Venus in context : exploring super-rotating atmospheric circulation regimes for slow (and fast) rotators

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Raymond Hide (1929-2016)

Plan

- What is super-rotation?
  - How to define and measure it
  - Why is it remarkable?
- Where is it observed?
- How might it work?
  - Axisymmetric circulations
  - Roles of waves and eddies?
- Trends and scalings: Studies using simple GCMs
  - Held-Suarez (constant forcing)
  - Semi-Gray 2-band radiation without/with diurnal cycles
- Slow rotators (Venus & Titan) in context?

50^{th} anniversary of Hide (1969) ["Hide's Theorem"]

What is Super-rotation?

- Follow Hide (1969) and define with respect to angular momentum
- In simple terms – Super-rotation is when air has more angular momentum than in solid body rotation with its underlying planet (NB not simply prograde rotation)
- Local super-rotation index. $s = \frac{m_{max}}{\Omega a^2} - 1$
- Global super-rotation index (mass-weighted). $S = \frac{\iint \rho m dA}{\iint \rho\Omega(a\cos\varphi)^2 dA} - 1$
  - Super-rotation => S or s_{max} > 0
  - For solid body rotation: S=s_{max} = 0 – represents a (weak!) “speed limit”

Hide's Theorem(s)

- Define specific (axial) angular momentum

$$m = (\Omega a \cos\varphi + u) a \cos\varphi$$

  - Where *a* = planetary radius; Ω = rotation rate, u = zonal velocity & ϕ = latitude

- In zonal mean:

$$\frac{\partial \overline{m}}{\partial t} + \nabla.(\overline{m}\overline{\boldsymbol{u}}^{*}) = \nabla.\boldsymbol{E} + F$$

mean advection | eddy stress | body forces/torque

[***E*** is ~Eliassen-Palm flux
u* is TEM meridional velocity]

- NB *m* materially and globally conserved in frictionless, axisymmetric flows (***E***, *F = 0*)

- HENCE
  - Equatorial local super-rotation is impossible in purely axisymmetric, inviscid flow
  - Local or global super-rotation must involve the existence of non-axisymmetric eddies

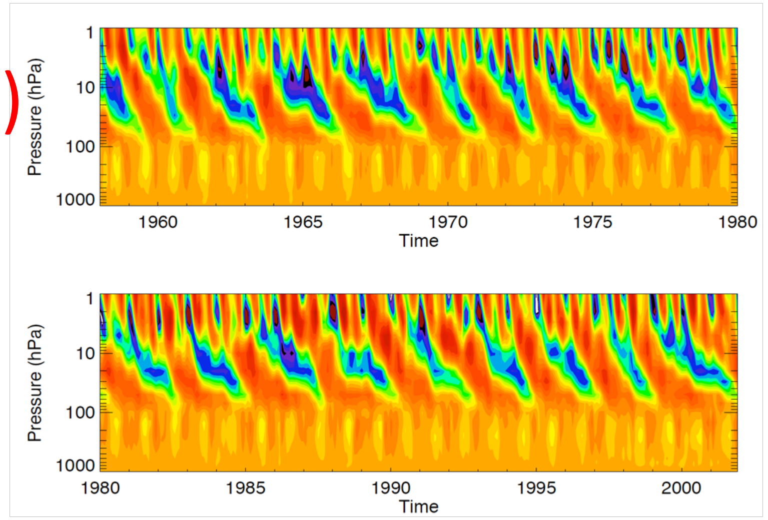
AND

  - Eddy angular momentum fluxes **E** must be able to transfer $\overline{m}$ up-gradient

Where is super-rotation observed?

Earth! (S ~ 0.01-0.02)

ERA-40 (Read & Castrejon-Pita 2012)

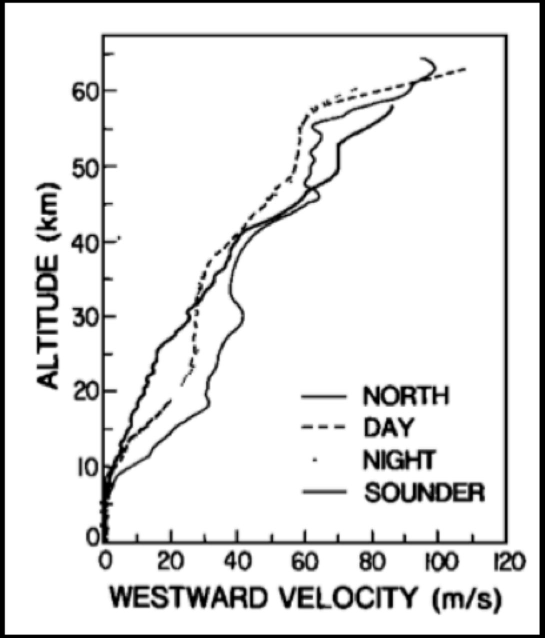


Venus (S ~ 7.7; s_{max} ~ 60:
see *Read & Lebonnois AREPS, 2018*)

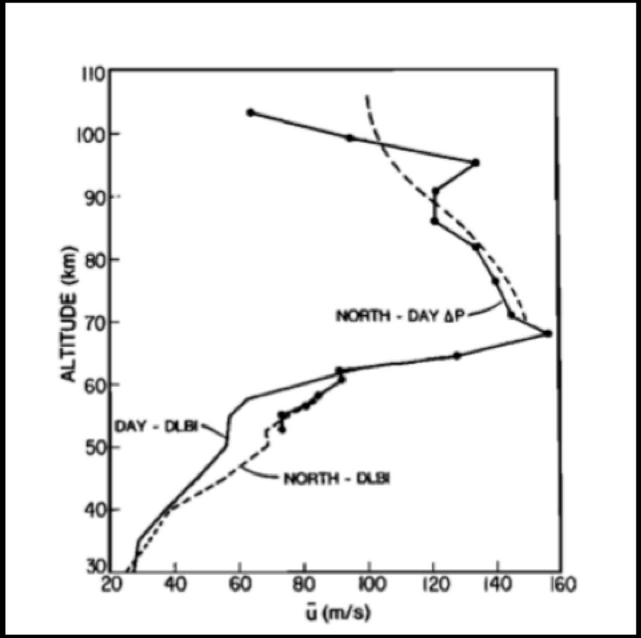
Titan (S ~ 2; s_{max} ~ 10)

Venus

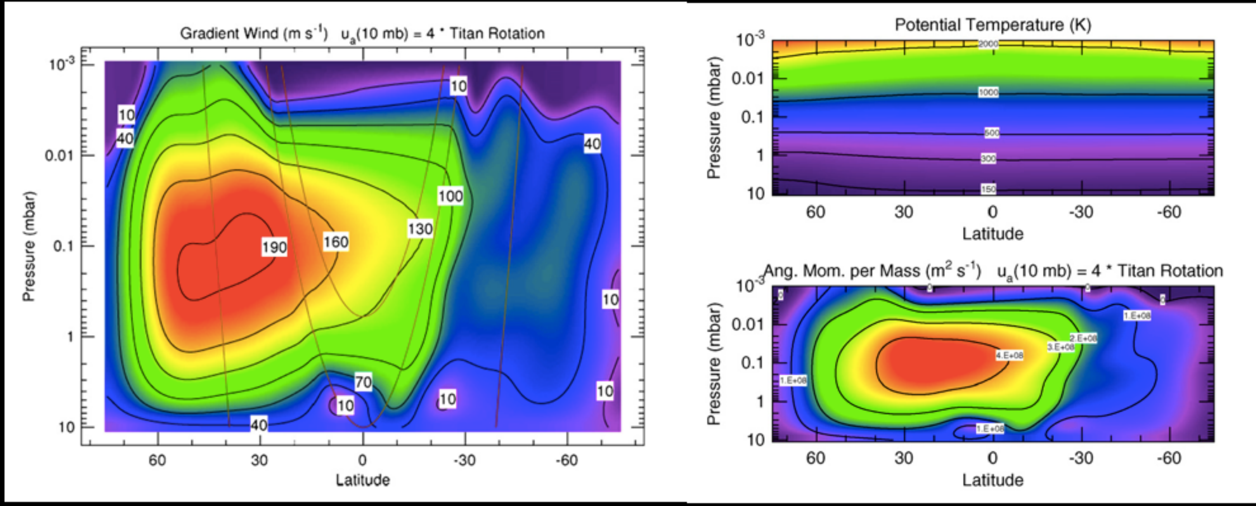
Lower atmosphere



Upper atmosphere

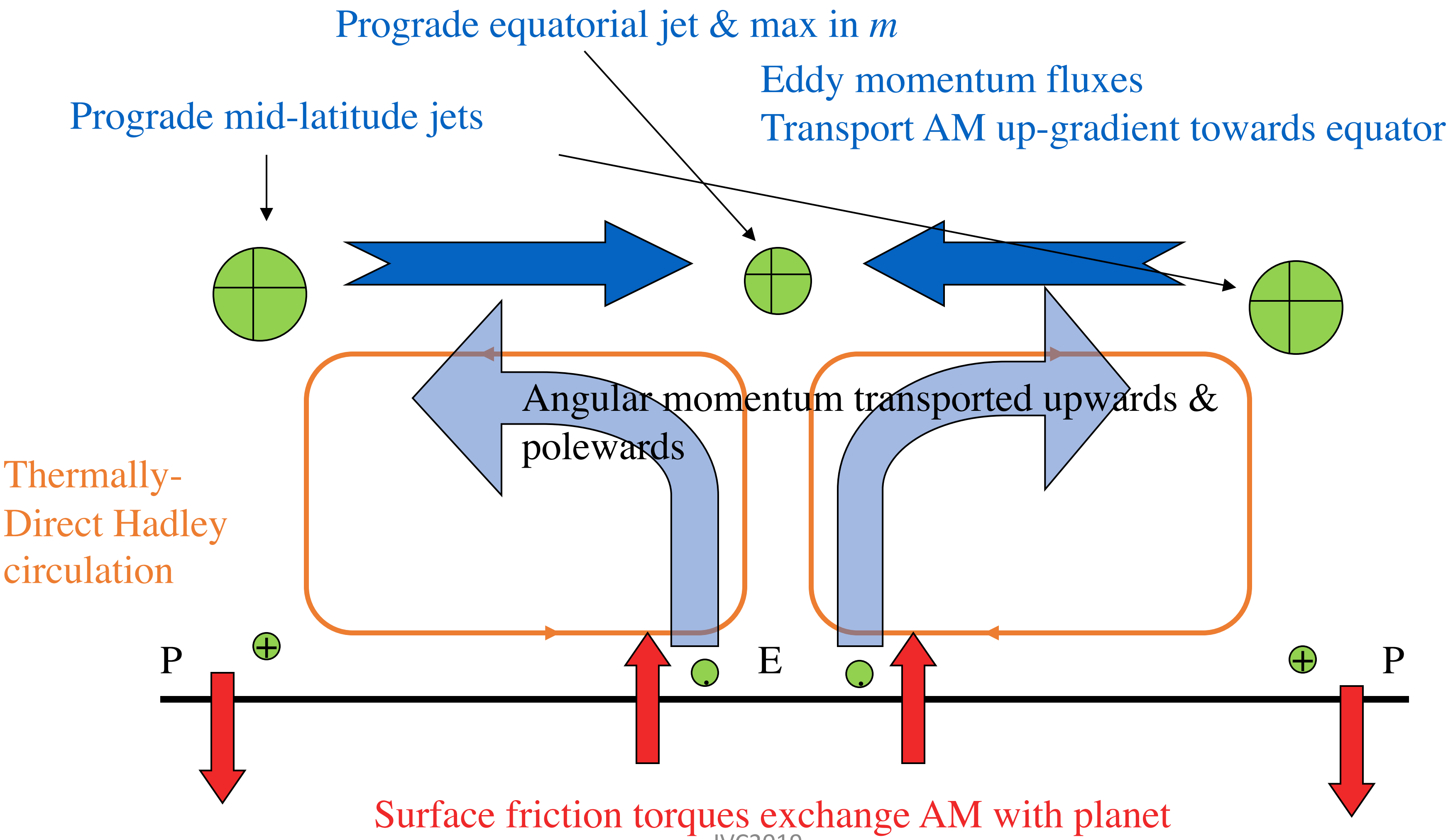


Titan



Achterberg et al. 08

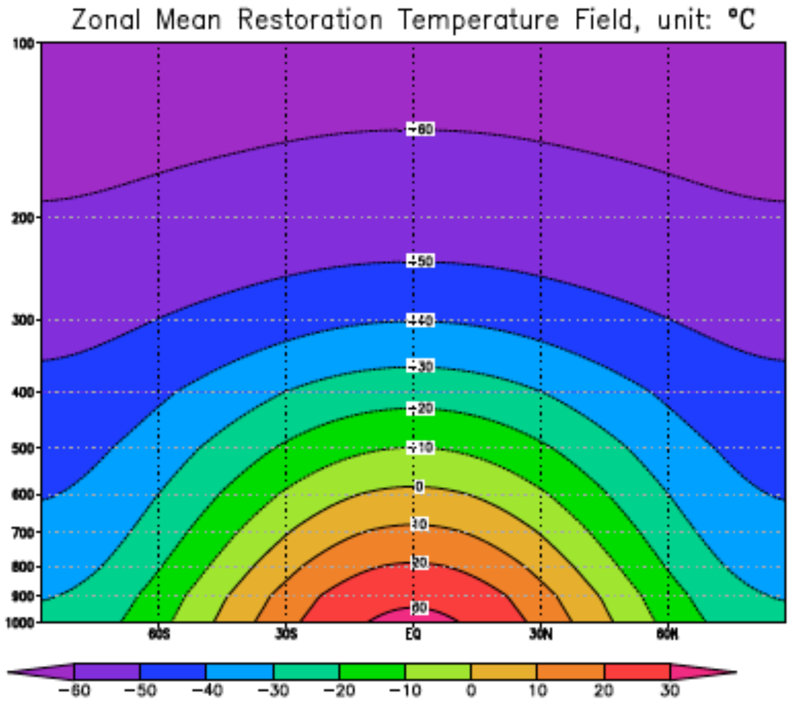
Super-rotation: Gierasch/Rossow-Williams conceptual model (1975 & 1979)



Exploring parameter space with simple [3D] climate models [PUMA and ISCA]

- Pseudo-spectral dynamical core
  - PUMA [Univ. of Hamburg]
  - ISCA [Univ. of Exeter]
- Spherical harmonics in horizontal, FD in vertical
- T21-T170 [7.5°x7.5° – 1°x1°], 10 levels [PUMA] or 30 levels [ISCA] **– see Neil Lewis Poster@!**
- Flat surface (no topography)
- Simple radiative forcing
  - Linear relaxation to specified $T_R(\phi,z)$ *OR*
  - Semi-gray radiative transfer [optical depths χ_s and χ_l]
- Linear drag at surface
  - Time constant τ_f
- Vary Ω - $\frac{1}{2048} \leq \Omega^* = \Omega/\Omega_E \leq 8$
  - Hence vary Ro_T and *Bu etc.*
- Run to equilibrium [~20 Earth yrs]

[Cf Earth in Perpetual equinox]



[Wang et al. 2018; Lewis 2019…]

Key planetary parameters defining circulation regimes?

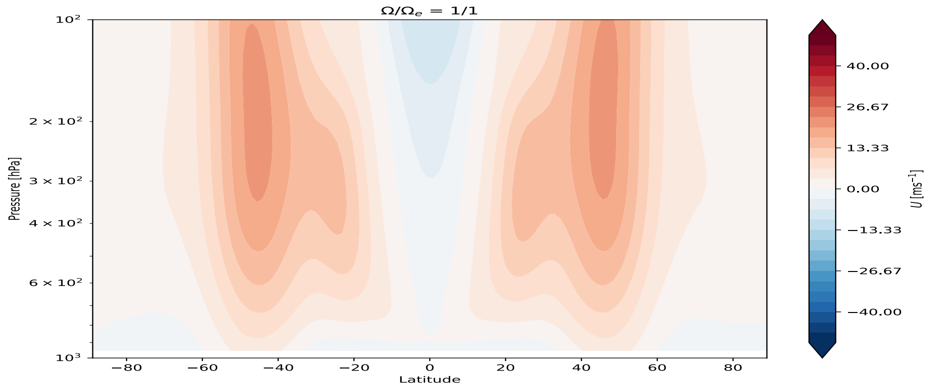
- Thermal Rossby [Hide] number *[-Ratio of forces]*
  - $Ro_T = \frac{U_T}{\Omega L} \approx \frac{gH\Delta_h\theta}{\theta_0\Omega^2 a^2} = \frac{R\Delta_h\theta}{\Omega^2 a^2}$
    - $H = \frac{RT}{g}$; atmospheric scale height
- Burger number *[-Ratio of length scales]*
  - $Bu = \frac{R\Delta_v\theta}{4\Omega^2 a^2} = \frac{L_d^2}{a^2}$
    - $L_d = \frac{NH}{f}$; Rossby deformation radius OR
    - $L_d = \left(\frac{NH}{\beta}\right)^{1/2}$; Equatorial deformation radius…? [slow rotators?]

Zonal wind fields (Isca)

- Earth-sized planet
- Held-Suarez relaxation forcing
- p_S = 1 bar

Ω_*

1



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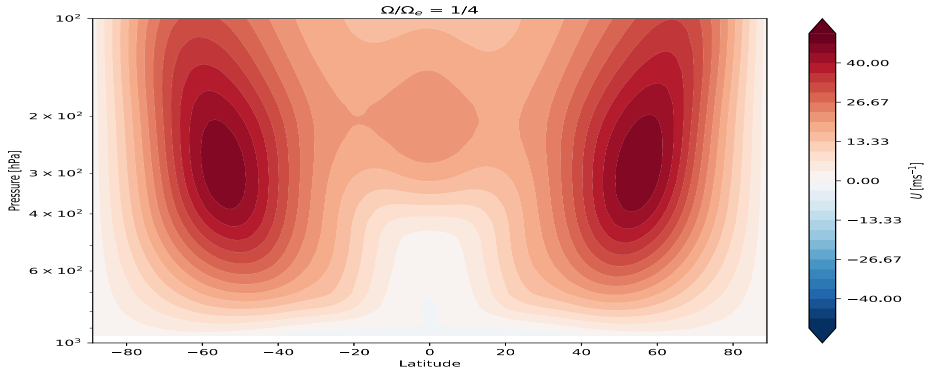

Ω_*

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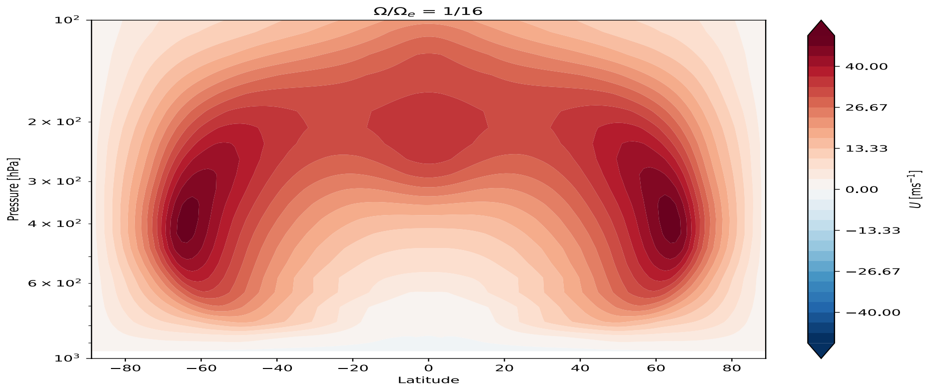

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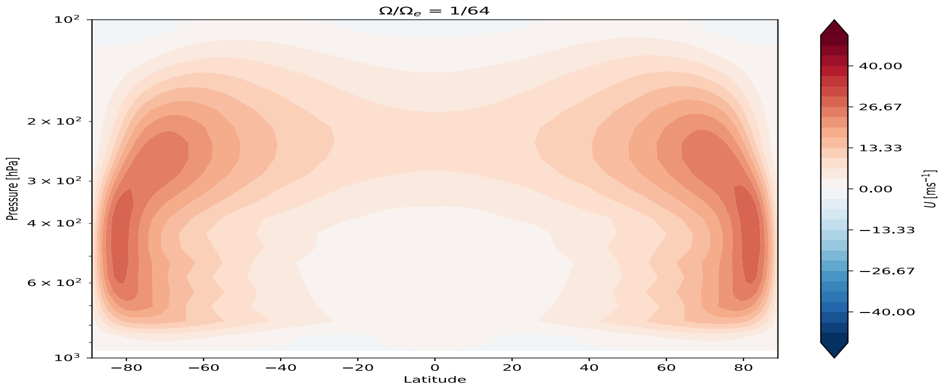

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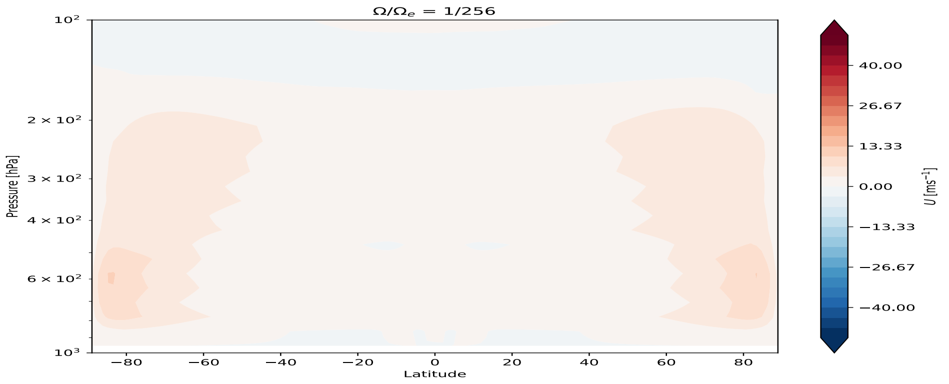
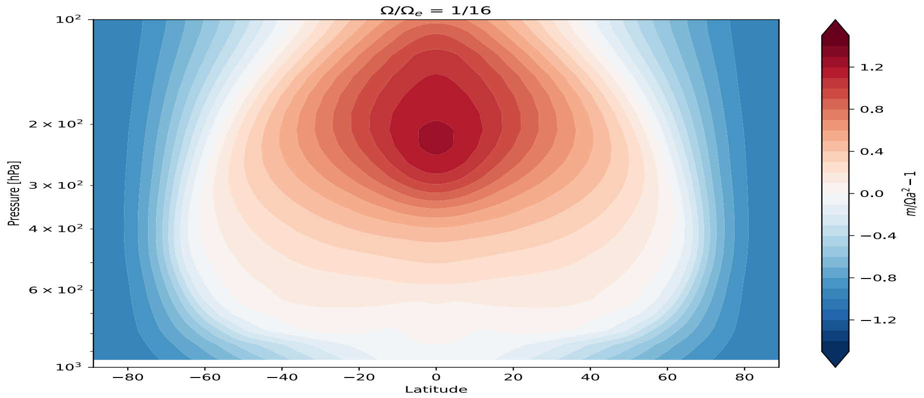


Local super-rotation fields s_{local} (Isca)



Ω_*

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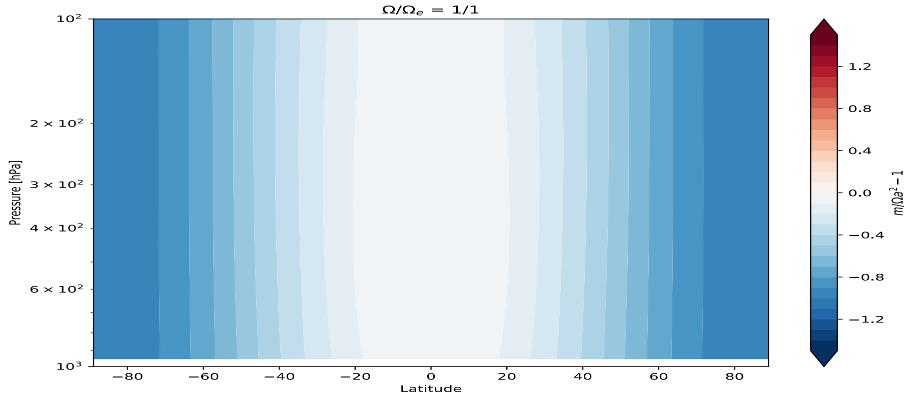
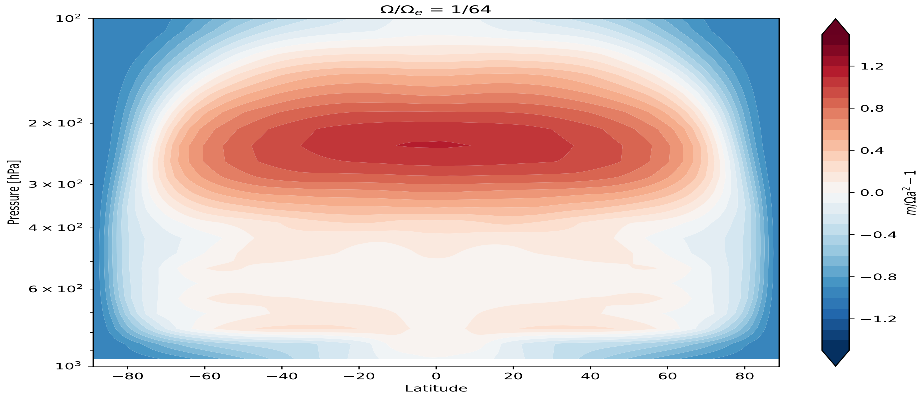
Ω_*

1





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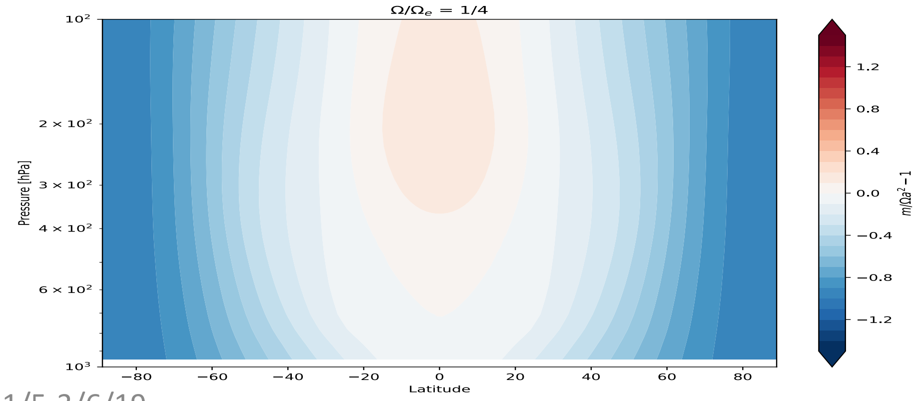

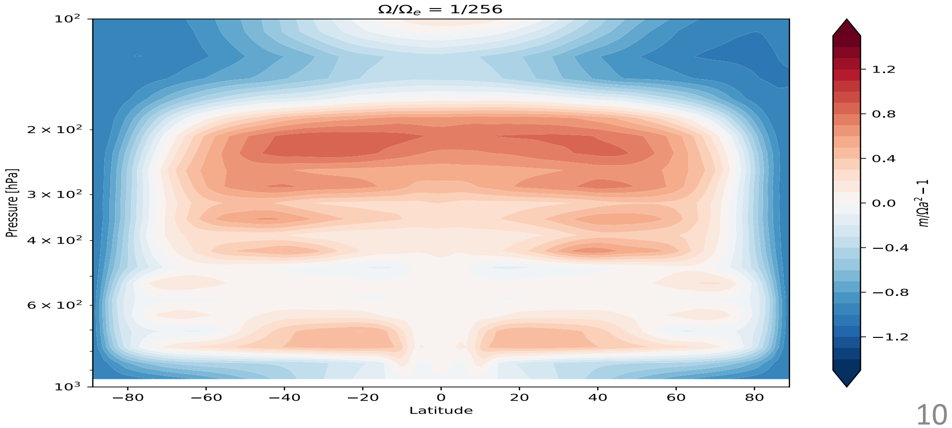

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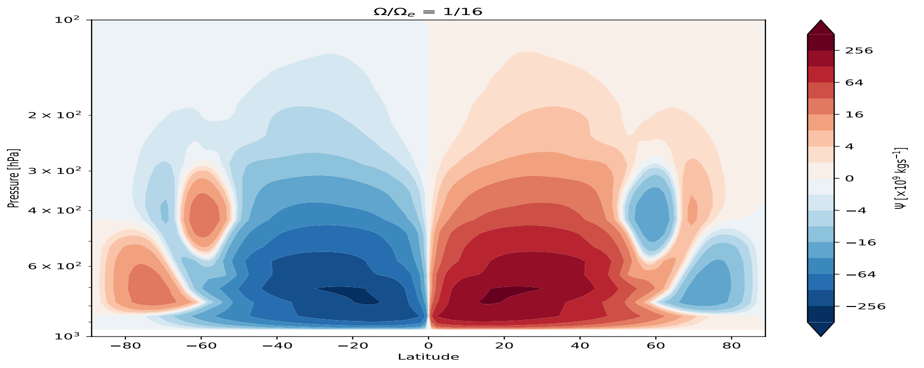
Mean meridional mass streamfunction (Isca)



Ω_*

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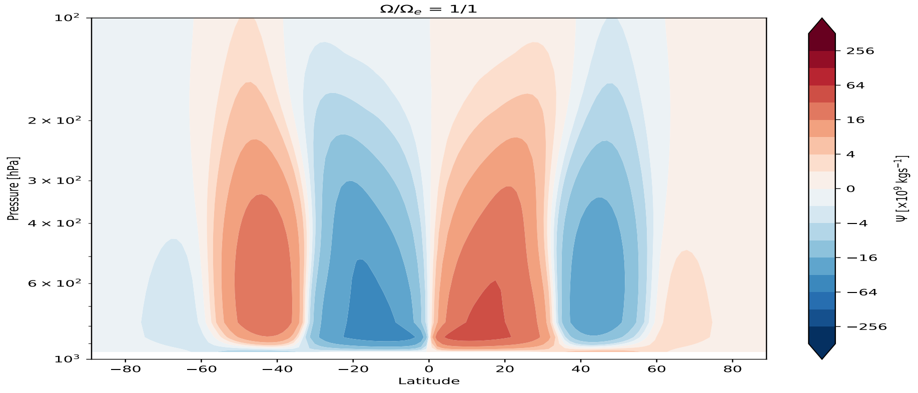
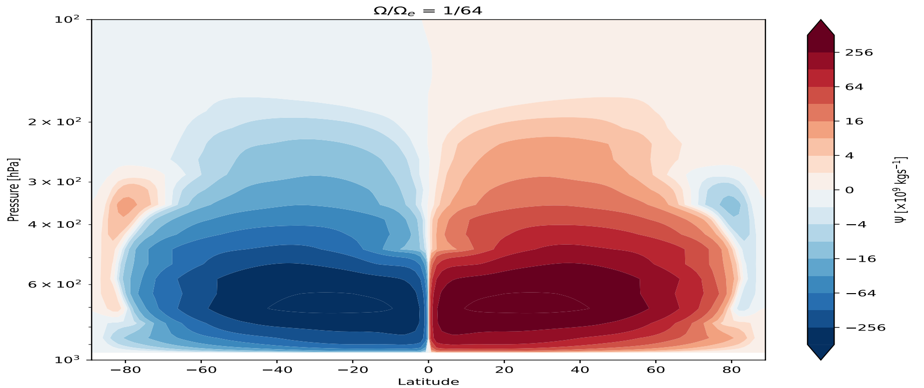
Ω_*

1





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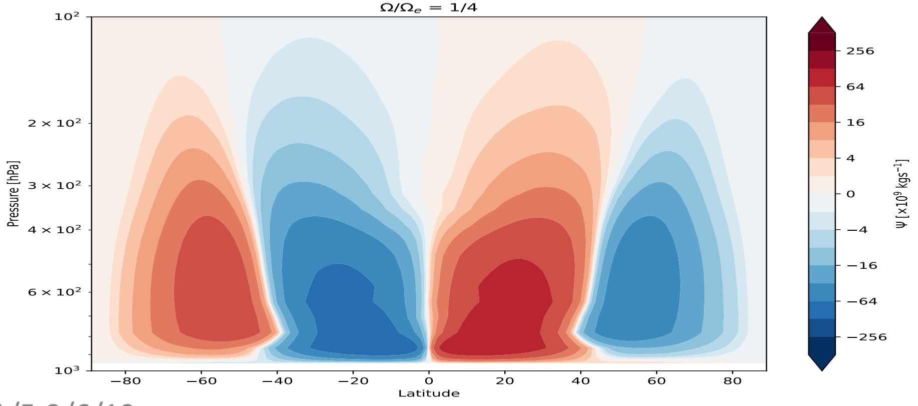

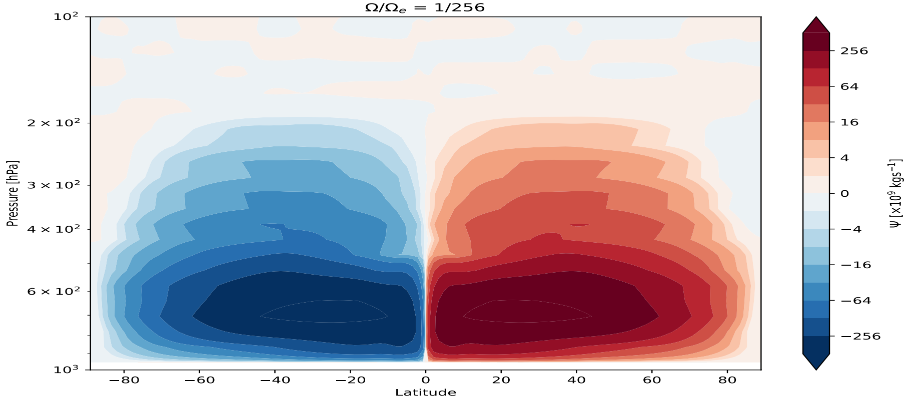

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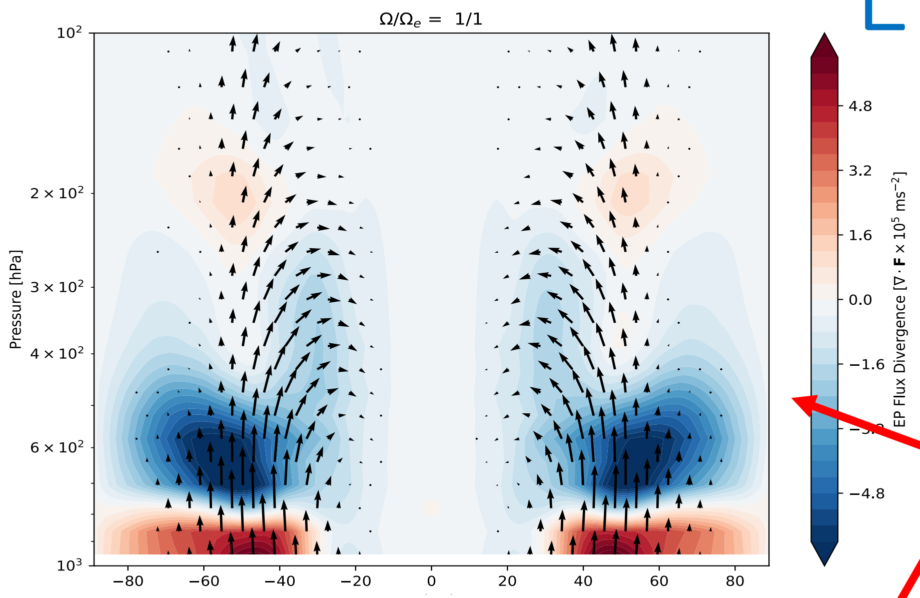
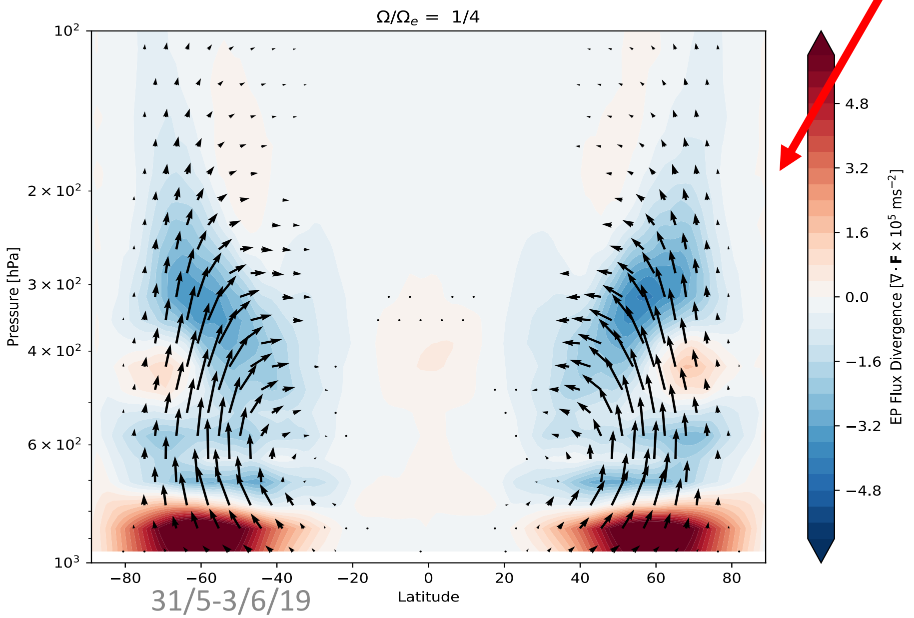
EP Fluxes(Isca)

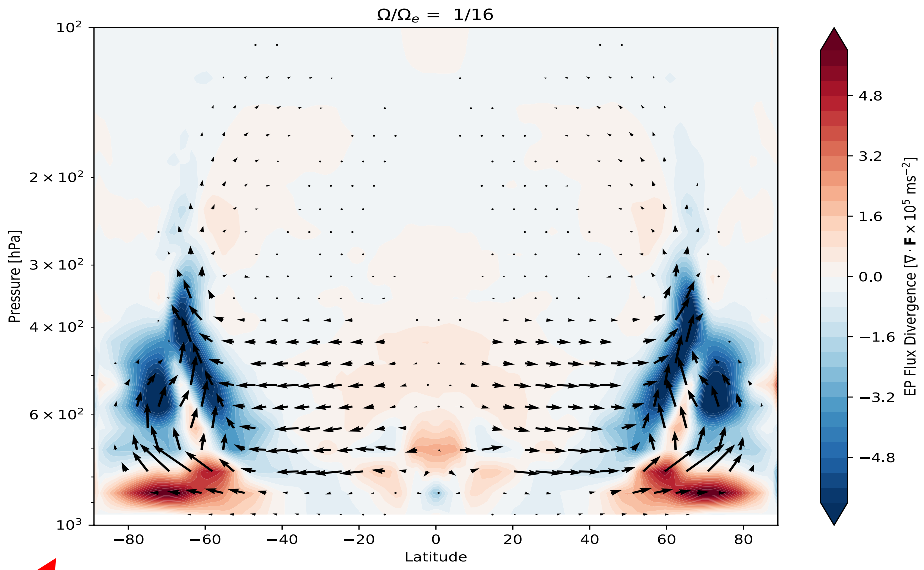


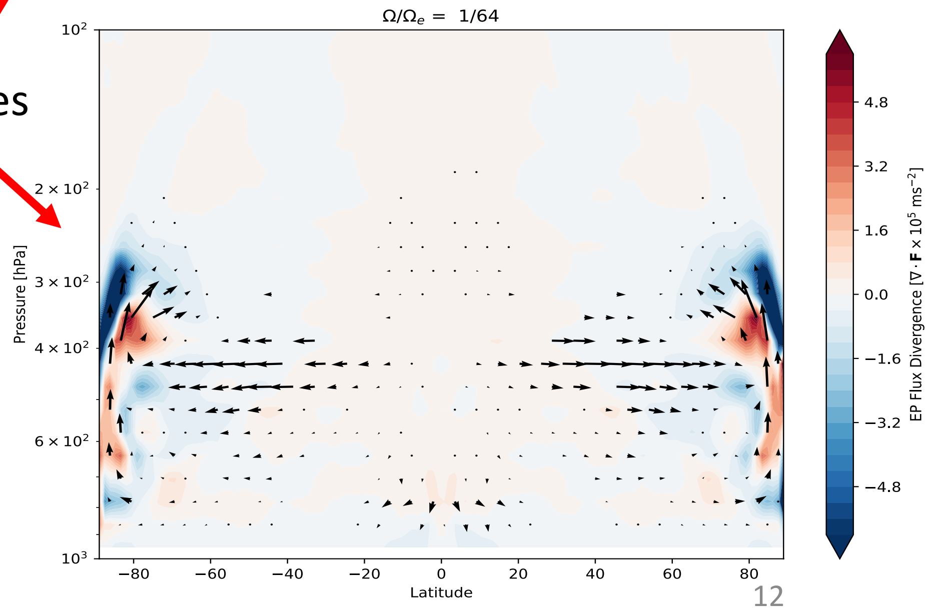


Ω_*	Ω_*
1	1/16
1/4	1/64

Dominated by Baroclinic (Rossby) waves at mid-latitudes

Dominated by Equatorial Kelvin/Rossby waves





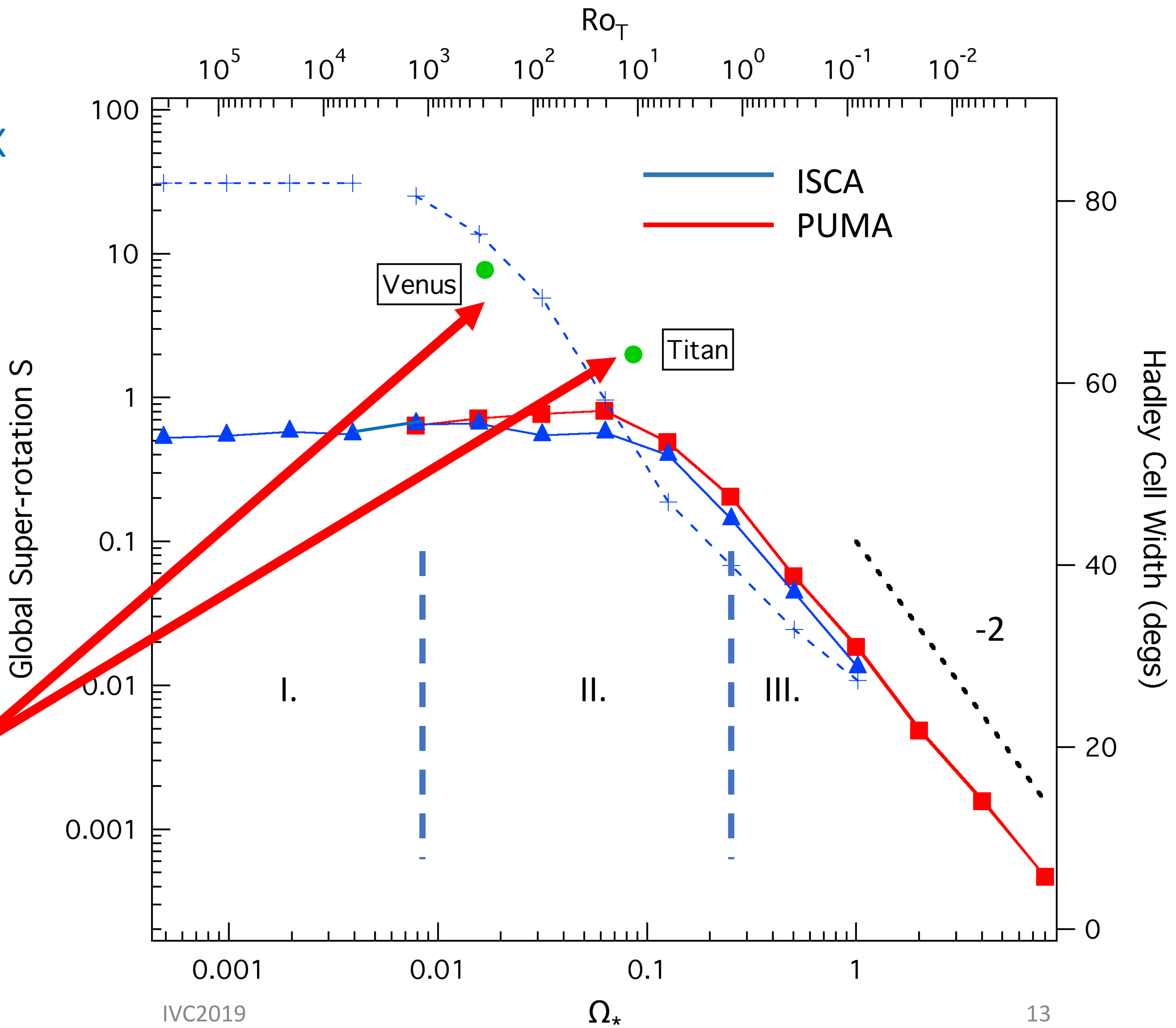
Trends in S and s_{max}

- 3 basic regimes
  - I. V. Slow rotation (angular momentum conserving outside PBL; Hadley cell width & Rossby radii > planetary radius a):

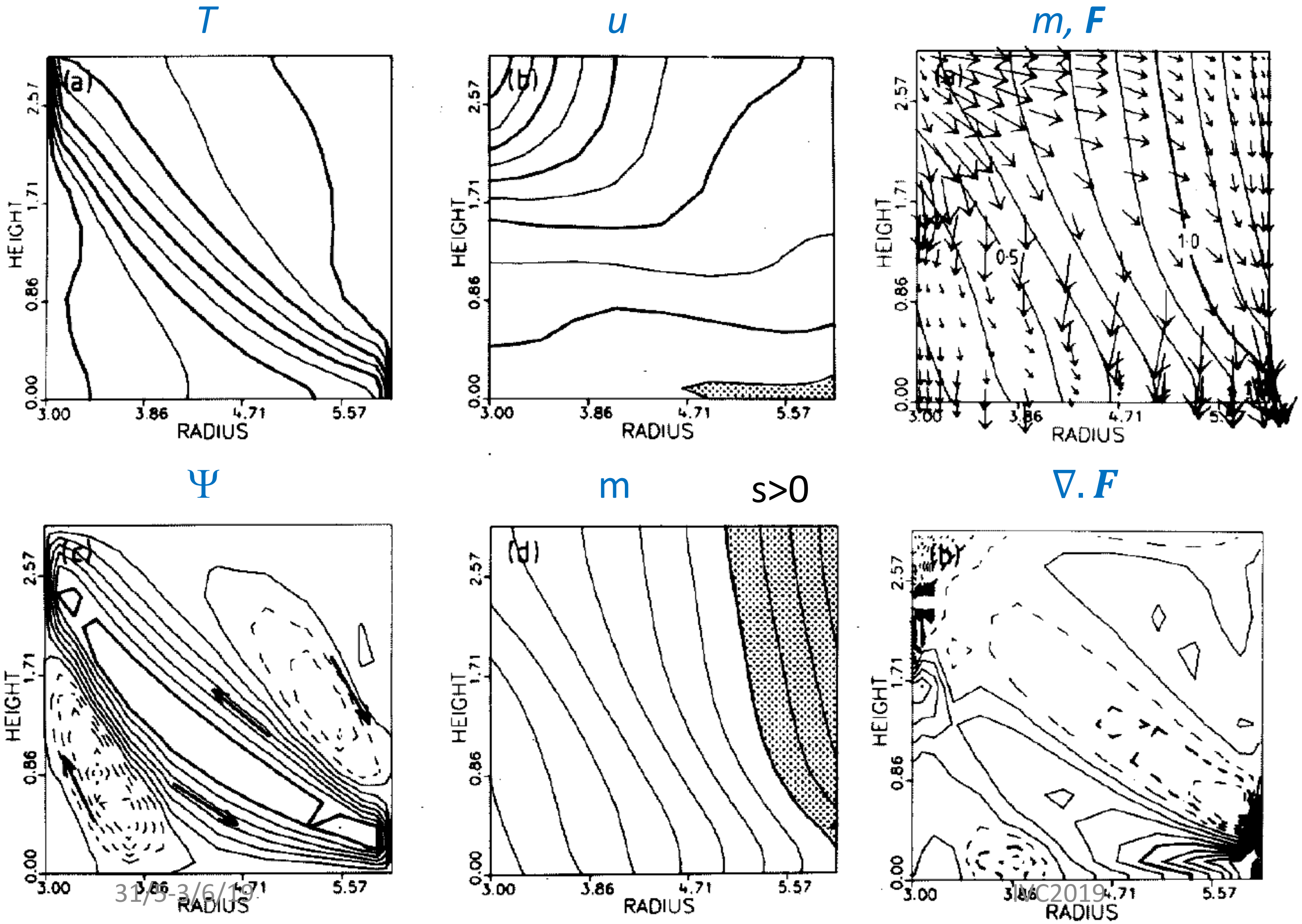
    S ~ constant O(1)
  - II. Moderate rotation (expanding Hadley cell; cyclostrophic u):

    S rises to shallow peak
  - III. Rapid rotation (quasi-geostrophic):

    $S \sim Ro_T^{-1} \sim \Omega^{-2}$
- NB underestimates S for both Venus (~8) and Titan (~2)
- $s_{max} \geq S$ for regimes I.& II. and $\leq$ S for regime III.
  - $S \ll s_{max}$ for Venus & Titan



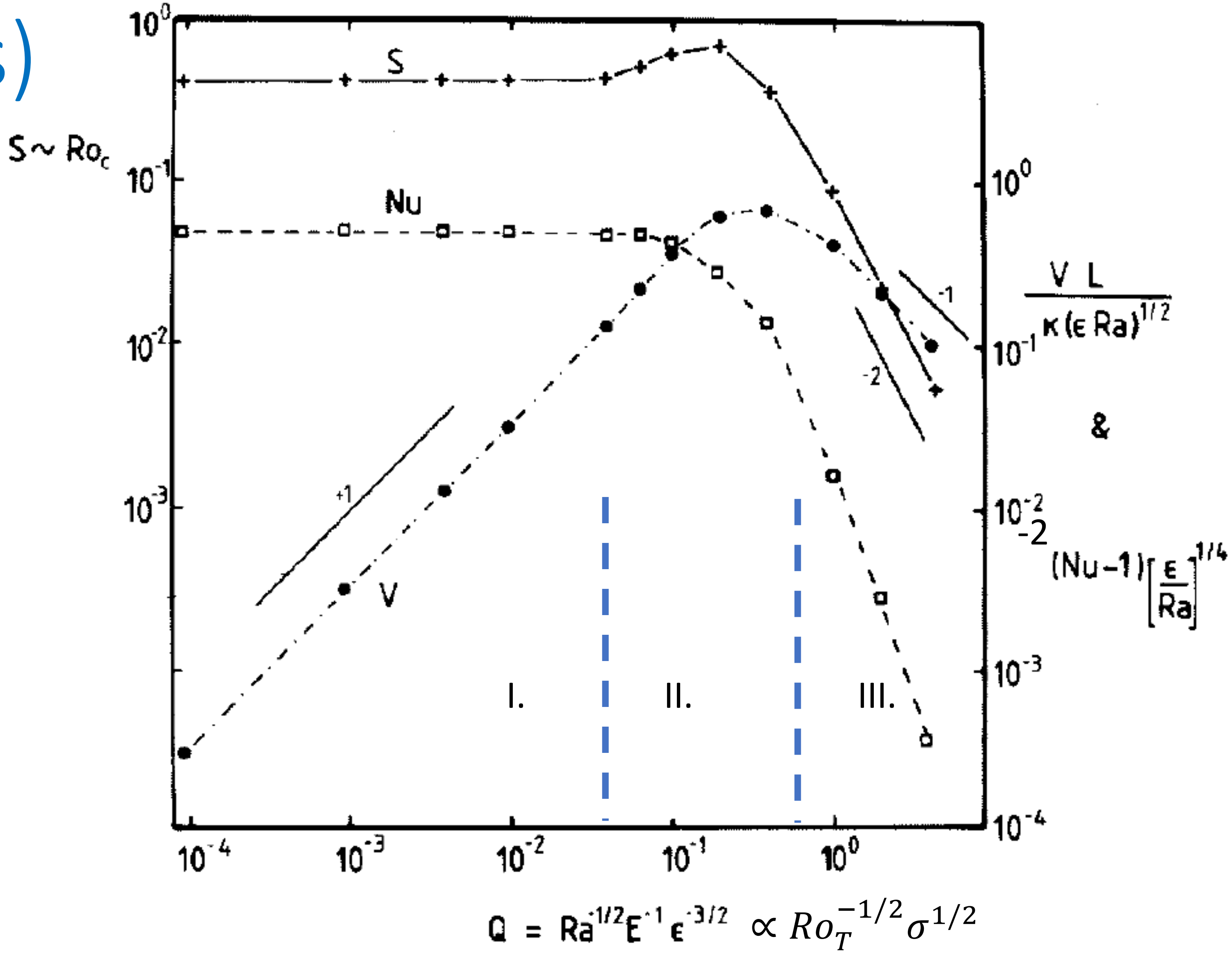
Super-rotation in axisymmetric viscous flow in a rotating cylindrical annulus (Read 1986)



- Axisymmetric flow in a differentially heated rotating annulus
  - Stress-free top and side boundaries
  - Non-slip lower boundary
- Fluid properties for water
  - Molecular viscosity and thermal conductivity
  - Prandtl number $\sigma=7$
- Maintains local and global super-rotation due to horizontally up-gradient viscous fluxes of *m*

Trends in S (cylindrical annulus)

- 3 basic regimes
  I. V. Slow rotation (~angular momentum conserving except in Ekman layer): S ~ constant
  II. Moderate rotation (cyclostrophic/gradient wind and diffusive interior): S rises to shallow peak
  $(S \approx \varepsilon \eta^{1/2} \sigma^{-1/2} Q^{-1})$
  III. Rapid rotation (quasi-geostrophic):
  $S \sim Q^{-2} \sim \Omega^{-2}$



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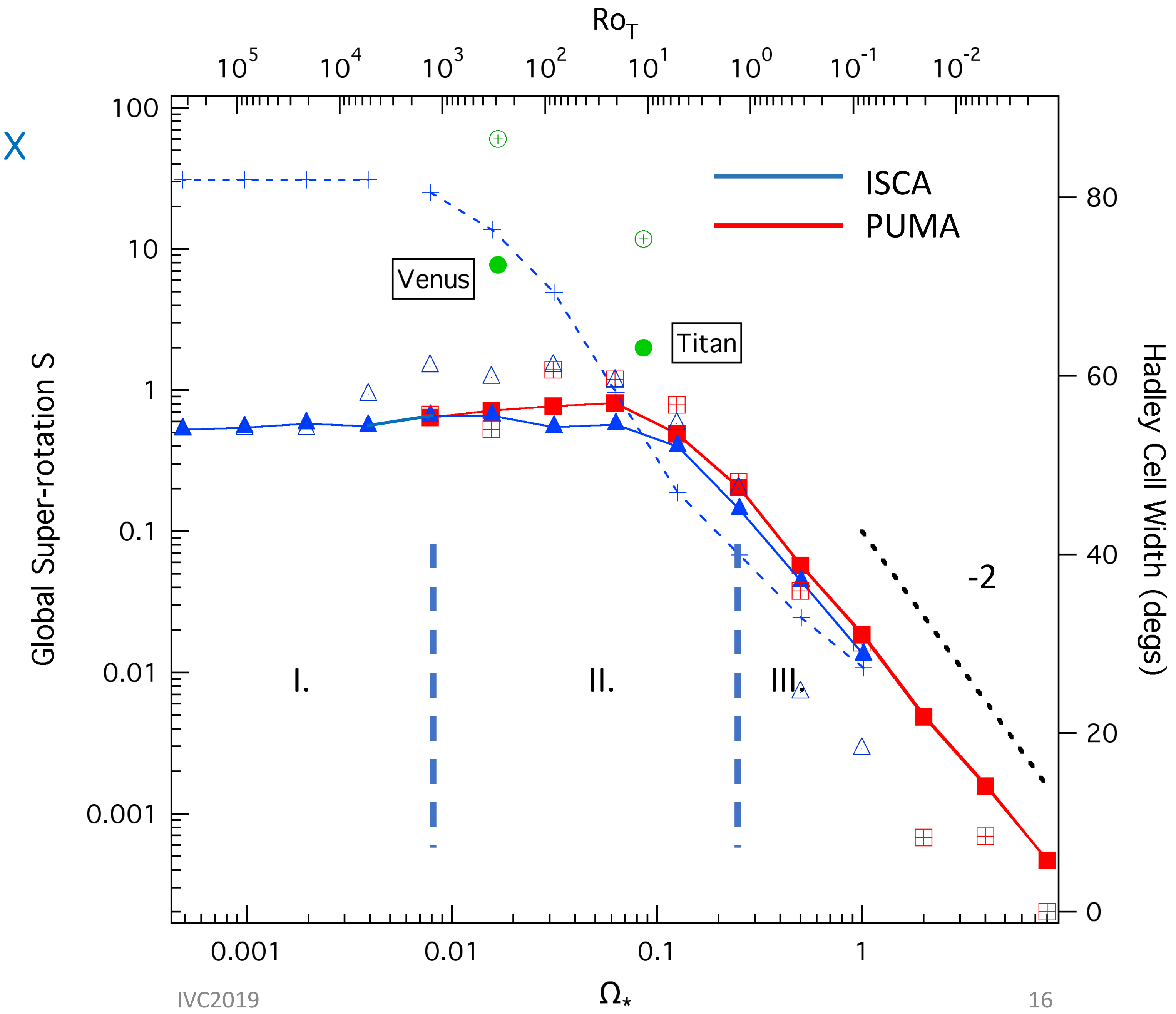
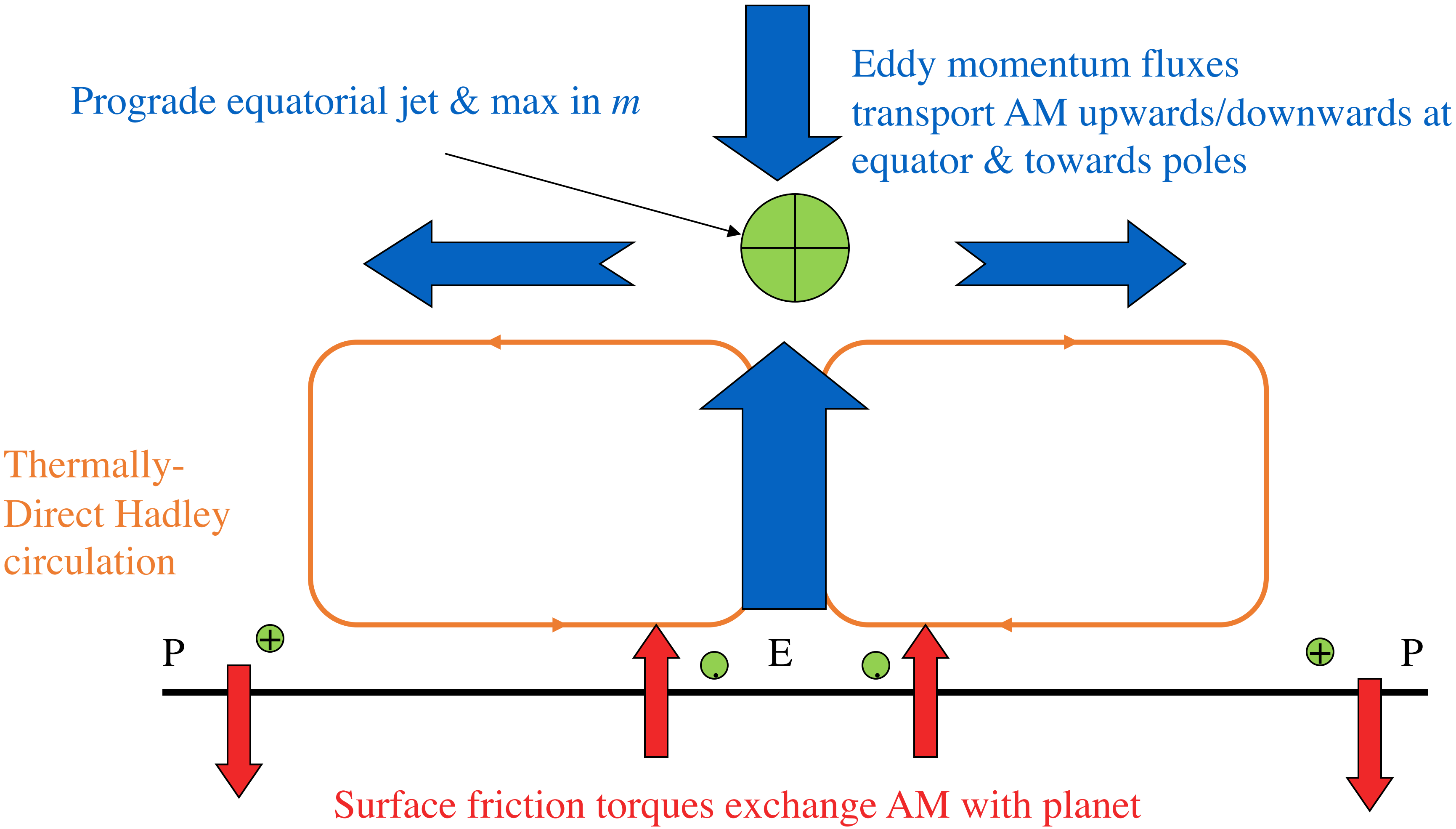


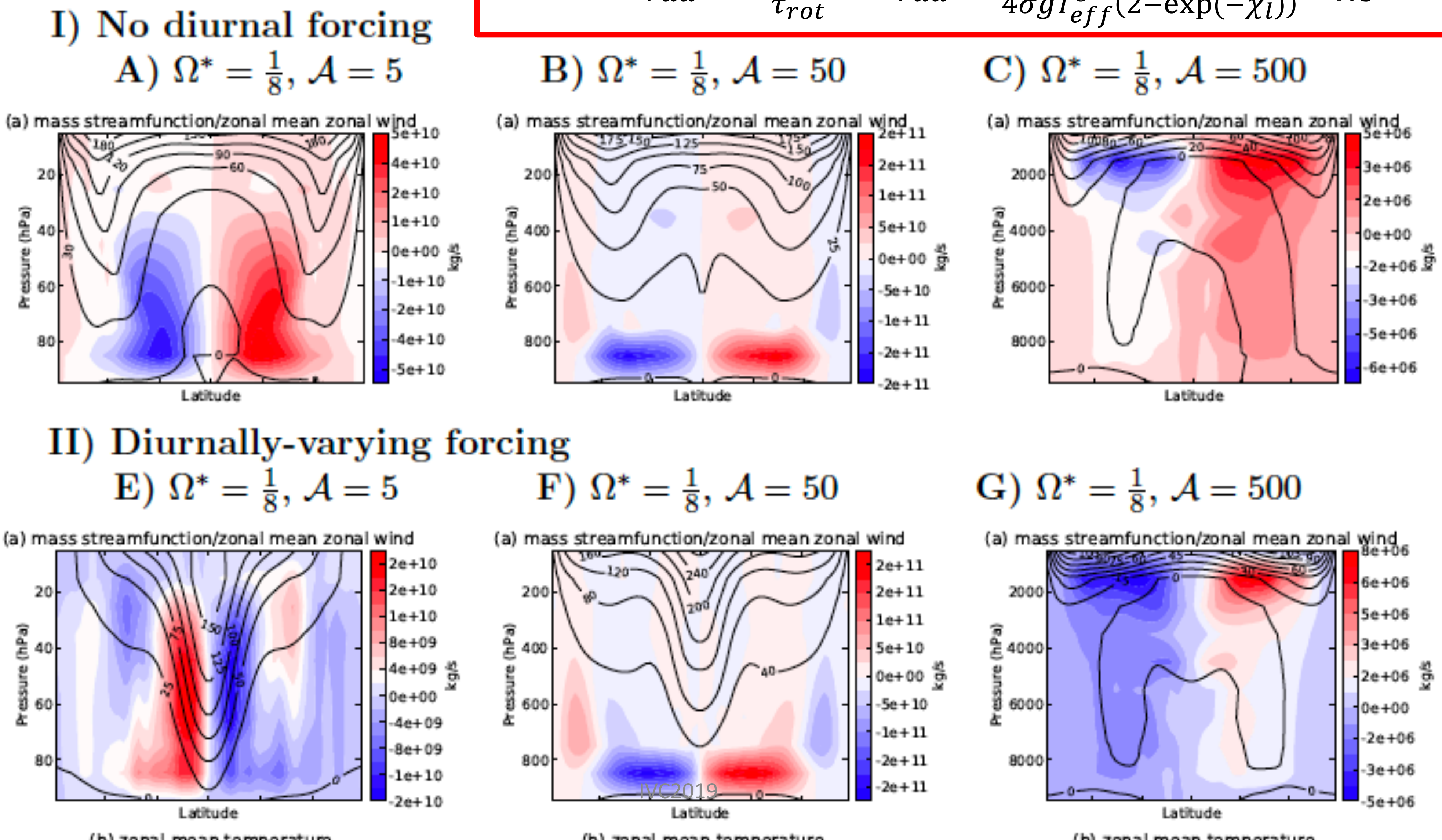
Super-rotation: an alternative "anti-GRW" scenario cf Earth's QBO; tidal jets….?



Super-rotation with/without diurnal forcing

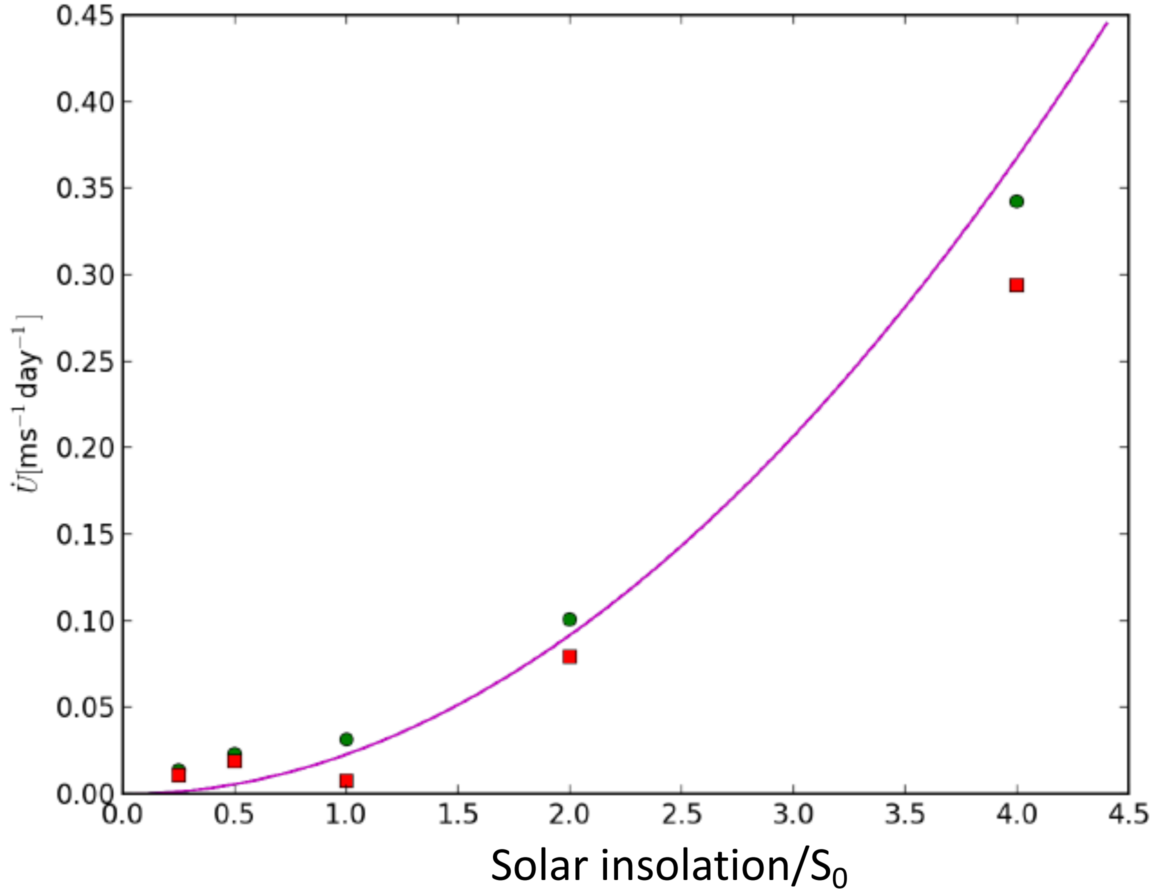
Tabataba-Vakili (2017)

$$\mathcal{A} = 2\Omega\tau_{rad} = \frac{4\pi\tau_{rad}}{\tau_{rot}};\ \tau_{rad} \approx \frac{c_p p_s}{4\sigma g T_{eff}^3(2-\exp(-\chi_l))};\ \ \chi_s = 5.67\chi_l$$



Scaling of super-rotation with diurnal forcing?

- Zonal acceleration by thermally-forced waves
  - $\frac{\partial u}{\partial t} \approx \left(\frac{\mathcal{P}\lambda_v}{2H_h}\right)^2$ (Fels & Lindzen 1974)
    - $\mathcal{P}$=absorbed heating power
    - λ_v=vertical tidal wavelength
    - H_h=Depth of heated layer
- Scale empirically using
  - $P \propto \frac{\left(\frac{\chi_S}{\chi_S+\chi_l}\right)}{\mathcal{A}}$
- Strong scaling of *S* for strong surface friction
  - Less clear for weaker friction….?



Tabataba-Vakili (2017)

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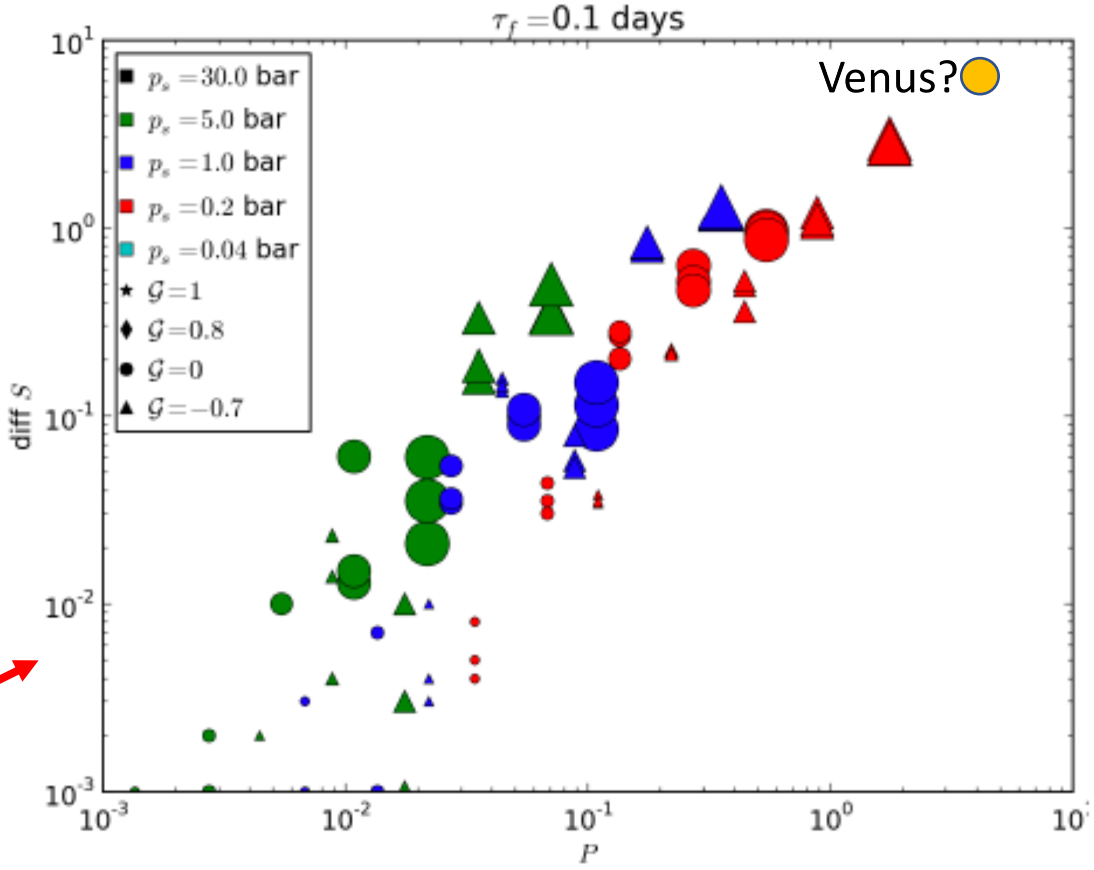

Tabataba-Vakili (2017)

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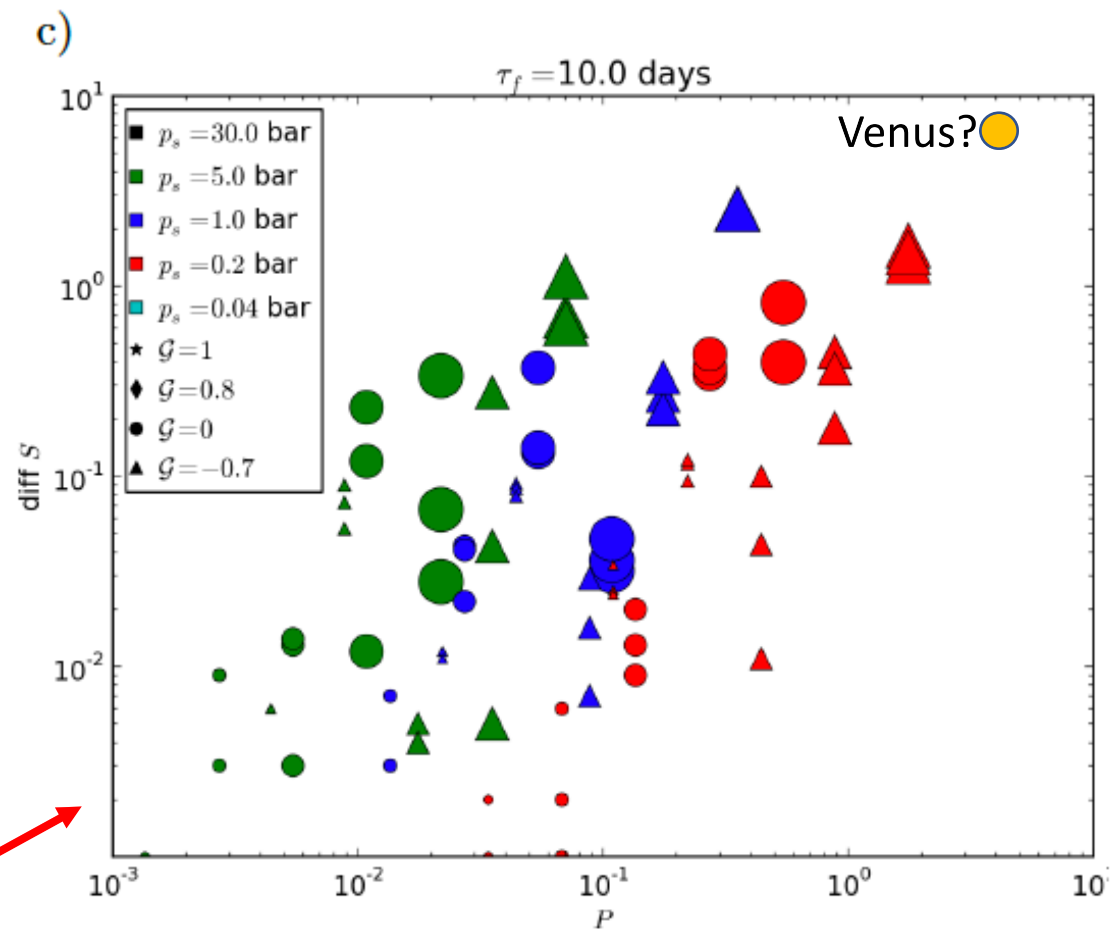
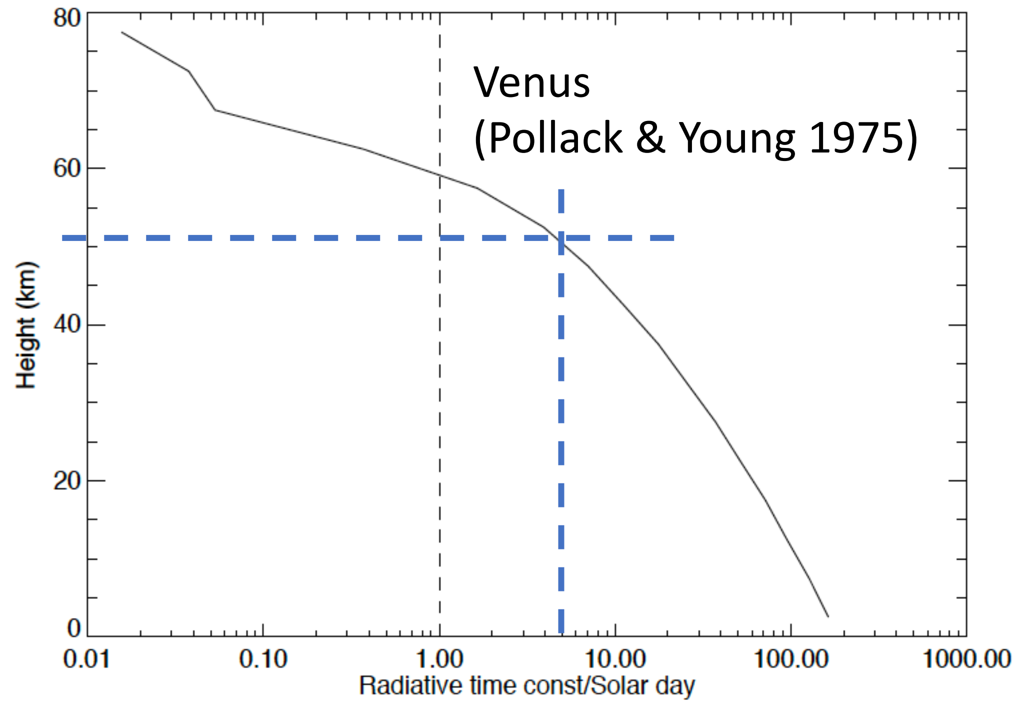


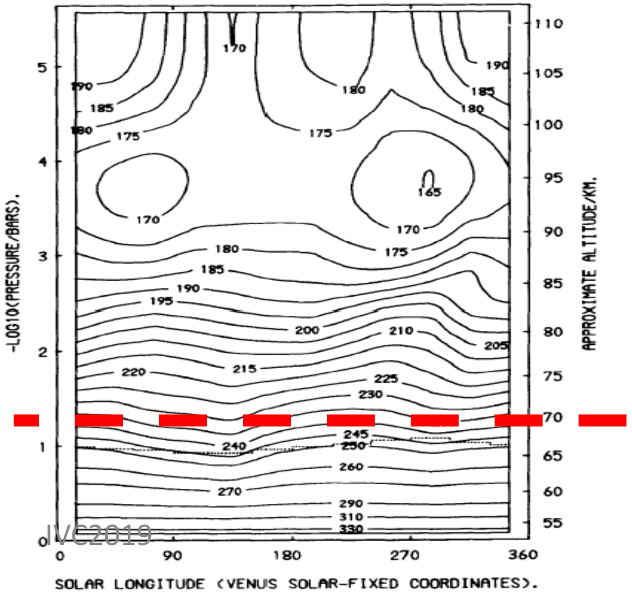
Tabataba-Vakili (2017)

Conclusions

- Super-rotation is ubiquitous, though not universal, in planetary atmospheres
  - Most clearly defined w.r.t. angular momentum constraints and AM of planet
  - Strongest in slowly rotating atmospheres
- GRW scenario
  - Emphasises combination of Hadley circulation and (*horizontally up-gradient*) wave transports
  - Three major regimes: max S, s_{max} found at moderate Ω^* (cyclostrophic) but still $\lesssim O(1)$?
  - Venus or Titan in regime II….?
- Diurnally-forced tides a powerful (anti-GRW) mechanism to enhance super-rotation
  - Requires strong atmospheric absorption/heating over deep layers
  - *Vertically up-gradient and horizontally down-gradient AM transport?*
  - S, s_{max} = O(10) seems possible – scaling….??
  - Especially important for Venus and other planets for which $\mathcal{A} = 2\Omega\tau_{rad} \leq O(50)$
  - Titan…..?



(Schofield & Taylor 1980)



(Kouyama et al. 2019)