Chapter 1

Hadley cell dynamics

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1.1 Introduction

Perhaps the simplest possible idealization of a circulation that transports heat from equator to poles is an axisymmetric circulation — that is, a circulation that is independent of longitude — where hot air rises at the equator, moves poleward aloft, cools, sinks at high latitudes, and returns equatorward at depth (near the surface on a terrestrial planet). Such a circulation is termed a *Hadley cell*, and was first envisioned by Hadley in 1735 to explain Earth's trade winds. Most planetary atmospheres in our Solar System, including those of Venus, Earth, Mars, Titan, and possibly the giant planets, exhibit Hadley circulations.

Hadley circulations on real planets are of course not truly axisymmetric; on the terrestrial planets, longitudinal variations in topography and thermal properties (e.g., associated with continent-ocean contrasts) induce asymmetry in longitude. Nevertheless, the fundamental idea is that the longitudinal variations are not *crucial* for driving the circulation. This differs from the circulation in midlatitudes, whose longitudinally averaged properties are fundamentally controlled by the existence of three-dimensional eddies.

Planetary rotation generally prevents Hadley circulations from extending all the way to the poles. Because of planetary rotation, equatorial air contains considerable angular momentum about the planetary rotation axis; to conserve angular momentum, equatorial air would accelerate to unrealistically high speeds as it approached the pole, a phenomenon which is dynamically inhibited. To illustrate, the specific angular momentum about the rotation axis on a spherical planet is $M = (\Omega a \cos\phi + u) a \cos\phi$,

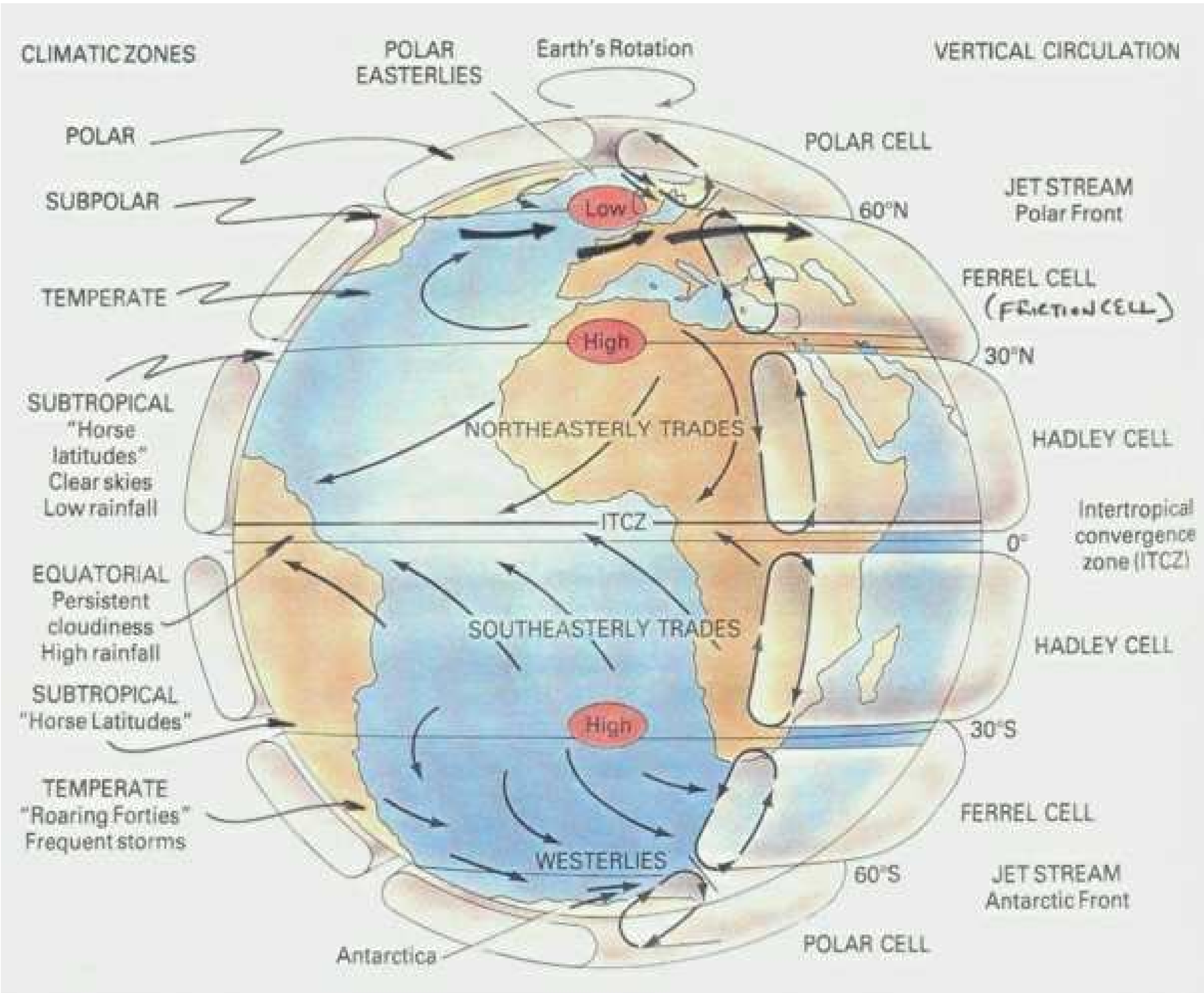


Figure 1.1: **Schematic of Earth's three-cell structure. The cell closest to the equator is the Hadley cell.**

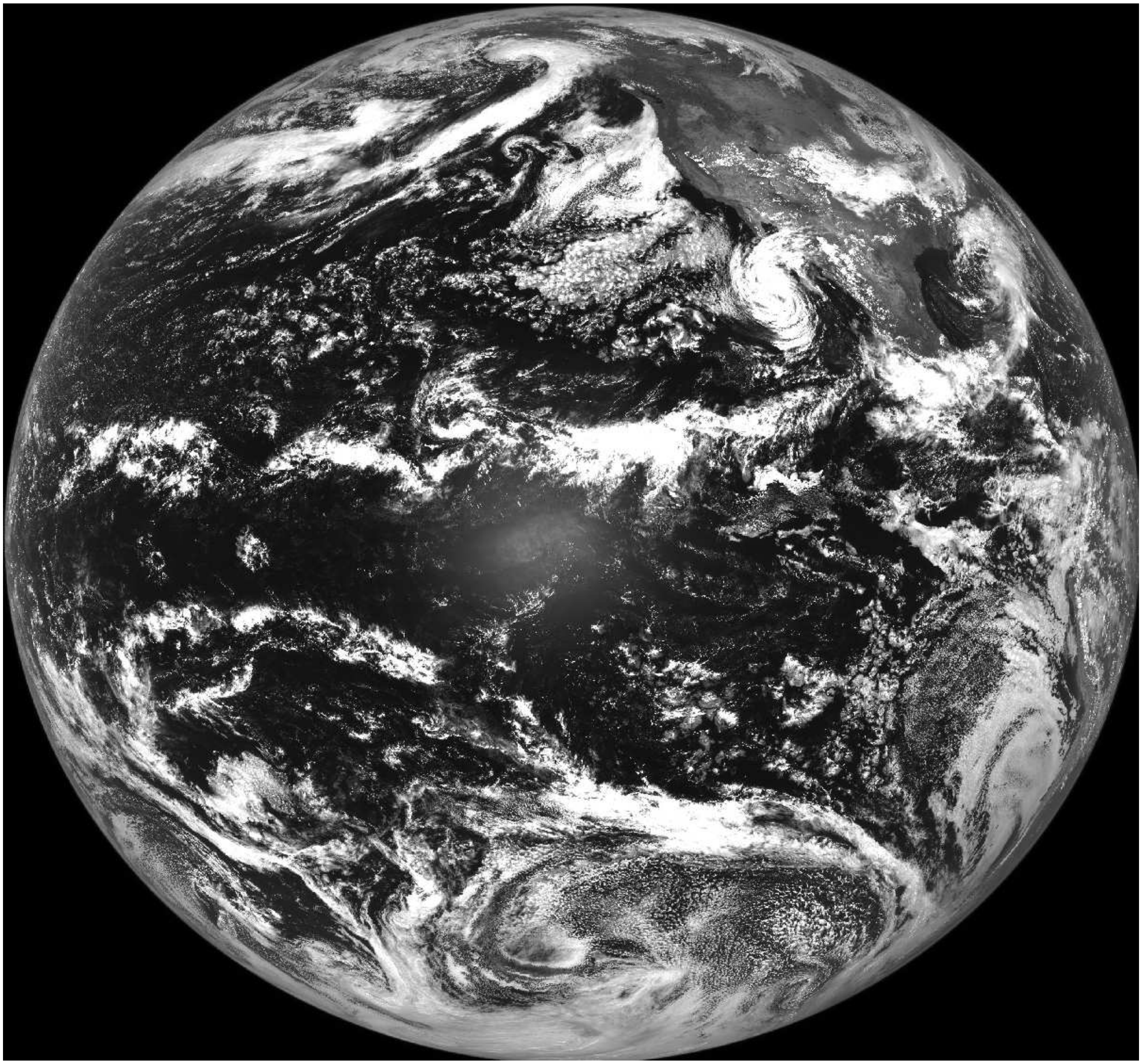


Figure 1.2: **Visible-wavelength image of Earth from GOES geostationary weather satellite. The Intertropical Convergence Zone (ITCZ) can be seen as a zonal band of clouds north of the equator. This is the rising branch of the Hadley cell where thunderstorm activity is prevalent.**

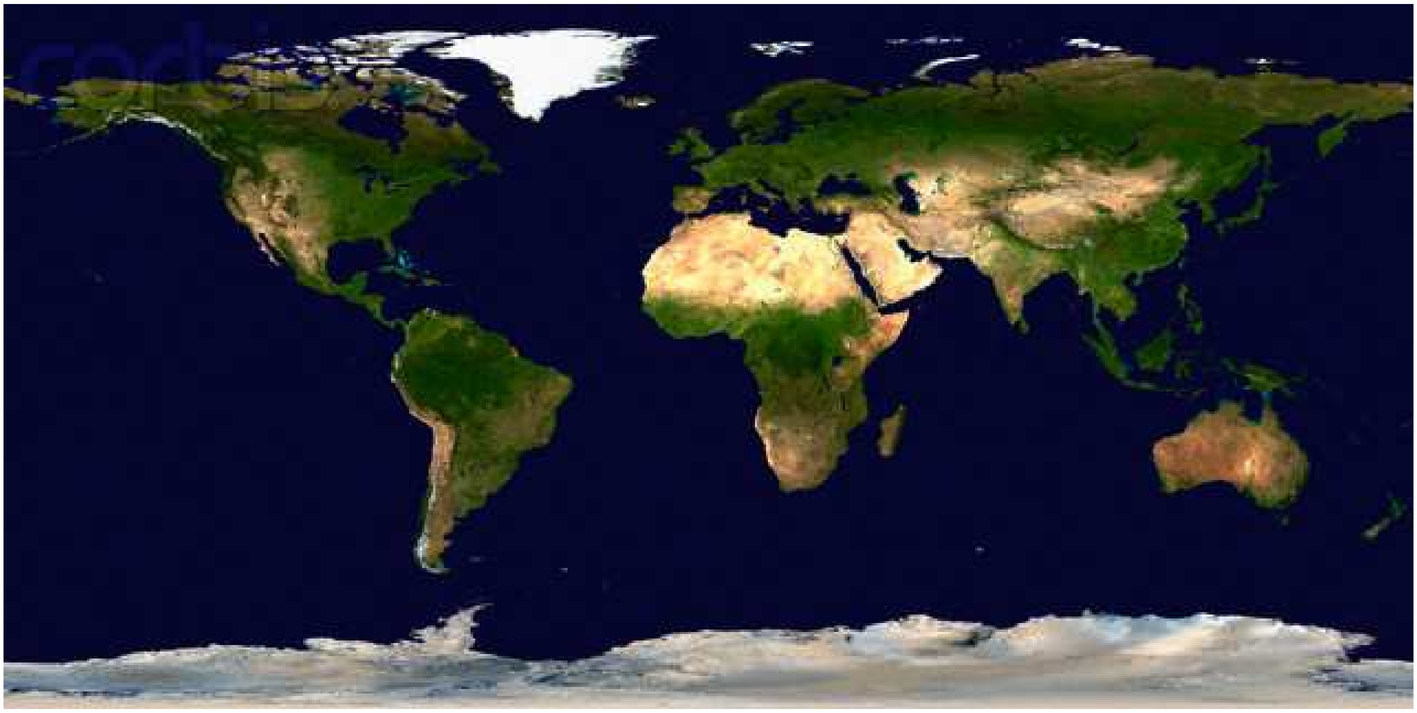


Figure 1.3: **Global mosaic of Earth without clouds or sea ice, illustrating the effect of the Hadley cell. Equatorial regions (within $\pm 20^\circ$ of equator) receive abundant rainfall and show up green; this is the rising branch of the cell. Subtropical regions at ~ 20–30° latitude receive little rainfall and show up brown; this is the descending branch of the cell.**

where the first and second terms represent angular momentum due to planetary rotation and winds, respectively. If $u = 0$ at the equator, then $M = \Omega a^2$, and an angular-momentum conserving circulation would then exhibit winds of

$$u = \Omega a \frac{\sin^2 \phi}{\cos \phi} \tag{1.1}$$

Given Earth's radius and rotation rate, this equation implies zonal-wind speeds of $134\,\mathrm{m\,sec^{-1}}$ at 30° latitude, $700\,\mathrm{m\,sec^{-1}}$ at 60° latitude, and $2.7\,\mathrm{km\,sec^{-1}}$ at 80° latitude. Such high-latitude wind speeds are unrealistically high and would furthermore be violently unstable to 3D instabilities. On Earth, the actual Hadley circulations extend to $\sim 30^\circ$ latitude.

The Hadley circulation exerts strong control over the wind structure, latitudinal temperature contrast, and climate. Hadley circulations transport thermal energy by the most efficient means possible, namely straightforward advection of air from one latitude to another. As a result, the latitudinal temperature contrast across a Hadley circulation tends to be modest; the equator-to-pole temperature contrast on a planet will therefore depend strongly on the width of the Hadley cell. Moreover, on planets with condensable gases, Hadley cells exert control over the patterns of cloudiness and rainfall. On Earth, the rising branch of the Hadley

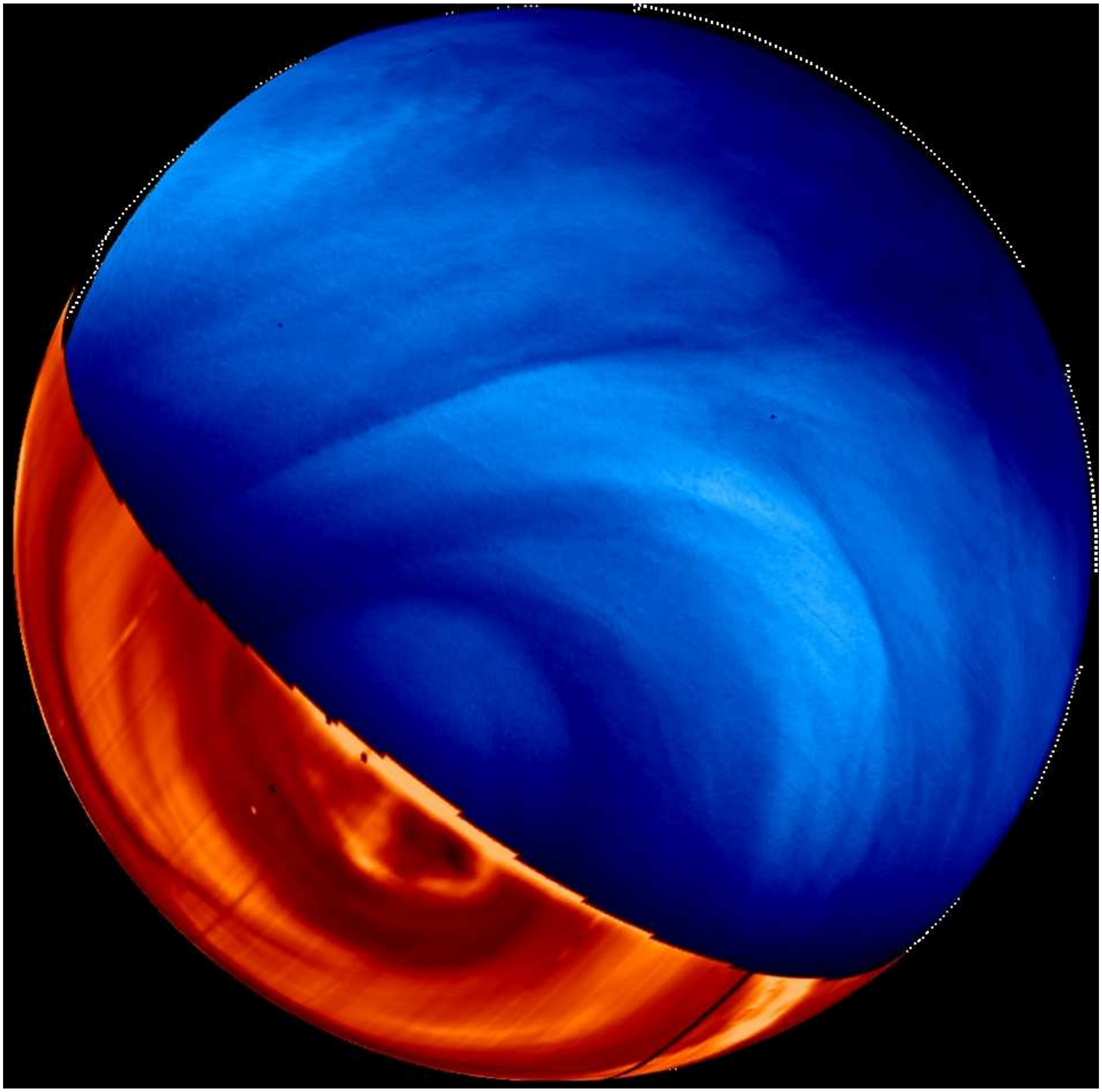


Figure 1.4: **Polar region of Venus in the UV (top; blue) and IR (bottom; red). Polar vortex is visible in the IR data and may represent descending branch of the Hadley cell; ascending branch would then cover most of the rest of the planet.**

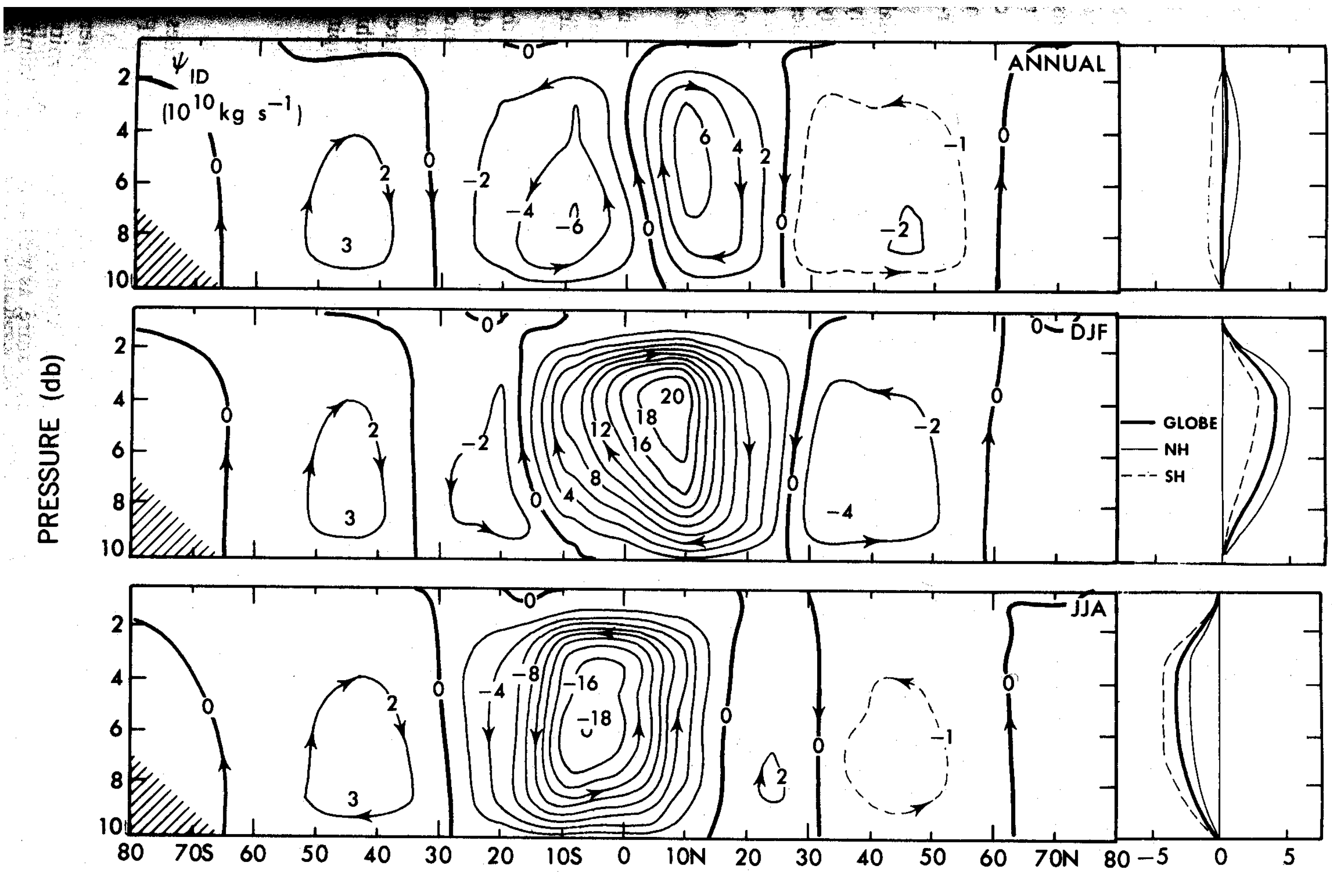
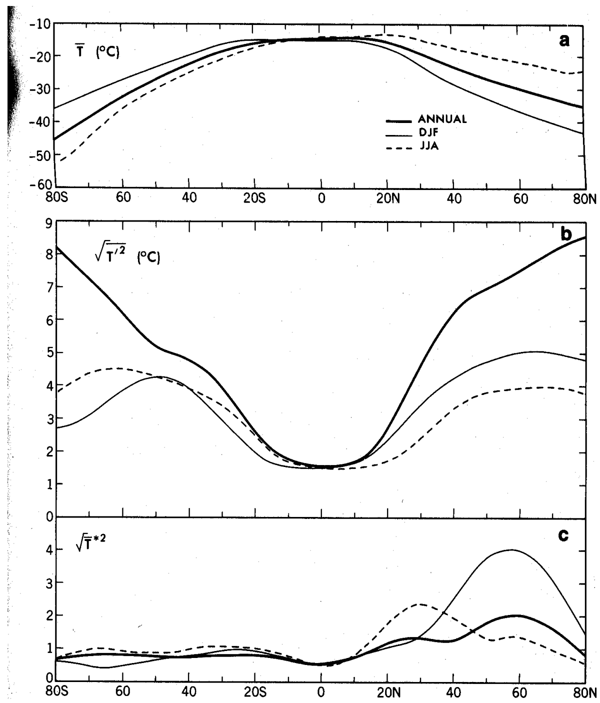
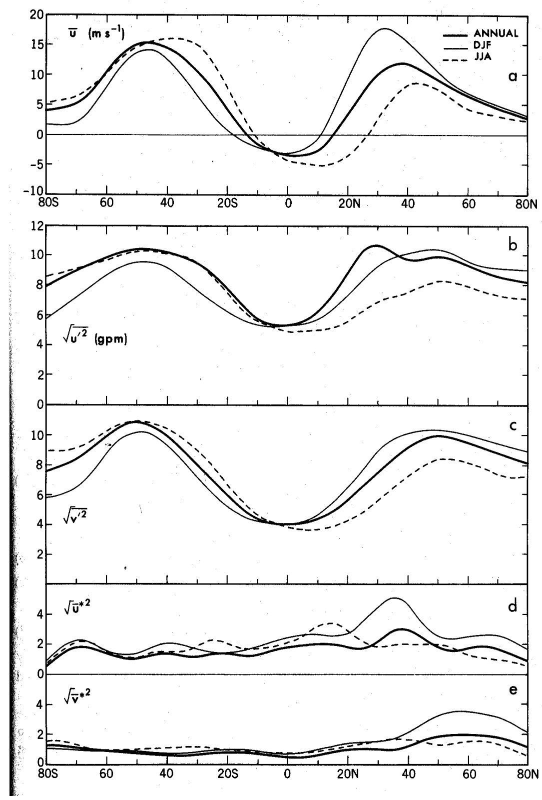


Figure 1.5: **Meridional streamfunction from Earth observations illustrating the Hadley cell. In the annual-mean, two Hadley cells occur (one in each hemisphere) with ascending motion at the equator and descending motion at $\sim$ 20–30° latitude. At solstice, however, a single cell dominates with ascending motion in the summer hemisphere and descending motion in the winter hemisphere. From Peixoto and Oort (1992, Fig. 7.19).**



(a) **Vertically and zonally averaged temperature structure. Top shows mean temperature, middle shows variance due to traveling eddies and bottom shows variance due to stationary eddies. The temperature structure near the equator is nearly isothermal and eddy-free, indicating the region of dominance of the Hadley cell. From Peixoto and Oort (1992, Fig. 7.9).**



(b) **Vertically and zonally averaged zonal-wind structure. Top shows mean zonal wind, middle shows variance due to traveling eddies and bottom shows variance due to stationary eddies. Near the equator, eddies are weak and the wind is westward but increases with latitude, showing the region of dominance of the Hadley cell. From Peixoto and Oort (1992, Fig. 7.20).**

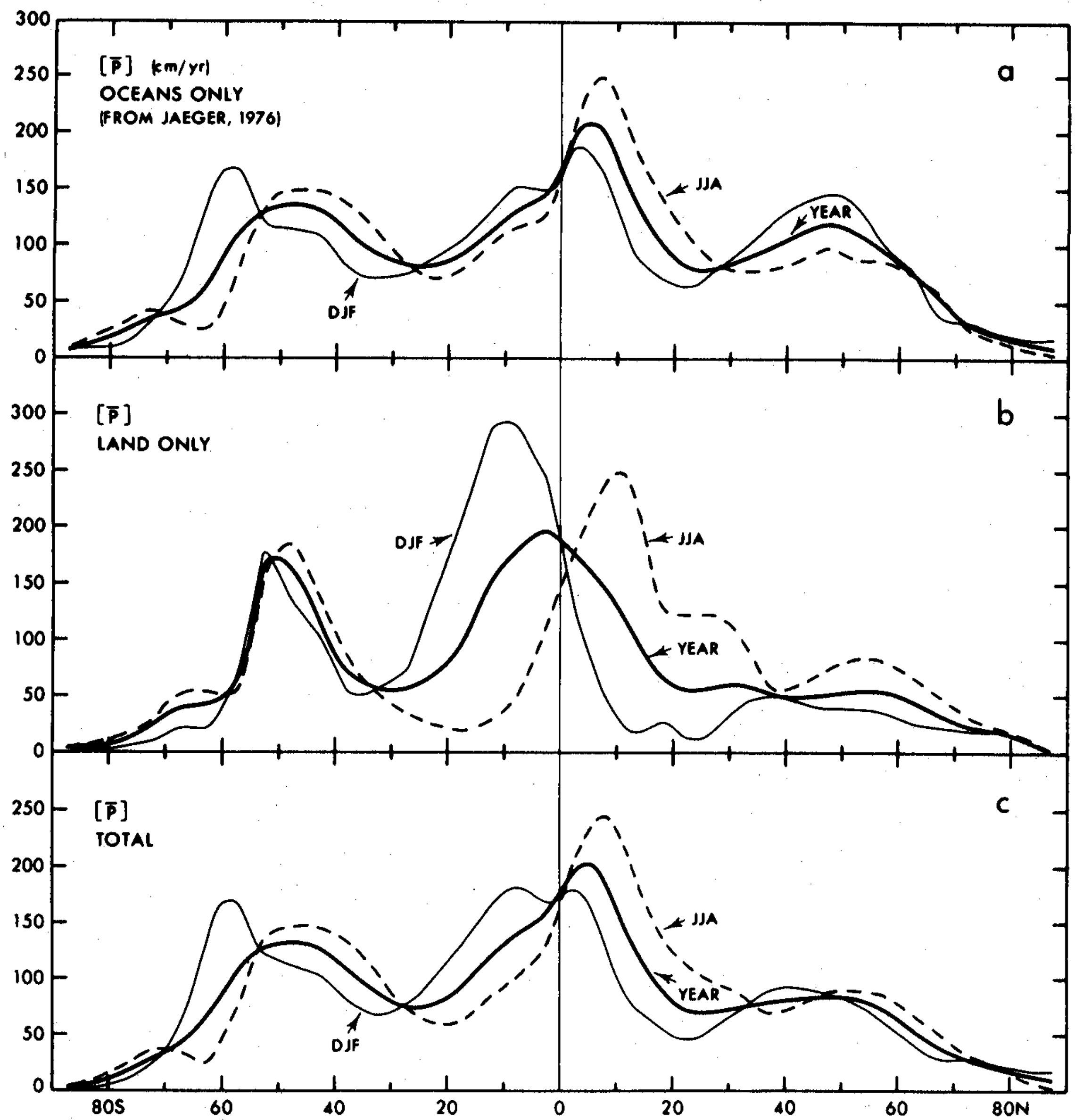


Figure 1.6: **Signature of the Hadley cell is visible in zonal-mean precipitation, which peaks at the equator but has local minima at ~ 20–30° latitude. From Peixoto and Oort (1992, Fig. 7.25).**

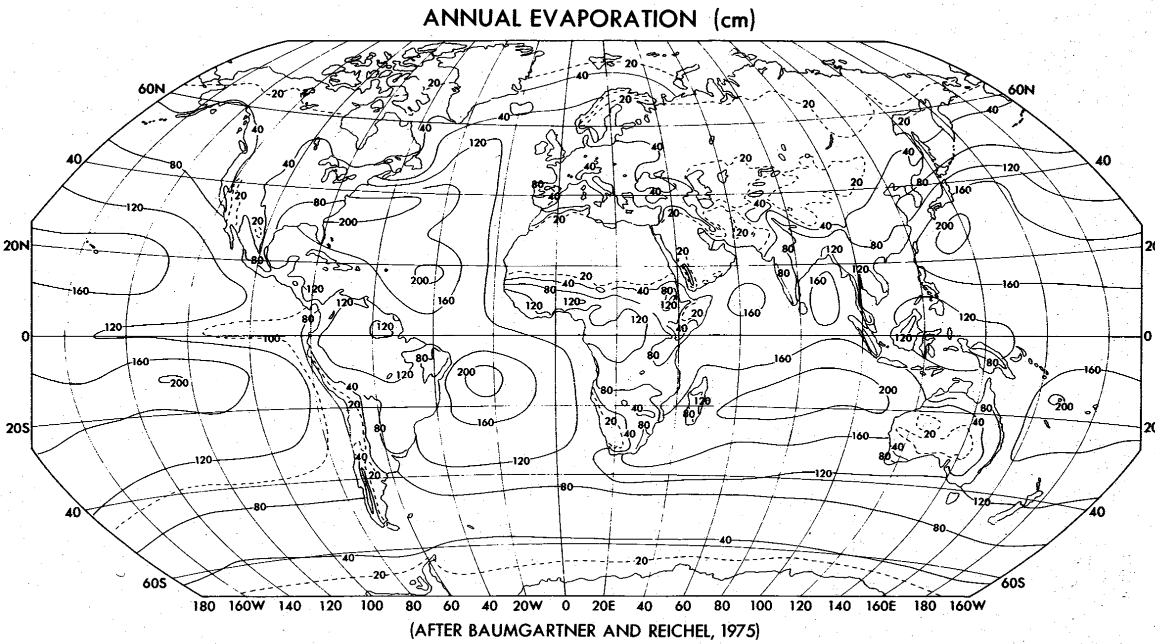


Figure 1.7: **Signature of Hadley cell is visible in this global map of annual evaporation. Continents cause large perturbations but in relatively undisturbed oceanic regions, such as across the Pacific, evaporation peaks in the subtropics at 20–30° latitude and has a local minimum at the equator. The high subtropical evaporation presumably results from the lesser cloud cover (promoting solar absorption at the surface) and dryness of the air relative to that at the equator, both effects resulting from the Hadley circulation. From Peixoto and Oort (1992, Fig. 7.26).**

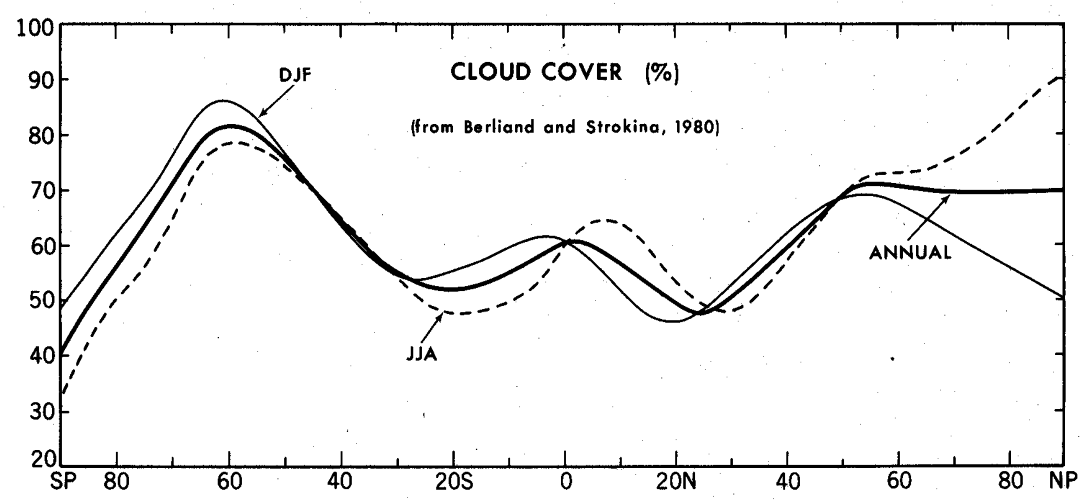


Figure 1.8: **Signature of Hadley cell is visible in zonal-mean cloud cover, which peaks at the equator and has local minima in the subtropics at 20–30° latitude. High-latitude cloud cover (poleward of 40°) results from a combination of baroclinic instabilities and cloud-topped boundary layers. From Peixoto and Oort (1992, Fig. 7.29).**

circulation leads to cloud formation and abundant rainfall near the equator, helping to explain for example the prevalence of tropical rainforests in Southeast Asia/Indonesia, Brazil, and central Africa.[1] On the other hand, because condensation and rainout dehydrates the rising air, the descending branch of the Hadley cell is relatively dry, which explains the abundances of arid climates on Earth at 20–30° latitude, including the deserts of the African Sahara, South Africa, Australia, central Asia, and the southwestern United States. The Hadley cell can also influence the mean cloudiness, hence albedo and thereby the mean surface temperature. Venus's slow rotation rate leads to a global equator-to-pole Hadley cell, with the descending branch confined to small polar vortices and the ascending branch covering most of the planet. Coupled with the presence of trace condensable gases, this near-global ascent leads to a near-global cloud layer that helps generate Venus' high bond albedo of 0.75. Different Hadley cell patterns would presumably cause different cloudiness patterns, different albedos, and therefore different global-mean surface temperatures.

A variety of studies have been carried out using fully nonlinear, global 3D numerical circulation models to determine the sensitivity of the Hadley cell to the planetary rotation rate and other parameters (e.g. Hunt, 1979; Williams and Holloway, 1982; Williams, 1988a,b; del Genio and Suozzo, 1987; Navarra and Boccaletti, 2002; Walker and Schneider, 2005, 2006). These studies show that as the rotation rate is decreased the width of the Hadley cell increases, the equator-to-pole heat flux increases, and the equator-to-pole temperature contrast decreases. Figs. 1.9–1.10 illustrates examples from Navarra and Boccaletti (2002) and del Genio and Suozzo (1987). For Earth parameters, the circulation exhibits mid-latitude eastward jet streams that peak in the upper troposphere ($\sim 200\,\mathrm{mbar}$ pressure), with weaker wind at the equator (Fig. 1.9). The Hadley cells extend from the equator to the equatorward flanks of the mid-latitude jets. As the rotation rate decreases, the Hadley cells widen and the jets shift poleward. At first, the jet speeds increase with decreasing rotation rate, which results from the fact that as the Hadley cells extend poleward (i.e., closer to the rotation axis) the air can spin-up faster (cf Eq. 1.1). Eventually, once the Hadley cells extend almost to the pole (at rotation periods exceeding $\sim$ 5–10 days for Earth radius, gravity, and vertical thermal structure), further decreases in rotation rate reduce the mid-latitude jet speed.

Perhaps more interestingly for planetary observations, these changes in the Hadley cell significantly influence the planetary temperature structure. This is illustrated in Fig. 1.10 from a series of simulations by del Genio

[1] Regional circulations, such as monsoons, also contribute.

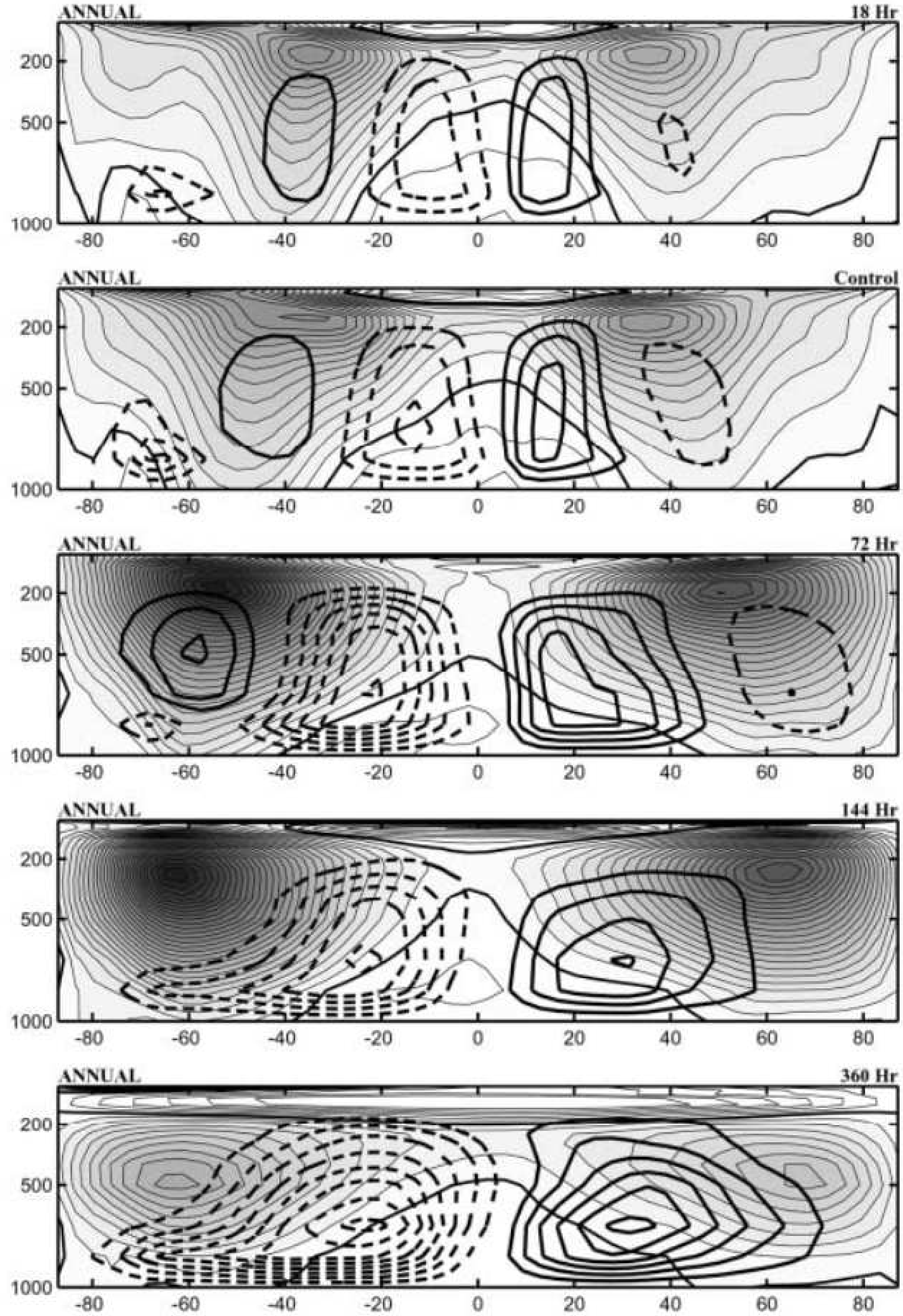


Figure 1.9: **Zonal-mean circulation versus latitude (abscissa) and pressure (ordinate) in a series of Earth-based GCM experiments from Navarra and Boccaletti (2002) where the rotation period is varied from 18 hours (top) to 360 hours (bottom). Greyscale and thin grey contours depict zonal-mean zonal wind, $\overline{u}$, and thick black contours denote streamfunction of the circulation in the latitude-height plane, with solid being clockwise and dashed being counterclockwise. The two cells closest to the equator correspond to the Hadley cell. As rotation period increases, the jets move poleward and the Hadley cell widens, becoming nearly global at the longest rotation periods.**

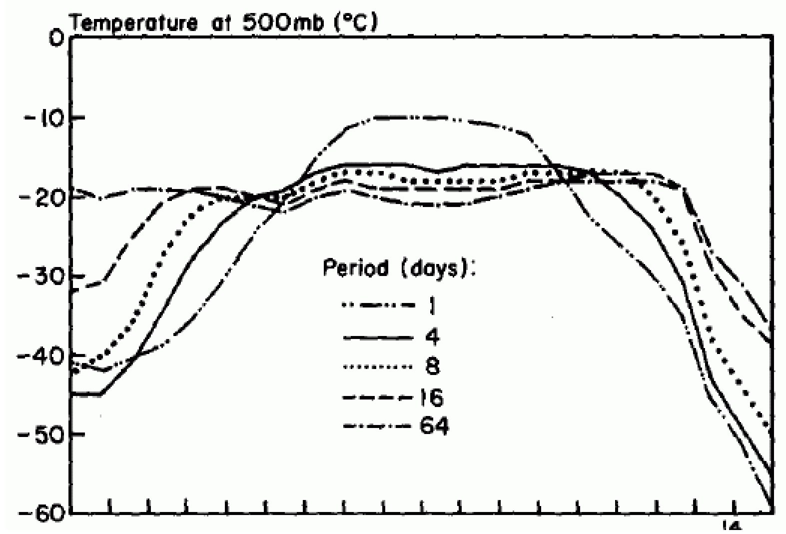


Figure 1.10: **Zonally averaged temperature versus latitude at 500 mbar (in the mid-troposphere) for a sequence of Earth-like GCM runs that vary the planetary rotation period between 1 and 64 Earth days (labelled in the graph). The flat region near the equator in each run results from the Hadley cell, which transports thermal energy extremely efficiently and leads to a nearly isothermal equatorial temperature structure. The region of steep temperature gradients at high latitudes is the baroclinic zone, where the temperature structure and latitudinal heat transport are controlled by eddies resulting from baroclinic instability. Note that the width of the Hadley cell increases, and the equator-to-pole temperature difference decreases, as the planetary rotation period is increased. From del Genio and Suozzo (1987).**

and Suozzo (1987). Because the Hadley cells transport heat extremely efficiently, the temperature remains fairly constant across the width of the Hadley cells. Poleward of the Hadley cells, however, the heat is transported in latitude by baroclinic instabilities, which are less efficient, so a large latitudinal temperature gradient exists within this so-called "baroclinic zone." The equator-to-pole temperature contrast depends strongly on the width of the Hadley cell.

Despite the value of the 3D circulation models described above, the complexity of these models tends to obscure the physical mechanisms governing the Hadley circulation's strength and latitudinal extent and cannot easily be extrapolated to different planetary parameters. A conceptual theory for the Hadley cell, due to Held and Hou (1980), provides considerable insight into Hadley cell dynamics and allows estimates of how, for example, the width of the Hadley cell should scale with planetary size and rotation rate [see reviews in James (1994, pp. 80-92), Vallis (2006, pp. 457-466), and Schneider (2006)]. Stripped to its basics, the scheme envisions an axisymmetric two-layer model, where the lower layer represents the equatorward flow near the surface and the upper layer represents the poleward flow in the upper troposphere. For simplicity, Held and Hou (1980) adopted a basic-state density that is constant with altitude. Absorption

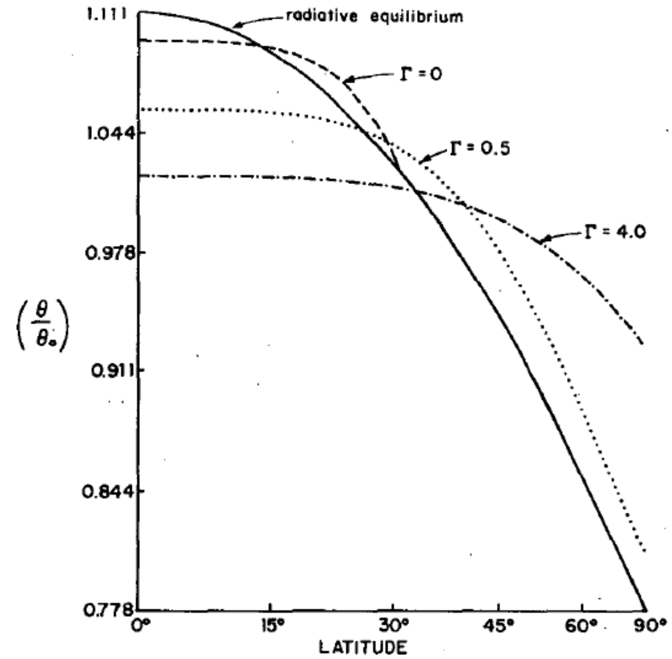


Figure 1.11: **Latitudinal temperature profiles for simplified Held-Hou-type axisymmetric models. Shown is the radiative equilibrium temperature profile and several solutions. $\Gamma = 0$ corresponds to the inviscid Held-Hou solution where angular momentum is conserved in the upper branch of the Hadley cell. Combined with thermal-wind balance, this leads to a $T \propto \phi^4$ dependence (Eq. 1.3). A constant ($\theta_{\rm equator}$ from Eq. 1.3) is added to ensure that the Hadley cell is thermally closed, which requires that the areas between the solution and the radiative-equilibrium profile sum to zero. This generally means that the solutions strike the radiative-equilibrium profile twice: once in the subtropics (equatorward of which heating occurs and poleward of which cooling occurs) and once closer to the pole; the latter defines the latitudinal extent of the Hadley cell. The $\Gamma > 0$ curves correspond to axisymmetric solutions where drag has been added to the upper branch of the Hadley cell. At low latitudes, these models produce profiles of temperature, heating, and zonal wind that agree better with Earth data than the $\Gamma = 0$ Held-Hou model. However, the $\Gamma > 0$ models shown here have Hadley cells that extend all the way to the pole. The fact that the Hadley cell does not extend to the pole hints that the Held-Hou model does not provide the correct explanation for the width of Earth's Hadley cell. From Farrell (1990).**

of sunlight and loss of heat to space generate a latitudinal temperature contrast that drives the circulation; for concreteness, let us parameterize the radiation as a relaxation toward a radiative-equilibrium potential temperature profile that varies with latitude as $\theta_{\rm rad} = \theta_0 - \Delta\theta_{\rm rad}\sin^2\phi$, where θ_0 is the radiative-equilibrium potential temperature at the equator and $\Delta\theta_{\rm rad}$ is the equator-to-pole difference in radiative-equilibrium potential temperature. If we make the small-angle approximation for simplicity (valid for a Hadley cell that is confined to low latitudes), we can express this as $\theta_{\rm rad} = \theta_0 - \Delta\theta_{\rm rad}\phi^2$.

In the lower layer, we assume that friction against the ground keeps the wind speeds low; in the upper layer, assumed to occur at an altitude H, the flow conserves angular momentum. The upper layer flow is then specified by Eq. 1.1, which is just $u = \Omega a \phi^2$ in the small-angle limit. We expect that the upper-layer wind will be in thermal-wind balance with the latitudinal temperature contrast[2]:

$$f\frac{\partial u}{\partial z} = f\frac{u}{H} = -\frac{g}{\theta_0}\frac{\partial \theta}{\partial y} \tag{1.2}$$

where $\partial u/\partial z$ is simply given by u/H in this two-layer model. Inserting $u = \Omega a \phi^2$ into Eq. 1.2 and integrating, we obtain a temperature that varies with latitude as

$$\theta = \theta_{\text{equator}} - \frac{\Omega^2 \theta_0}{2ga^2 H} y^4 \tag{1.3}$$

where θ_{equator} is a constant to be determined.

At this point, we introduce two constraints. First, Held and Hou (1980) assumed the circulation is energetically closed, i.e. that no net exchange of mass or thermal energy occurs between the Hadley cell and higher latitude circulations. Given an energy equation with radiation parameterized using Newtonian cooling, $d\theta/dt = (\theta_{\text{rad}} - \theta)/\tau_{\text{rad}}$, where τ_{rad} is a radiative time constant, the assumption that the circulation is steady and closed requires that

$$\int_0^{\phi_H} \theta\, dy = \int_0^{\phi_H} \theta_{\text{rad}} dy \tag{1.4}$$

where we are integrating from the equator to the poleward edge of the Hadley cell, at latitude ϕ_H. Second, temperature must be continuous with latitude at the poleward edge of the Hadley cell. In the axisymmetric model, baroclinic instabilities are suppressed, and the regions poleward of the Hadley cells reside in a state of radiative equilibrium. Thus, θ must equal θ_{rad} at the poleward edge of the cell. Inserting our expressions for θ and θ_{rad} into these two constraints yields a system of two equations for ϕ_H and θ_{equator}. The solution yields a Hadley cell with a latitudinal half-width of

$$\phi_H = \left(\frac{5\Delta\theta_{\text{rad}} g H}{3\Omega^2 a^2 \theta_0}\right)^{1/2} \tag{1.5}$$

in radians. This solution suggests that the width of the Hadley cell scales as the square root of the fractional equator-to-pole radiative-equilibrium temperature difference, the square root of the gravity, the square root of the height of the cell, and inversely with the rotation rate. Inserting Earth annual-mean values ($\Delta\theta_{\text{rad}} \approx 70\,\text{K}$, $\theta = 260\,\text{K}$, $g = 9.8\,\text{m}\,\text{sec}^{-2}$, $H = 15\,\text{km}$, $a = 6400\,\text{km}$, and $\Omega = 7.2 \times 10^{-5}\,\text{sec}^{-1}$) yields $\sim 32°$.

[2] This form differs slightly from Eq. **??** because Eq. 1.2 adopts a constant basic-state density (the so-called "Boussinesq" approximation) whereas Eq. **??** adopts the compressible ideal-gas equation of state.

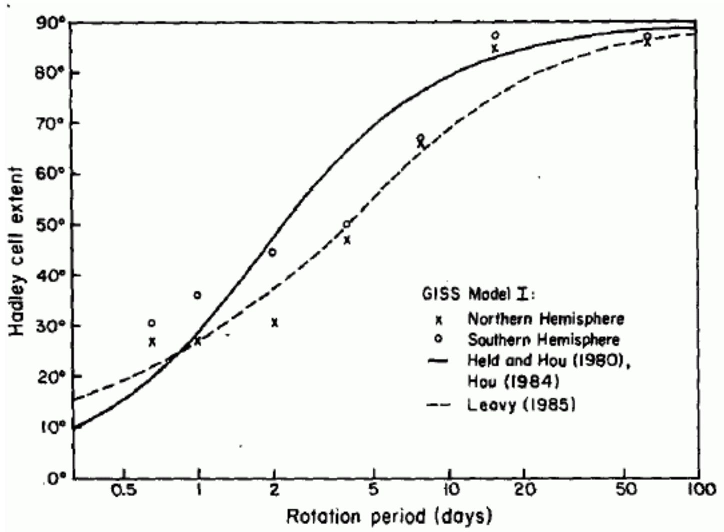


Figure 1.12: **Latitudinal width of the Hadley cell from a sequence of Earth-like GCM runs from del Genio and Suozzo (1987) that vary the planetary rotation period (symbols) and comparison to the predicted width from the Held-Hou theory (solid curve).**

Redoing this analysis without the small-angle approximation leads to a transcendental equation for ϕ_H (see Eq. 17 in Held and Hou, 1980), which can be solved numerically. Figure 1.12 (*solid curve*) illustrates the solution. As expected, ϕ_H ranges from $0°$ as $\Omega \to \infty$ to $90°$ as $\Omega \to 0°$, and, for planets of Earth radius with Hadley circulations $\sim$ 10 km tall, bridges these extremes between rotation periods of $\sim$ 0.5 and 20 days. Although deviations exist, the agreement between the simple Held-Hou model and the 3D GCM is surprisingly good given the simplicity of the Held-Hou model.

Importantly, the Held-Hou model demonstrates that latitudinal confinement of the Hadley cell occurs even in an axisymmetric atmosphere. Thus, the cell's latitudinal confinement does not require (for example) three-dimensional baroclinic or barotropic instabilities associated with the jet at the poleward branch of the cell. Instead, the confinement results from energetics: the twin constraints of angular-momentum conservation in the upper branch and thermal-wind balance specify the latitudinal temperature profile in the Hadley circulation (Eq. 1.3). This generates equatorial temperatures colder than (and subtropical temperatures warmer than) the radiative equilibrium, implying radiative heating at the equator and cooling in the subtropics. This properly allows the circulation to transport thermal energy poleward. If the cell extended globally on a rapidly rotating planet, however, the circulation would additionally produce high-latitude temperatures *colder* than the radiative equilibrium temperature, which in steady state would require radiative *heating* at high latitudes. This is thermodynamically impossible given the specified latitudinal dependence of θ_{rad}. The highest latitude to which the cell can extend without encountering this problem is simply given by Eq. 1.4.

The model can be generalized to consider a more realistic treatment of radiation than the simplified Newtonian cooling/heating scheme employed by Held and Hou (1980). Caballero et al. (2008) reworked the scheme using a two-stream, non-grey representation of the radiative transfer with parameters appropriate for Earth and Mars. This leads to a prediction for the width of the Hadley cell that differs from Eq. 1.5 by a numerical constant of order unity.

Although the prediction of Held-Hou-type models for ϕ_H provides important insight, several failures of these models exist. First, the model underpredicts the strength of the Earth's Hadley cell (e.g., as characterized by the magnitude of the north-south wind) by about an order of magnitude. This seems to result from the lack of turbulent eddies in axisymmetric models; several studies have shown that turbulent three-dimensional eddies exert stresses that act to strengthen the Hadley cells beyond the predictions of axisymmetric models (e.g. Kim and Lee, 2001; Walker and Schneider, 2005, 2006; Schneider, 2006).[3] Second, the Hadley cells on Earth and probably Mars are not energetically closed; rather, mid-latitude baroclinic eddies transport thermal energy out of the Hadley cell into the polar regions. As a result, net heating occurs throughout the latitudinal extent of Earth's Hadley cell (see Fig. 1.13) — rather than heating in the equatorial branch and cooling in the poleward branch as postulated by Held and Hou (1980). Third, the poleward-moving upper tropospheric branches of the Hadley cells do not conserve angular momentum — although the zonal wind does become eastward as one moves poleward across the cell, for Earth this increase is a factor of $\sim$ 2–3 less than predicted by Eq. 1.1. The Hadley cell also experiences a net torque with the surface (Fig. 1.14), which can only be balanced by exchange of momentum between the Hadley cell and higher-latitude circulations. Overcoming these failings requires the inclusion of three-dimensional eddies.

Several studies have shown that turbulent eddies in the mid- to high-latitudes — which are neglected in the Held-Hou and other axisymmetric models — can affect the width of the Hadley circulation and alter the parameter dependences suggested by Eq. 1.5 (e.g., del Genio and Suozzo, 1987; Walker and Schneider, 2005, 2006). Turbulence can produce an acceleration/deceleration of the zonal-mean zonal wind, which breaks the

[3] Held and Hou (1980)'s original model neglected the seasonal cycle, and it has been suggested that generalization of the Held-Hou axisymmetric model to include seasonal effects could alleviate this failing (Lindzen and Hou, 1988). Although this improves the agreement with Earth's observed *annual-mean* Hadley-cell strength, it predicts large solstice/equinox oscillations in Hadley-cell strength that are lacking in the observed Hadley circulation (Dima and Wallace, 2003).

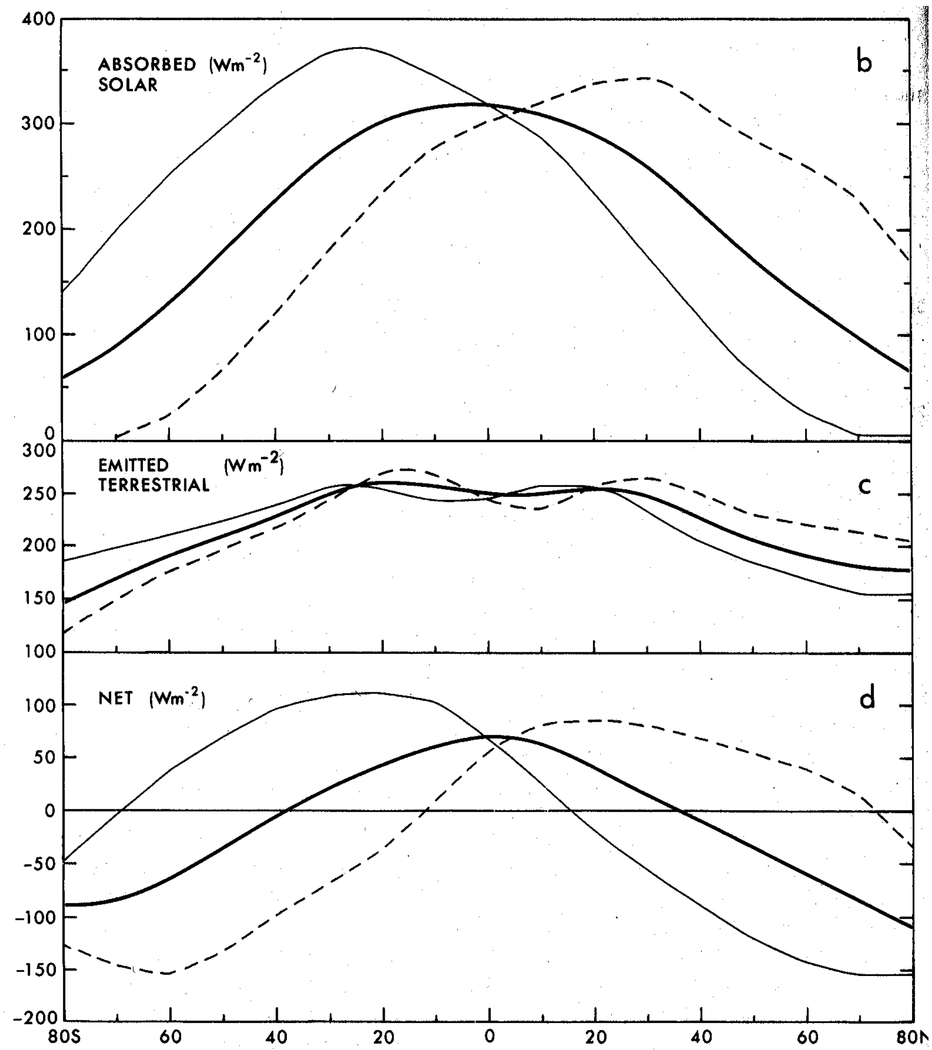


Figure 1.13: **Zonal-mean solar absobed flux, emitted IR flux, and net (solar − IR) heating/cooling versus latitude from Earth observations. The net heating rate is positive from the equator all the way to 30–40° latitude, implying that** *heating occurs throughout the entire width of the Hadley cell.* **This is inconsistent with the Held-Hou model, which predicts that heating occurs in the equatorial part of the Hadley cell and that cooling occurs in the subtropical part of the cell. The implication is that, contrary to the assumption of the Held-Hou model, the Hadley cell is not energetically closed but transports net thermal energy into midlatitudes. From Peixoto and Oort (1992, Fig. 6.14.)**

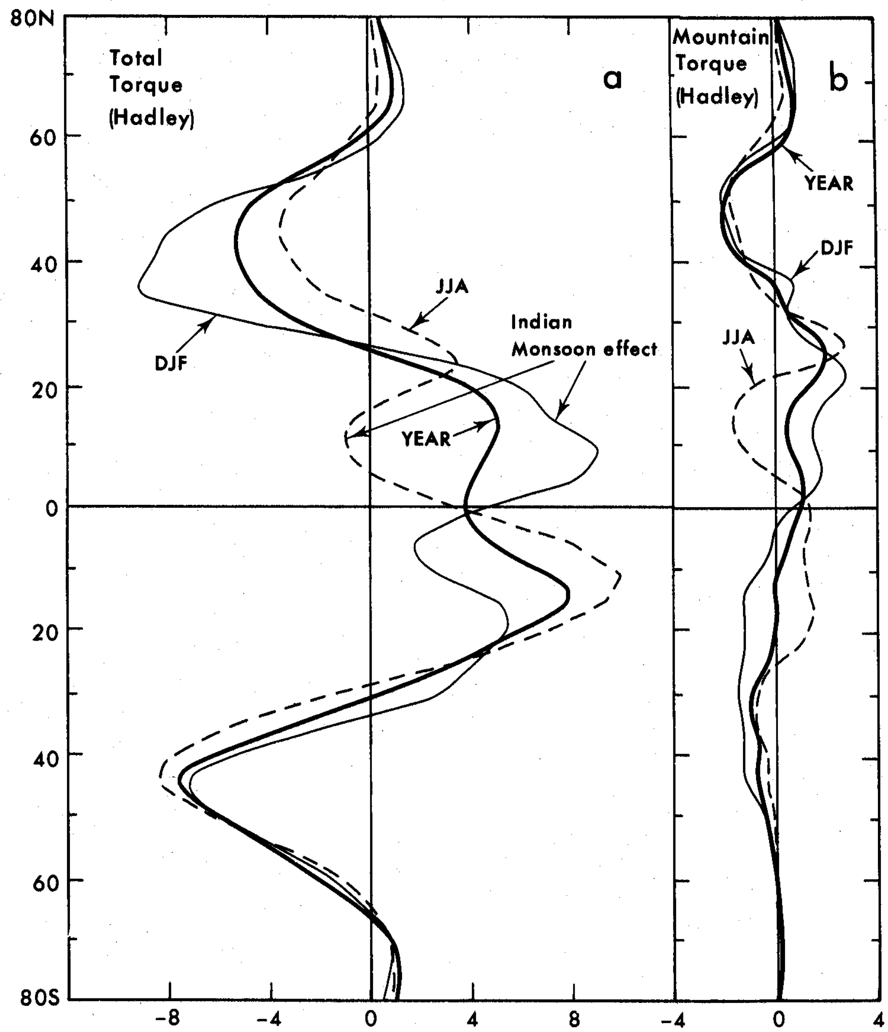


Figure 1.14: **Latitudinal profile of the zonal-mean torque on the atmosphere (caused by interaction with the surface) from Earth observations. The torque is positive (eastward) from the equator to $\sim 30^\circ$ latitude, implying that the Hadley cell experiences a net eastward acceleration caused by its frictional interaction with the surface. This is inconsistent with the Held-Hou model, which assumes that the Hadley cell is closed and hence that the surface torque integrated across the Hadley cell is zero. The observed eastward torque implies that the Hadley cell exchanges angular momentum with the mid-latitude circulation (specifically, that mid-latitude eddies transport westward momentum into the Hadley cell, causing a westward drag that counteracts the eastward torque associated with the surface). Because much of this eddy acceleration occurs in the upper troposphere, it moreoever implies that the upper branch of the Hadley cell does not conserve angular momentum, contrary to the assumption of the Held-Hou model. Again, this suggests that the Held-Hou model does not provide a correct description of the width of the Hadley cell. From Peixoto and Oort (1992, Fig. 11.12.)**

angular-momentum conservation constraint in the upper-level wind, causing u to deviate from Eq. 1.1. With a different $u(\phi)$ profile, the latitudinal dependence of temperature will change (via Eq. 1.2), and hence so will the latitudinal extent of the Hadley cell required to satisfy Eq. 1.4. Indeed, within the context of axisymmetric models, the addition of strong drag into the upper-layer flow (parameterizing turbulent mixing with the slower-moving surface air, for example) can lead Eq. 1.4 to predict that the Hadley cell should extend to the poles even for Earth's rotation rate (e.g., see Fig. 1.11; Farrell, 1990).

It could thus be the case that the width of the Hadley cell is fundamentally controlled by eddies. For example, in the midlatitudes of Earth and Mars, baroclinic eddies generally accelerate the zonal flow eastward in the upper troposphere; in steady state, this is generally counteracted by a westward Coriolis acceleration, which requires an *equatorward* upper tropospheric flow — backwards from the flow direction in the Hadley cell. Such eddy effects can thereby terminate the Hadley cell, forcing its confinement to low latitudes. Based on this idea, Held (2000) suggested that the Hadley cell width is determined by the latitude beyond which the troposphere first becomes baroclinically unstable (requiring isentrope slopes to exceed a latitude-dependent critical value). Adopting the horizontal thermal gradient implied by the angular-momentum conserving wind (Eq. 1.3), making the small-angle approximation, and utilizing a common two-layer model of baroclinic instability, this yields (Held, 2000)

$$\phi_H \approx \left(\frac{gH\Delta\theta_v}{\Omega^2 a^2 \theta_0}\right)^{1/4} \tag{1.6}$$

in radians, where $\Delta\theta_v$ is the vertical difference in potential temperature from the surface to the top of the Hadley cell. Note that the predicted dependence of ϕ_H on planetary radius, gravity, rotation rate, and height of the Hadley cell is weaker than predicted by the Held-Hou model. Earth-based GCM simulations suggest that Eq. 1.6 may provide a better representation of the parameter dependences (Frierson et al., 2007; Lu et al., 2007; Korty and Schneider, 2008). Nevertheless, even discrepancies with Eq. 1.6 are expected since the actual zonal wind does not follow the angular-momentum conserving profile (implying that the actual thermal gradient will deviate from Eq. 1.3). Substantially more work is needed to generalize these ideas to the full range of conditions relevant for other planets.

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