Fast and Slow: The Dynamics of Superrotation Phenomena in Planetary Atmospheres: V. Slow rotators

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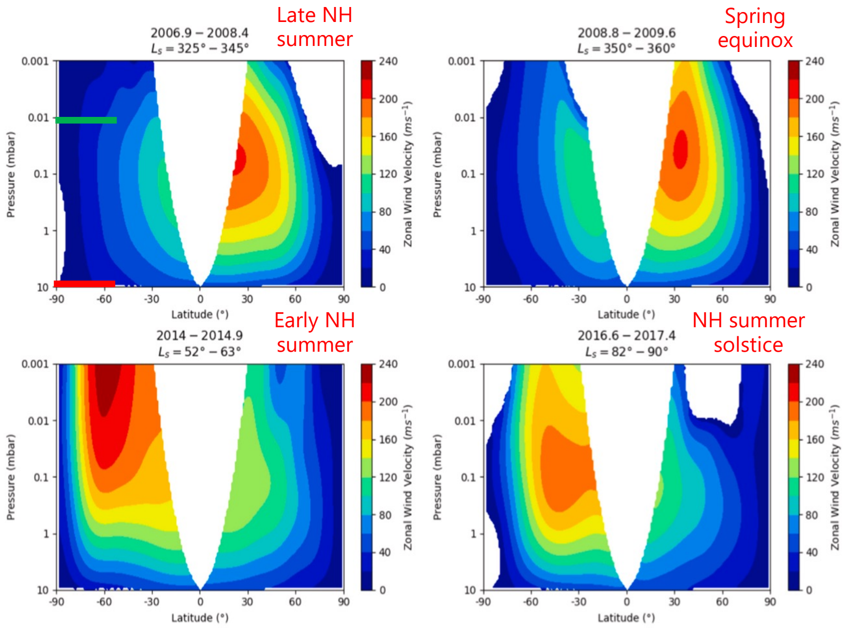
Plan

- Local and global super-rotation in atmospheres around slowly rotating planetary bodies
  - Titan
    - Observations
    - Models and mechanisms
  - Venus
    - Observations
    - Models and mechanisms
  - Tidally-locked exoplanets
    - Equatorial jets?
    - Mechanisms
- Conclusions, synthesis and outlook

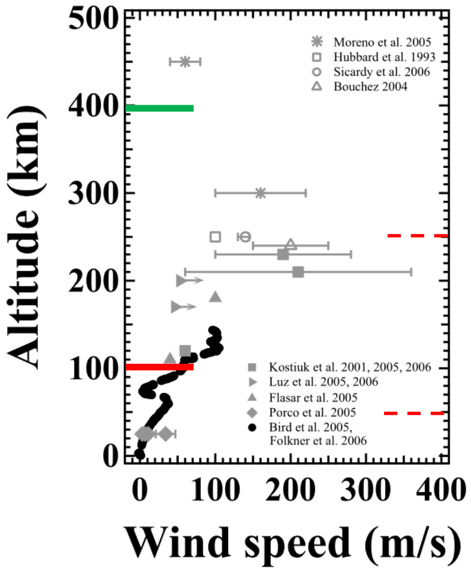
Key features of Titan

Parameter	Titan	Earth
★ Radius (km)	2575	6371
★ Rotation period (Earth days)	16	1
★ Surface gravity (m s-2)	1.35	9.81
★ Surface pressure (bar)	1.5	1
★ Atmospheric composition	94% N_2 5% CH_4	78% N_2 21% O_2 ~.1% H_2O
★ Insolation (W m-2)	14.9	1368
★ Obliquity (deg)	27	23.45
Eccentricity	0.029	0.0167
★ Length of year (Earth years)	29	1

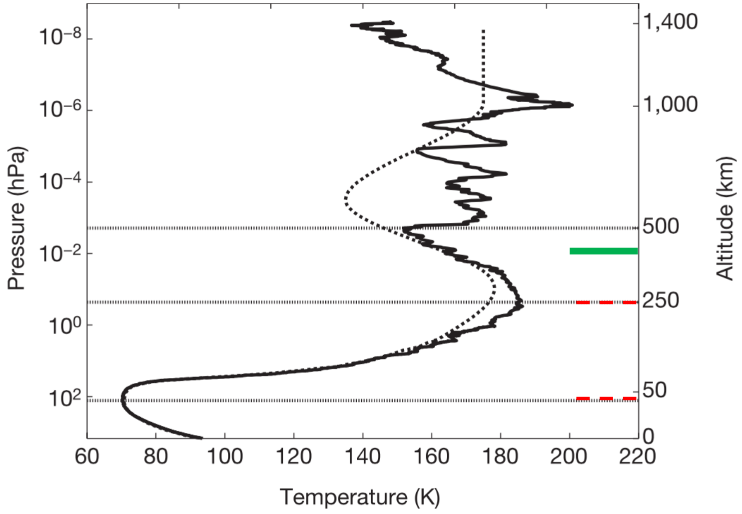
(Sharkey et al., 2021)



(Hörst, 2017)

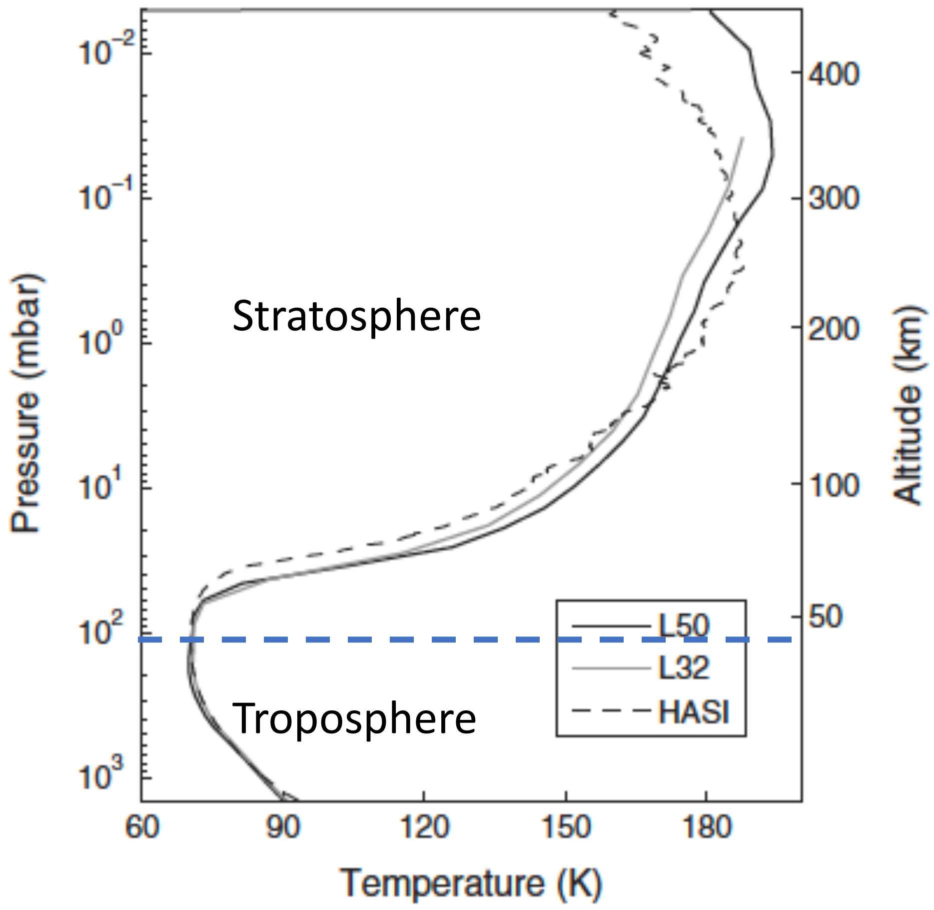


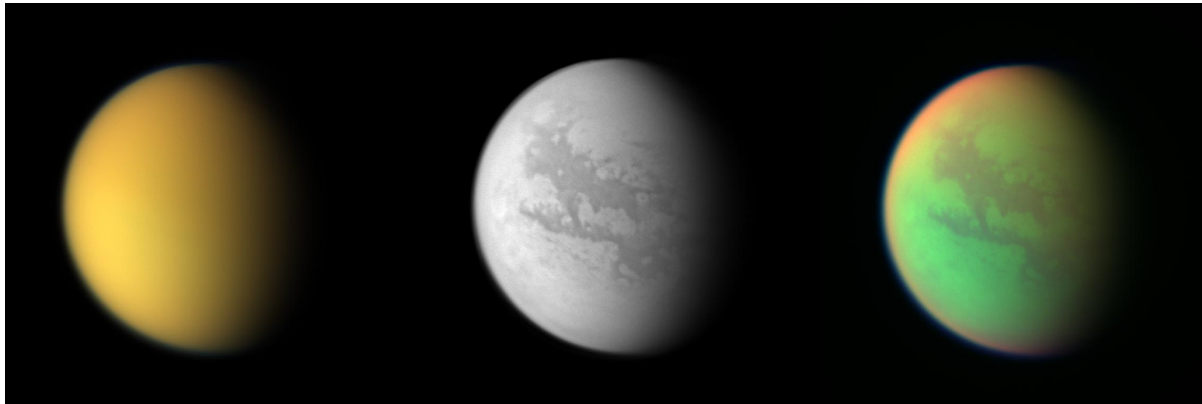
(Fulchignoni et al., 2005)



Key features of Titan

- Complicated radiative budget and T profile
  - Greenhouse-like troposphere
    - Heated via surface
  - Anti-greenhouse stratosphere
    - Heated directly via hazes
- Complicated chemistry and thermodynamics
  - Optically thick photochemical hazes in stratosphere
  - Condensible constituents (CH_4) with clouds, rain, lakes….
- Strong seasonal variability

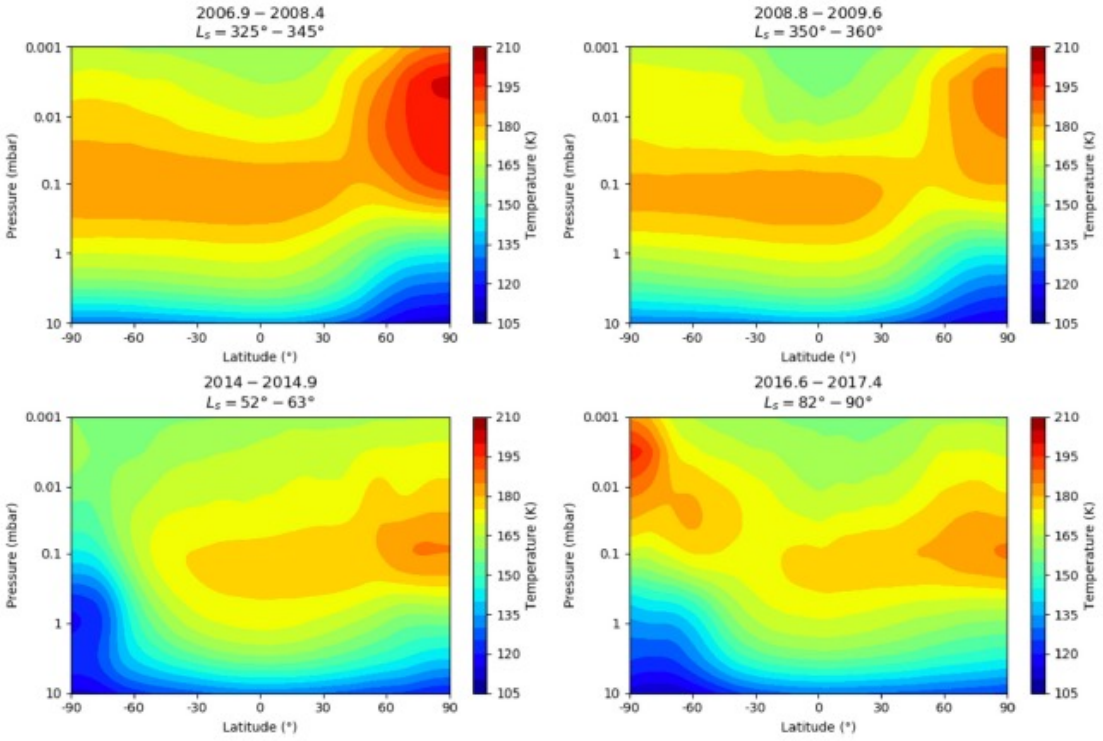




How do we know Titan's atmosphere super-rotates?

[Sharkey et al. 2021]

- Observations
  - BUT very few cloud/haze features to track
  - IR remote sensing [Voyager, Cassini]
    - T via gradient thermal wind equation
    - Not valid close to the equator!
  - Stellar occultations
    - Central flash senses $\rho(\varphi, z \approx 0.25\ hPa)$
  - Doppler spectroscopy in IR, visible and microwaves
    - Senses p ~ 0.1 – 1 hPa
  - Huygens descent probe



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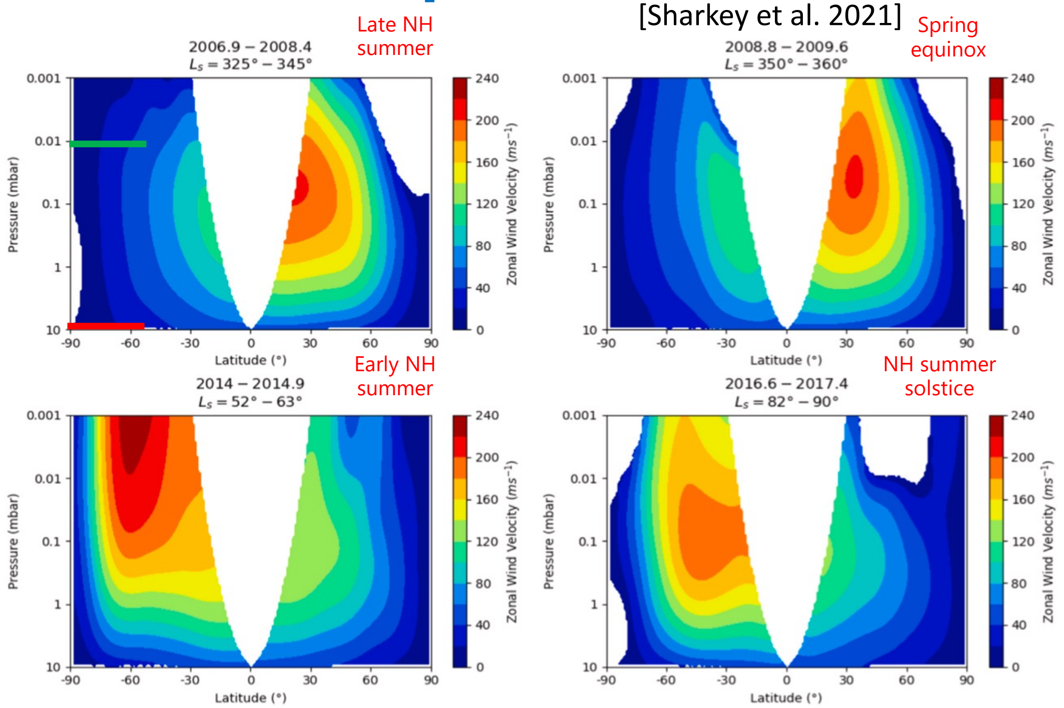
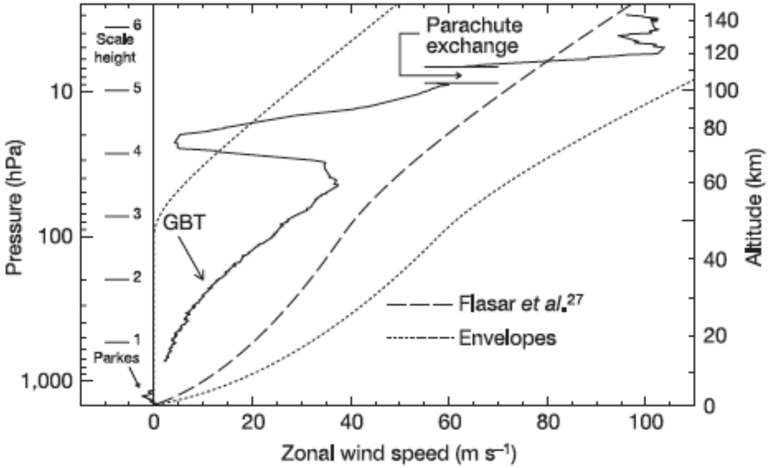
    - Senses p ~ 0.1 – 1 hPa
  - Huygens descent probe
    - $\varphi \approx 10^{o}$ S
    - >100 m s^{-1} prograde winds above 100 km altitude

[Sharkey et al. 2021]





(Bird et al. 2005)

How do we know Titan's atmosphere super-rotates?

- Observational coverage is sparse and incomplete
- Need to rely significantly on models and simulations
  - Simple GCMs
    - Cases where $\mathcal{R} \approx 10$ are relevant to time-mean climatology
  - Comprehensive GCMs
    - Realistic parameterizations of radiative transfer, sub-grid dynamics, clouds, hazes and even chemistry
    - Variable success in capturing super-rotation….?
      - Though see Hourdin et al. [1995] for early sucess

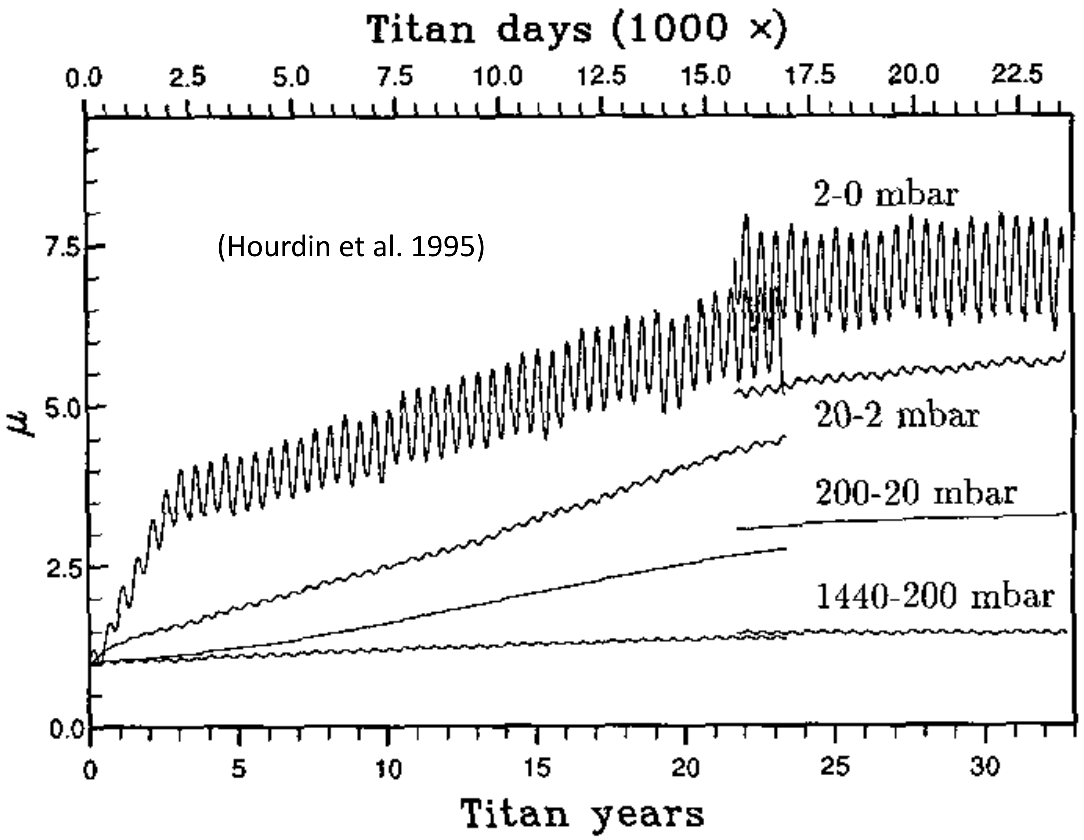


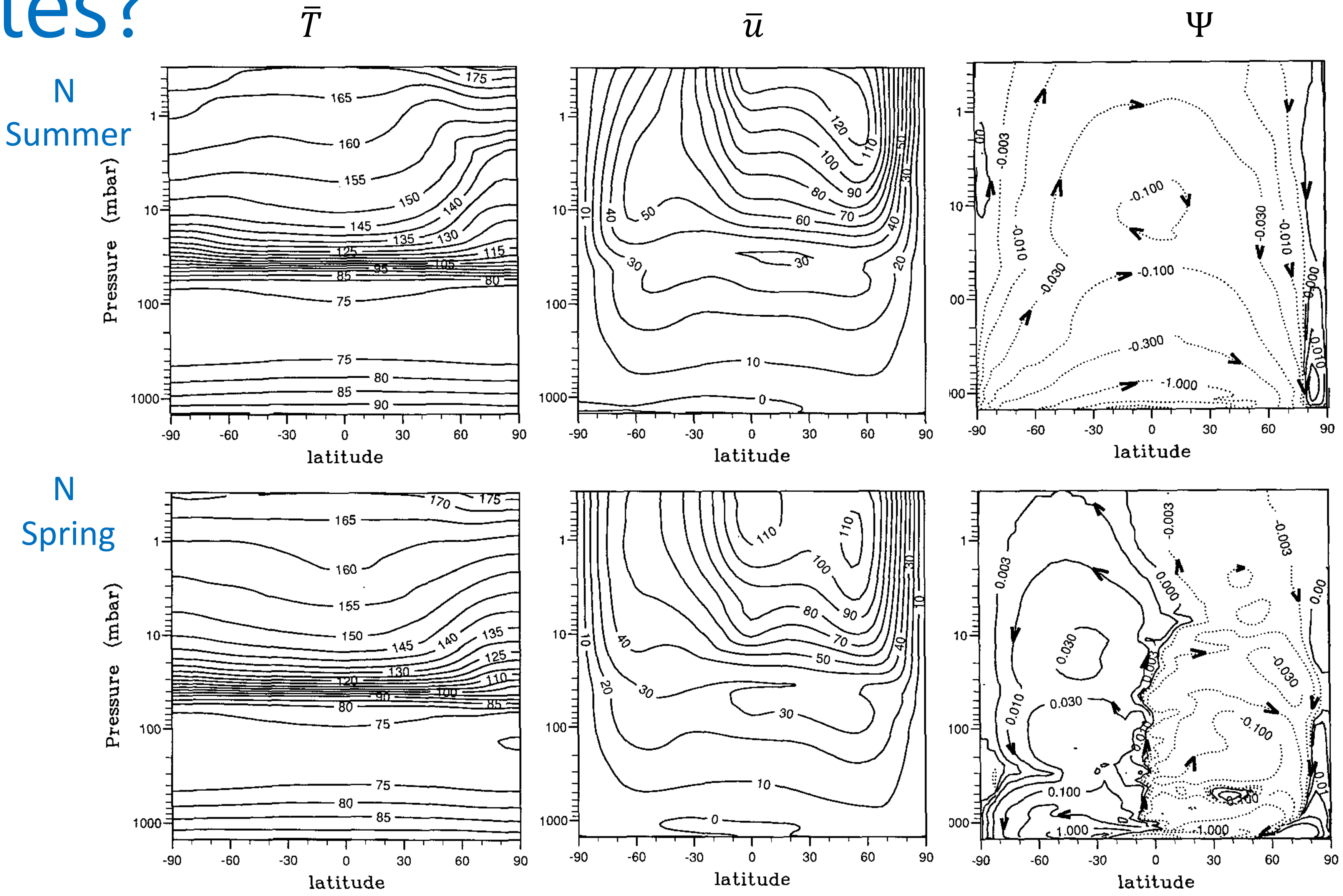
FIG. 3. Time evolution of the planetary average of the dimensionless angular momentum μ.

[Here $\mu = m/\left(\frac{2}{3}\Omega a^2\right)$]

How do we know Titan's atmosphere super-rotates?

- Comprehensive GCMs
  - Variable success in capturing super-rotation….?
  - Seasonal variations in T, $\bar{u}$ and Ψ

(Hourdin et al. 1995)

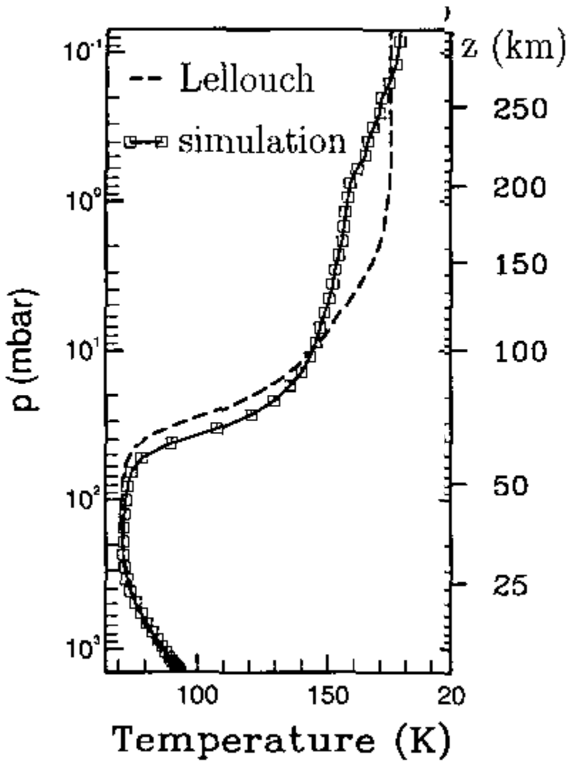


How do we know Titan's atmosphere super-rotates?

(Hourdin et al. 1995)

- Comprehensive GCMs
  - Variable success in capturing super-rotation….?
  - Seasonal variations in T, $\bar{u}$ and Ψ
  - T, $\bar{u}$ compare reasonably well with (sparse!) observations….

T



$\bar{u}$

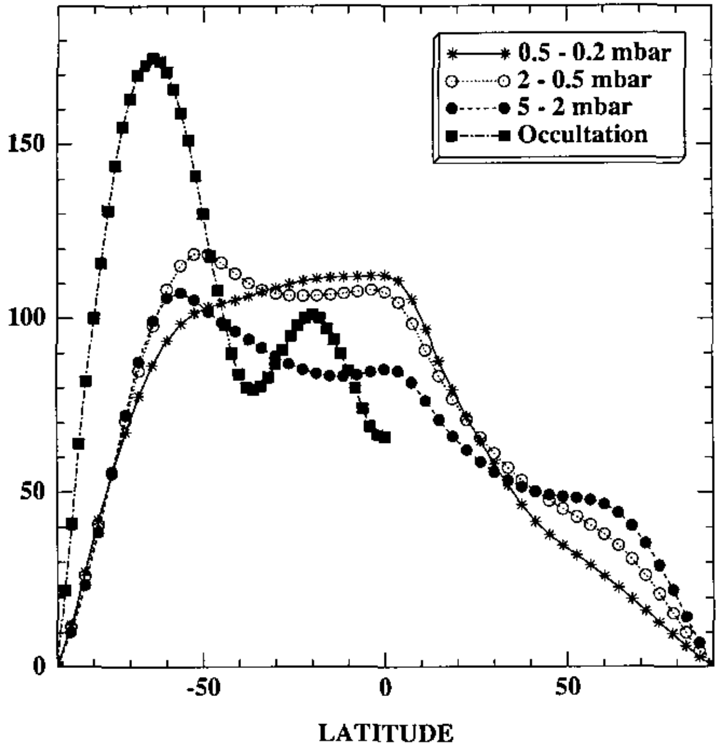


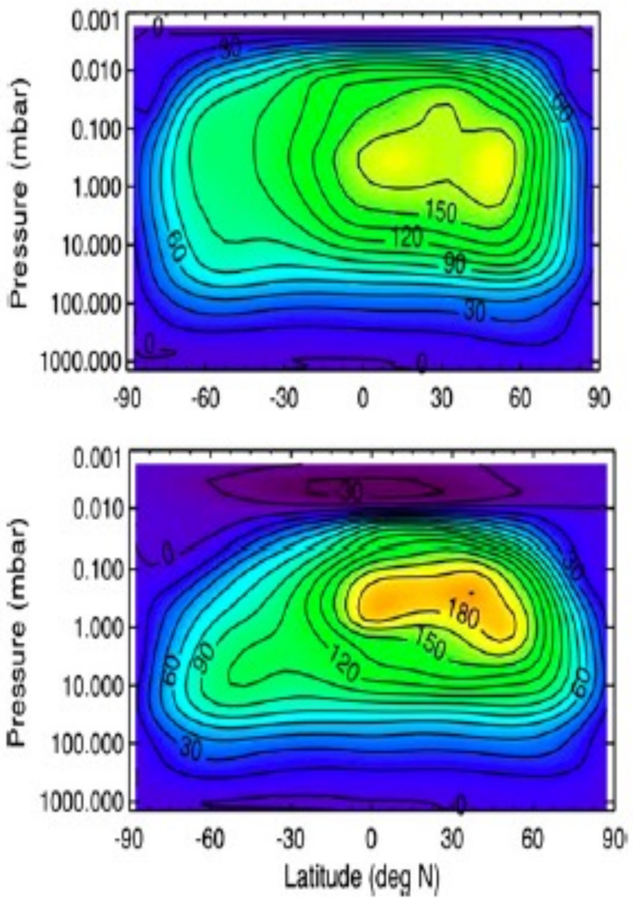
FIG. 9. Latitudinal zonal wind profile deduced by Hubbard *et al.* (1993) from the 28-Sgr occultation which corresponds to a pressure level near 0.25 mbar (squares). The other three curves show the zonally averaged zonal wind as produced by the GCM for the same season ($L_S \approx 128$) and for three pressure ranges.

How do we know Titan's atmosphere super-rotates?

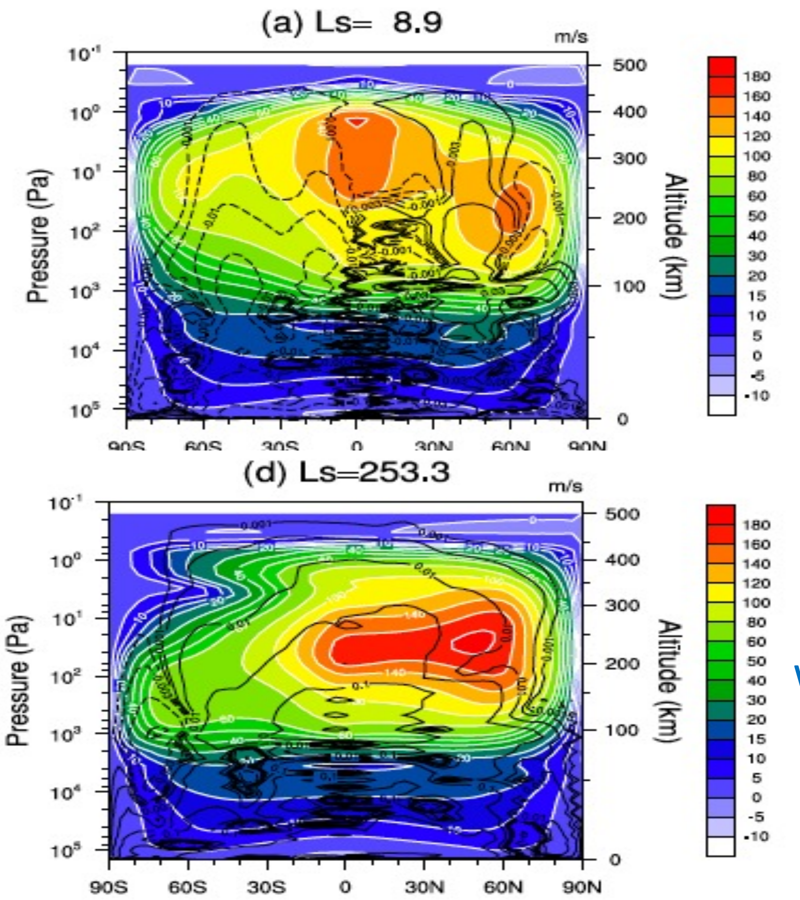
- Comprehensive GCMs
  - Most successful for super-rotation from 3 main groups?
    - IPSL [France]
    - TitanWRF [US/UK]
    - TAM [US]
    - [Though see also TitanCAM [US] and Köln group [Germany]]
  - Reasonable consistency between models…?

TitanWRF
[Newman et al. 2011]

$\bar{u}$



IPSL
[Lebonnois et al. 2012]



N
Spring

N
Winter

How do we know Titan's atmosphere super-rotates?

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  - Most successful for super-rotation from 3 main groups?
    - IPSL [France]
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TitanWRF
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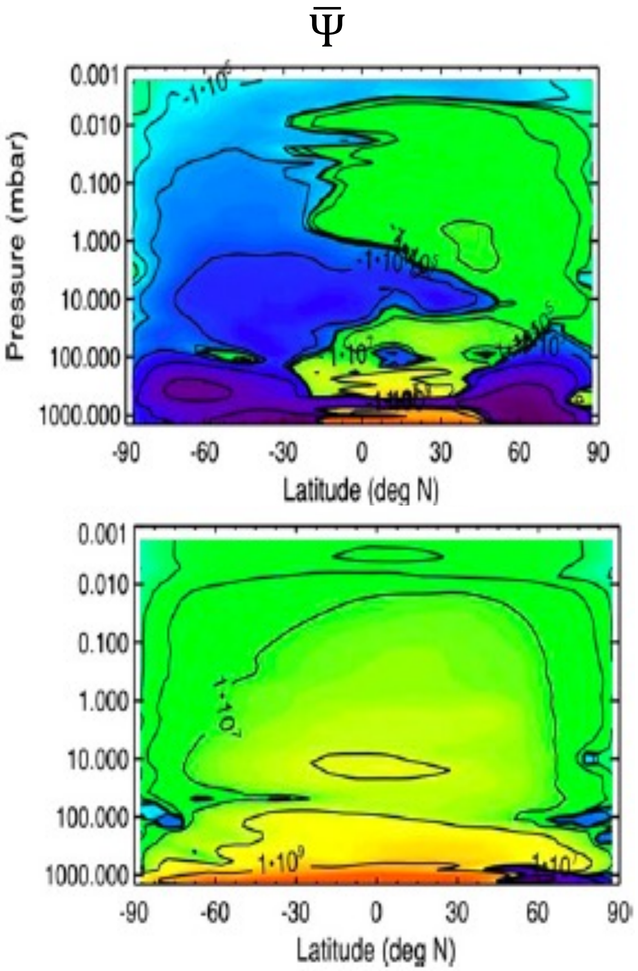

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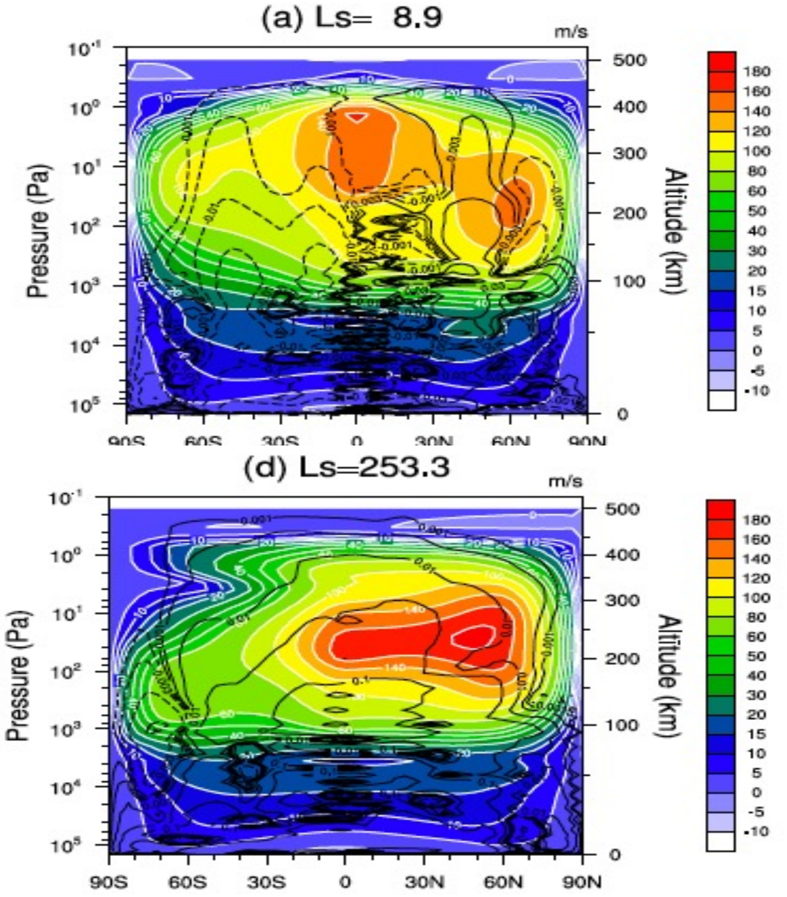


N Spring

N Winter

Mechanisms for Titan’s atmospheric super-rotation

- GRW-type scenario
  - Poleward AM transport by mean meridional circulation

  Balanced by
  - Equatorward AM transport by (transient) eddies
  - Common to all main models in time-mean
  - Seasonal variations?
  - Mechanisms to generate eddies?
- Vertical AM transport?
  - Seems weak in comparison to horizontal eddies
- Tides?

Lebonnois et al. [2012]

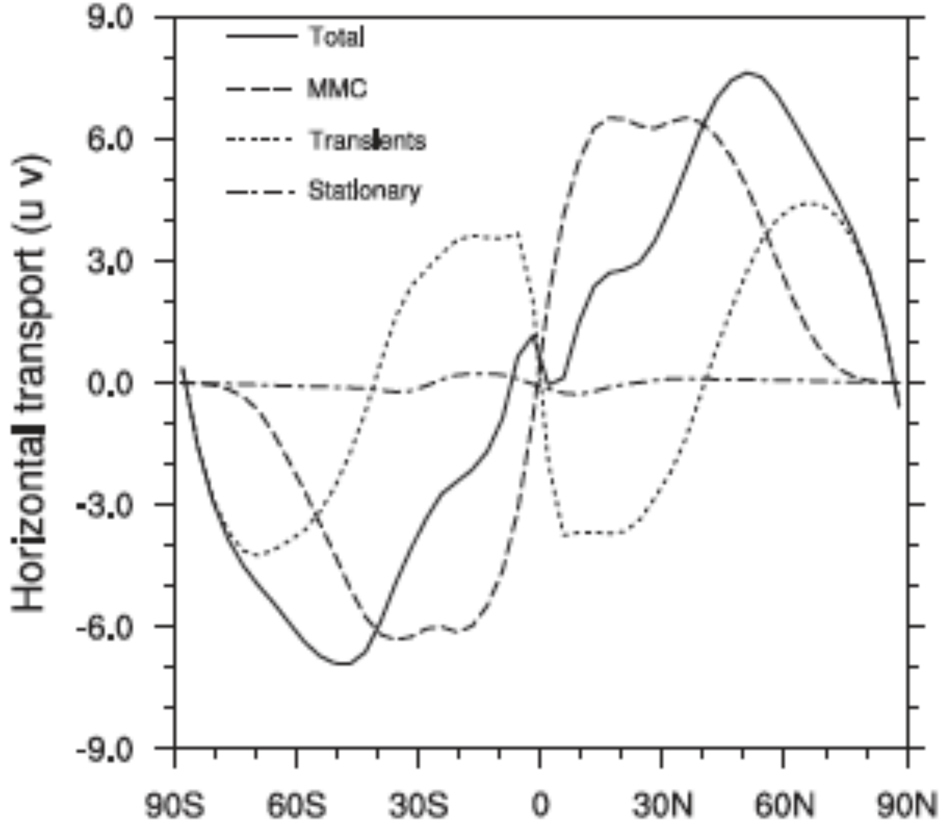
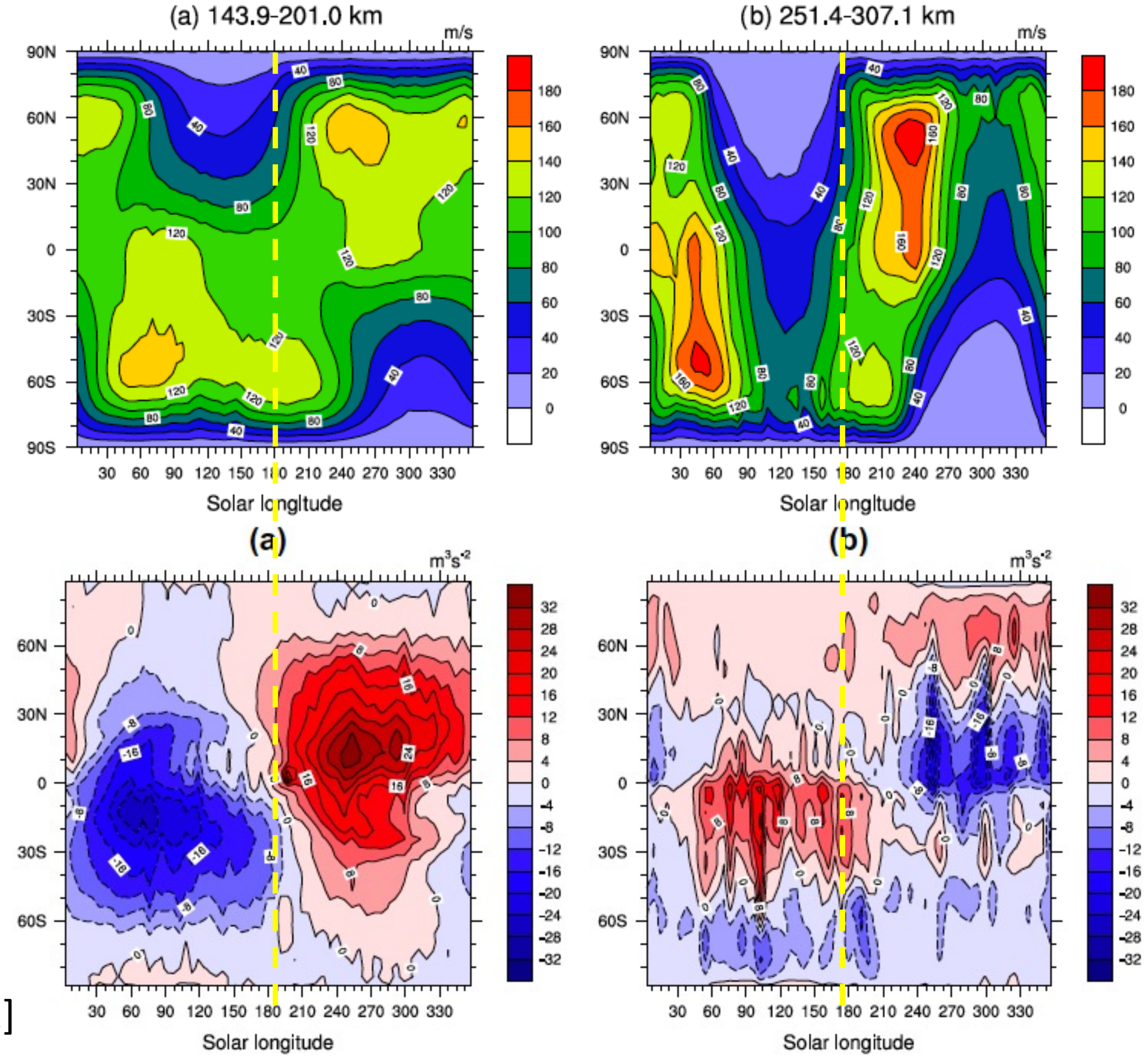


Fig. 11. Annual average of the latitudinal transport of angular momentum by mean meridional circulation (MMC, dashed line), transient waves (dotted line) and stationary waves (dash-dotted line). Total is shown in solid line. Unit is $10^3\ m^3/s^2$, positive values are northward.

Mechanisms for Titan's atmospheric super-rotation

- Seasonal variations in $\bar{u}$

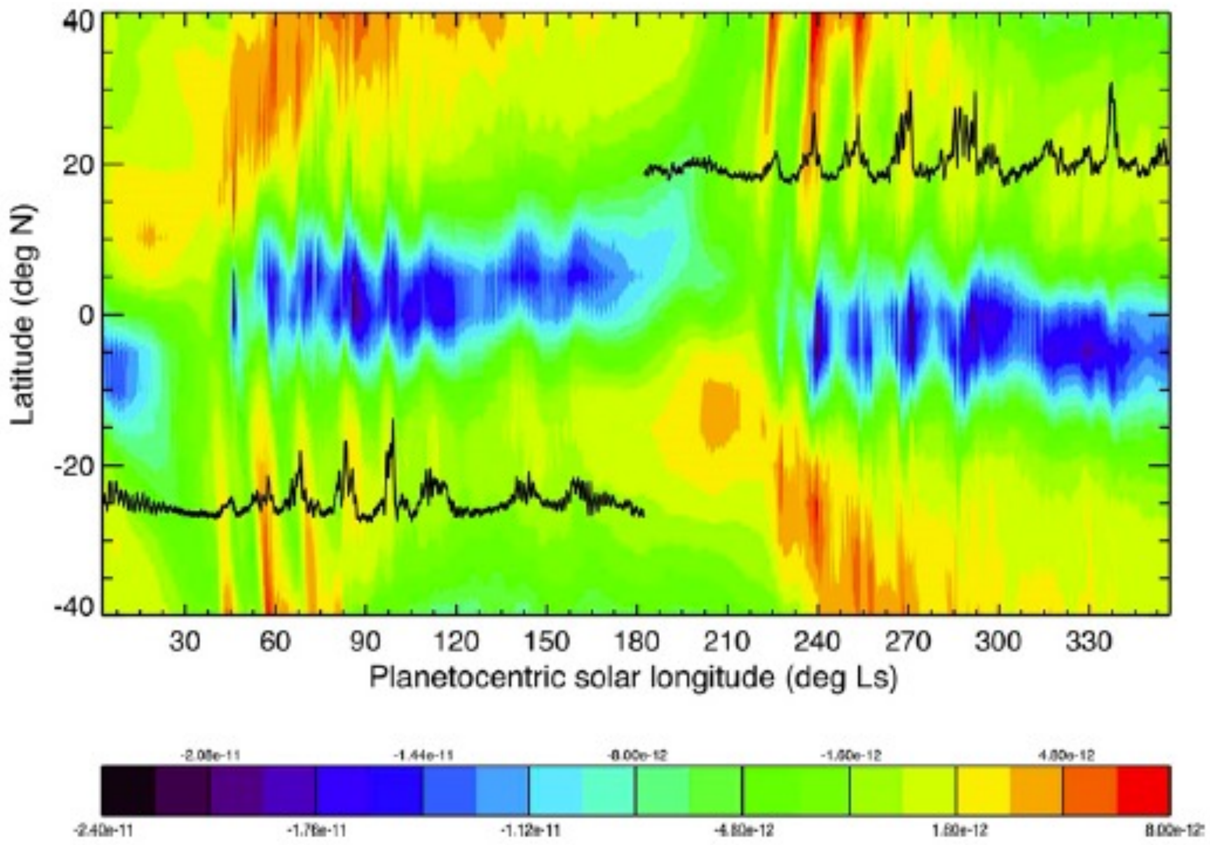


- AND AM transport

Lebonnois et al. [2012]

Mechanisms for Titan's atmospheric super-rotation

Newman et al. [2011] $\partial\bar{q}/\partial y$ & $\partial M/\partial t$



- GRW-type scenario: Mechanisms to generate eddies?
  - Barotropic instabilities at midlatitudes?
    - $\partial\bar{q}/\partial y$ must change sign
    - Highly variable in time?
    - Intermittent bursts of instabities
  - Other (baroclinic?) instabilities at high latitudes in troposphere only
    - [Lebonnois et al. 2012]?
    - Transports AM poleward….?

Mechanisms for Titan's atmospheric super-rotation

Bézard et al. [2018]

- Vertical AM transport?
  - Seems weak in comparison to horizontal eddies
- Tides?
  - Thermal
    - Radiative time constant too long for significant diurnal tide?

    Radiative timescale $\tau_{rad} \approx \frac{c_p p_s}{\sigma g T_{eff}^3 (2-\epsilon)}$;

    [transmissivity ϵ]

    Or

    $\tau_{rad} \approx T/$radiative cooling rate
    - Weak westward diurnal waves found in some models [Newman et al. 2011]
    - Models don't seem to need it to reproduce super-rotation....
  - Gravitational?

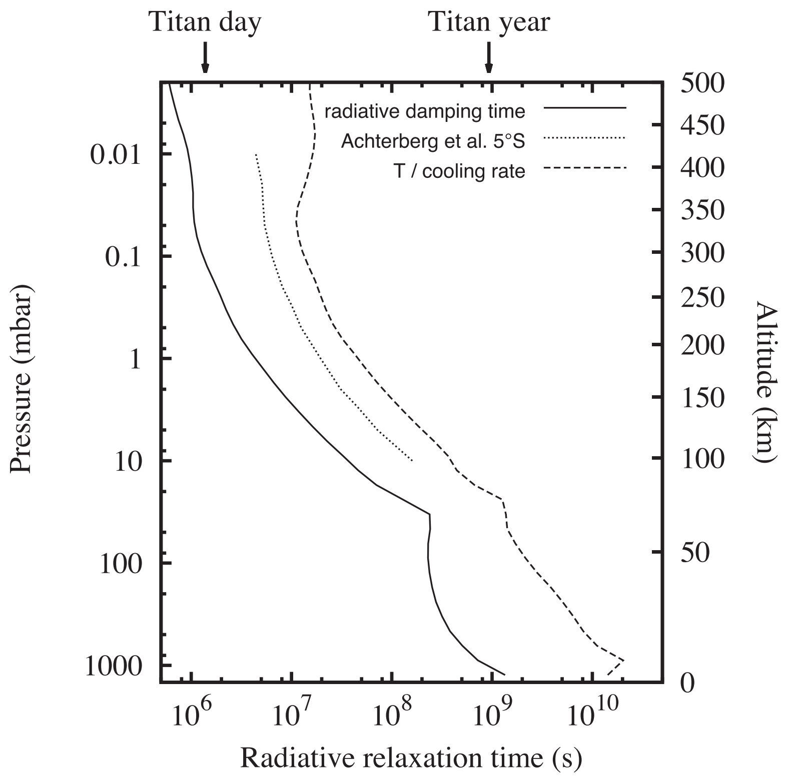
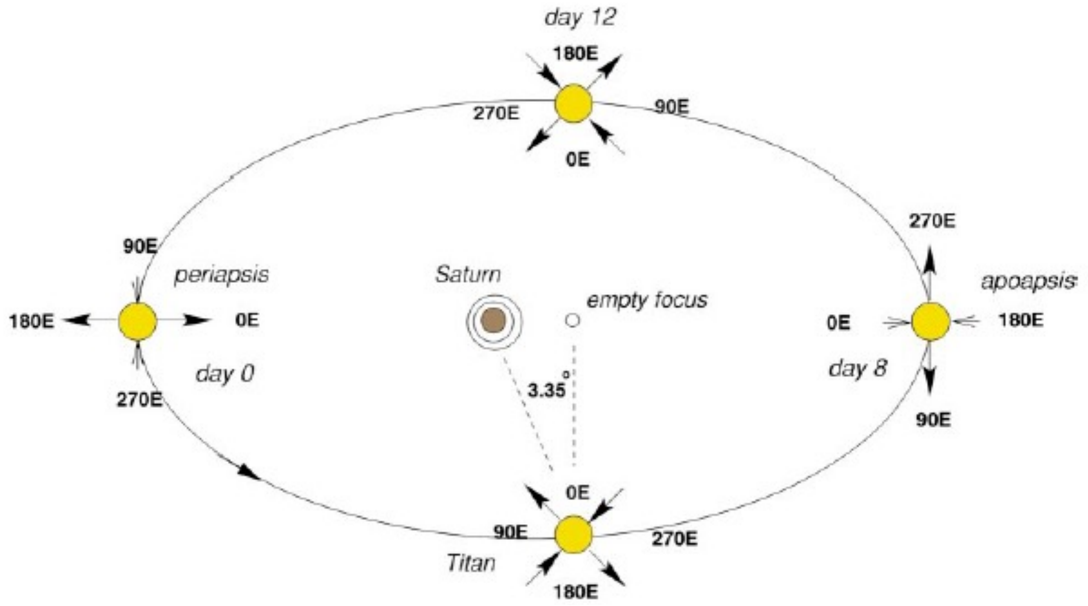


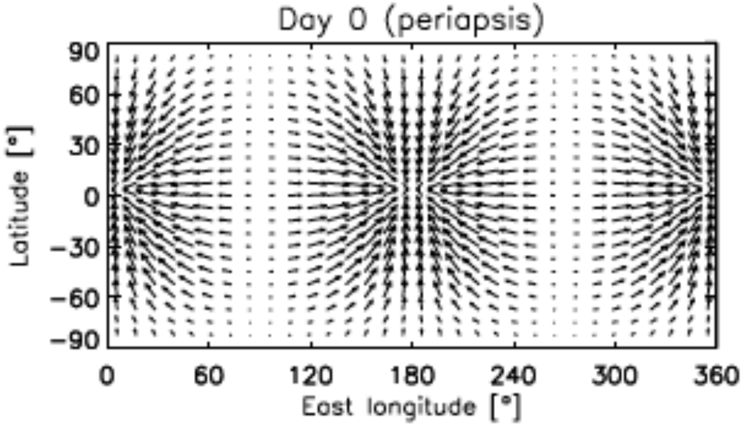
Fig. 6. Vertical profiles of radiative relaxation time in Titan's atmosphere. The solid line corresponds to damping out a Gaussian temperature perturbation having a full width at half maximum of one pressure scale height. The dotted line shows the radiative time constant calculated by Achterberg et al. (2011) at 5°S using the direct cooling-to-space approximation for the radiative cooling. The dashed line represents the temperature divided by the cooling rate, following the approach of Strobel et al. (2009).

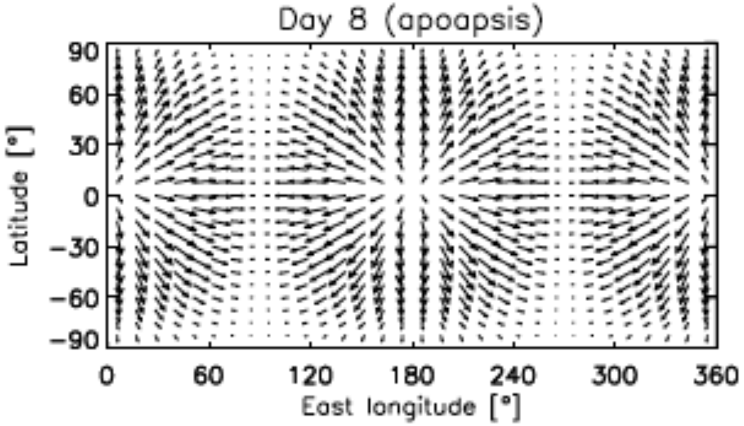
Mechanisms for Titan's atmospheric super-rotation

- Vertical AM transport?
  - Seems weak in comparison to horizontal eddies
- Tides?
  - Gravitational?
    - Excites m=2 wave



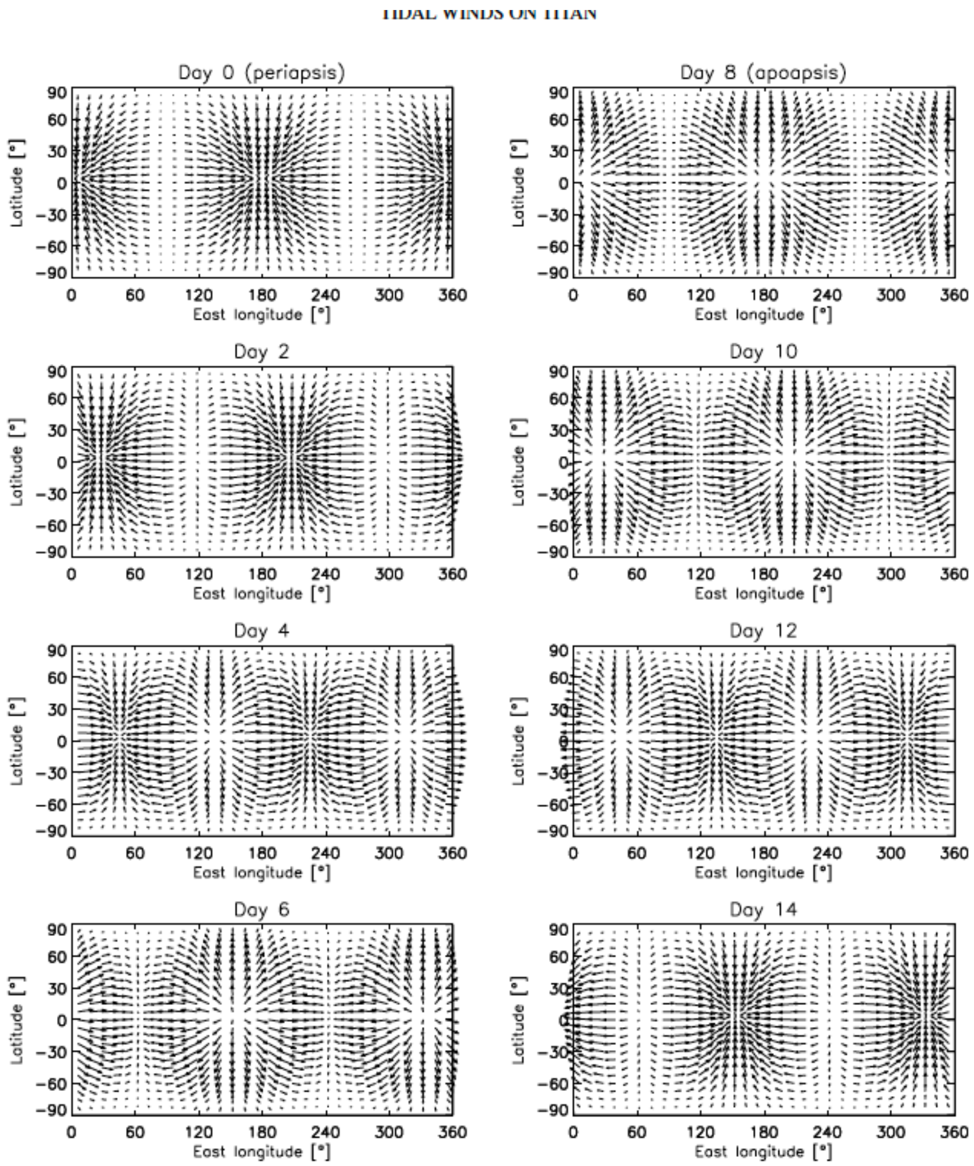
TIDAL WINDS ON TITAN





Mechanisms for Titan’s atmospheric super-rotation

- Vertical AM transport?
  - Seems weak in comparison to horizontal eddies
- Tides?
  - Gravitational?
    - Excites m=2 wave
    - Travels around planet
    - Effect on circulation (AM transport etc.....)?
    - Seems to be weak or negligible in most (but not all) models

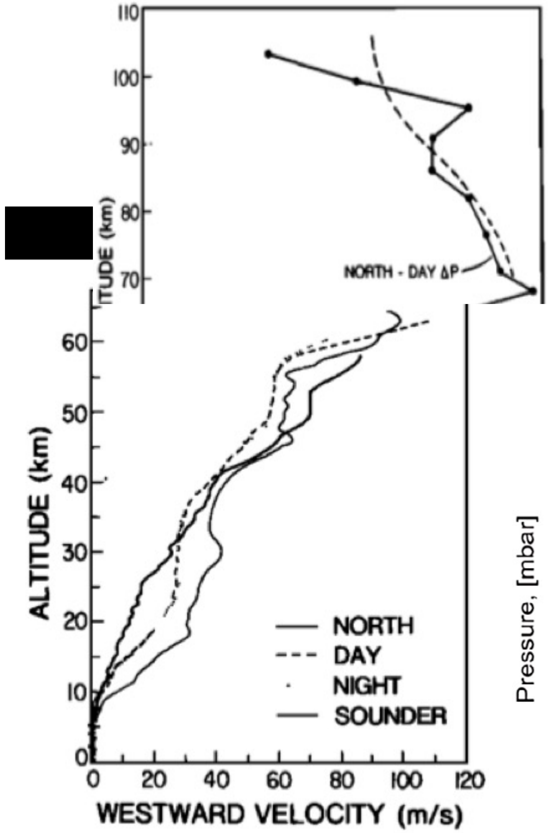


Titan: Mechanisms for super-rotation?

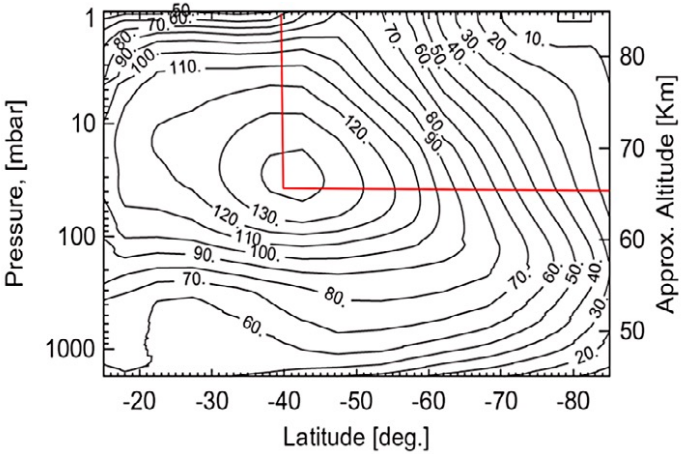
- GRW scenario seems to work effectively in most models
  - Driven mainly by barotropic instabilities at mid-latitudes
  - Intermittent rather than continuous?
  - Other instabilities?
- Thermal tides may be present [Newman et al. 2011] though don't contribute much
- Gravitational tides....?

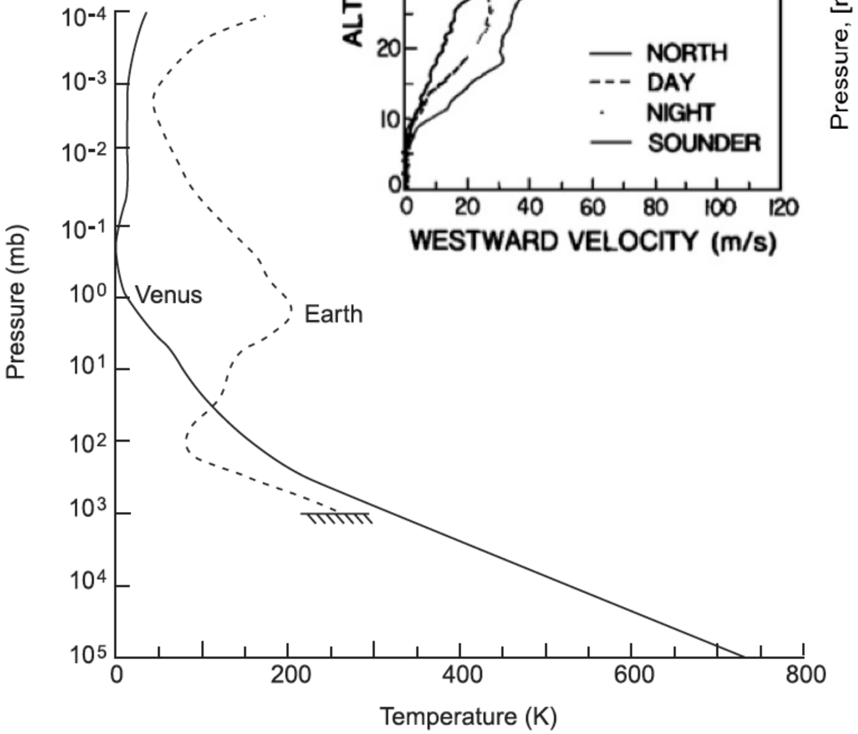
Key features of Venus

	Parameter	Venus	Earth
★	Radius (km)	6052	6371
★	Rotation period (Earth days)	243.7	1
★	Surface gravity (m s-2)	8.87	9.81
★	Surface pressure (bar)	92	1
★	Atmospheric composition	96.5% CO_2 3.5% N_2	78% N_2 21% O_2 ~.1% H_2O
★	Insolation (W m-2)	2617	1368
★	Obliquity (deg)	177.4	23.45
	Eccentricity	0.0068	0.0167
★	Length of year (Earth years)	0.615	1



[Picciali et al. 2012]

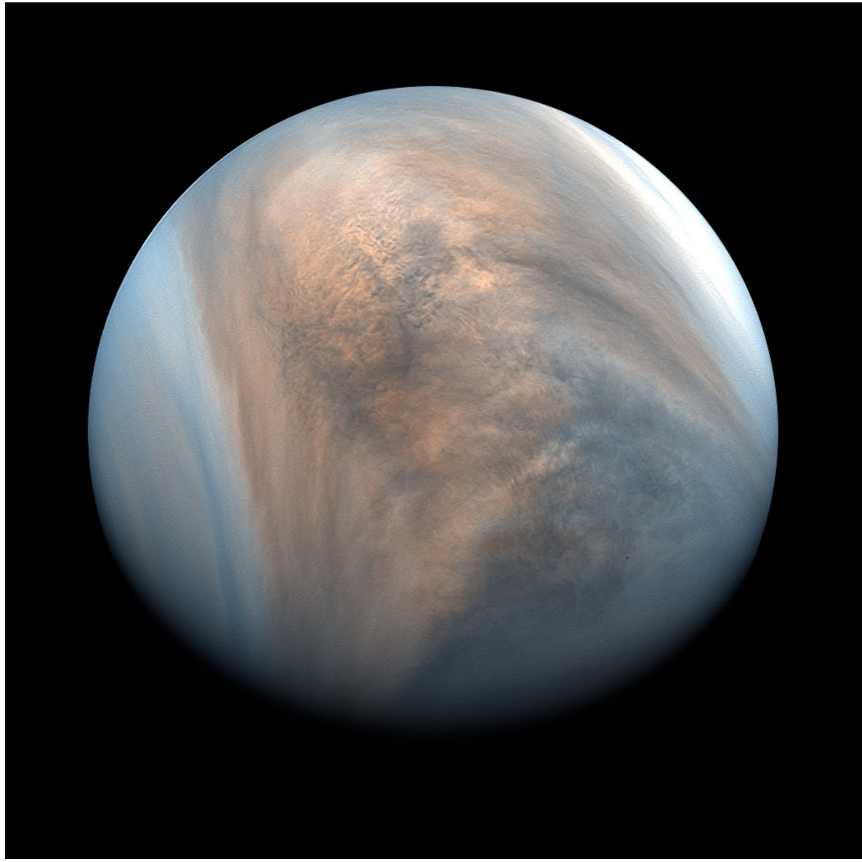




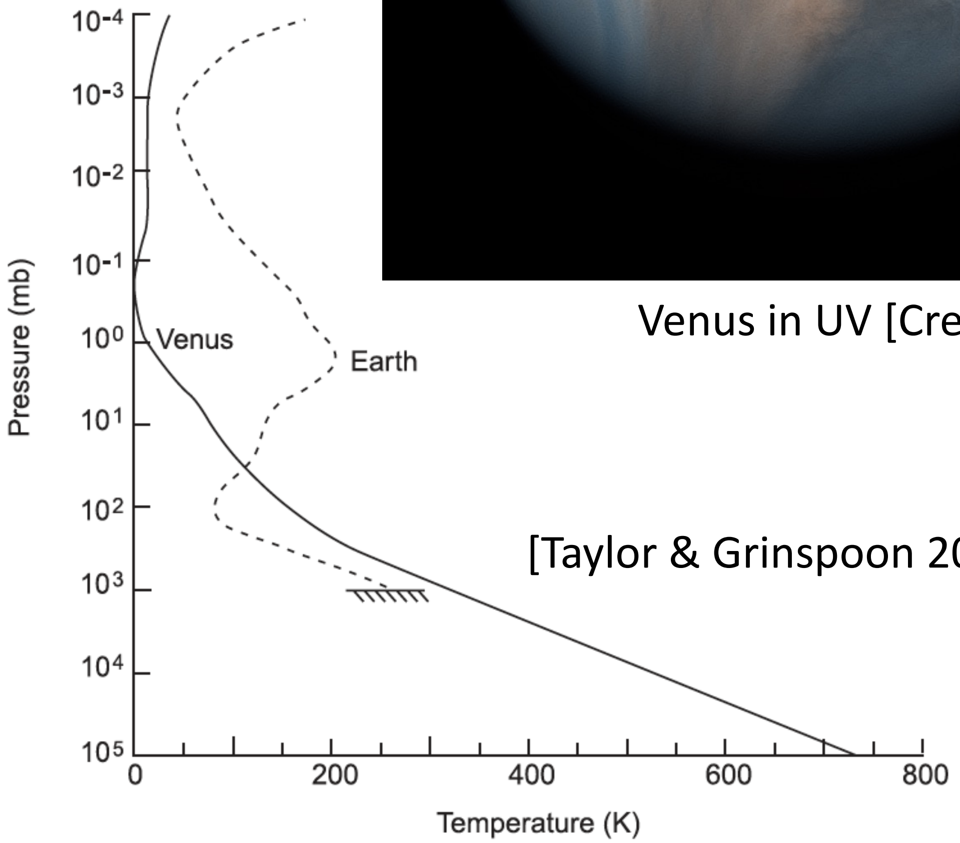
[Taylor & Grinspoon 2009]

Key features of Venus

- Complicated radiative budget and T profile
  - Deep, greenhouse-like troposphere
    - Heated via surface
  - Nearly isothermal stratosphere [z > 80 km]
- Complicated chemistry and thermodynamics
  - Condensible constituents (H_2SO_4) with ubiquitous clouds
  - Featureless in the visible but with clear markings in UV
  - Unknown UV absorber….?
  - Deep atmosphere may be super-critical for CO_2….
- No seasonal variability
  - But other variability often seen



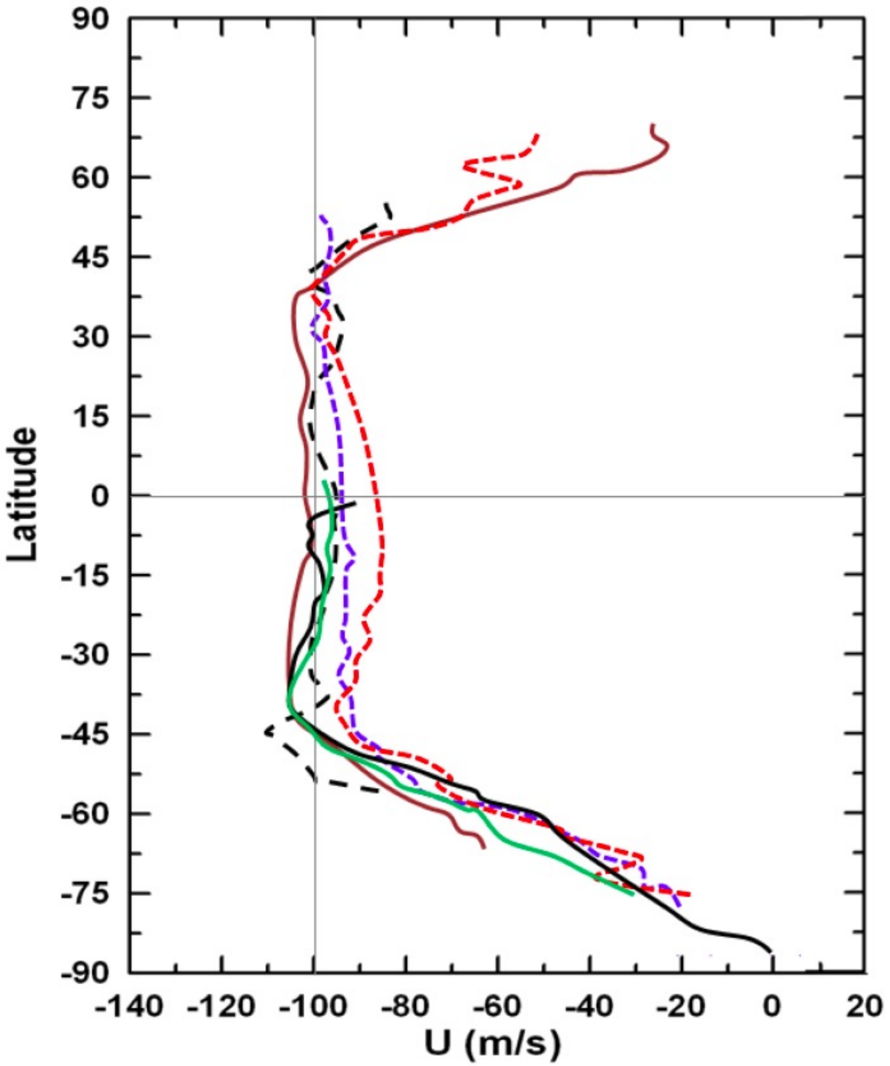
Venus in UV [Credit: JAXA]



[Taylor & Grinspoon 2009]

How do we know Venus's atmosphere super-rotates?

- Observations
  - Tracking cloud features in the UV and IR
    - Prograde winds up to 100 m s^{-1} or more at cloud tops, even on the equator
  - Entry probes
    - Doppler tracking as probes descend
    - Venera (USSR) and Pioneer Venus (USA) sampled different latitudes
  - Balloons
  - Doppler spectroscopy
  - O_2 (airglow) and NO emissions
  - IR remote sounding



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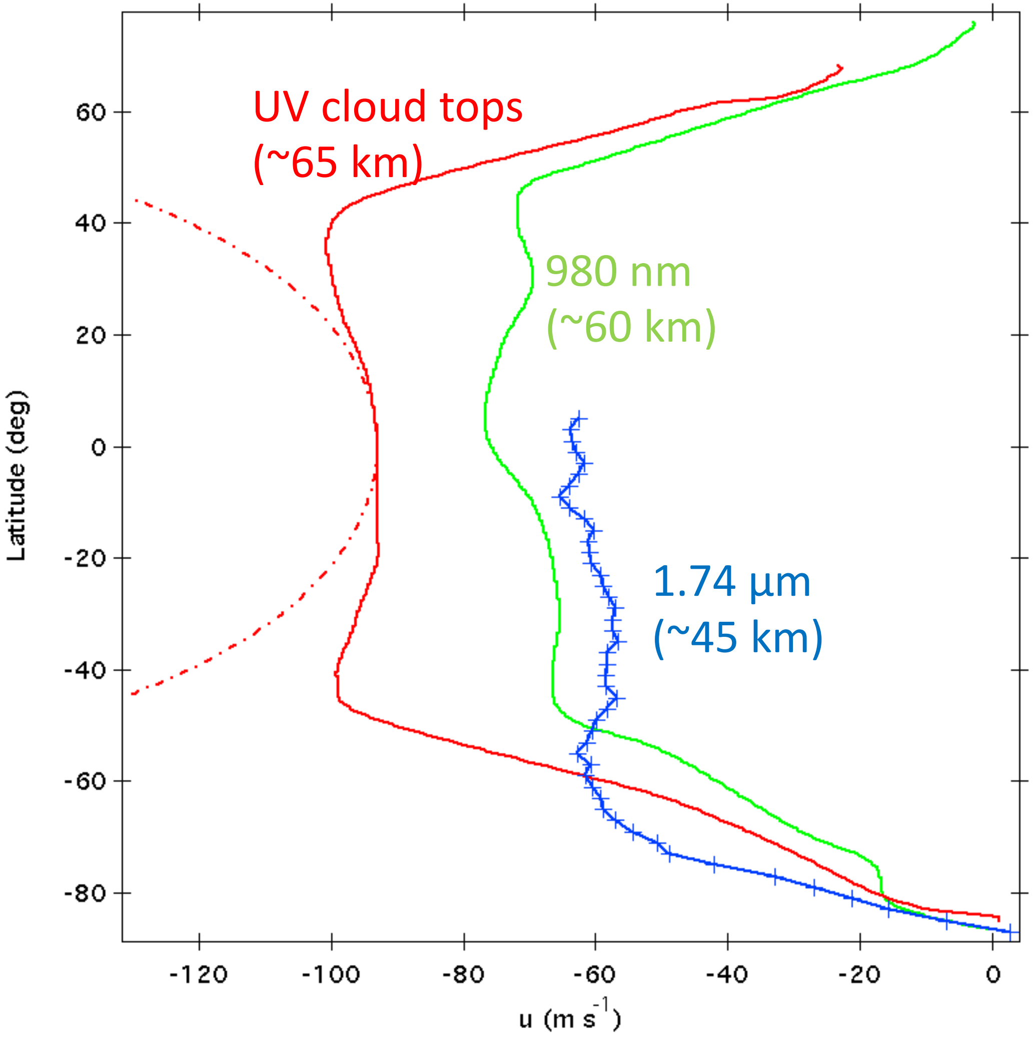

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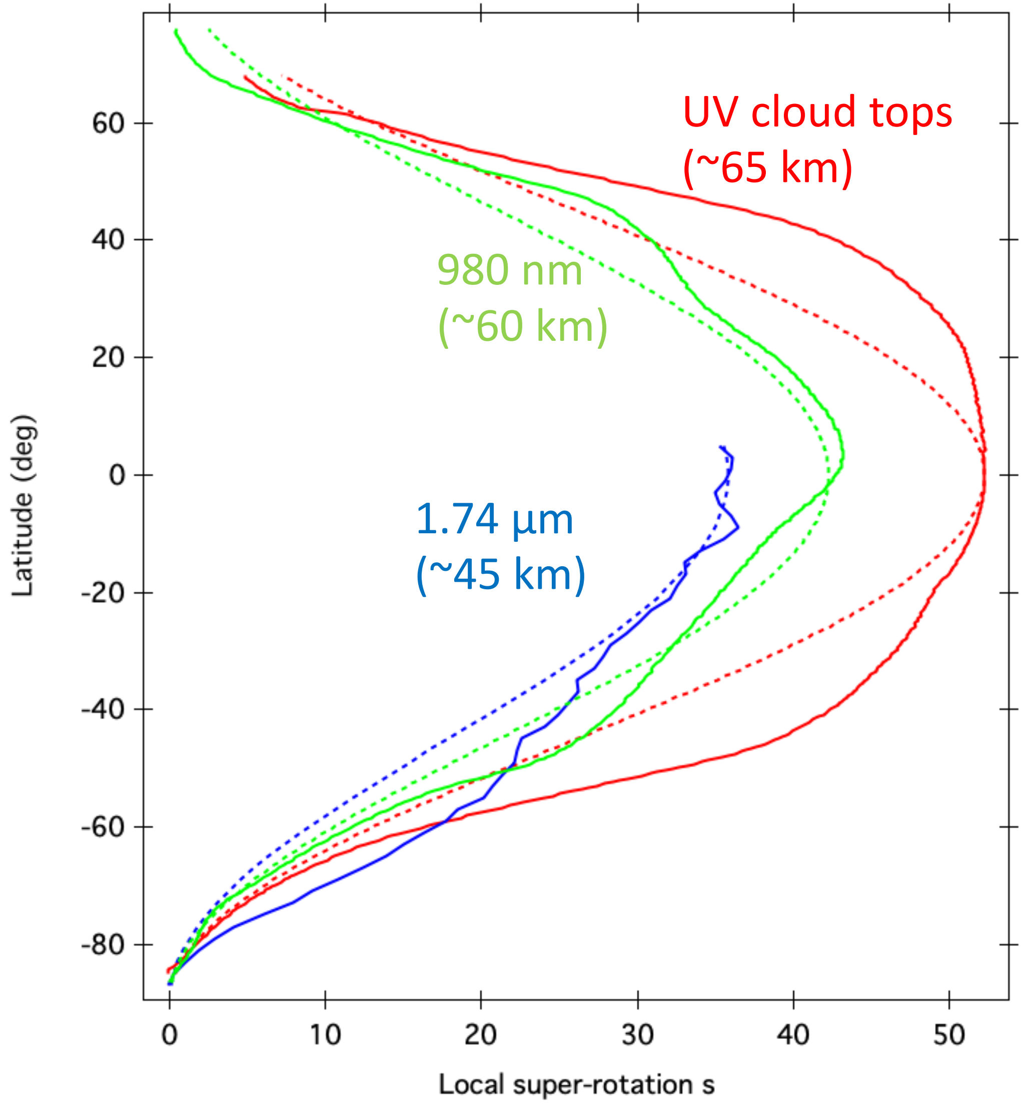

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  - Tracking cloud features in the UV and IR
    - Prograde winds up to 100 m s^{-1} or more at cloud tops, even on the equator
    - Very large local super-rotation *s*
    - Zonal AND meridional velocities
  - Entry probes
    - Doppler tracking as probes descend
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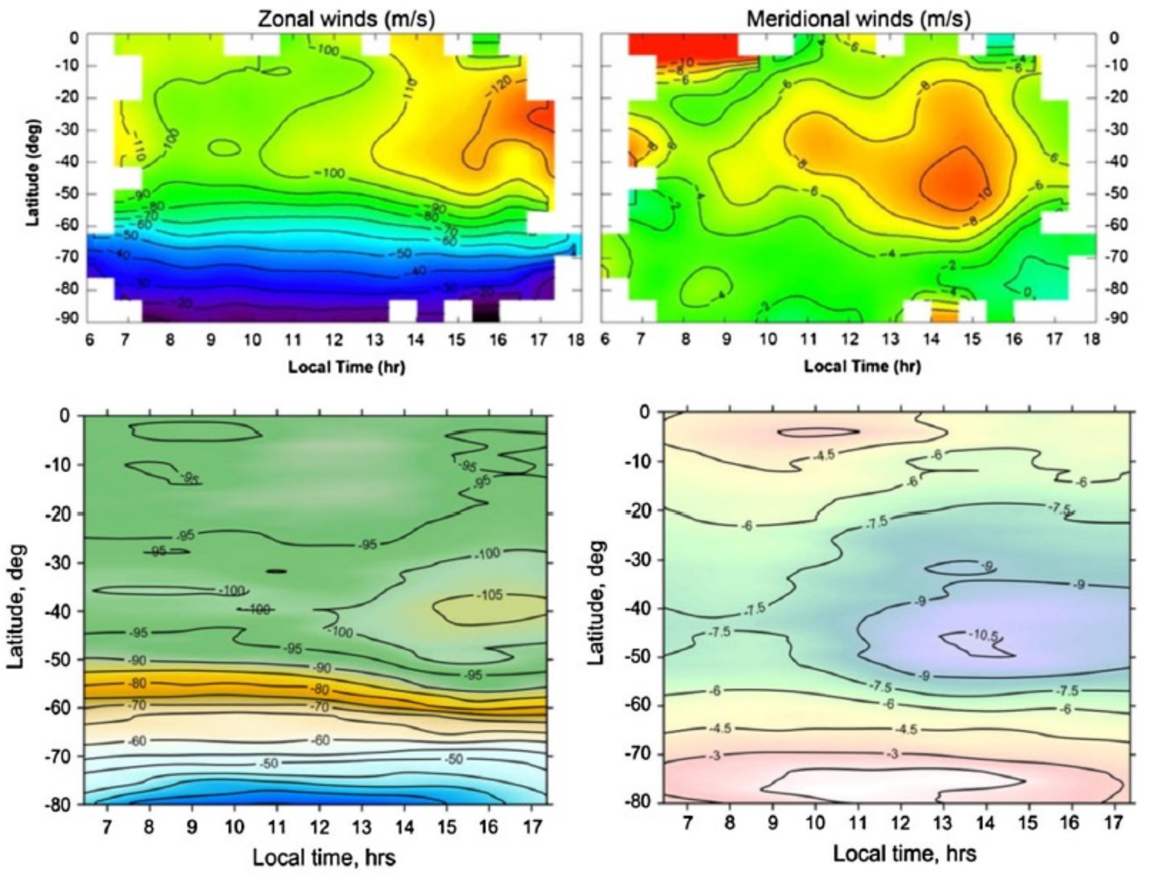

Fig. 7 The long-term averaged horizontal wind velocity as a function of latitude and local time from the tracking of cloud motions with Venus Express. *Upper panel*: VIRTIS measurements 2006-12 (Hueso et al. 2015). *Lower panel*: VMC measurements (Khatuntsev et al. 2013)

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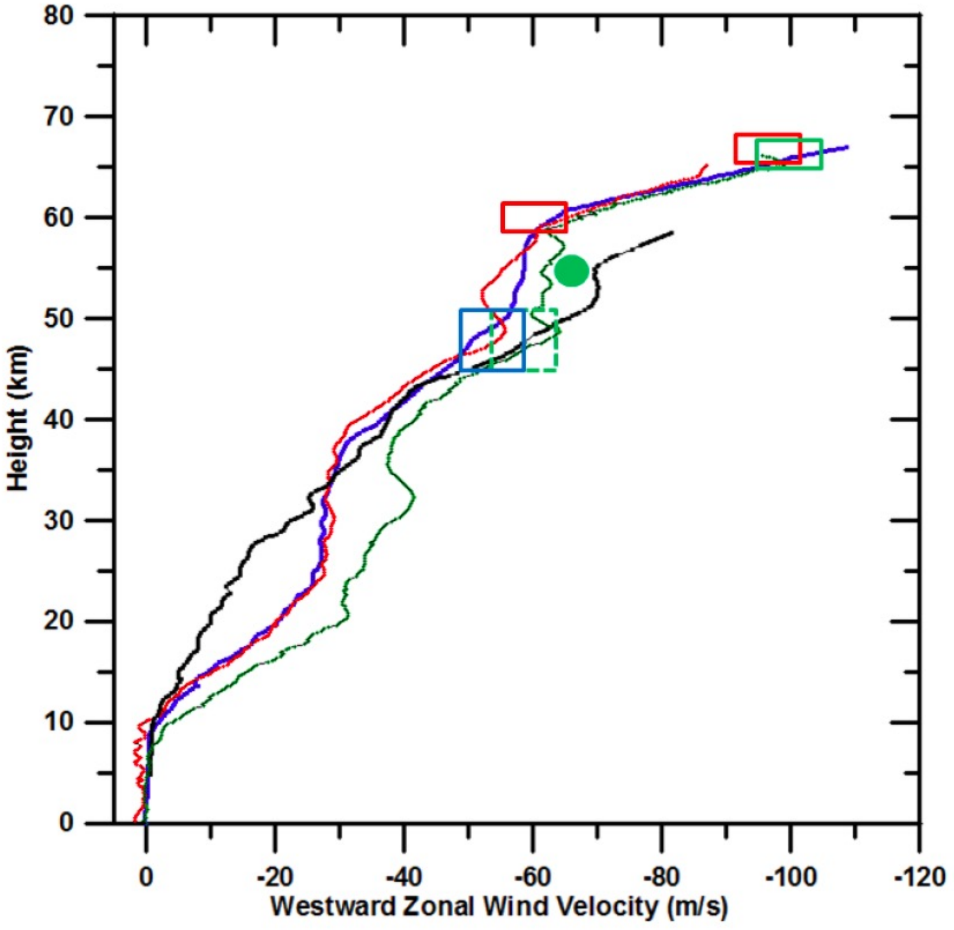
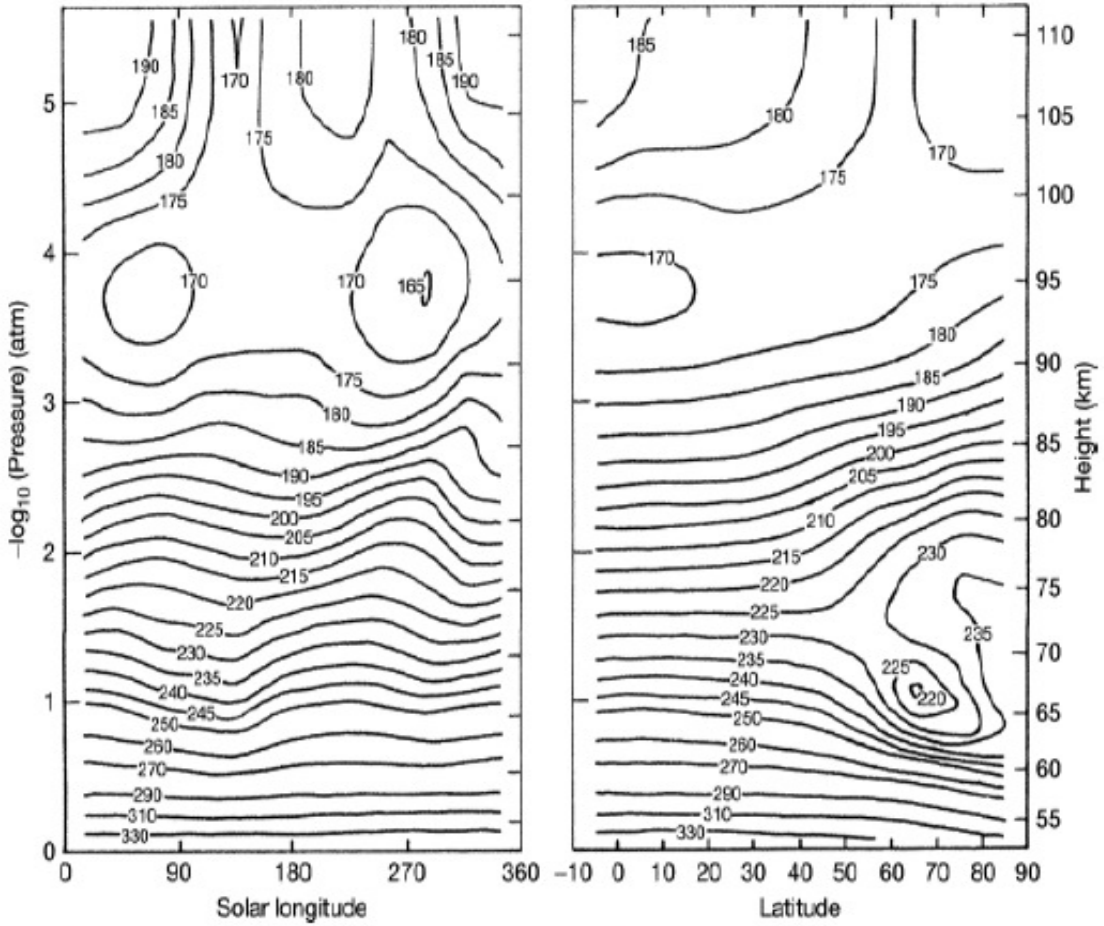


How do we know Venus's atmosphere super-rotates?

[Schofield & Taylor 1980]



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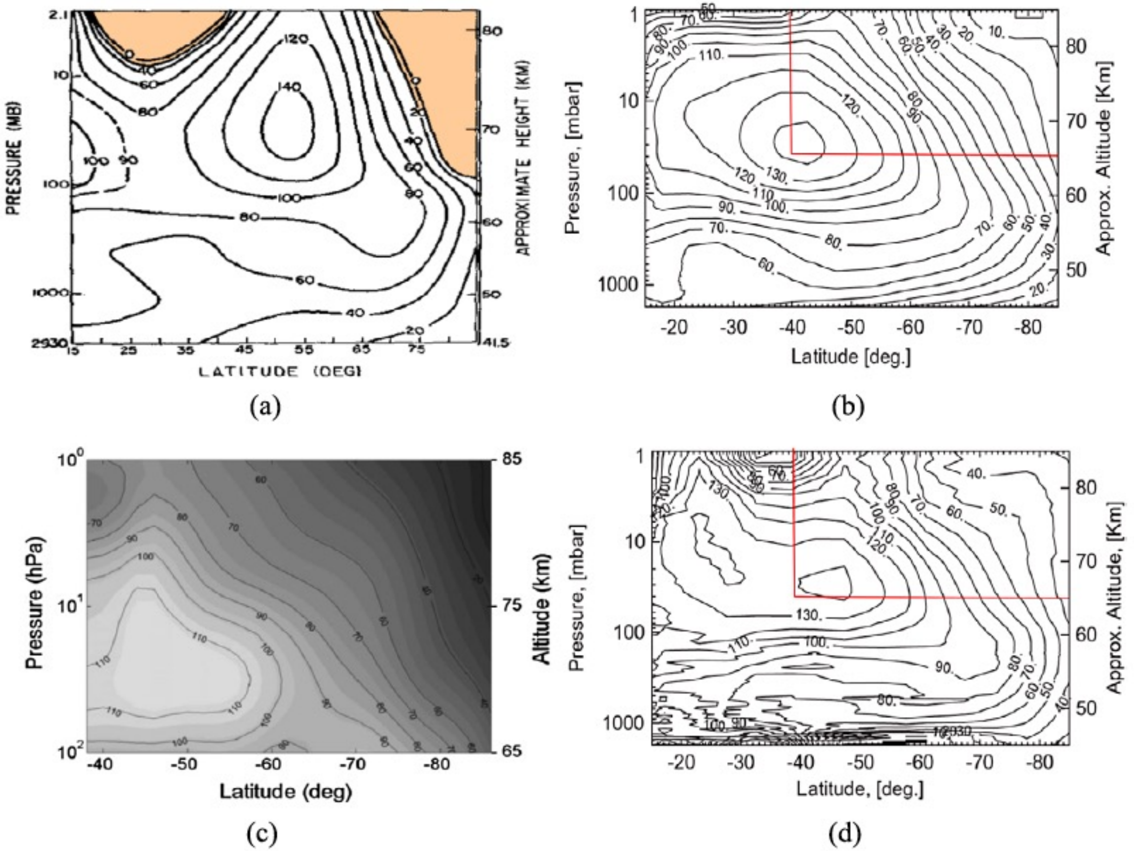


Fig. 9 Zonal velocity fields derived from integrating Eq. (4) upwards from a given velocity profile: (**a**) from Pioneer Venus radio-occultation temperatures (Newman et al. 1984), (**b**) & (**c**) from the VIRTIS instrument on the Venus Express spacecraft (Grassi et al. 2010) by (**b**) Piccialli et al. (2012) and (**c**) Mendonca et al. (2012); (**d**) zonal velocity field retrieved by direct application of Eq. (3) using $z(p)$ data from VeRA on Venus Express (Piccialli et al. 2012). Regions where no solution for u is possible are shown shaded in (**a**). The region in (**c**) is indicated by *red lines* in (**b**) and (**d**) for comparison

How do we know Venus's atmosphere super-rotates?

- Observations
  - Spatial coverage for (u,v) is reasonably good within/above main cloud decks
  - Poor at deeper levels
  - No vertical velocities....
  - Local time coverage?
- Also need to rely on models and simulations
  - Explore hypotheses for dynamical mechanisms
  - Predict circulation in places inaccessible to observations
  - Simple GCMS
  - Comprehensive GCMs

Simple GCMs for Venus's atmosphere

- Full PEs but with simplified parameterisations
  - Linear relaxation to T_{eq}
  - Surface drag
  - Dry convection
  - No diurnal cycle?
- Success reproducing realistic super-rotation has been highly variable
  - Based on GRW scenario
  - Depends on model accuracy and conservation properties

2 - 2 YAMAMOTO AND TAKAHASHI: VENUSIAN SUPERROTATION

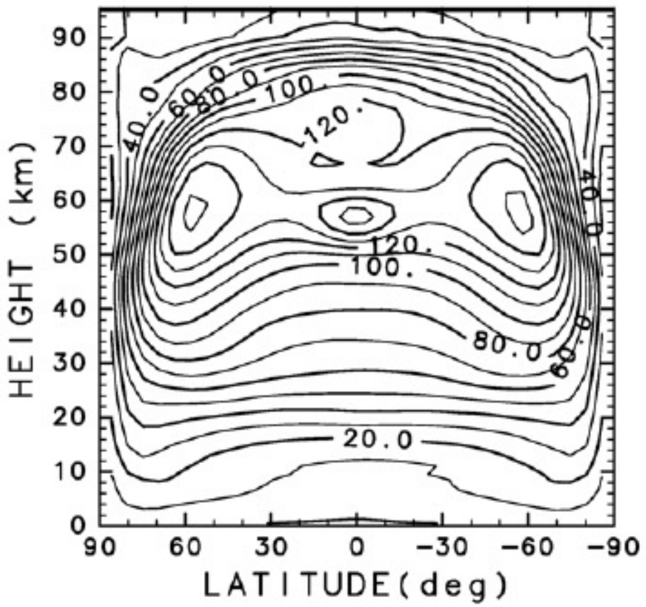


Figure 1. Latitude–height cross section of longitudinally averaged zonal flow (m s^{-1}).

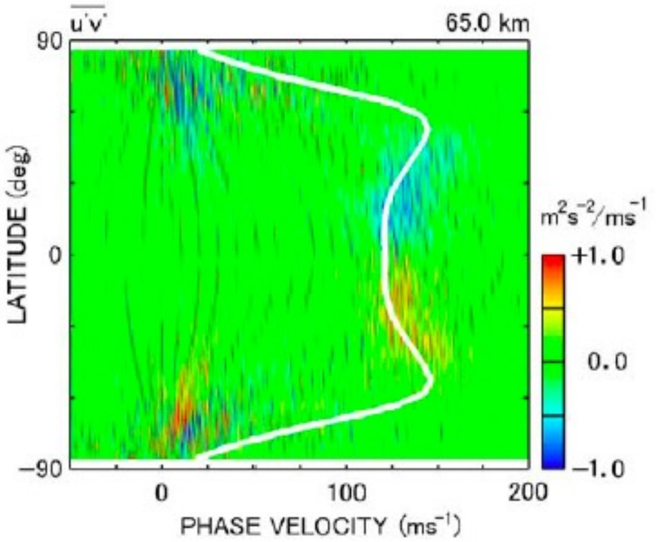
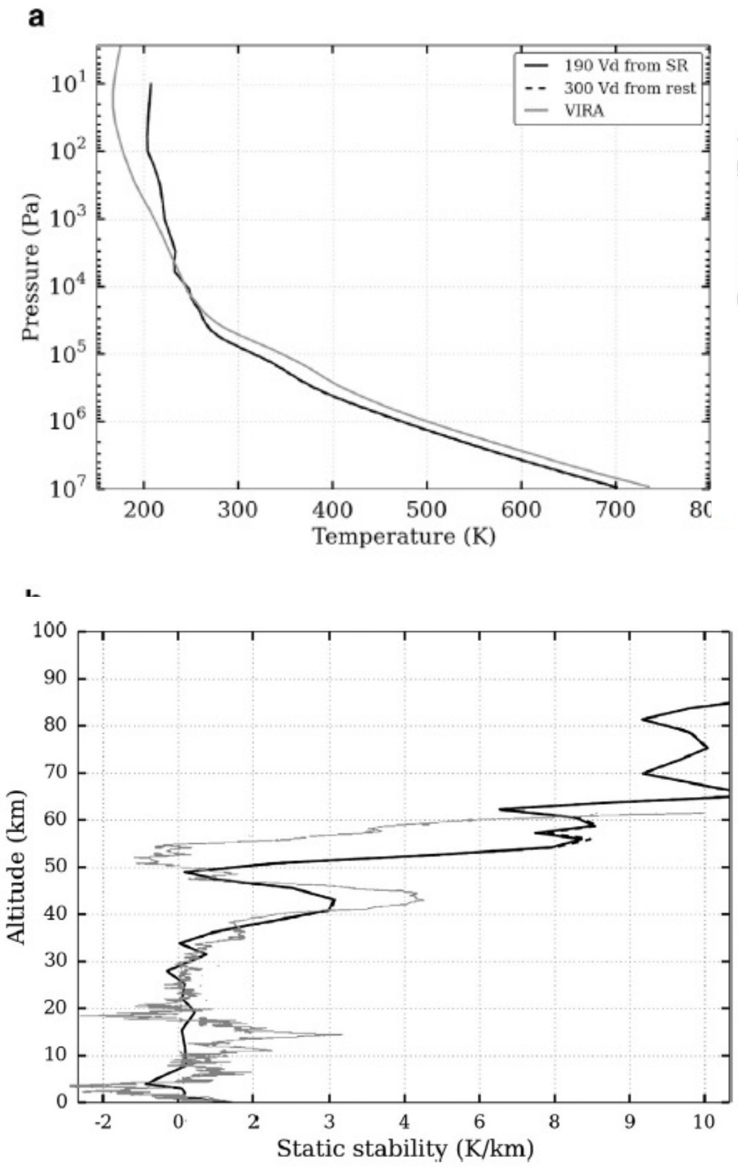


Figure 2. Phase-velocity–latitude cross section of spectrum of $\overline{u'v'}$ at 65 km altitude. The white curve indicates mean zonal flow.

Comprehensive GCMs for Venus's atmosphere

[Lebonnois et al. 2018]

- Full PEs with more realistic parameterisations
  - Full radiative transfer
  - Boundary layer turbulence
  - Surface topography
  - Clouds and chemistry?
- Reproduce realistic T structure
  - And velocity fields near cloud tops
  - Some deficiencies in $\bar{u}(z)$ in deep atmosphere (z < 50 km)?



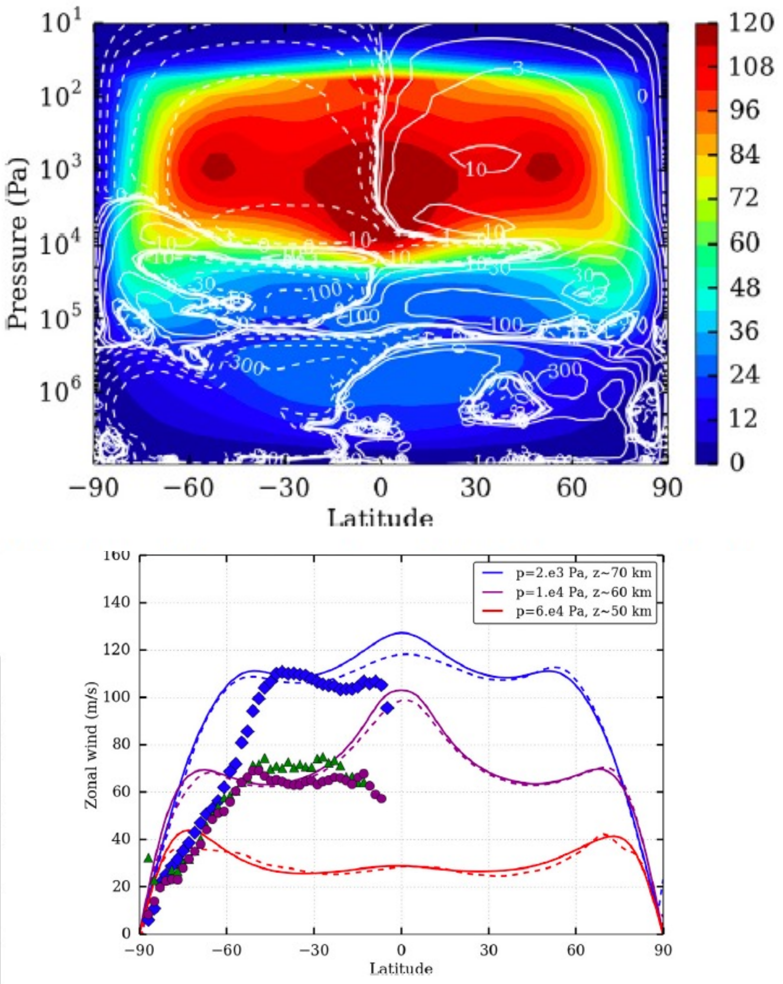


Fig. 6. Zonal and temporal averaged profiles of the zonal wind: (a) vertical profiles at three different latitudes, compared to observed profiles from Venera and Pioneer Venus probes (gray, adapted from Schubert, 1983); (b) latitudinal profiles at roughly 50, 60 and 70 km altitude, compared to averaged cloud-tracking zonal wind profiles obtained with VIRTIS-M images at UV (blue diamonds), visible (green triangles) and near-IR (magenta circles) wavelengths. They correspond to altitudes 66–72 km for UV spectral range, and a few kilometers below that level for visible/near-IR wavelengths (adapted from Hueso et al., 2015). The dashed lines are from the simulation started from rest, after 300 Vd. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Comprehensive GCMs for Venus's atmosphere

[Lebonnois et al. 2018]

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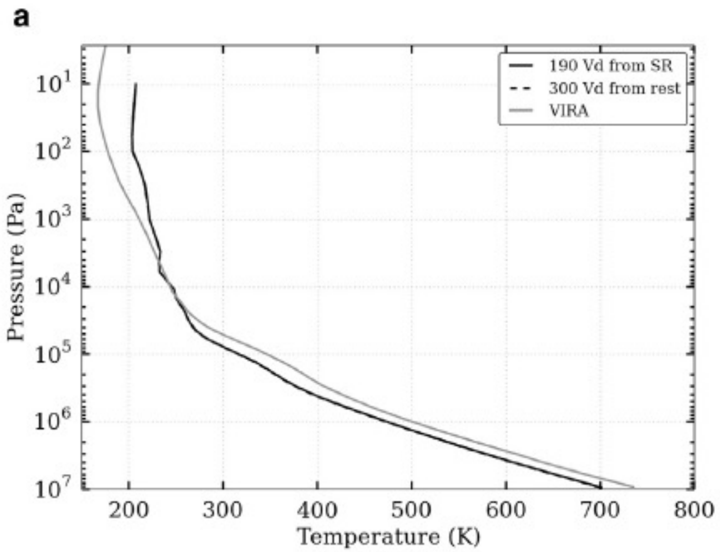
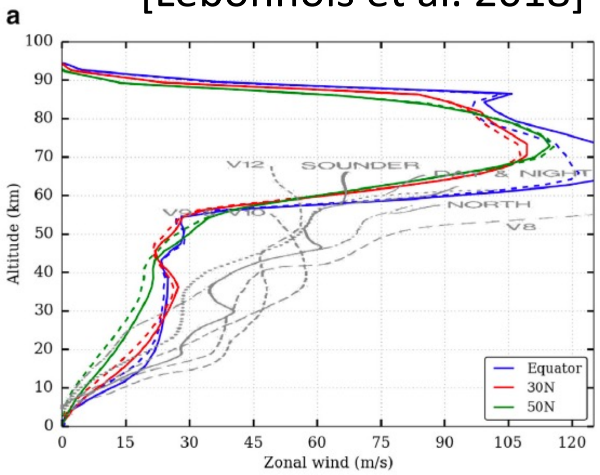
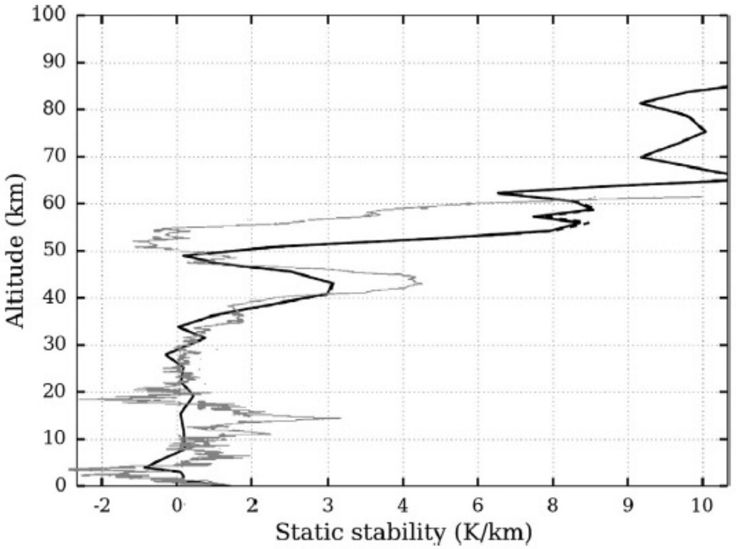
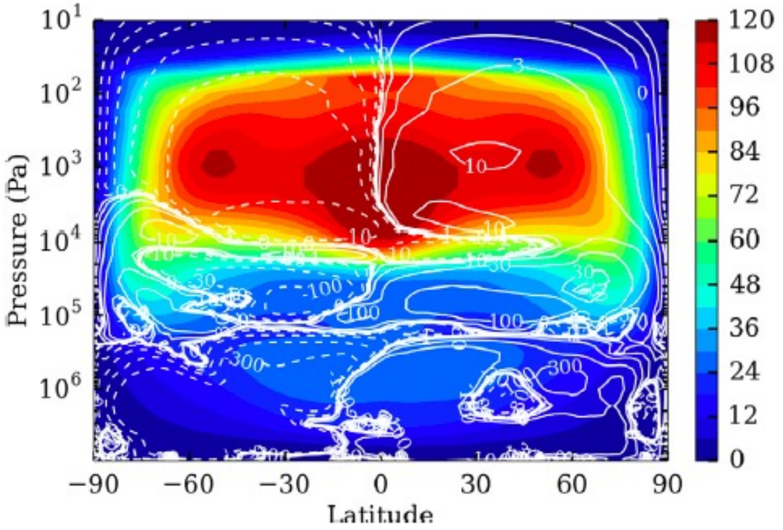








near-IR (magenta circles) wavelengths. They correspond to altitudes 66–72 km for UV spectral range, and a few kilometers below that level for visible/near-IR wavelengths (adapted from Hueso et al., 2015). The dashed lines are from the simulation started from rest, after 300 Vd. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Venus super-rotation: key questions

- Mechanisms to accelerate and maintain super-rotation?
  - Structure and role of meridional overturning circulations?
  - Which wave modes dominate eddy AM transport?
  - Origin of principal wave modes?
    - Instabilities? [Which?]
    - Tides?
    - Topography?
  - Impact of waves on observable features?
    - Clouds, temperatures etc….
- How to verify models?
  - Which observations?
  - Feasibility and role of data assimilation….?

Venus super-rotation: key questions

- Which kinds of waves? [Summary from Lebonnois et al. 2016]
    - Thermal tides
        - Semi-diurnal
        - Diurnal

      Contribute significantly to vertical AM transport
    - Equatorial planetary waves
        - Rossby
            - Periods ~6-20 d, mainly at high-mid latitudes
        - Kelvin
            - Period ~7 d, centred on equator
        - MRG….
            - Period ~ 16 d
    - Inertia-gravity waves
        - High frequencies and short wavelengths
- Mixture depends to some extent on the model and large-scale atmospheric structure, static stability etc.!

Venus super-rotation: key questions

Observed: [Del Genio & Rossow 1990]

- Which kinds of waves?
  - Thermal tides
    - Semi-diurnal
    - Diurnal
  - Equatorial planetary waves
    - Rossby
      - Periods ~5 d, mainly at high-mid latitudes
    - Kelvin
      - Period ~4 d, centred on equator
    - MRG….
      - Period ~ 16 d
  - Inertia-gravity waves
    - High frequencies and short wavelengths
- Mixture depends to some extent on the model and large-scale atmospheric structure, static stability etc.!

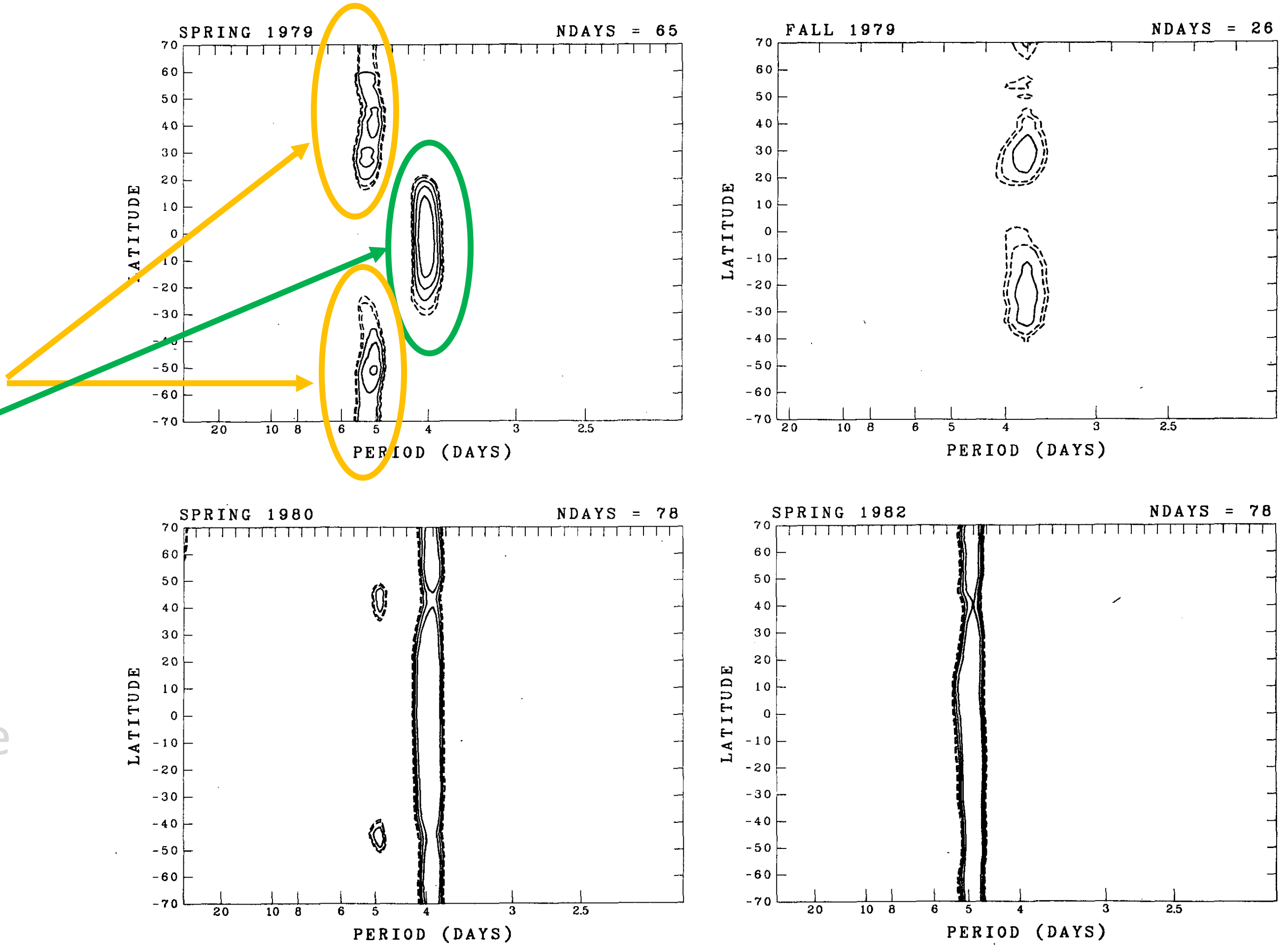


FIG. 1. Time series power spectra of UV brightness fluctuations as a function of latitude and wave period. The contours represent constant statistical significance at the 75% and 85% levels (dashed) and the 95%, 99%, and 99.9% levels (solid) with respect to a white noise spectrum for 2.6 degrees of freedom (Del Genio and Rossow 1982). Tickmarks at top indicate resolved frequencies in cycles/NDAYS. NDAYS is 1 less than the values given in Table 1 because of the Fourier analysis procedure (Rossow et al. 1980). Upper left: spring 1979; upper right: fall 1979; lower left: spring 1980; lower right: spring 1982.

Venus super-rotation: key questions

Observed: [Imai et al. 2019]

- Which kinds of waves?
  - Thermal tides
    - Semi-diurnal
    - Diurnal
  - Equatorial planetary waves
    - Rossby
      - Periods ~5.1 d, mainly at high-mid latitudes
    - Kelvin
      - Period ~3.8 d, centred on equator
    - MRG….
      - Period ~ 16 d
  - Inertia-gravity waves
    - High frequencies and short wavelengths
- Mixture depends to some extent on the model and large-scale atmospheric structure, static stability etc.!

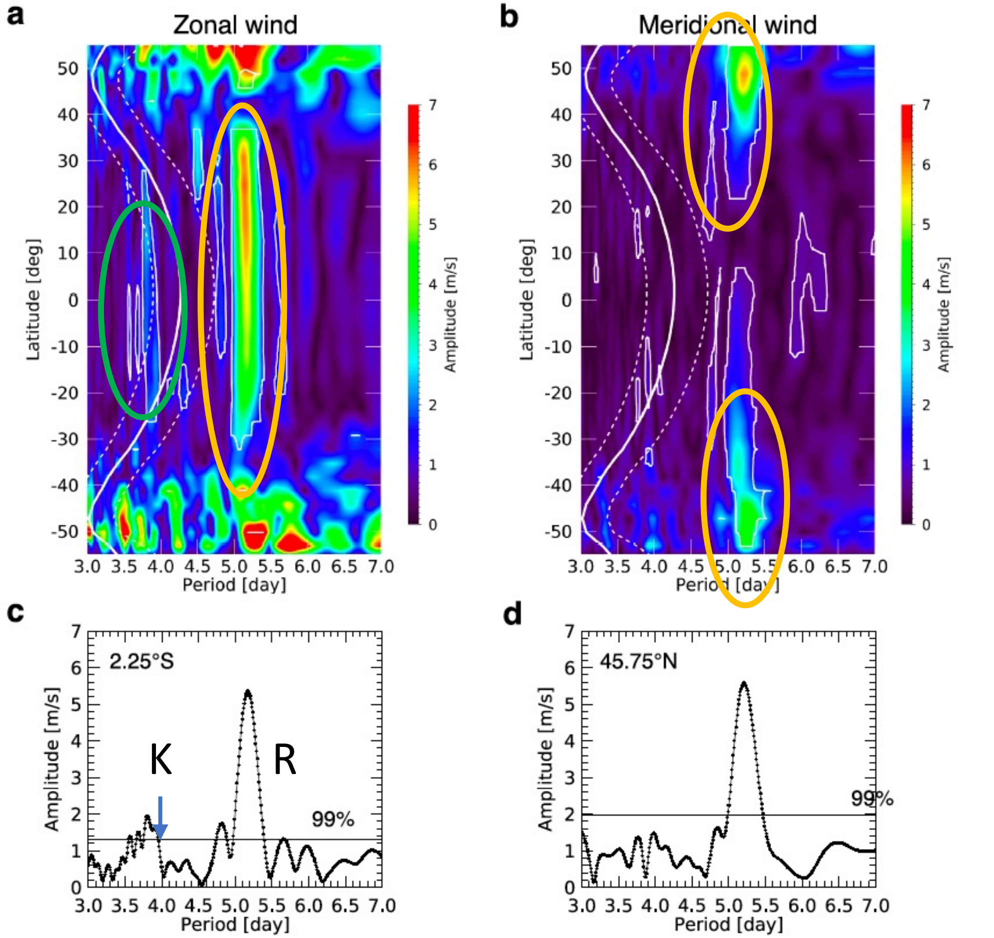
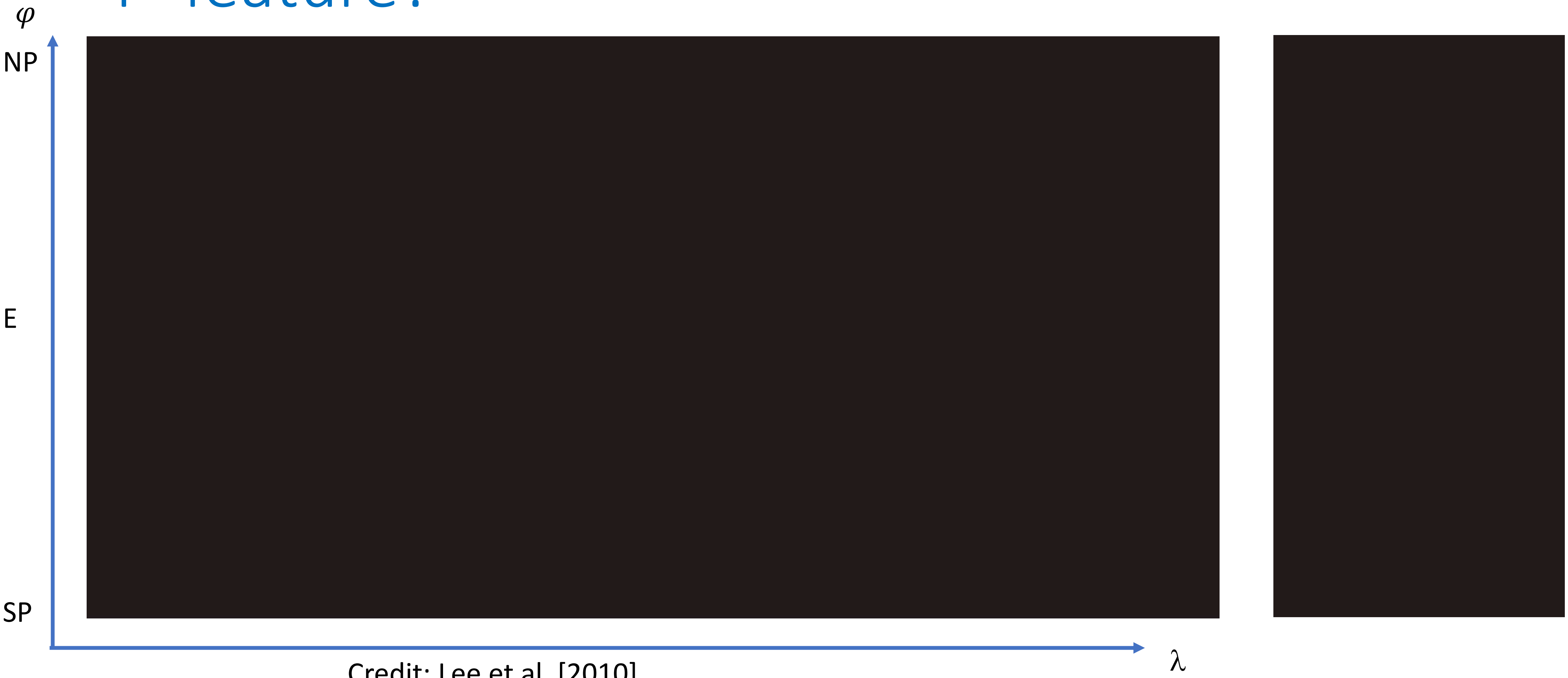


Figure 7. Amplitude spectra of the (a) zonal and (b) meridional wind as a function of latitude obtained from the Lomb-Scargle periodogram analysis. The colored regions enclosed by the thin solid white lines possess >99% significance. The thick solid white line and dashed white lines indicate the corresponding period of the background dayside mean zonal wind and the ±10 m/s statistical variation, respectively. (c and d) The amplitude spectra of the zonal wind at 2.25°S and meridional wind at 45.75°N, and the horizontal lines indicate the 99% significance level.

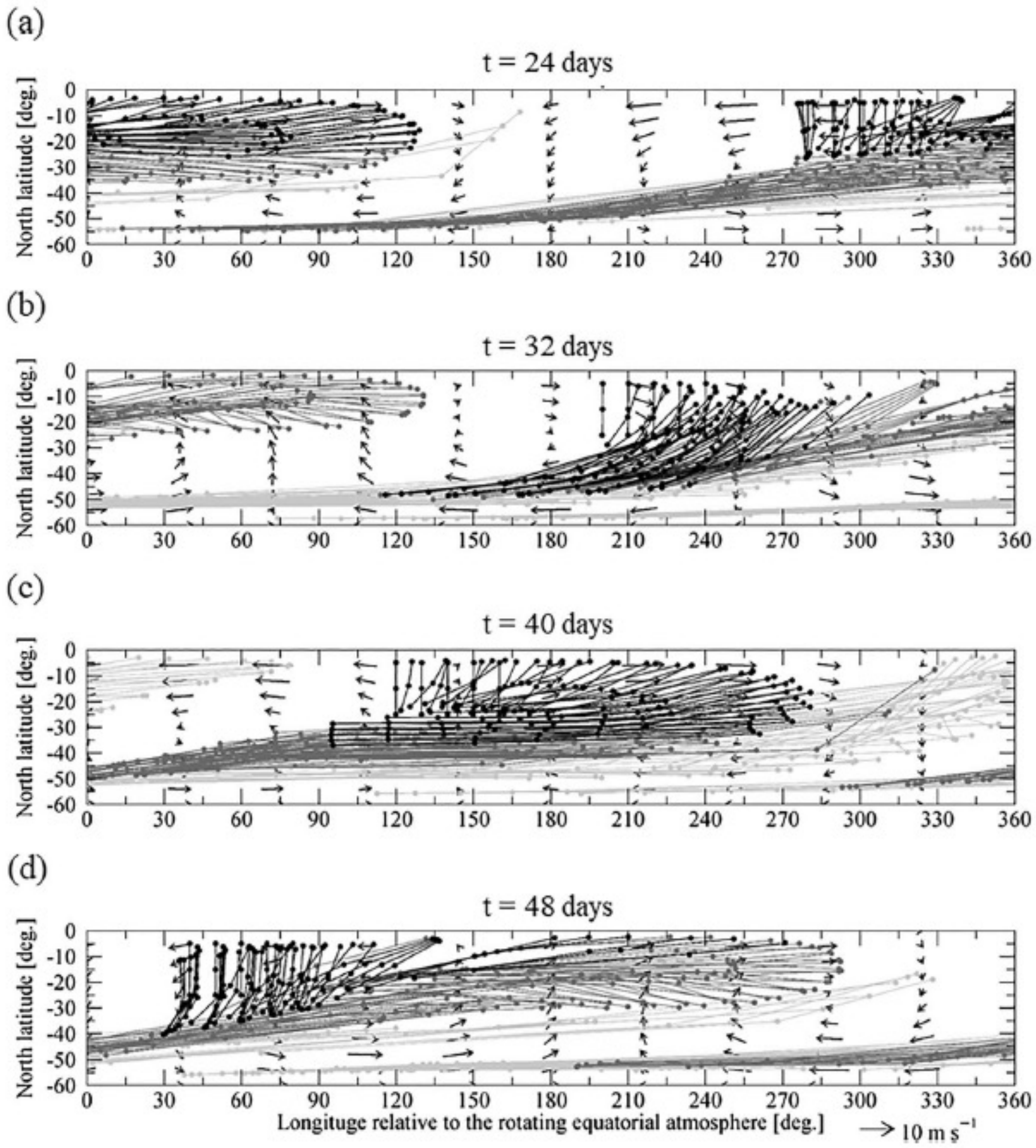
Impact of planetary waves on clouds: origin of ‘Y’-feature?



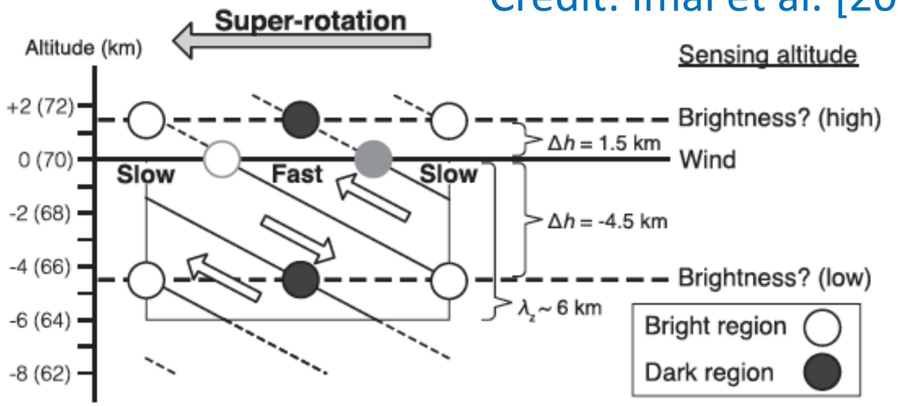
Credit: Lee et al. [2010]

Impact of planetary waves on clouds: origin of 'Y'-feature?

- Produced by vertical and horizontal advection of cloud tracers by Kelvin and Rossby(?) waves within the cloud layers
  - Generated in SGCM by Lee et al. [2010]
  - Confirmed in observations and explicit transport model by Nara et al. [2019]



Credit: Imai et al. [2010]



Venus super-rotation: key questions

- Origin of waves
  - Thermal tides
    - Semi-diurnal
    - Diurnal

    Directly forced in and above main cloud decks [p < 1bar]
  - Equatorial planetary waves
    - Rossby
      - Barotropic and baroclinic instabilities
    - Kelvin
      - ??Barotropic Rossby-Kelvin instability??
    - MRG….
      - ??Ditto??
  - Inertia-gravity waves
    - Local convection and KH instabilities?
- Mixture depends to some extent on the model and large-scale atmospheric structure, static stability etc.!
  - Mechanisms also vary significantly with location:
    - Tropics vs midlatitudes or polar regions?
    - Cloud decks vs upper levels or deep atmosphere?

Venus super-rotation: key questions

Credit: [Sugimoto et al. 2014]

- Origin of waves
  - Thermal tides
    - Semi-diurnal
    - Diurnal
  - Equatorial planetary waves
    - Rossby
      - Barotropic and baroclinic instabilities
    - Kelvin
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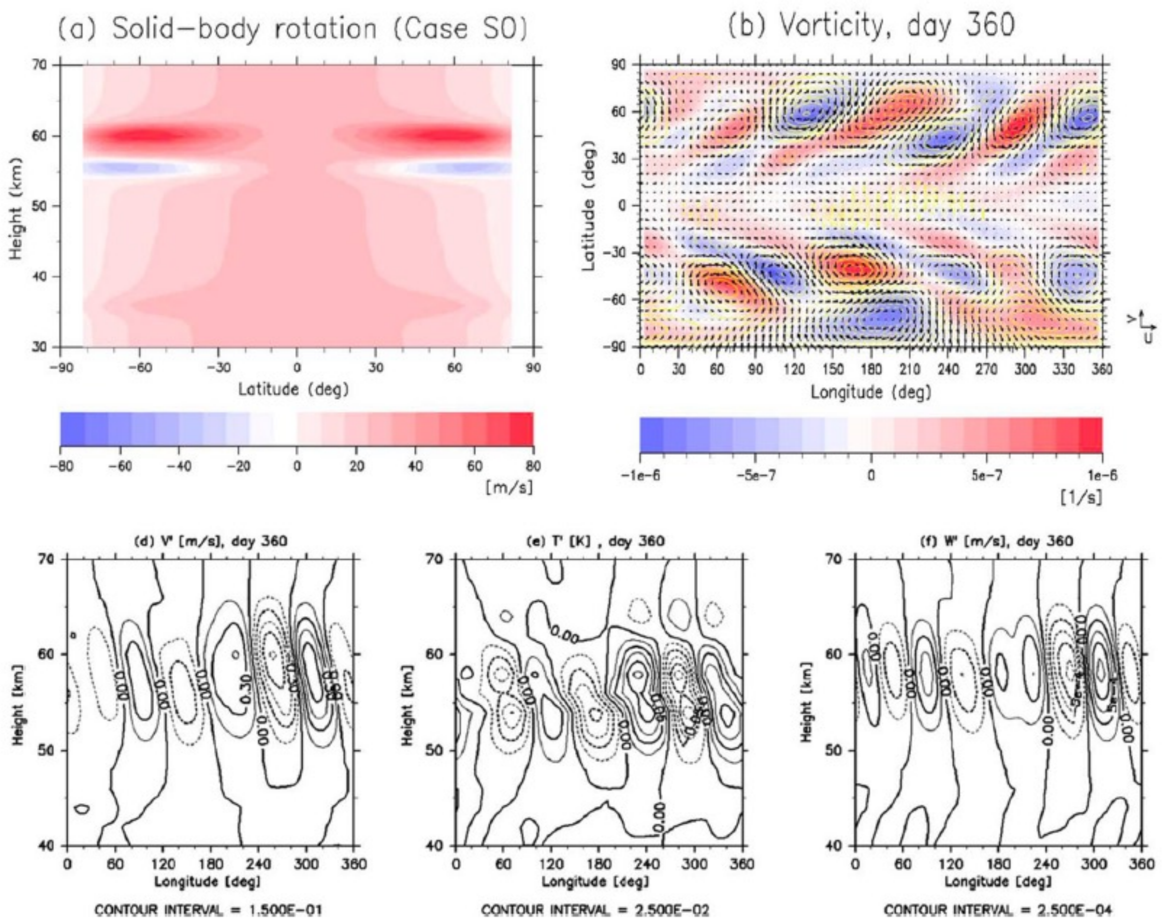
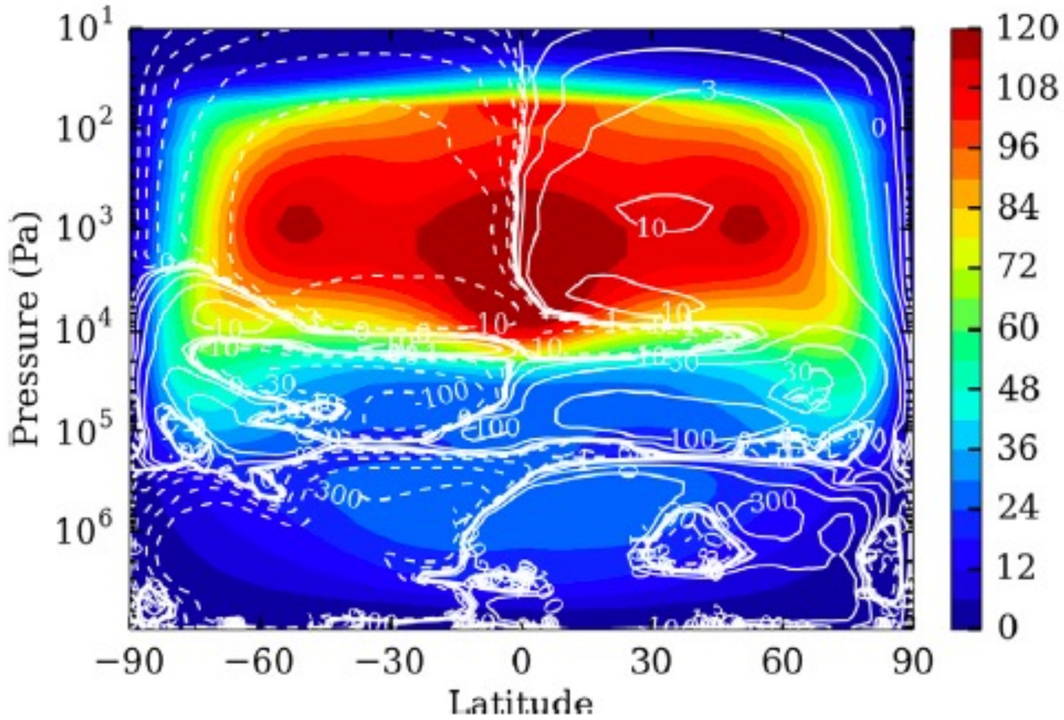
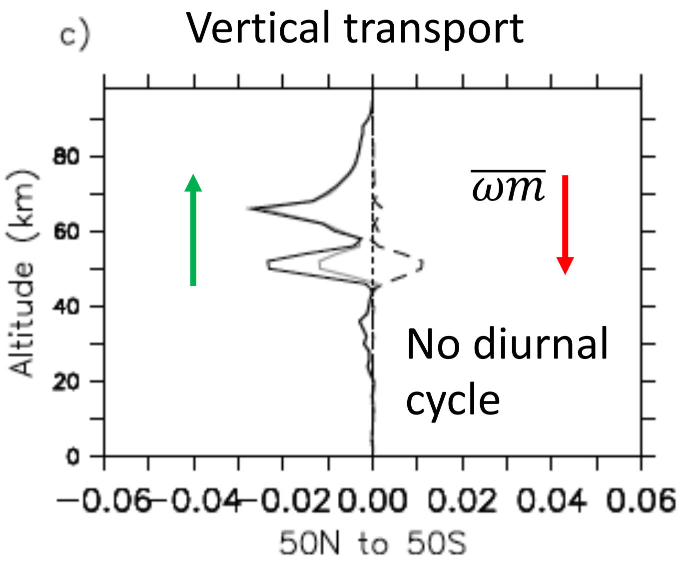


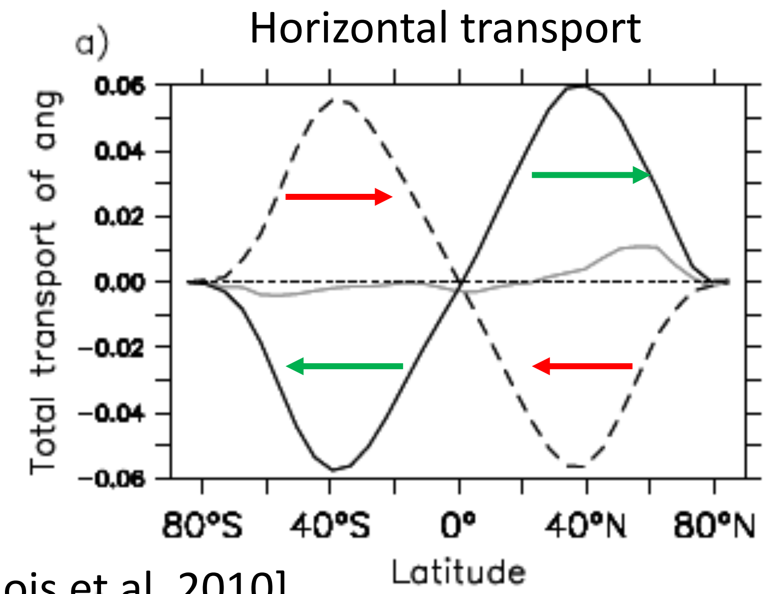
Fig. 24 Results from numerical simulations (by Sugimoto et al. 2014a, 2014b) of the nonlinear baroclinic instability of a cyclostrophically balanced, vertically-sheared initial state in local solid-body rotation under Venus conditions; (**a**) basic state potential vorticity gradient, (**b**) velocity vectors and eddy vorticity field at 54 km altitude, (**c**)–(**e**) longitude-height maps of (**c**) eddy meridional velocity, (**d**) temperature perturbation and (**e**) vertical velocity. (**b**)–(**e**) are shown at day 360 from an initialized state

Venus super-rotation:

- Mechanisms to accelerate and maintain super-rotation?
  - Structure and role of meridional overturning circulations?
    - Complex, multi-cellular structure
    - Transports AM upwards and polewards [green]
    - Transient eddies transport AM downwards and equatorwards



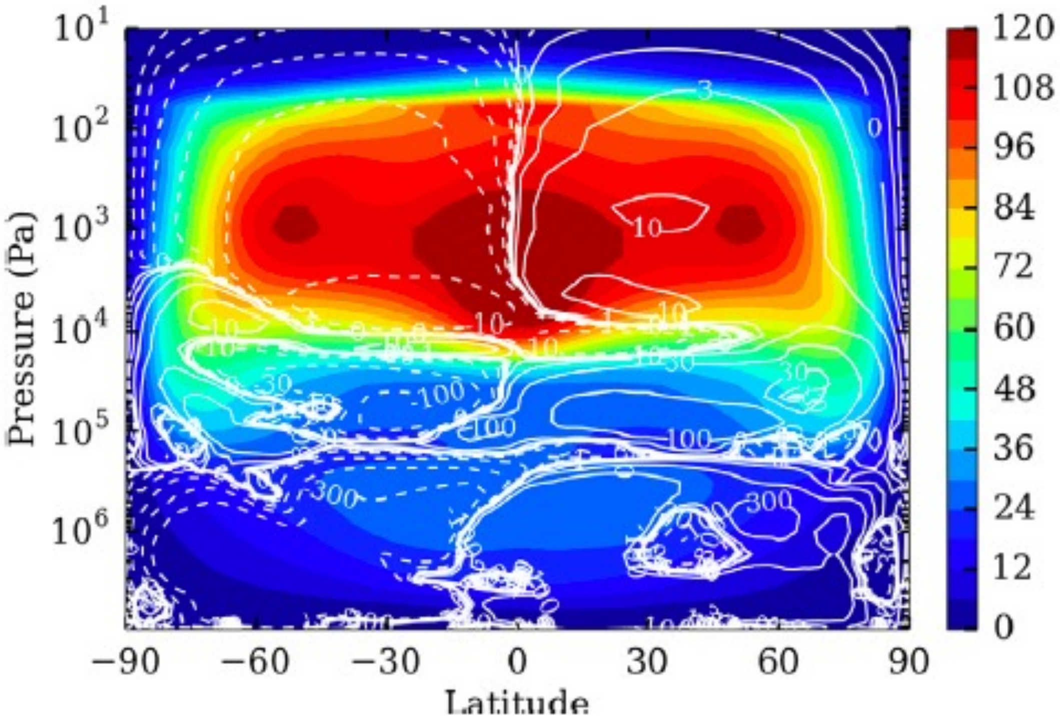


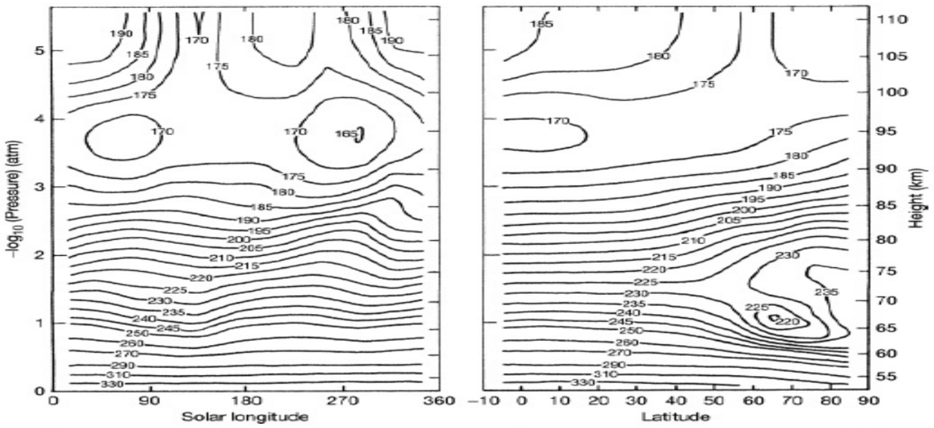


[Lebonnois et al. 2010]

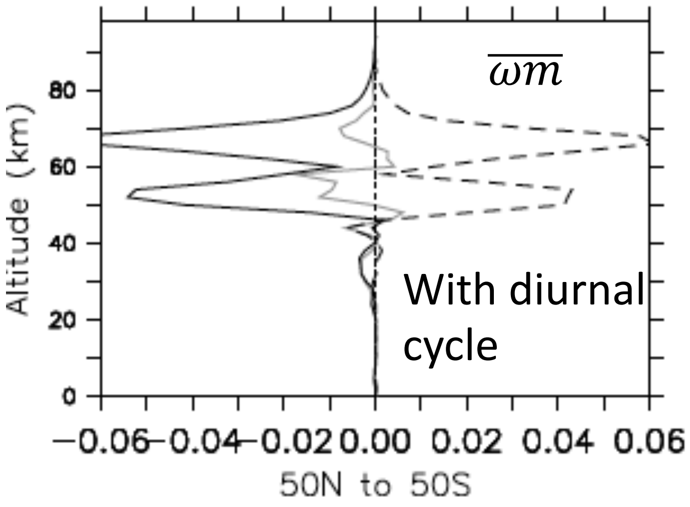
Venus super-rotation:

- Mechanisms to accelerate and maintain super-rotation?
  - Structure and role of meridional overturning circulations?
    - Complex, multi-cellular structure
    - Transports AM upwards and polewards
    - Enhanced/modified by diurnal cycle

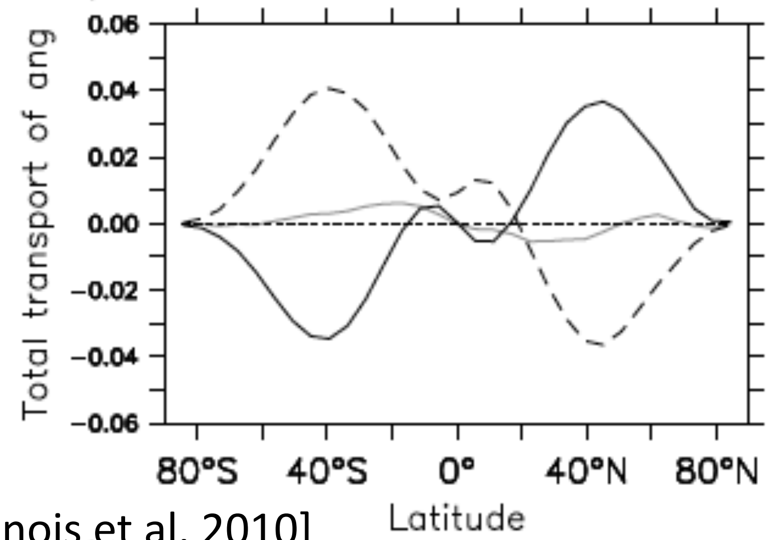




Vertical transport



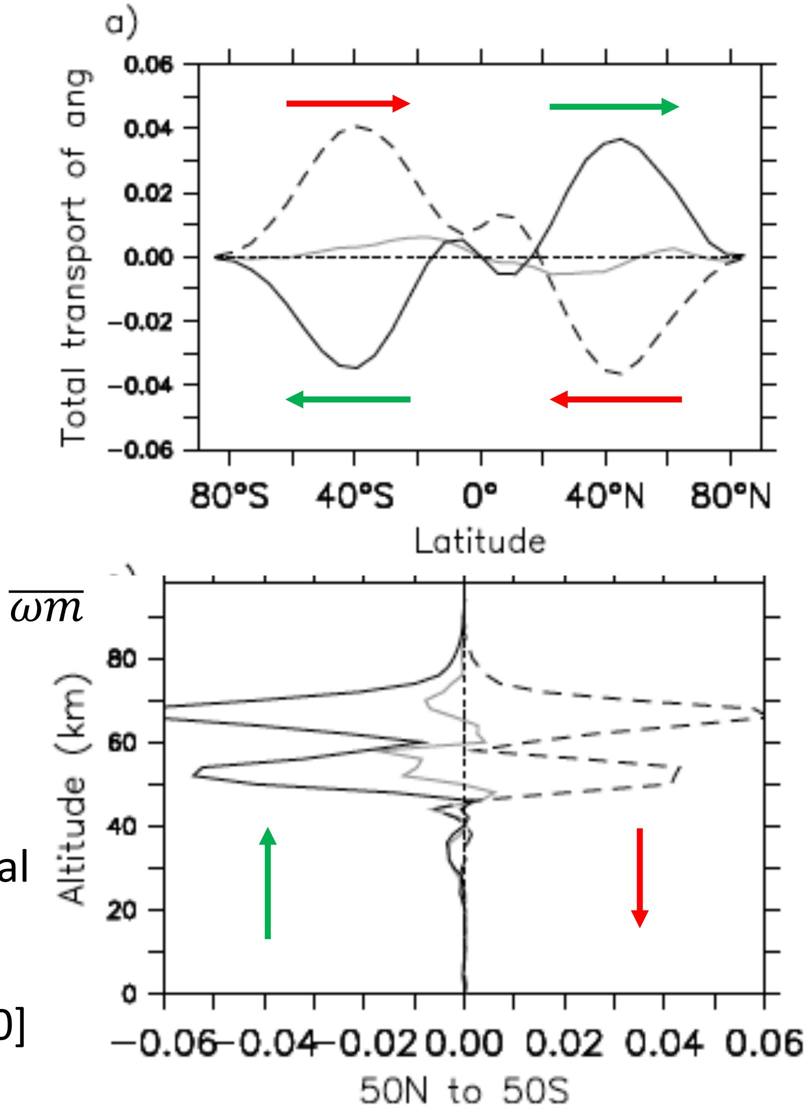
Horizontal transport



[Lebonnois et al. 2010]

Venus super-rotation: key questions

- Mechanisms to accelerate and maintain super-rotation?
  - Structure and role of meridional overturning circulations?
    - Complex, multi-cellular structure
    - Transports AM upwards and polewards
    - Enhanced/modified by diurnal cycle
  - Role of waves (with tides)?
    - Equatorward transport of *m*?
    - Downward transport of *m*?



With diurnal cycle

[Lebonnois et al. 2010]

Venus super-rotation: key questions

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    - Transports AM upwards and polewards
    - Enhanced/modified by diurnal cycle
  - Role of waves?
    - Equatorward transport of *m*
    - Downward transport of *m?*
- Zonal momentum budget

$$\frac{\partial \bar{u}}{\partial t} = -\overline{\boldsymbol{u}_*}.\nabla m - \nabla.\boldsymbol{F} + \bar{X}$$

Mean mer. circulation. EP flux convergence

With diurnal cycle

[Mendonça & Read 2016]

J.M. Mendonça, P.L. Read

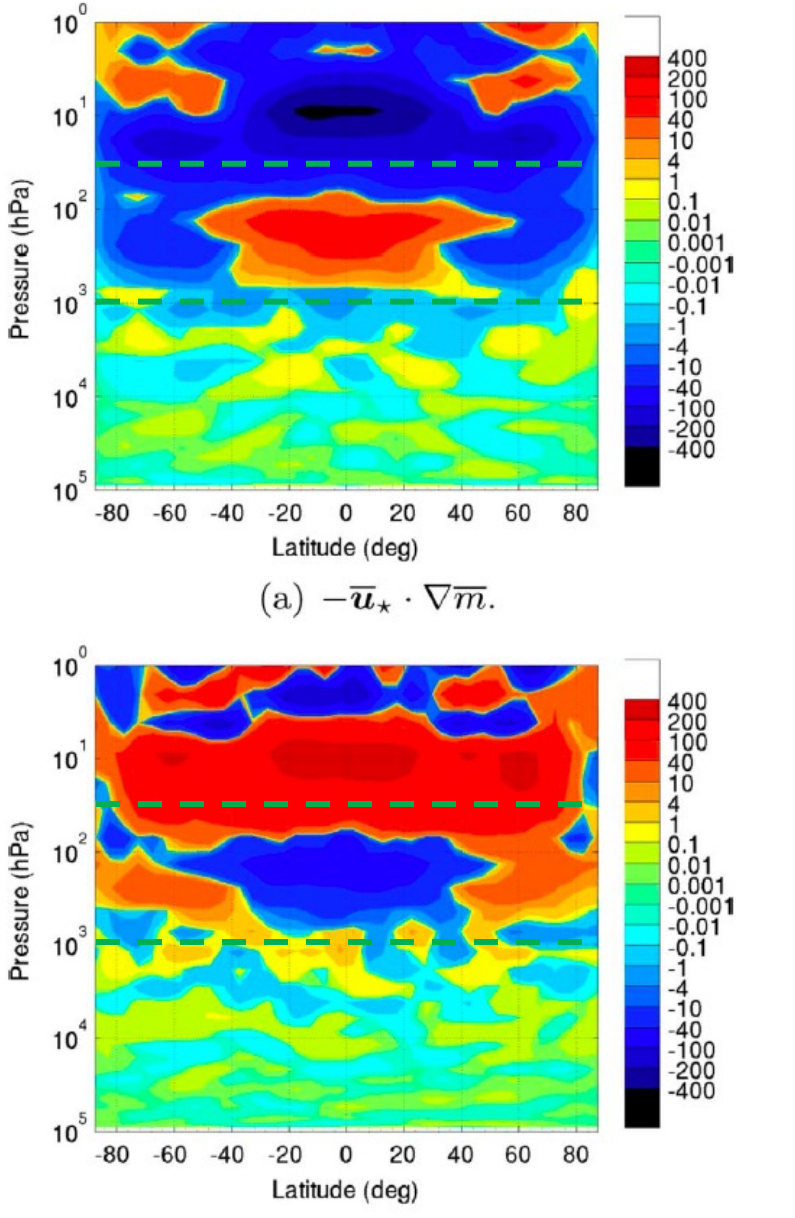

Fig. 9. Eliassen–Palm flux diagnostics: (a) acceleration due to mean circulation; (b) acceleration due to resolved waves. The units are in $m^2 s^{-2}$.

Venus super-rotation: key questions

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- Zonal momentum budget

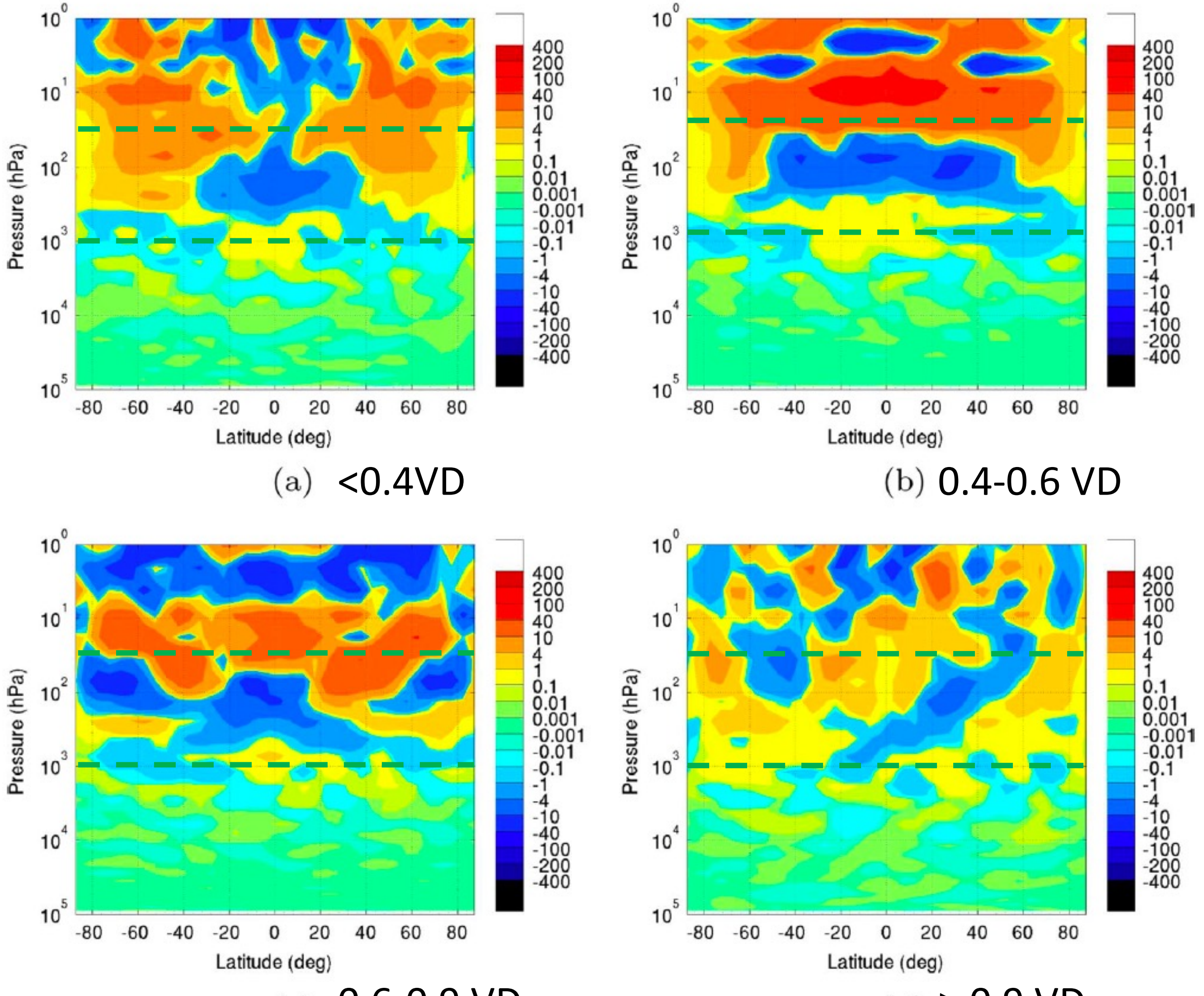
$$\frac{\partial \bar{u}}{\partial t} = -\overline{\boldsymbol{u}_*}.\nabla m - \nabla.\boldsymbol{F}[+\bar{X}]$$

Mean mer. circulation. EP flux convergence

  - Which wave modes?

[Mendonça & Read 2016]

$-\nabla.\boldsymbol{F}$



(a) <0.4VD (b) 0.4-0.6 VD (c) 0.6-0.9 VD (d) > 0.9 VD

Venus super-rotation: key questions

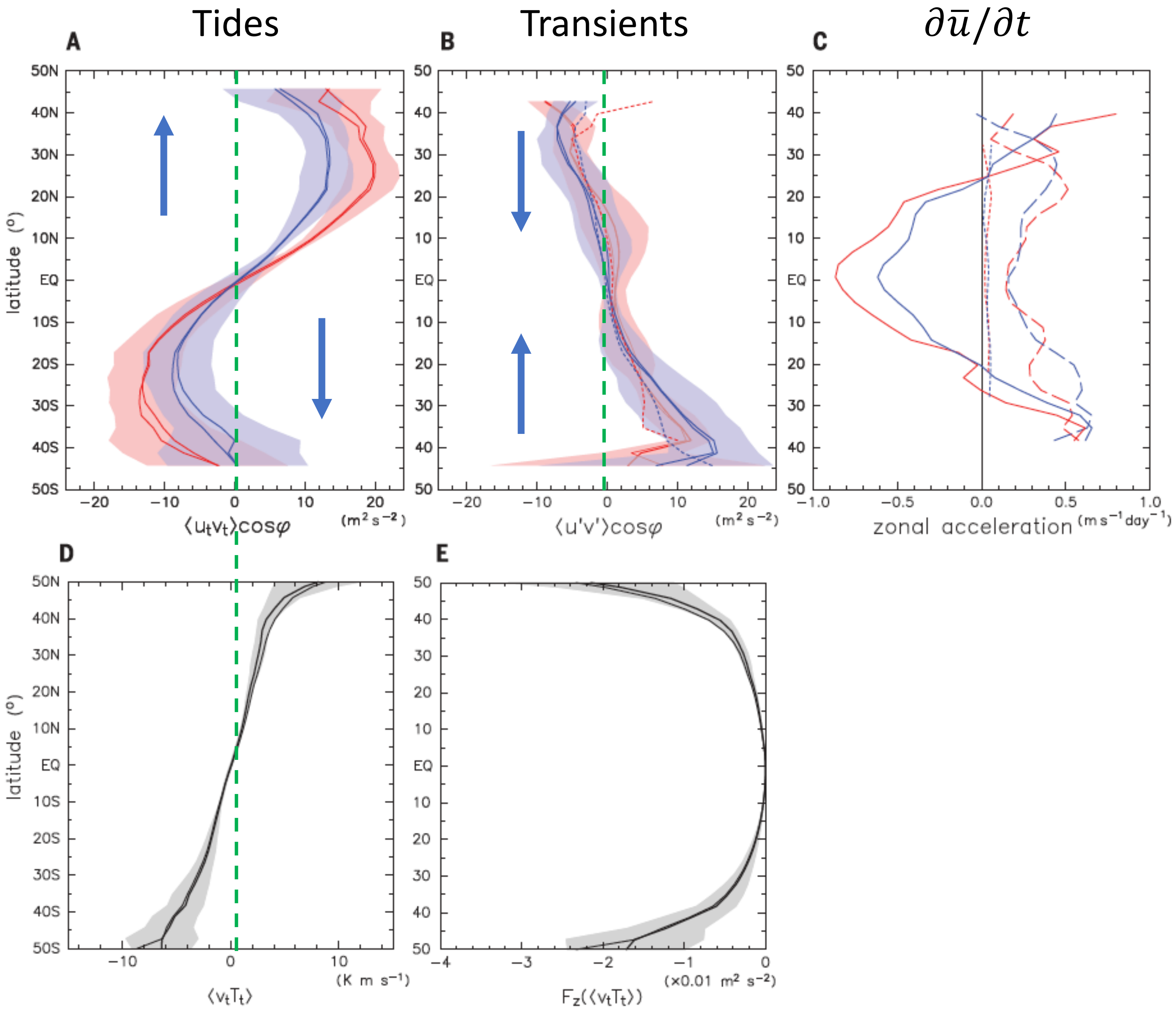
Credit: Horinouchi et al. [2020]

- Zonal momentum budget

$$\frac{\partial \bar{u}}{\partial t} = -\overline{\boldsymbol{u}_*}.\nabla m - \nabla.\boldsymbol{F}[+\bar{X}]$$

Mean mer. circulation.   EP flux convergence

- Observational verification?
  - Cloud-level velocity and T_b from Akatsuki measurements
    - Horinouchi et al. [2020]
  - Thermal tides converge westward AM in tropics, accelerating super-rotation
  - Transient waves diverge westward AM, decelerating super-rotation?

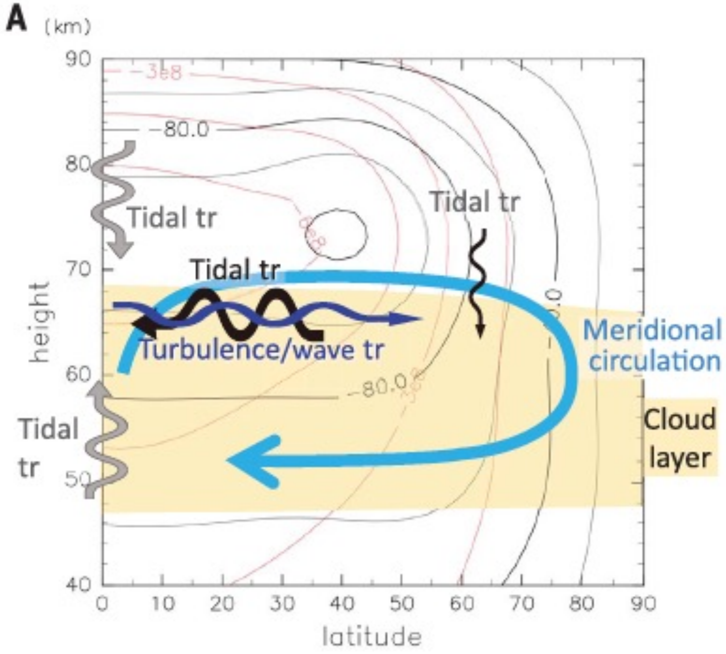


Venus super-rotation: key questions

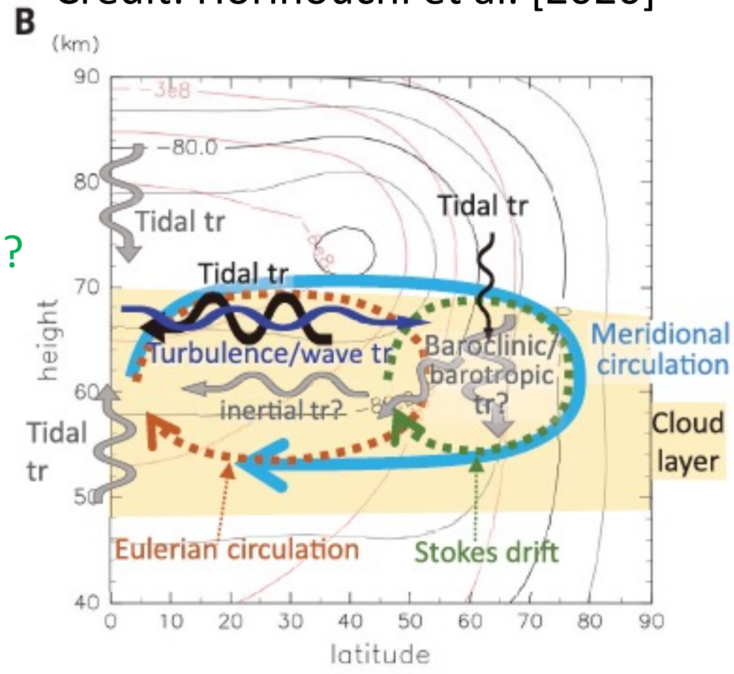
- Zonal momentum budget
$$\frac{\partial \bar{u}}{\partial t} = -\overline{\boldsymbol{u}_*}.\nabla m - \nabla.\boldsymbol{F}[+\bar{X}]$$
- Observational verification?
  - Cloud-level velocity and T_b from Akatsuki measurements
    - Horinouchi et al. [2020]
  - Thermal tides converge westward AM in tropics, accelerating super-rotation
  - Transient waves diverge westward AM, decelerating super-rotation?

?? Possible negative feedback??

- Suggests a non-classical GRW scenario, dominated by thermal tides?



Credit: Horinouchi et al. [2020]

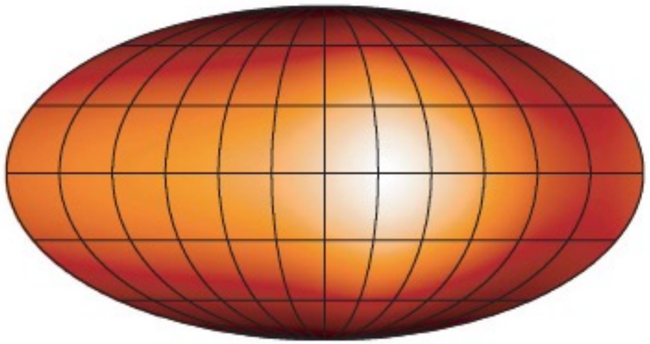


Venus super-rotation: Summary

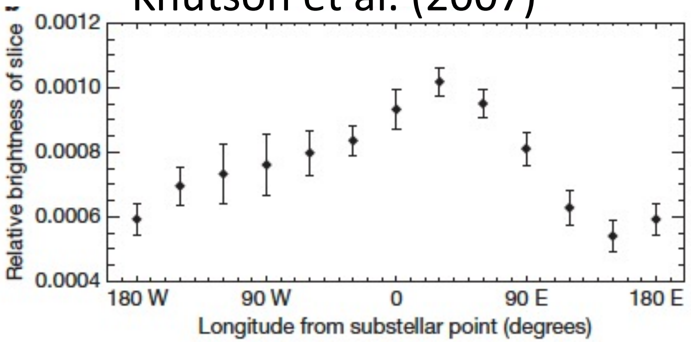
- Venus super-rotation is the most dramatic exemplar of atmospheric wave-zonal flow interactions
- Complex circulation involving multi-cellular meridional overturning and a rich spectrum of waves
- Numerical models/GCMs are able to simulate many aspects of this circulation, but not all!
  - Deep atmosphere and surface interactions?
- Seems to follow a GRW-style mechanism near cloud decks, dominated by thermal tides with smaller contributions from other waves
  - Consensus between models and observations?
  - Variability in time....?

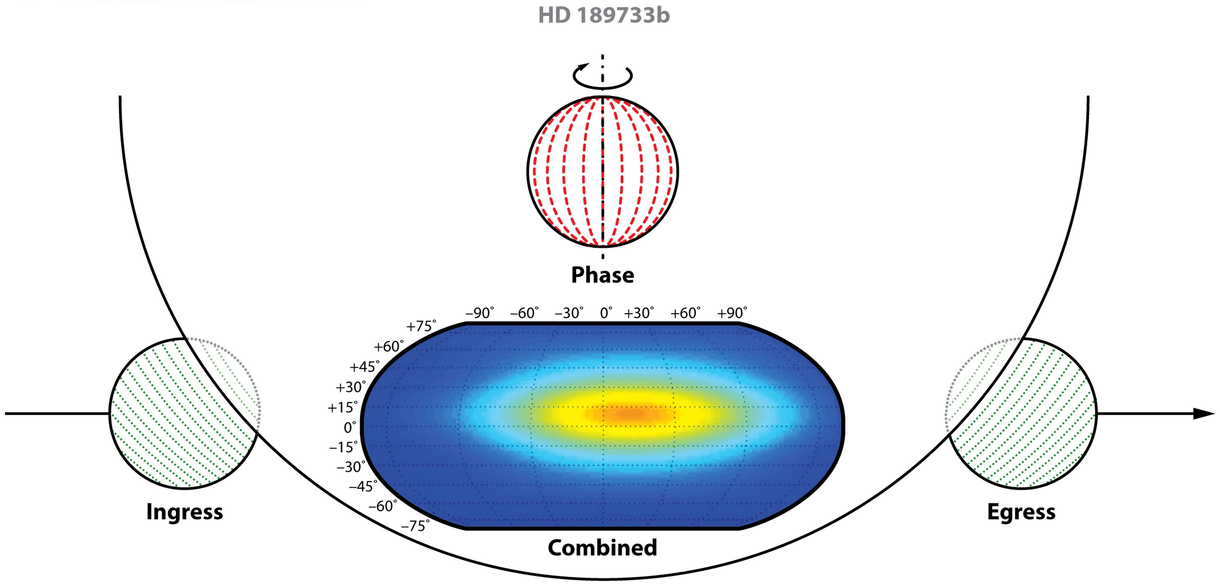
Super-rotation on tidally-locked exoplanets

- Orbital period ~ few days
- Rotation likely to be locked in 1:1 resonance with orbit, due to gravitational tides
- Phase curves from secondary transits indicate eastward displacement of sub-stellar hot spot
- Advected by strong (>1000 m s^{-1}) eastward (super-rotating) flow…?
- Mechanisms…?
  - Wave-zonal flow response to a stationary day-night heating pattern



Knutson et al. (2007)





Heng K, Showman AP. 2015.
Annu. Rev. Earth Planet. Sci. 43:509–40

Super-rotation on tidally-locked exoplanets

- Mechanisms...?
  - Wave-zonal flow response to a stationary day-night heating pattern
  - Applies for motion on scales $L \sim L_{RE}$ [equatorial deformation radius]

$$L_{RE} \sim \left(\frac{NHa}{2\Omega}\right)^{1/2}$$

  - Where L_{RE} << a we can apply equatorial β-plane
  - Used by Matsuno [1966] and Gill [1980] to obtain analytical solutions for linear response
  - With weak damping, takes the form of a superposition of Kelvin and Rossby modes
    - "Fleur-de-lis" pattern!

O. Shamir, C.I. Garfinkel, E.P. Gerber and N. Paldor [2023]

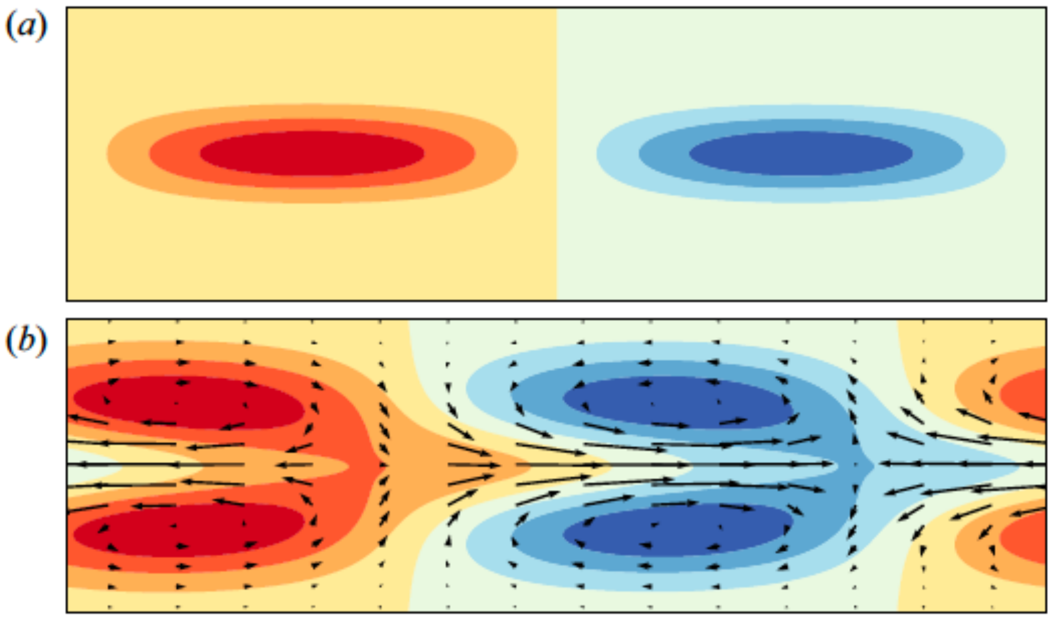
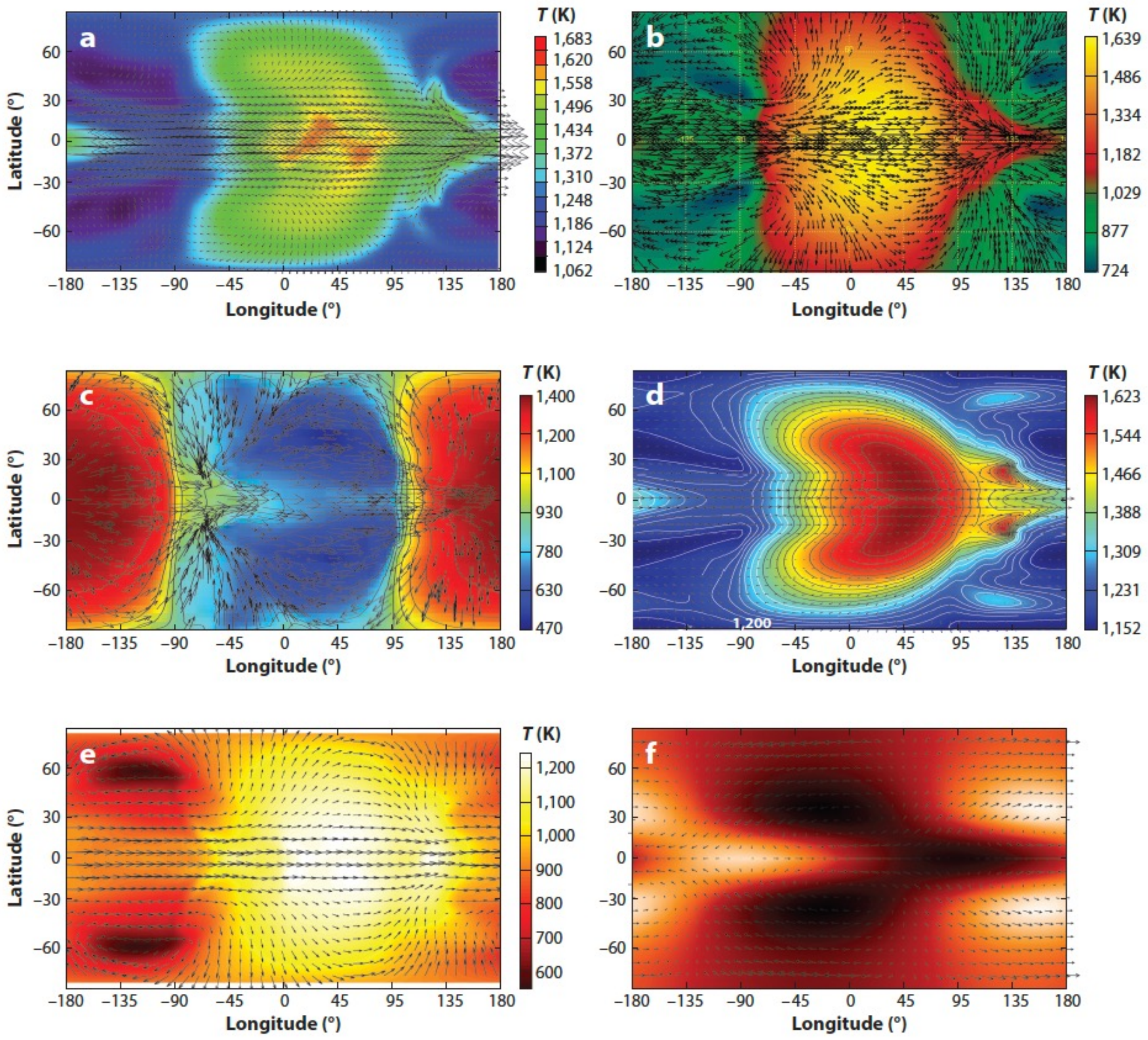


Figure 1. The fleur-de-lis on the β-plane: rendition of figure 9 in Matsuno (1966). (a) The mass source/sink – forcing. (b) The steady-state geopotential (colour shading) and winds (arrows) – response. The meridional domain extends from −18° to 18°. The equatorial Rossby deformation radius is 5.7° (637 km). Contours range from −1 (deep blue) to 1 (strong red) every 0.25.

Super-rotation on tidally-locked exoplanets

- Mechanisms…?
  - Similar ”fleur-de-lis’ patterns appear in tidally locked exoplanet GCM simulations
  - But accompanied by strong, prograde equatorial jets
    - Width ~ L_{RE}
  - Matsuno-Gill pattern also occurs in slowly rotating tidally-locked circulations on planetary scale
    - But no longer a simple Rossby-Kelvin wave pattern
  - How to predict the strength of $\overline{u}$?

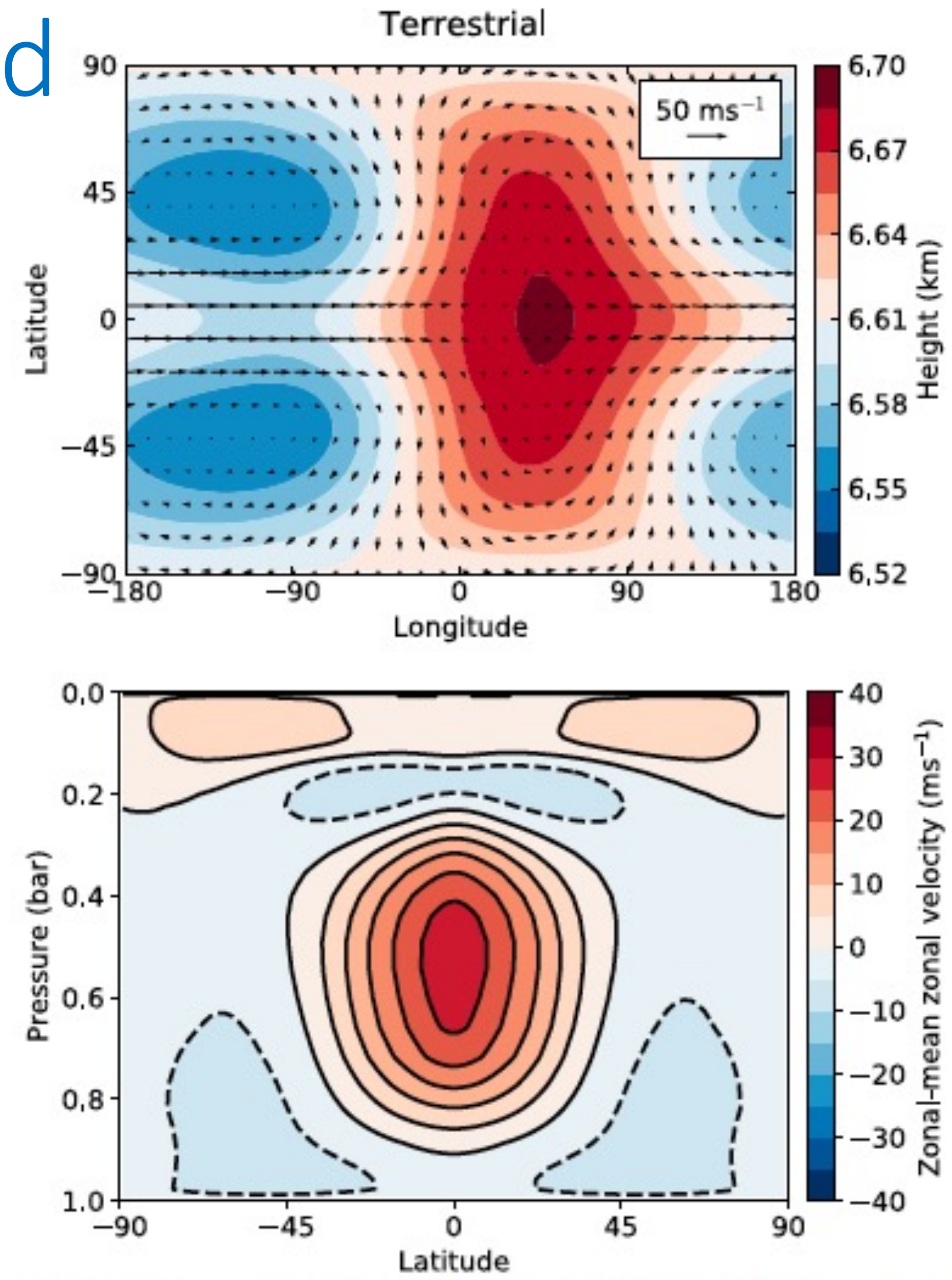
Heng & Showman [2015]



Super-rotation on tidally-locked exoplanets

- Interpret GCM simulated circulation via Helmholtz decomposition of velocity field
    - $\boldsymbol{u} = \boldsymbol{u}_{div} + \boldsymbol{u}_{rot}$

    Following Hammond & Lewis [2021]
- Example for tidally-locked terrestrial planet



Super-rotation on tidally-locked exoplanets

- Interpret GCM simulated circulation via Helmholtz decomposition of velocity field
  - $\boldsymbol{u} = \boldsymbol{u}_{div} + \boldsymbol{u}_{rot}$

  Following Hammond & Lewis [2021]
- Example for tidally-locked terrestrial planet
  - Divergent component dominated by Kelvin-like wave
  - Rotational component dominated by zonal jet + Rossby-like wave

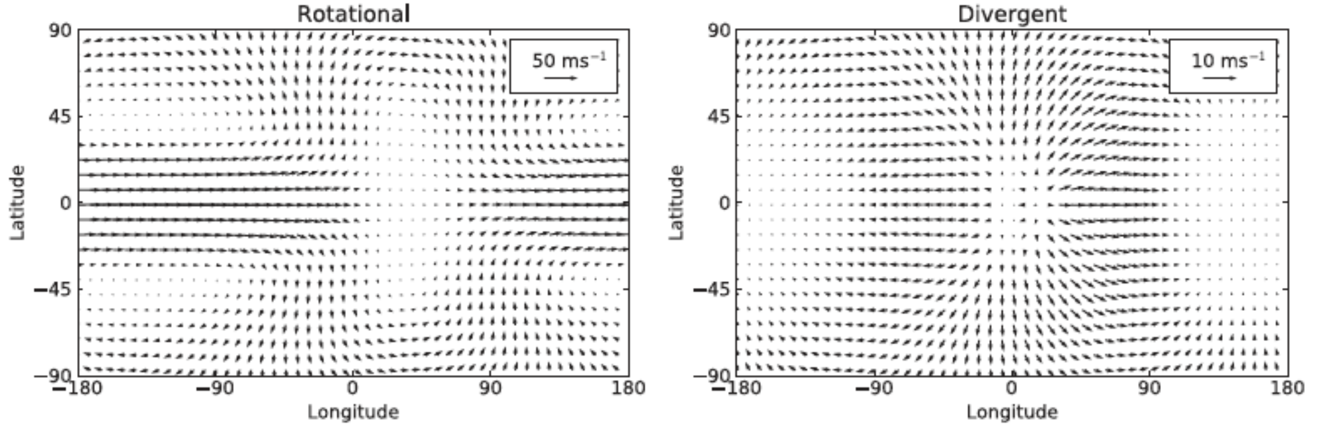


Fig. 2. Helmholtz decomposition of horizontal velocity $\boldsymbol{u}$ for the terrestrial simulation at 0.4 bar. (*Left*) Rotational component of $\boldsymbol{u}$, $\boldsymbol{u}_r$. Fig. 3 shows that this component is composed of the zonal-mean eastward equatorial jet and a stationary wave with zonal wavenumber 1. (*Right*) Divergent component of $\boldsymbol{u}$, $\boldsymbol{u}_d$. At the pressure level shown here, the divergent component is dominated by an isotropic flow away from the substellar point (0°, 0°), which we will show to be associated with a single overturning cell.

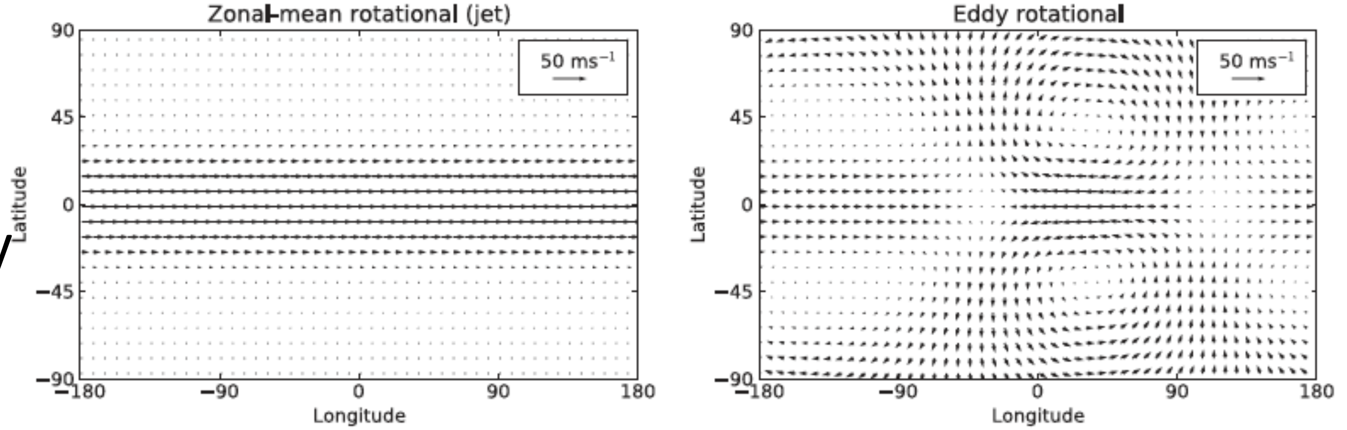


Fig. 3. The two physical components of the rotational circulation in Fig. 2. (*Left*) Zonal-mean part of $\boldsymbol{u}_r$, $\overline{\boldsymbol{u}}_r$, which is the eastward equatorial jet. (*Right*) Eddy (total minus zonal mean) part of $\boldsymbol{u}_r$, $\boldsymbol{u}'_r$, which is dominated by a wave with zonal wavenumber 1.

Super-rotation on tidally-locked exoplanets

- Interpret GCM simulated circulation via Helmholtz decomposition of velocity field
    - $\boldsymbol{u} = \boldsymbol{u}_{div} + \boldsymbol{u}_{rot}$
    Following Hammond & Lewis [2021]
- Example for tidally-locked terrestrial planet
    - Divergent component dominated by Kelvin-like wave
    - Rotational component dominated by zonal jet + Rossby-like wave
- Divergent component roughly axisymmetric about sub-stellar/anti-stellar axis

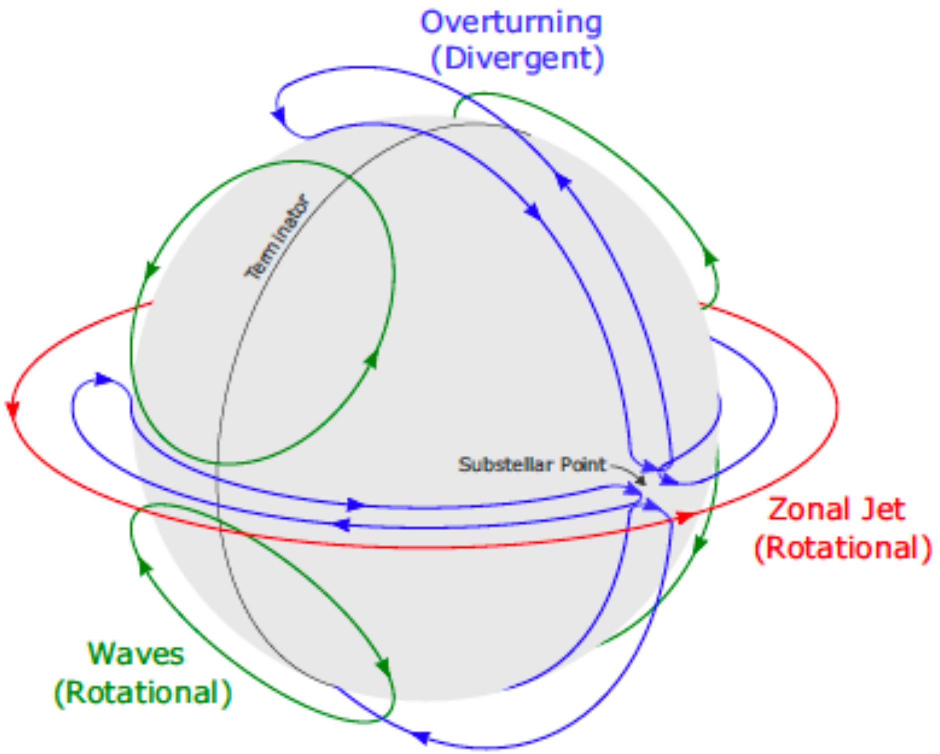


Fig. 10. A schematic showing the three main circulation components identified in this study. Divergent, overturning circulation (blue) rises at the substellar point and extends roughly isotropically across the terminator, before descending on the night side at a location that depends on the strength of the circulation. The rotational circulation is divided into the zonal-mean jet (red) and the eddy stationary waves (green). The divergent circulation has approximate symmetry around the axis connecting the substellar and antistellar points, which motivates the use of the tidally locked coordinate system to analyze it.

Super-rotation on tidally-locked exoplanets

- How to predict the strength of zonal jet $\bar{u}$?
  - Estimate following Hammond et al. [2020]
  - Approximate zonal mean momentum Eq on the equator by

$$\frac{\partial \bar{u}}{\partial t} \approx \underbrace{-\bar{\omega}\frac{\partial \bar{u}}{\partial p}}_{\text{MV}} \underbrace{- \frac{\partial}{\partial p}\left(\overline{u'\omega'}\right)}_{\text{SV}} \underbrace{- \frac{1}{a\cos^2\varphi}\frac{\partial}{\partial \varphi}\left(\overline{u'v'}\cos^2\varphi\right)}_{\text{SH}}$$

  - Solve linear equations for waves + $\bar{u}$ on a β–plane and set $\frac{\partial \bar{u}}{\partial t}$=0 so

$$\bar{u} \approx \int \frac{1}{\bar{\omega}}(\mathrm{SV} + \mathrm{SH})dp$$

Super-rotation on tidally-locked exoplanets

- How to predict the strength of $\bar{u}$?
  - Estimate following Hammond et al. [2020]
  - Approximate $\bar{u} \sim -\frac{H}{\bar{w}}\frac{\partial}{\partial p}(\overline{u'\omega'})$;

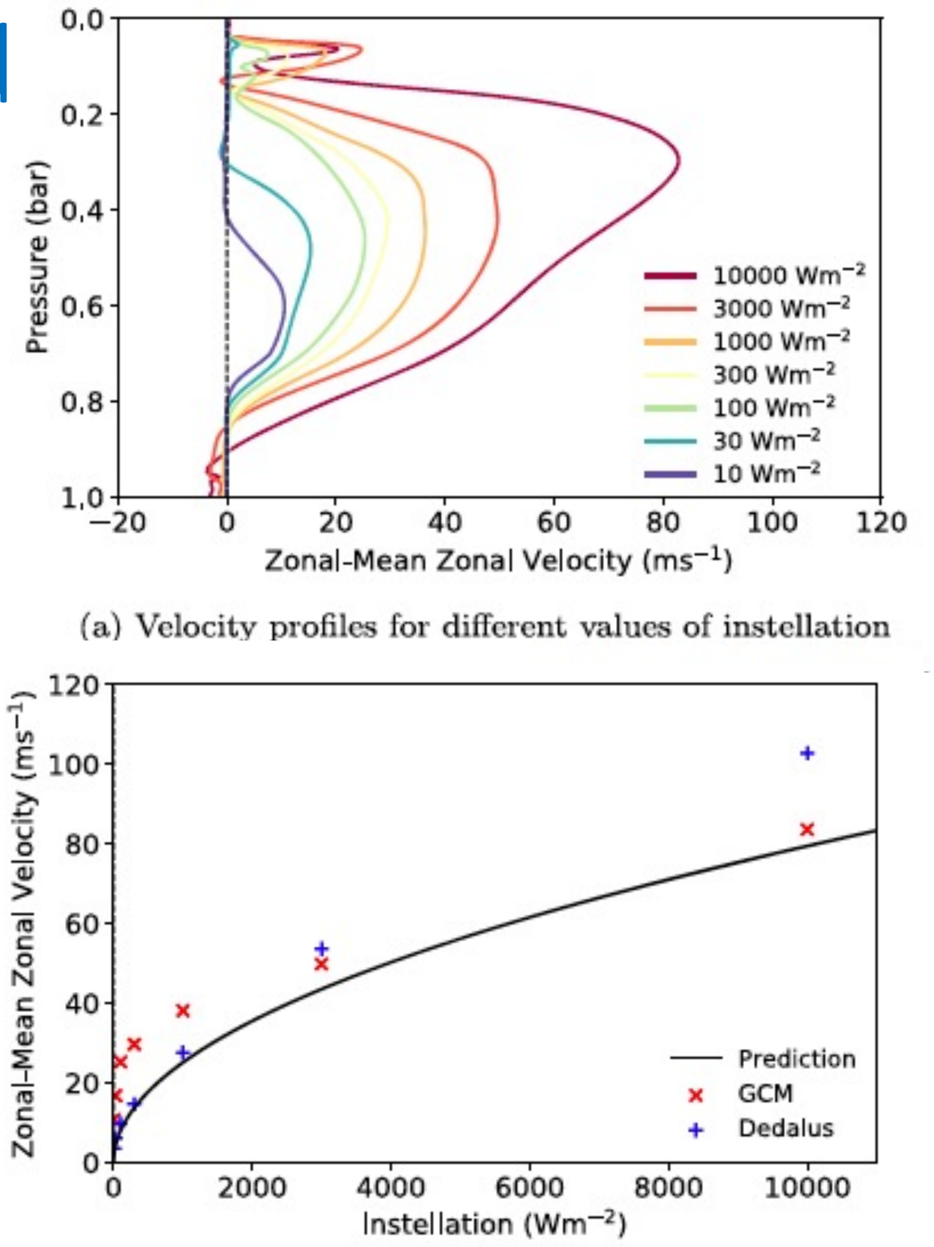
$$w' \sim \frac{RQ}{N^2 H}; \text{ and}$$

$$u' \sim \frac{w'a}{H} \approx \frac{RaQ}{N^2 H^2}$$

  - Leading to

$$\bar{u} \sim \frac{2.53\pi a g^3 \sigma^{1/2}}{RN^2 \rho_0 c_p} F_0^{1/2}$$

  - Scaling ~consistent with GCMs….?



(a) Velocity profiles for different values of instellation

(b) Maximum jet speed versus instellation

Summary/Conclusions

- Venus & Titan both seem to super-rotate via a form of GRW mechanism at cloud level
  - Barotropic instabilities generate dominant waves on Titan
  - Mixture of thermal tides and barotropic/baroclinic instabilities on Venus?
- Common occurrence of Rossby and Kelvin waves associated with variability
- Rossby & Kelvin waves play important roles in accelerating zonal jets in tidally-locked planets
  - Matsuno-Gill phase-locked pattern
- Scaling of zonal wind magnitude….?

Open issues

- Super-rotating bifurcations and Earth climate change….?
  - Super- or sub-critical?
- Mechanism for gas/ice giant equatorial jets?
  - Deep or shallow?
- Verification of what drives Titan’s super-rotation?
  - Which waves are active?
  - Observations….?
- Venus super-rotation
  - Time variations?
  - Deep atmosphere processes?
- How valid/useful are scaling theories for super-rotation?