Lecture 3: Terrestrial Planets

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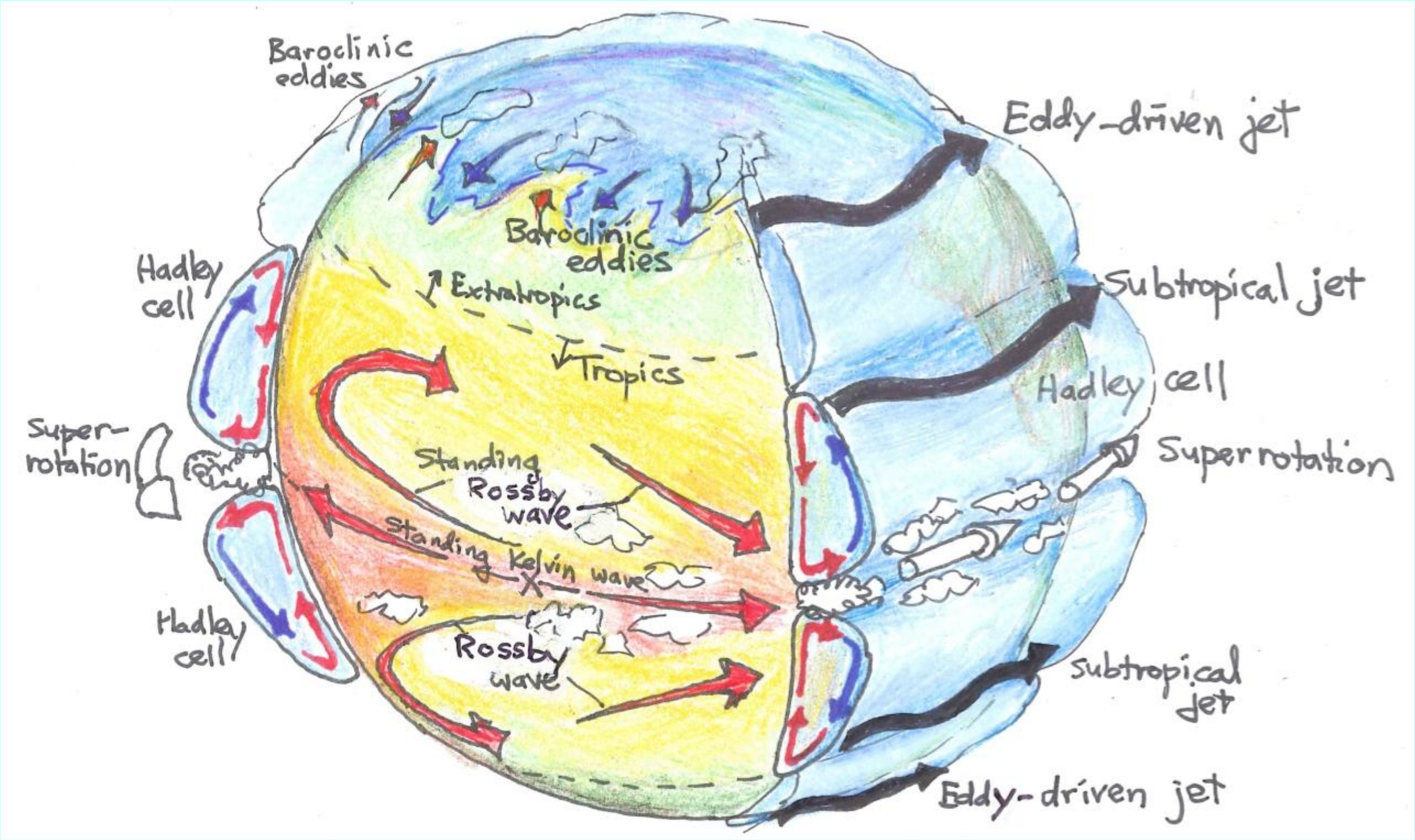
Recap of qualitative dynamical regimes:



Showman et al. (2013b, “Atmospheric circulation of terrestrial exoplanets” in the book *Comparative Climatology of Terrestrial Planets*)

Key dynamical length scales

In the extratropics, the natural horizontal length scale associated with geostrophic adjustment (and other processes involving the interaction of gravity and rotation) is the Rossby deformation radius,

$$L_D = \frac{c}{f}$$

where *c* is the gravity wave speed. In the tropics the equivalent natural length scale, called the equatorial deformation radius, is

$$L_D = \left(\frac{c}{\beta}\right)^{1/2}$$

where $\beta = df/dy$ is the gradient of the Coriolis parameter with northward distance, *y*.

Extratropics

Ro << 1; dynamics is in geostrophic balance

Geostrophy enables large horizontal temperature contrasts (cf Charney 1963)

$$\frac{\delta\theta_{horiz}}{\theta} \sim \frac{fUL}{gD} \sim \frac{F}{Ro}$$

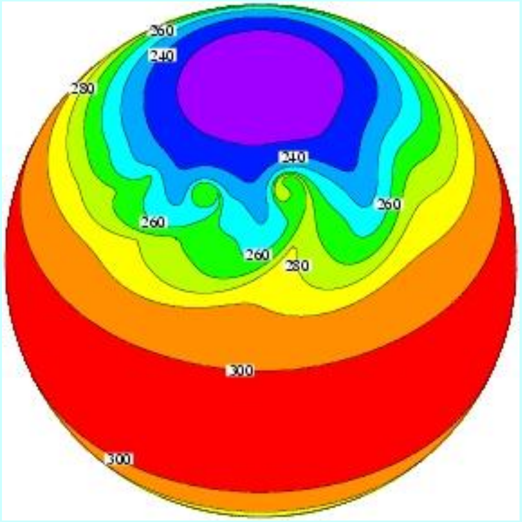
where $F=U^2/gD$ is a Froude number and $Ro=U/fL$ is the Rossby number. Here D is the depth of the system, U is wind speed, f is Coriolis parameter, L is horizontal lengthscale, and g is gravity. For Earth-like parameters, we obtain a temperature difference of ~0.01.

Large horizontal temperature contrasts and sloping isentropes imply that extratropics are generally baroclinically unstable. In analytic theory, the most unstable zonal wavelength is typically ~4L_D, with growth rates scaling with

$$(f/N)\partial u/\partial z$$

For Earth-like conditions, these imply length scales of ~4000 km and growth timescales of 3-5 days.

Baroclinic instabilities generate eddies that dominate much of the dynamics, controlling equator-pole heat fluxes, temperature contrasts, meridional mixing rates, vertical stratification, and jet formation



Tropics

Ro ~ 1; dynamics is inherently ageostrophic

Horizontal temperature contrasts tend to be small (cf Charney 1963)

$$\frac{\delta\theta_{horiz}}{\theta} \sim \frac{U^2}{gD} \sim F$$

which is significantly smaller than in the extratropical case. Inserting Earth parameters gives ~0.001.

Baroclinic instability less important or negligible (compared to the extratropics)

Temperature structure regulated by Hadley circulations and wave adjustment, contributing to the relatively small horizontal temperature differences, the so-called "weak temperature gradient" or WTG regime.

Let's look at some GCM experiments to illustrate these mechanisms and address the following questions:

- **How do fundamental mechanisms of atmospheric circulation vary with rotation rate, atmospheric mass/composition, incident stellar flux, etc? How do these parameters affect strength, width, location, properties of Hadley cell, jet streams, mixing rates, temperature distributions, wind speeds, etc?**

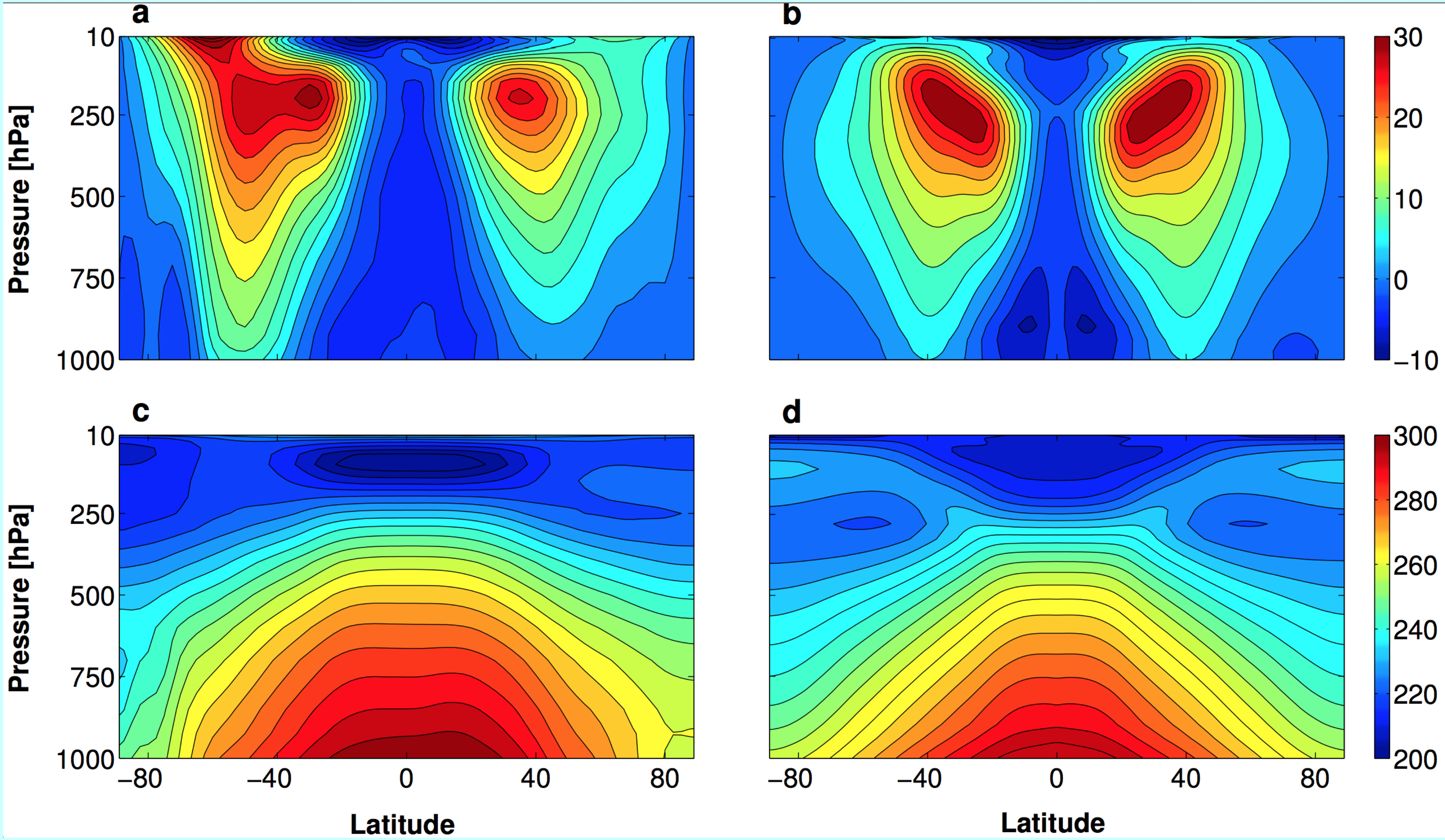
- **Why are equator-to-pole temperature differences on Venus and Titan so much smaller than on Earth? Why is that of Mars greater? What controls the equator-pole temperature contrast generally?**

- **Implications for habitability?**

- **Implications for observations of terrestrial exoplanets?**

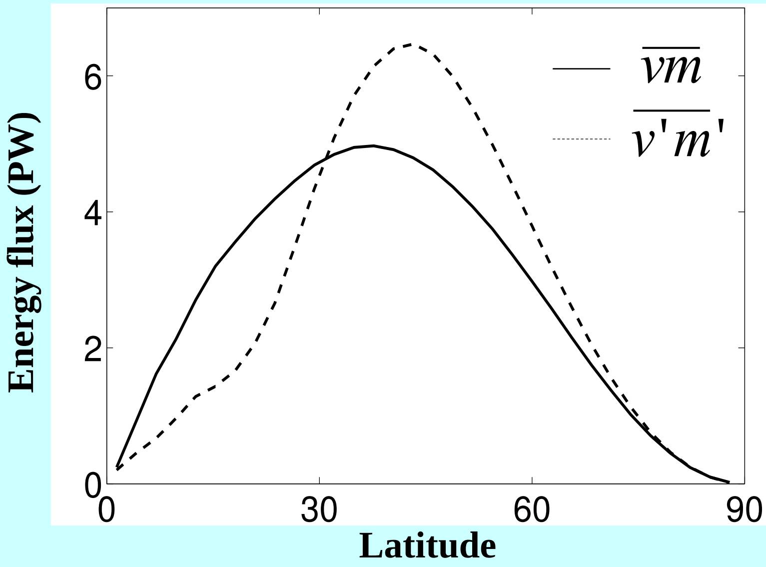
Observations

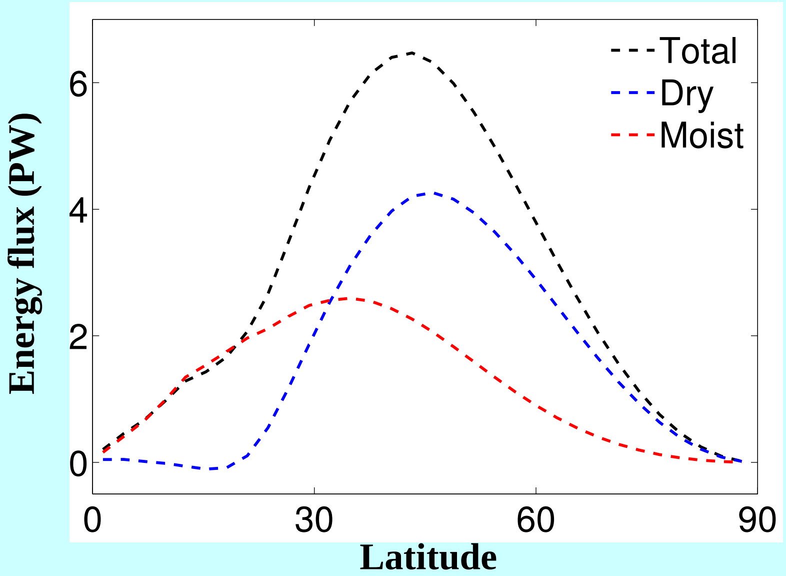
Reference Earth GCM experiment



Kaspi & Showman (2015)

Meridional temperature distribution (Earth case)





m **= moist static energy**

$$= C_p T + gz + Lq$$

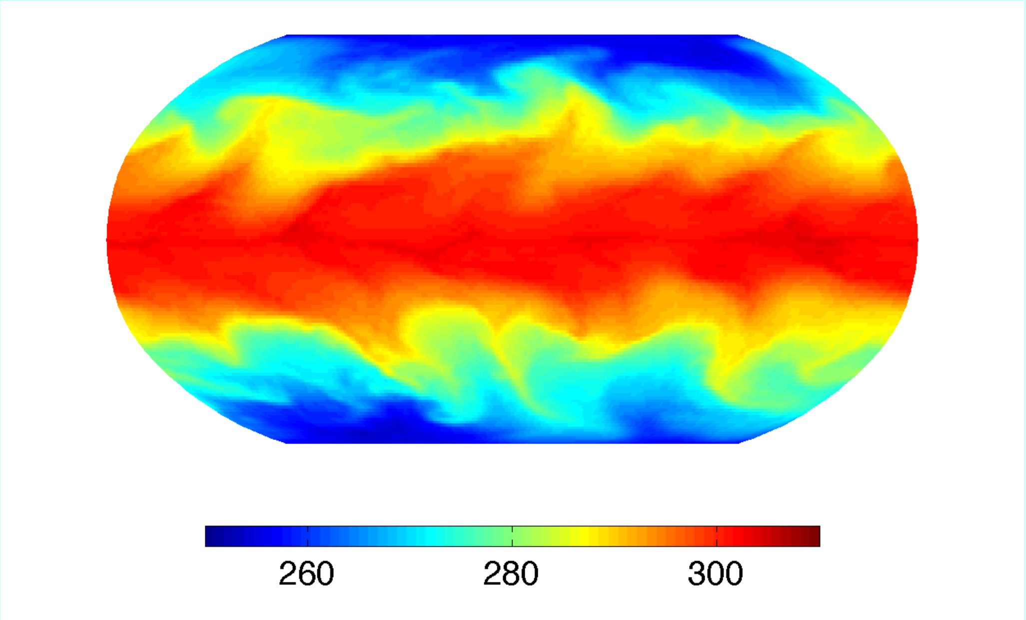
$$\overline{vm} = \bar{v}\bar{m} + \overline{v'm'}$$

T = **temperature**

z = **geopotential**

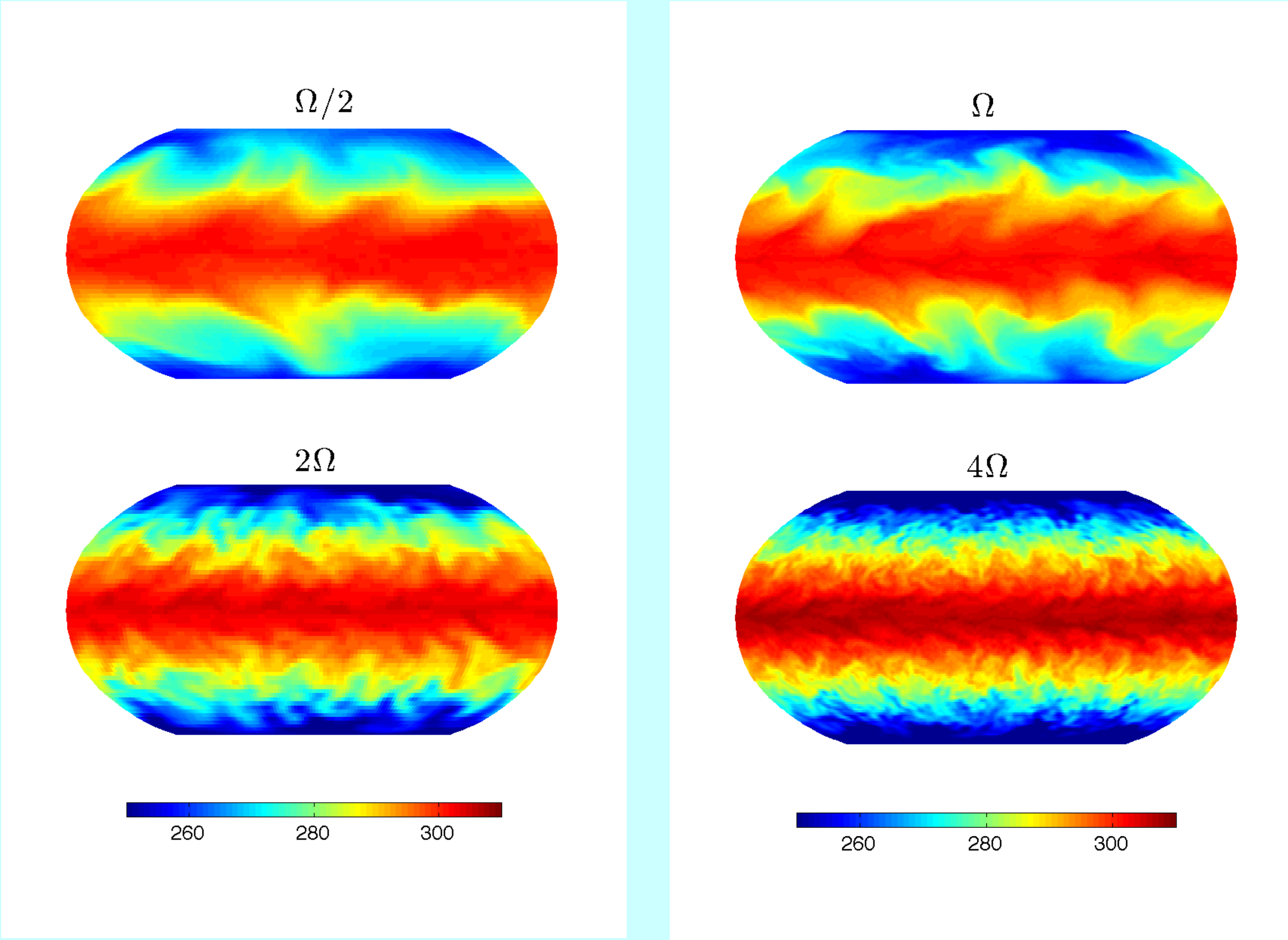
s = **specific humidity**

L = **latent heat of vaporization**



Kaspi & Showman (2015)

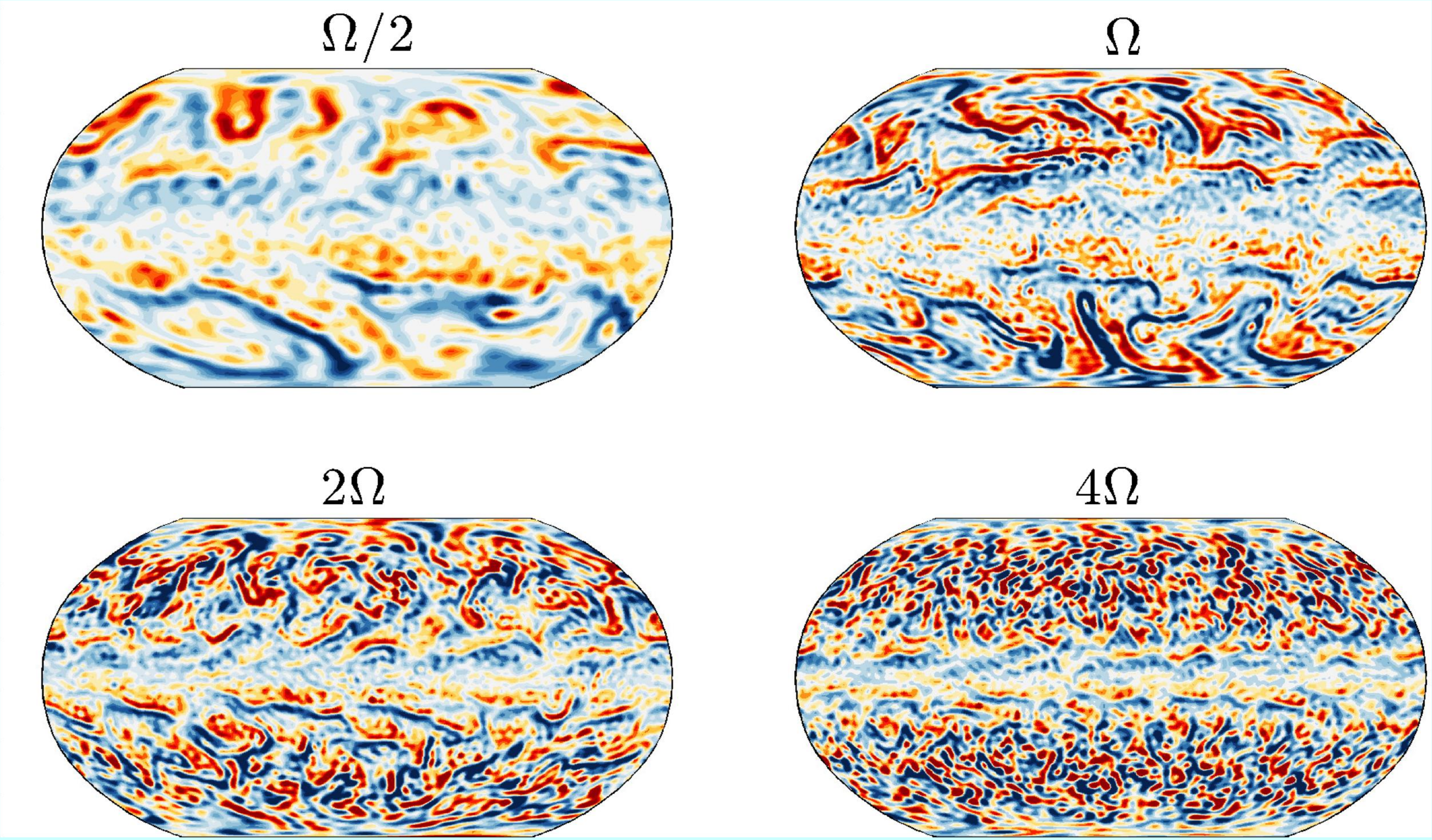
Effect of planetary rotation on baroclinic eddies



Eddy length scale decreases inversely with rotation rate, as expected from analytic theory. Note the greater equator-pole temperature differences at high rotation rate.

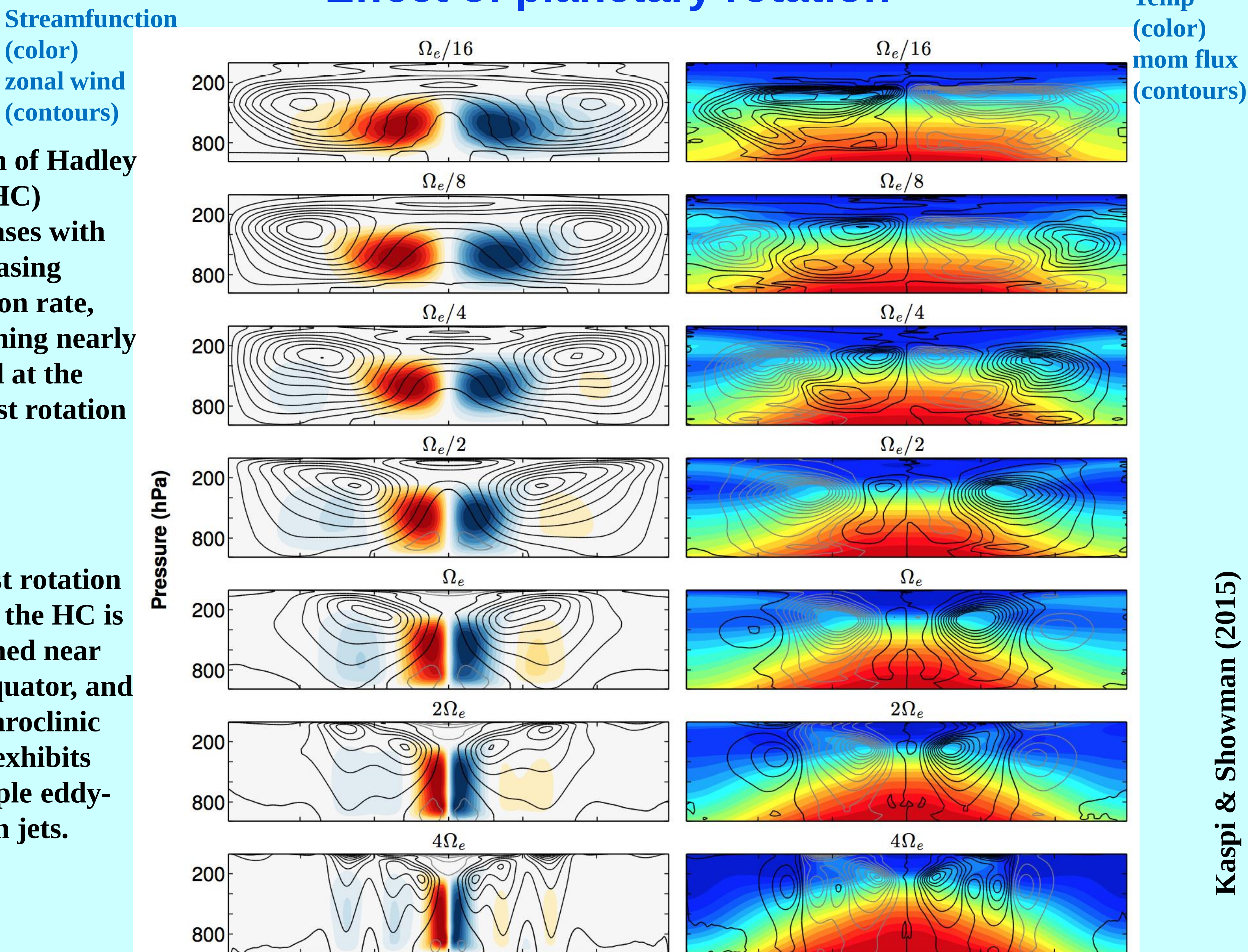
Kaspi & Showman (2015)

Mid-troposphere vorticity



Kaspi & Showman (2015)

Effect of planetary rotation



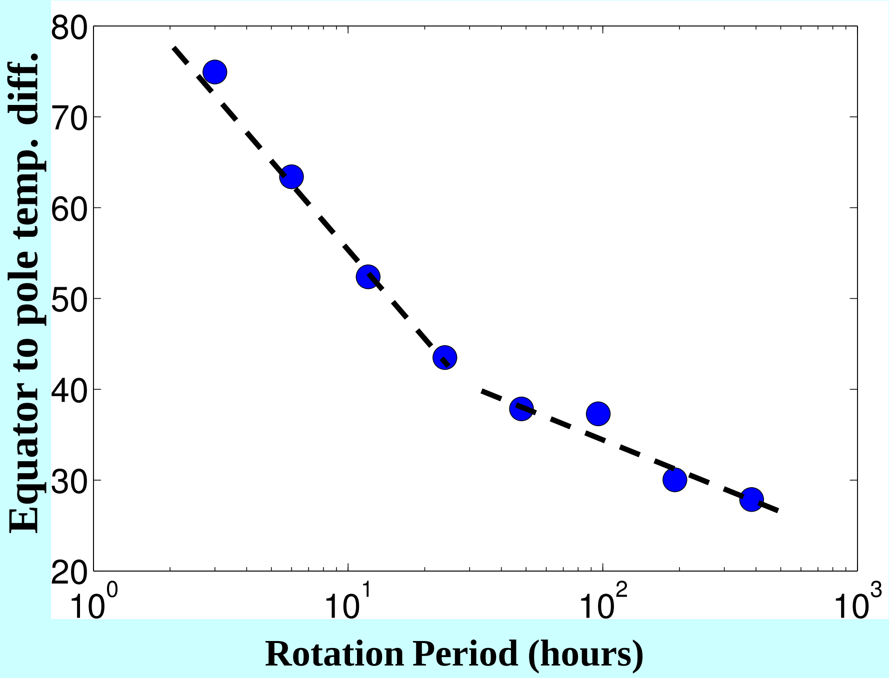
Width of Hadley cell (HC) increases with decreasing rotation rate, becoming nearly global at the slowest rotation rates.

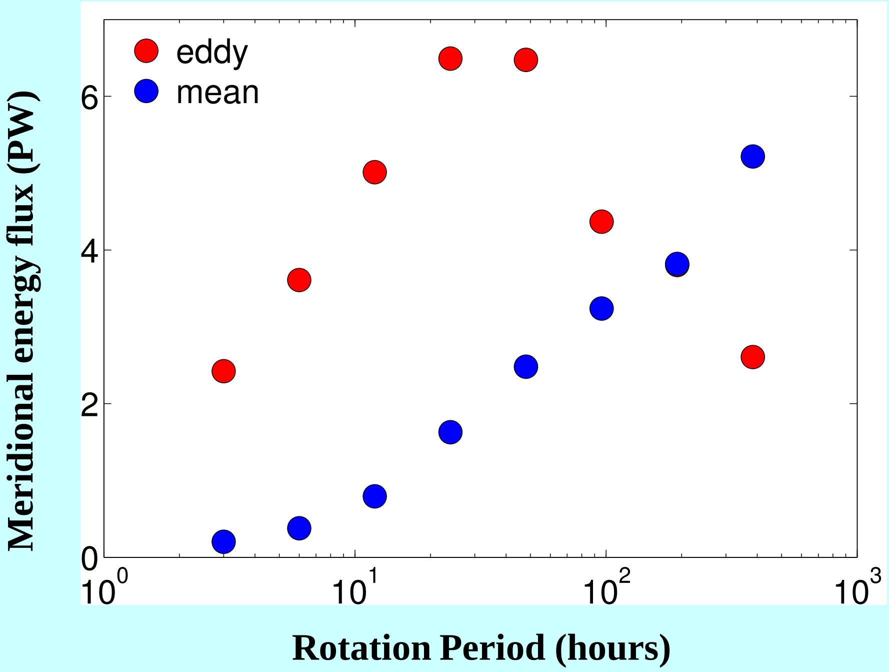
At fast rotation rates, the HC is confined near the equator, and the baroclinic zone exhibits multiple eddy-driven jets.

Kaspi & Showman (2015)

Effect of planetary rotation

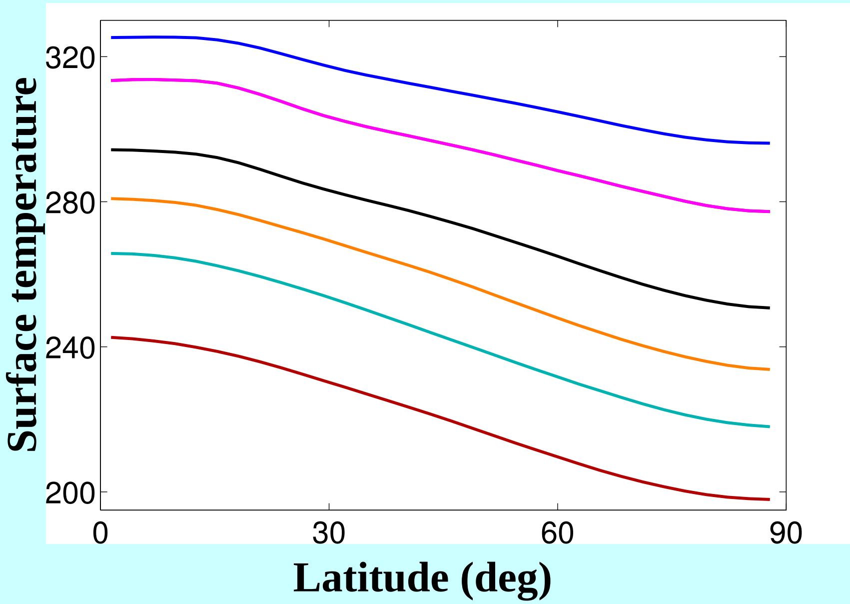
The smaller eddies in the more rapidly rotating models are less efficient at transporting thermal energy, and the Hadley cell is narrower, both of which contribute to greater equator-to-pole temperature difference at fast rotation rate.

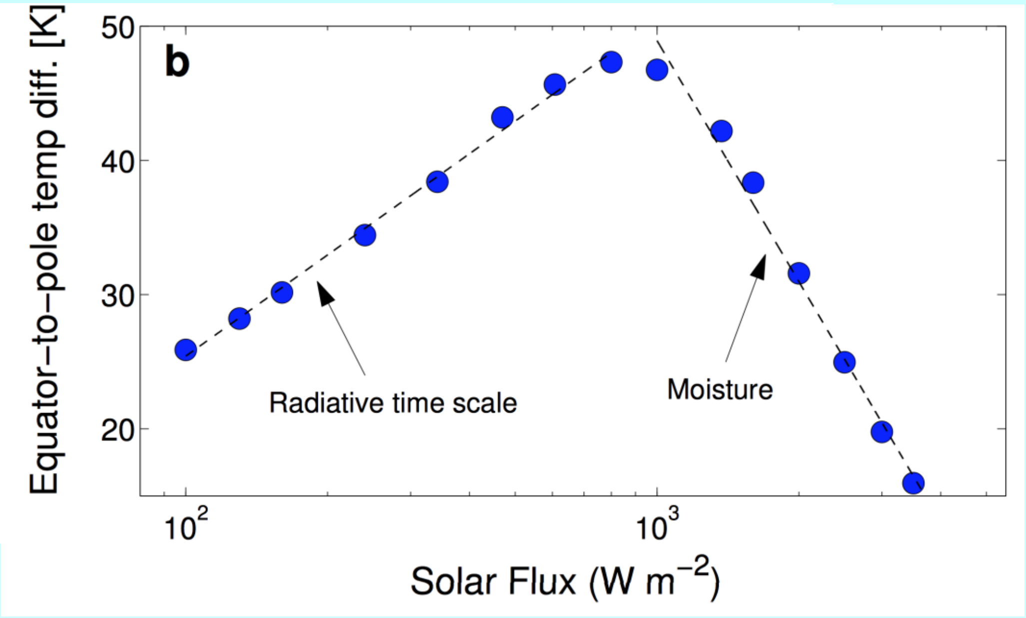




Kaspi & Showman (2015)

Incident stellar flux

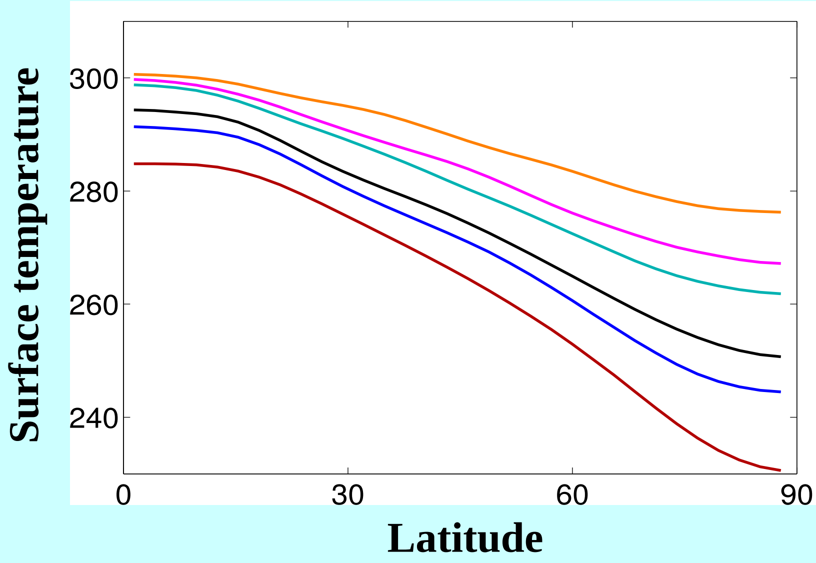


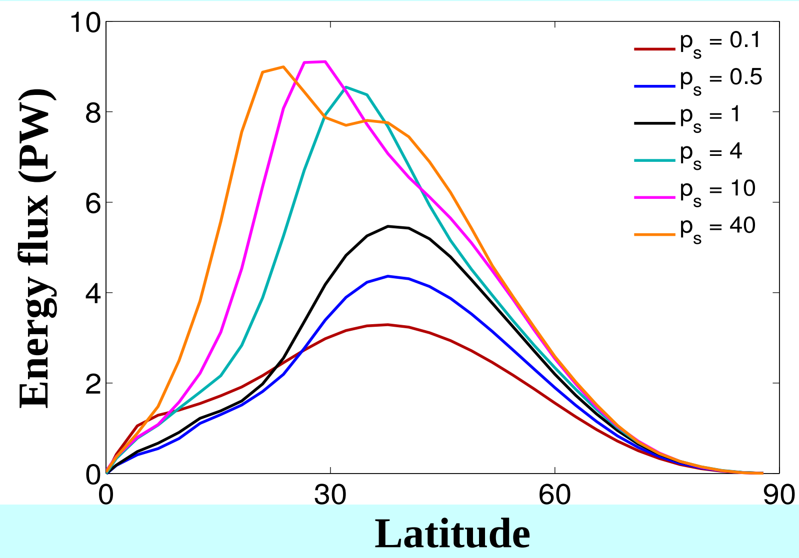


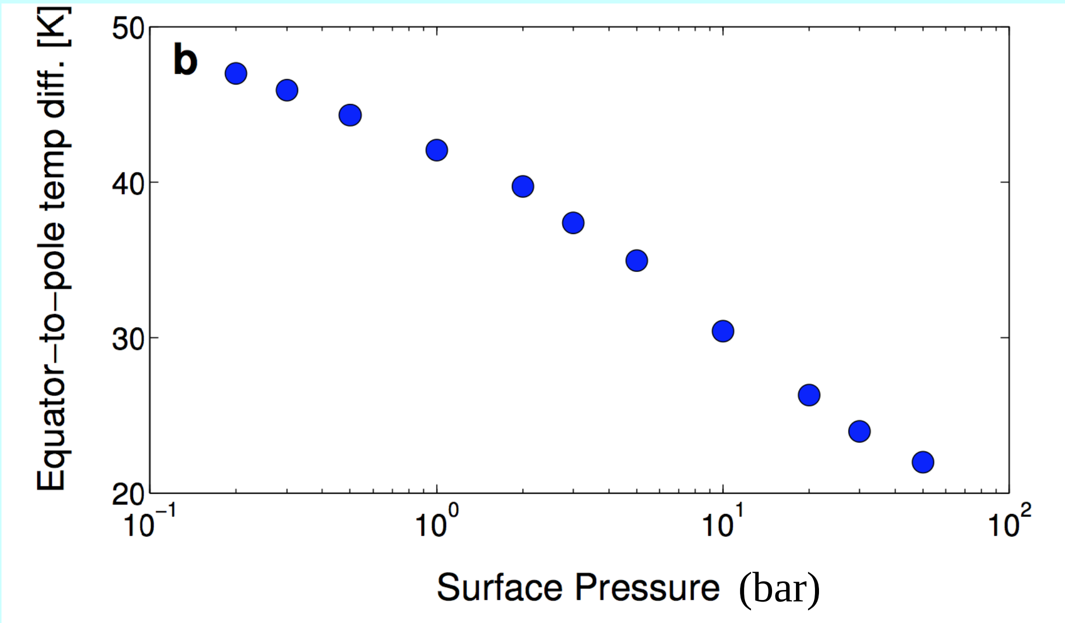
Kaspi & Showman (2015)

Atmospheric Mass

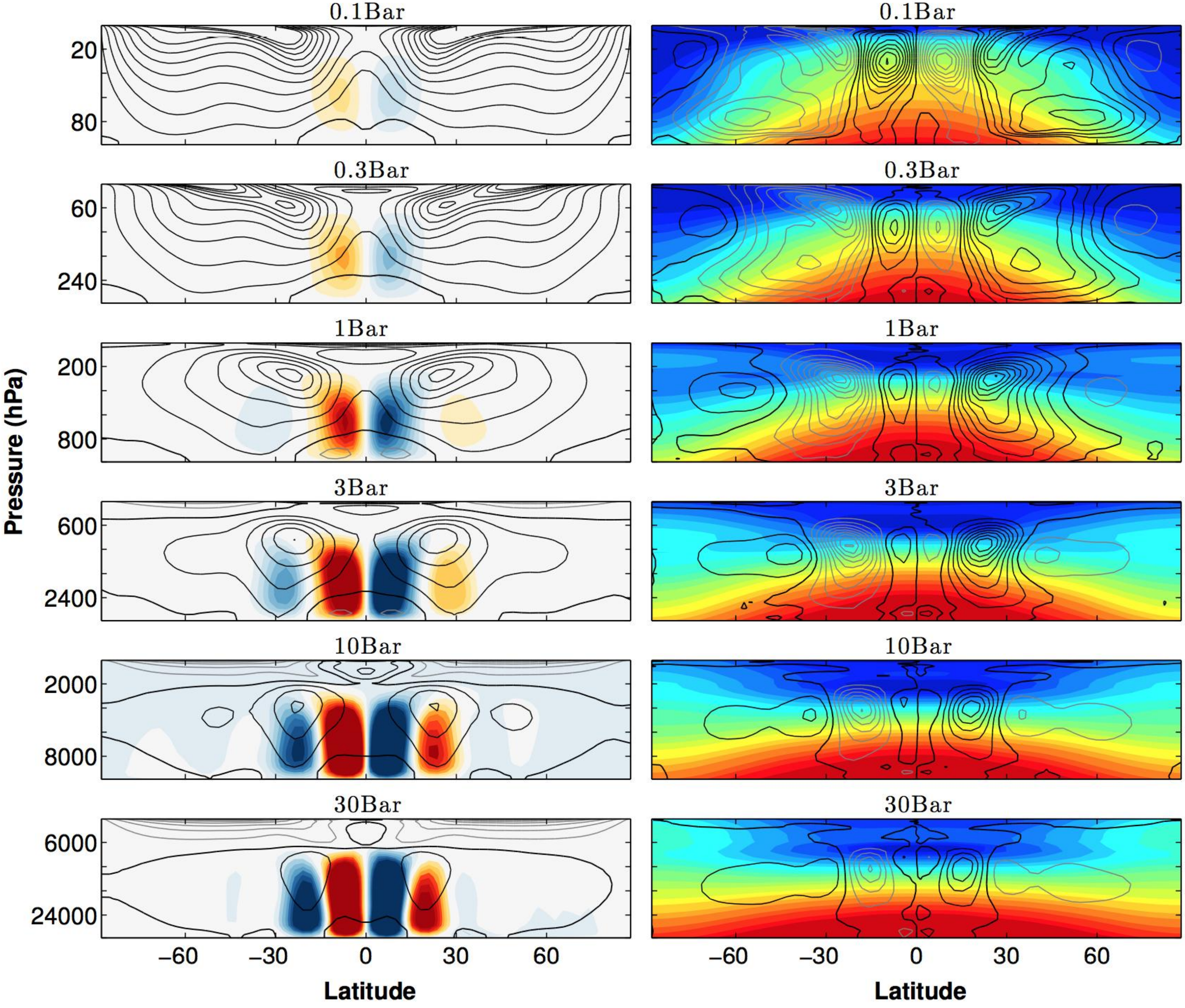
Vary surface pressure, keeping gravity constant at Earth value







Kaspi & Showman (2015)



Kaspi & Showman (2015)

Summary

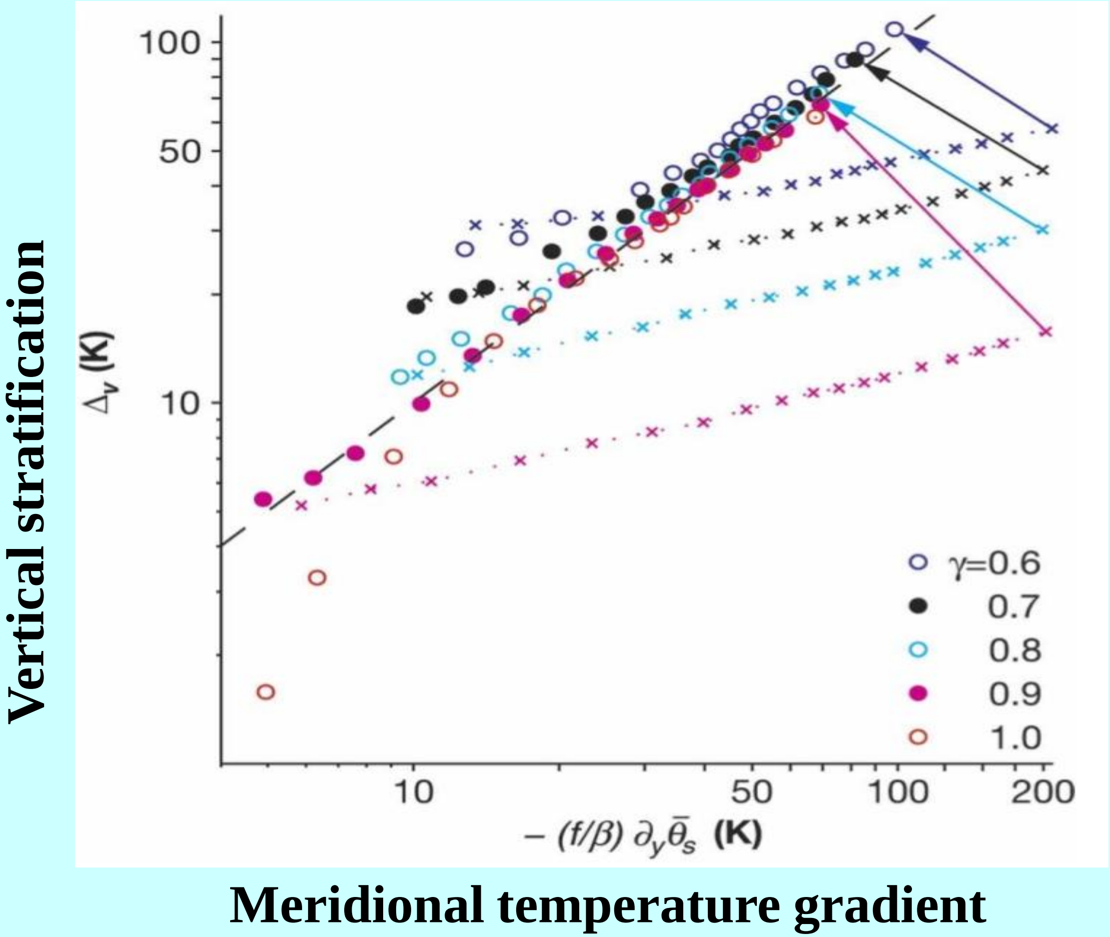
- **Rotation rate, atmospheric mass, solar constant, planetary mass and planetary mean density have an order unity affect on the dynamical structure of the circulation, including the equator to pole temperature gradient.**

- **The equator to pole temperature gradient is important in characterizing climate and habitability (e.g., it is important for determining whether a planet can enter a snowball state).**

Temperature gradients increase	Temperature gradients decrease
• Faster rotation • Larger planetary mass • Larger planetary density	• Larger atmospheric mass • Larger solar flux • Larger radiative time scale

Extratropics: Role of baroclinic eddies in controlling thermal structure

Some numerical evidence suggests that baroclinic instabilities cause the extratropics to adjust to a state where isentropes slope by a scale height over a planetary radius (implying that vertical stratification scales with meridional temperature gradient). This could explain this property of Earth's extratropics. More on this in the lecture on jets.

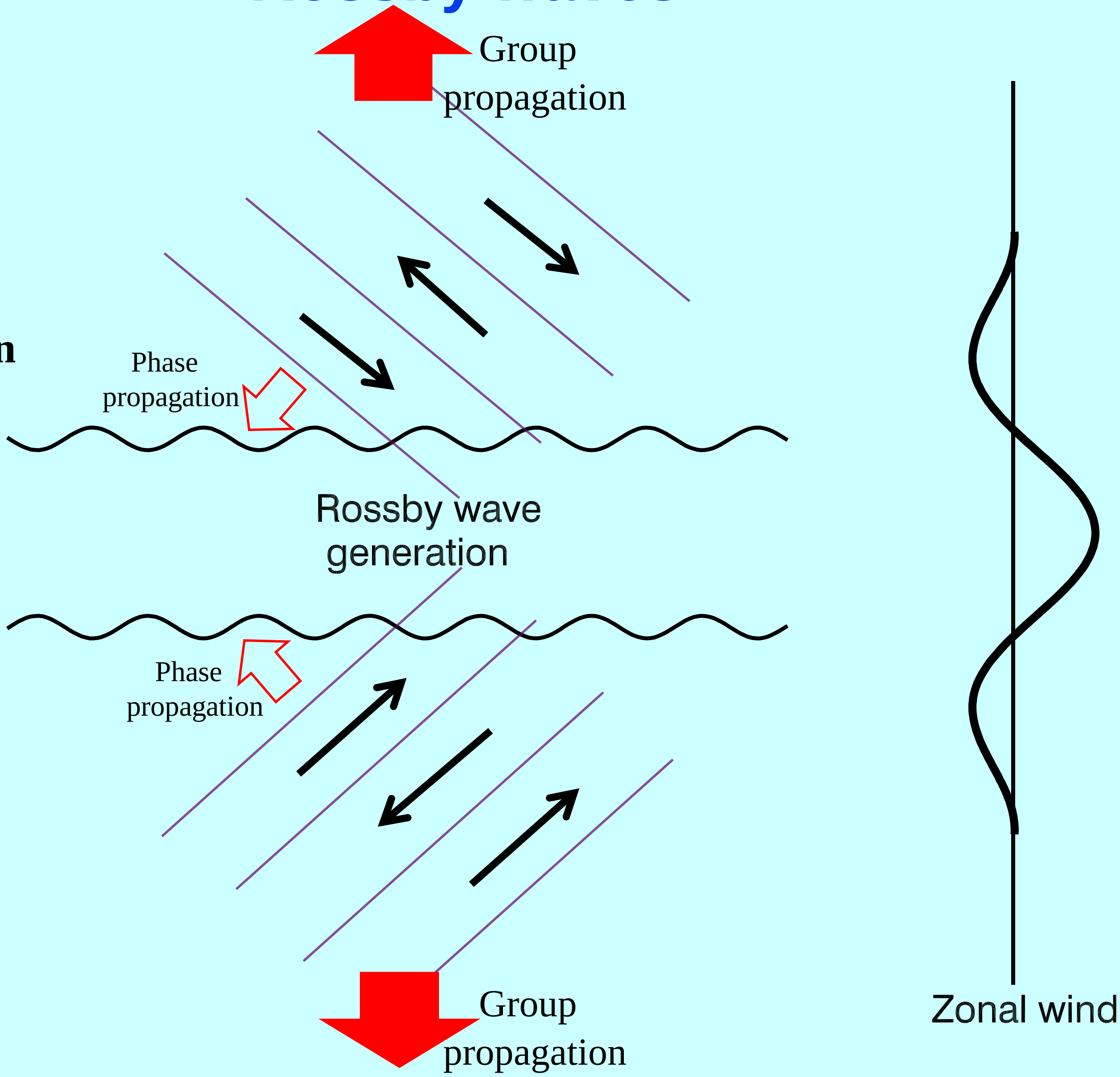


Schneider & Walker (2006)

Rossby waves

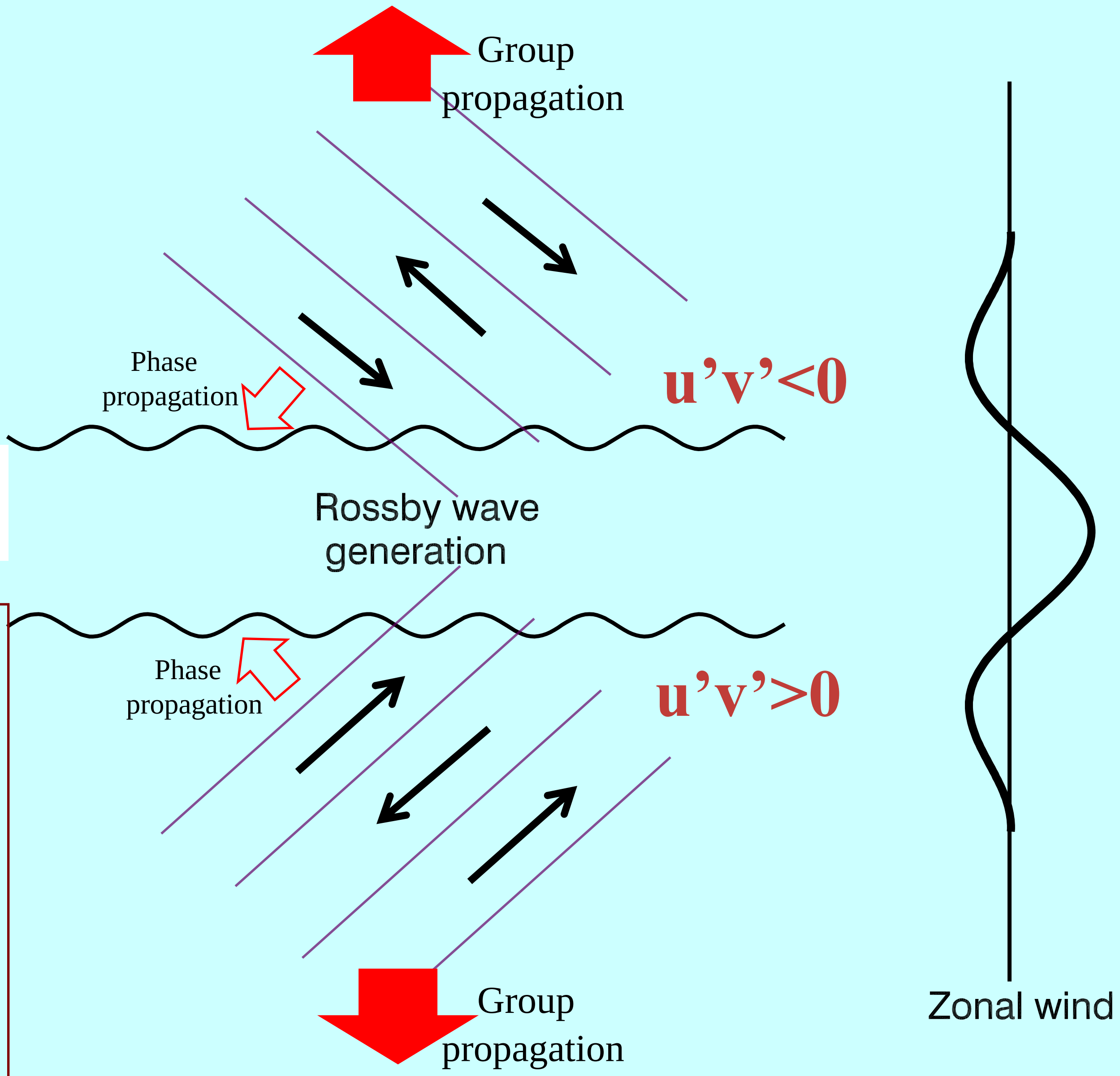
Mechanisms of extratropical jet formation: role of Rossby waves

In the extratropics, regions of Rossby wave generation correspond to eastward eddy-driven jets. Regions of Rossby wave damping correspond to westward flow.



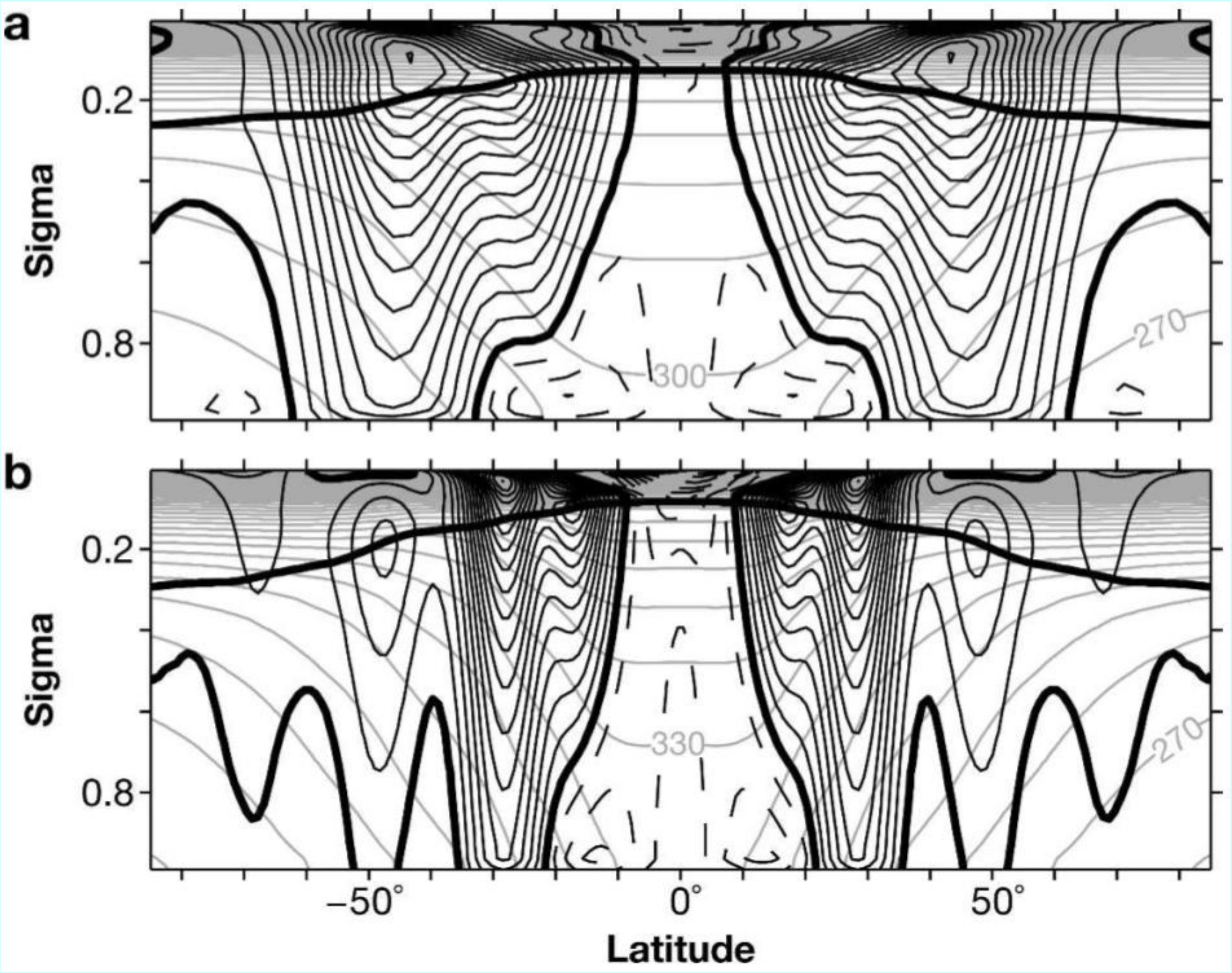
Mechanisms of jet formation: role of Rossby waves

$$\frac{\partial \overline{u}}{\partial t} = -\frac{\partial(\overline{u'v'})}{\partial y} - \frac{\overline{u}}{\tau_{\text{drag}}}$$



The eddy acceleration term is positive (eastward) in the region of Rossby wave generation, and negative (westward) in the region of Rossby wave damping/breaking.

Zonal jets



Schneider & Walker (2006)

Hadley circulation

Regulates the thermal structure in the tropics. Exerts a significant effect on the mean climate. Although the real Hadley cell has strong 3D structure, it can be idealized as a 2D circulation—unlike the case of heat transport by baroclinic eddies in the extratropics.

All the terrestrial planets with thick atmospheres—Earth, Mars, Venus, Titan—have Hadley circulations.

Planetary rotation exerts strong control over the Hadley circulation. It's useful to think about the limit where the upper branch conserves angular momentum about the rotation axis,

$$m = (\Omega a \cos\phi + u) a \cos\phi,$$

where *a* is planetary radius. If the ascending branch is at the equator and exhibits zero zonal wind, then the zonal wind in the upper (poleward flowing) branch is

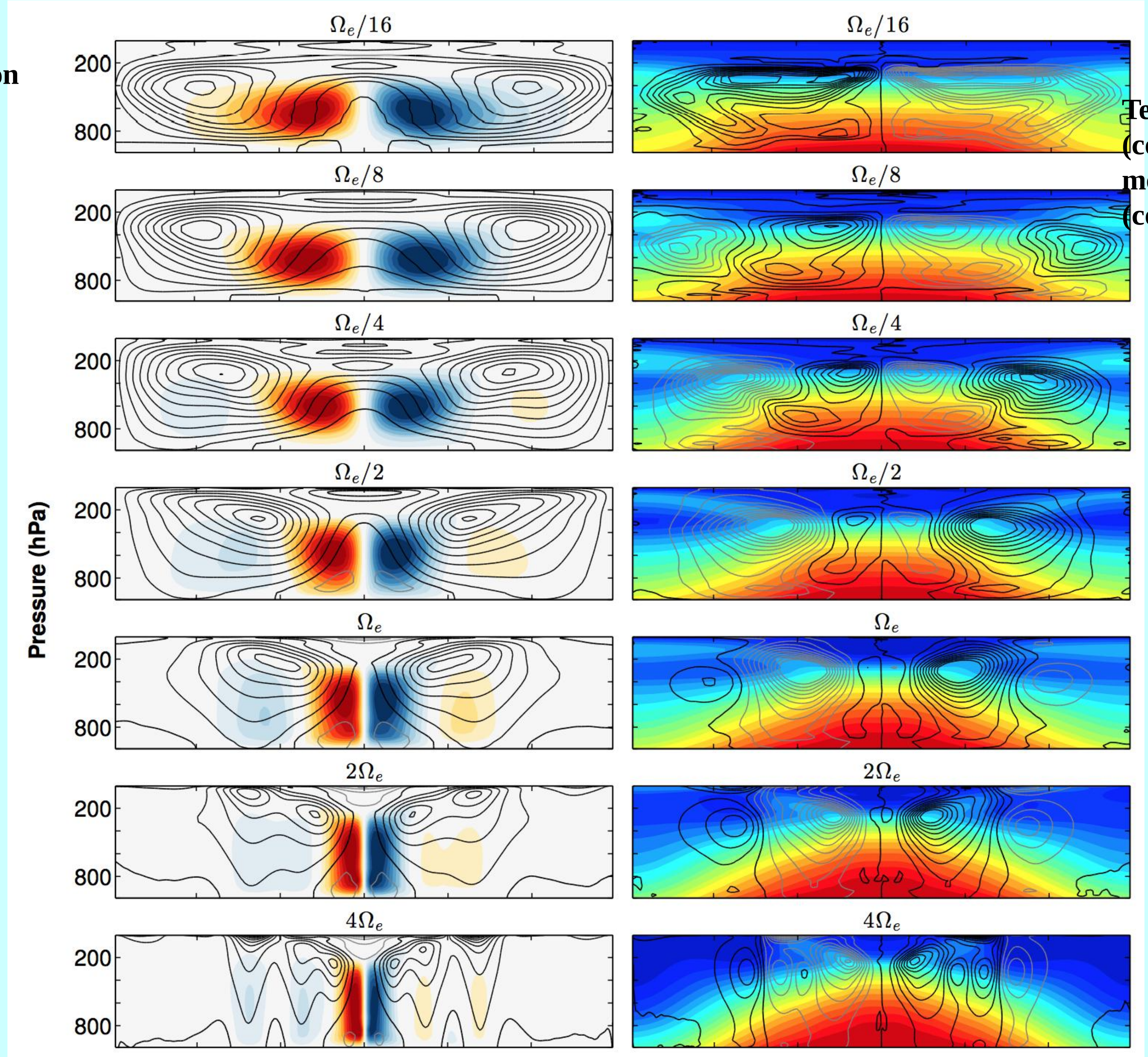
$$u = \Omega a \frac{\sin^2\phi}{\cos\phi}$$

For Earth conditions, this yields wind speeds of 134 m/s, 1000 m/s, and infinite at latitudes of 30^o, 67^o, and the poles. This is of course impossible, and implies that rotation, if sufficiently strong, will confine the Hadley circulation to low latitudes.

This eastward upper tropospheric wind, which peaks near the outer edge of the Hadley cell, is the *subtropical jet.*

Effect of planetary rotation

Streamfunction (color) zonal wind (contours)



Temp (color) mom flux (contours)

Note how width of Hadley cell increases with decreasing rotation rate, becoming nearly global at the slowest rotation rates.

Temperature gradients are relatively weak across most of the Hadley cell.

Kaspi & Showman (2015)

Hadley circulation

The Hadley circulation can exhibit different regimes depending on the extent to which the upper branch is angular-momentum conserving. Consider the zonal-mean zonal wind equation from 3D primitive equations, using pressure as a vertical coordinate:

$$\frac{\partial \overline{u}}{\partial t} = (f+\overline{\zeta})\overline{v} - \overline{\omega}\frac{\partial \overline{u}}{\partial p} - \frac{1}{a\cos^2\phi}\frac{\partial(\cos^2\phi\,\overline{u'v'})}{\partial \phi} - \frac{\partial(\overline{u'\omega'})}{\partial p}$$

where $\omega = dp/dt$ is the vertical velocity in pressure coordinates. Overbars and primes denote zonal means and deviations therefrom. Denote the eddy terms by $-S$ and consider the statistical steady state:

$$(f+\overline{\zeta})\overline{v} = \overline{\omega}\frac{\partial \overline{u}}{\partial p} + S$$

For Earth, the first term on the right side is not dominant, so that we can write (e.g., Held 2000, Walker & Schneider 2006):

$$(f+\overline{\zeta})\overline{v} = f(1 - Ro_H)\overline{v} \approx S$$

where $Ro_H = -\zeta/f$ is a Rossby number associated with the Hadley circulation.

Essentially, Ro_H is a measure of the strength of eddies on the Hadley cell, which exhibits different behaviors depending on whether Ro_H is large or small.

Hadley circulation

$$(f+\overline{\zeta})\overline{v} = f(1-Ro_H)\overline{v} \approx S$$

The Hadley circulation exhibits different behavior depending on whether *Ro_H* is large or small.

When eddy accelerations are negligible, then *S*=0, and for non-zero circulations the absolute vorticity must therefore be zero within the upper branch, i.e., *$f+\zeta$*=0, or, in other words, *$Ro_H \rightarrow 1$*. The definitions of relative vorticity and angular momentum imply that

$$f+\overline{\zeta} = \frac{1}{a^2\cos\phi}\frac{\partial\overline{m}}{\partial\phi}$$

A circulation with zero absolute vorticity therefore exhibits angular momentum that is constant with latitude. This is simply the angular-momentum conserving limit. The Hadley cell in this limit is thermally driven.

On the other hand, eddy accelerations are often important in shaping the Hadley circulation. If *$Ro_H \ll 1$*, then the zonal momentum balance is

$$f\overline{v} = S$$

which means that the strength of the Hadley circulation is solely controlled by the amplitude of the eddy acceleration (and not, at least directly, by thermal forcing).

Real Hadley circulations lie between these two extremes.

Hadley circulations

For Earth and Mars, the primary eddy effects result from absorption of equatorward-propagating Rossby waves that reach critical levels on the flanks of the subtropical jets. These waves break and cause a net westward torque, removing angular momentum.

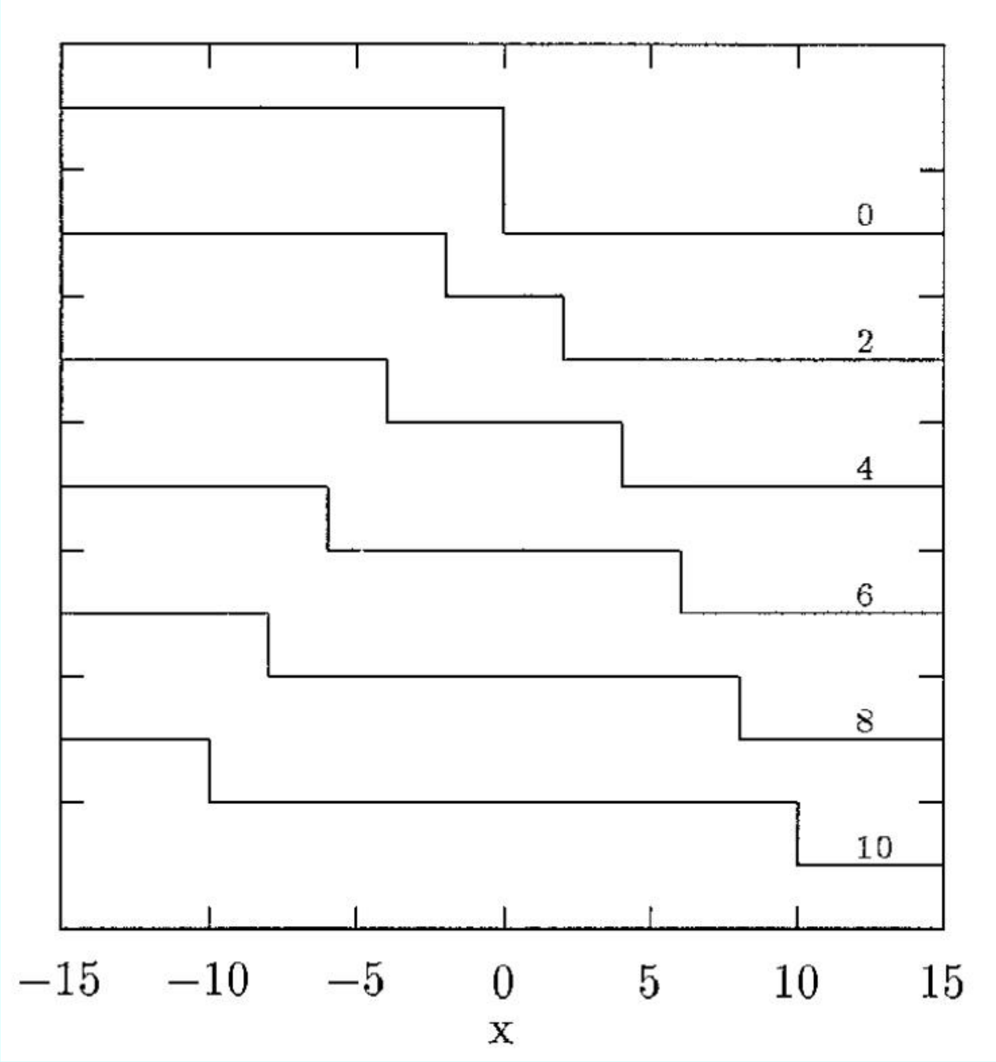
This implies that the angular momentum in the upper branch decreases with latitude away from the equator, and helps explain why the subtropical jet is a factor of several weaker than the angular-momentum conserving limit would suggest.

There is strong seasonality—if the rising branch is located off the equator, as occurs during solstice, then the so-called "winter cell" (the cell that crosses over the equator into the winter hemisphere) will have strongly westward winds near the equator, which tend to lack critical levels and is therefore relatively transparent to the waves.

Ro_H varies from ~0.3-0.4 in the equinoctal and summer cells to ~0.7-0.8 in the winter cell (Schneider & Bordoni 2008, Bordoni & Schneider 2008).

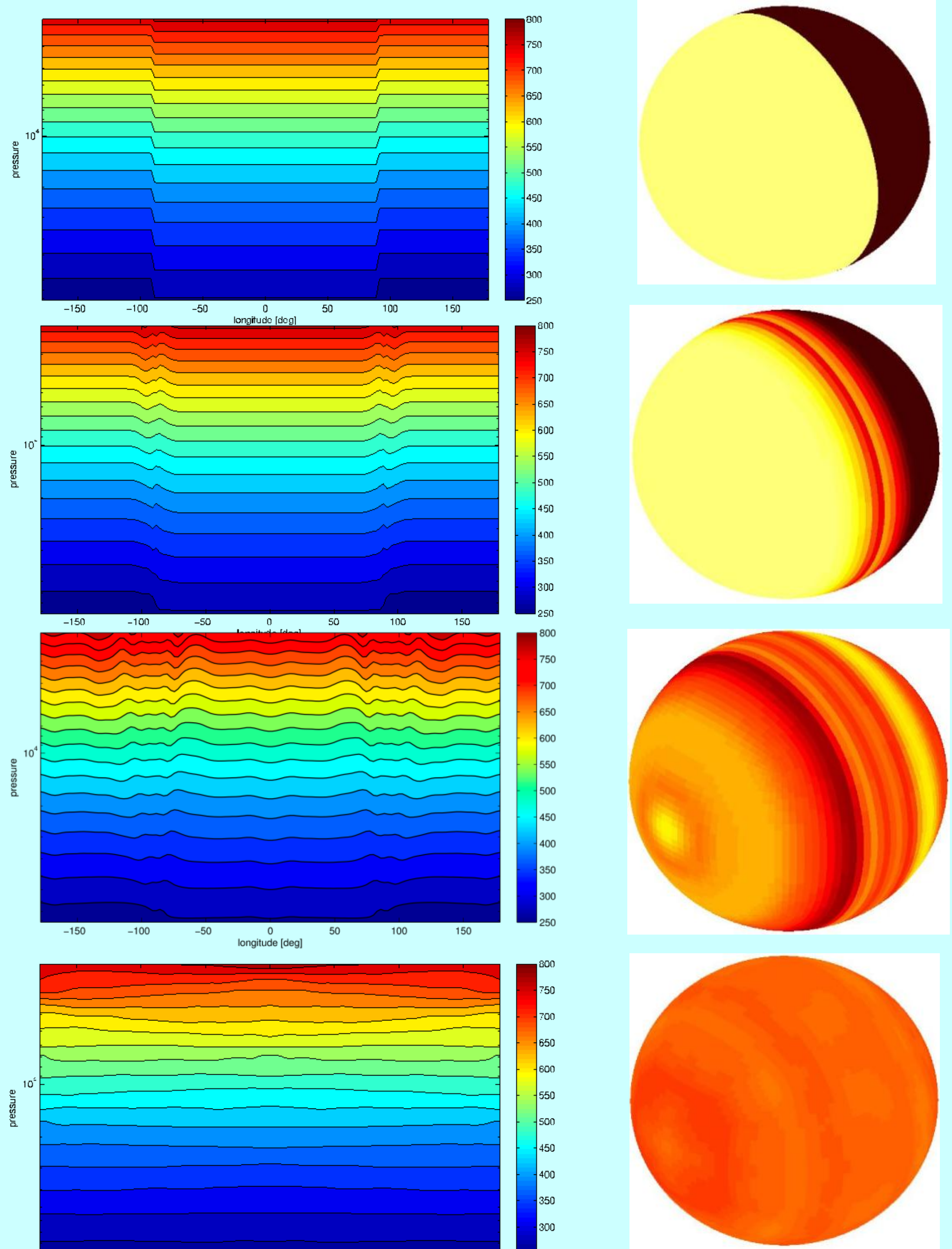
Wave adjustment

The "dam break" problem for the non-rotating case:



Kuo & Polvani (1997)

In a 3D tropical atmosphere, wave adjustment erases horizontal temperature differences



Showman et al. (2013b, “Atmospheric circulation of terrestrial exoplanets” in the book *Comparative Climatology of Terrestrial Planets*)

Timescale arguments associated with adjustment

- **Generally one might crudely expect that if**

$$\tau_{damp} \geq \tau_{dyn} \quad \Longrightarrow \text{ small fractional temperature differences}$$

$$\tau_{damp} \leq \tau_{dyn} \quad \Longrightarrow \text{ large fractional temperature differences}$$

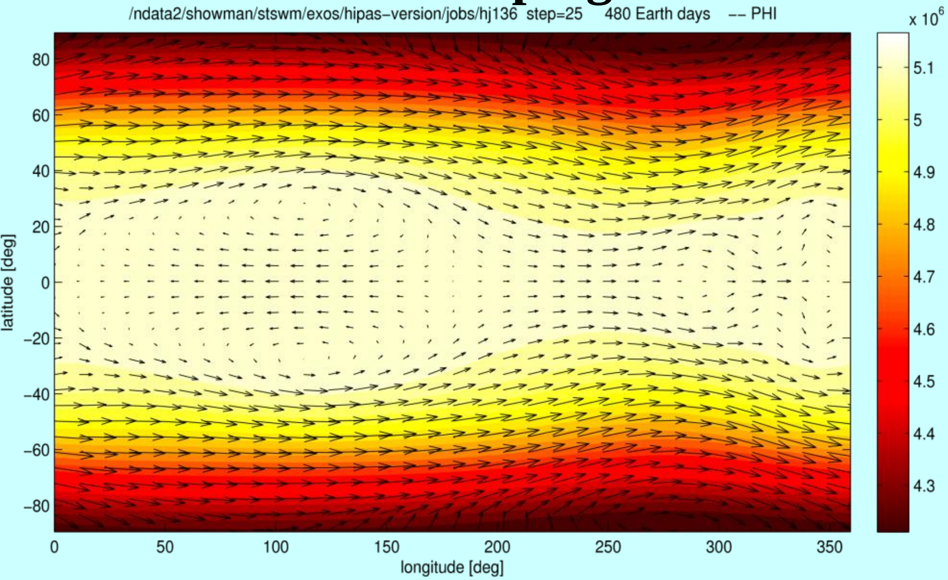
- **Relevant damping timescales include friction and radiative timescales. Dynamical timescales can be horizontal wave propagation timescales, although advection and rotation timescales may be relevant. The precise timescale comparison is thus probably more complex than shown above (e.g., see Komacek & Showman 2016).**

- **The adjustment timescale is often much shorter than the mixing timescale.**

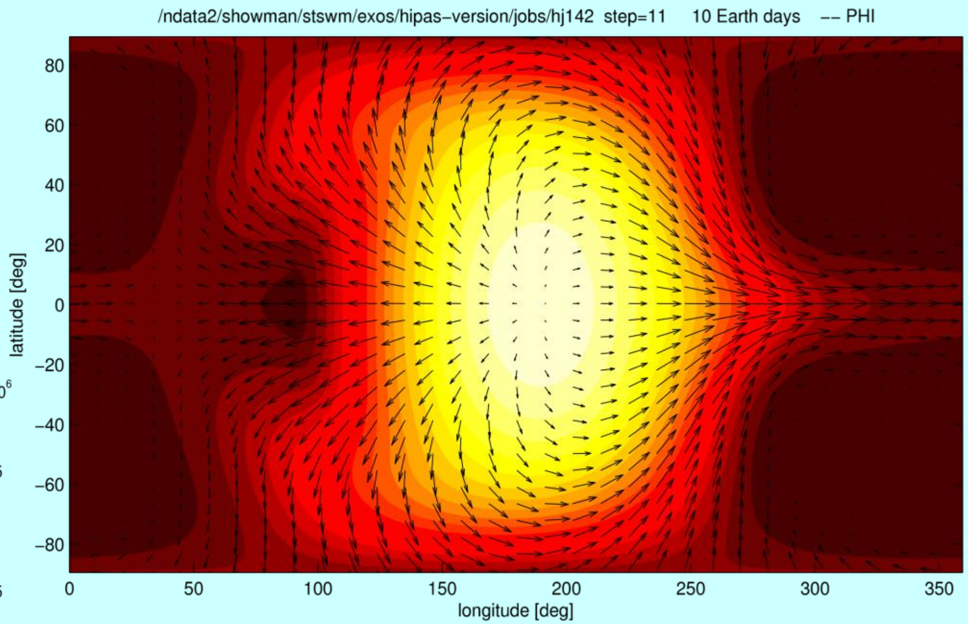
- **For synchronously rotating Earth-like planets, these arguments suggest large temperature differences if atmospheric pressure $\lesssim$ 0.1 bar. For hot Jupiters, they suggest large temperture differences if the planet is hot enough.**

This has important implications for atmospheric collapse on synchronously rotating planets (e.g., Joshi et al. 1997), and for explaining IR data for hot Jupiters.

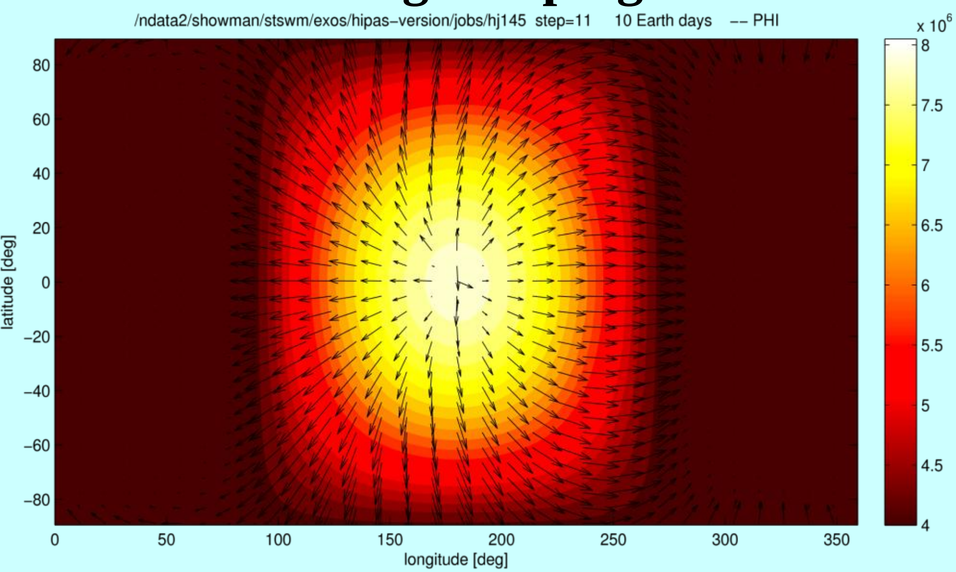
Weak damping



Moderate damping



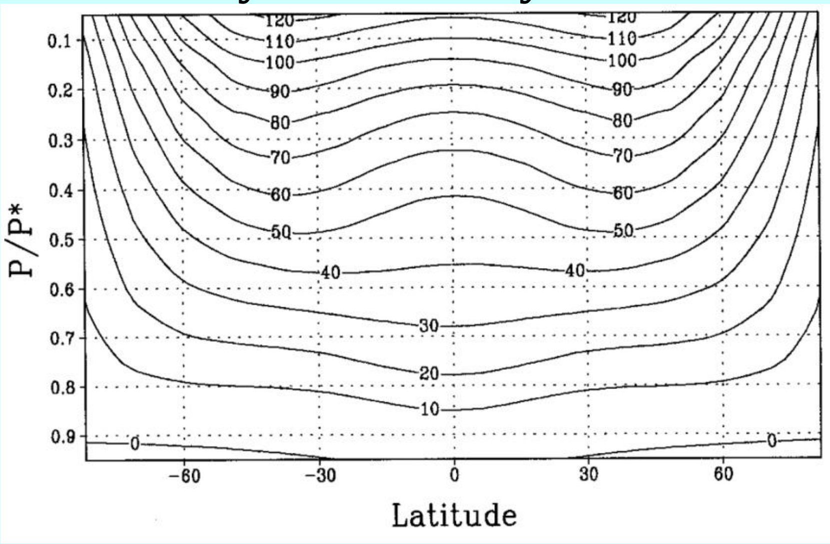
Strong damping

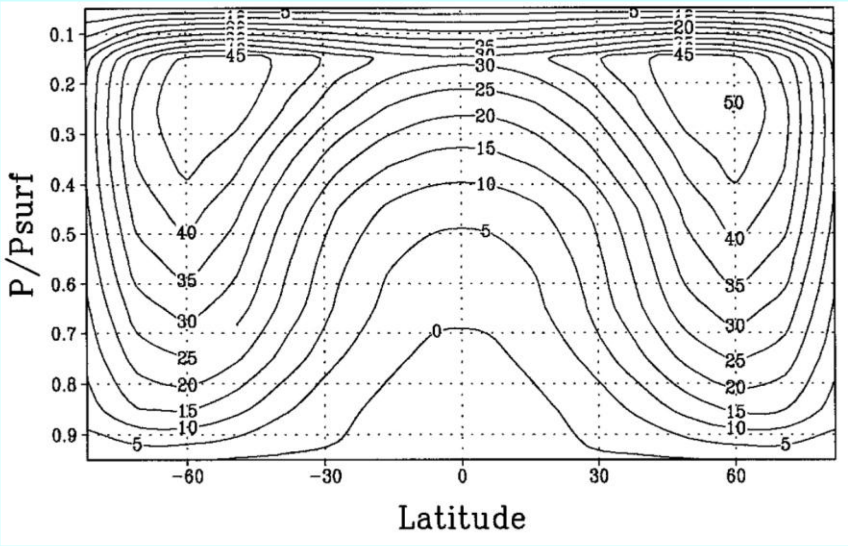


Showman et al. (2013a)

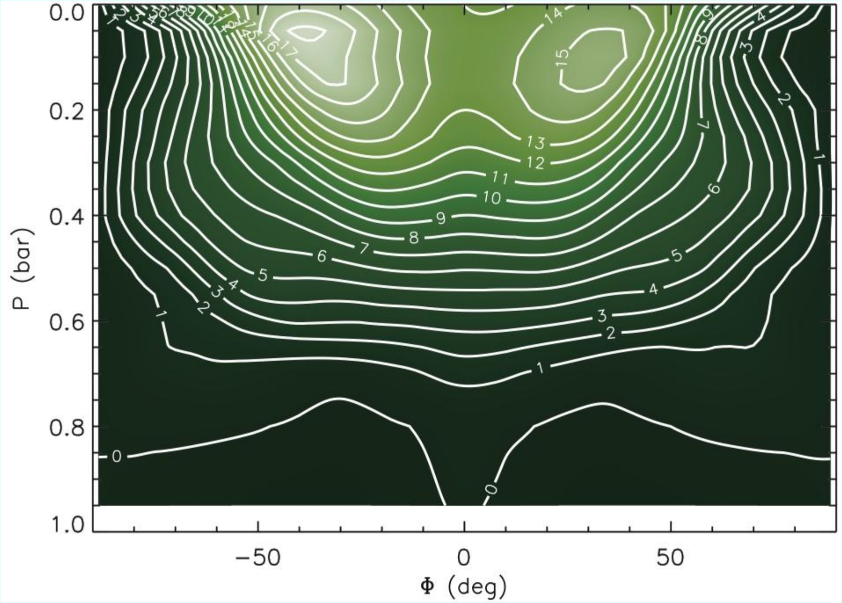
Equatorial superrotation is expected on tidally locked exoplanets

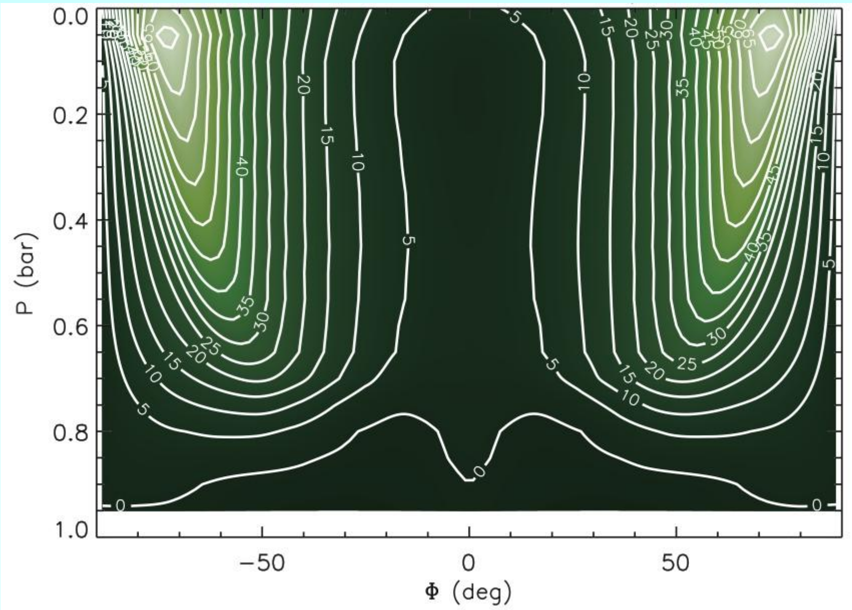
Synchronously locked | **Axisymmetric forcing**





Joshi et al. (1997)

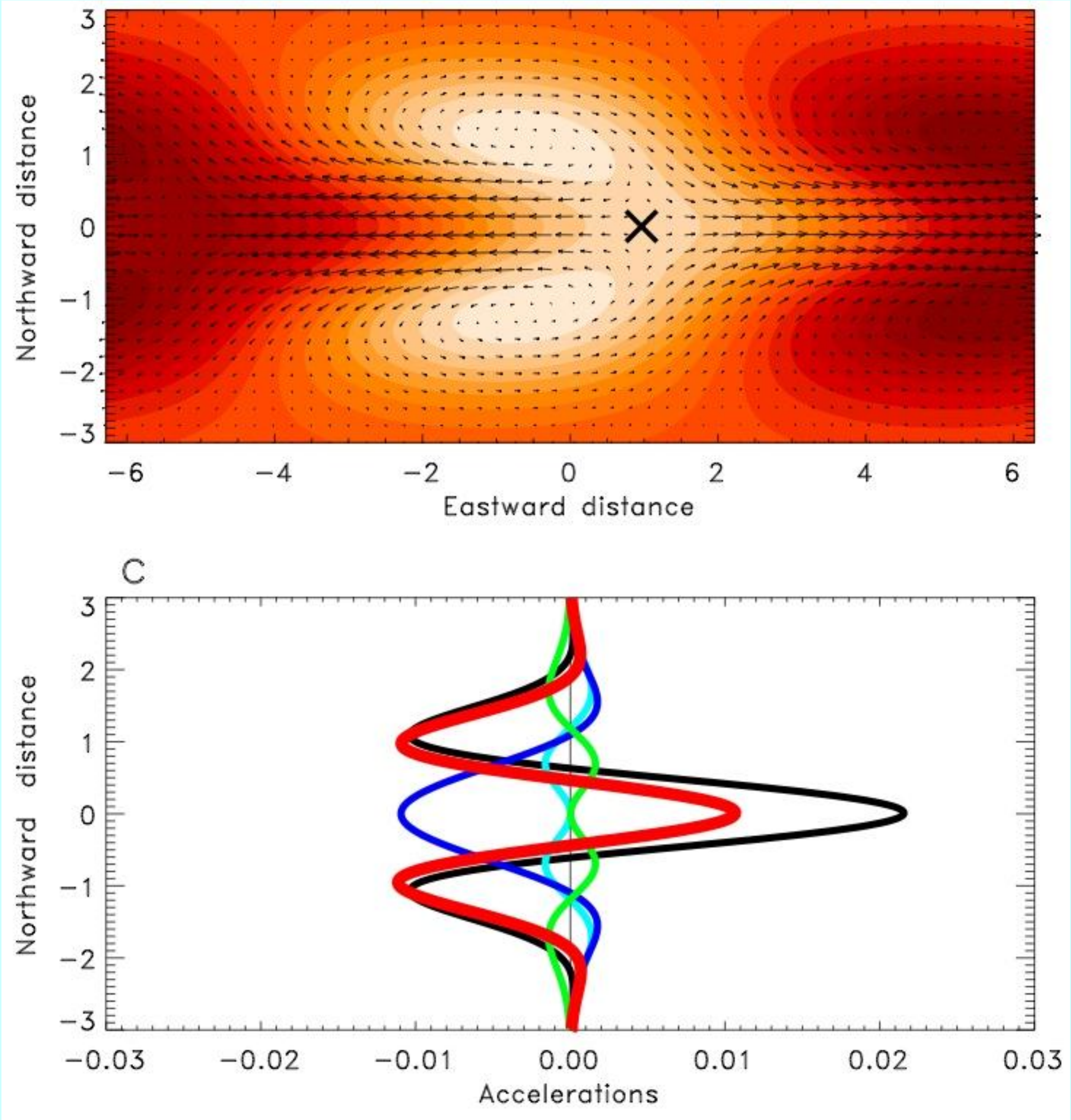




Heng & Vogt (2010)

See also Merlis & Schneider (2010), Wordsworth et al. (2011), Edson et al. (2011)

Showman & Polvani (2011) showed that the superrotation results from momentum transport by standing, planetary-scale waves driven by the day-night thermal forcing

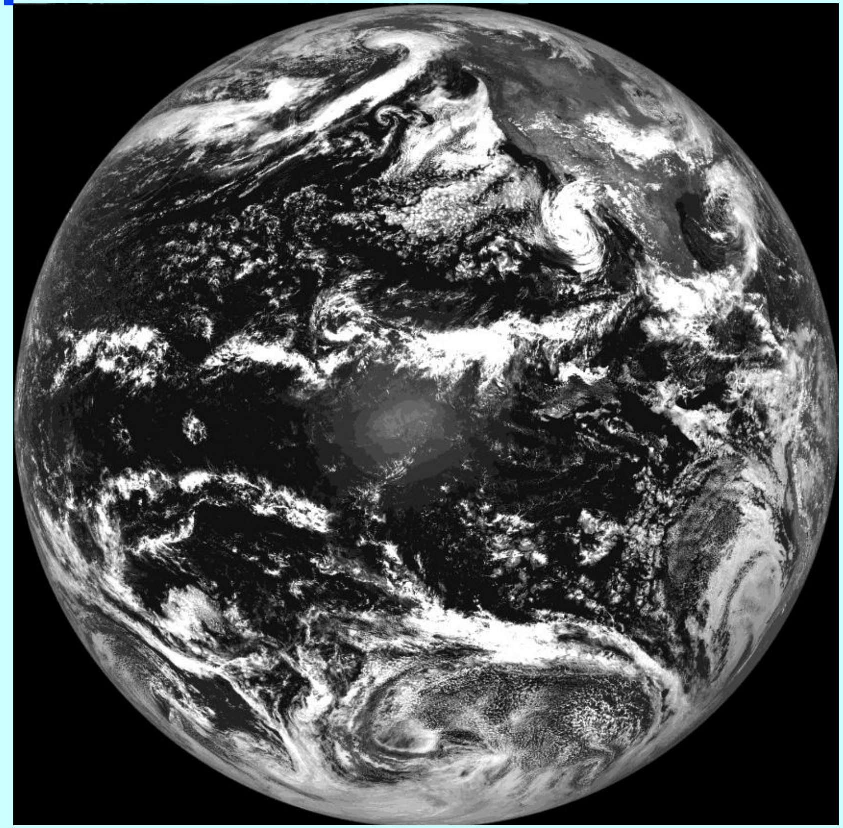


Showman & Polvani (2 011, *ApJ* 738, 71)

That's it for theoretical aspects.

Now let's do a brief observational tour of the Solar System's terrestrial planet climates.

Earth as a planet



- **Earth is the largest terrestrial planet, with a 1-bar N_2 atmosphere and trace amounts of CO_2 and water vapor sufficient to keep temperatures above freezing.**

- **The 3.7-km deep ocean is 260 times the atmosphere mass, implying that Earth has more fluid volatiles at its surface than any other solid object in the solar system.**

- **Viewing Earth as a planet leads to major questions: why is the atmosphere made mostly of N_2? Why does it have this mass? Why isn't the ocean ten times more or less massive? Is it a coincidence that the ocean volume is *large* enough to cover most of the globe but *small* enough to allow continents to stick abovewater?**

What processes control Earth's climate—what are the fundamental global climate feedbacks, how do they interact with the circulation and how do they relate to planetary climate and habitability in general?

Earth as a planet: circulation

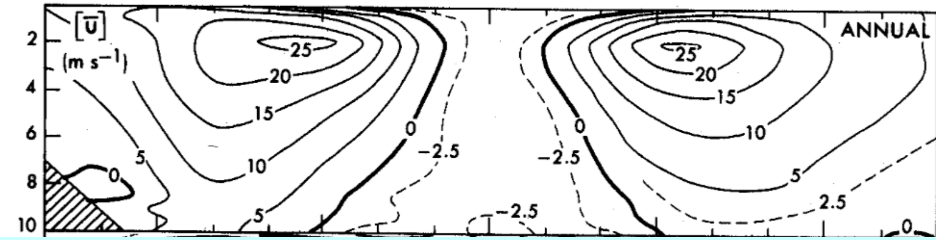
- Earth has a *Hadley cell* at low latitudes and a *baroclinic zone* at high latitudes, leading to subtropical and eddy-driven jet streams in the midlatitudes, relatively flat temperature patterns in the tropics, and steeper isentropes in the midlatitudes.

- The Hadley cell transports heat poleward in the tropics, and baroclinic instabilities do so in the extratropics.

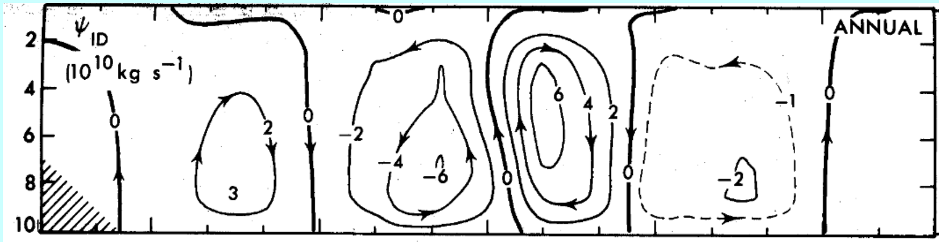
- Much of this structure remains poorly understood at a deep level. We still do not have a predictive theory for what controls Hadley cell width, strength, and temperature constrasts, nor for the equator-pole temperature difference, nor for what sets the rate at which baroclinic instabilities transport heat poleward under given background conditions

Answering these questions requires a "planetary perspective," and will be aided by comparison to other planets.

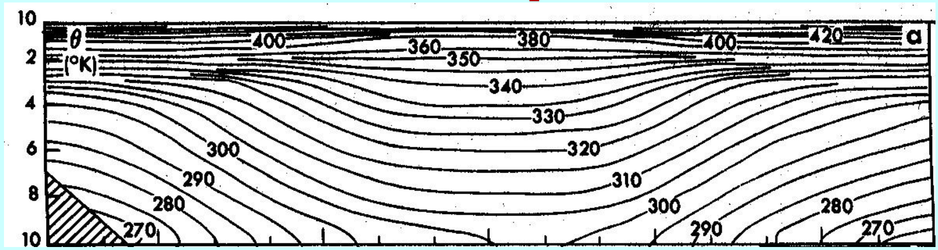
Zonal-mean zonal wind



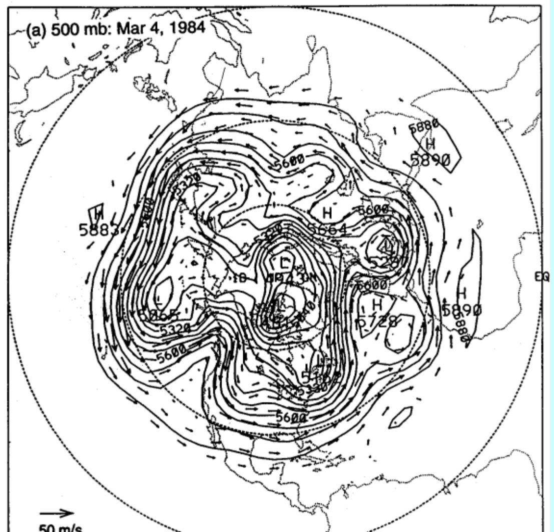
Mean-meridional streamfunction



Isentropes

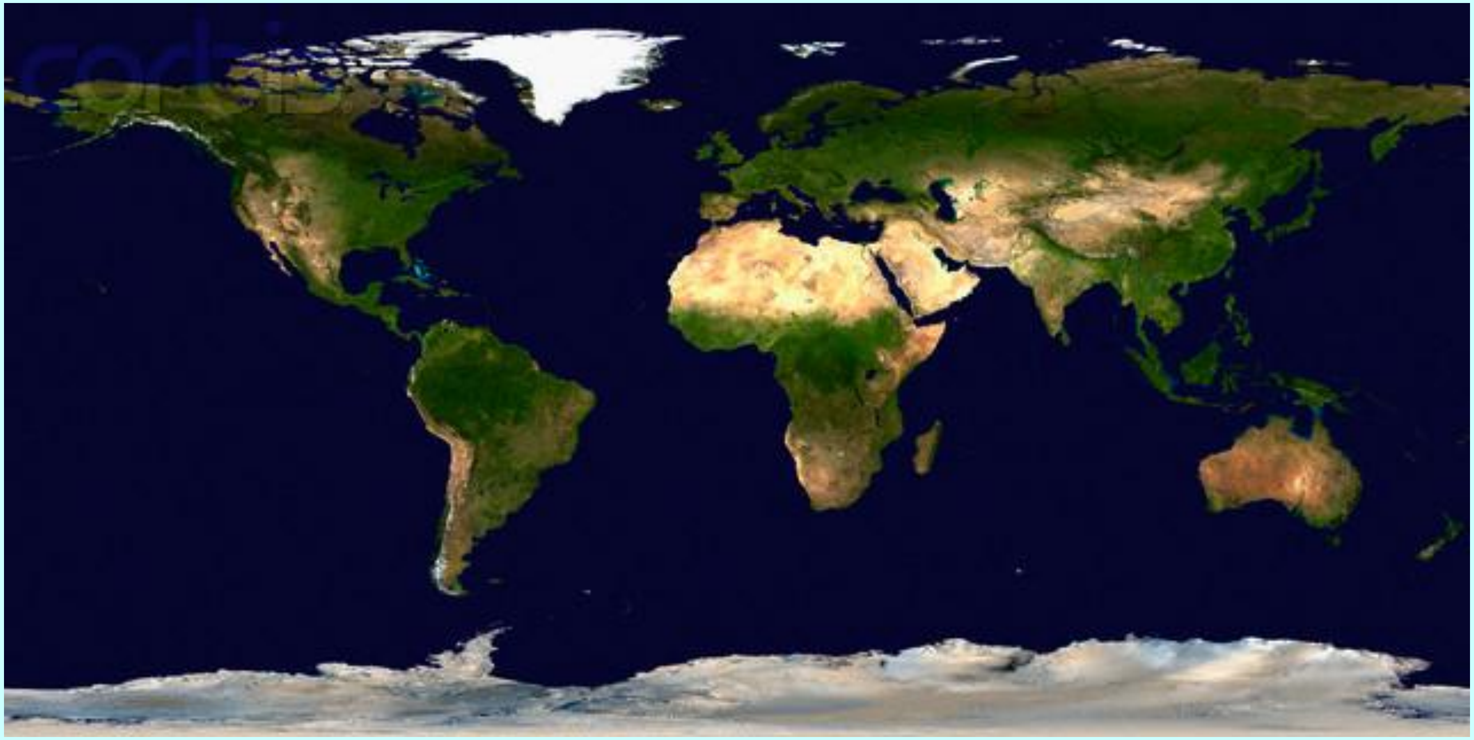


Peixoto & Oort (1992)

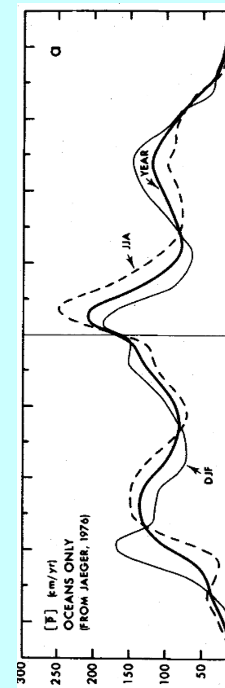


Salby (1996)

Earth precipitation/vegetation regimes are controlled by its circulation



Annual-mean Precipitation



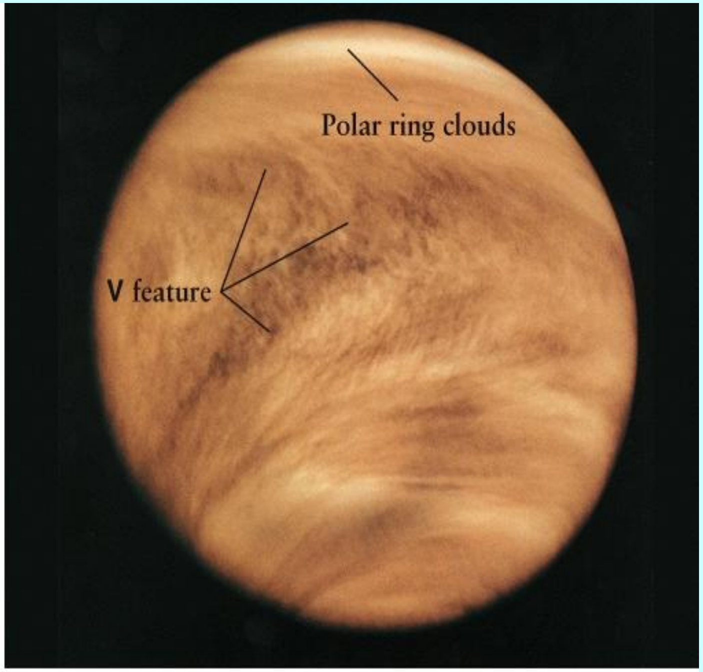
Peixoto & Oort (1983)

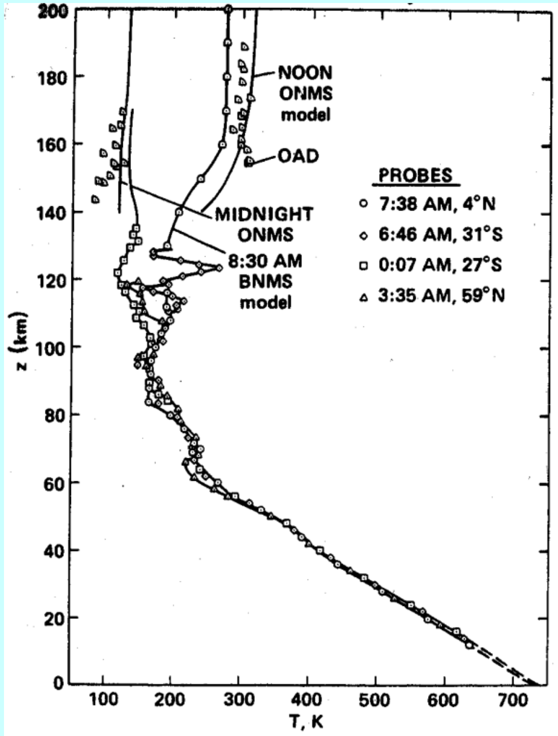
Width/strength of the Hadley cell and width/structure of the baroclinic zone determine the location of rainforests and deserts

So what would happen if Earth were rotating faster or slower, if the atmospheric mass were different, if the gravity were different, if the sunlight were different? These are planetary questions!

Venus

- Venus, geophysically, is a near-twin of Earth: radius and mass 94% and 81% of Earth's. Bulk interior composition probably very similar. Orbits at 0.728 AU.
- But atmosphere is very different: sulfuric acid cloud layer gives bond albedo of 0.75, reflecting most of the sunlight
- 90 bars of CO_2 (~300,000 times more than Earth!).
- Venus therefore exhibits a monstrous greenhouse effect—surface temperature of 740 K—*despite absorbing less sunlight than Earth!*
- Venus is a slow rotator: siderial day 243 Earth days; solar day 117 Earth days. This drastically changes the dynamics (compared to Earth)
- There is *very little* horizontal temperature variability below 60-km altitude, due to a combination of the massive atmosphere and slow rotation.





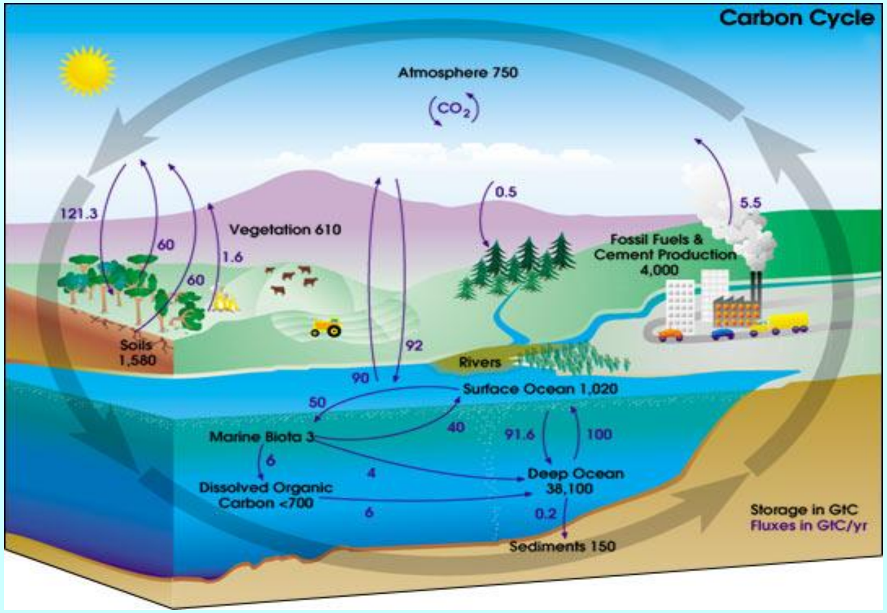
Seiff (1983)

Climate: Why is Venus so different from Earth?

- **Earth's CO_2 is maintained by the carbonate-silicate cycle—a climate feedbacks that keeps atmospheric CO_2 levels low and keeps most of the carbon stored in carbonate rocks.**

- **This cycle relies on the existence of the oceans, which greatly speed up the loss of atmospheric CO_2.**

- **Earth keeps its oceans because the atmospheric cold trap keeps water out of the upper atmosphere.**



- **BUT if Venus ever had oceans, the cold trap may have been less effective, allowing gradual loss of ocean…. at which point CO_2 would start building up in the atmosphere. D/H on Venus is 100 times the Earth value, consistent with this idea.**

- **This raises obvious questions: Did oceans ever exist (can we find evidence for them)? What does the high D/H ratio imply about initial water abundance? What are the noble gas abundances and what do they imply about volatile inventories supplied to Venus? What are the conditions (atmospheric composition, solar flux) under which oceans are lost? How does the carbonate-silicate feedback cycle really work on Earth or on planets**

Venus circulation/clouds

- Due to the slow rotation, Venus, dynamically, is an “all tropics” planet—Rossby number >> 1 everywhere.
- Unlike Earth, Venus exhibits a global (equator-to-pole) Hadley circulation.
- The atmosphere superrotates, carrying cloud-level air around the planet in 4 days—60 times faster than the underlying planet moves!
- This means that the atmosphere has *much* more angular momentum per unit mass than the planet itself—a major puzzle.
- The clouds form a global deck at about 50-60 km altitude, which may trigger local convection and gravity waves that may be important for the circulation.
- Despite the clouds, the planet is very dry

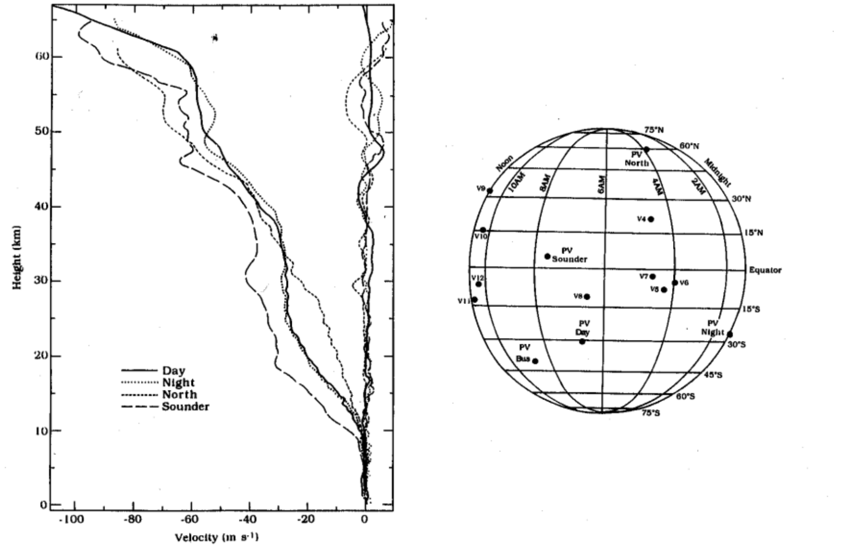


Figure 5. (Left) Zonal and meridional velocity profiles from Pioneer Venus probe tracking (Counselman et al. 1980). (Right) Locations of entry probes. “Day” and “Night” are designations for the two probes that entered in the southern hemisphere. Also indicated are the descent locations of Russian Venera probes.

Gierasch et al. (1997)

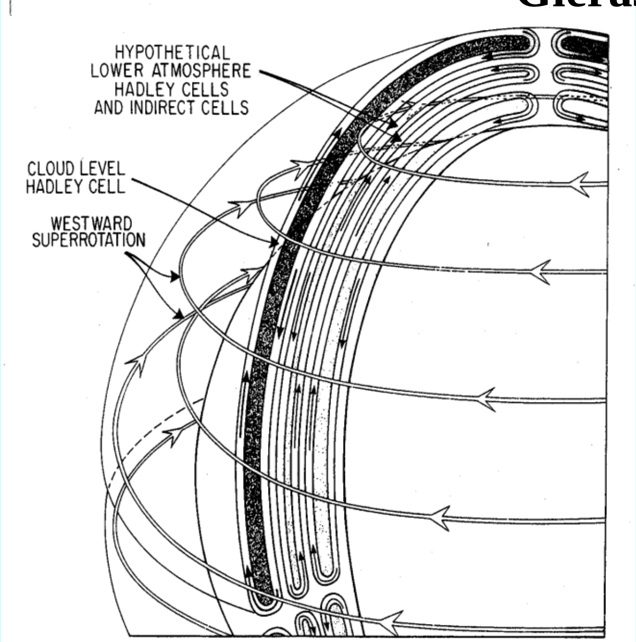
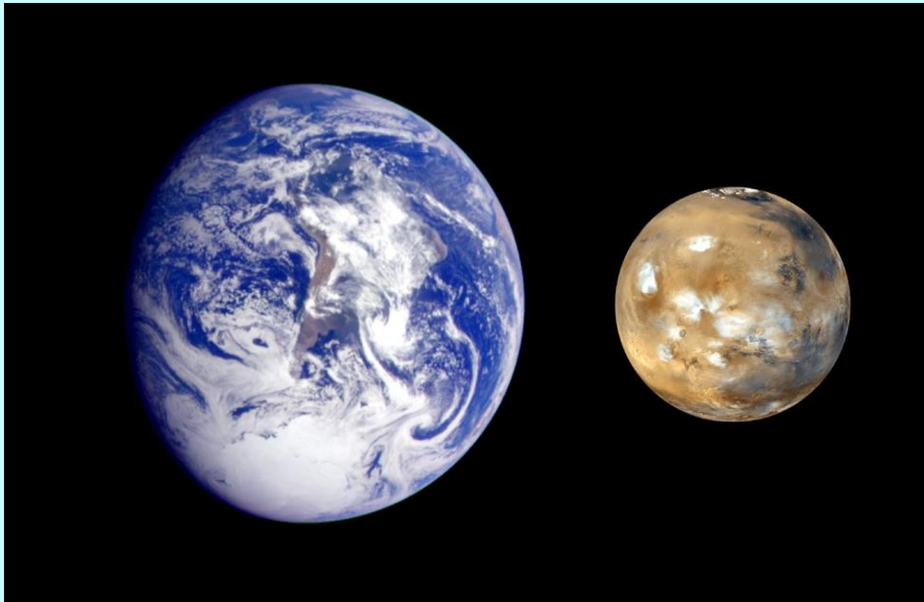


Fig. 24. Cloud level Hadley cell carrying the excess radiative energy deposited at high altitudes in the equatorial region to polar latitudes. Below the clouds there is probably a series of alternating direct and indirect meridional cells, including a ground-level Hadley cell.

Schubert (1983)

Mars

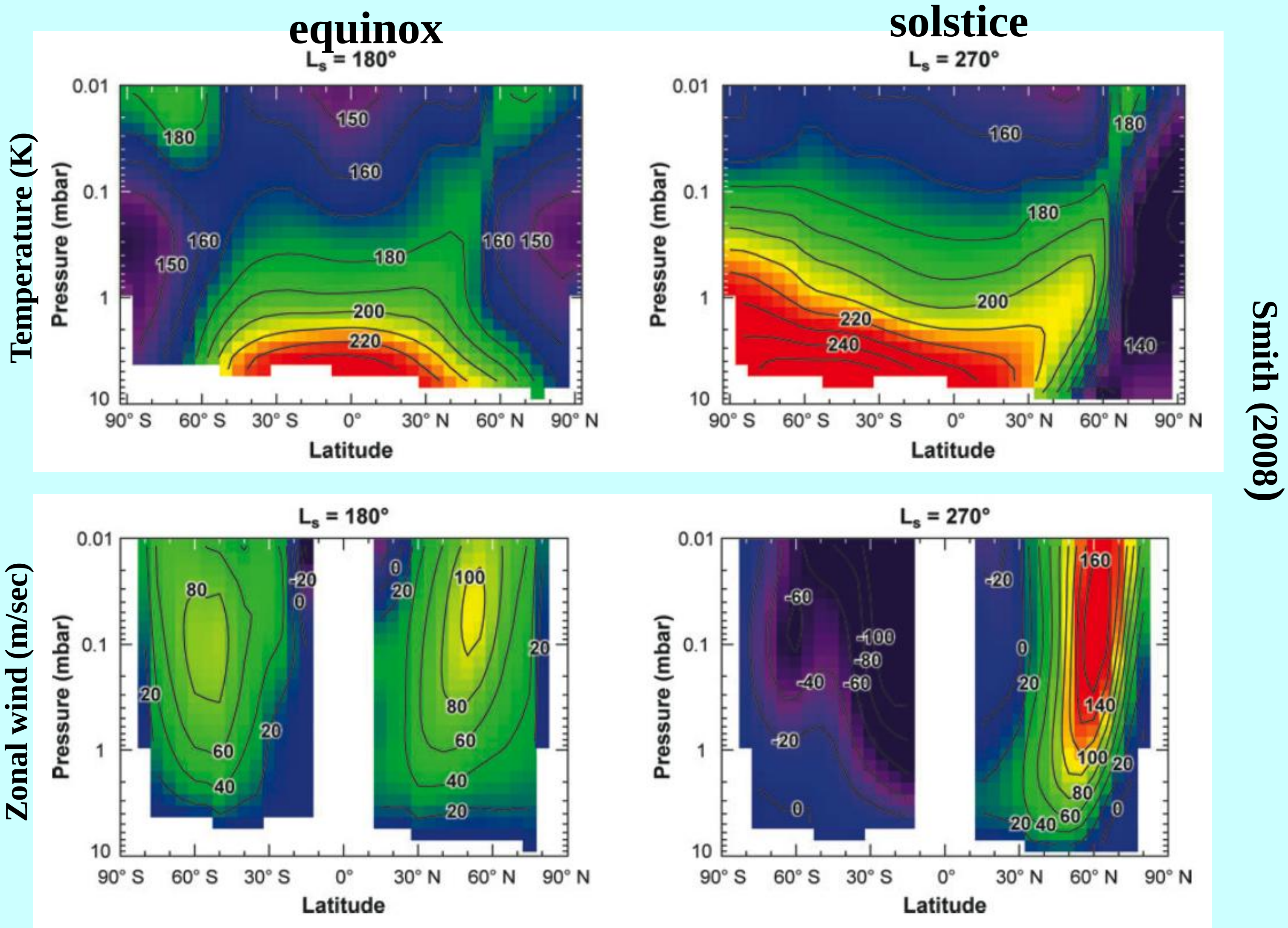
- **Mars has a thin (0.006 bar) atmosphere of CO_2. Liquid water is not stable at the surface.**
- **Greenhouse effect is weak due to low pressure, despite having a column abundance of CO_2 ~15 times greater than that on Earth. Atmospheric dust has a strong effect on thermal structure.**
- **Mars has the most Earth-like weather of any planet in the Solar system, because of its similar length of day (24.6 hours) and axial tilt (25 deg).**
- **So circulation regime is similar: Hadley cell at low latitudes, geostrophic flow comprising a baroclinic zone and jet streams at high latitudes, where Ro~0.1. Heat transported to poles by baroclinic instabilities.**
- **Mars gives an example of weather and climate on a dry world. Comparing the behavior of Hadley cell, jets, instabilities on Mars and Earth can yield insights into these processes generally, and the role of moisture in them.**



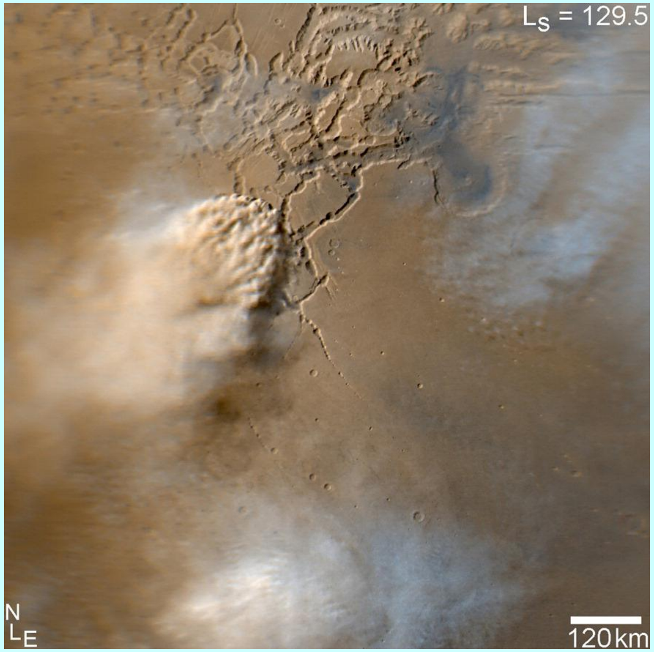
Mars

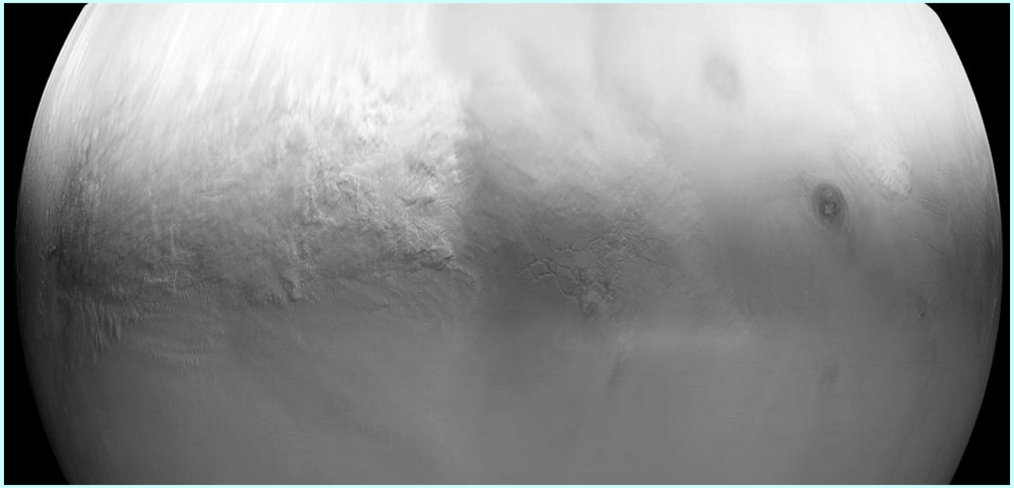
- **Because of the thin atmosphere, the radiative time constant is short on Mars, leading to larger equator-pole and day-night temperature differences. This leads to faster winds and strong seasonal cycles.**

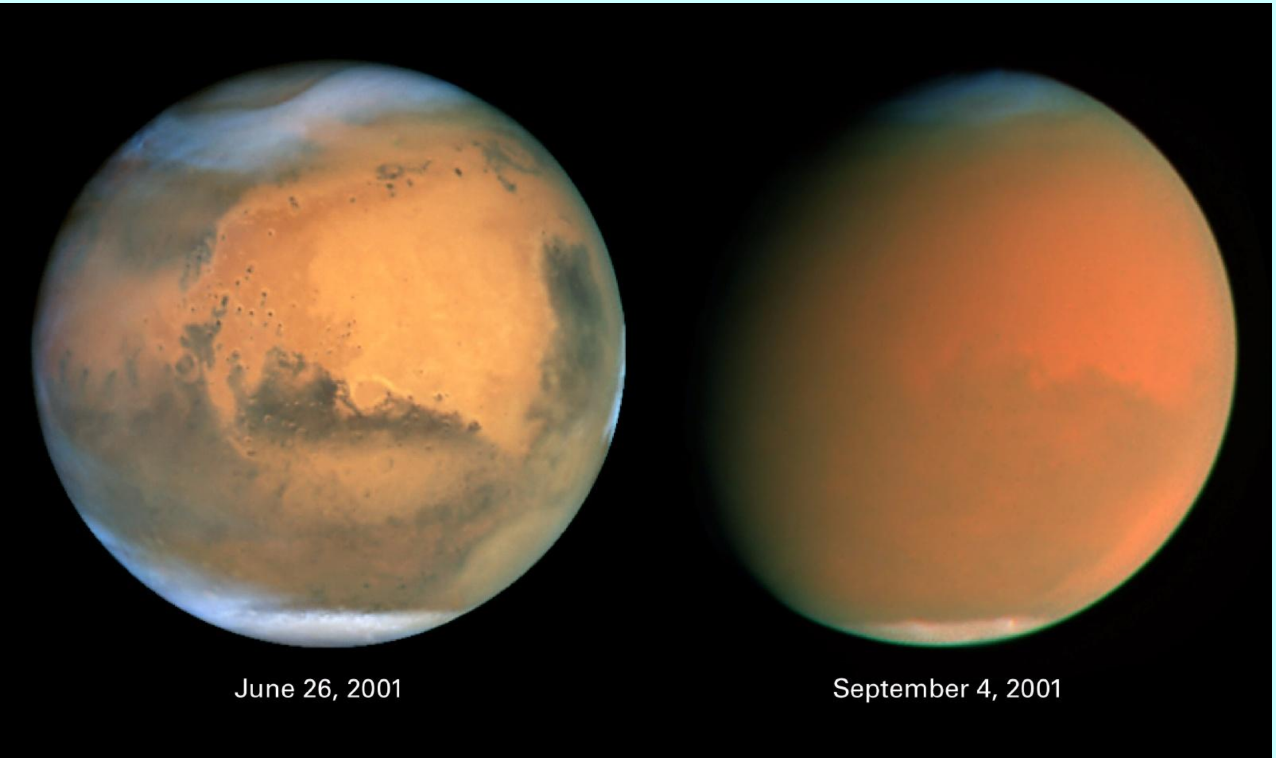
Diagnosis of zonal winds from observed temperatures using thermal-wind analysis:



Mars climate: dust storms







How these dust storms work, including why they sometimes become global, is not well understood!

Water ice on Mars

- **Liquid water is not stable at Mars' surface today, but the planet has significant reservoirs of ice at high latitudes. We know from the Gamma Ray Spectrometer on the Mars Odyssey spacecraft that the uppermost ~1 m of much of the polar regions of Mars (latitudes > 60 deg) is dominated by a hydrogen-bearning material, probably water ice. The ice could extend significantly deeper.**

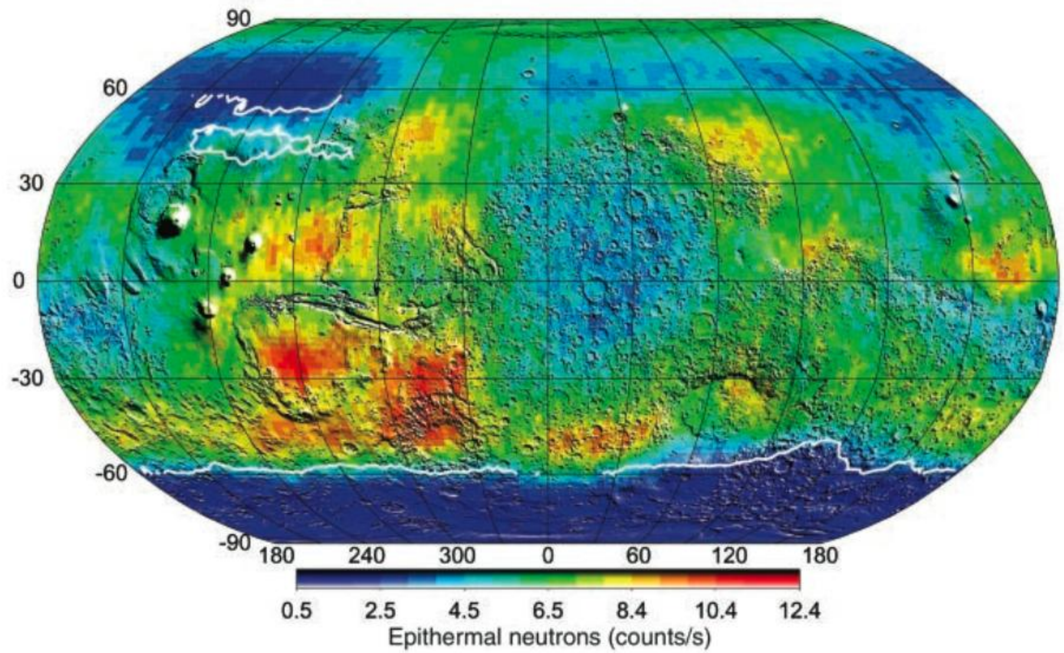
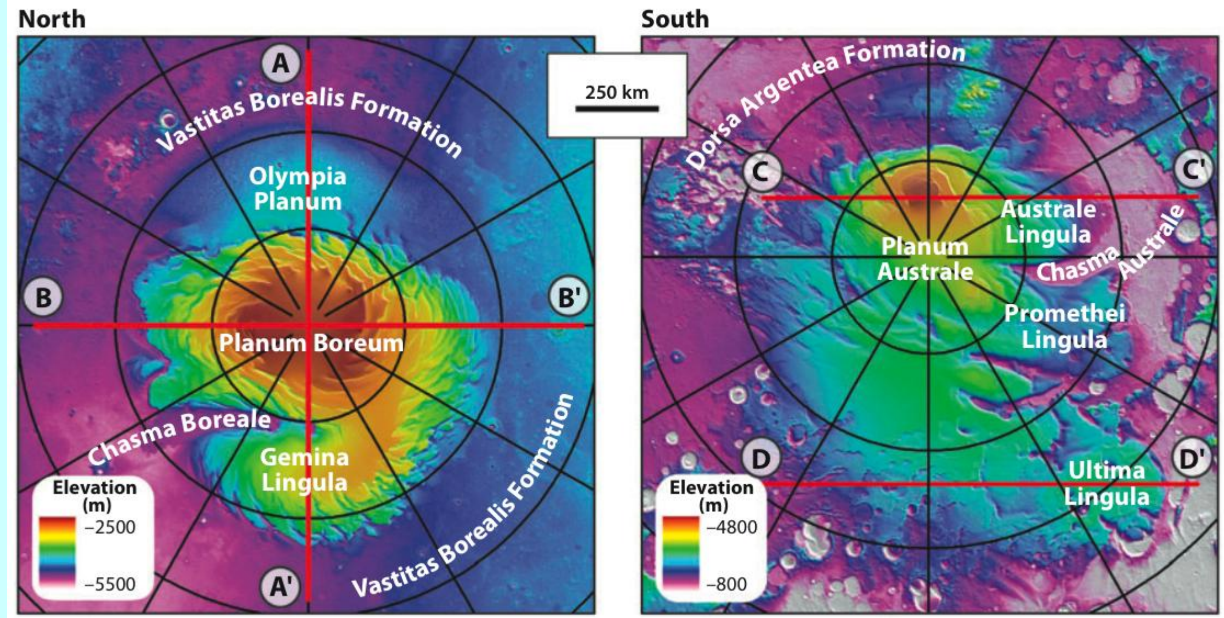


Fig. 6. Map of epithermal neutron flux from the Neutron Spectrometer. Low epithermal flux is indicative of high hydrogen concentration (*8*). Contours (in white) are shown of the regions where water ice is predicted to be stable at 80 cm depth (*21*) (no predictions were made poleward of 60° latitude because no data on thermal inertia were available). Note the correlation between regions of predicted ice stability and the low epithermal flux. The only exception is the small closed region of predicted ice stability, which is not observed in the epithermal neutron flux.

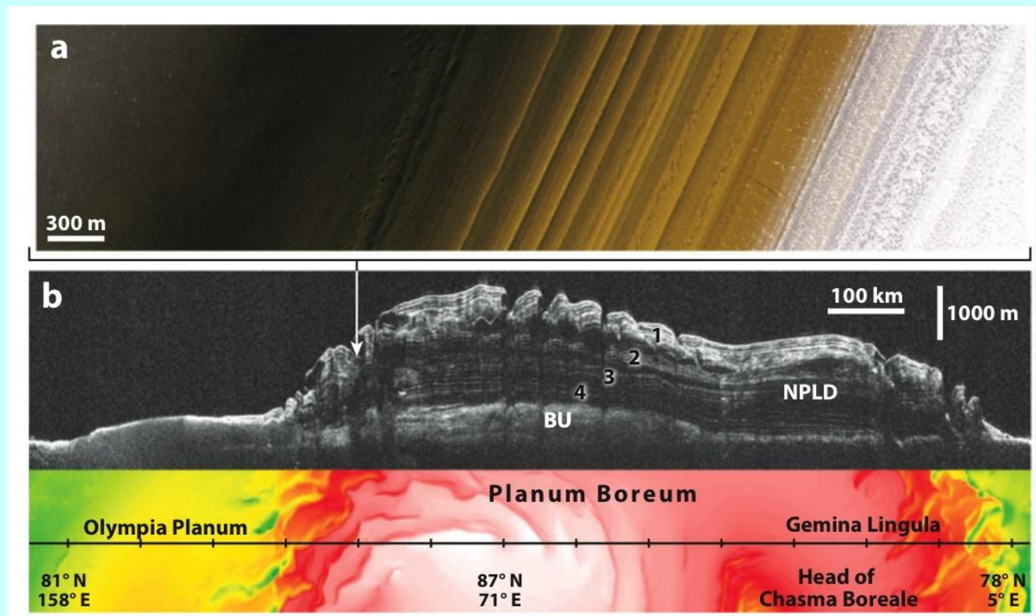
Boynton et al. (2002)

Mars polar caps

- The topography within 10 deg of both poles is locally elevated, and is known from radar, imaging, and other data to consist of a water-ice deposit ~2 km thick and ~1000 km across. These are the *north and south polar layered deposits*.



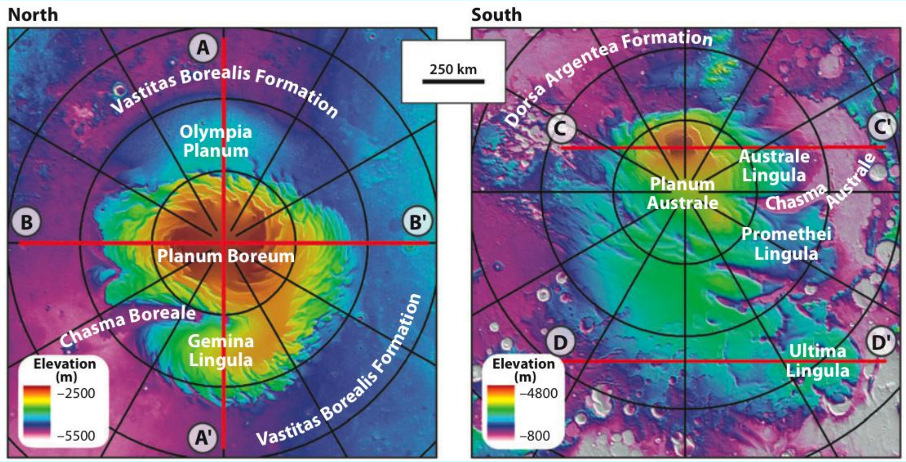
- Outcrops and radar exhibit fine-scale layering, probably layers of a few % dust intermixed with the ice. This layering records episodic deposition associated with climate cycles over millions of years.



Byrne (2009, *Annu. Rev.*)

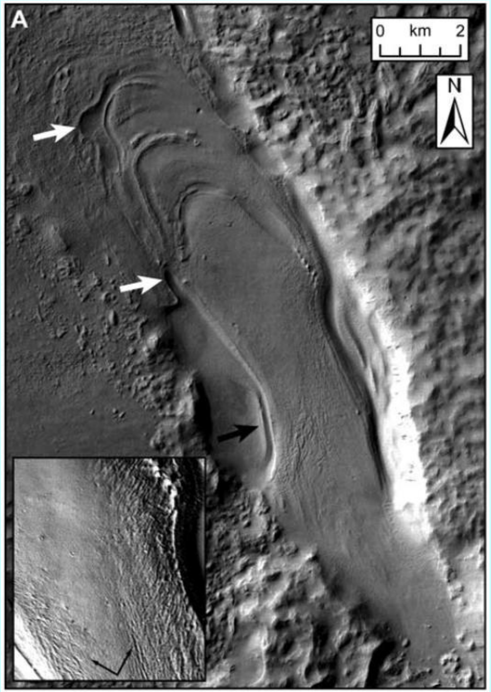
Ice ages on Mars

- **Both poles have water ice caps 1-2 km deep, and subsurface ice exists to latitudes ~60 deg, where it is stable.**
- **Yet, evidence exists for ice glaciers at low latitudes *where the ice is not currently stable***
- **Mars' obliquity oscillates, and climate models show that, at high obliquity, ice is stable at low latitudes (and less so at poles)**
- **Thus, we seem to be witnessing a form of ice ages on Mars—ice oscillates between low and high latitudes in response to Milankovitch cycles**
- **There are numerous unanswered questions about how this works and analogies with Milankovitch cycles and ice ages on Earth.**

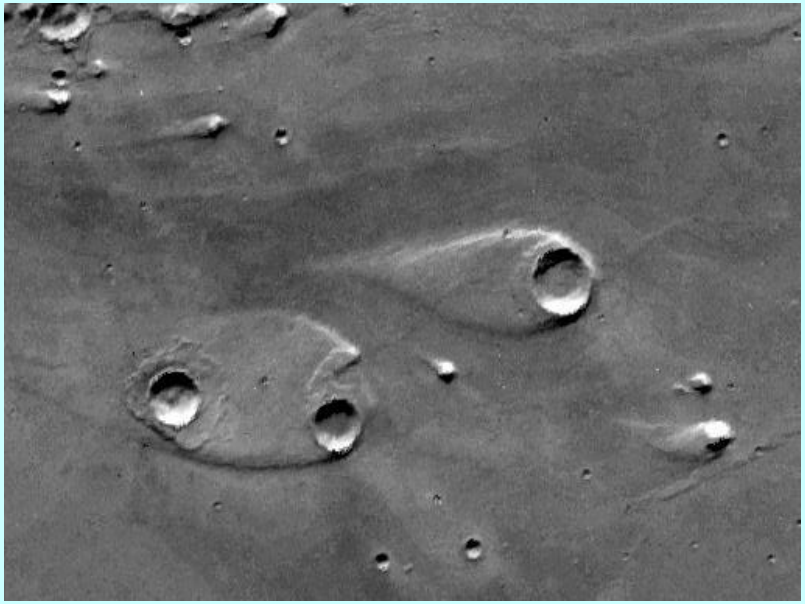


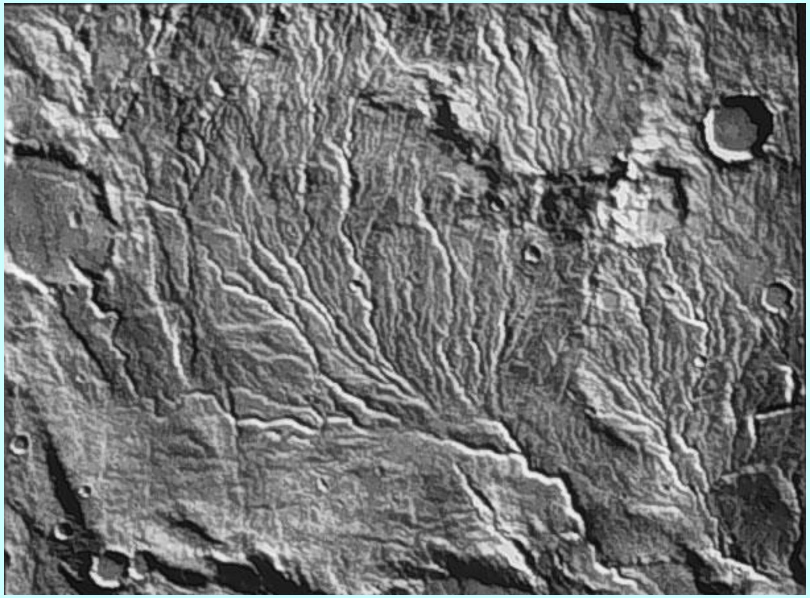
Byrne (2009)

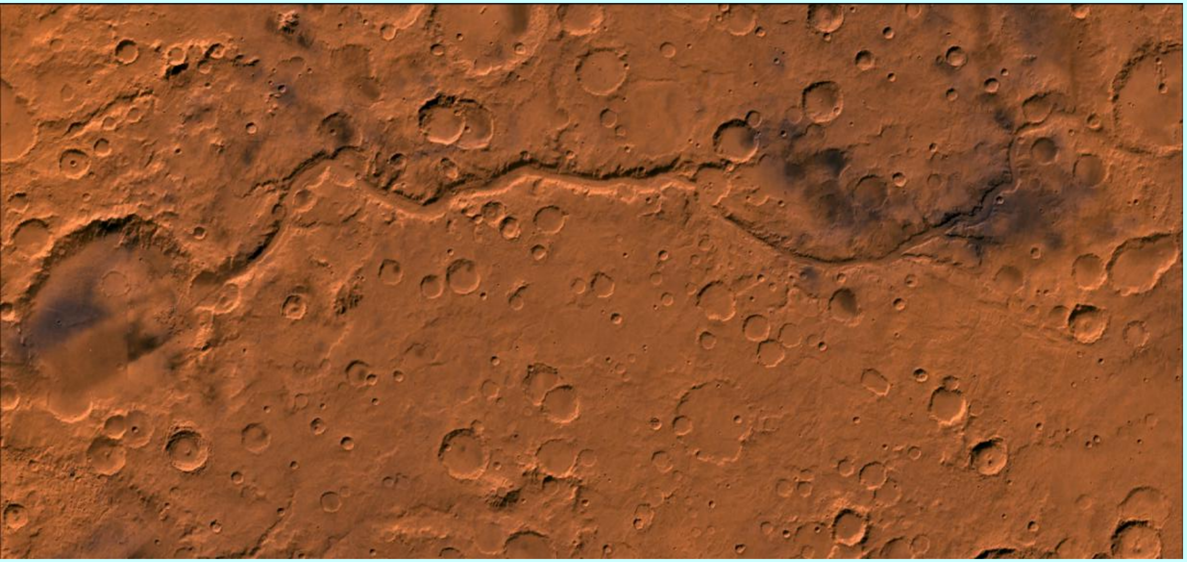
Low-latitude glaciers (Head et al. 2005, Shean et al. 2007):



Long-term climate on Mars







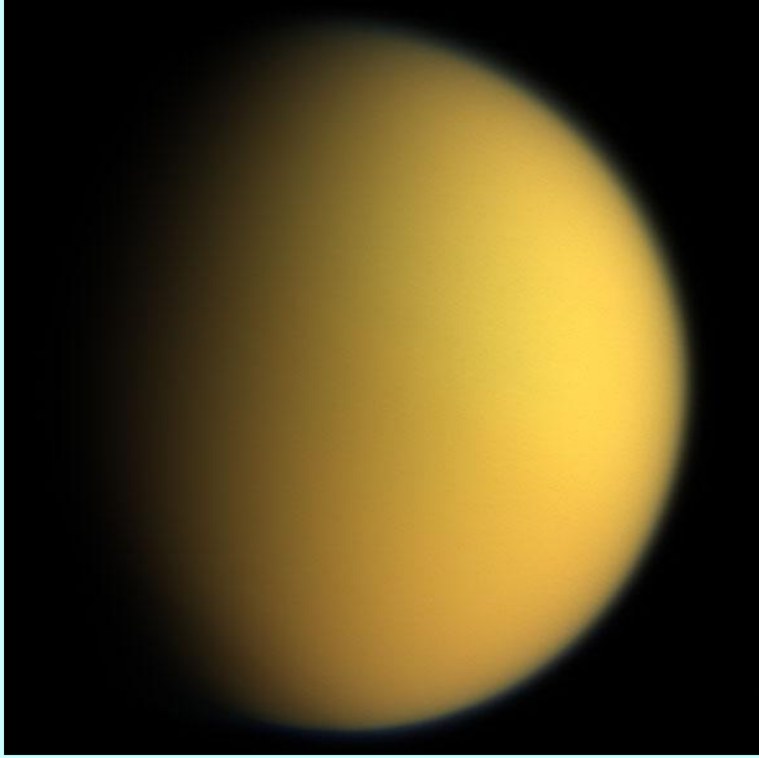
Numerous channels and valley networks suggest that Mars had a warmer, wetter past.

But how warm? How wet? Did it once have a thicker CO_2 atmosphere with a significant greenhouse effect?

If so, where did the atmosphere go?

And was the planet ever habitable?

Titan



- Titan is an icy satellite of Saturn with a thick (1.5 bar) N_2 atmosphere and a surface temperature of 97 K. The "bedrock" is H_2O. Radius 2500 km, gravity 1.3 m/s^2.

- Methane forms a hydrological cycle like water on Earth—methane evaporates out of surface lakes, forms clouds, and rains, carving valleys in the ice.

- Only other terrestrial planet besides Earth with a thick N_2 atmosphere, and with an active hydrological cycle!

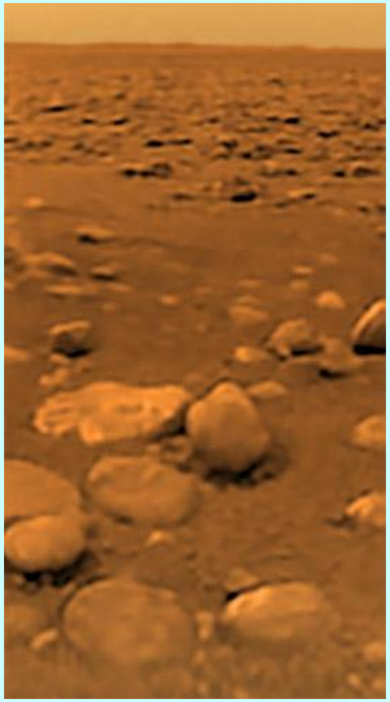
- Photolysis of atmospheric methane leads to escape of hydrogen to space and production of higher-order hydrocarbons, many of which are liquids or solids. This produces a global, opaque, high-altitude haze layer, which obscures the surface from view. These materials slowly settle down onto the surface.

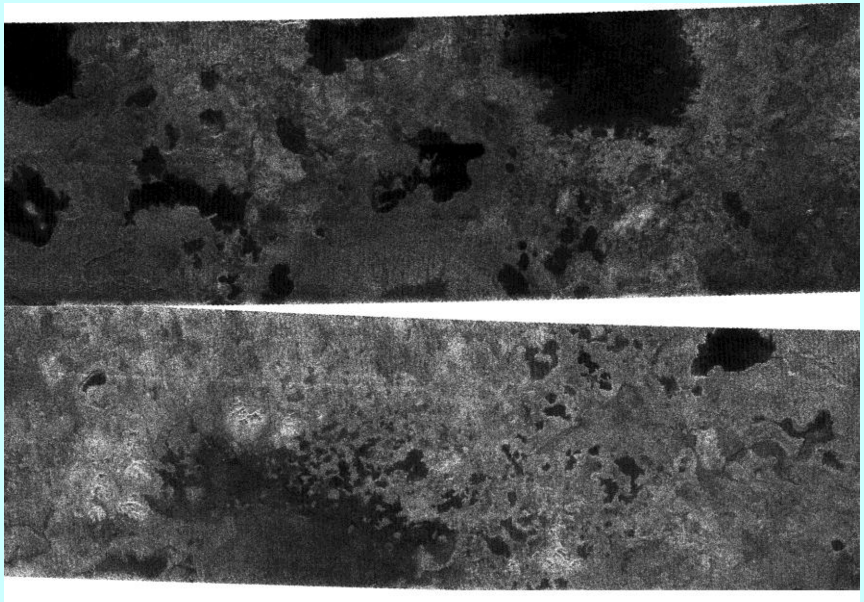
- If not resupplied, all of Titan's atmospheric methane would be destroyed by photolysis in ~10^7 years. The existence of atmospheric methane thus suggests that methane is resupplied from the surface to the atmosphere.

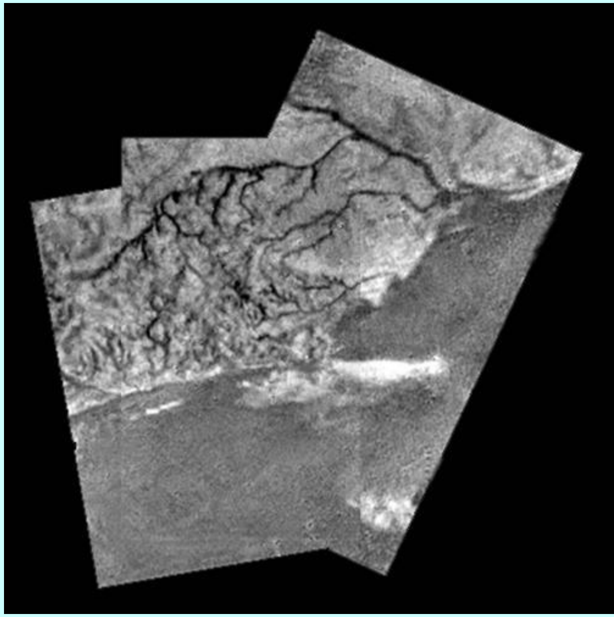
- It was thought in the 1980s to ~2000 that, over solar-system history, photolysis of all that methane would lead to a global layer of ethane ~0.5 km thick. Thus global oceans of ethane (and dissolved methane) were predicted.

- Groundbased data, Cassini and Hugyens showed that there is no global ocean but a desert-like landscape with river valleys, sand dunes, etc, with lakes near the poles.

- It's unclear where the missing organics are. Some may be below-ground in an aquifer. Some may be in solid form.   Or perhaps Titan didn't always have abundant atmospheric methane over its history, which would mean that less ethane would have been produced.







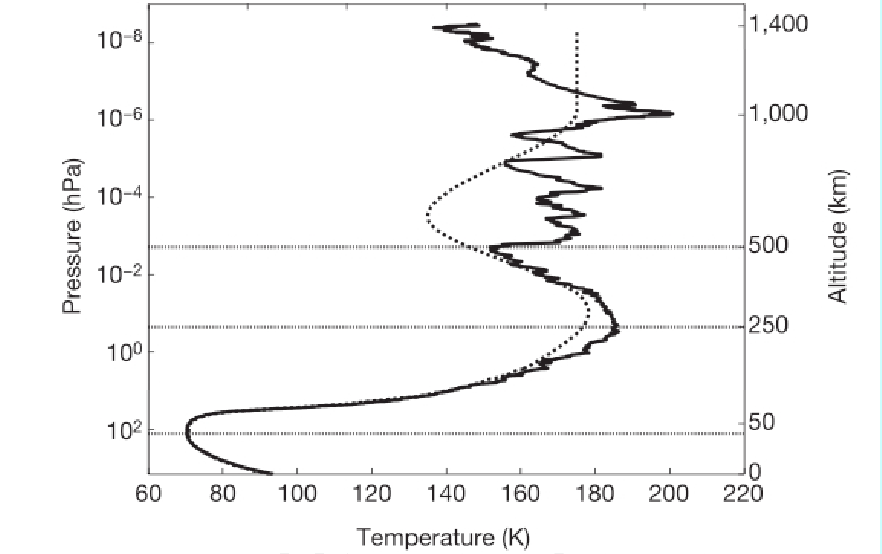
Thermal structure and humidity

- Titan has a well-defined troposphere 40 km thick, overlain by a stratosphere and a thermosphere. Here are measurements from the Huygens probe. Wiggles are caused by atmospheric waves.

- Methane is cold trapped at the tropopause, but because of the low latent heat of methane, the effect is not strong. The (constant) mole fraction of methane in the stratosphere is only a factor of several less than at the surface.

- This helps enable irreversible methane destruction/loss over time.

- This differs from Earth, where stratospheric water vapor is ~10^4 times less than at the tropical surface.



Fulchignoni et al. (2005)

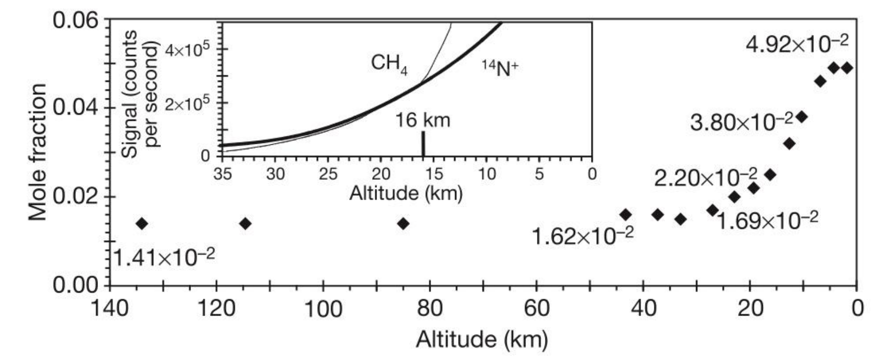
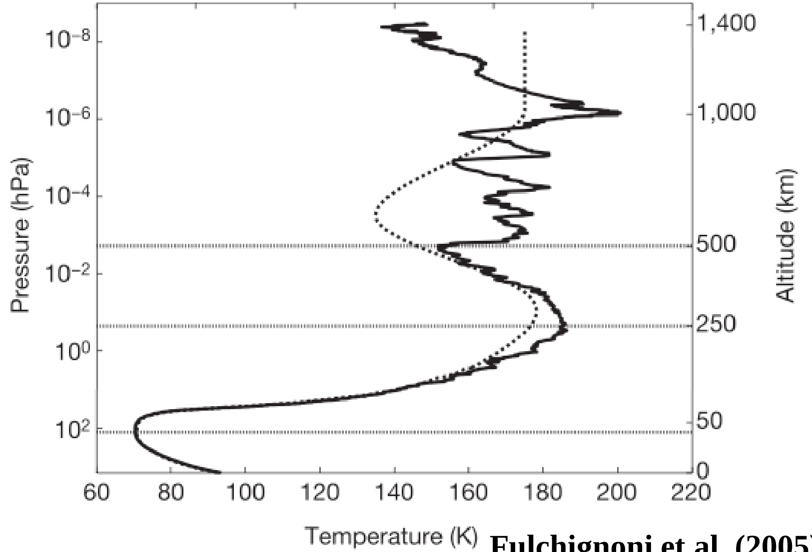


Figure 2 | The mole fraction of methane to nitrogen in the Titan atmosphere is plotted versus altitude. The CH_4 mole fraction is 1.41×10^{-2} in the stratosphere. It begins increasing below 32 km. At about 8 km, it reached a plateau of about 4.9×10^{-2}. The inset shows an increase of methane at 16 m/z, when compared to nitrogen (in this case $^{14}N^{+}$) at $m/z = 14$, near 16 km. This is probably due to condensates evaporating in the inlet system of the mass spectrometer as the Huygens probe passed through the methane haze.

Niemann et al. (2005)

Titan circulation

- **Titan is a slow rotator (16 day period), meaning it is (nearly) an "all tropics" world**
- **Hadley cell is nearly global; like Venus, Titan lacks an extensive "baroclinic zone"**
- **Like Venus, Titan's atmosphere superrotates. Comparisons of Venus and Titan may help elucidate the mechanism.**
- **Hazes exhibit considerable structure and seasonality, and rainstorms can be monitored from Earth and spacecraft**



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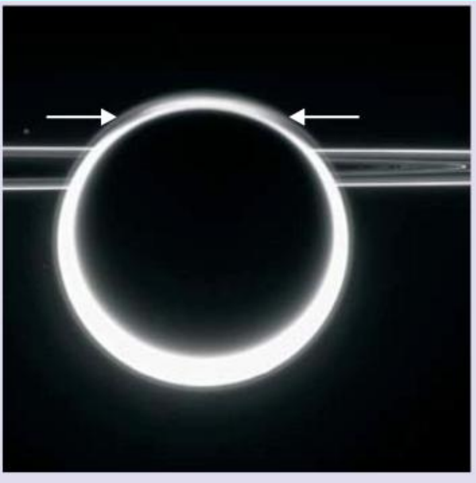

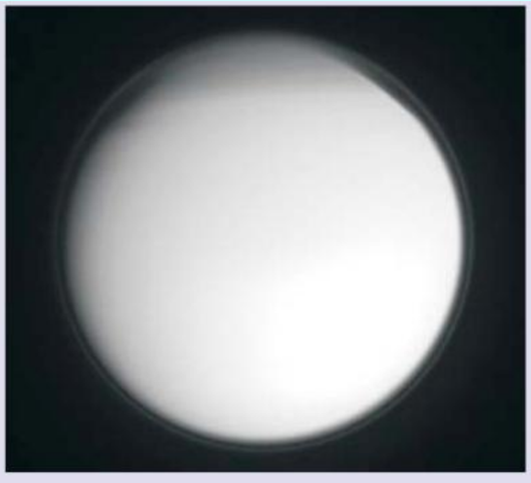

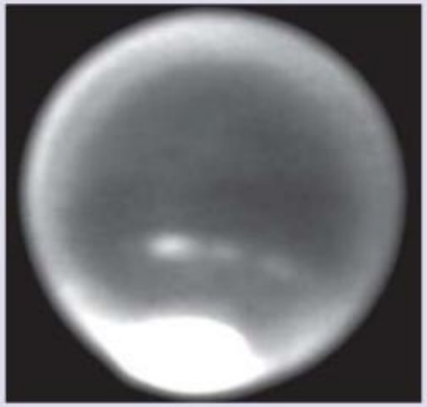

Local methane clouds

References1

- Boynton, W.V., Feldman, W.C., Squyres, S.W., Prettyman, T.H., Brückner, J., Evans, L.G., Reedy, R.C., Starr, R., Arnold, J.R., Drake, D.M., Englert, P.A.J., Metzger, A.E., Mitrofanov Igor, Trombka, J.I., d'Uston, C., Wänke, H., Gasnault, O., Hamara, D.K., Janes, D.M., Marcials, R.L., Maurice, S., Mikheeva, I., Taylor, G.J., Tokar, R., Shinohara, C., 2002: Distribution of hydrogen in the near surface of Mars: evidence for subsurface ice deposits, Science, 297, 81-85.
- Byrne, S., 2009: The polar deposits of Mars, Annu. Rev. Earth Planet Sci, 37, 535-560.
- Fulchignoni, M., Ferri, F., Angrilli, F., Ball, A.J., Bar-Nun, A., Barucci, M.A., Bettanini, C., Bianchini, G., Boruck, W., Colombatti, G., Coradini, M., Coustenis, A., Debei, S., Falkner, P., Fanti, G., Flamini, E., Gaborit, V., Grard, R., Hamelin, M., Harri, A.M., Hathi, B., Jernej, I., Leese, M.R., Lehto, A., Lion Stoppato, P.F., López-Moreno, J.J., Mäkinen, T., McDonnell, J.A.M., McKay, C.P., Molina-Cuberos, G., Neubauer, F. M., Pirronello, V., Rodrigo, R., Saggin, B., Schwingenschuh, K., Seiff, A., Simões, F., Svedhem, H., Tokano, T., Towner, M.C., Trautner, R., Withers, P., Zarnecki, J.C., 2005: In situ measurements of the physical characteristics of Titan's environment, Nature, 438, 785-791.
- Gierasch, P.J., Goody, R.M., Young, R.E., Crisp, D., Edwards, C., Kahn, R., McCleese, D., Rider. D., Del Genio, A., Greeley, R., Hou, A., Leovy, C.B., Newman, M., 1997: The general circulation of the Venus atmosphere: An assessment, Venus II---Geology, Geophysics, Atmosphere, and Solar Wind Enviroment, University of Arizona Press, 459-500.

References2

- Head, J.W., Neukum, G., Jaumann, R., Hiesinger, H., Hauber, E., Carr, M., Masson, P., Foing, B., Hoffmann, H., Kreslavsky, M., Werner, S., Milkovich, S., S. van Gasselt, The HRSC Co-Investigator Team, 2005: Tropical to mid-latitude snow and ice accumulation, flow and glaciation on Mars, Nature, 434, 346-351.
- Heng, K., Vogt, S.S., 2010: Gliese 581g as a scaled-up version of Earth: atmospheric circulation simulations, MNRAS, 415, 2145-2157.
- Joshi, M.M., Haberle, R.M., Reynolds, R.T., 1997: Simulations of the atmospheres of synchronously rotating terrestrial planets orbiting m dwarfs: conditions for atmospheric collapse and the implications for habitability, Icarus, 129, 450-465.
- Kaspi, Y., Showman, A.P., 2015: Atmospheric dynamics of terrestrial exoplanets over a wide range of orbital and atmospheric parameters, Astrophys. J., 804, 60.
- Kuo, A.C., Polvani, L.M., 1997: Time-dependent fully nonlinear geostrophic adjustment, J. Phys. Oceanogr., 27., 1614-1634.
- Niemann, H.B., Atreya, S.K., Bauer, S.J., Carignan, G.R., Demick, J.E., Frost, R.L., Gautier, D., Haberman, J.A., Harpold, D.N., Hunten, D.M., Israel, G., Lunine, J.I., Kasprzak, W.T., Owen, T.C., Paulkovich, M., Raulin, F., Raaen, E., Way, S.H., 2005: The abundances of constituents of Titan's atmosphere from the GCMS instrument on the Huygens probe, Nature, 438, 779-784.
- Peixóto, J.P., Oort, A.H., 1983: The atmospheric branch of the hydrological cycle and climate, Variations in the Global Water Budget, 5-65.

References3

- Peixóto, J.P., Oort, A.H., 1992: Physics of climate, American Institute of Physics, pp.520.
- Salby, M.L., 1996: Fundamentals of atmospheric physics, Academic Press, pp.627.
- Schneider, T., Walker, C.C., 2006: Self-organization of atmospheric macroturbulence into critical states of weak nonlinear eddy eddy interactions, J. Atmos. Sci., 63, 1569-1586.
- Schubert, G., 1983: General circulation and dynamical state of the Venus atmosphere, Venus, University of Arizona Press, 681-765.
- Seiff, A., 1983: Thermal structure of the atmosphere of Venus, Venus, University of Arizona Press, 215-279.
- Shean, D.E., Head, J.W., Fastook, J.L., Marchant, D.R., 2007: Recent glaciation at high elevations on Arsia Mons, Mars: Implications for the formation and evolution of large tropical mountain glaciers, J. Geophys. Res. Planets, 112, E3.
- Showman, A.P., Fortney, J.J., Lewis, N.K., Shabram, M., 2013a: Doppler signatures of the atmospheric circulation on hot Jupiters, Astrophys. J., 762, 24.
- Showman, A.P., Polvani, L.M., 2011: Equatorial superrotation on tidally locked exoplanets, Astrophys. J., 738, 71.
- Showman, A.P., Wordsworth, R.D., Merlis, T.M., Kaspi, Y., 2013b: Atmospheric circulation of terrestrial exoplanets: Comparative Climatology of Terrestrial Planets, University of Arizona Press, 277-326.
- Smith, M.D., 2008: Spacecraft observations of the Martian atmosphere, Annu. Rev. Earth Planet. Sci., 36, 191-219.

References4

- (p.4) http://clasp-research.engin.umich.edu/groups/admg/baroclinic_wave_T850hPa_day9.jpg
- (p.34) https://disc.gsfc.nasa.gov/education-and-outreach/additional/science-focus/images/ITCZ_GOES_large.jpg
- (p.36左) http://eoimages.gsfc.nasa.gov/images/imagerecords/57000/57752/land_shallow_topo_2048.jpg
- (p.37上) http://nssdc.gsfc.nasa.gov/image/planetary/venus/pvo_uv_790226.jpg
- (p.38) https://upload.wikimedia.org/wikipedia/commons/5/55/Carbon_cycle-cute_diagram.jpeg
- (p.40) http://free-photos-ls01.gatag.net/images/lgf01a201306282100.jpg
- (p.42左上) http://www.universetoday.com/wp-content/uploads/2011/10/MarsDustStorms.jpg
- (p.42右上) http://cache.boston.com/universal/site_graphics/blogs/bigpicture/mars_06_20/mars13.jpg
- (p.42下) http://imgsrc.hubblesite.org/hu/db/images/hs-2001-31-a-small_web.jpg
- (p.46左上) http://solarviews.com/raw/mars/islands.gif
- (p.46右上) http://solarviews.com/raw/mars/network.gif
- (p.46左下) http://photojournal.jpl.nasa.gov/jpeg/PIA00414.jpg

References5

- (p.47) https://upload.wikimedia.org/wikipedia/commons/8/84/Titan_in_natural_color_Cassini.jpg
- (p.48左) https://media1.britannica.com/eb-media/63/97263-004-BE71CA07.jpg
- (p.48中) http://photojournal.jpl.nasa.gov/jpegMod/PIA08630_modest.jpg
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- (p.50左下) https://www.nasa.gov/images/content/151384main_pia08211_detail.jpg
- (p.50中下) http://conservapedia.com/images/4/43/Titan_haze_2007.jpg
- (p.50右下) https://apod.nasa.gov/apod/image/0410/titan1_cassini_big.jpg
- (p.50中右) http://www2.keck.hawaii.edu/science/titan/041007_nb2108_128.png