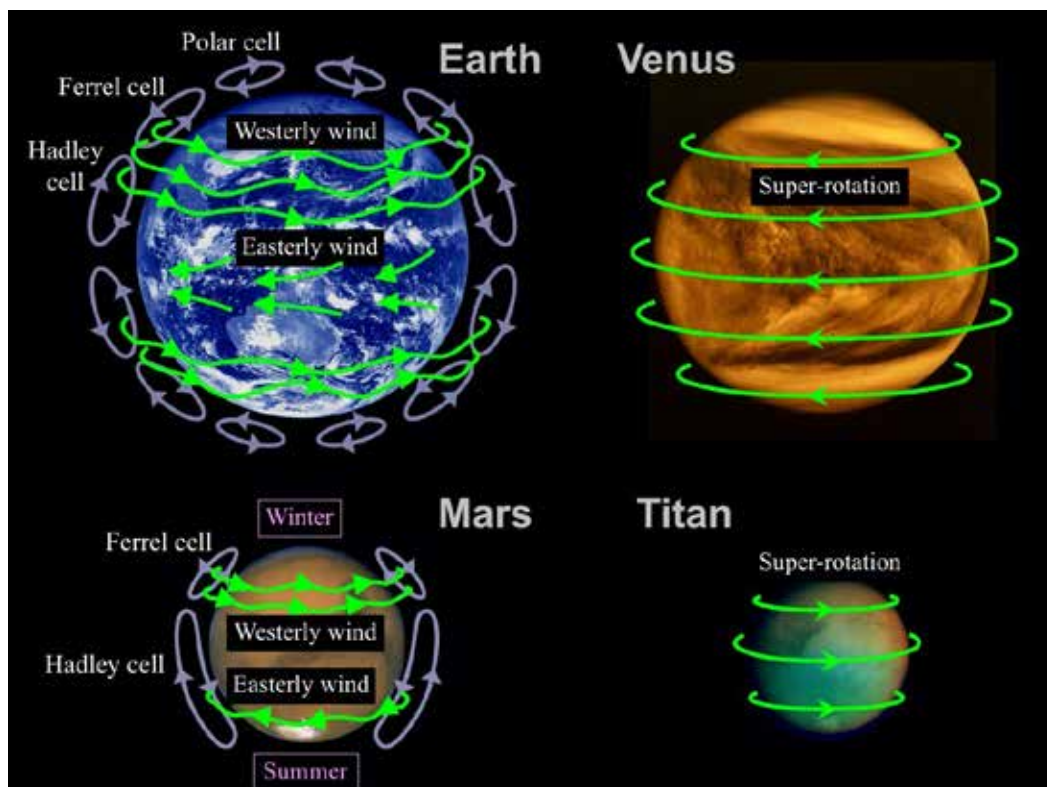
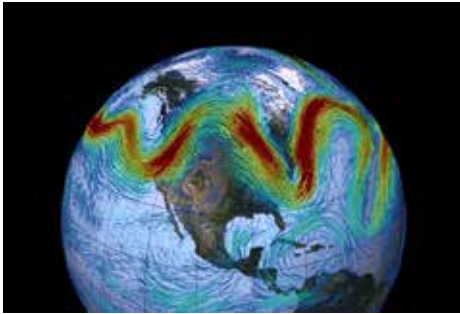


Atmospheric dynamics II

Planetary-scale atmospheric circulation



Baroclinic wave disturbances



Frontal dust storms on Mars
(Wang et al. 2005)

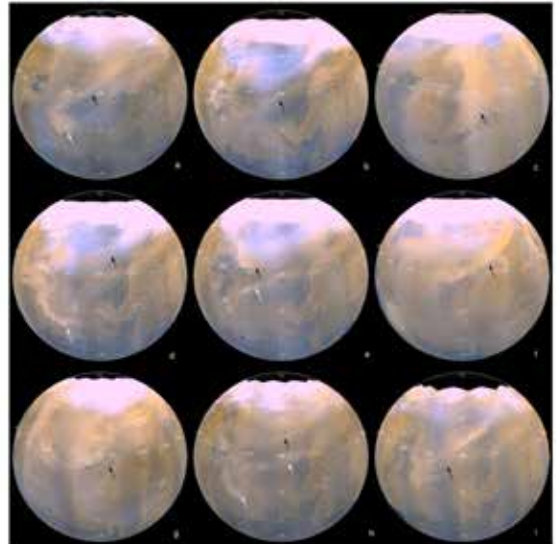


Figure 5. Examples of frontal dust storms in different channels, seasons, and years. Each panel is a Mars daily global map projected onto a sphere with black arrows pointing to the main frontal features. The three rows from the top to the bottom are for MGS mapping Years 1 (1999–2001), 2 (2001–2003), and 3 (2003–2005), respectively. Figures 5a, 5b, 5d, 5e, 5h, and 5i are for the Acidalia channel. Figure 5c is for the Arcadia channel. Figures 5f and 5g are for the Utopia channel. The λ_a values are (a) 210°, (b) 314°, (c) 336°, (d) 316°, (e) 324°, (f) 334°, (g) 207°, (h) 214°, and (i) 230°.

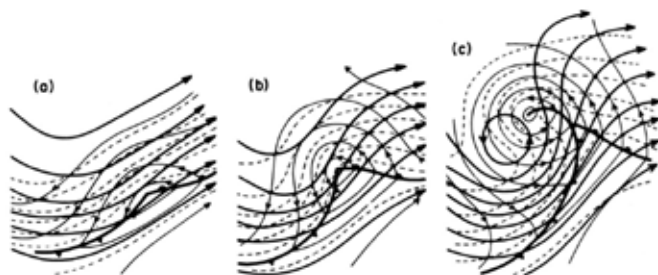


Fig. 6.5 Schematic 500-hPa contours (heavy solid lines), 1000-hPa contours (thin lines), and 1000–500 hPa thickness (dashed) for a developing baroclinic wave at three stages of development. (After Palmén and Newton, 1969.)

Holton 2012

Quasi-geostrophic vorticity equation

$$\frac{\partial \xi_g}{\partial t} = -\vec{v}_g \cdot \nabla(\xi_g + f) + f_0 \frac{\partial \omega}{\partial p}$$

∇ : horizontal differentiation

$$\xi_g \equiv \frac{\partial v_g}{\partial x} - \frac{\partial u_g}{\partial y} = \frac{\nabla^2 \Phi'}{f_0} \quad : \text{geostrophic vorticity}$$

$$\vec{v}_g \equiv \frac{1}{f_0} \vec{k} \times \nabla \Phi \quad : \text{geostrophic wind}$$

Φ : geopotential

f : Coriolis parameter (planetary vorticity)

$\omega \equiv dp/dt$: vertical velocity in pressure coordinate

Equation of thermodynamics

$$\left(\frac{\partial}{\partial t} + \vec{v}_g \cdot \nabla \right) \frac{\partial \Phi'}{\partial p} + \sigma \omega = 0$$

$$\Phi(x, y, p, t) = \bar{\Phi}(p) + \Phi'(x, y, p, t) \quad : \text{geopotential}$$

$$\sigma \equiv -\frac{1}{\bar{\rho} \bar{\theta}} \frac{\partial \bar{\theta}}{\partial p} = \frac{1}{p} \frac{d}{dp} \left(p \frac{d\bar{\Phi}}{dp} - \frac{R}{c_p} \bar{\Phi} \right) \quad : \text{(static stability)}$$

$$\partial \bar{\Phi} / \partial p = -R\bar{T}/p \quad : \text{(temperature)}$$

$$\partial \Phi' / \partial p = -R\bar{T}'/p \quad : \text{(temperature)}$$

Omega equation

Combining the vorticity equation and the thermodynamics equation to eliminate the time derivative term, we get the “omega equation”:

$$\left(\nabla^2 + \frac{f_0^2}{\sigma} \frac{\partial^2}{\partial p^2} \right) \omega = \frac{f_0}{\sigma} \frac{\partial}{\partial p} \left[\vec{v}_g \cdot \nabla (\zeta_g + f) \right] + \frac{f_0 R}{\sigma p} \left[\nabla^2 (\vec{v}_g \cdot \nabla T) \right]$$

(A)

Let us consider a sinusoidal perturbation

$$\omega \propto \sin(\pi p/p_s) \sin(kx) \cos(ly)$$

Then the term (A) becomes

$$\left(\nabla^2 + \frac{f_0^2}{\sigma} \frac{\partial^2}{\partial p^2} \right) \omega \approx - \left[k^2 + l^2 + \frac{1}{\sigma} \left(\frac{f_0 \pi}{p_0} \right)^2 \right] \omega$$

Since the sign of the vertical velocity w is opposite to that of ω ($w \approx -\omega$), (A) is proportional to the vertical velocity. (Upward motion is forced where the right-hand side is positive and downward motion is forced where it is negative.)

Vertical motion forced by the advection of vorticity

Omega equation

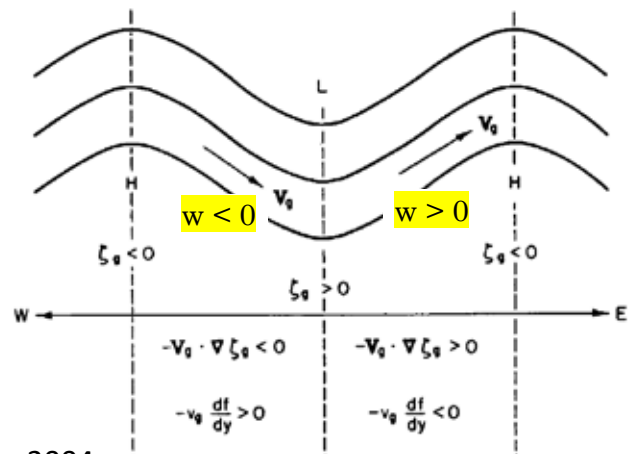
$$\underbrace{\left(\nabla^2 + \frac{f_0^2}{\sigma} \frac{\partial^2}{\partial p^2} \right) \omega}_{\approx w} = \underbrace{\frac{f_0}{\sigma} \frac{\partial}{\partial p} \left[\vec{v}_g \cdot \nabla (\zeta_g + f) \right]}_{(B)} + \frac{f_0 R}{\sigma p} \left[\nabla^2 (\vec{v}_g \cdot \nabla T) \right]$$

The term (B) is rewritten as

$$(B) \propto \frac{\partial}{\partial z} \left(-\vec{v}_g \cdot \nabla \zeta_g - v_g \frac{\partial f}{\partial y} \right)$$

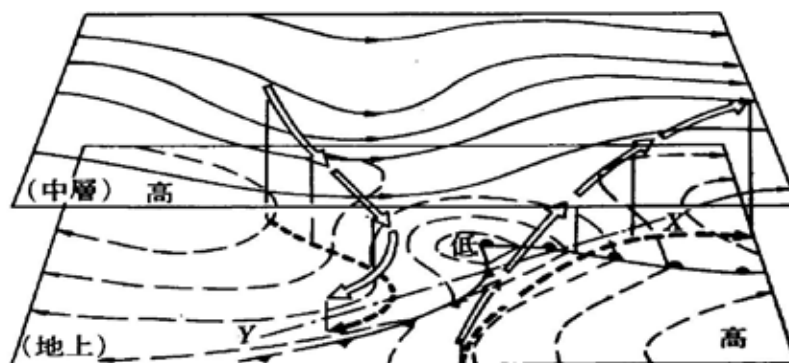
For a short- wave system where relative vorticity advection is larger than the planetary vorticity advection, the pattern of vertical motion forced by the advection of vorticity by the thermal wind has

$w < 0$: west of trough
 $w > 0$: east of trough



Holton 2004

3D structure of baroclinic wave disturbance (→ Ferrel cell)



(伊藤 1976)

rising warm air to the east of trough & subsidence of cold air to the west of trough
 → conversion from eddy potential energy to eddy kinetic energy

cold advection below trough → development of trough
 warm advection below ridge → development of ridge

Meridional transport

$$\overline{v'T'}$$

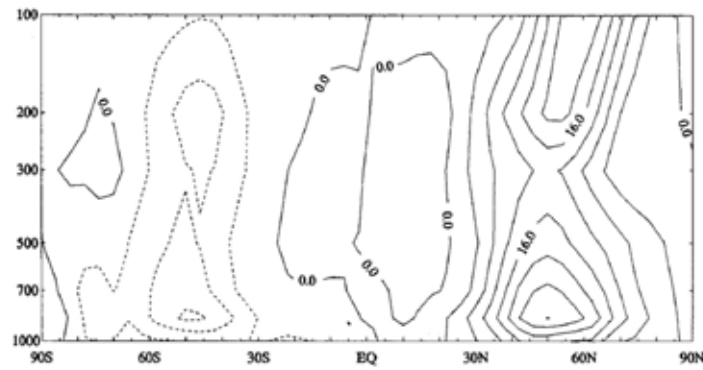


Fig. 10.3 Observed northward eddy heat flux distribution ($^{\circ}\text{C m s}^{-1}$) for Northern Hemisphere winter. (Adapted from Schubert et al., 1990.)

stream
function

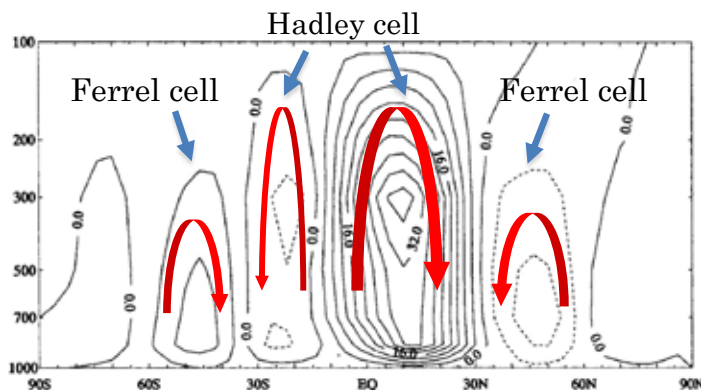


Fig. 10.7 Streamfunction (units: $10^2 \text{ kg m}^{-1} \text{ s}^{-1}$) for the observed Eulerian mean meridional circulation for Northern Hemisphere winter, based on the data of Schubert et al. (1990).

Holton 2004

Surface meteorological measurements on Mars by Viking-2

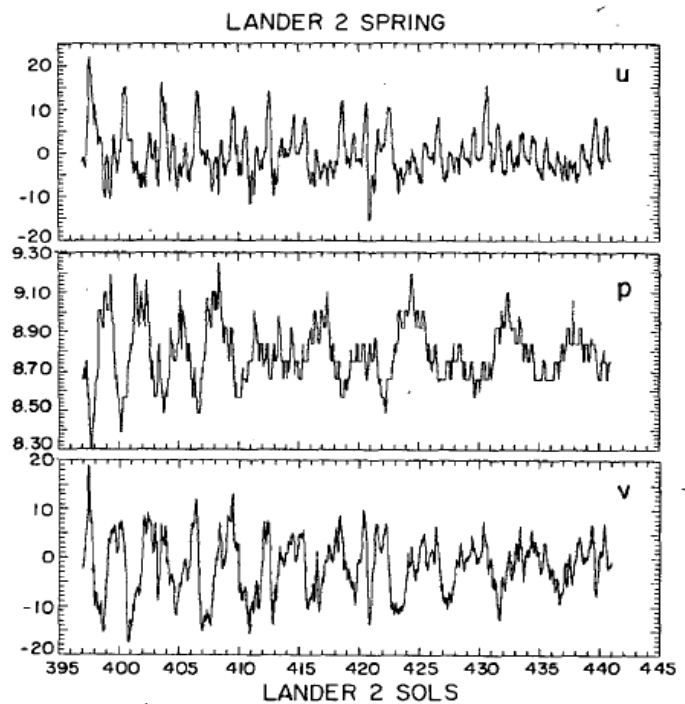
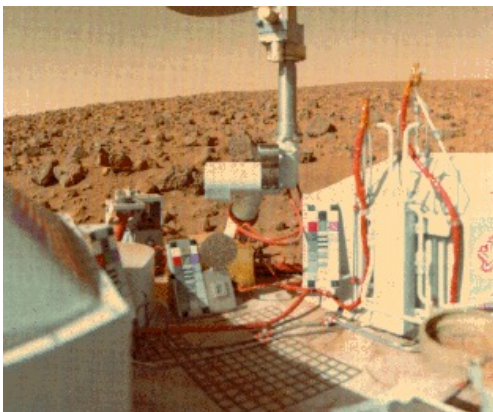


FIG. 2. The unfiltered pressure and zonal (u) and meridional (v) wind data for a 44-sol portion of the spring period at Lander 2. The pressure is in mb, with the wind speeds in m s^{-1} .

(Barnes, 1980)

Frontal dust storms on Mars (Wang et al. 2005)

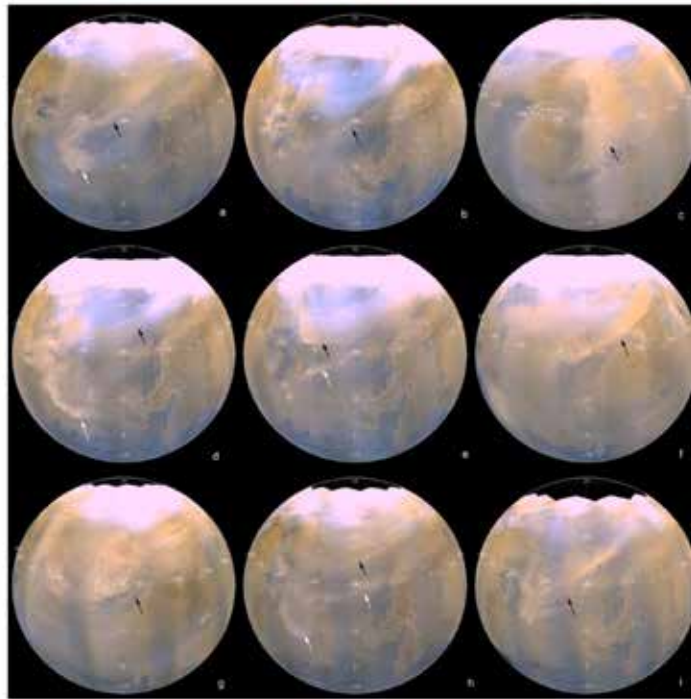


Figure 5. Examples of flushing dust storms in different channels, seasons, and years. Each panel is a Mars daily global map projected onto a sphere with black arrows pointing to the main frontal features. The three rows from the top to the bottom are for MGS mapping Years 1 (1999–2001), 2 (2001–2003), and 3 (2003–2005), respectively. Figures 5a, 5b, 5d, 5e, 5h, and 5i are for the Acidalia channel. Figure 5c is for the Arcadia channel. Figures 5f and 5g are for the Utopia channel. The L_s values are (a) 210°, (b) 314°, (c) 336°, (d) 316°, (e) 324°, (f) 324°, (g) 207°, (h) 214°, and (i) 230°.

Meridional circulation in a Martian GCM (general circulation model)

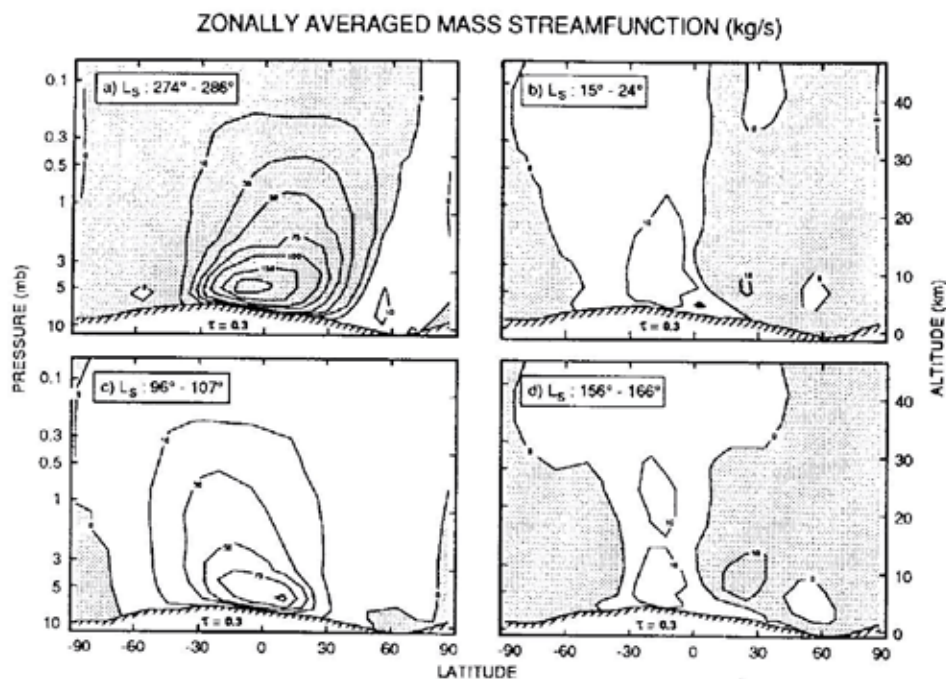
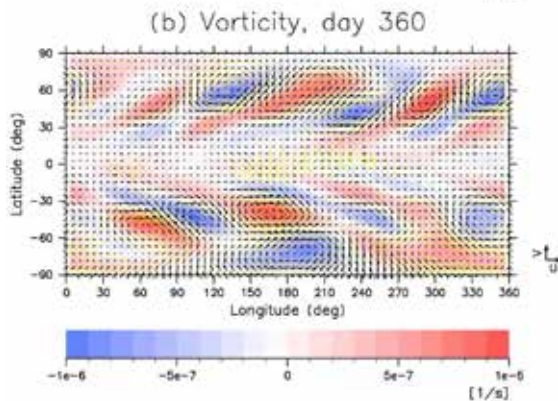


Fig. 19. Mass-weighted stream functions computed by the Mars-GCM (Pollack et al. 1990a) for early northern winter (a: $L_s \approx 280^\circ$), early northern spring (b: $L_s \approx 20^\circ$), early northern summer (c: $L_s \approx 103^\circ$) and late northern summer (d: $L_s \approx 161^\circ$). A background dust opacity of $\tau = 0.3$ was assumed. Flow in the meridional plane is clockwise around minima (negative values are shaded) and anti-clockwise around maxima; winds are strongest where contours are closest.

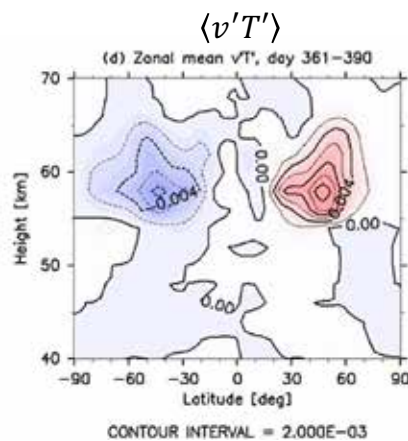
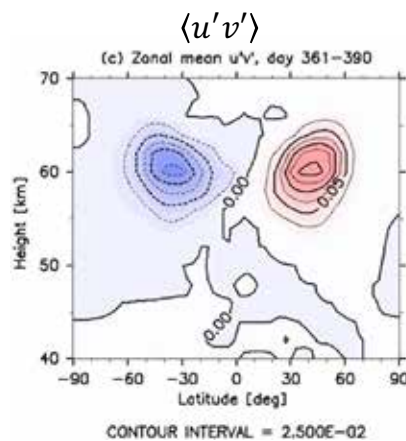
(Pollack et al 1990)

Baroclinic instability in Venusian atmosphere?



Sugimoto et al. (2014)

The superrotation of the atmosphere takes the place of planetary rotation, thereby sustaining baroclinic instability



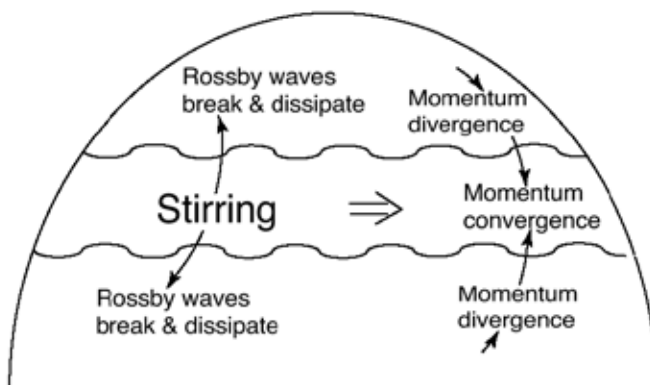
wave momentum transport

baroclinic instability

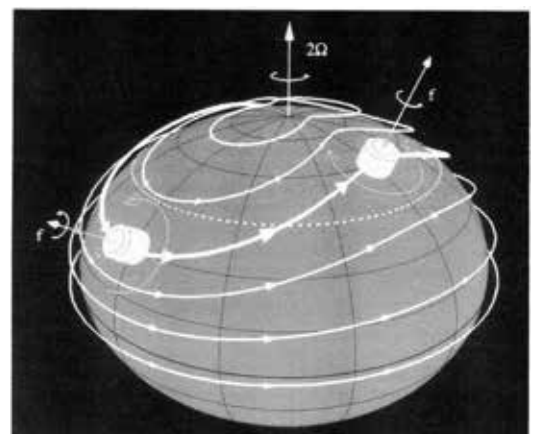
→ generation of Rossby waves

→ Rossby waves take away retrograde (westward) angular momentum from the mid-latitude

→ maintenance of (eastward) mid-latitude jets



(Vallis, 2005)



(Salby, 1996)

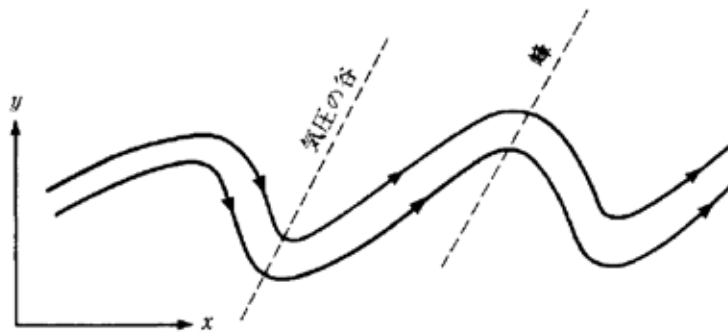


図 8.7 絶対角運動量が偏西風帯の波状擾乱によって極向きに輸送されていることを示す模式図.

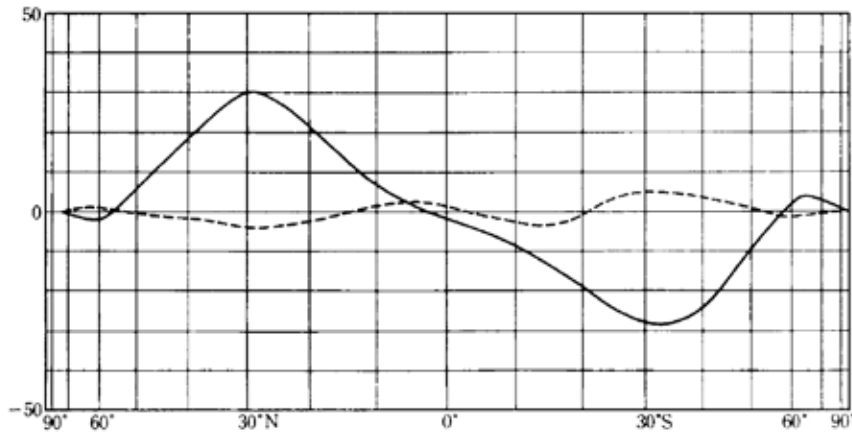


図 8.6 子午面内循環による絶対角運動量の極向き輸送量 (破線) と擾乱による輸送量 (実線) の年平均 (Lorenz, 1967).
単位は $10^{18} \text{ kg m}^2 \text{ s}^{-2}$.

小倉(1978)

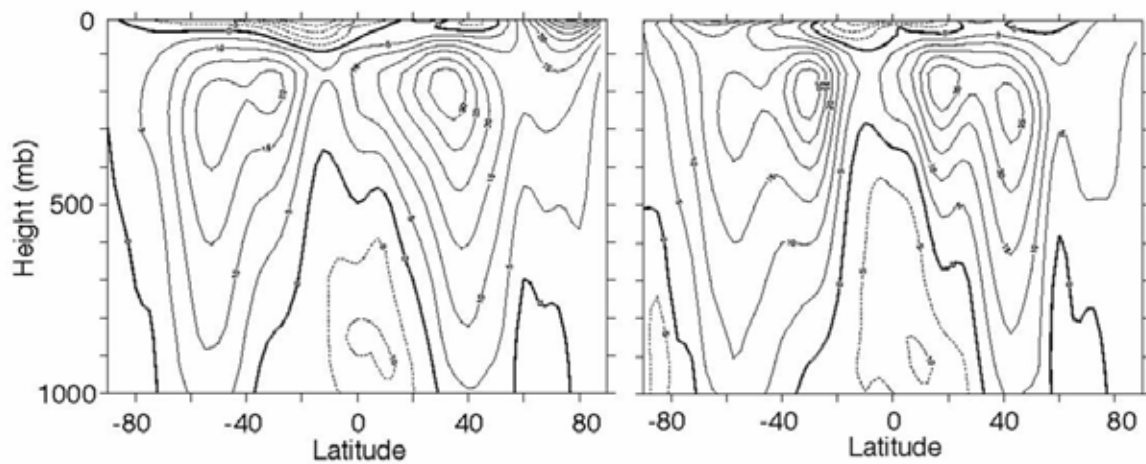
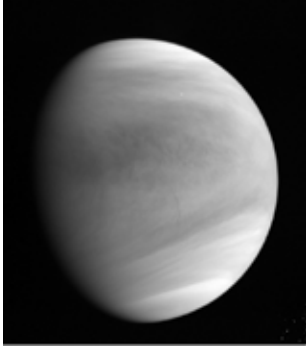


Fig. 3.1 The time-averaged zonal wind at 150°W (in the mid Pacific) in December-January February (DJF, left), March-April-May (MAM, right). The contour interval is 5 m s^{-1} . Note the double jet in each hemisphere, one in the subtropics and one in midlatitudes. The subtropical jets is associated with strong meridional temperature gradient, whereas the midlatitude jets have a stronger barotropic component and are associated with westerly winds at the surface.

Vallis (2006)

Latitudinal structures



Rotation period
243 days



1 day



10 hours

Rossby radius of deformation

$$L_R = \frac{\sqrt{gH}}{f}$$

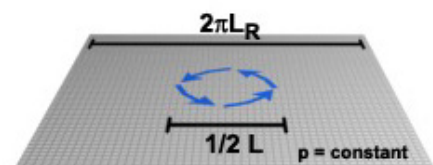
g : gravitational acceleration

H : depth of the system

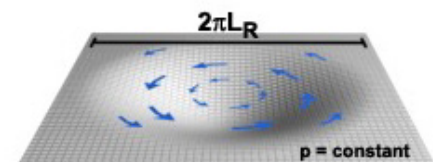
$f = 2\Omega \cos \theta$: Coriolis parameter

The characteristic scale at which the velocity field and the pressure field adjust with each other to maintain geostrophic flow

Faster planetary rotation leads to large f , and then shorter L_R



Initial disturbance



Final adjusted state

Parameter study of the atmospheric circulation of Earth-like planets with general circulation models (GCMs)

Williams (1988)

Zonal velocity

white : eastward

shade : westward

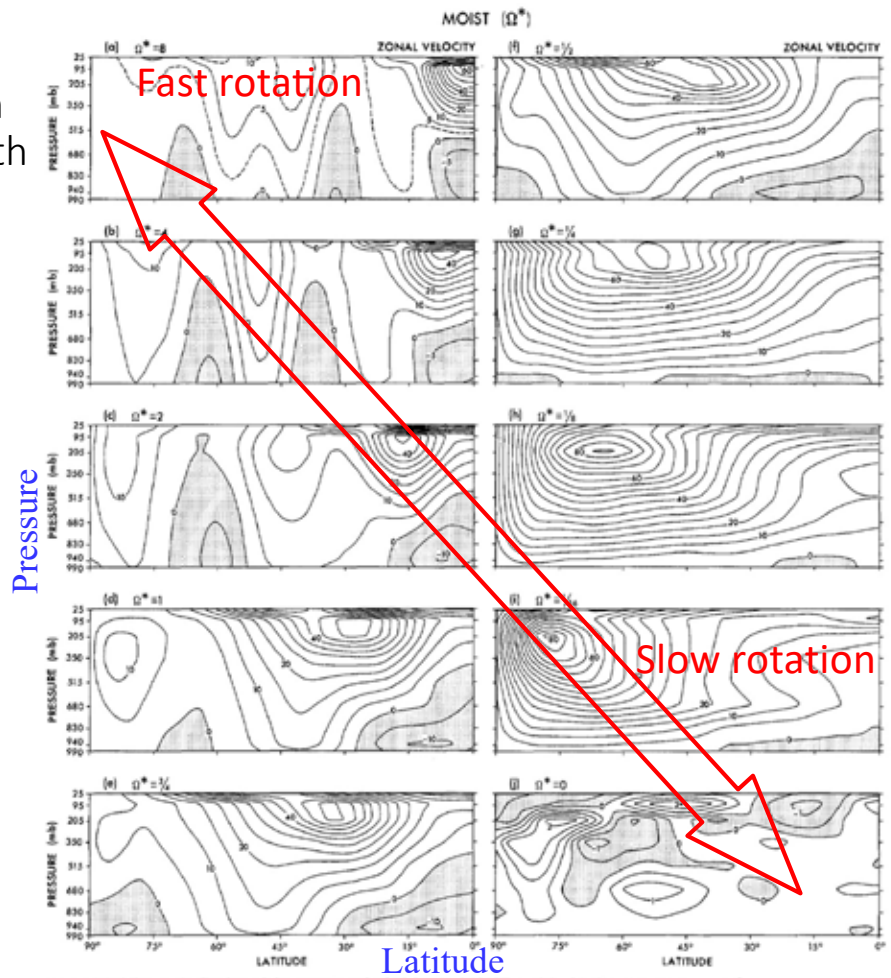


Fig. 2. Meridional distribution of the mean zonal wind for the MOIST model with $\Omega^* = 0-8$. Units: m s^{-1}

Meridional stream function

white : anti-clockwise

shade : clockwise

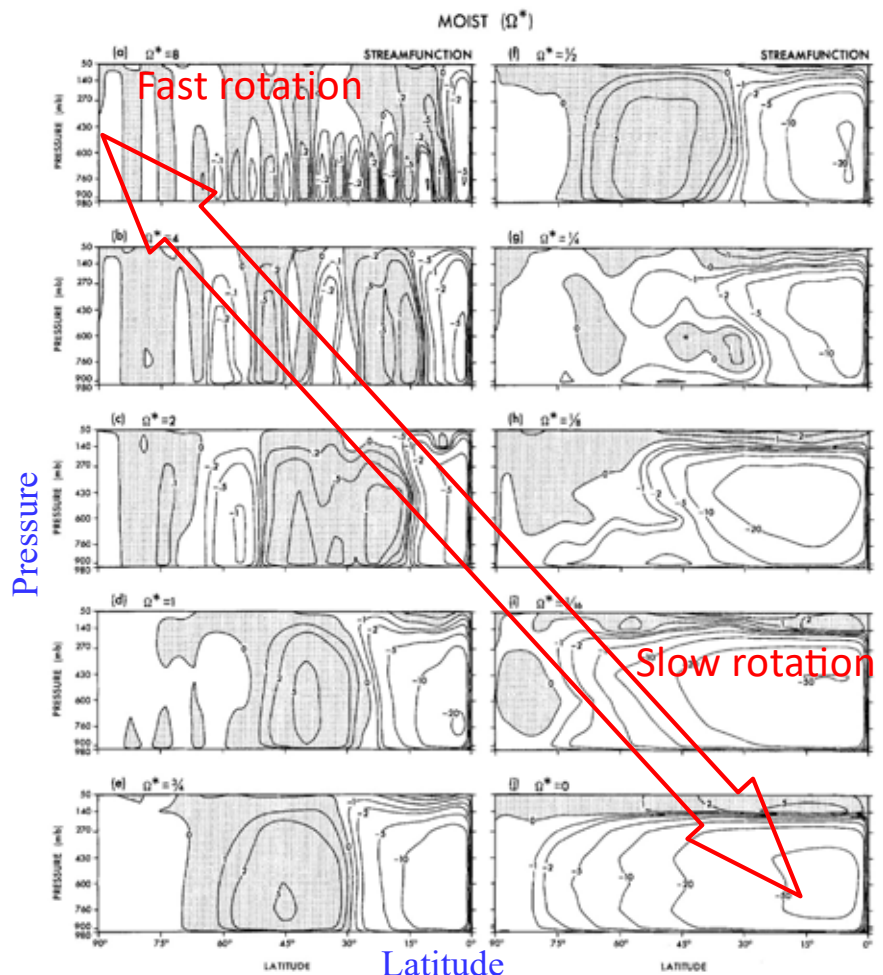


Fig. 3. Meridional distribution of the mean stream function for the MOIST model with $\Omega^* = 0-8$. Units: 10^{13} g s^{-1}

Temperature
 white : $> 220\text{K}$
 shade : $< 220\text{K}$

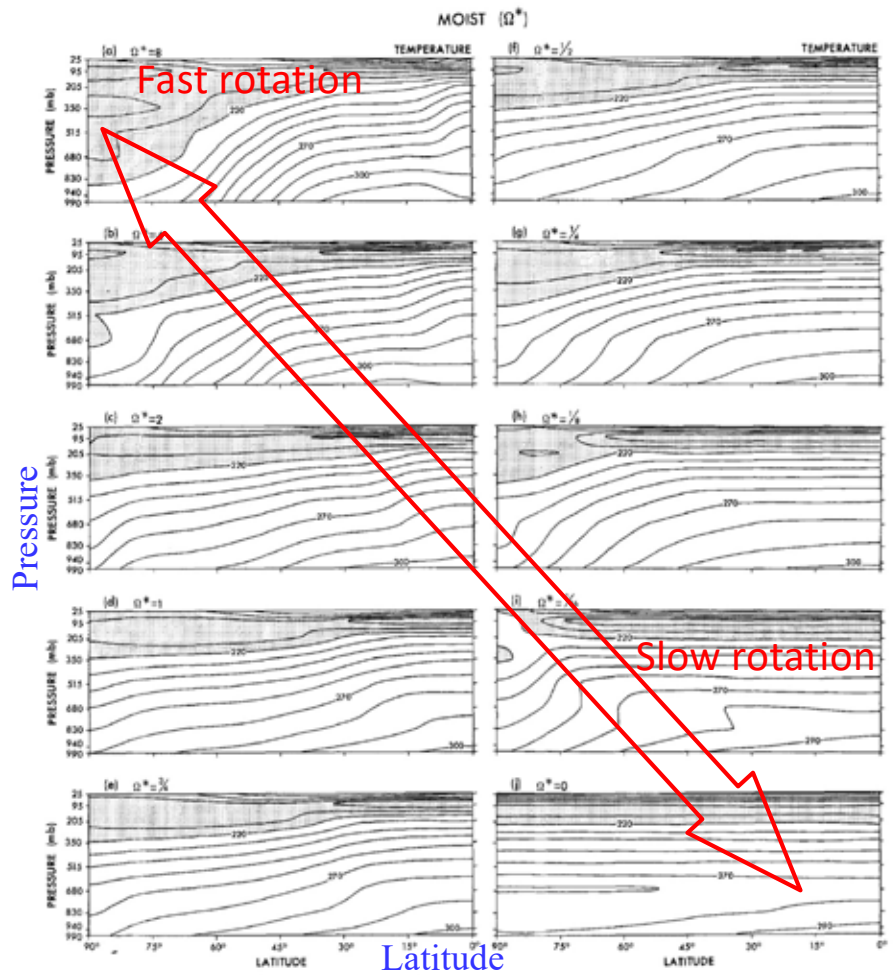


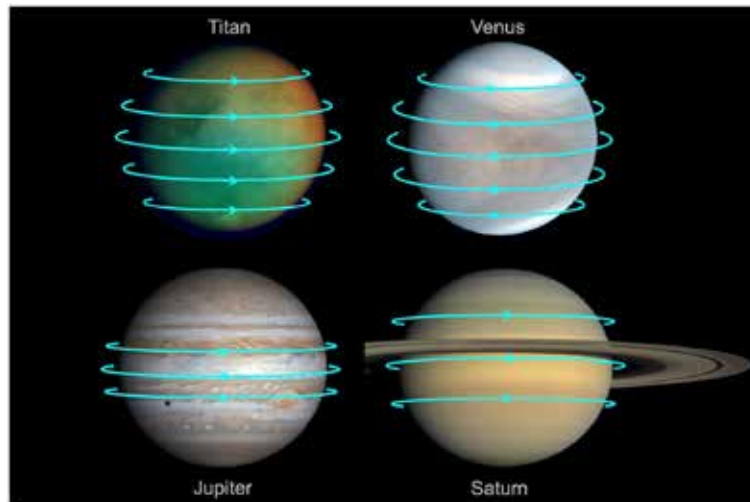
Fig. 4. Meridional distribution of the mean temperature for the MOIST model with $\Omega^* = 0-8$. Units: K.

Superrotation



taken by Akatsuki UV Imager

Observed superrotating atmospheres



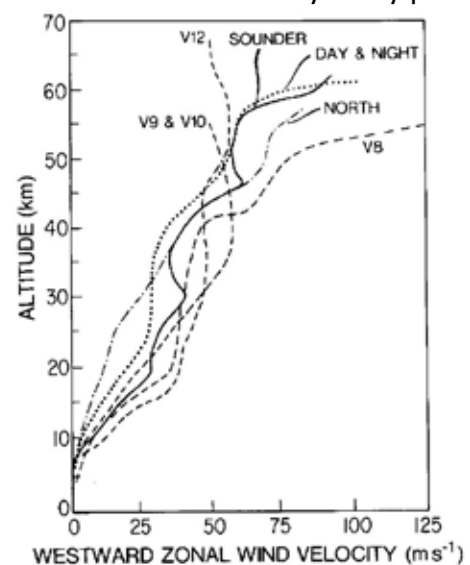
Planet	Radius (km)	Rotation period (days)	Equatorial rotation speed (m/s)	Equatorial wind speed (m/s)	Superrotation index, s , on the equator
Venus	6,052	243	1.81	100–120	55–66
Titan	2,576	16.0	11.7	100–180	8.5–15
Jupiter	69,911	0.41	12,300	60–140	0.005–0.011
Saturn	58,232	0.44	9,540	350–430	0.037–0.045
HD 189733b	79,500	2.2	2600	2400	0.92

Imamura et al. (2020, *Space Sci. Rev.*)

Superrotation of Venus' atmosphere



Zonal winds measured by entry probes



60 times faster rotation of the atmosphere (period=4 Earth days) than the solid planet (period=243 Earth days)

Superrotation of Venus' atmosphere

Latitudinal profiles of the zonal wind speed at different levels (20–60 km) measured by entry probes

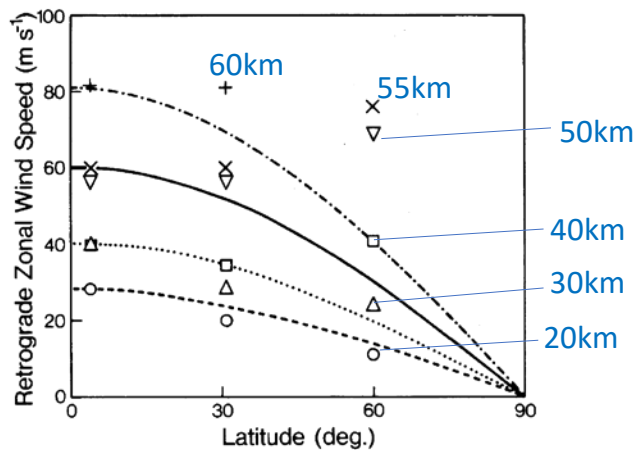
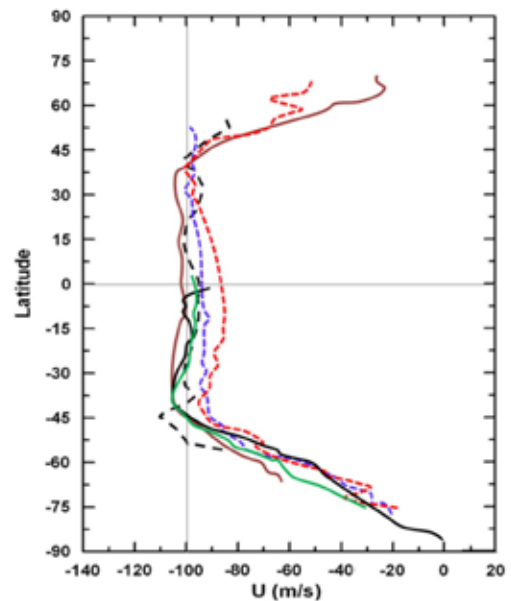


Fig. 10. Latitudinal variation of retrograde zonal wind speeds measured by interferometric tracking of Pioneer Venus probes. The symbols refer to different altitudes: 20 km, (○); 30 km, (Δ); 40 km, (□); 50 km, (▽); 55 km, (×); and 60 km, (+). The curves represent solid body rotation at different rates. It is assumed that the zonal circulation is approximately symmetric about the equator, so the wind speeds for the Day and Night probes can be plotted at 31°N.

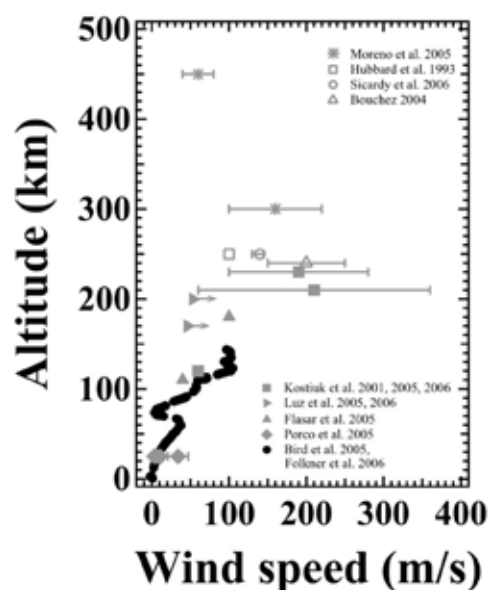
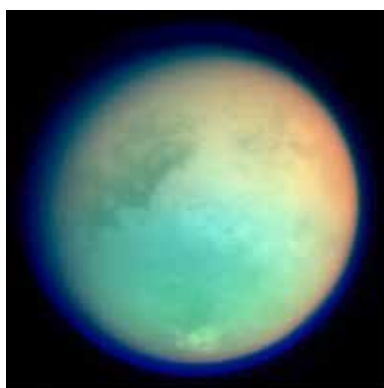
Cloud-tracked winds from various missions



Sánchez-Lavega et al. (2017)

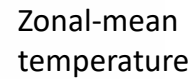
Superrotation of Titan' atmosphere

Hörst et al. 2017



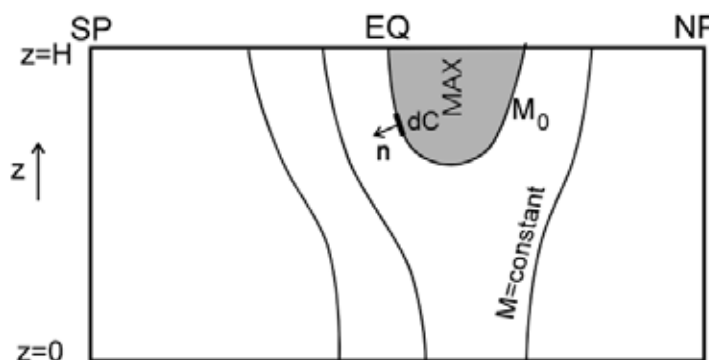
The atmosphere circulates 10 times faster than the rotation of the solid planet.

Achterberg et al. 2008



Zonal winds calculated from the temperature using thermal wind relation

Hide (1969) showed that non-axisymmetric eddies (waves) are needed to maintain the jets aloft the surface and that the required momentum convergence should be provided by upgradient angular momentum transport.



(Vallis, 2005)

Difference between Venus and Titan

- hot Venus (740 K) vs. cold Titan (90 K)
- large Venus (radius = 6050 km) vs. small Titan (2575 km)

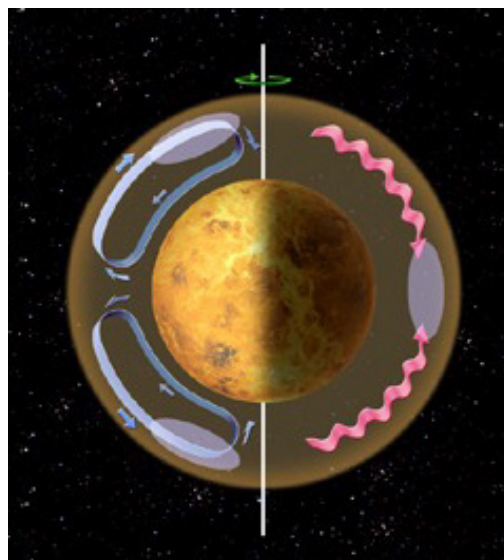
Similarity between Venus and Titan

- slow rotation (period = 243 days for Venus, 16 days for Titan)
- thick aerosol layer
- long radiative relaxation time (30 years for Venus, 100 years for Titan)

Hypothesis: Acceleration by meridional circulation and horizontal eddies (Gierasch, 1974; Rossow & Williams, 1979)

Hadley circulation

transports angular momentum poleward, thereby creating high-latitude jets.



Horizontal eddies

transport angular momentum equatorward to smooth out the differential rotation of the atmosphere.

The combination of the two processes leads to an accumulation of angular momentum in the equatorial upper atmosphere.

2D simulation in a slowly-rotating system

(Williams and Rossow 1979)

- planetary rotation same as Venus
 - momentum forcing at high latitudes
- baroclinic instability, followed by generation of large-scale waves and equatorward momentum transport

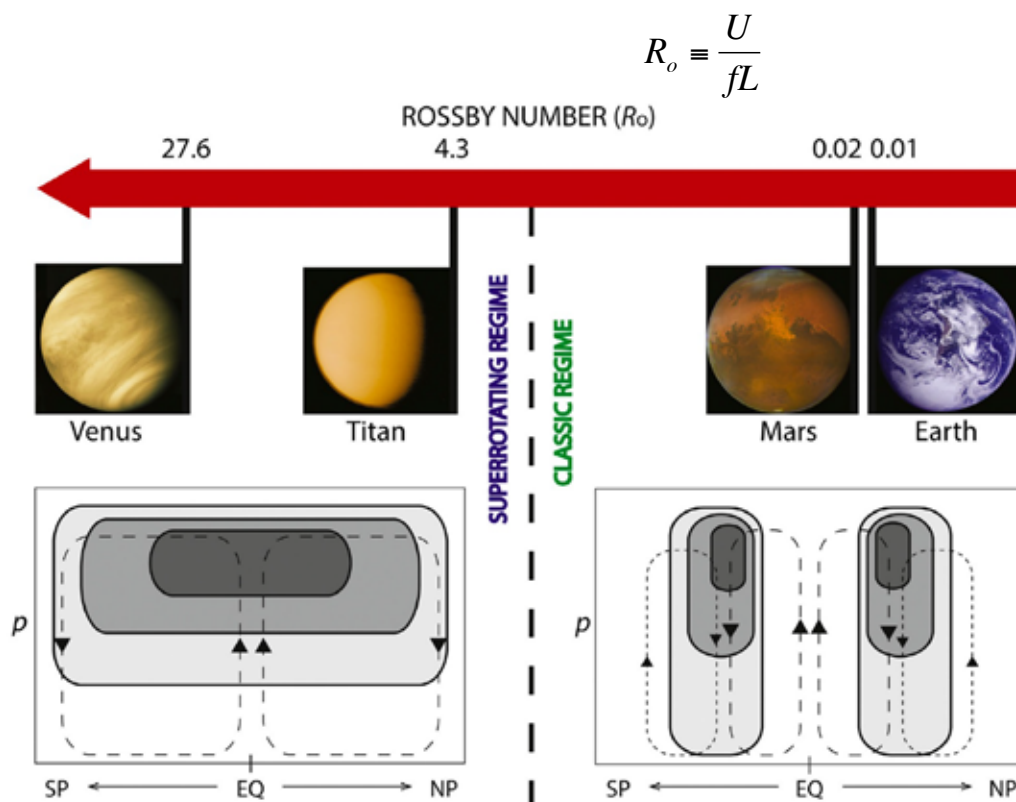
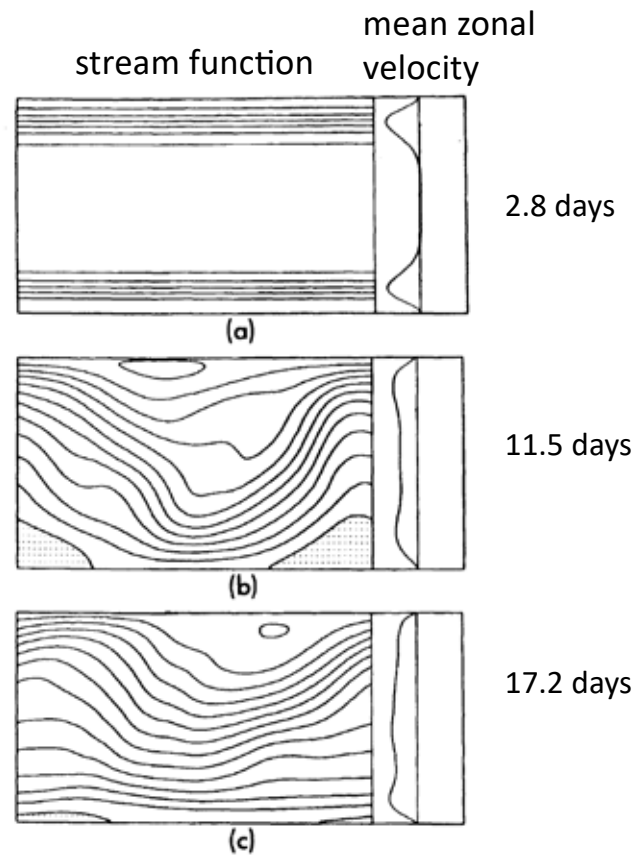


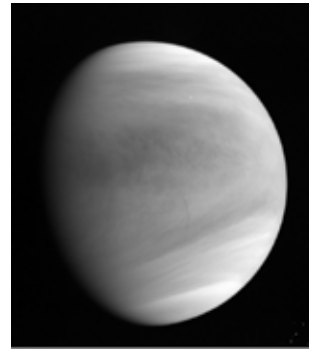
Fig. 1. Schematic view of the different Rossby numbers (R_o) and circulation regimes found on the terrestrial bodies of the Solar System with substantial atmospheres. R_o was computed based on typical scales of zonal winds (around 100 m s^{-1} for Venus and Titan and 10 m s^{-1} for Earth and Mars), rotation rate, and planetary radius. The lower panels depict a hypothetical vertical cross section of zonal mean zonal wind (shaded, arbitrary scale) and mean overturning circulation (dashed lines, arbitrary scales) characteristic of each body's atmospheres. See text for more details (photo credits: NASA/JPL).

Difference in wave characteristics between Earth and Venus

Earth



Venus



Rotation period 1 day

243 days



Small waves



Large waves



Poleward AM transport

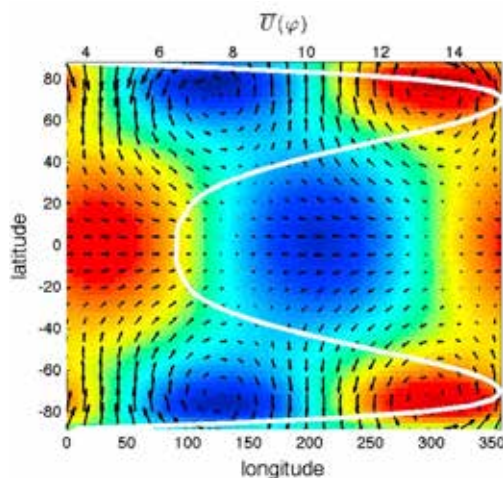


?

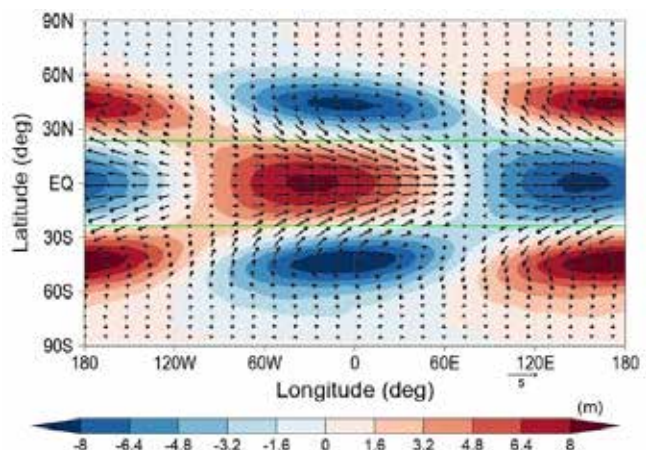
Rossby-Kelvin instability

(Sakai 1989; Iga and Matsuda 2005; Wang & Mitchell 2014)

Coupled mode seen in a Titan-like GCM (Wang & Mitchell 2014)

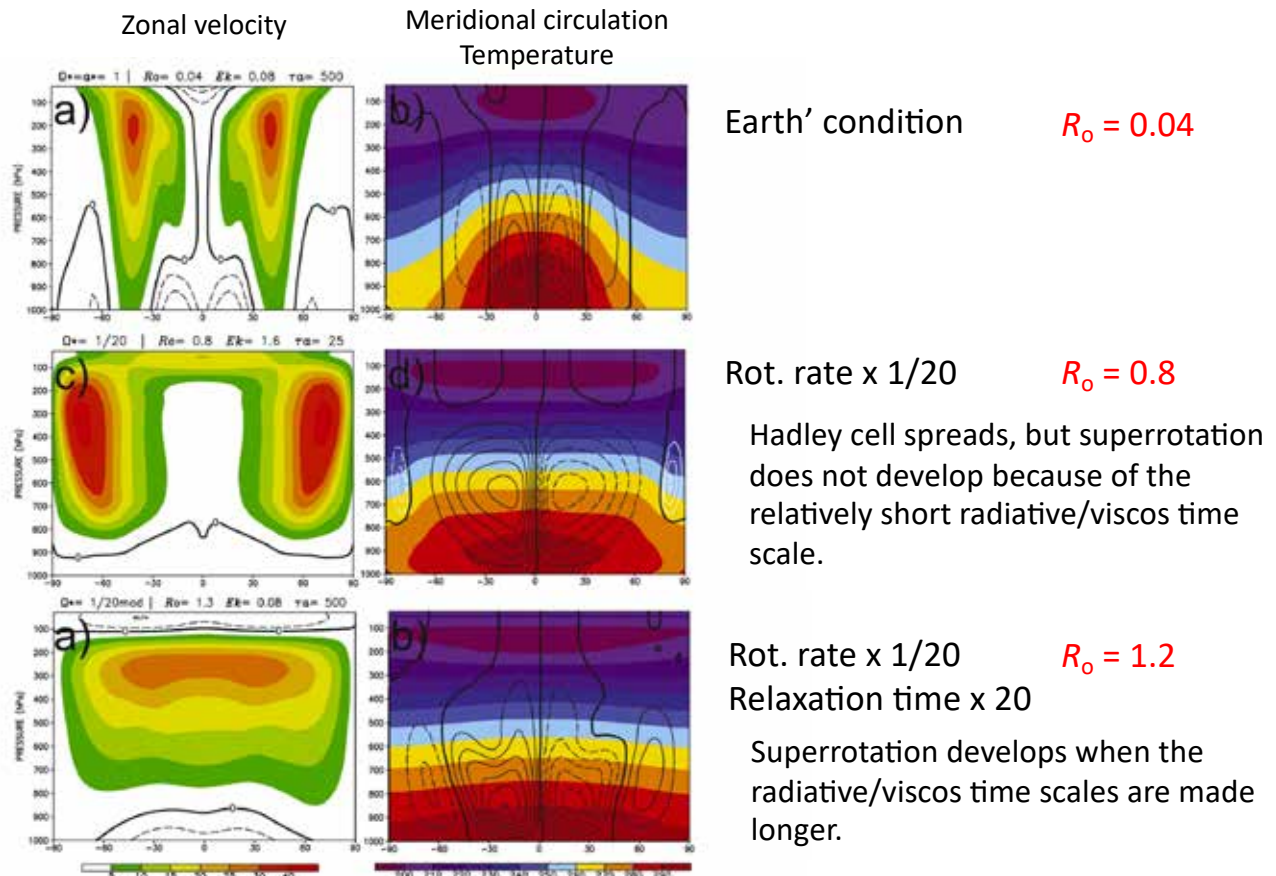


Coupled mode seen in a Venus GCM (Takagi et al. 2022)



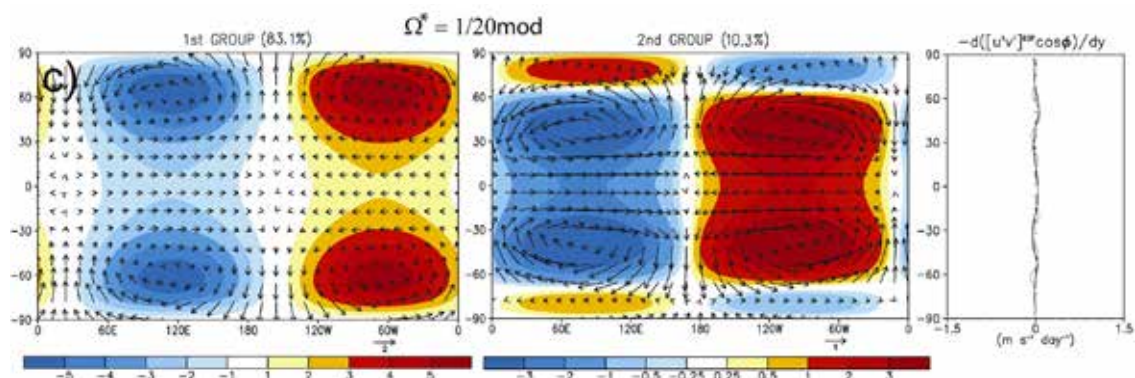
Planetary-scale shear instability can transport angular momentum equatorward

Parameter dependence in Earth-like GCM (Dias Pinto & Mitchell 2014)



Wave structures (EOF 1, 2)

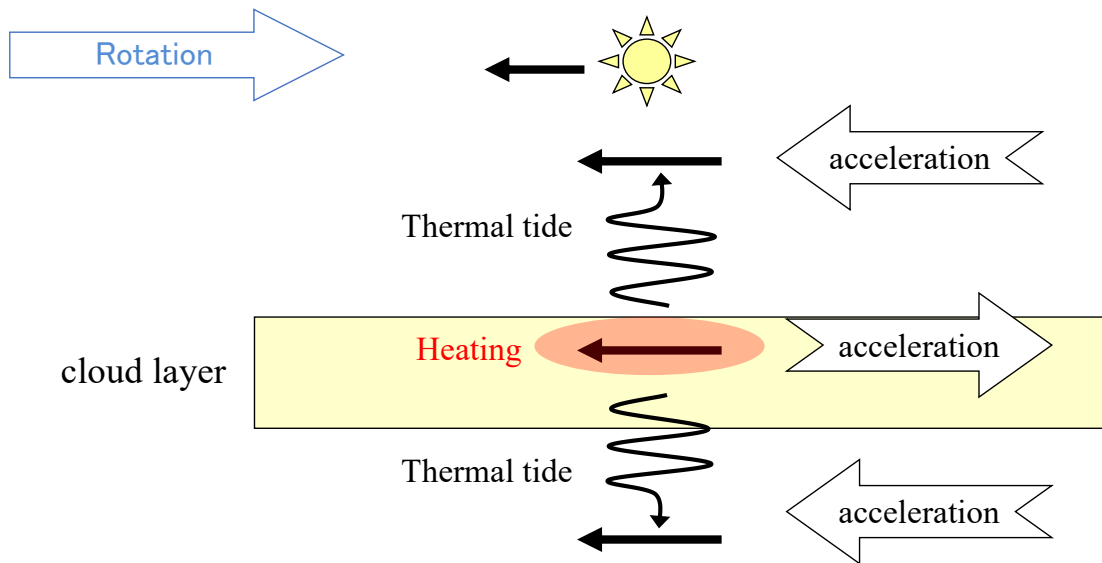
Rot. rate x 1/20 , Relaxation time x 20



In order for superrotation to develop, the relaxation time needs to be long in addition to a large Rossby number.

→ Condition on Venus and Titan

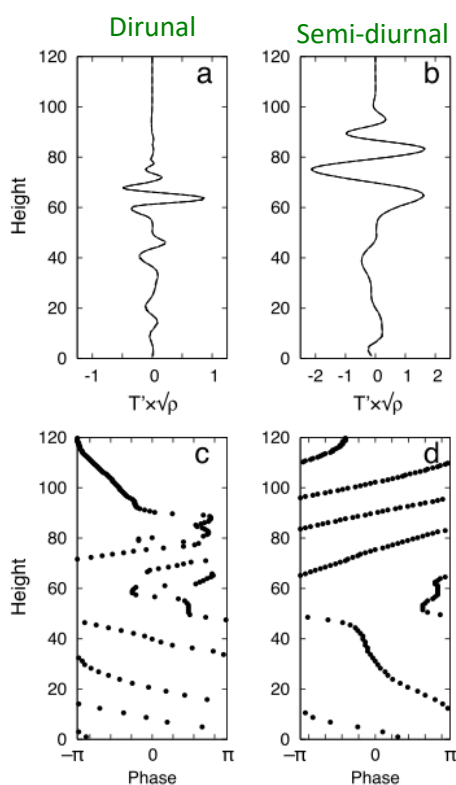
Hypothesis: Acceleration by thermal tides (Fels & Lindzen 1974)



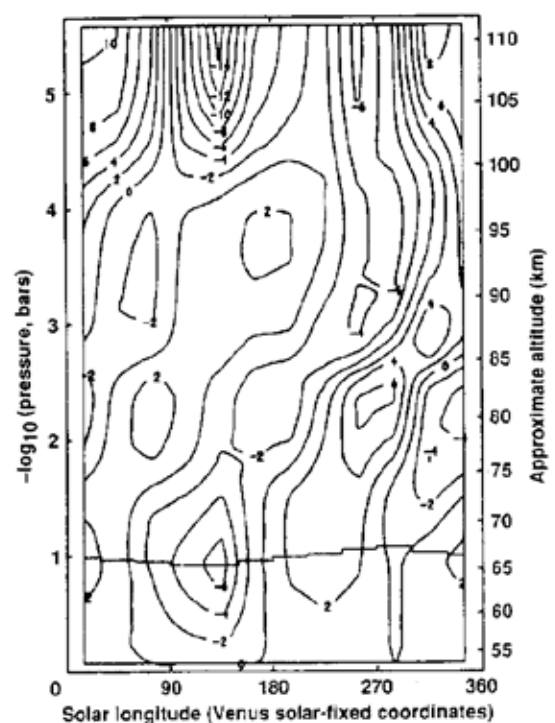
太陽光加熱域の移動により、東向き運動量を持つ重力波が励起されて上下に伝搬 → 雲層が反動で西向きに加速

Vertical structure of thermal tides in Venus's atmosphere

Linear solution (Takagi & Matsuda, 2006)

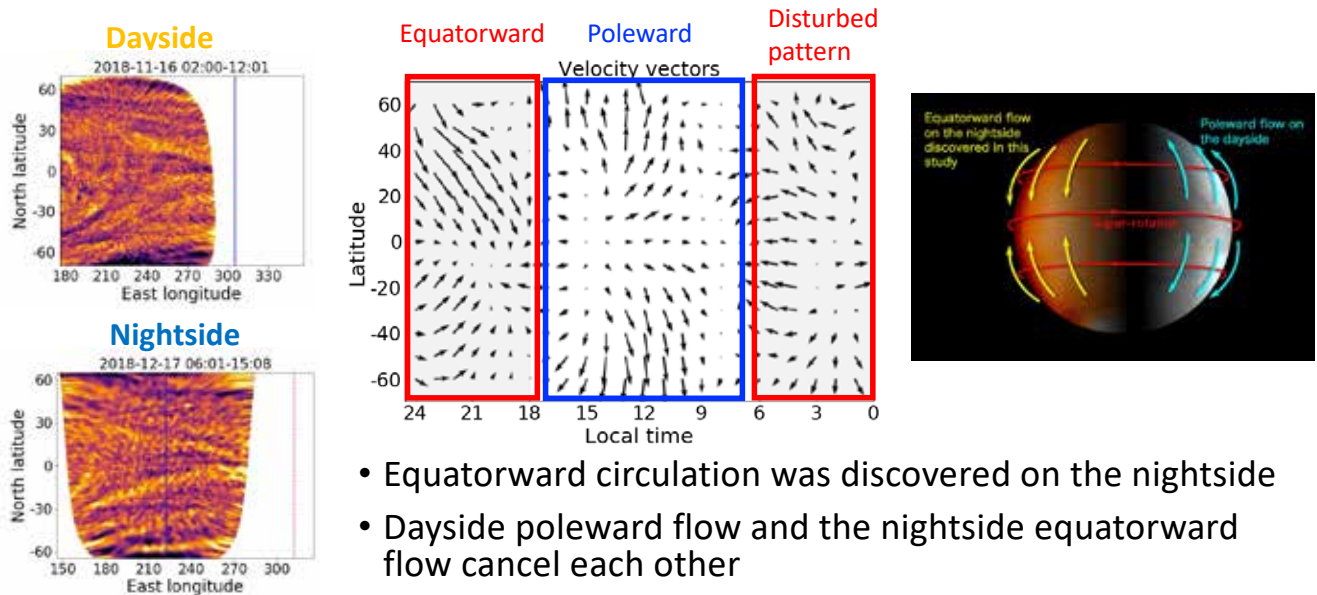


Temperature perturbation (Schofield & Taylor 1983)



Wind field of thermal tides on Venus (Fukuya et al. 2021)

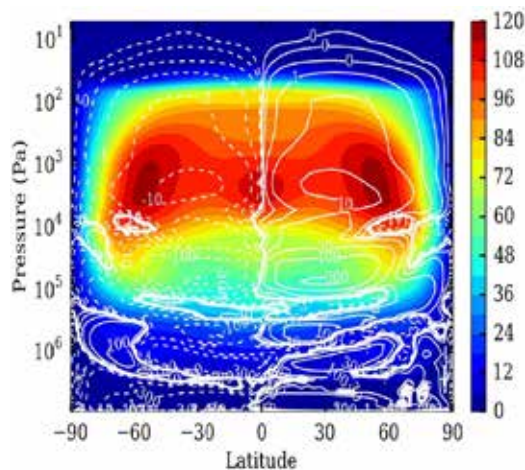
Clouds seen in thermal IR



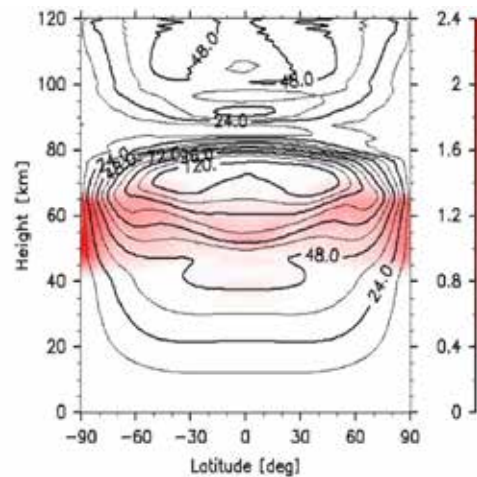
Numerical models

Zonal winds

Garate-Lopez and Lebonnois (2018)



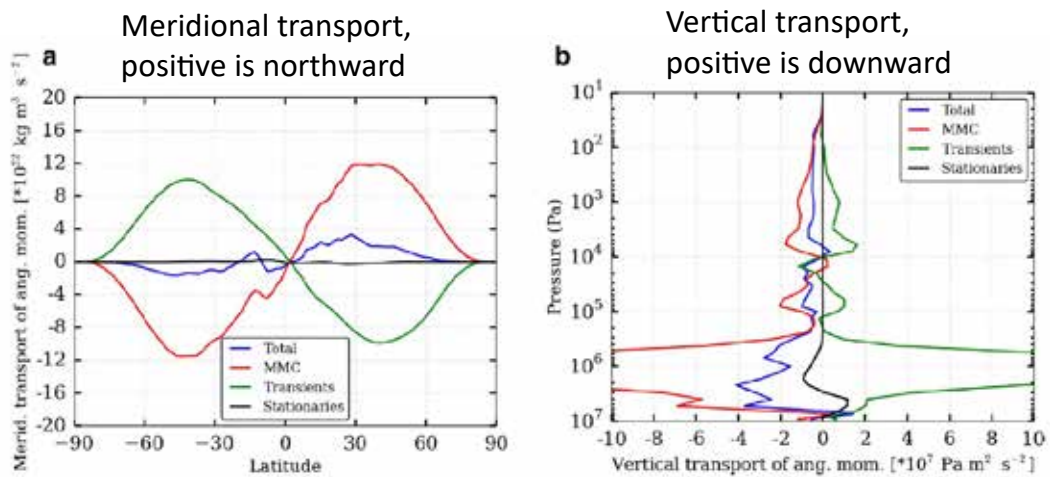
Sugimoto et al. (2014)



Numerical models

Transport of angular momentum

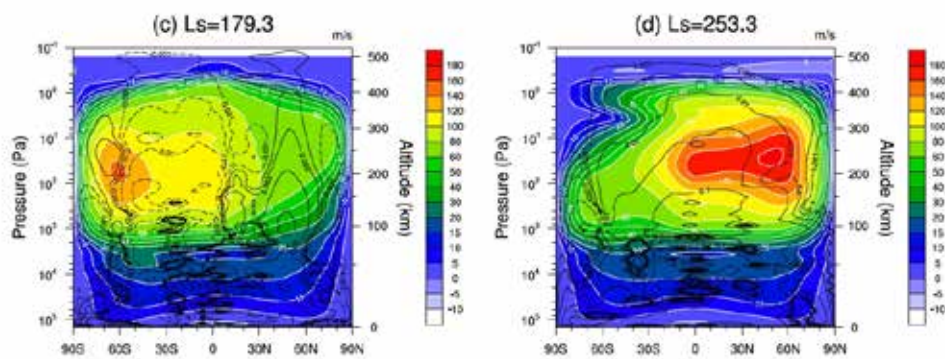
Lebonnois et al. (2016)



Numerical model of Titan

Lebonnois et al. (2012)

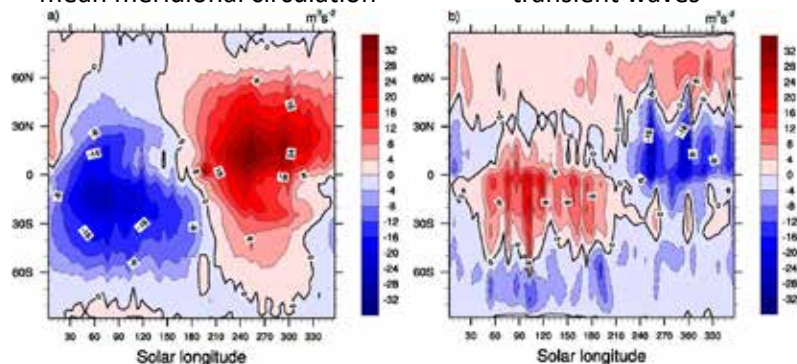
Mean zonal wind and meridional stream function



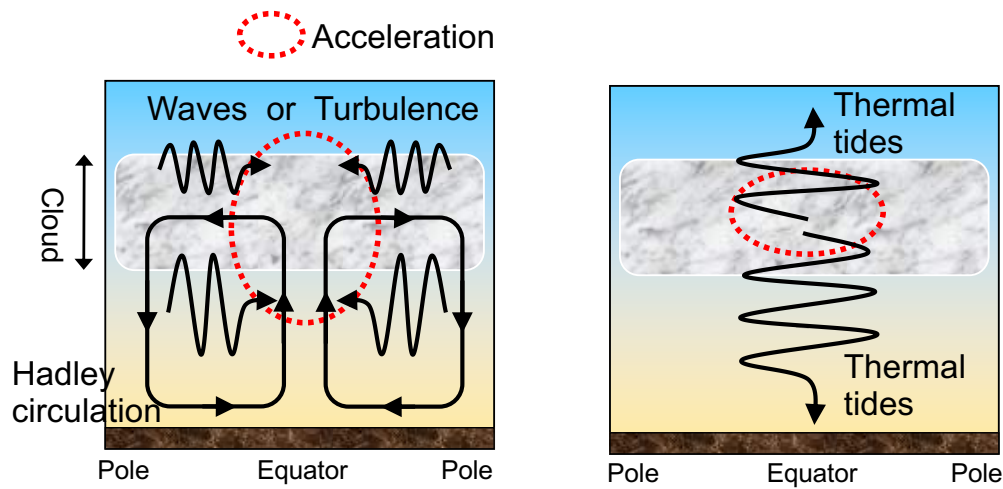
Seasonal variations of the vertically-integrated latitudinal transport of angular momentum

mean meridional circulation

transient waves



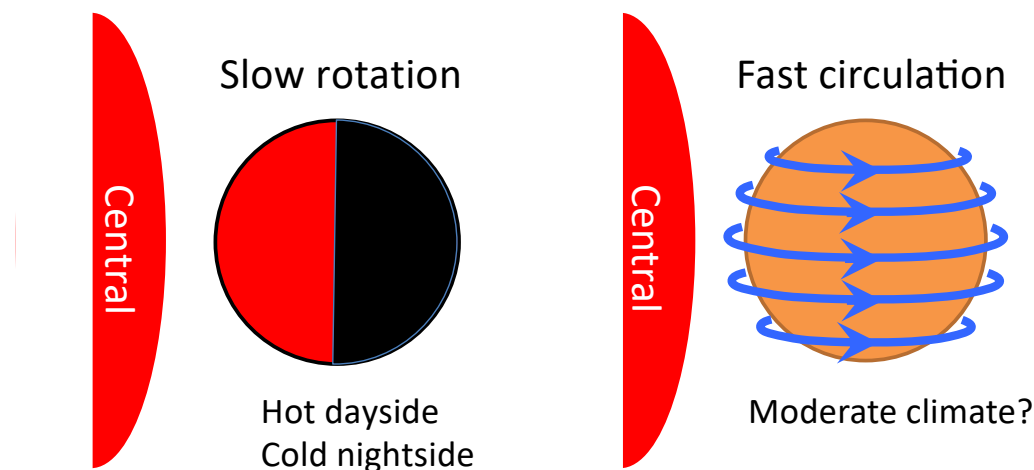
Candidate mechanisms of super-rotation

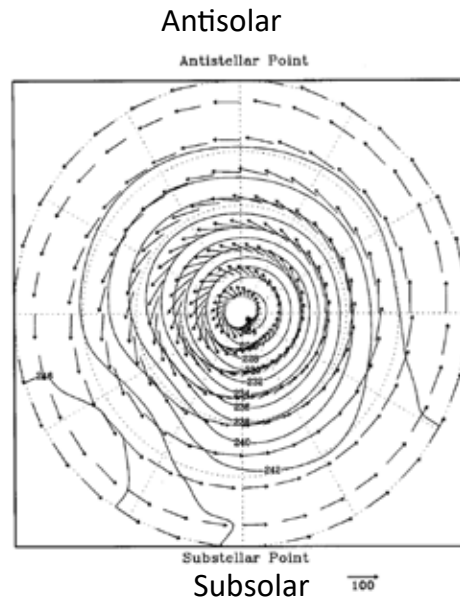


- Both mechanisms predict anti-superrotational winds near the surface.
 - On the other hand, existence of mountain waves requires superrotational winds prevailing from the cloud level to the surface.
- Open question

Implications for exoplanets

- Tidally-locked planets are mostly slow rotators like Venus.
- Super-rotation can redistribute thermal energy along the local time on such planets.



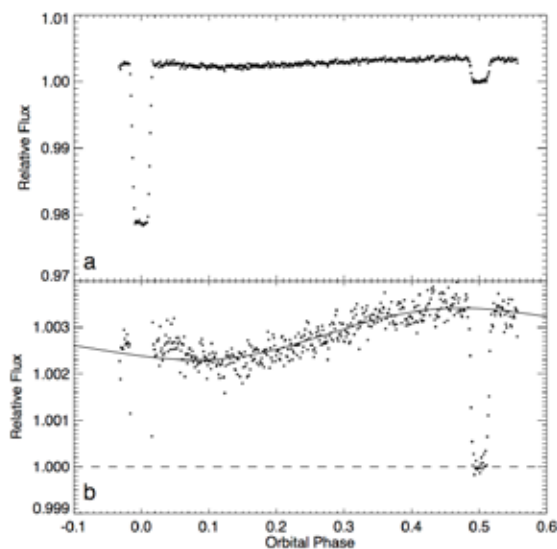


Polar view of the atmospheric circulation and temperature distribution at 20 km altitude on a synchronously rotating terrestrial planet (Joshi et al., 1997)

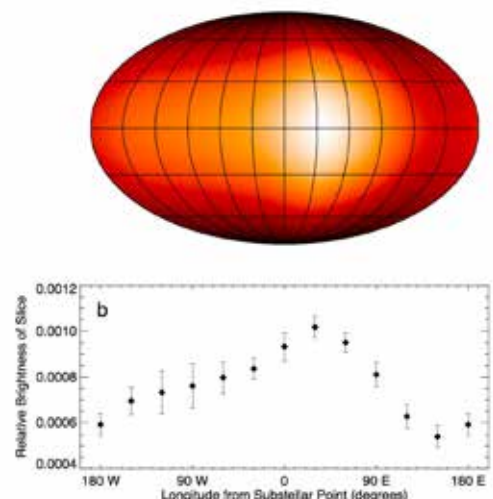
A map of the day-night contrast of the extrasolar planet HD 189733b (Knutson et al. 2007)

A minimum brightness temperature of 973 ± 33 K and a maximum brightness temperature of 1212 ± 11 K at a wavelength of 8 microns, indicating that energy from the irradiated dayside is efficiently redistributed throughout the atmosphere

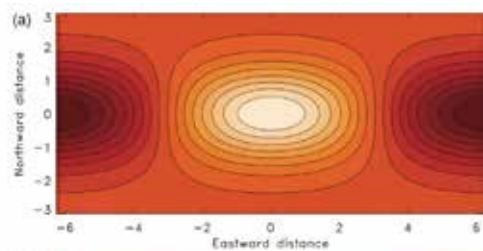
Observed phase variation for HD 189733b, with transit and secondary eclipse visible.



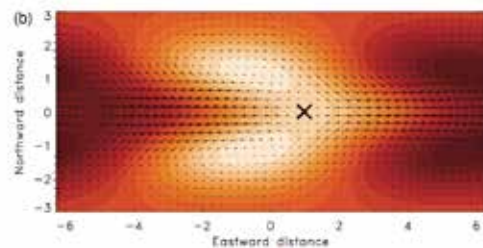
Brightness estimates for 12 longitudinal strips on the surface of the planet



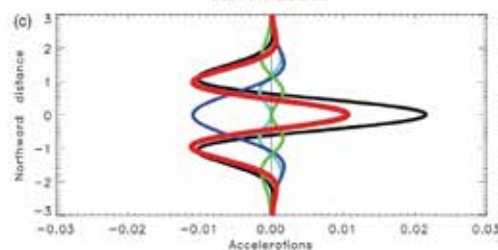
Linear, analytic solution for parameters relevant to hot, tidally locked exoplanets
(Showman & Polvani 2011)



radiative-equilibrium height field



Height field (orange scale) and horizontal wind velocities (arrows)



Acceleration

Matsuno-Gill pattern (Matsuno 1966; Gill 1980)

- Heat-induced tropical circulation composed of Rossby wave and Kelvin wave
- Plays crucial roles in Earth's troposphere

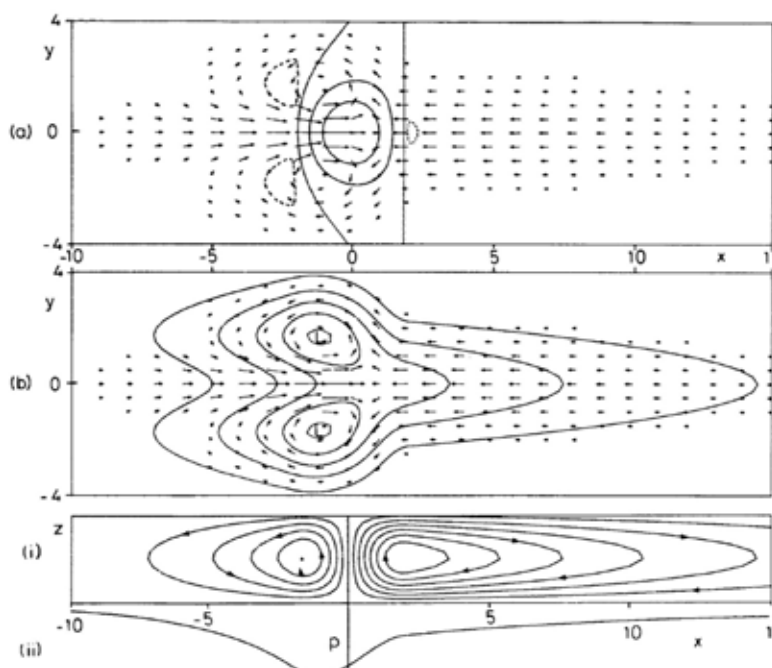


Figure 1. Solution for heating symmetric about the equator in the region $|x| < 2$ for decay factor $\varepsilon = 0.1$.

(a) Contours of vertical velocity w (solid contours are 0, 0.3, 0.6; broken contour is -0.1) superimposed on the velocity field for the lower layer. The field is dominated by the upward motion in the heating region where it has approximately the same shape as the heating function. Elsewhere there is subsidence with the same pattern as the pressure field.

(b) Contours of perturbation pressure p (contour interval 0.3) which is everywhere negative. There is a trough at the equator in the easterly regime to the east of the forcing region. On the other hand, the pressure in the westerlies to the west of the forcing region, though depressed, is high relative to its value off the equator. Two cyclones are found on the north-west and south-west flanks of the forcing region.

(c) The meridionally integrated flow showing (i) stream function contours, and (ii) perturbation pressure. Note the rising motion in the heating region (where there is a trough) and subsidence elsewhere. The circulation in the right-hand (Walker) cell is five times that in each of the Hadley cells shown in (c).

Driving forces of the zonally-averaged structure

Transformed Eulerian-mean equations:

$$\frac{\partial \bar{u}}{\partial t} + \bar{v}^* \left(\frac{\partial \bar{u}}{\partial y} - f \right) + \bar{w}^* \frac{\partial \bar{u}}{\partial z} = \boxed{\frac{1}{\rho_0} \left(\frac{\partial F^{(y)}}{\partial y} + \frac{\partial F^{(z)}}{\partial z} \right)} \quad \text{wave forcing}$$

Residual mean meridional circulation

$$\bar{v}^* = \bar{v} - \frac{1}{\rho_0} \frac{\partial}{\partial z} \left(\rho_0 \frac{\overline{v' \theta'}}{\bar{\theta}_z} \right)$$

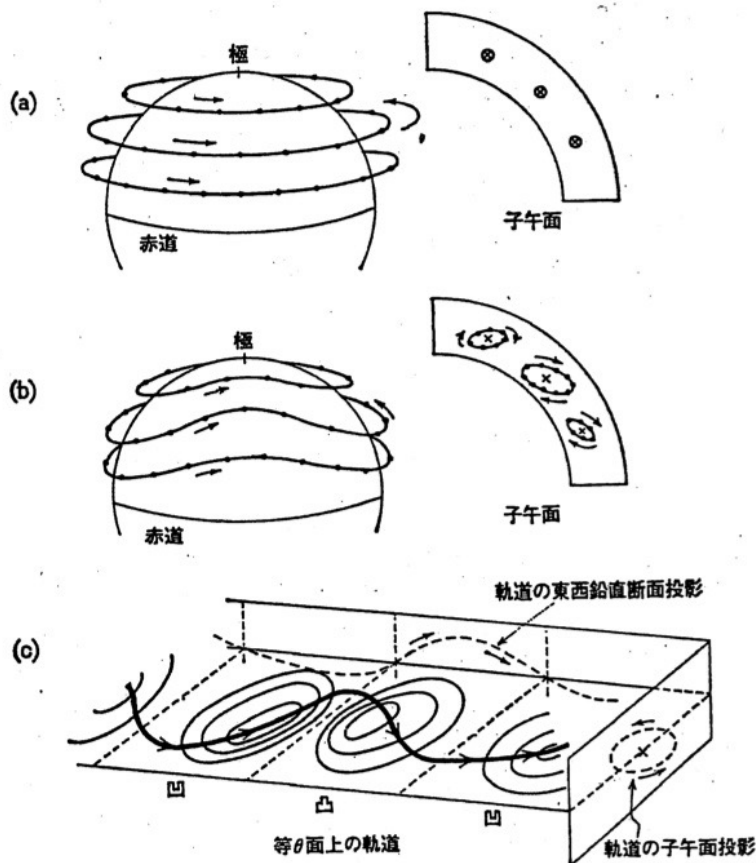
$$\bar{w}^* = \bar{w} + \frac{1}{\rho_0} \frac{\partial}{\partial y} \left(\rho_0 \frac{\overline{v' \theta'}}{\bar{\theta}_z} \right)$$

Eliassen-Palm flux (EP flux)

$$F^{(y)} = -\rho_0 \overline{u' v'}$$

$$F^{(z)} = -\rho_0 \left(\overline{u' w'} - f \frac{\overline{v' \theta'}}{\bar{\theta}_z} \right)$$

$$\frac{\partial \bar{\theta}}{\partial t} + \bar{v}^* \frac{\partial \bar{\theta}}{\partial y} + \bar{w}^* \frac{\partial \bar{\theta}}{\partial z} = \boxed{\bar{Q}} \quad \text{diabatic heating}$$



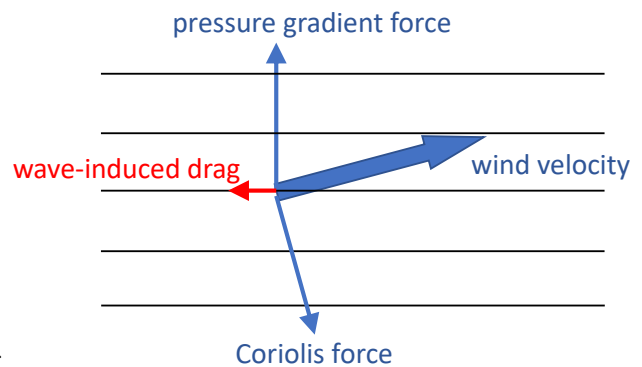
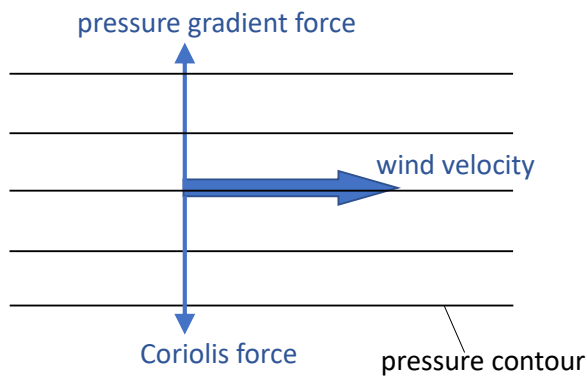
木田秀次(1983)

図 5.6 偏西風の中を
プラネタリー波が鉛直
伝播するときの空気塊
の振動. 小さい黒点は,
微小空気塊を表す.
(a) 波が不在の場合.
(b) 波が在る場合. ×
印は子午面断面上の元
の位置. (c) 等温位面
上の空気塊の軌道. 子
午面投影では主軸が傾
斜した楕円軌道になる.

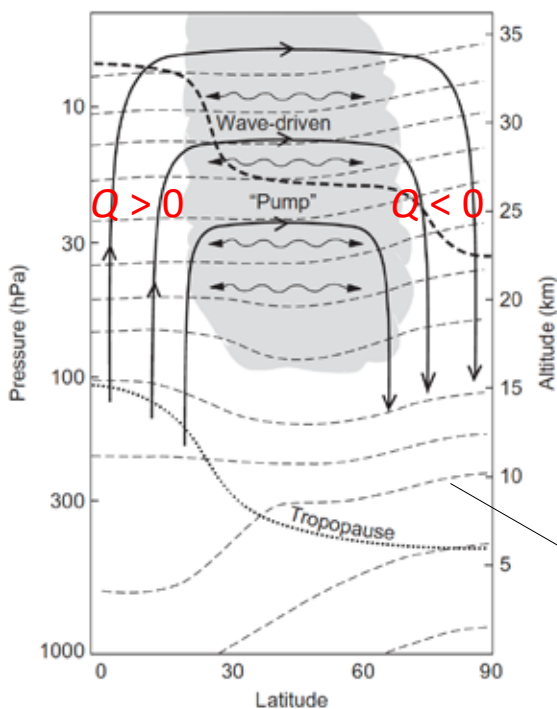
Wave-driven meridional circulation

$$\cancel{\frac{\partial \bar{u}}{\partial t}} + \bar{v}^* \left(\cancel{\frac{\partial \bar{u}}{\partial y}} - f \right) + \bar{w}^* \cancel{\frac{\partial \bar{u}}{\partial z}} = \frac{1}{\rho_0} \left(\frac{\partial F^{(y)}}{\partial y} + \frac{\partial F^{(z)}}{\partial z} \right) \quad \text{wave forcing}$$

$$\therefore f \bar{v}^* = \frac{1}{\rho_0} \left(\frac{\partial F^{(y)}}{\partial y} + \frac{\partial F^{(z)}}{\partial z} \right)$$



Earth's stratospheric meridional circulation (Holton 2012)



Diabatic circulation

$$\cancel{\frac{\partial \bar{\theta}}{\partial t}} + \bar{v}^* \cancel{\frac{\partial \bar{\theta}}{\partial y}} + \bar{w}^* \frac{\partial \bar{\theta}}{\partial z} = \bar{Q} \quad \text{diabatic heating}$$

$$\bar{w}^* \frac{\partial \bar{\theta}}{\partial z} = \bar{Q}$$

Earth's mean meridional circulation in the troposphere

Holton 2004

Eulerian-mean

$$(\bar{v}, \bar{w})$$

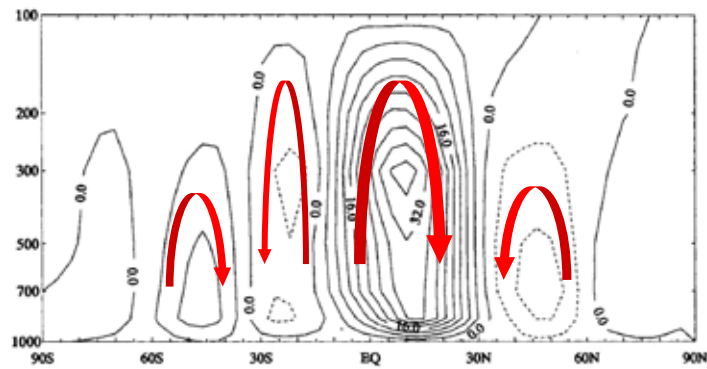
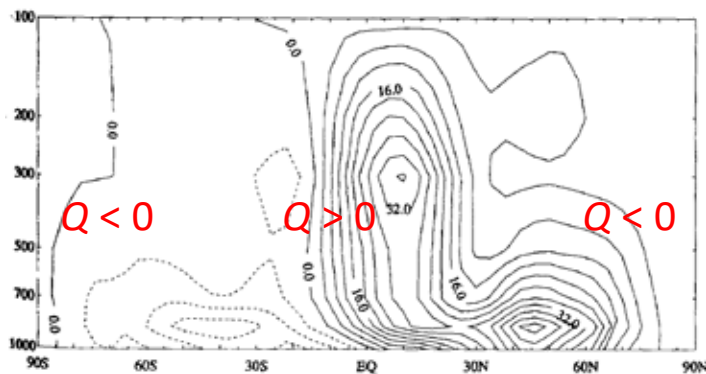


Fig. 10.7 Streamfunction (units: $10^2 \text{ kg m}^{-1} \text{ s}^{-1}$) for the observed Eulerian mean meridional circulation for Northern Hemisphere winter, based on the data of Schubert et al. (1990).

Lagrangian-mean

$$(\bar{v}^*, \bar{w}^*)$$



Meridional circulation of Mars atmosphere (Santee & Crisp 1995)

Mean temperature

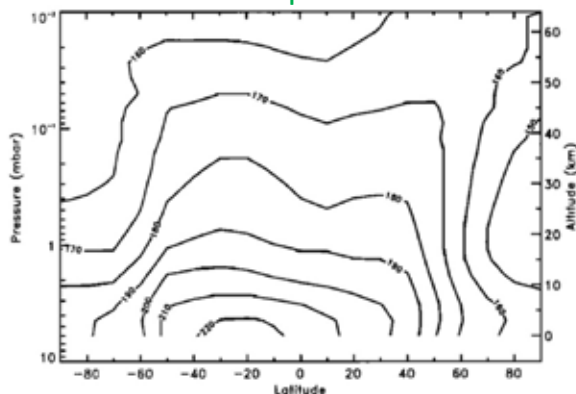


Figure 1a. Diurnal-mean temperatures obtained by averaging the 1400 LT and 0200 LT temperature maps retrieved from the Mariner 9 IRIS spectra in Paper I. For consistency with the results of Paper I, the vertical coordinate in this and all subsequent figures is the atmospheric pressure p . The approximate altitude z corresponding to a given pressure level is also included in these figures (see section 2.1). This correlation of altitude with pressure is based on the following values: $p_s = 6.0 \text{ mbar}$, $R = 191.0 \text{ J K}^{-1} \text{ kg}^{-1}$, $g = 3.74 \text{ m/s}^2$, and $T_0 = 196 \text{ K}$ (the globally and diurnally averaged value of the atmospheric temperature at the surface), resulting in a mean scale height $H = 10 \text{ km}$.

Net radiative heating rate, Q

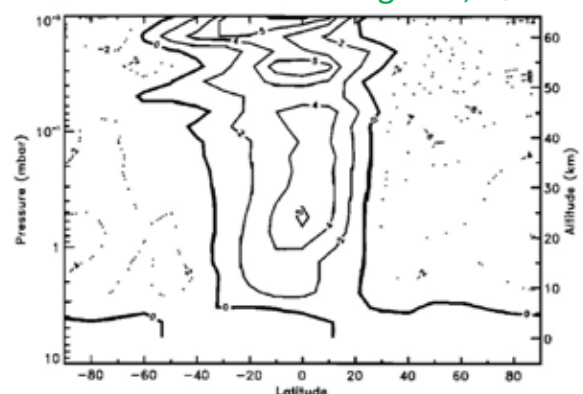


Figure 3. Net radiative heating rates (K/d) calculated from retrieved IRIS temperatures and dust abundances using the radiative transfer model described by Crisp [1990] and in the appendix of Santee [1993]. Negative contours are dashed, the zero contour is thicker, and the contour interval is nonuniform.

Meridional circulation of Mars atmosphere (Santee & Crisp 1995)

Meridional velocity (\bar{v}^*)

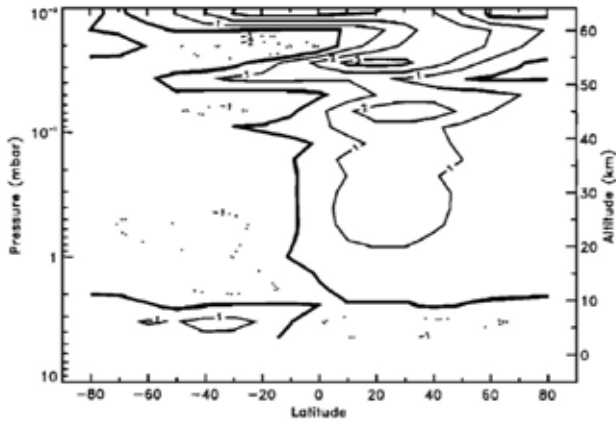


Figure 4a. Diabatic meridional velocity, in m/s. Positive values represent northward winds, negative contours are dashed, and the zero contour is thicker.

Vertical velocity (\bar{w}^*)

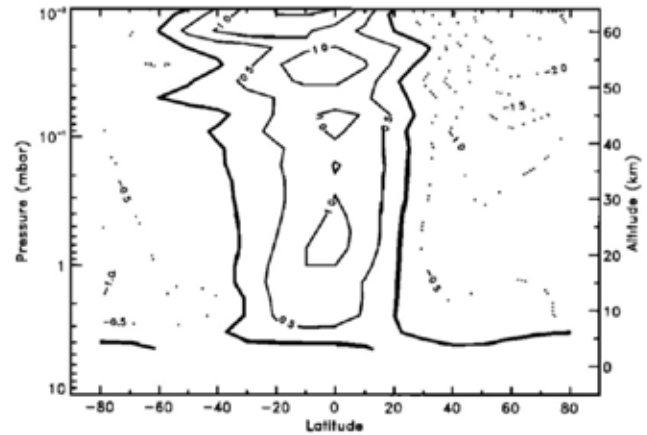


Figure 4b. Diabatic vertical velocity, in cm/s. Positive values represent upward winds, negative contours are dashed, and the zero contour is thicker.

Meridional circulation of Mars atmosphere (Santee & Crisp 1995)

Stream function

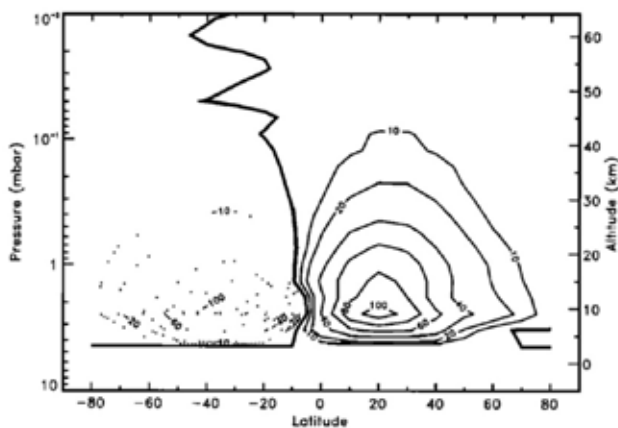


Figure 4c. Mass-weighted stream function, Ψ_m , in units of 10^7 kg/s. Positive values represent clockwise flow, negative contours are dashed, the zero contour is thicker, and the contour interval is nonuniform.

E-P flux divergence (zonal acceleration)

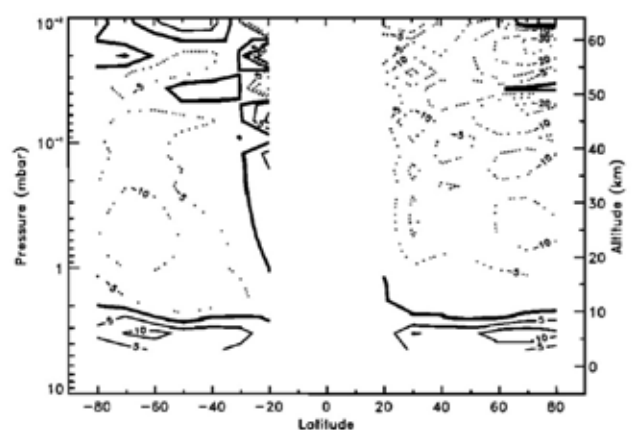


Figure 5. Eliassen-Palm flux divergence $((\rho a \cos \phi)^{-1} \nabla \cdot \mathcal{F})$ in units of ms^{-1}/d . Negative contours are dashed, the zero contour is thicker, and the contour interval is nonuniform.

Meridional circulation of Venus atmosphere

Lee et al. (2015)

temperature field

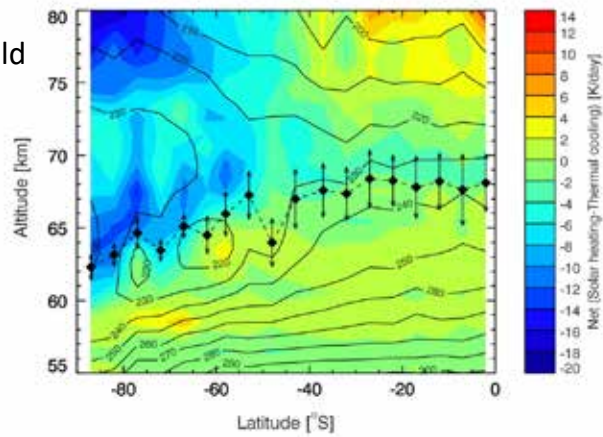
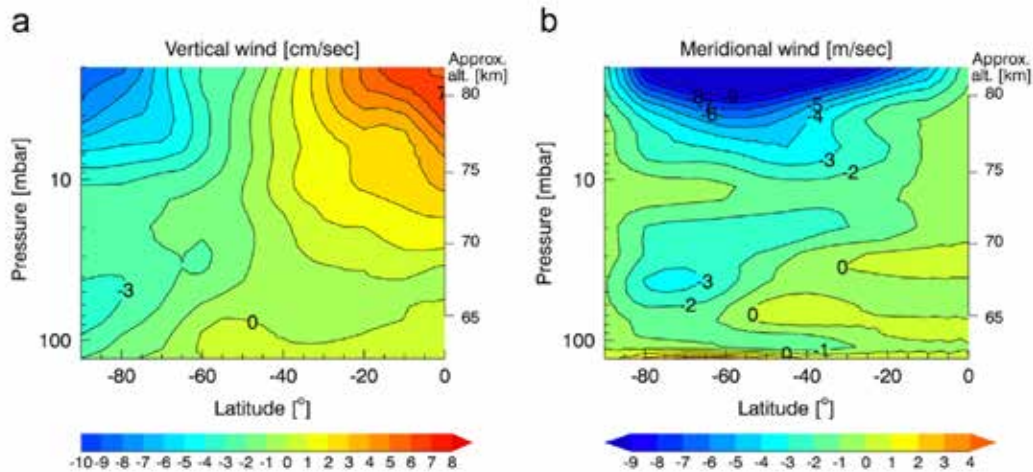
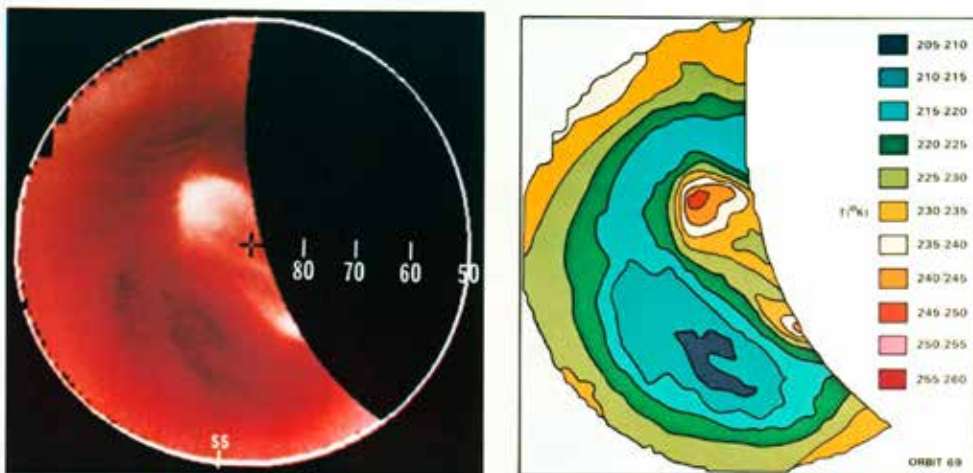


Fig. 14. Latitude-altitude field of the net radiative forcing in the Venus mesosphere. The temperature and cloud top structure are the same as in Figs. 9 and 13.



Hot polar dipole & cold collar at Venus's cloud top

Pioneer Venus thermal infrared mapping of the North polar region (Taylor et al. 1980)



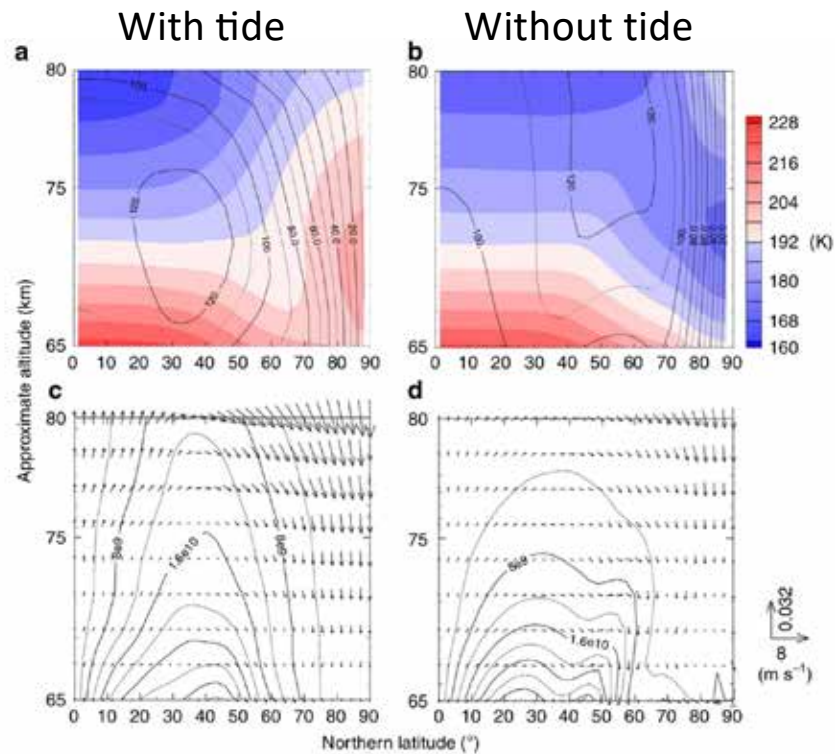
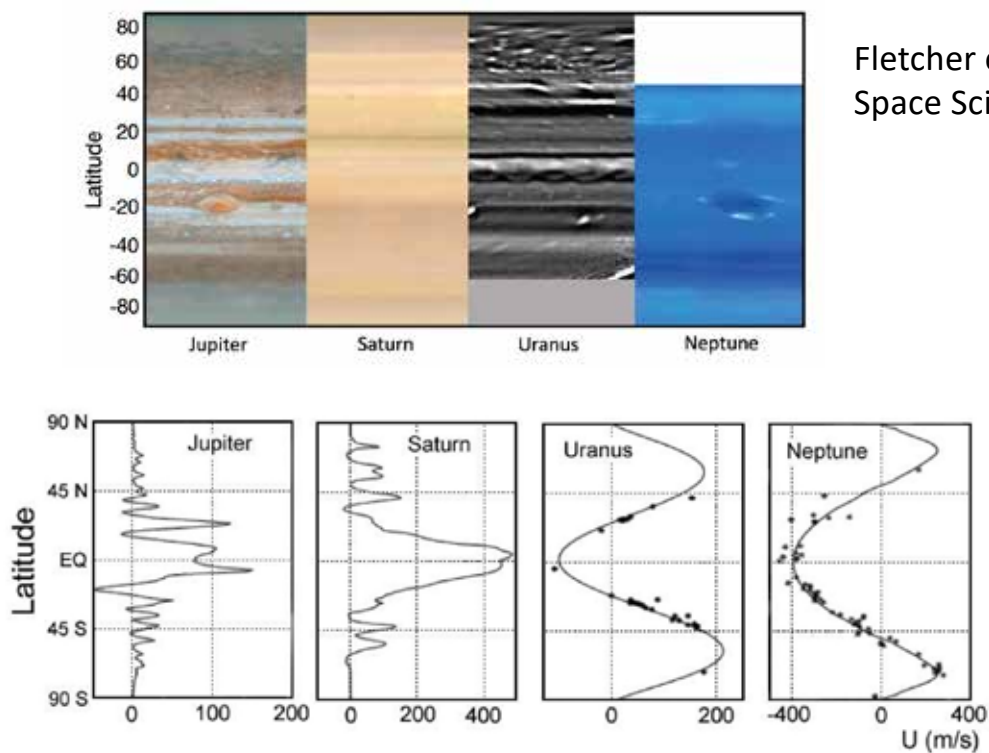


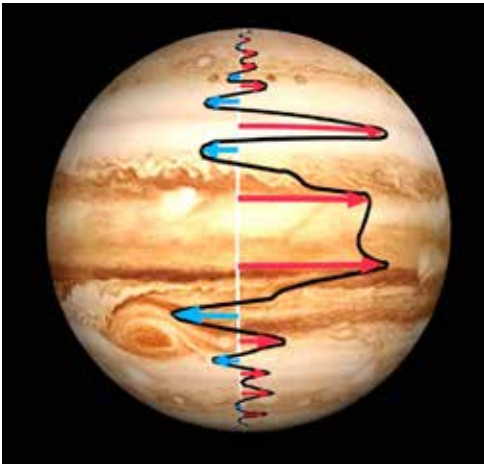
Figure 6 | Meridional cross-sections of the zonally and temporally averaged zonal wind (solid line) and temperature (colour shade) and the horizontal and vertical components of the residual mean meridional circulation (vector) and mass stream function (contour). (a) Zonal wind and temperature in Case A. (b) Those in Case B. (c) Residual mean meridional circulation vector and mass stream function in Case A. (d) Those in Case B. Averaged period is two Venusian solar days (234 Earth days) after settling into the quasi-steady state.

Belt/zone circulation of giant planet atmospheres



Fletcher et al. (2020,
Space Sci. Rev.)

Winds on Jupiter

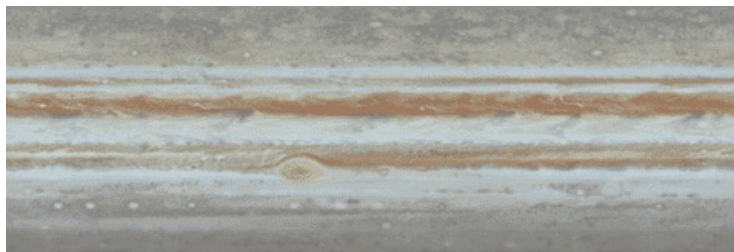


Zones :

- Reflective white bands of low temperatures, and elevated aerosol opacities
- Anti-cyclonic vorticity

Belts :

- Darker bands of warmer temperatures, and depleted aerosols
- Cyclonic vorticity

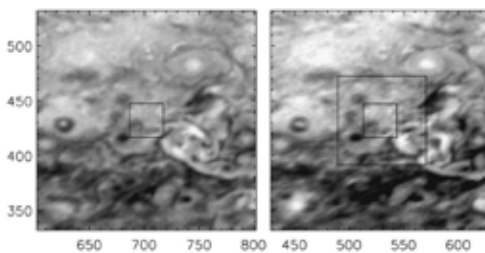


Cloud movie taken by Cassini spacecraft during its Jupiter flyby

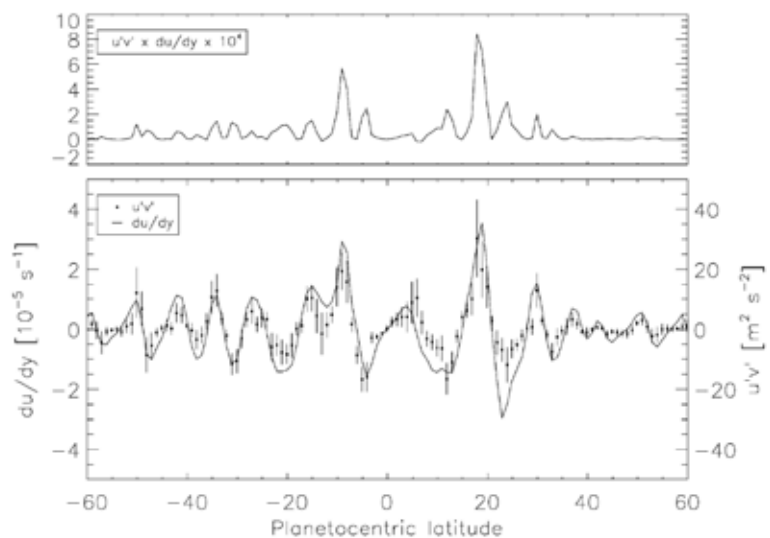
Eddy momentum transport on Jupiter

Salyk et al. (2006)

Analysis of Cassini imaging data

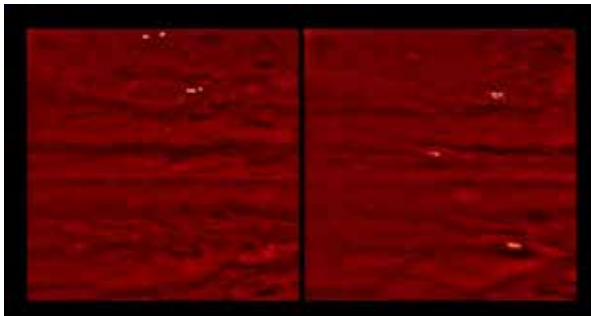


High positive correlation between eddy momentum flux, $\langle u'v' \rangle$, and the variation of zonal velocity with latitude, du/dy , was found.



Thunderstorms on Jupiter

Becker et al. (2020)



Lightning storms on the night side of Jupiter along with clouds dimly lit by moonlight from Io (taken by Galileo spacecraft)

On Jupiter, energy is transferred from the warm interior of the planet to the visible atmosphere to feed thunderstorms. Lightning occurs in the low-pressure regions.

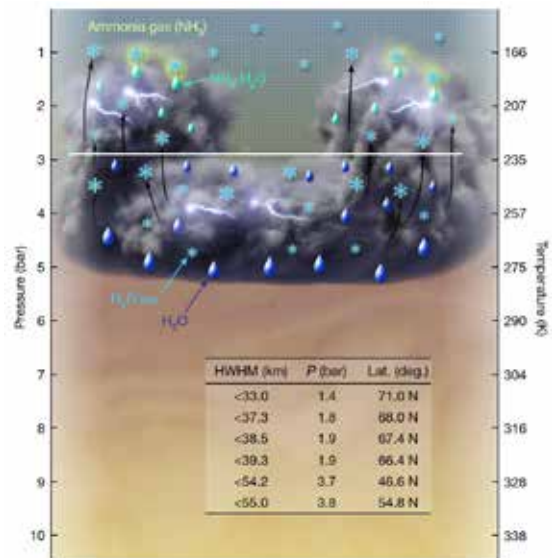
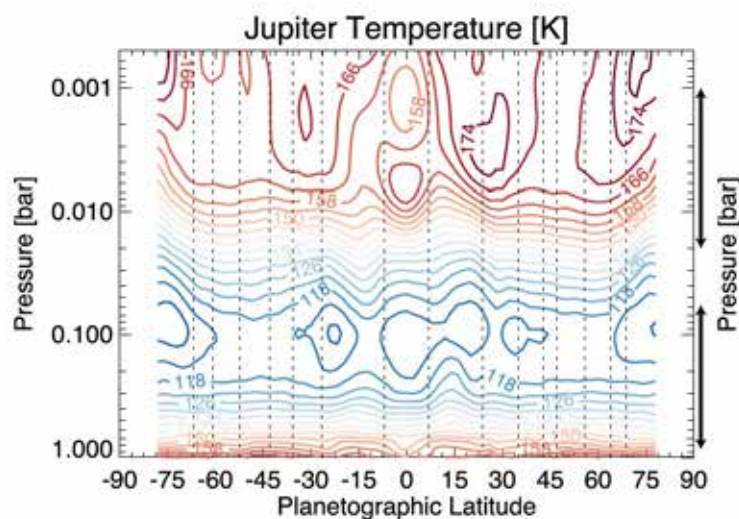


Fig. 3 Conceptual illustration of lightning generation above and below the 3-bar level in Jupiter's atmosphere. Energetic updrafts (black arrows) loft water-ice particles to altitudes between 1.1 and 1.5 bar, where adsorption of ammonia gas onto ice particles melts the ice, creating falling liquid ammonia-water ($\text{NH}_3\text{-H}_2\text{O}$) particles (green drops). Charge separation occurs as the $\text{NH}_3\text{-H}_2\text{O}$ particles collide with upward moving water-ice, followed by lightning. At pressures greater than about 3 bar, temperatures are above the limit for supercooled water (white line, about 233 K) and lightning is generated in pure water clouds. Inset, radial half-width at half-maximum (HWHM) intensity distances, estimated maximum depths of origin (P , pressure level) and latitudes (lat.) of observed SRU lightning flashes.

Temperature field above the clouds of Jupiter retrieved from infrared observations



Above clouds (upper-troposphere), the equatorward flanks of eastward jets (anticyclonic vorticity) are colder than the poleward flanks (cyclonic vorticity).

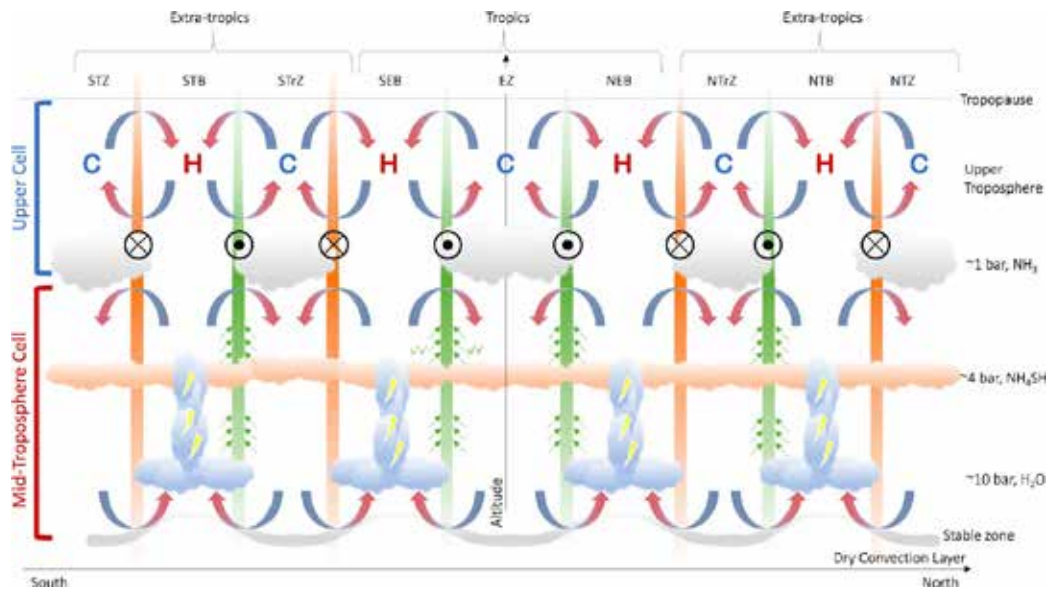
→ Thermal wind balance implies that the cloud-top winds decay with altitude.

$$\frac{\partial u_g}{\partial p} = \frac{R}{f p} \frac{\partial T}{\partial y}$$

Vertical dotted lines : Prograde jets

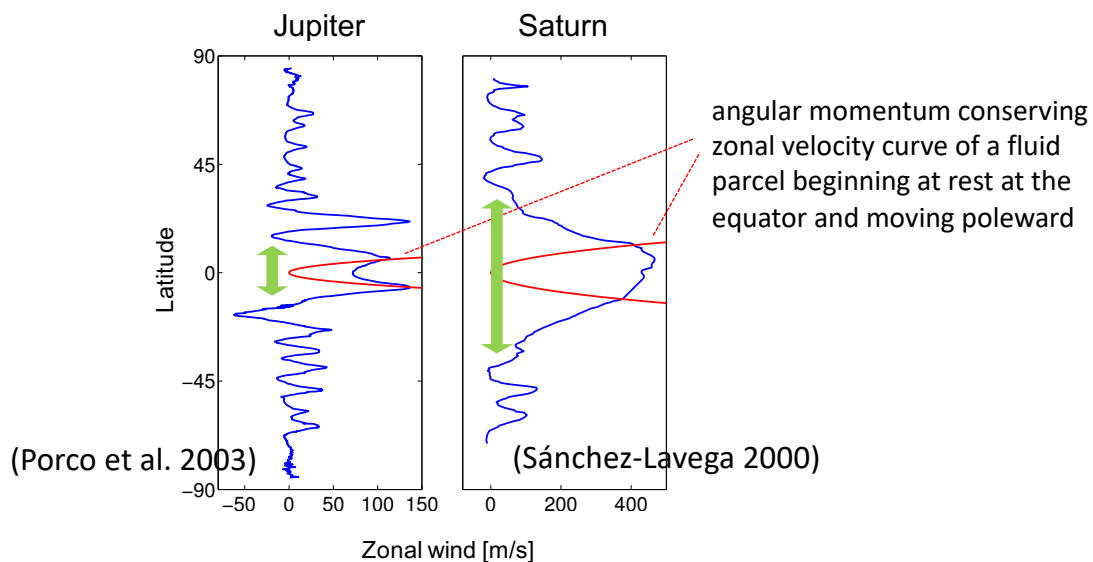
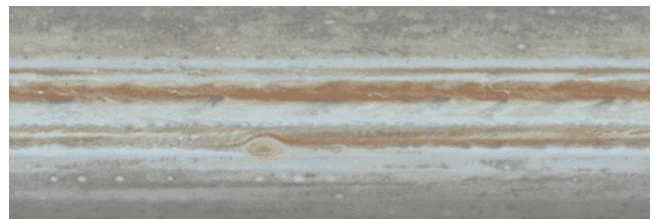
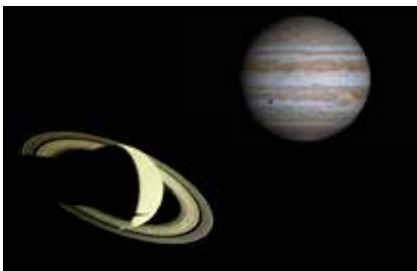
Fletcher et al. (2020, Space Sci. Rev.)

Upwelling in zones inferred from the upper tropospheric temperature structure, which implies decay and dissipation of the zonal jets with altitude above the clouds



Upwelling in belts inferred from the convergence of eddy angular momentum into the eastward zonal jets at the cloud level

Superrotation on the gas giants



Modeling Jupiter and Saturn's zonal flows

- Shallow models

- The dynamics are shallow, such as on a terrestrial planet
- The strong east-west flows can result from 2D geostrophic turbulence and/or baroclinic instability

- Deep models

- the observed jets are the surface manifestation of convective columns originating from the hot interiors

Two-dimensional turbulence

- Small eddies tend to organize large eddies as time passes
- Turbulent energy cascade toward large scales (smaller wavenumber k)

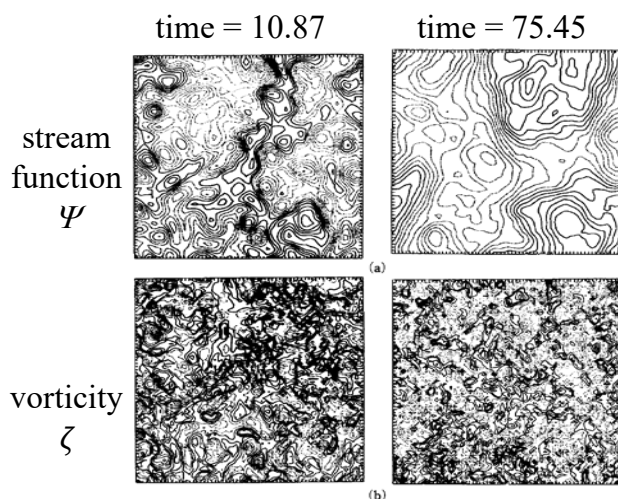
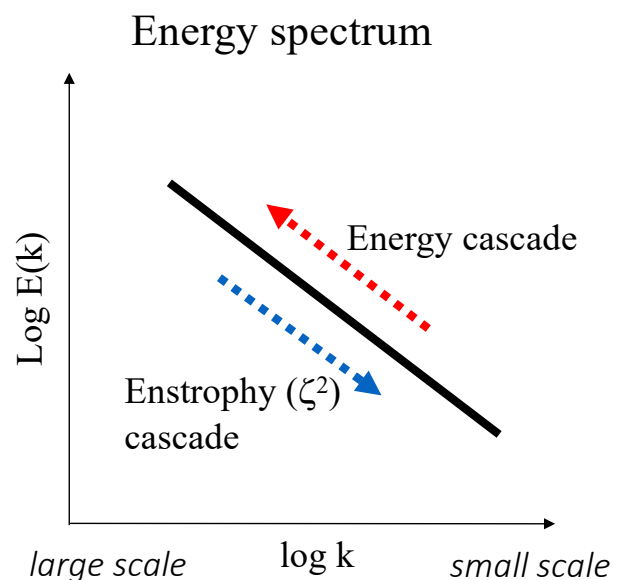


図 4.1 リリー (Lilly, 1969) の 2 次元乱流の数値実験の結果
左側の図が $t=10.87$, 右側の図が $t=75.45$ での結果。(a)は流線関数, (b)は
渦度の分布図。

Lilly (1969)



Rhines scale

- Vorticity equation

$$\left(\frac{\partial}{\partial t} + \vec{v}_g \cdot \nabla \right) (\xi_g + f) = 0$$

$$\frac{\partial \zeta}{\partial t} + u \frac{\partial \zeta}{\partial x} + v \frac{\partial \zeta}{\partial y} + \beta v = 0$$

nonlinear term
= origin of
turbulence

beta effect
= origin of
Rossby wave



$k^2 U^2 > \beta U$: turbulence
 $k^2 U^2 < \beta U$: Rossby wave

β : df/dy
 U : typical velocity

- Rhines scale

$$k_\beta = \sqrt{\frac{\beta}{U}}$$

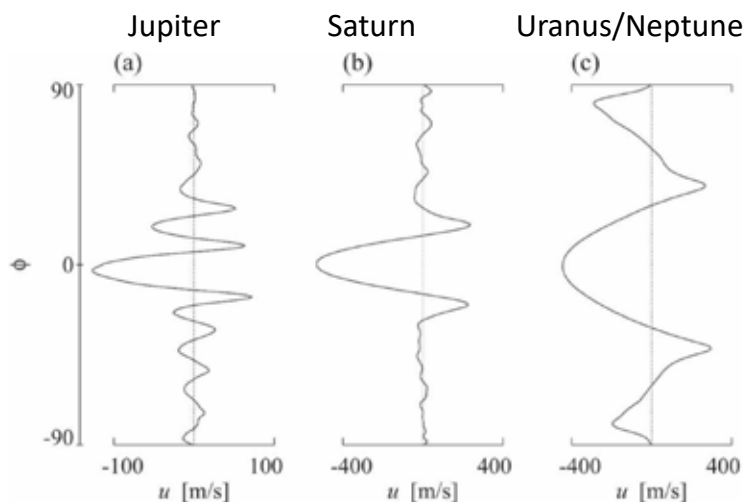
Upward cascade of turbulence energy stops at smaller scales ($k < k_\beta$)

Shallow-water turbulence on the sphere of the giant planets

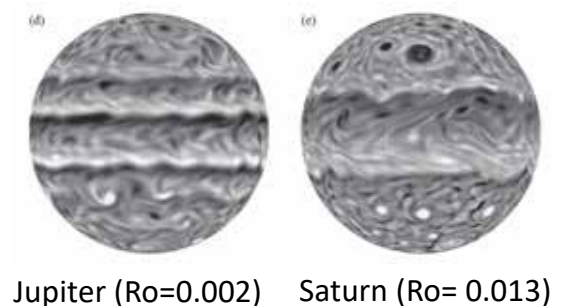
- Forcing are given to the vorticity field as a small-scale, random process, or eddies are generated by baroclinic instability
- Inverse energy cascade generates multiple jets on the order of the Rhines scale
- The simulated equatorial flow is mostly retrograde

Zonal velocity

Scott & Polvani (2007)

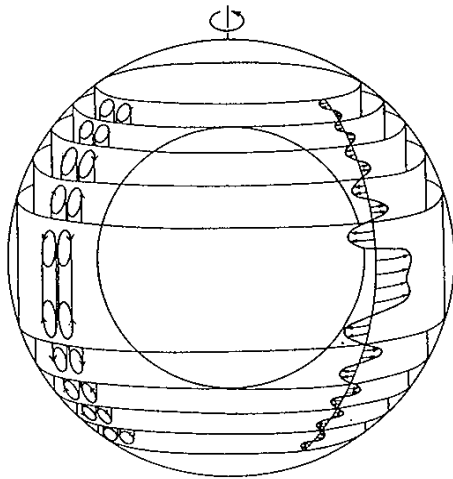


Vorticity field



Deep models: Taylor–Proudman theorem

- In a fluid that is steadily rotated, the fluid velocity will be uniform along any line parallel to the axis of rotation.



Busse (1994)

Momentum equation in rotational frame

$$\frac{d\vec{v}}{dt} + 2\vec{\Omega} \times \vec{v} + \frac{1}{\rho} \nabla p + \nabla \Phi = 0$$

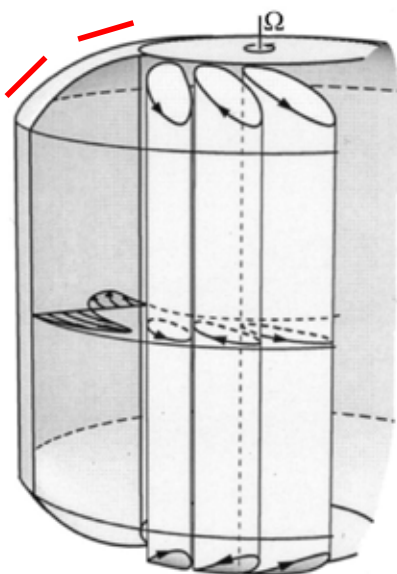
Assuming non-compressivity and $d/dt=0$, the curl is applied to give

$$\vec{\Omega} \cdot \nabla \vec{v} = 0$$

Taking z-axis along the planet's rotational axis,

$$\frac{\partial \vec{v}}{\partial z} = 0$$

Thermal Rossby wave



Busse (2002)

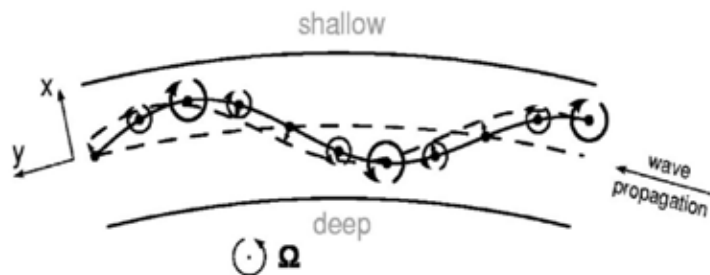


FIG. 2. The mechanism of propagation of a Rossby wave visualized in the equatorial plane of the rotating annulus: Fluid columns originally resting at the mid-surface acquire anticyclonic vorticity relative to the rotating system when they are displaced outwards towards the shallow region. Cyclonic vorticity is acquired by the displaced columns inwards. The action of the columnar motion on the neighboring fluid columns is such that an initial sinusoidal displacement propagates in the prograde direction.

The columns are tilted because the thermal Rossby wave has the tendency to propagate faster on the outside than on the inside. A prograde differential rotation on the outside with a retrograde one near the inner cylinder must thus be expected.

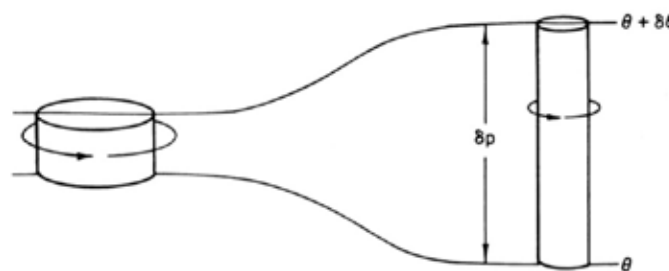
Quasi-geostrophic vorticity equation

$$\frac{\partial \xi_g}{\partial t} = -\vec{v}_g \cdot \nabla(\xi_g + f) + f_0 \frac{\partial \omega}{\partial p}$$

$$\xi_g \equiv \frac{\partial v_g}{\partial x} - \frac{\partial u_g}{\partial y} = \frac{\nabla^2 \Phi'}{f_0} \quad : \text{geostrophic vorticity}$$

Vorticity changes with time through

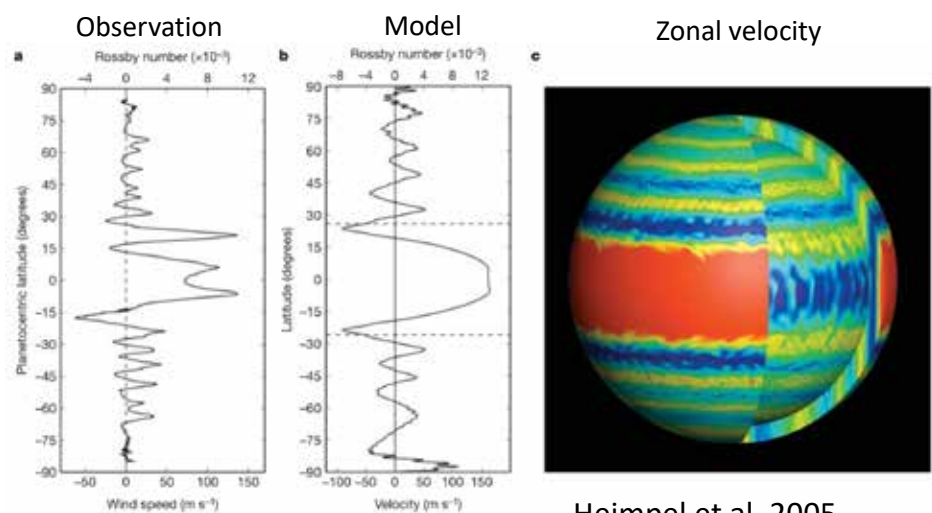
- advection of absolute vorticity ($\xi_g + f$) by geostrophic wind (\vec{v}_g)
- vertical divergence (horizontal divergence)



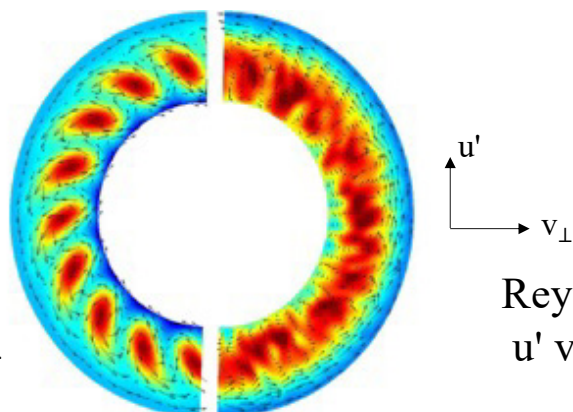
Holton (2004)

Fig. 4.7 A cylindrical column of air moving adiabatically, conserving potential vorticity.

Deep models



Heimpel et al. 2005



Reynolds stresses
 $u' v_{\perp}' > 0$

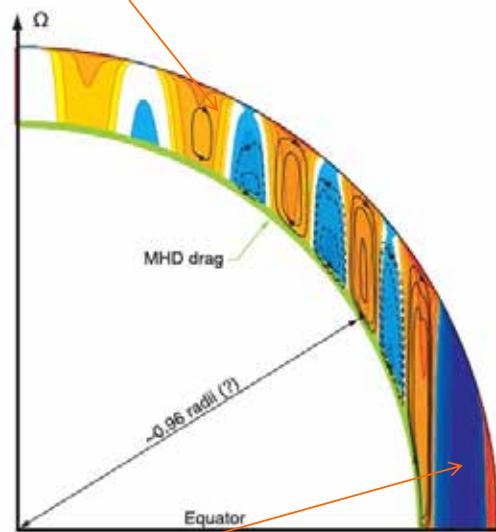
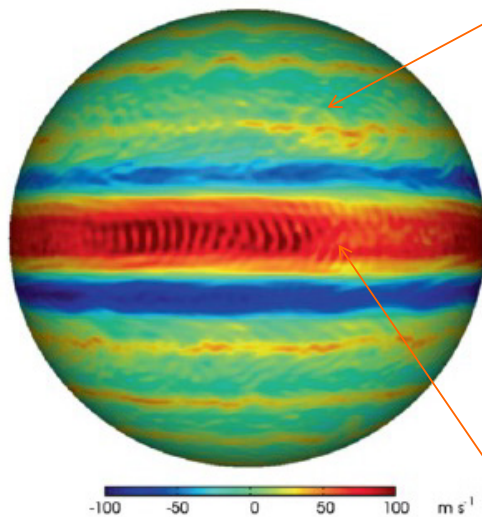
Showman et al. 2011

Modeling of Jupiter

Schneider & Liu, 2009

baroclinic eddies generated by differential radiative heating are responsible for Jupiter's off-equatorial jets

zonal velocity

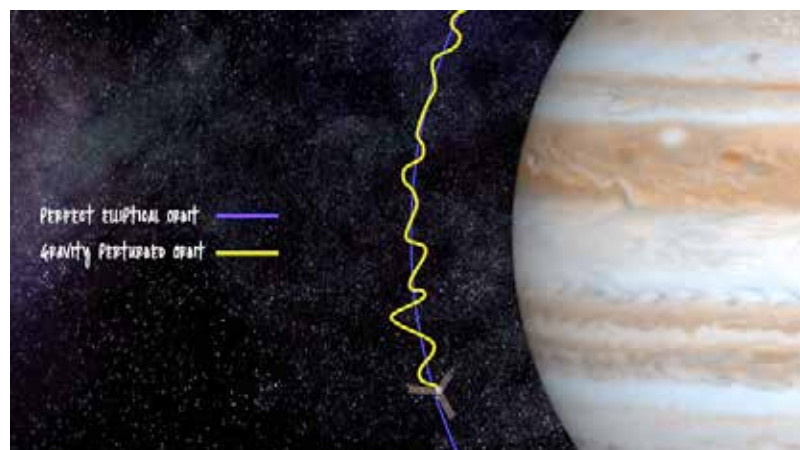


Rossby waves generated by intrinsic convective heat fluxes are responsible for the equatorial superrotation

Doppler tracking of Juno spacecraft

Less et al. (2018)

- The spacecraft acts as a test particle falling in the gravity field of the planet. Jupiter's gravity is inferred from range-rate measurements between a ground antenna and the spacecraft during perijove passes.
- The ground station transmits carrier signals, and the on-board translator lock the incoming carrier signals and retransmit them back to the ground. The range-rate (Doppler) observable is obtained by comparing the transmitted and received frequencies.
- Spherical harmonics representation of planetary gravity fields is determined by the density distribution inside the body.



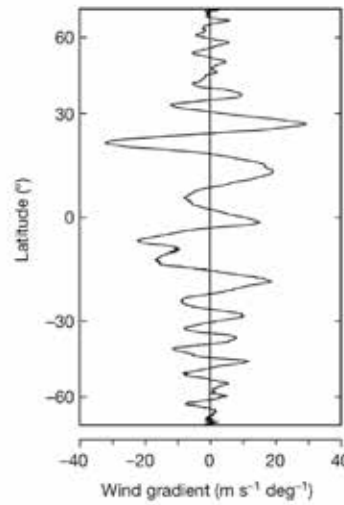
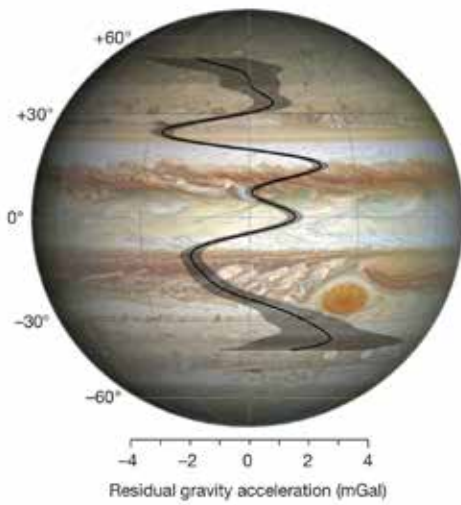
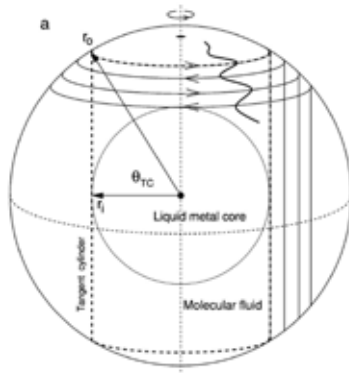


Figure 3 | Gravity disturbances due to atmospheric dynamics. **a**, An image of Jupiter taken by the Hubble Wide Field Camera in 2014 (<https://en.wikipedia.org/wiki/Jupiter>), showing the latitudinal dependence of residual gravity acceleration (in milligals, positive outwards) and associated 3σ uncertainty (shaded area) at a reference distance of 71,492 km, when the gravity from the even zonal harmonics J_2 , J_4 , J_6 and J_8 is removed. The residual gravity field, which is dominated by the dynamics of the flows, shows marked peaks correlated with the band structure. **b**, Latitudinal gradient of the measured wind profile. The largest (negative) peak of -3.4 ± 0.4 mGal (3σ) is found at a latitude of 24° N, where the latitudinal gradient of the wind speed reaches its largest value. The relation between the gravity disturbances and wind gradients is discussed in an accompanying paper⁴.

Less et al. (2018)



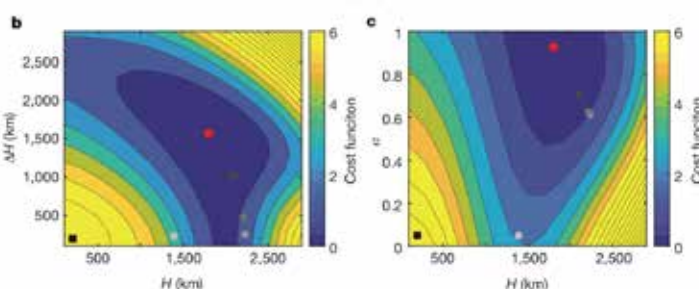
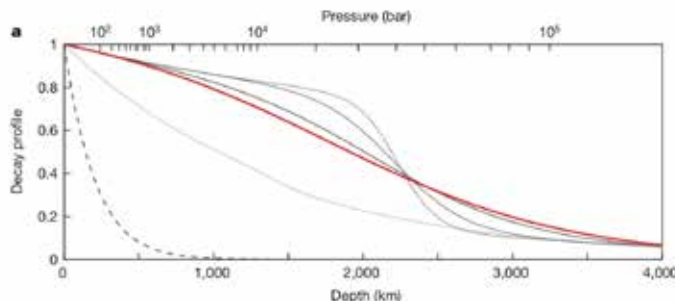
$$u(r, \theta) = u_{\text{cyl}}(s) Q(r) \quad (12)$$

where $u_{\text{cyl}}(s)$ is the cloud-level azimuthal wind projected downward along the direction of the axis of rotation, and $s = r \cos(\theta)$ is the distance from the axis of rotation. $Q(r)$ is the radial decay function we optimize, given by

$$Q(r) = (1 - \alpha) \exp\left(\frac{r - a}{H(\theta)}\right) + \alpha \frac{\tanh\left(\frac{-a - H(\theta) - r}{\Delta H}\right) + 1}{\tanh\left(\frac{H(\theta)}{\Delta H}\right) + 1} \quad (13)$$

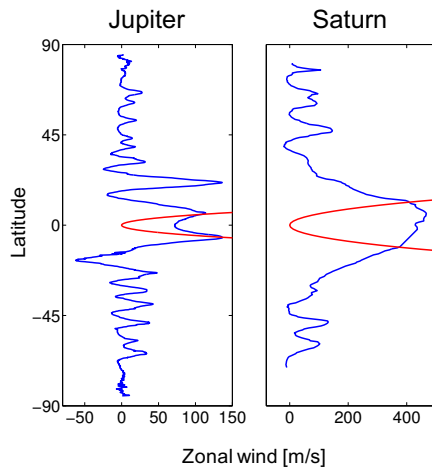
where a is the planetary radius, α is the contribution ratio between an exponential and a normalized hyperbolic tangent function and ΔH is the width of the hyperbolic tangent. We take a hierarchical approach using this profile at several levels of

Kaspi et al. (2018)

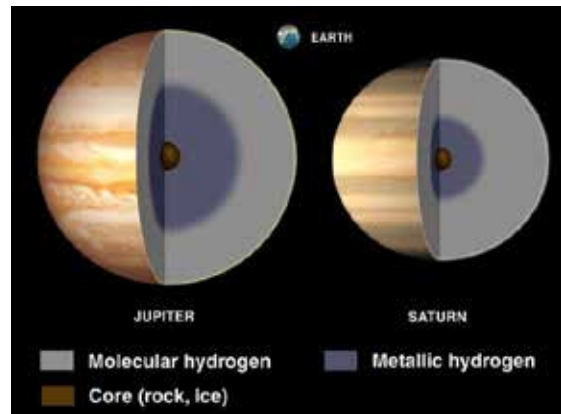


The observed jet streams, as they appear at the cloud level, extend down to depths of thousands of kilometres beneath the cloud level, probably to the region of magnetic dissipation at a depth of about 3,000 kilometres

Difference between Jupiter and Saturn



(Porco et al. 2003) (Sánchez-Lavega 2000)

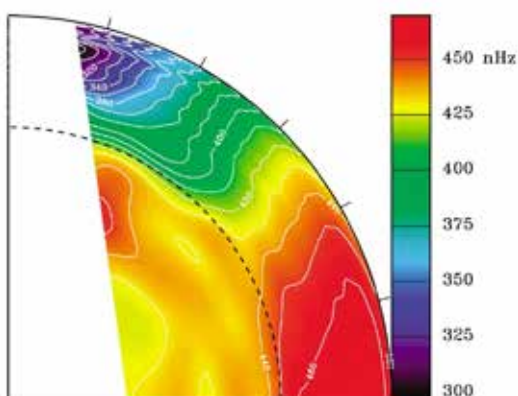


from Wikipedia

- JunoとCassini の重力計測によれば土星のジェットは木星に比べて3倍の深さまで及んでいる(木星: 3000 km vs. 土星: 9000 km). これは大気が導電性を持ちオーム抵抗が生じる深さに対応すると考えられる。
- 赤道スーパーローテーションの到達緯度は木星では 13° 、土星で 31° くらい。これは導電性が生じる深さから自転軸方向に伸ばした直線が表面と交わるあたりに相当する。

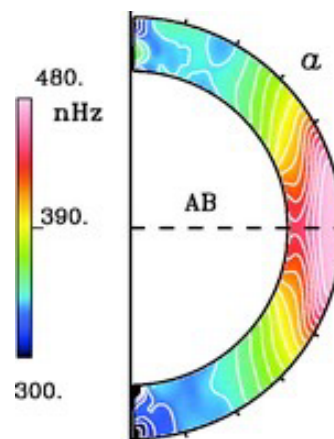
Equatorial superrotation in the Sun

Rotation rates revealed by helioseismology

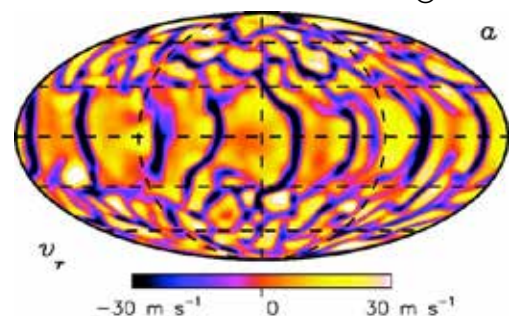


Rot. rate = 25 days on the equator
36 days near the poles

Numerical modeling (Miesch 2000)



Vertical velocity
at $r = 0.95 R_\odot$



Equatorward angular momentum transport by slant convection ?