Analytical Estimation of the Widths of Hadley Cells in the Solar System

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Abstract

Analytical descriptions of the angular width of Earth’s Hadley cell show it to be related to the square root of the product of the tropospheric thickness and buoyancy frequency, and to the inverse square root of the angular velocity and planetary radius. Here, the applicability of this formulation is examined for other planetary bodies in the solar system. Generally, good consistency is found between predictions and observations for terrestrial planets provided the pressure scale height rather than the tropopause height is assumed to determine the thickness of the tropospheric circulation. For gas giants, the relevant thickness is deeper than the scale height, possibly due to the internal heat produced by Kelvin–Helmholtz contraction. On Earth, latent heat release within deep convection may play a similar role in deepening and widening the Hadley cell.

Key words: Earth – planets and satellites: atmospheres – planets and satellites: gaseous planets – planets and satellites: terrestrial planets

1. Introduction

The Hadley cell on Earth is its dominant circulation pattern, defined by the moist tropics in its ascending branch and the dry sub-tropical deserts in its descending branch. Approximately axisymmetric, it is bounded by the equator and 30° latitude in either hemisphere (Köppen & Geiger 1933). In an early effort to derive an analytical expression for the Hadley cell width, Schneider (1977) considered circulations within an idealized, nearly inviscid atmosphere, assuming that zonal winds are geostrophic, and that they conserve angular momentum with increasing latitude. Provided there is a balance in the cell between latent heating by tropical cumulus and the top-of-the-atmosphere infrared cooling, the derived cell width is

\[ \phi_s \approx \left( \frac{5}{4} \right)^{1/4} \left( \frac{NH}{\Omega a} \right)^{1/2} \]

where \( R_L = NH/2\Omega \) is the Rossby radius of deformation for a stratified atmosphere, \( a \) is the radius of the Earth, \( N \) is the tropospheric Brunt–Väisälä or buoyancy frequency, \( H \) is the depth of the tropical atmosphere, and \( \Omega \) is the planetary angular velocity. Through substitution, \( \phi_s \approx \left( \frac{5}{4} \right)^{1/4} (aNH/\Omega)^{1/2} \). Converting to an angle through \( \phi = y/a \):

\[ \phi_s \approx \left( \frac{5}{4} \right)^{1/4} \left( \frac{NH}{\Omega a} \right)^{1/2}. \]  

A similar result was obtained by Held (2000), who also assumed that zonal winds conserve angular momentum, but that the cell width is determined by the latitude at which vertical wind shear due to baroclinic instability leads to development of large-scale eddies. Expressing Equation (1) in terms of latitude, Held found that \( \phi_H \approx (gH\Delta \theta_r/\Omega^2 a^2 \theta_0)^{1/4} \), where \( g \) is the gravitational constant, \( \Delta \theta_r \) is the vertical change in virtual potential temperature with height and \( \theta_0 \) is the virtual potential temperature at the surface. Substituting the Brunt–Väisälä frequency where \( N^2 = g/H((\Delta \theta_r)/\theta_0) \), the expression simplifies to

\[ \phi_H \approx \left( \frac{NH}{\Omega a} \right)^{1/2}. \]

Despite the difference in approaches, Equations (1) and (2) differ by just 6%. Both results implicitly express the angular width of the Hadley cell as a ratio of the square root of two velocities: \( NH \) is proportional to the square root of the available buoyant potential energy in a stratified atmosphere (Tailleux 2013) and \( \Omega a \) is proportional to the square root of the atmosphere’s rotational energy. Notably, the relevant atmospheric depth was assumed to be that of the troposphere, \( H_{\text{top}} \). The reason for this choice is not obvious, as it might be argued that the atmospheric density scale height \( H_{\text{scale}} \) is most directly tied to mass and heat transfer in the general circulation. A straightforward expression of Hadley cell width for Earth suggests suitability for other planetary bodies. Here, we explore the general validity of Equation (2) for predictions of Hadley cell width by examining a range of planetary bodies in the solar system, paying particular attention to the value of \( H \) and exploring the possible dependence of \( \phi_H \) on internal convective energy sources.

2. Observed Planetary Parameters

Table 1 summarizes planetary parameters relevant to calculation of Equation (2) along with the observed width of the Hadley cell. For planetary bodies in the solar system other than Earth, the latitude \( \phi_{\text{obs}} \) of the Hadley cell subsidence zones is most often determined through off-equatorial jet analysis supplemented by visual estimates of where cloud banding is related to jet activity (Yamazaki et al. 2005; Showman et al. 2010). However, observational limitations lead to varying uncertainty. Among terrestrial bodies, studies of Hadley cell dynamics has focused on Earth and Mars (Schneider 1977; Held 2000; Richardson & Wilson 2002; Frierson et al. 2007). For Venus, observational uncertainty owes to its thick atmosphere (Sánchez-Lavega et al. 2017). Titan, despite recent Huygens and Cassini measurements (McKay et al. 1997; Brown et al. 2010) supported by numerical modeling of the atmospheric general circulation (Newman et al. 2016), lacks specificity as the Hadley cell migrates seasonally between poles (Tokano 2007; Newman et al. 2016); during the Saturnian summer and winter seasons, Titan’s unusual Hadley cell spans nearly the entire moon, with a semi-permanent polar vortex in the winter hemispheric pole. It then splits into two as the vortex transitions between poles during the spring and fall over the course of Saturn’s 30 yr seasonal cycle (Tokano 2007).

The greatest observational uncertainties are for the gas giants, particularly for Uranus and Neptune as these have not
Table 1
Observed Planetary Parameters

| Planet | a (km) | N (10⁻² s⁻¹) | Ω (10⁻⁵ rad s⁻¹) | H_{scale} (km) | H_{trop} (km) | φ_{obs} (deg) |
|--------|--------|---------------|------------------|----------------|--------------|--------------|
| Venus  | 6050   | 1.05          | 2.31             | 15.9           | 65.0         | 60           |
| Earth  | 6370   | 1.12          | 7.27             | 8.5            | 17.0         | 30           |
| Mars   | 3396   | 0.78          | 7.10             | 11.1           | 45.0         | 40           |
| Jupiter| 71,400 | 1.51          | 17.8             | 27.0           | 124.3        | 18           |
| Saturn | 60,270 | 0.67          | 16.5             | 59.5           | 274.0        | 25           |
| Titan  | 2575   | 0.25          | 0.45             | 40.0           | 50.0         | 170          |
| Uranus | 25,560 | 1.02          | 9.70             | 27.7           | 127.6        | 30           |
| Neptune| 24,760 | 1.33          | 1.62             | 20.0           | 92.1         | 50           |

Notes. a: planetary radius, N: Brunt–Väisälä frequency, Ω: planetary rotation rate, H_{scale}: pressure scale height, H_{trop}: tropopause height, defined for gas giants as the height between 10 and 0.1 bar, φ_{obs}: observed location of the descending branch of the Hadley cell in degrees.

* Adjusted for superrotation.

had a spacecraft flyby since Voyager 2 in 1986 and 1989 (Lunine 1993). Friedson & Moses (2012) used data taken by the Cassini spacecraft between 2007 and 2010 to propose a Hadley circulation on Saturn that exhibits strong subsidence at ±25° latitude. A previous estimate had used jet analysis to find subsidence closer to 30°. Bolton et al. (2017) described an Earth-like Hadley circulation on Jupiter with equatorial upwelling and a downwelling branch between 10° and 20° latitude, consistent with a previous jet analysis estimate of a subsidence zone at 18° (Showman et al. 2010). Atmospheric upwelling and downwelling are mechanically driven by the mean, zonal, cloud-top flow (Ingersoll et al. 2007). However, the forcing mechanisms of these zonal jets are still an open question, with two prevailing theories. In the deep-forcing model, cylindrical Taylor columns drive differential rotation in the deep interior of the planet, which manifest as zonal midlatitude jets that span from the deep interior to the upper cloud level (Ingersoll 1969), reproducing a Hadley cell in equatorial regions (Kaspi et al. 2009). Alternatively, a shallow-forcing model suggests that zonal jets result from turbulence generated by moist convection, baroclinic instability, horizontal differential solar heating, or other weather-layer processes. Some combination of both theories may be most appropriate, with the first valid in tropical regions and the second more relevant at higher latitudes (Vasavada & Showman 2005).

For the value of Ω in Equation (2), all of the planetary giants exhibit some superrotation or subrotation in their atmospheres. On Saturn, Uranus, and Neptune, the subrotating or superrotating jets are thought to be confined to the upper troposphere and only to constitute of order 1% of the total atmospheric circulation (Showman et al. 2010) and have a negligible influence relative to the planetary body on the total rotation rate of the atmosphere. For Jupiter, the Juno spacecraft (Kaspi et al. 2018) revealed surprisingly deep atmospheric jets extending ~3000 km into the planet’s interior, suggesting that a relatively large fraction of the atmosphere is rotating at speeds faster than the planetary rotation rate. Also, Venus has an extremely slow planetary rotation rate of 3 × 10⁻⁷ rad s⁻¹ relative to the atmospheric rotation rate between the surface and the upper-level tropospheric jets (Ainsworth & Herman 1975; Walterscheid et al. 1985; Showman et al. 2010). Thus, for Venus and Jupiter, the atmospheric rotation rate Ω is assumed to be determined from the strength of the midlatitude jet divided by the planetary radius.

The square of the atmospheric buoyancy or Brunt–Väisälä frequency is approximated from the atmospheric temperature profile through $N^2 = g/T_e(\Gamma_g - \Gamma)$, where $T_e$ is the planetary thermal emission temperature, $\Gamma_g = g/c_p$ is the dry adiabatic lapse rate specific to the planet where $c_p$ is specific heat at constant pressure, and $\Gamma$ is the environmental lapse rate obtained from temperature profiles observed by either radio occultation (Carlson et al. 1988; Seiff et al. 1996) or from probe or lander data (Eshleman 1970; Ainsworth & Herman 1975; McKay et al. 1997). Environmental lapse rates for gas giants are determined from the difference between the average temperature at 1 bar and the average temperature at 0.1 bar (Williams 2016).

For all planetary bodies, $H_{scale}$ is the tropospheric pressure scale height (McKay et al. 1997; Williams 2016). For terrestrial planets, the tropopause height $H_{trop}$ is determined from available soundings (Eshleman 1970; Ainsworth & Herman 1975; Brown et al. 2010), with the exception of Earth, for which an average tropical tropopause height is used. For gas giants, it is related to the scale height from the pressures at 10 mb and 0.1 mb $H_{trop} = H_{scale}\ln(10/0.1)$ (Robinson & Catling 2014).

3. Comparison of Theoretical and Observed Hadley Cells

Figure 1 shows a comparison of observed values of Hadley cell width with values calculated from Equation (2) assuming $H = H_{scale}$ for all bodies, allowing for adjustments for superrotation with Venus and Jupiter. A least-squares regression through the origin yields a scaling $\phi_{scale} = b\phi_{obs}$ where $b$ has 95% confidence bounds of $b = 0.927 \pm 0.158$. The largest discrepancies between observed and predicted widths are observed with the gas giant planets, which have discrepancies ranging from ~36% to ~64% and from ~8° to ~32° latitude. The discrepancies are smallest for terrestrial bodies ranging from ~1% to ~14% and ~1° to ~6° (Table 2). Assuming instead that $H = H_{trop}$ then $b = 1.21 \pm 0.285$. The largest discrepancies between observed and predicted widths are observed for the terrestrial planets, ranging from 11% to 108% and from 7° to 65° latitude. The discrepancies are smallest for gas giants ranging from ~2% to ~38% and ~0.4° to 11° (Table 2).

4. Discussion

Thus, there appears to be justification for applying Equation (2) beyond Earth to other planetary bodies in the solar system. Nonetheless, predicted cell widths can deviate...
The dashed lines are where bounds for a least-squares best cell width using Equation (2) (Figure 1). Observed values of Hadley cell width vs. values calculated with Equation (2) using $H_{\text{scale}} (\phi_{\text{scale}})$, $H_{\text{trop}} (\phi_{\text{trop}})$, and $H_{\text{eff}} (\phi_{\text{eff}})$

| Planet | $\phi_{\text{scale}}$ (deg) | Discrepancy (%) | $\phi_{\text{trop}}$ (deg) | Discrepancy (%) | $\phi_{\text{eff}}$ (deg) | Discrepancy (%) |
|--------|------------------------------|-----------------|-----------------------------|-----------------|-----------------------------|----------------|
| Venus  | 61.8                         | 3               | 125.0                       | 108             | 61.8                        | 3              |
| Earth  | 26.0                         | −13             | 36.8                        | 23              | 26.0                        | −13            |
| Mars   | 34.3                         | −14             | 69.1                        | 73              | 34.3                        | −14            |
| Jupiter| 10.1                         | −43             | 22.0                        | 22              | 22.1                        | 23             |
| Saturn | 11.5                         | −54             | 24.6                        | −2              | 23.5                        | −6             |
| Titan  | 168.7                        | −1              | 188.6                       | 11              | 168.7                       | −1             |
| Uranus | 19.3                         | −36             | 41.4                        | 38              | 21.4                        | −29            |
| Neptune| 18.0                         | −64             | 38.6                        | −23             | 46.3                        | −7             |

Hadley Cell Effective Height $H_{\text{eff}}$, Physical Constants for Heat Source Determination, and Distance Parameter $d$ (Equation (3))

| Planet | $H_{\text{eff}}$ (km) | $H_{\text{trop}}$ (km) | $\alpha$ | $S_0$ (W m$^{-2}$) | $T_e$ (K) | $F_{\text{lw}}$ (W m$^{-2}$) | $F_{\text{sw}}$ (W m$^{-2}$) | $R$ | $d$ |
|--------|------------------------|------------------------|----------|-------------------|-----------|-----------------------------|-----------------------------|-----|-----|
| Venus  | 15.0                   | 15.9                   | 0.75     | 2601.3            | 232       | 164.26                      | 162.58                     | 1.00 | −0.02 |
| Earth  | 11.3                   | 8.50                   | 0.31     | 1361.0            | 255       | 239.74                      | 238.18                     | 1.00 | 0.33 |
| Mars   | 15.1                   | 11.1                   | 0.25     | 586.2             | 210       | 110.27                      | 109.91                     | 1.00 | 0.12 |
| Jupiter| 83.0                   | 125                    | 0.50     | 53.5              | 124       | 13.41                       | 6.69                       | 2.01 | 0.57 |
| Saturn | 283                    | 251                    | 0.34     | 14.8              | 95        | 4.62                        | 2.44                       | 1.89 | 1.04 |
| Titan  | 40.6                   | 40.0                   | 0.26     | 15.2              | 85        | 2.96                        | 2.80                       | 1.00 | 0.06 |
| Uranus | 66.9                   | 34.1                   | 0.30     | 3.7               | 59        | 0.69                        | 0.65                       | 1.06 | 0.39 |
| Neptune| 155                    | 133                    | 0.29     | 1.5               | 59        | 0.69                        | 0.27                       | 2.57 | 1.87 |

Figure 1. Observed values of Hadley cell width vs. values calculated with Equation (2) using $H_{\text{scale}}$ as the value of $H$ and adjusted for superrotation as indicated in Table 1. The blue dotted lines show 95% confidence interval bounds for a least-squares best fit of $\phi_{\text{obs}} = b\phi_{\text{scale}}$ where $b = 0.927 \pm 0.158$. The dashed lines are where $\phi_{\text{obs}} = \phi_{\text{scale}}$.

significantly from observations, particularly when using $H_{\text{scale}}$ for gas giants and $H_{\text{trop}}$ for terrestrial bodies.

As a point of reference, we can define an effective atmospheric depth $H_{\text{eff}}$ that yields agreement between the calculated Hadley cell width using Equation (2) and the observed cell width, i.e., $H_{\text{eff}} = \Omega a \phi_H^2 / N$. The relative value of $H_{\text{eff}}$ to $H_{\text{trop}}$ and $H_{\text{scale}}$ can then be quantified with a distance parameter:

$$d = \frac{H_{\text{eff}} - H_{\text{scale}}}{H_{\text{trop}} - H_{\text{scale}}}.$$  

which is shown in Table 3 as the point where a value of zero represents $H_{\text{eff}} = H_{\text{scale}}$ and a value of 1 represents $H_{\text{eff}} = H_{\text{trop}}$. Values greater than unity indicate an effective height greater than the tropopause height.

For terrestrial objects, $H_{\text{eff}}$ is closest to $H_{\text{scale}}$, with a mean $d$ value of 0.10 and a standard deviation of 0.15. With the exception of Uranus, gas giants have values of $H_{\text{eff}}$ closest to $H_{\text{trop}}$ with a mean value and standard deviation of $d = 0.97 \pm 0.57$. Neptune has a value of $d$ considerably greater than unity, with a cell circulation that extends higher than the tropopause (Figure 2), consistent with recent modeling of Neptune’s global circulation (de Pater et al. 2014).

Why do gas giants generally have higher values of $d$? One notable distinction is that they are characterized by an internal heat source arising from Kelvin–Helmholtz contraction due to compression and interior heating (Guillot 2005). Expressing the planetary absorbed shortwave flux as $F_{\text{sw}} = (1 - \alpha)S_0 / 4$, where $\alpha$ is the bond albedo (Li et al. 2011, 2018; Williams 2016) and $S_0$ is the solar flux at the top of the atmosphere (Li et al. 2011, 2018; Williams 2016), and the outgoing longwave flux is $F_{\text{lw}} = \sigma T_e^4$, where $\sigma$ is the Stefan–Boltzmann constant and $T_e$ is the global blackbody emission temperature (Showman et al. 2010), then the ratio of the emitted longwave heat flux to the absorbed solar flux is

$$R = F_{\text{lw}} / F_{\text{sw}}.$$  

Global values are used for the latent heat flux and outgoing longwave radiation so that $R$ is independent of the characteristics.
of the Hadley cell. For example, on Earth, there is an imbalance in the tropics between incoming and outgoing radiation; equilibrium temperatures are maintained due to the meridional heat flux out of the tropics in large part due to the Hadley Cell.

Each of the terrestrial bodies can be assumed to be in radiative equilibrium with no significant internal heat source and \( R = 1 \) (Avduevsky et al. 1970; Li et al. 2011). For the gas giants, as shown in Table 3, excess internal heat is largest on Neptune, with \( R = 2.57 \); while Uranus is more similar to terrestrial planets with \( R = 1.06 \). Figure 3 shows a high degree of linear correlation between \( d \) and \( R - 1 \), suggesting an adjustment to the circulation height that accounts for the internal heat flux given by

\[
H_{\text{hf}} = H_{\text{scale}} + (R - 1)(H_{\text{top}} - H_{\text{scale}}).
\]  

(5)

As shown in Table 2, using \( H_{\text{hf}} \) in place of \( H_{\text{scale}} \) appears to reduce discrepancies between calculated and observed values for the Hadley cell width. The largest discrepancies by percentage using this method are for Uranus (−29%) and Jupiter (23%), but all the calculated cell widths for all planets lie within 10° latitude of their observed values. As shown in Figure 4, the revised coefficient \( b \) relating calculated and observed values, \( \phi = b\phi_{\text{obs}} \), is \( b = 0.978 \pm 0.084 \).

While Earth is a terrestrial planet with \( R = 1 \), it nonetheless has a value of \( H_{\text{hd}} \) that is higher than \( H_{\text{scale}} \). The value of \( d \) is 0.33, which is relatively large compared to other terrestrial planets. Earth is not characterized by an internal heat source from Kelvin–Helmholtz contraction as with the gas giants. However, deep convection in the tropics is driven by an unusually high degree of latent heat release (Williams et al. 2012; Read et al. 2016). Recent refinements to Earth’s global energy budget suggest that the latent heat flux is \( 88 \pm 10 \text{ W m}^{-2} \) or approximately one third of the outgoing longwave flux (Stephens et al. 2012). By comparison, latent heat release on Titan from the methane cycle constitutes on the order of 0.01% of \( F_{\text{lw}} \) (Williams et al. 2012), and on Mars latent heat release from the CO2 cycle is only about 1% of the total energy budget (Read et al. 2016).
If latent heat release LH is taken to act as an internal heat source that pushes the upper boundary of Earth’s Hadley circulation upward, then $R - 1 = LH/F_{lw} = 0.37$, closely corresponding to the inferred value of $d = 0.33$. The implication is that internal heat sources on gas giants and latent heat release on Earth may have a similar influence on Hadley cell width through their contribution to convective processes, causing the atmospheric circulation to deviate upward from the pressure scale height. Remaining disagreement between observations and prediction that is not accounted for using $H_{at}$ in place of the pressure scale height may be due to uncertainties in estimates of $f_{obs}$ and $N$. Tropospheric temperature profiles for Neptune and Uranus exist only from radio occultation data (Lunine 1993), and the global circulation pattern for Neptune has been inferred only indirectly by telescopes at the infrared and radio wavelengths (de Pater et al. 2014). Perhaps revealingly, it was not until the release of recent Juno and Cassini probe data for Jupiter and Saturn that the existence of deeply penetrating atmospheric jets became known (Kaspi et al. 2018), as well as the latitudinal locations of atmospheric downwelling (Friedson & Moses 2012; Bolton et al. 2017). Using older data for Saturn’s observed Hadley cell width and superrotation on Jupiter, the difference between theory and observations for Saturn and Jupiter is $-26\%$ and $23.2\%$, respectively, compared with $-6\%$ and $22.7\%$ using the newer data sets.

5. Conclusions

An analytical expression for Hadley cell latitudinal width on Earth given by Equation (2) appears to provide estimates for other solar system planetary bodies that agree well with observations, provided that an account is made where necessary for atmospheric superrotation and an adjustment is made to the pressure scale height for any internal heat source, including latent heat release. Even so, there remain relatively large discrepancies between predictions and observations for Uranus and Neptune, perhaps due to a comparative lack of direct measurements of their atmospheres. Although the mechanisms driving global circulations on gas giants remain poorly understood, recent data from the Juno and Cassini missions revealed locations of atmospheric downwelling on Jupiter and Saturn (Friedson & Moses 2012; Bolton et al. 2017) that bring closer agreement between observations and predictions made by Equation (2). The broad consistency between Equation (2) and observations of diverse solar system planetary bodies lends support to applying the expression to warmer climates on Earth. A deeper tropopause and a more stable atmosphere should be expected to lead to poleward expansion of the tropics (Frierson et al. 2007). Looking further afield, measurements of exoplanet atmospheres are rapidly improving (Kaspi & Showman 2015), so this study may help guide estimates of their general circulation patterns and possible habitability.

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