On the other hand, we can expect a steeper-than-moist-adiabatic lapse rate below cloud base due to the relative dearth of condensation. This acts to make T_s warmer than it would be if the stratification

was moist adiabatic all the way to the surface — the more so the steeper the lapse rate or the deeper the subcloud layer. Given the level of approximation we are working at, these (at least partially) canceling influences lead us to simply take $\theta_{eb} \approx T_s$.

Under this assumption, the AMC θ_{eb} profile obeys

$$\theta_{eb} - T_t \ln \frac{\theta_{eb}}{\theta_{eb,a}} = \theta_{eb,a} - \frac{\Omega^2 a^2 (\cos^2 \varphi_m - \cos^2 \varphi)^2}{2c_p \cos^2 \varphi}. \quad (\text{B5})$$

This is not readily solvable analytically but is so numerically via standard root-finding algorithms (in this case, Brent's method as implemented in the *scipy* package for the Python programming language).

Figure B1 shows critical potential temperature profiles for three different fixed tropospheric depths and with varying depth for three different tropopause temperatures, in all cases with $\varphi_a = 23.5^\circ$ and $\theta_{eb,a} = 350$ K. By construction, all curves are equal to θ_{bm} at φ_m . The θ_{eb} distribution attained with varying tropopause temperature has less meridional curvature at the equator and a weaker equator-to- φ_m gradient than the original, fixed tropopause version. The default cases (orange solid and middle dashed curves) differ by roughly 3 K at the equator, with the fixed- T_t case warmer and thus with a smaller equator-to-maximum gradient.

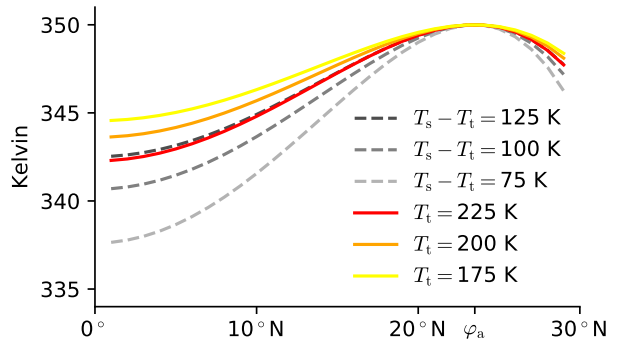


FIG. B1. Subcloud equivalent potential temperature profiles for which gradient wind balance yields AMC zonal wind at the tropopause in the CQE case, with an imposed maximum of $\theta_{eb,a} = 350$ K at $\varphi_m = 23.5^\circ$. The dashed curves assume a fixed tropospheric depth; the solid curves assume fixed tropopause temperature and a surface temperature equal to the lowest level potential temperature. Within either category, different colors correspond to different assumed values of the free parameter, according to the legend.

c. Relationship between Boussinesq and CQE results

The exponential operator in (B4) arises from the use of entropy rather than potential temperature as the thermodynamic tracer (see e.g. Ch. 1 of Vallis 2017). A first-order

Taylor expansion of (B4) yields

$$\frac{\theta_{\text{eb}}(\varphi) - \theta_{\text{eb},a}}{\theta_{\text{eb},a}} \approx -\frac{\Omega^2 a^2}{2c_p(T_s - T_t)} \frac{(\cos^2 \varphi_a - \cos^2 \varphi)^2}{\cos^2 \varphi}, \quad (\text{B6})$$

Comparing (B6) and (7), we see that the Boussinesq $\hat{\theta}_{\text{amc}}$ amounts to a linearization about φ_a of its dry CQE counterpart.

This is demonstrated in Figure B2, which shows (7) and (B4) over one hemisphere with forcing maxima of 0, 20, 40, 60, and 80°N, assuming $\theta_{\text{eb},a} = 350$ K and $T_s - T_t = 100$ K in the Emanuel (1995) solution, and with the Lindzen and Hou (1988) parameters $H = 12$ km and $\theta_0 = 290$ K chosen subjectively and by eye to minimize the difference between the two models. Both versions are mirror-symmetric about the equator, with $\sim \varphi^4$ dependence at the equator for $\varphi_a = 0^\circ$, thereby preventing equatorial westerlies (Schneider 2006; Hill et al. 2019). The Boussinesq solutions have the undesirable feature of passing through absolute zero, but the CQE cases likewise lose their physical meaningfulness once surface temperatures drop to sufficiently low values, certainly once $\theta_{\text{eb}} \sim T_t$.

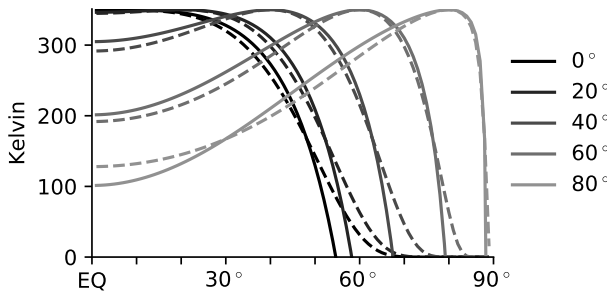


FIG. B2. (Solid curves) Boussinesq $\hat{\theta}_{\text{amc}}$ fields given by (7) and (dashed curves) CQE $\theta_{\text{eb},\text{amc}}$ fields given by (B4). Pairs of curves with the same grey shading are the solutions for a given φ_a , ranging from 0° to 80° by 20° increments. In all cases the potential temperature value ($\hat{\theta}_{\text{amc}}$ for Boussinesq, $\theta_{\text{eb},\text{amc}}$ for CQE) at the maximum is set to 350 K. For the CQE profiles, the difference between the surface and tropopause temperatures, $T_s - T_t$, is taken as a constant 100 K. The free parameters of the Lindzen and Hou (1988) profiles were then chosen subjectively to minimize the differences between the Lindzen and Hou (1988) and Emanuel (1995) solutions. In particular, the assumed tropospheric depth is 12 km, and the reference potential temperature is 290 K. Note that, unlike figures in the main text, the horizontal spacing is linear in latitude, rather than sine of latitude, to make the high-latitude- φ_a curves more easily seen.

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